Shaku Design

Shakuhachi Index

Updated 12/22/06

The following pages are presented in the order they were developed, thus they reflect the directions my understanding took as it deepened. From the onset this project was two-fold: 1) to understand the acoustics of end-blown flutes--the shakuhachi in particular and 2) to design a new type general purpose utility flute which is simple to make, easy to own, and has excellent aural qualities--a true Zen flute as it were, something with an abundant spirit of resilience.

Didge Design

General Rules-of-Thumb for the Design of Didgeridus

Updated 8/18/05

This page is part of an ongoing attempt to create a general set of guidelines for the design of Didgeridus.

Didgeridus belong to the family of musical instruments called areophones in which the sound is produced by the vibration of air. A subgroup of lip-buzzed horns contain simple or primitive trumpets, alphorns and Didgeridus among others. Generally these instruments are conical (with the larger end away from the player) and often curved.

We'll first consider cylindrical tubes to gain a general understanding of a portion of sound physics. The rate of vibration of air in an open tube (like a Didge) is determined by the length of the tube along with other smaller factors like the Aspect Ratio and how much friction the surface of the inner tube wall produces.

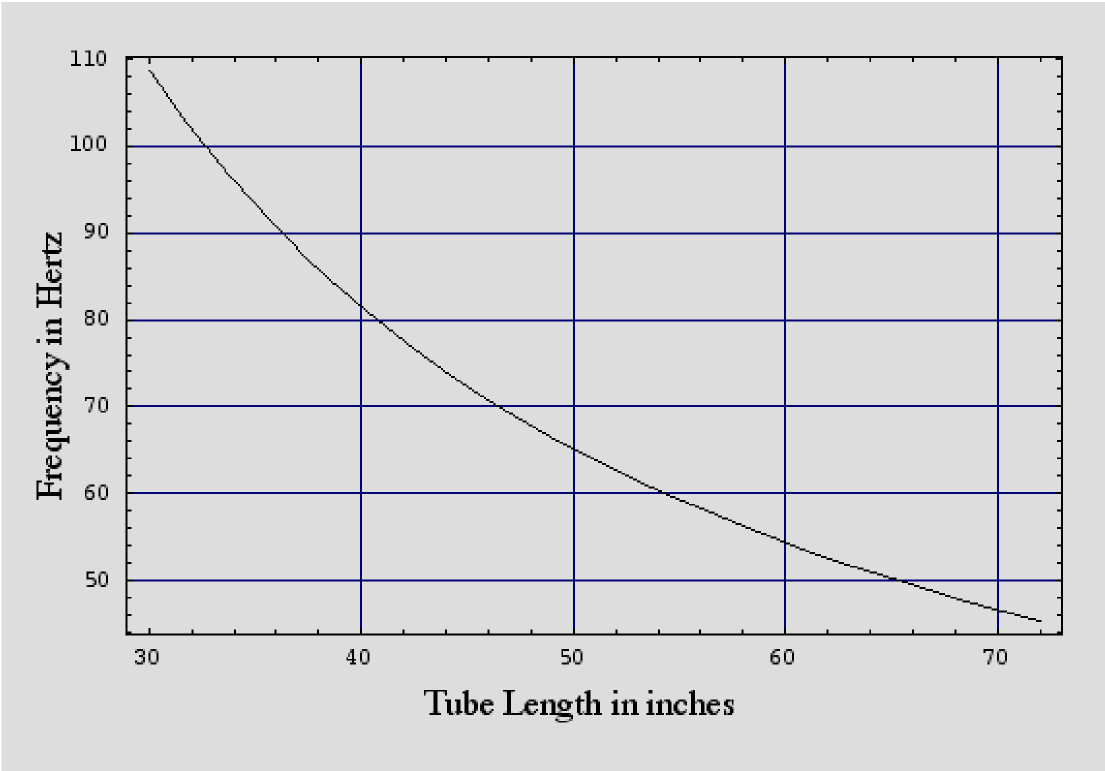
The cross-sectional shape of an air column has relatively little acoustic consequence. Instead, cross-sectional area is the important consideration. An air column which is square in cross section, and of uniform dimensions over its entire length, behaves very nearly the same as a cylindrical pipe of the same cross-sectional area. A straight-sided square pipe which increases in cross section at a uniform rate behaves like a conical pipe.

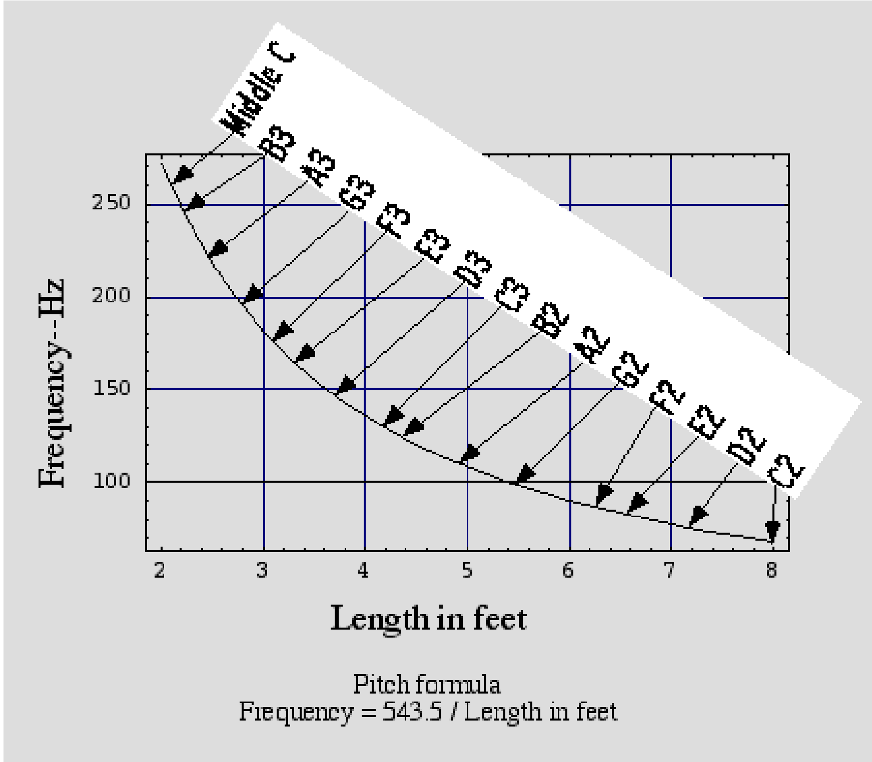
It is also generally assumed that as long as the cross-sectional area retains the intended value, it doesn't matter how the tube may curve and snake around--a cylindrical pipe will still behave acoustically like a cylindrical pipe even after bending, as long as there are no sharp angles or kinks.

Perfect Pitch Dreaming

One of the first considerations in design is setting the **pitch** (frequency as measure in Hertz or cycles/second). Fortunately, it's one of the most straight forward parts of Didge design. Ignoring a handful of niggling small factors, pitch is determined by tube length. The pitch of most Didges is between 50 and 100 Hz so that's the range we'll concentrate on.

How long should a tube be to get a D note? The answer, and it should also be applied to all such questions like it, is that it's the length of the tube when sounding a D note. This isn't a trick answer, it is meant to convey that much about Didge building is experiential instead of theoretical. Theory will get us close but actual construction and tuning is the final word. Instead of attempting to precisely account for a dozen or so variables (large and small) it's usually easier just to build the thing.





An open tube will support a standing wave (sound) who's frequency (pitch) is proportional to the length. The frequency is equal to the speed of sound (1087.1 ft/sec) times 3, times the length in inches. F = 3261.3 / L Or to say it another way: 3216.3 / Length = Frequency. **And yet another way, the tube length divided by three, times the fundamental frequency equals the speed of sound.** A 50" tube will produce a sound of 65.2 Hz.

Slightly different formulas factor in bore measurements:

L = (3216.3 / F) - 1.35 B for a pipe open at one end
L = (3216.3 / F) - 1.65 B for a pipe open at both ends

M. Cavaillé-Coll, the French organ builder, used:

L = (3216.3 / F) - (5/3) B for cylindrical pipes open at one end
L = (S / F) - 2 A for square pipes open at one end with A as inner side

How long should a tube be to get a D note (73.4 Hz)?

We get various answers:
L = (3216.3 / F) L = 3261.4 / 73.4 = 44.43"
L = (3216.3 / F) - 1.35 B = 42.27" (1.5"ABS pipe with a bore = 1.6")

Theoretical Lengths and Pitches

Note	Frequency	Inches	Cm
G#	103.8	31.42	79.8
G	98.0	33.28	84.5
F#	92.5	35.26	89.6
F	87.3	37.36	94.9
E	82.4	39.58	100.5

D#	77.8	41.92	106.5
D	73.4	44.43	112.9
C#	69.3	47.06	119.5
C	65.4	49.87	126.7
B	61.7	52.86	134.3
A#	58.3	55.94	142.1
A	55.0	59.30	150.6
G#	51.9	62.84	159.6

If having a 'tuned' Didge is a goal, remember, this table is for a straight-walled tubes. Since it derives from ideal, theoretical circumstances, when cutting add a couple inches to compensate for any general weirdness which might creep in. Altitude makes a difference. I'm at 7000' so my Didges run long. Toward the end of fabrication tune by trimming to length.

Tambourine Dreaming

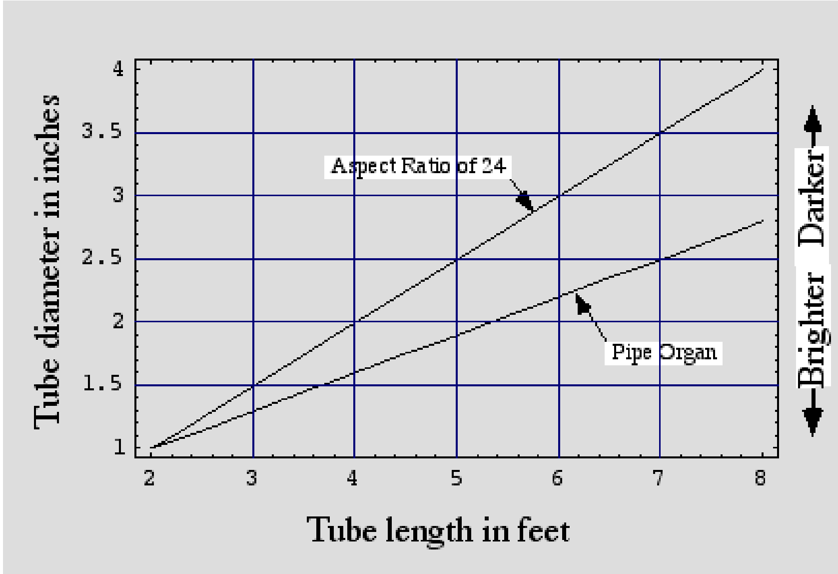
Another important consideration in design is the **Aspect Ratio (AR)**--the ratio of tube length divided by its diameter. This ratio largely determines the **overall tonal quality of sound--the timbre.**

'Fat' air columns (low AR) are generally poorer in overtones than skinny ones. At the extremes, excessively fat pipes will not speak at all, and excessively slender ones tend to break up into harmonics rather than produce the fundamental. You can see this effect at work in the ranks of a large pipe organ: the thickest pipes are the ones called "flute pipes" which are characterized by a strong fundamental and relatively weak higher overtones. The ones called "string pipes" are much more slender, and they show prominent harmonic overtones.

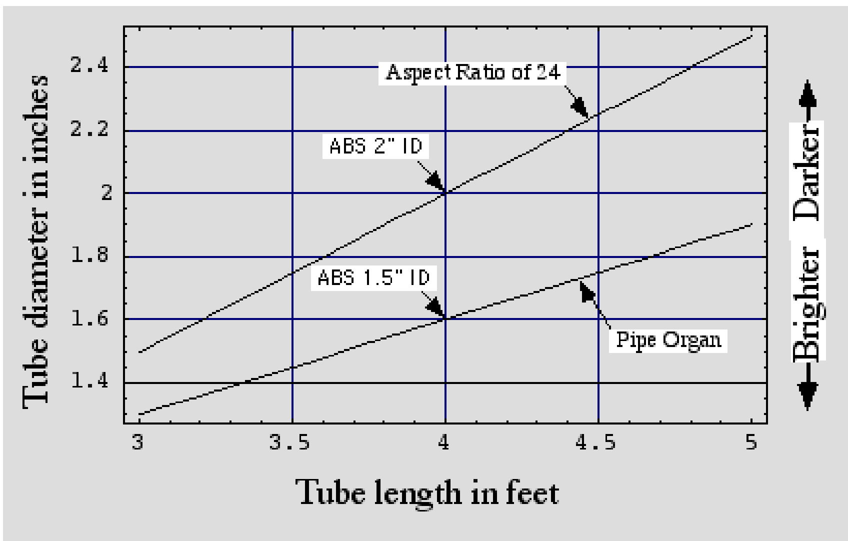
Is there an ideal Aspect Ration one can strive for? For a 24" flute a diameter near 1" is considered ideal by some--a good balance of fundamental and harmonics. But as the example of the organ above indicates, people will select different ratios as they seek different tone qualities.

It seems logical that if we adopt the AR (24) from the flute above that this ratio should produce the same quality of sound in any length pipe. **However, this isn't the case.** It turns out that the ear hears lower pitched pipes as relatively dark, and the higher ones as relatively bright. To create greater unity of timbre in a pipe organ, the lower pitched pipes should be a bit thinner relative to length, creating a slightly richer harmonic spectrum. A rule of thumb developed by European organ builders over the years has been to make tube diameter one and two thirds (5/3) as large for each doubling in length. So in pipe organs **the AR isn't constant**; it increases as a pipe's length grows.

For the sake of this example let's adopt an Aspect Ratio of 24 as optimal for a two foot tube. The graph below plots both a constant AR of 24 and the 5/3 doubling used in large pipe organs.



(An expanded view)



Timbre is greatly influenced by the Aspect Ratio.

•Increasing the tube's diameter increases the mass of the air in the tube making it harder to oscillate. If you have any doubt about this put a coin in your hand and see how rapidly you can shake your fist. Now try a brick. Greater tube diameter makes a Didge sound woodier, darker, breathier; this will increase its fundamentals. Increased diameter requires a greater force to play.

•Decrease the diameter to create a brighter, airier, clearer tone--more string-like with harmonic overtones. Decreased diameter requires less force to play.

Since a Didge sounds only one 'note' it's important that this note be pleasing to the player. Conveniently, the two lines in the graphs work out, **at four feet**, to be perfect for ABS plumbing pipe. For ABS pipe the ID's are actually 2.03" and 1.58"--an excellent match to the graph. Experimenting with these two diameters of unmodified straight pipe will give you a sense of the effect of Aspect Ratio. And will provide a good idea of the general AR you want your Didge to have. With the dimensions mentioned here we're talking about ARs of 24 and 30. **So, as a general rule the Aspect Ratio of Didges should probably be between 20 and 28--**plenty of room for individual preference.

A low AR favors the fundamental--a high AR favors harmonics.

Again, remember the Aspect Ratio doesn't remain constant when scaled. That 3' Didge you love the sound of **will not** have the same timbre when both length and diameter dimensions are doubled.

For some precise hole measurements and instructions leading to some great practice shaks visit PVC Shakuhachi. The Aspect Ratio's role in the sound of the shakuhachi becomes clear in these examples.

Chuck Yeager Dreaming

There is a lot of traditional lore about which materials are best for wind instruments. In practice, however, any reasonably heavy, hard, smooth and rigid material will sound much like any other such, and have the same potential for producing a good-sounding instrument. A prize shakuhatchi, for example, has a bore like a mirror--it's like looking into the navel of infinity. However, extremely hard reflective surfaces are not necessarily the ideal: people sometimes prefer the mellower tone of somewhat damped resonances--in a Didge, for example.

Timbre is greatly influenced by air friction in the bore.

Wind instrument tubing materials that are light and/or yielding will dampen air resonance within the tube to some degree, and lower the resonate frequencies slightly. Walls made of rough or porous materials also have noticeable damping effects. Increased damping leads to poorly defined resonance peaks, especially in the high frequencies, creating a sound that is less than bright.

We don't ordinarily think of friction within a Didge, the air flow doesn't seem to be traveling very fast. But we're thinking at the wrong scale. What's going on in your Didge is happening at **Mach 1--the speed of sound.** The air volume in the bore of a Didge may turn over at a leisurely rate but the molecules making up the sound waves are moving at Chuck Yeager speeds. So think about the surface of something you would put in a wind tunnel to be tested a Mach 1. The smoother, more polished, mirror-like the surface the less drag it has. Such a surface is 'slippery'. And the same circumstances are true in the bore of a Didge.

So what kind of inner surface is best for a Didge? Well, it depends. A smooth surface brightens the timbre, rough darkens it. And we're talking more about the micro-surface rather than obvious irregularities. If the surface is rough, air drag increases and thus a greater force is needed to oscillate the air. The instrument isn't as 'quick' and supple as it could be. So in answer to which surface is preferable we need to realize that the texture of the inner bore surface needs to be weighted against the Aspect Ratio.

We can brighten a Didge's tone by: 1) raising the AR, and/or 2) polishing the bore.
The tone can be darkened by: 1) lowering the AR and/or 2) increasing friction in the bore.

A thin pipe with a slippery (fast) bore is doubly bright.
A fat pipe with a rough (slow) bore is doubly dark.

So if a Didge's AR is a little low we could polish the bore and come out about right. How to polish a bore? A good coat of varnish, lacquer, polyurethane, etc. is a quick, easy way. Part of the reason for the tradition of pouring water down a Didge at corroboree is to "polish" the bore a bit. A wet surface is smoother to air molecules. Slop some water down the bore of an untreated rough wooden Didge and it's tone will brighten.

How to roughen a bore? There are the obvious ways--steel wool, etc. Affix a big wad of coarse steel wool to the end of a rod and then use an electric drill. Gluing sand on the bore surface is another possibility. Mix up a diluted mixture of wood glue and water, coat the inside, fill with dry sand, leave overnight, then drain the sand out. But there are other more interesting and subtle possibilities.

To get and/or increase that nice mellow, breathy, woody, dark timbre we need to increase air friction in the bore. But this doesn't necessarily mean **on** the bore wall. To get a feel for the effects of air friction, snake an ACE bandage down the 4' test pipes (above) you were using to explore ARs. Try it stretched and then loose. It's a simple matter to experiment with different materials inserted in the bore to alter the air friction. Make sure they're fairly thin or their cross-sectional area will alter the AR of your pipe. You can 'place' strips of cloth using string tied to the ends. Try adding friction in the top half of the tube, the bottom, the middle. You get the picture.

What surface do we want? The one which **coupled with the Aspect Ratio** produces the tone we like. These two: **AR and friction** need to be complimentary and balanced. So it's quite possible to have a very rough bore and a fairly bright tone or a glassy-smooth bore and a dark haunting tone. One of the woodiest, darkest tones I ever got was from a polished plexiglas tube--but it's AR was quite low.

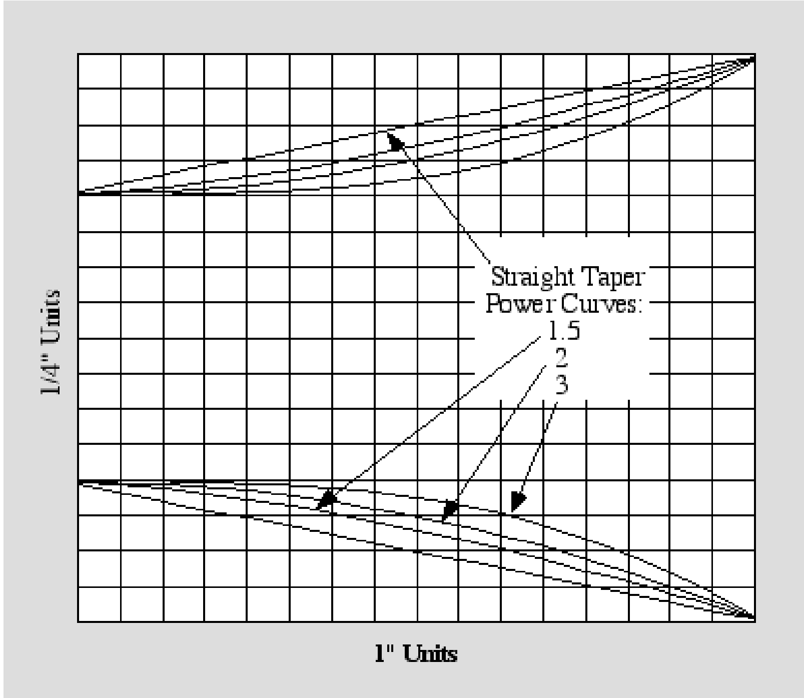
Power Curve Dreaming

The end of a wind instrument tube, where the enclosed air meets the outer airs, is a critical point. A large opening is good for sound projection, since it creates a lot of 'surface area' for radiating the sound. The sound that radiates into space from a small opening will be restricted, even when the internal wave is quite strong. You can increase the size of the opening, and thus increase radiation efficiency, by flaring the bell at the end of the tube. The presence of a bell affects the tuning and relative prominence of the overtones Brass instruments makers have learned to compensate for these effects, but the factors involved are rather subtle. Estimating the effective tube length for a tube with a belled end is difficult, but it is safe to act as if the tube effectively ends at some point mid-bell.

Didges are usually (often?) tapered, ending with a flair or bell toward the end. Do we want a straight-walled taper, a curved taper? Here is where ideal musical physics and didges part ways. The shape of a Didge's taper doesn't derive from any ideal mathematical standard as do many modern brass instruments. It comes from what the eucalyptus tree thinks is the best taper for growth. That being said, the graph below uses power (X to the n) curves to sketch out possible taper variations.

Creating a Didge out of any but naturally occurring materials requires that we make decisions about taper. For the purpose of these exercise stick with ABS pipe in the four foot length as above. In both 1.5" and 2" ABS pipe wall thickness runs about 0.160". With a modicum of care it can be heated and stretched until it's half as thick. Therefore, we can create a diameter twice as great. A bell on a 2" pipe can reach 4" without much trouble.

Using ABS pipe we can **double** the internal diameter--let's use that as a design setting. Next we need to decide how much of the tube we want to taper. A quarter? Third? Half? To get started let's make it a third or 16" for a 4' tube. Cut a mandrel out rigid material (1/8" masonite?) to check and measure the taper.



Template of a 16" Didge Taper Mandrel for a 2" ABS Tube

(Note that the length and width scales are different so the schematic will fit on this page)

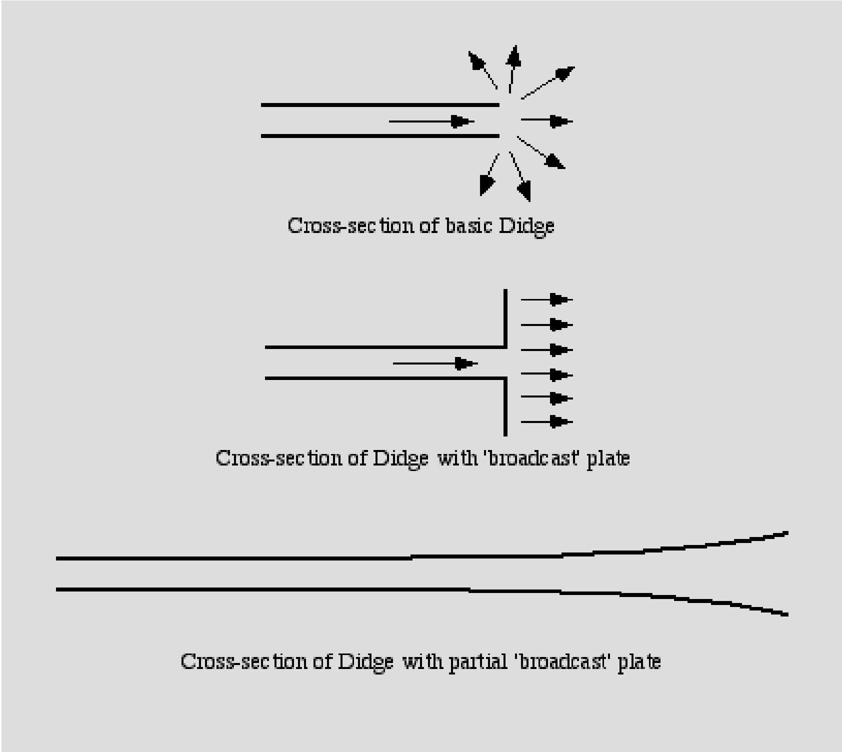
Probably in the end, applying air pressure to a heated tube is the most reliable way to expand it. What you'll attempt to do is create a bubble who's shape you have control over. Since both ends of the tube need to be 'stoppered' when applying air pressure you'll end up losing a foot or so of tubing when cutting the end off the bell. A way around this is to create a 'double' mold which will produce two Didges at a time--bell to bell. Then just cut them apart.

Construct a tapered mold and place the heated third of the tube within it--then apply air pressure. Such a mold doesn't have to be elaborate, it ends up being a frame more than a mold. Wire mesh seems a good choice from which to create experimental 'molds' as you can apply heat through the wire.

Tapering at least a third of the tube seems a good general guideline. Any of the tapers shown in the graph will produce a respectable sound.

The three main musical qualities are pitch, timbre, intensity. The first two have already been discussed. Intensity is determined by the force of the air the player uses, the 'efficiency' of the tube and the 'broadcast' portion of the bell. Why can the tuba in the marching band be heard blocks away? One factor is that a tuba is low pitched (like a Didge) and low frequency sound travels better. But the factor we're interested in here is the 'broadcast ' portion of the bell. Think tuba. Think that **big** round, nearly flat portion of the bell. If you want your Didge to BROADCAST then a surface is required. That means flattening out the edge of the taper/bell. The sound waves need something to 'push' against. 'Loud' horns have large effective broadcast plates.

The first two examples in the graph below are extreme cases: No broadcast surface and one specifically designed to do so.

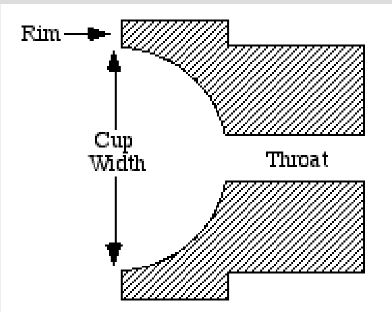


The upshot is this: if you want your Didge to have greater intensity, start flaring the lip of the bell. The greater it's turned and flared the greater the sound amplification and projection. Try different mandrel shapes and curves until you get the balance of timbre and sound projection you like.

Everything effects everything. Change the bell shape to increase the intensity and the timbre begins to go south. Cut the tube to raise the pitch and the Aspect Ration starts to tank. Each change favors one quality over another. It's kind of like herding turkeys--they all want to go different directions. There is no **perfect** Didge--there's only a **balanced** Didge. Designing a Didge (or most any musical instrument for that matter) is an exercise in compromise. Keeping that in mind will making designing go much easier.

Bush Wax Dreaming

Back to the tuba analogy. If the Didge were to have a mouthpiece other than a wax rim it would be something like the mouthpiece of a tuba. The mouthpiece in the schematic below is intended to fit into the end of a 1.5" ABS tube. **Such a mouthpiece makes the Didge much easier to play.**



Didge Mouthpiece Prototype
in cross section

The mouthpiece has three elements: Cup, Rim and Throat. As always, each element must be balanced with the others.

•Cup

Cup width is determined by mouth size--1.25" is a good general adult size. A wide cup favors endurance, while a narrow width favors flexibility and range.

The cup can be deep or shallow and the drawing above (using a half-circle for cup shape) is fairly deep. A deep cup favors sonorous dark tones (lower registers), increases volume and lowers pitch. Shallow is the opposite The qualities of cups are deep/shallow and large/small.

•Rim

Rim width had to do with lip comfort and playing dexterity. A round rim favors comfort while a sharp rim favors brilliance and precision of attack. The inner rim edge should be sharper than the outer. Rims are wide/narrow and round/sharp.

•Throat

Throat diameter should run between 3/8" and 1/2". Start small so you can drill them out. A small throat favors the higher registers and endurance. The throat size should create a little 'resistance' or back pressure. If it gets too large the sound becomes 'breathy'. Throats are small/large and short/long.

The following table is a very general set of parameters --someplace to start.

Table of General
Mouthpiece Measurements

	Inches	mm
Cup Width	1.25	31.7
Cup Depth	0.63	15.9
Rim Width	0.20	5.0
Throat Diameter	0.38	9.5
Throat Length	1.00	25.4

Another advantage of using mouthpieces is that you can get different qualities of sound from a single Didge by switching mouthpieces.

Possible methods of manufacture: standard lathe techniques, ceramics (building from clay and firing), molding using a thermosetting polymer such as Sculpy (available at most craft/art stores). Put some grooves around the outer side of the rim so it's easier to pull the mouthpiece out of the tube. If needed use wax for tight fit.

Bandicoot Dreaming

Domestic cats all purr at the same frequency! Big cats, scrawny cats, old tom cats, kittens--same frequency. Which indicates that purring isn't some physiological phenomenon but must be driven centrally from the brain. Purring is associated with contentment, well-being, good health and a trancey kind of behavior. Do cats purr to 'massage' their neurons? Do the neurons operate to 'massage' the cat with sound?

In any event, the frequency for cats is **25.9 hertz**. A Didge needs to be about 10.5 feet long to resonate at that frequency. But if we employ frequency doubling (octave jumping--we're talkin' G# here) we can end up with a 'relative' to cat purring at **51.8 Hz (63") and 103.6 Hz (31.5")**. Something special might be happening with sound in these ranges emanating from Didges about those lengths.

Do Bandicoots purr? If so, we have a good idea of the possible frequencies. This whole vibratory deal may be specific to neuron health and as possessors of a few billion of the suckers humans might be well disposed to 'purr' occasionally. What better way to do so than with a Didge. It's a thought.

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Utility Flute

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There's a Zen story about Tan-hsia who arrived at a monastery late one stormy night. Everyone had long been asleep and when the master couldn't find wood for the fire he burned the ornate wood carvings of Agyo and Ungyo, the temple guardians. Finally, warm and dry he fell asleep by the hearth.

There's another story about a master who, on handing a beautifully lacquered bowl to a monk, asked, "What's the most important part of this bowl." The monk carefully examined the detailed and delicate gold work, the polish and sheen of the bowl's urushi surface and finally admitted he didn't know. "This part.", the master said and with a sweep of his hand indicated the inner volume of the bowl.

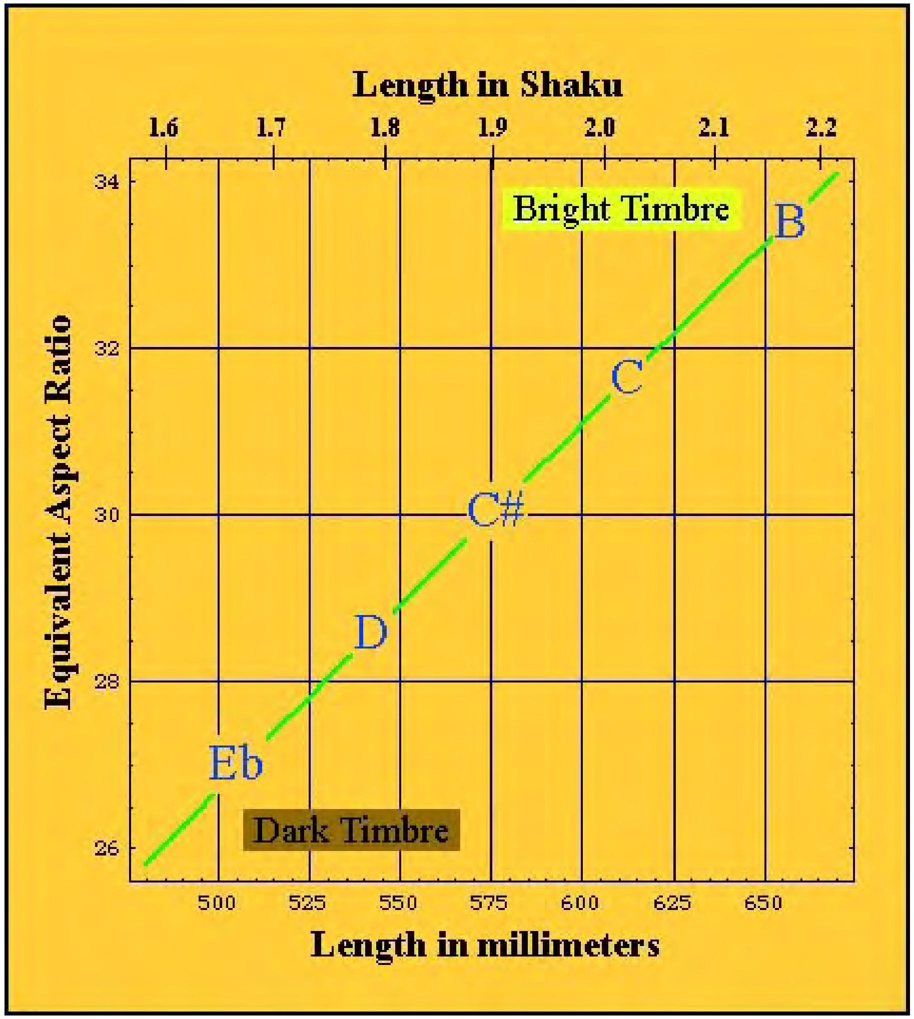
Penetrate these two stories and you'll know flutes--they've driven our inquiry as to the nature of end-blown flutes. The stories allowed us to cut through persistent shakuhachi myths. Along the way, we devised our own Zen riddle--From whence does the flute sound come? And found that it comes not from the bamboo or the lacquer or the material aspects of a flute but from the shape of the void within the flute. **Flute sounds come directly from the void.**

Based on this knowledge and utilizing the precept of direct simplicity, we've designed and developed a new type of end-blown flute made of custom-extruded, custom-colored, **custom-sized**, high impact grade RPVC. It's crack proof, waterproof, scratch resistant, dent proof and has excellent acoustical qualities created by careful attention to the inner geometry. **This is the flute to serve you in your pursuit rather than the other way round.** Do you spend your time defending your flutes from the elements/extremes? This resilient flute is well able to take care of itself and allow you to keep your mind on what's important. Durability matched with playability makes the Utility Flute a suitable tool to serve your quest. Arising from Shinto/Taoist sensibilities, the Utility Flute is intended for use out-of-doors and close to nature; with five holes it has a minor pentatonic scale. All flutes are handmade, one at a time.

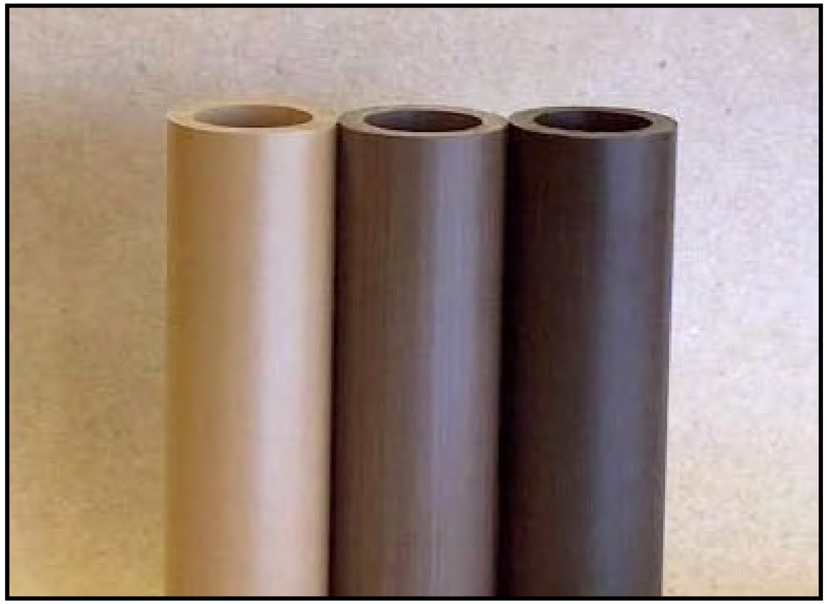
> The late Bizen potter Kaneshige Michiaki (1934-1995) said of tradition:
>
> *Tradition is sometimes confused with transmission. Copying Momoyama pieces is transmission. Producing contemporary pieces incorporating Momoyama period techniques is tradition. Tradition consists of retaining transmitted forms and techniques in one's mind when producing a contemporary piece. Tradition is always changing. A mere copy of an old piece has not changed; it is nearly the same as its prototype of four hundred years ago. Tradition consists of creating something new with what one has inherited.*

There are three ways to order a Utility Flute--by Note, Length or Equivalent Aspect Ratio. The graph below ties all three together.

1) The Utility Flute is made in the standard keys of Eb, D, C#, C, B.
2) It can also be made in any length between 485 and 660mm.
3) Or you can specify any EAR between 26 and 34. (Using a EAR of 30 as the median, numbers above 30 result in a brighter timbre with darker below)



Now for your second set of choices--the **color** of your flute.



Light------Midrange-----Dark

And the third choice--the Utaguchi (blowing edge)

The Utility flute comes with either an overcut or undercut edge. The overcut is a little more conducive to pitch bending (meri/kari) and the undercut is more stable in outdoor air conditions and/or movement while playing. If you're really into pitch bending, there's a radical overcut which will allow bending up to two full notes. So, the three utaguchi choices: Radical Overcut, Standard Overcut or Standard Undercut.

Radical Overcut -- Standard Overcut -- Standard Undercut

Hochiku

We're offering a **Bb flute** in a larger tube size--**dark gray PVC**. These have a nice deep, mellow, breathy tone. Same cost ($95) as the others and a choice of blowing edges (see above).

Anasazi Flute

In the summer and fall of 1931, Earl H. Morris led an expedition from The Carnegie Institution of Washington to the Prayer Rock district of Northeastern Arizona. His team unearthed thousands of artifacts. Among them were wooden flutes which were constructed between 620 and 670 A.D.

We are now making a reproduction of these flutes, pitched to **B**. Fashioned from any of the **three PVC colors** above**,** they are Rim-blown with six small holes. The prehistoric flutes use a modified major pentatonic scale which is faithfully replicated. Rim-blown are perhaps the most difficult of the end-blown flutes to play and as the Anasazi flute has a fairly high aspect ratio, its emphasis is on the higher registers. **$95**

Customer feedback:

•• *By the way, your* site *is magnificent. It is very informative, easy to read, and through. I have never seen such detailed study of the theory, physics, and playing of any other musical instrument. The love and attention that went into the production of this site makes you a NATIONAL TREASURE of our country. I am fascinated just how much I know about the Shakuhachi flute after reading through your site.*

•• *Thanks for making & sending my 2.0 so quickly. I love it!*

•• *I have been playing shakuhachi for thirty years with flutes from two well-known makers. The sound and playability of your Bflat flute is definitely superior. I will be ordering another one soon.*

•• *It has a VERY nice weight and balance, and that the detail work is very refined! My expectations were very much exceeded! Makes me wish I knew more people that were trying to learn to play, so I could recommend that they buy from you!*

•• *Got it, sounds great, bombproof, and a real value.*

•• *Great work man! I've been playing everyday since it arrived and either I'm a reincarnated shaku master, or you have built an remarkably playable intrument.*

•• *I received my 2.4 in the mail Thursday. Wow! you hit this one out of the park! it sounds great and is as easy to play as my 1.8. thanks for the good job. (and i even like the color)*

•• *I am enjoying playing the other flutes you sent me. They are very easy to play and have a beautiful sound.*

•• *The information you published on the shakuhachi influenced my playing, since knowing more about how it works gives more interesting choices about what to do at the level of interacting with the shakuhachi physically.*

•• *The flute arrived today. I am really pleased with the timbre. This is a fine instrument.*

•• *I have been playing the D Utility Shakuhachi that you sent me all day. It is so much easier to play than my standard shakuhachi.*

•• *I've already sent one praising email for the flute, but... I wanted to send another. I'm really pleased with the tone color...I love the sound of this flute...and it's incredibly easy to play.*

•• *I've been practicing on the flute you recently sent and I'm really enjoying it. Really nice sound and feel. I think I also want to order a Bb.*

•• *Flute arrived today. Very nice. Had only a few minutes to try it, but was impressed by the clarity of the sound and the ease* *of play. Thanks again for the fast service.*

•• *I just blew through my beginner lessons on it, and I like it a lot. The overall tone strikes me as "reedy"; that is, like a reed or cane flute. Light, rather than dark, but not at all over-bright or shrill. The tone color seems especially constant across the registers. With other flutes, I've noticed the middle "ro" sounds covered - too much of the lower harmonics, I guess. On the utility flute, it sounds nice and open. The meris seem very distinct, I feel like I definitely know when I'm hitting it just right (I'm a beginner, remember).*

•• *Thanks again for your *remarkably fast* service and your patience with all my questions.*

•• *Well, hearing that your flute is made of PVC turned me off, then I looked at the Bamboo flute prices and your PVC is looking pretty good.*

•• *I'm pleased to report that your shakuhachi is easier to play than what I've been attempting to learn on, the changed shape at the top does indeed make a difference.*

•• *My complements on your in-depth research of this intriguing instrument.*

•• *What a fantastic service you have created for those of us interested in the physical and acoustic aspects of the shakuhachi.*

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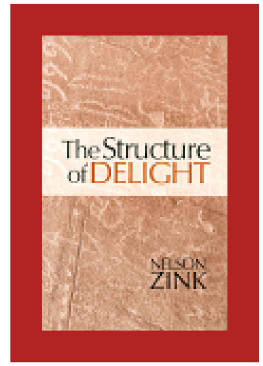

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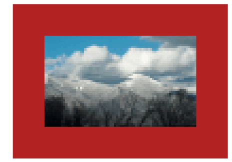

View from
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(For effects mouseover thumbnails)

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Shaku Design	Tuning the Shakuhachi

Updated 12/22/06

You want to tune a shak? Well, it may help to know something about **the game and rules** before you start.

To get a grasp of what lies ahead you'll need to realize you were lied to in freshman physics. Yes Bucky, it happened. Remember all that stuff about organ pipes and lengths and frequencies? And how it all came out nice and even and tidy? Well, that's not quite right. They lied to you and did so with a straight face. It turns out that when a tube resonates at higher octaves the waves lengths aren't **exactly** even numbered divisions of the fundamental wavelength. They're a **tad longer** than they told you in physics class and it's this tad that we're dealing with in tuning.

To get started let's agree on some terms: Sharp (in a musical sense) means the wavelength is a little shorter than it should be--thus the pitch is higher. So sharp means shorter, higher. Flat is just the opposite. **Sharp, short, higher. Flat, long, lower.**

In a tube the higher octaves are flatter than they should be for proper Western even-tempered, chromatic tuning--they're a tad **flat, longer, lower** than they should be. And the higher octaves are the shorter wavelengths. I shouldn't really say higher octaves as we're only dealing with maybe 1.2 octaves above the fundamental. In a Shakuhachi we have the first octave (the fundamental), the second octave and the beginning part of the third octave.

So what's the game? To make the short wavelengths shorter and the long wavelengths longer. The second octave is flat which means it's wavelengths are long so we need to shorten them. The first octave is sharp which means the wavelengths are short, we need to lengthen them.
Say it again: Make the short wavelengths shorter and/or the long wavelengths longer. Muttering this to yourself as you work makes the time go faster. Keeps you clearheaded and focussed as you know what you're supposed to be accomplishing. It doesn't really matter whether you lengthen or shorten, what we're talking about is the relationship between long and short--between low and high notes. And in practice you'll end up doing some of both.

Now that you understand the game let's cover the rules. How do you change the length of a wavelength in a tube? It's called perturbation and how it works is that if you change (squeeze or expand) the diameter (thus the cross-sectional area) in some portion of the tube the wavelength(s) will get a little longer or shorter. Got It? That's what all the messing with Shakuhachi bores is mostly about. Changing for timbre is another topic for another time, we're just changing for pitch and tuning here. So you're going to add or subtract material from the tube to shorten or stretch the wavelengths to get the notes in chromatic order. Notice that I didn't say add or subtract material from the **inner wall** of the tube. That's the way it's usually done. **But you could insert a stick into the tube and if its shape was correct you'd get the same tuning effect.** All we're really after is **any method to increase or decrease the cross-sectional area** of the tube at specific places along it length. That's the first part of **perturbational theory**, the second part is a little tricker.

Which part of the bore (hence wave) you squeeze or expand determines what will happen. Where along the wave you mess with it determines the effect you'll produce. Every wave has two types of nodes, let's call them **pressure nodes** and **flow nodes**. At a pressure node the air doesn't move much, the pressure changes. At flow nodes the pressure doesn't change much, the air moves one way and then the other--that's what sound is. For the fundamental wavelength (the base note of your flute, figure 1) the flow nodes are at the ends and a pressure node exists at the center of the flute.

An example-- Tom Deaver in Japan has a deep intuitive understanding of perturbation theory as exemplified by his remarks:

One of those exceptional flutes showed up at my shop with a big blob in the bore near the 5th finger hole. The excess unhardened urushi in the hole wasn't noticed and removed and the piece just happened to be placed for drying in a position that let the urushi run out of the hole into the bore. I was asked to remove this blob and refinish the damage from doing so. I refused at once. ***It was probably this blob that made the flute exceptional or at least the blob was part of it.***

Time for the graphics.

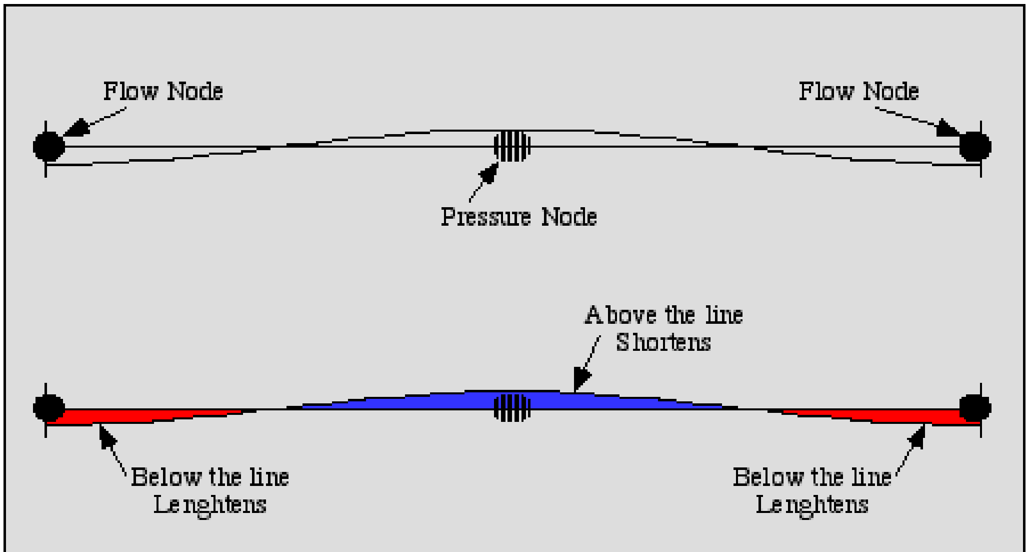


Figure 1

Note! From here on we're only talking about **CONSTRICTING** the tube, adding material to it to affect wavelength shifts, thus the tuning. **When removing material from the tube just reverse everything said from here on.** How are we going to constrict the tube, squeeze it? By adding/ inserting stuff. Putty, paper, 'gi' paste, lima beans--whatever. What the additions do is take up space that's otherwise used by the air column. By controlling the geometry of the space in the tube we control the pitch of the notes.

Figure 1 illustrates the base note of your flute. Flow nodes at the open ends and pressure node in the center. Now for the tricky part. If you add material anywhere in the flow node region (**below the line**) the wave will **lengthen**. Add in the pressure region (**above the line**) and the note is **sharpened**. **So it matters both how much stuff you put in the bore of your Shakuhachi AND where you put it.** Put stuff right where the wave crosses the line (getting a bit of flow and pressure) and the addition cancels out--no effect. This crossover point is the Flat Spot and holds particular interest as a candidate for hole placement.

OK, you now know the game and the rules. Time to see the playing field.

The follow is a schematic of the wavelengths (with nodes) which will exist in your flute.
The left side is the top end and right the foot. The measurements are for a standard 1.8 Shaku.
To the right is a graph of the pitch of the notes indicating how far from being in tune each is.
This is set up for a uniform tube so the phenomenon of the sharper low notes and flatter high notes (green line) is made clear.

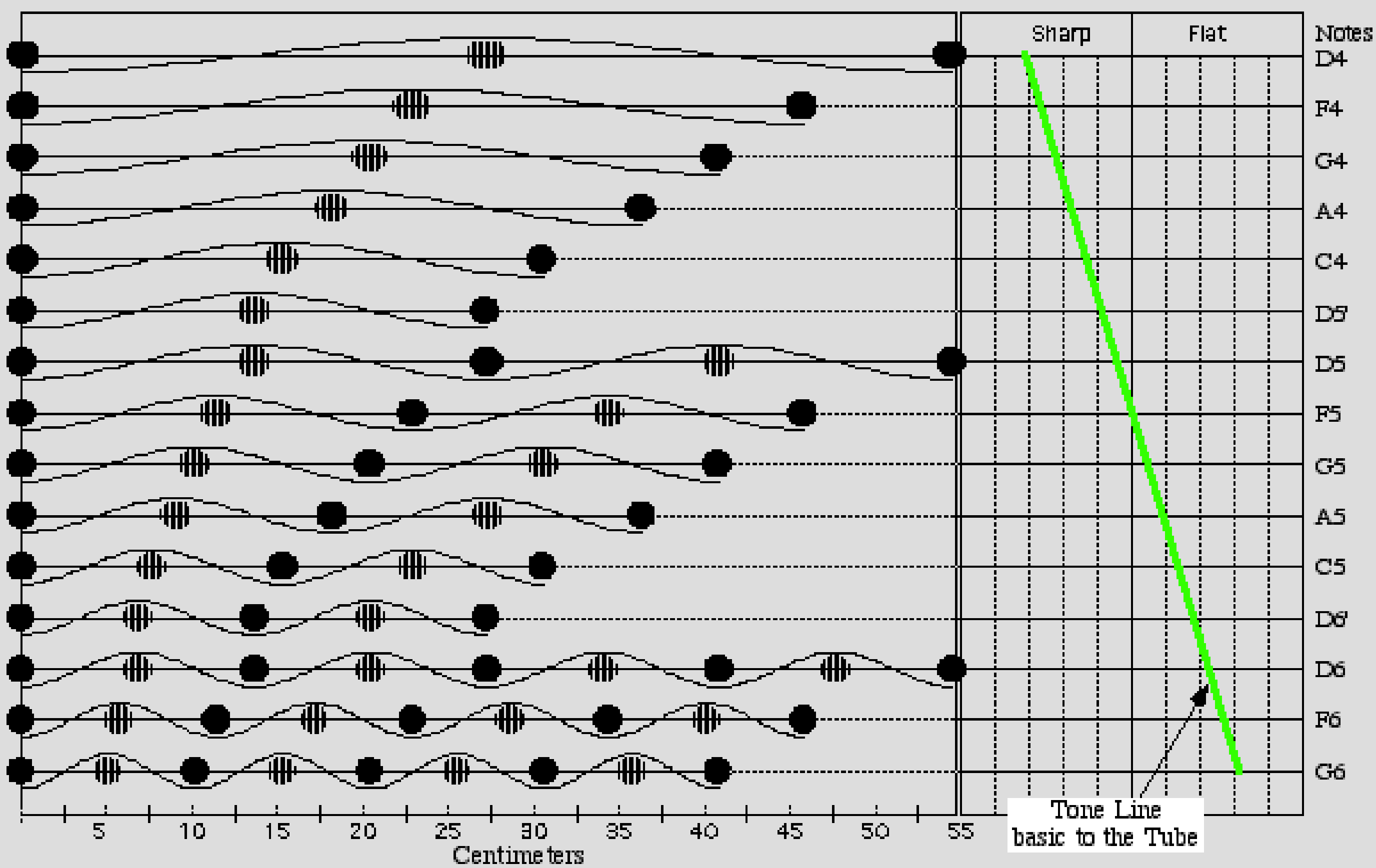
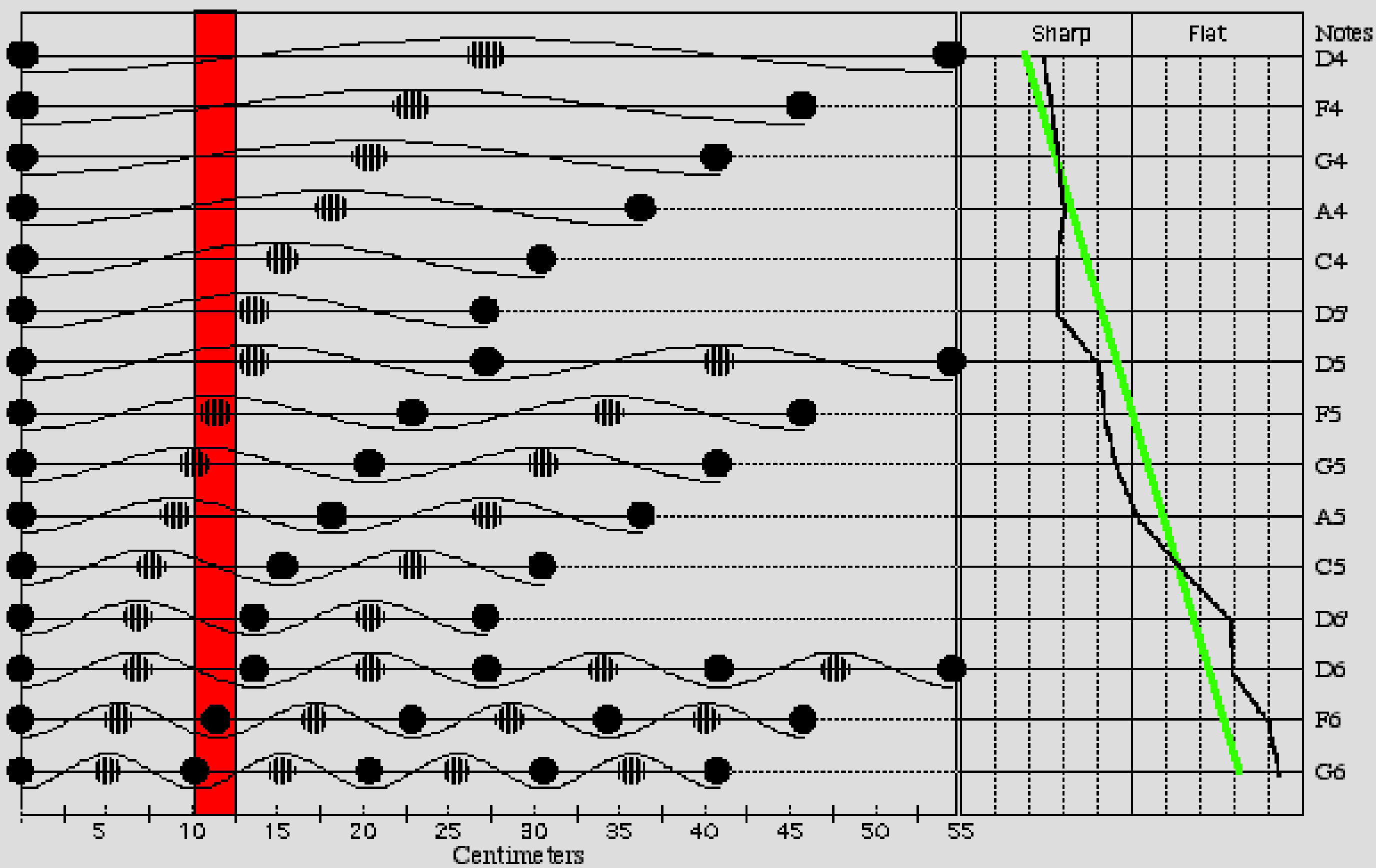


Figure 2

You've got 45 flow nodes and 30 pressure nodes for 15 notes. Leaving out the flow nodes on the left (at the mouth of your flute) and it's thirty and thirty. Kind of like a Go board on peyote--and it's your move. Your assignment (should you choose to accept) is by way of adding stuff (and thereby constricting the bore) to make the **tone line** straight and vertical. Do this and you've won the game.

But first, let me show you what you're up against.

The next two figures show the tonal effect of adding 25mm of stuff at different locations along the bore. **Figures 3-5 all have the slant of the Tone Line in figure 2 as a base. It's something like ground zero of the basic tube.** I've left it in as a reference so you can see the changes the additions make. Compare the Tone Lines of figures 2-5.



Sharp
Flat
Notes
D4
F4
G4
A4
C4
D5'
D5
F5
G5
A5
C5
D6'
D6
F6
G6
5
10
15
20
25
30
35
40
45
50
55
Centimeters

Figure 2

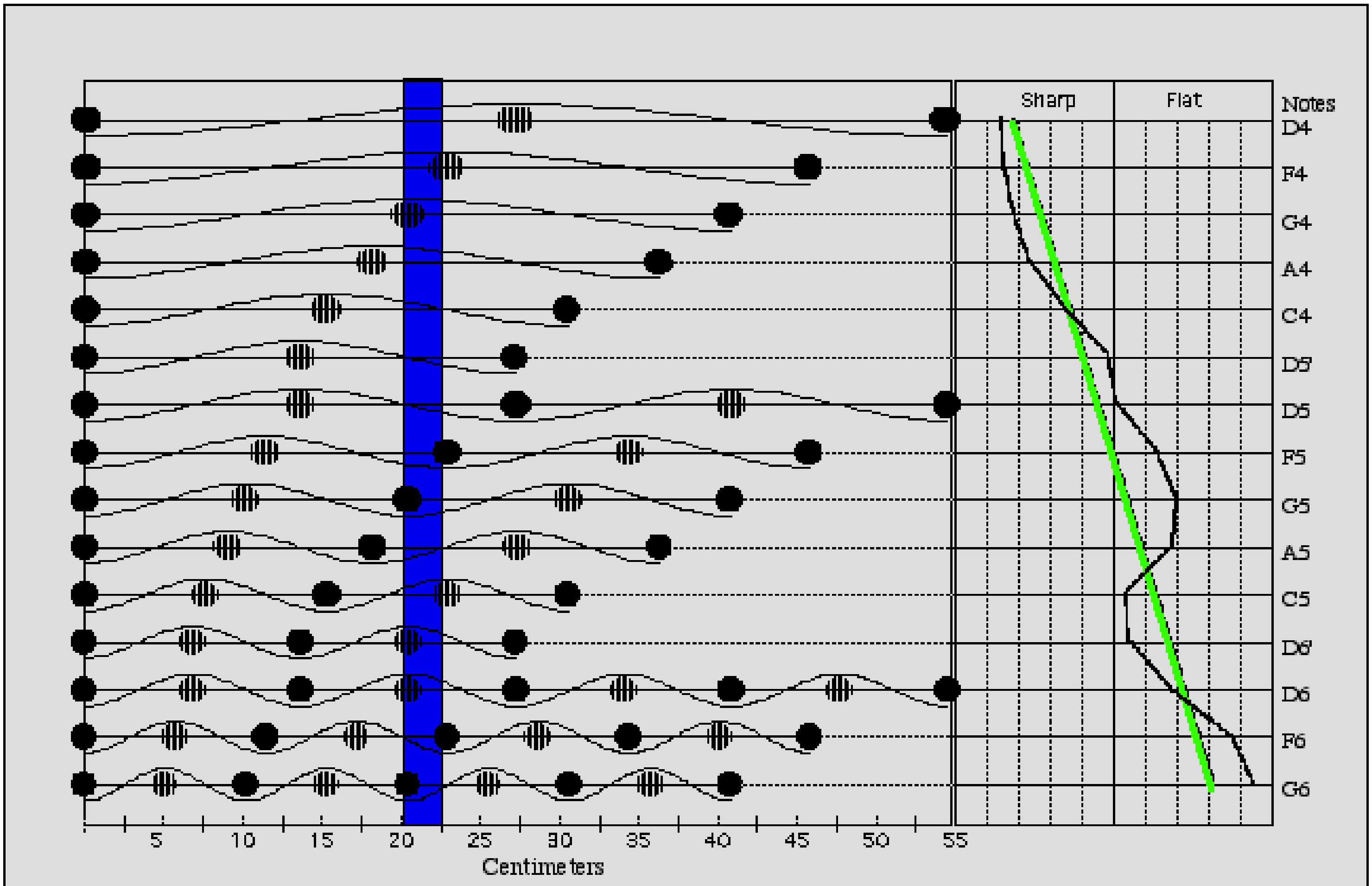


Figure 2

Had it not occurred to you, it should be evident by now that addition of stuff usually affects ALL notes--and not in an immediately obvious way. By carefully examining which part of the wave (above or below the line) the colored strip crosses you can predict what pitch difference it will make to each note.

Now let's view a tuning game in progress.

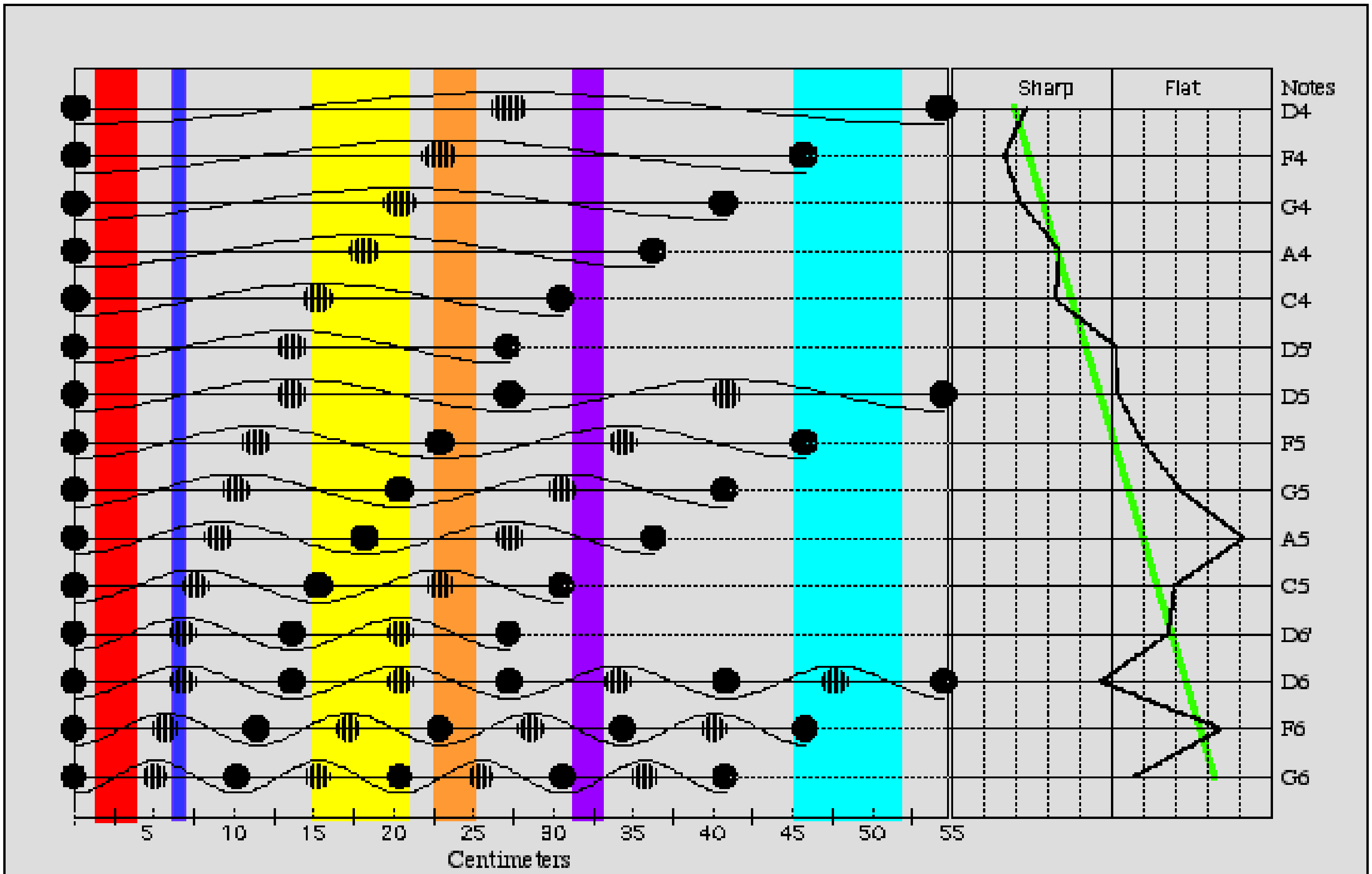


Figure 5

Hmmm, not going well for the Home Team--maybe by the playoffs.

Remember: The goal is to make the Tone Line straight and vertical--ducks in a row.

There are a couple tricks which utilize the **length** of the additions made to the bore. Look at the bottom of the yellow bar in figure 5. It spans the crest of a pressure node to the crest of a flow node. Because it's that particular length it has no effect on the pitch of the G6 note--the two effects cancel out. So it's possible to make additions to the bore which are transparent to a particular note. For example, you want to make an addition but want to leave D5 untouched? Make your addition (in the case of a 1.8 Shak) 545/4 mm long and D5 will remain untouched. **And that's regardless of thickness of the addition or its location anywhere along the bore.** To engineer such 'transparencies' just calculate the distance from the crest of a pressure node to the crest of a flow node for the note you want left undisturbed.

As a general rule-of-thumb, long additions affect the low notes more than the high and short additions affect the high notes more than the lower.

So you have two conceptual tools at your disposal: The length of the material you place in the bore and the location of where you put it. The thickness just amplifies the effect.

For a literal demonstration of perturbation effects visit the Throated Flutes page.
For Nodal Tuning of Jinashi flutes.

Notice that we haven't talked about the flute holes. From a perturbational/spatial point-of-view just consider them as negative space that has to be compensated for. In the end we're just talking about space, hence volume, and how it affects note pitch. One good measurement, which is seldom if ever done, is to determine the volume of the bore. Tape the holes and the bottom and fill with water and then measure in cubic centimeters. If water scares you use sand or some other fine medium. Knowing the volume of flute bores will tell you a lot about how they behave.

The way it works is when you're ready to tune, carefully play each note and make a Tone Line graph--which notes are high, which low and by about how much. **The holes, the basic tube shift, the effect of the shape of the bore, etc. will all be reflected in this graph.** Then by consulting the Node Graphic (figure 2) you can calculate and make judicious additions to the bore--thereby making the Tone Line straight and vertical. Remember, when removing stuff from the bore of your shak just reverse everything said above.

That's it. You're now equipped with the basic tuning theory and a detailed map of the terrain. If you want to get into shak tuning pull up your socks and pack a lunch, it'll be a long day. Good luck!

There's a great Sound Color Analyzer and Tuner for Shakuhachi.

It's a free download for Mac(PPC only) or Windows 95, 98, 2000, NT.

While we're at it let's talk about holes and their location. For those who have read Benade and/or Hopkin talking about Benade, the following is for you. The Benade/Hopkin algorithm strains normal patience and understanding. About the third time through trying to remember what the 'tube cut-off location' is your brain does a cut-off. Anyway, the following graphs will erase any fears that they know something you don't. Figure 6 is calculated for a standard **straight walled tube** of 1.8 shak length and **4.5mm wall thickness**, tuned to D4 (293.66hz). The only two variables (in figure 6) are tube internal diameter and hole size (10&11mm). By-and-large there is small difference between 10 and 11mm holes until you get to larger diameters. Notice the 10mm holes peeking out from behind the 11mm holes in the 25mm row. Given the conditions listed this is where Benade/Hopkin say the holes should go. Now you can sleep at night.

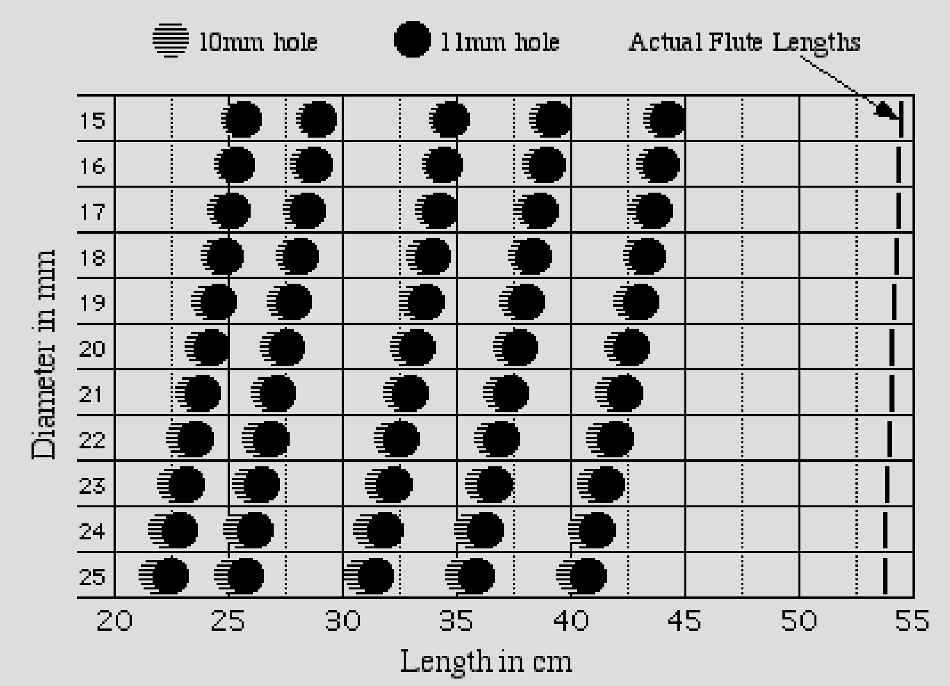


Figure 6

In figure 6 we varied tube diameter, in figure 7 we'll vary wall thickness keeping a constant 20mm ID.

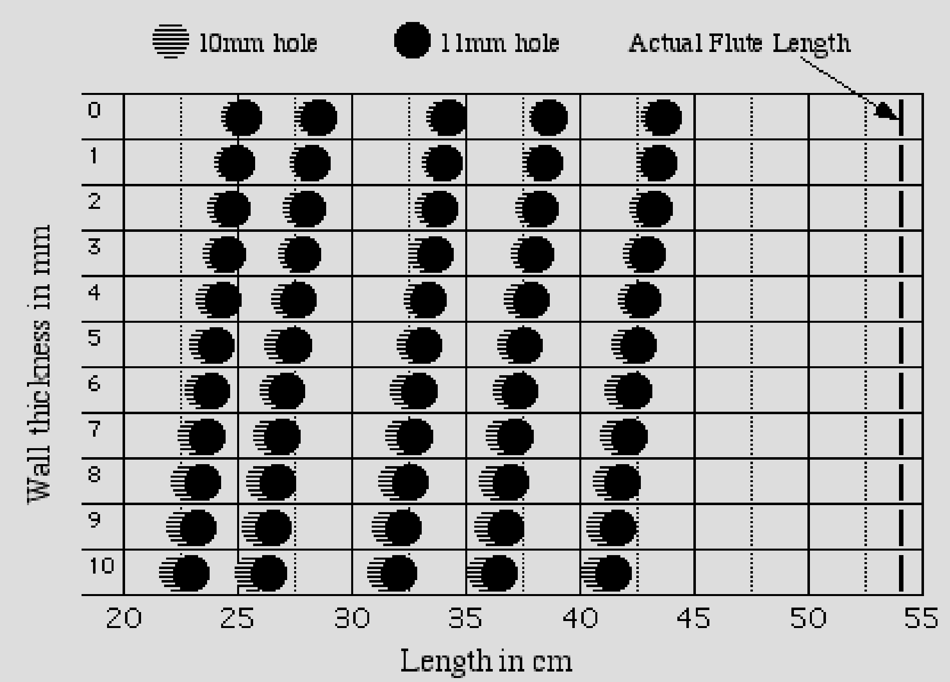


Figure 7

Figures 6&7 give you a comprehensive picture of how changes in tube diameter and wall thickness affect the locations of holes.

For some precise hole measurements and instructions for making some great practice shaks visit *The Synthesis*.

For more read:

Air Columns and Toneholes by Bart Hopkin, (pp.10-12 for tuning, pp. 14-24 for hole location) Get it from Monty Levenson.

Fundamentals of Musical Acoustics by Arthur H. Benade (pp.473-476 for tuning)

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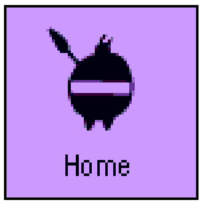
Shaku Design | Searching for the Edge



Updated 1/15/04

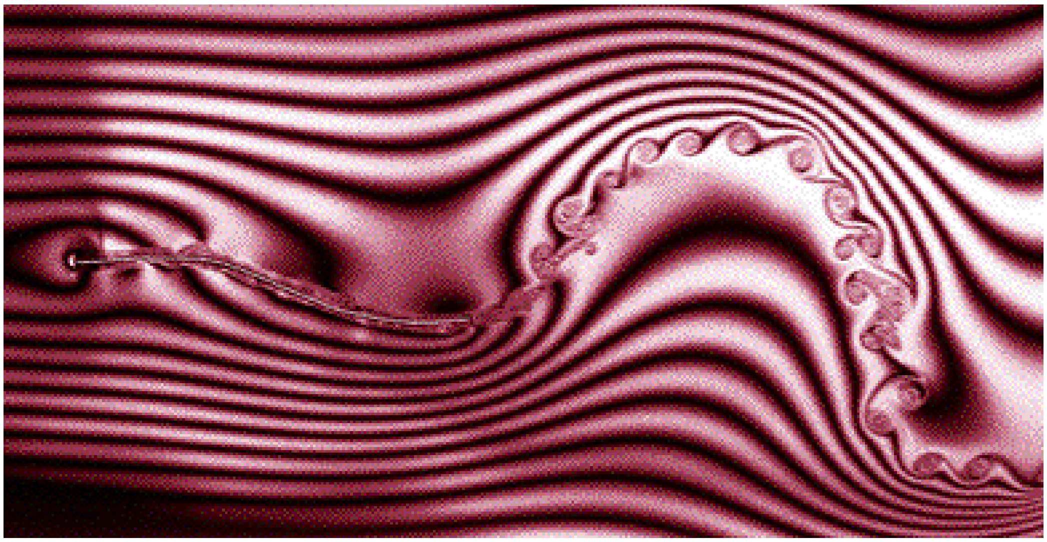
You want to know something about the mystery of the Shakuhachi? Much of it can be found in the mystery of the airstream. Let's first talk about what you need for a basic flute. You need an air stream, an edge and a resonator. That's about it. To make a flute work, direct an airstream onto an edge which is coupled with a resonator (usually a tube of some kind) and a sound results. Simple, right? Well, maybe--kind of.

Since we're talking generally about the Shakuhachi, we're talking about an airstream formed by the lips (and maybe the mouth, throat, lungs, etc.). Let me say maybe because it turns out this airstream isn't a simple affair and isn't understood very well. The thing waves and flaps around--something like a flag in the wind. And why does a flag flap in the wind?

Two Zen monks were arguing about a flag. One said, "The flag is moving."

The other said, "The wind is moving." The Sixth Patriarch happened to be passing by and he told them, "Not wind, not flag; mind is moving."

Jun Zhang, a physicist at New York University, has a slightly different answer as can be seen in the graphic below.



We're not going to settle the flag debate here, but will adopt the preceding graphic as something conceptually close to what the airstream looks like. As the airstream moves from left to right it flaps up and down. Why? It just does.

First, let's combine an airstream with an edge. Blow on the edge of a credit card. Actually dig one out and blow on it. What do you hear? Kind of a hiss? Good. This is called **edge tone(s)**. Why does blowing on the edge create a sound? It just does. If you need some kind of explanation, it's the flapping of the airstream which flaps above and then below the edge. But how does this result in a sound? We're back to where we started--it just does. Here's the point of this paragraph: **An airstream naturally has a dynamic turbulent flow something like the graphic above.** It's non-linear and for the most part, unstable. The thing is alive and sensitive to most any influence. You can employ the Navier-Stokes equations, Reynold's Number, spread on a good layer of Bernoulli, and/or learn Chaos Theory and mess with bifurcating points--but you'll just end up with the fact that the thing's alive and sensitive to most any influence.

Blow on an edge and you get edge tones. What are they? For the most part they're white noise--a packet of random frequencies. Couple white noise with a resonator (a tube which is tuned by its length) and you get a stable tone. So the tube does two things: It's a filter which filters out all but a selected frequency and an amplifier, amplifying that frequency. A small fact you can tuck away in the back of your mind: A flute is about 1% efficient in turning the energy of the airstream into defined sound. Only about one percent of what you blow ever gets turned into anything you wanted to hear.

The airstream follows its own will-o'-the-wisp path, easily influenced by everything around it. Have a bushy moustache, for example? This can make a big difference in the flow pattern of the airstream. This is what Joe Wolfe is getting at talking about 'face' impedance.The tube is fixed and not very influenced by anything except the holes which just change the tube's length. And between these two we have the edge.

So what kind of edge is best? Surprisingly, it doesn't make a lot of difference. Don't believe me? Blow on other edges besides credit cards. Razor blades, thin paper, the edge on your ruler, the edge of different kinds of files (the ones in your workshop), the edge of quarter inch plywood. Blow across a pencil, nails, the edge of floor tile. You hear anything dramatically different? Nope. Just that hiss--white noise**,** also called **aeolian tones.** Now, if you do this experiment and do it carefully you'll notice that the general frequency (if there is such a thing) of the edge tones is lower when the edge is thicker. That's about the only difference you'll find with edge tones. And in fact, there's an equation for it--frequency is inversely proportional to edge thickness.

Still don't believe it? Try edges of different geometries. Round ones, square ones. Tapered, sharp, blunt, etc. Try them all and you'll get about the same sound. Which means that **the edge in a Shakuhachi perhaps doesn't make as much difference as you might have thought.** Yes, different kinds of edges may do slightly different things--but not dramatically so.

Still not ready to give up? Try rough edges, polished edges and anything else you can think of. And in the end you'll come to realize that the graphic above is the way it is regardless of the edge. **The Shakuhachi sounds the way it does in large part because it exploits the natural instability of a dramatically turbulent**

airstream. So we've moved from the tube to the edge and finally to the airstream. What controls the airstream? As much as it can be controlled it's controlled by the lips--the embouchure. The airstream in a recorder or a pipe organ is about as controlled as an airstream can be. The thickness, width and distance from the edge are all fixed and about all that's left up to the player is the air pressure. With a Shakuhachi all this is within the player's control. So if you're seeking a better sound and are offered a better instrument or better embouchure--choose the lips.

And speaking of lips, whistle just using your lips. Where does the sound come from? No edge, no resonator. Ready to accept the possibility that there's plenty going on just with lips and airstreams?

Adopting a flame analogy, the flame of a candle is fairly stable and quiescent, while the flame of a campfire is turbulent and unpredictable--airstreams are the same. At very low pressure and speed airstreams are quiet and steady like a candle flame, but at the pressure and speed at which most playing is done they're wild like a campfire flame. And much of the Shakuhachi's sound and possible effects exist only because of the airstream's turbulence. So a Shakuhachi is an instrument designed to make aurally present the turbulence of a flame of air--to make flames speak. To squeeze this analogy even further, campfires make a sound--yes, low frequency white noise.

So feel free to experiment with different edge configurations and/or don't worry too much about achieving a particular configuration.

For some precise hole measurements and instructions leading to some great practice shaks visit PVC Shakuhachi. The Aspect Ratio's role in the sound of the shakuhachi becomes clear in these examples.

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Exploring the Bore

Updated 1/15/04

This is the part of Shakuhachi design where things get complicated and subtle. Generally, the bore of the shak is tapered--going from maximum internal diameter at the blowing end to a **choke point** toward the bottom and then flaring out again to the bottom. As a general rule the choke point is somewhere around three-quarters (or less) the diameter of the throat and located at or near the flow node of the first note above the fundamental. This places it at 0.84 times the flute length from the top and/or 0.16 times the flute length from the bottom. If you like precision put it Length / 2 Pi from the bottom.

The reasons for a tapered bore are at least threefold:

1) The natural growth geometry of the root end of bamboo tends toward a decreasing internal diameter the closer to the root one gets. Thus while forming the bore there is a natural (and therefore traditional) tendency to follow the growth pattern.

2) The **timbre** (tone color) of the flute is changed (improved?) by choking it.

3) Octave tuning (the problem of notes being flattened the higher they are) may be helped by employing a taper.

European flutes and recorders went through this same evolution toward a tapered bore, moving from Renaissance to Baroque. Central to the question of bore design is the question of what a Shakuhachi should sound like? To some a taper sounds mellow, to others it's stuffy. To some a straight tube sounds bright to others it's shrill. **Part of the problem in shak bore design is that timbre and tuning are inner-mingled in the same geometry.** It's hard if not impossible to discern whether some bump or undulation affects timbre or tuning the most. Fortunately, octave tuning and changes in timbre can both be achieved in ways other than employing a taper and in ways which tend to separate the problems. Timbre is directly affected by **Aspect Ratio** (tube length divided by diameter) and tuning can be done by way of perturbations.

But first, let's look at some bore profiles. For the uninitiated, be aware that these graphs amplify and thus distort the look of the taper--that's their purpose. The vertical scale is 1/10 that of the horizontal scale. Actual bores are much slimmer and svelte looking. All the following graphs represent a D4/1.8 shak.

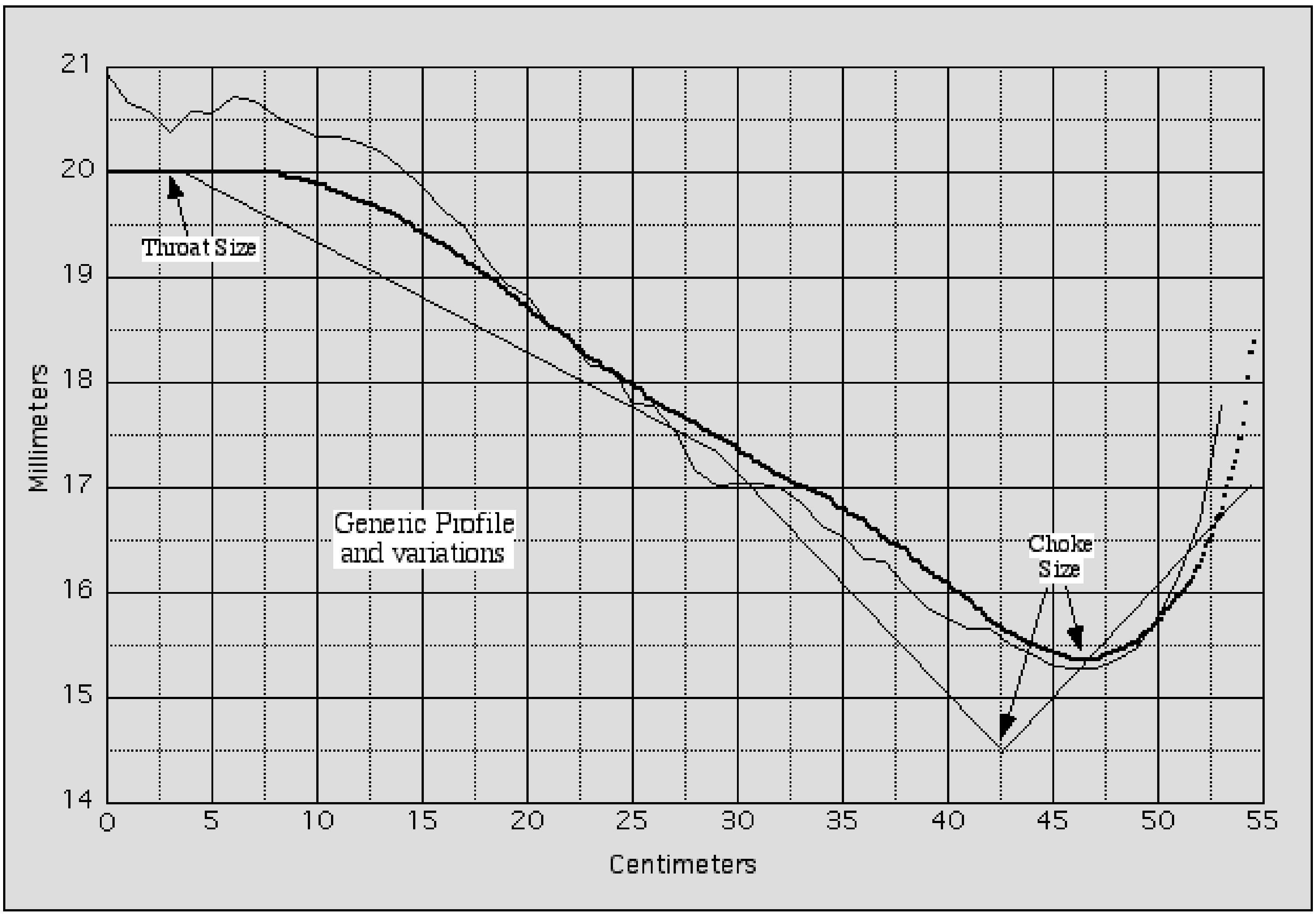


Figure 1

It's hard to figure out much from these examples. **What part of a given curve is dedicated to tuning and what part to timbre?** 20mm is a good general throat size for a 1.8 shak, so the range is maybe 19 to 21mm, with a choke point diameter of 13 to 16mm. In a way, these two measurements are inversely related to each other. A big throat can be compensated by a smaller choke and conversely with a smaller throat the choke can be opened up some. **Think of it this way: if the throat continued to get smaller and the choke larger, at some point you'd have a straight-walled tube.**

Another way to think of the throat/choke relationship is to make the cross-sectional area of the tube at the choke point 1/2 the area of the throat. Square the throat diameter, divide by 2, then take the square root. For a 20mm throat this amount to 14.14mm

Part of the difficulty with tapers is that a taper can be devised which makes any single note sound great but begins to fail on the other notes. Compromise, compromise, compromise. And after all that compromising is done you have to compromise still further to get the tuning right. Buried under all that compromising and tuning is some idea of what a taper should be but its nearly impossible to dig it out. With tapers people tend to end up using what's worked before so bore evolution is a slow process. Kind of like the Red Barn phenomena in the Midwest. When farmers are asked why they paint their barns red they explain that red paint is the cheapest. At the hardware store if you ask why red paint is the cheapest they'll tell you it's because they sell so much.

Now let's approach the bore from a more theoretical standpoint. It's possible to create a waveform through the addition of the Sine waves of notes (with any number of harmonics)--kind of the reverse of doing a Fourier Transform. **We'll build our waveforms by specifying what we want the flute to sound like.** And then it's possible to generalize the waveform into a smoother result.

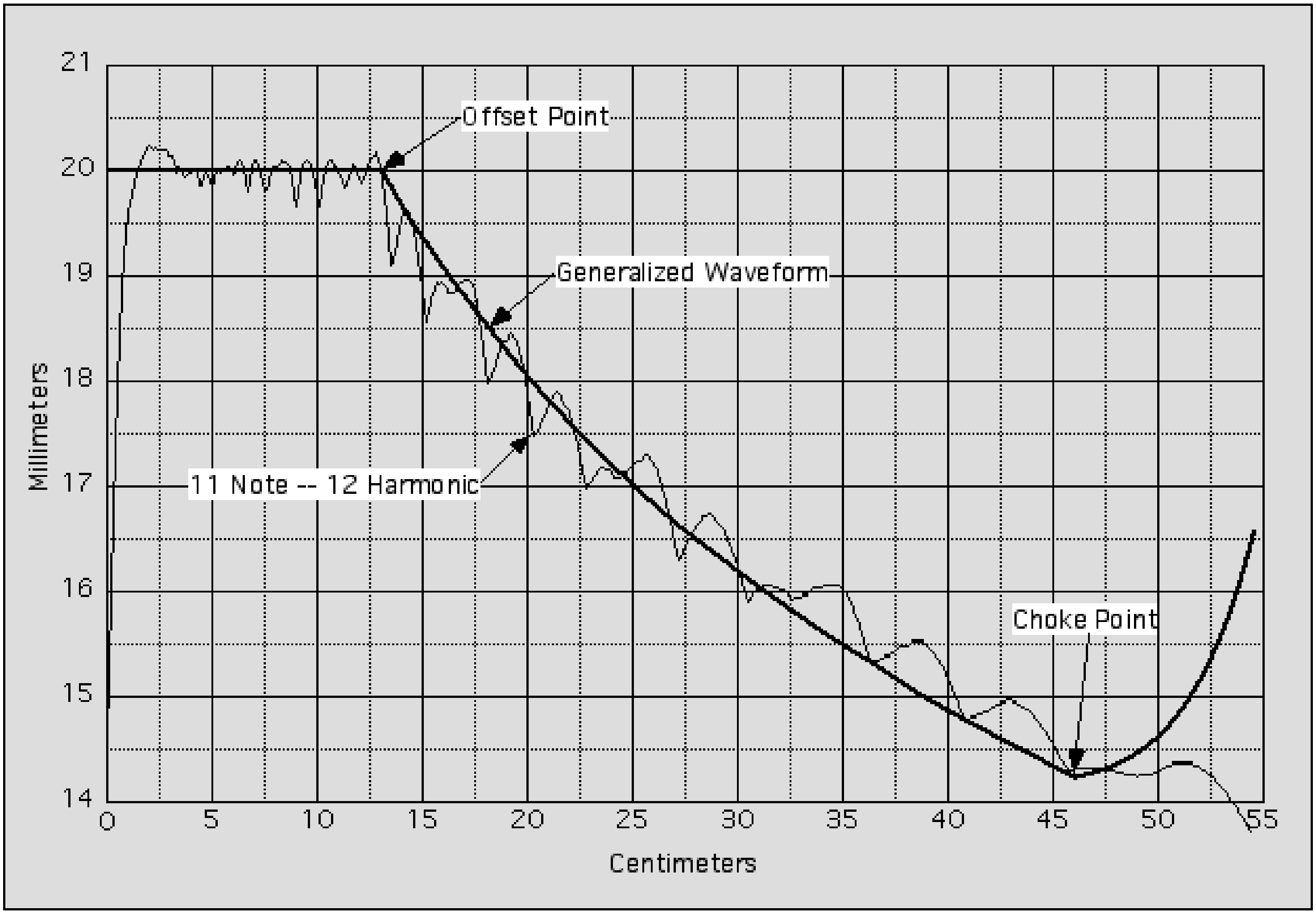


Figure 2

We can easily stretch/shrink the waveform to fit any throat and choke dimensions--let's call these the vertical dimensions. But the interesting part is that an **'Offset Point'** naturally emerges from the algorithm and it's value is based on the number of notes and harmonics we specify. Notice in figure 1 there's an Offset Point in each bore profile. Never noticed it? Well it's there.

Let's learn a little more about the location of this point. First, the **existence of an Offset Point** seems to arise from specifying the number of harmonics we want--as can be seen in the next figure. From the third harmonic on, the waveforms are similar beyond thirteen centimeters. By the sixth harmonic the waveform has leveled off and is pretty flat across the first 13 centimeters of the flute's throat. Beyond the 12th harmonic the first 13 centimeters just flattens out until it becomes virtually a line.

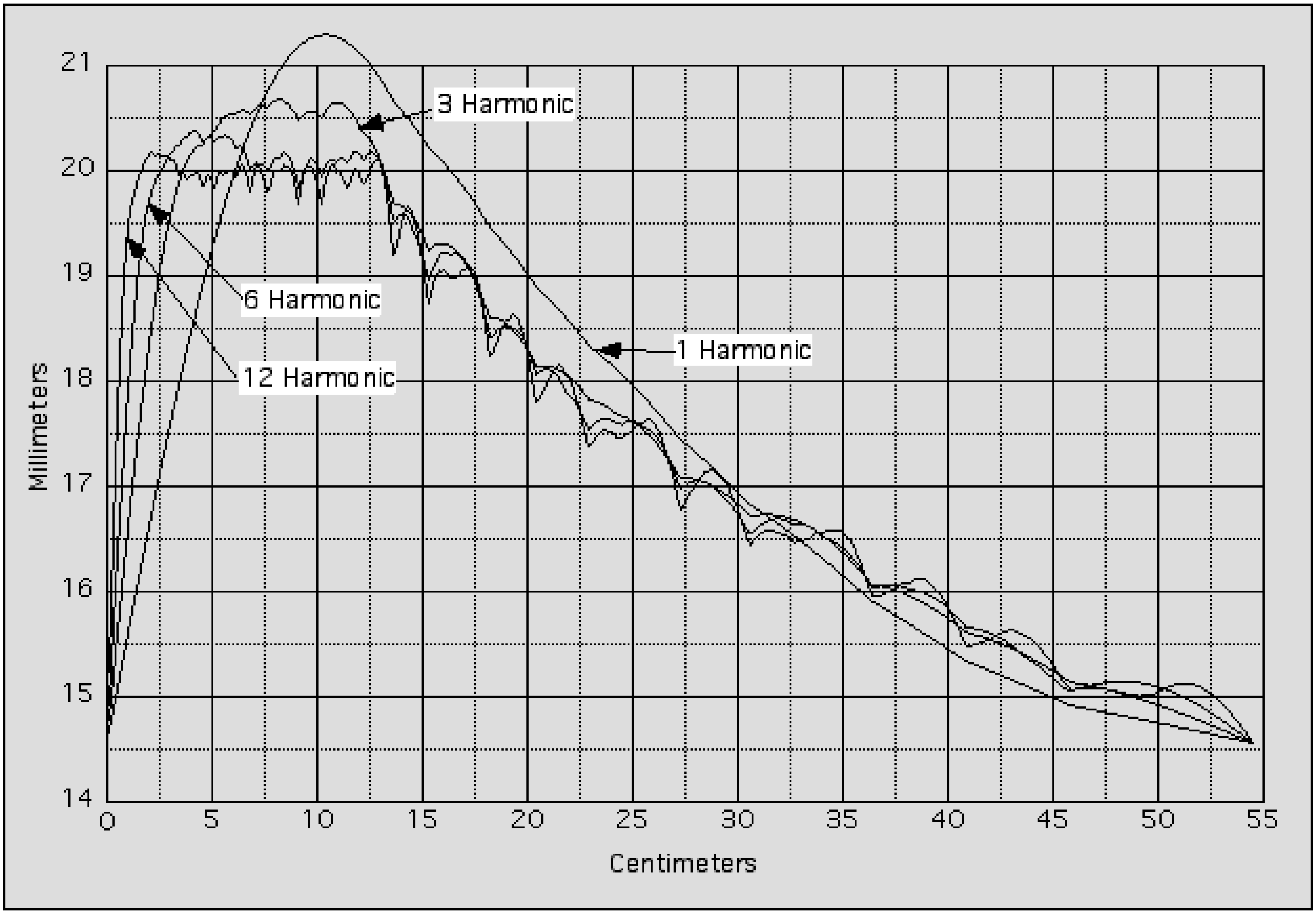


Figure 3

Where this line breaks into a taper is the **location of the Offset Point** (horizontal dimension) and is governed by the number of notes you want your flute to play well. And by notes, I mean the pentamic notes the Shakuhachi is designed to play. So designing for 11 notes, for example, we're designing to extend to the first note of the third octave (F6).

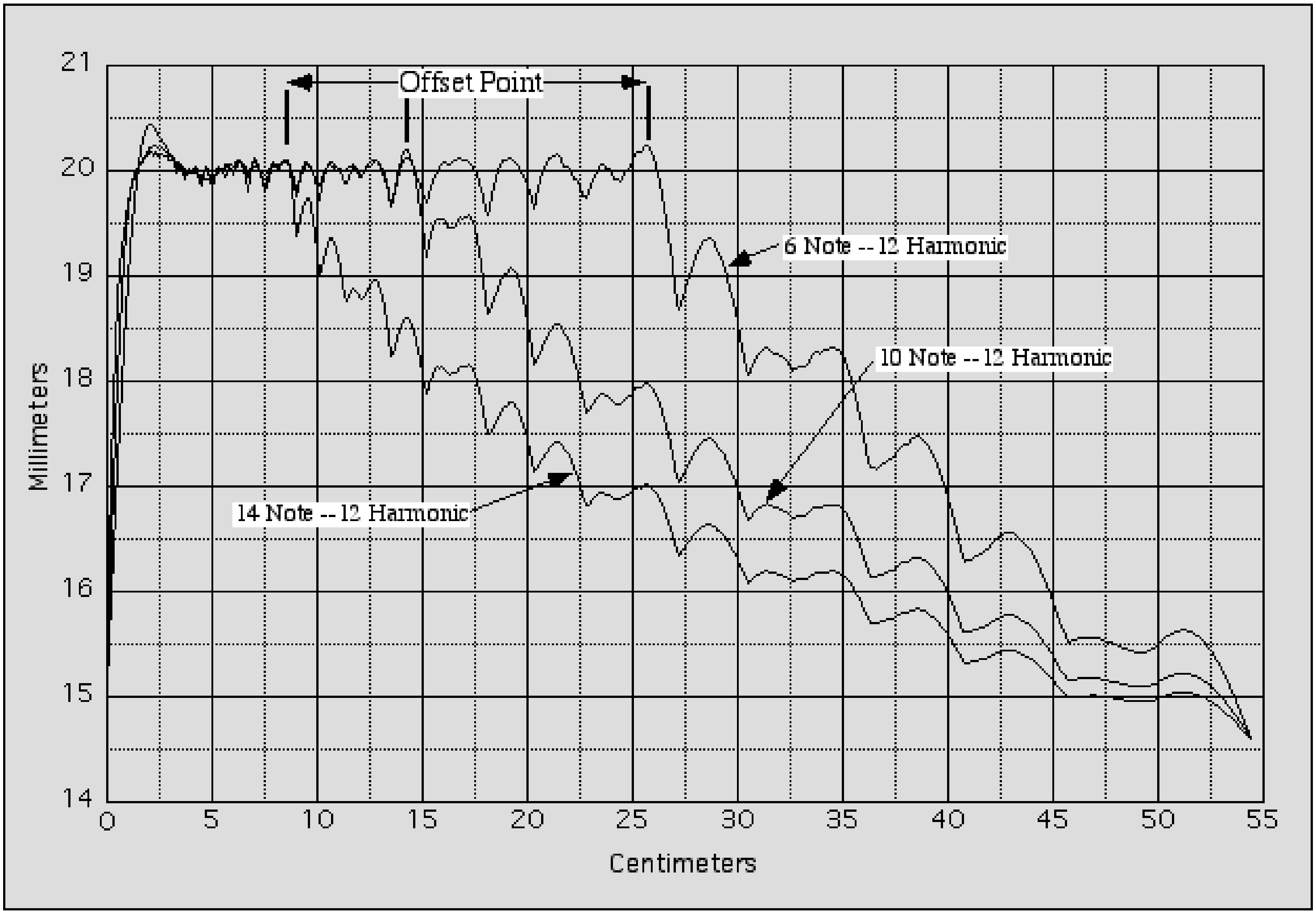


Figure4

If the algorithm works (and that's still an if) we can design a generalized bore optimally configured for different note ranges. Tuning would be completed after shaping a particular profile for a particular range. The closer to the mouth the Offset Point is placed the greater range the flute should have. Notice also that there's a gradual shrinking of the Choke Point that goes along with this. Part of the process of generalizing the waveform is computing a very high number of harmonics--thousands, and so it can safely be said that the generalized form contains all harmonics--at least all you could ever hear.

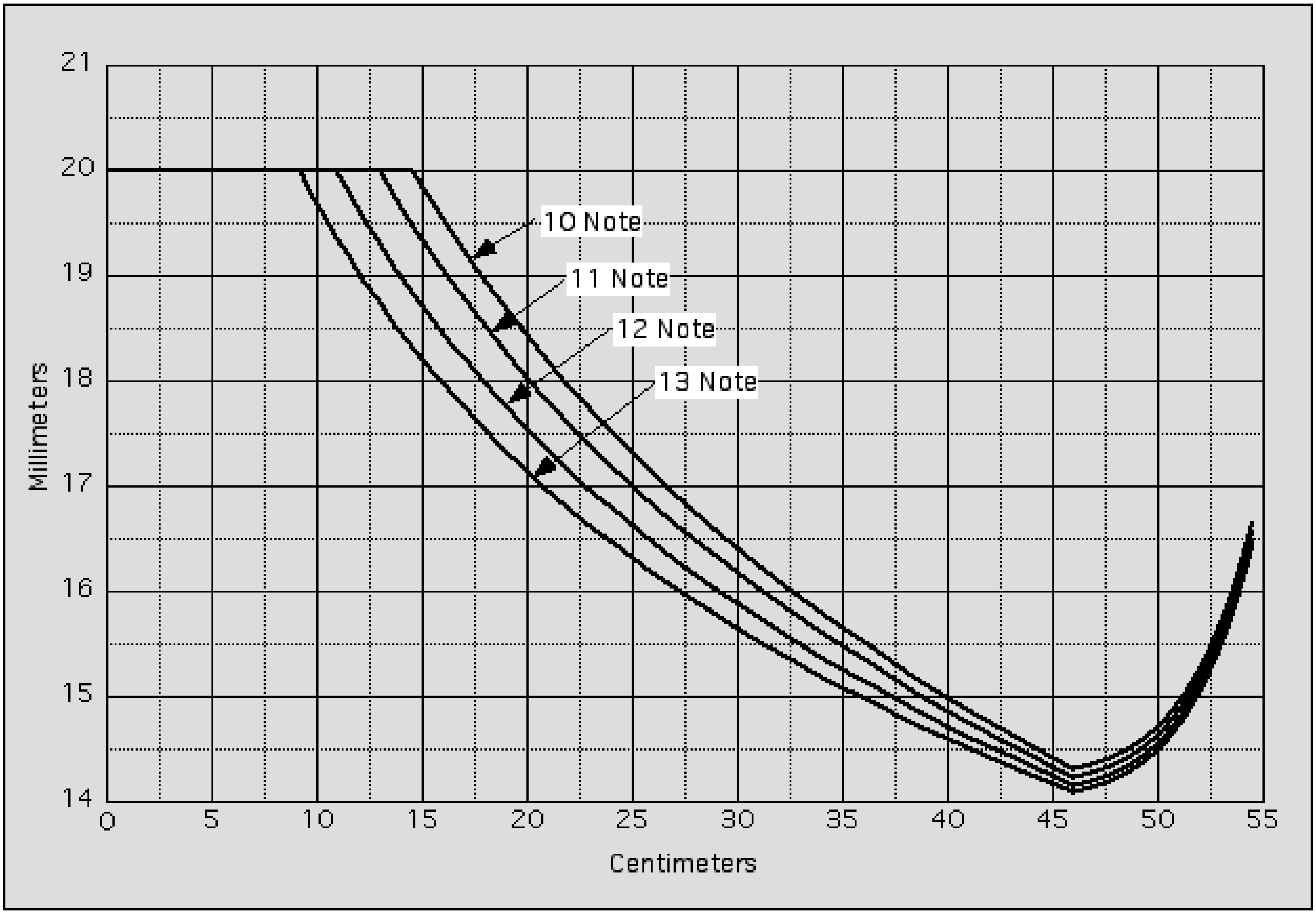


Figure 5

So much for theory, now let's investigate doing it another way--messing with a **straight tube**. As mentioned before, timbre and range are both greatly influenced by Aspect Ratio. The following graphic will give you an idea of Aspect Ratios for shaks in the D4-C3 range. The bottom of the 'Third Octave Zone' (an Aspect Ratio of about 30) is the dividing line between second and third octave (the range) flutes. As the Aspect Ratio rises (numerically) the timbre gets brighter--lower and the timbre is darker. A D4 shak with an internal diameter of 18mm is right on that line. **So generally, if you want a straight-walled shak to favor the low notes design it with an Aspect Ratio of 30 or less--the high notes, 30 to 32.** Simply said, whether tapered or straight if you're having trouble getting the high notes shrink the diameter and conversely, expand to boost the low notes.

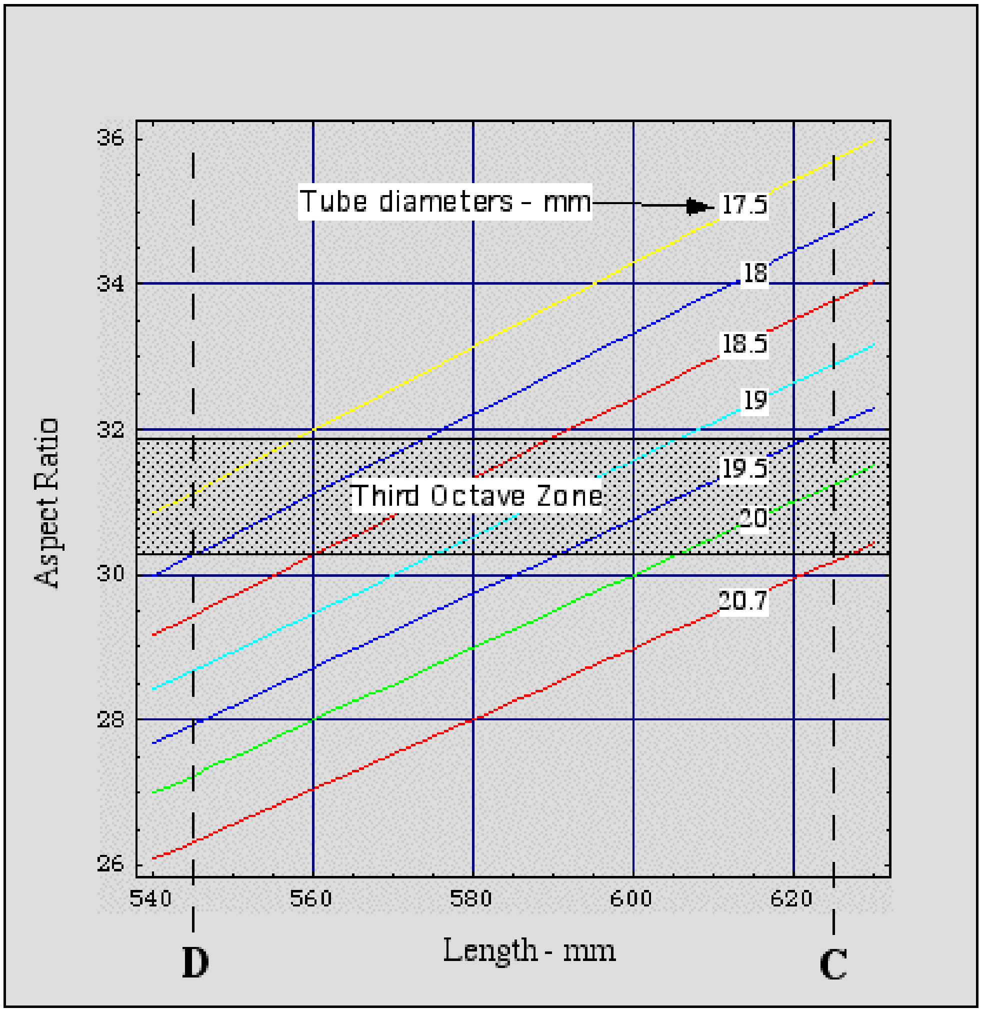


Figure 6

For those with an strong interest in subject of Aspect Ratio, this is an experiment really worth doing. Get a length of 3/4" CPVC (surprise! ID 18mm) and hook it up to a mouthpiece from a recorder or whistle. I just taped the mouthpiece from an old 16" recorder onto the CPVC with electrical tape. You'll need a fipple mouthpiece like that of a recorder because blowing pressure is ultra-sensitive in this experiment. Don't have a mouthpiece lying around? Make one or buy a cheap plastic recorder, band-saw off the mouthpiece and proceed. Cut the CPVC to 5 feet (or so)--we're talkin' an Aspect Ratio of somewhere around 85! Now play and try to get the tube's fundamental. Usually, if you blow softer and create a more quiestent airstream you'll find another lower note clear to the limit of hearing. Anyway, start at the (a) low note (about 300Hz) and you should be able to play every hundred Hz up to 1200 or 1300. About there my dog starts going nuts and interrupts the playing. **And this is all just with the breath and a very high Aspect Ratio.** You'll be jumping octaves, thirds?, fifths? and I'm not sure what else.

Playing this instrument is a rather peculiar and meditative experience. You can gently 'push' notes and listen as they gradually evolve and break into the next (other?) note(s). 'Other worldly' doesn't quite describe the sound, but it's probably unlike anything you've ever heard. Playing is pleasant, easy, and informative. Call this instrument a Hiasra (HIgh ASpect RAtio) and enjoy and learn about Aspect Ratios.

Another nice thing is that the Hiasra takes very little air, basically you can play as long as you can hold your breath. Mouth, tongue and throat effects easily translate into music. Didge techniques apply. You can even indulge in 'Tuvan throat singing' by humming a drone sound. Because the Hiasra is so sensitive to airstream characteristics water droplets in the windway can foul the works. Just blow them out and proceed when the instrument goes mute. Slap on an end cap (pick one up when you buy the pipe) for less interesting 'minor notes'. After you've completed this experiment you're on your own with other pipes and Aspect Ratios.

The Sound Color Analyzer and Tuner for Shakuhachi is a big help during this experiment. It's a free download for Mac (PPC only) or Windows 95, 98, 2000, NT.

There is a lot of traditional lore about which materials are best for wind instruments. In practice, however, any reasonably heavy, hard, smooth and rigid material will sound much like any other and have the same potential for producing a good-sounding instrument. However, extremely hard reflective surfaces are not necessarily the ideal: people sometimes prefer the mellower tone of somewhat damped resonances.

Wind instrument tubing materials that are light and/or yielding will dampen air resonance within the tube to some degree, and lower the resonant frequencies slightly. Walls made of rough or porous materials also have noticeable damping effects. Increased damping leads to poorly defined resonance peaks, especially in the high frequencies, creating a sound that is less than bright. **Although not generally realized, any deviation from a circular bore leads to the possibility of wall flexing.** In other words, the walls of a very thin-walled, strongly elliptical bore will flex. Whether you want this or not is another question. Some people believe this is the sign of a superior shak. Vibrations in the walls while playing is the result of wall flexing. If you want it, thin the walls and increase the elliptical nature of the bore--the less circular the stronger the effect. On the downside, wall vibrations are inefficient as far as turning the energy of the airstream into sound--which only runs about 1% anyway.

Timbre is greatly influenced by air friction in the bore.

We don't ordinarily think of friction within a shak, the air flow doesn't seem to be traveling very fast. But we're thinking at the wrong scale. What's going on in your shak is happening at **Mach 1--the speed of sound.** The air volume in the bore of a shak may turn over at a leisurely rate but the molecules making up the sound waves are moving at Chuck Yeager speeds. Think about the surface of something you would put in a wind-tunnel to be tested a Mach 1. The smoother, more polished, mirror-like the surface the less drag it has. Such a surface is 'slippery'. And the same circumstances are true in the bore of a shak.

So what kind of inner surface is best for a shak? Well, it depends. A smooth surface brightens the timbre, rough darkens it. And we're talking more about the micro-surface rather than obvious irregularities. If the surface is rough, air drag increases and thus a greater force is needed to oscillate the air. The instrument isn't as 'quick' and supple as it could be. So in answer to which surface is preferable we need to realize that the texture of the inner bore surface needs to be weighted against the Aspect Ratio.

We can brighten a shak's tone by: 1) raising the AR, and/or 2) polishing the bore.
The tone can be darkened by: 1) lowering the AR and/or 2) increasing friction in the bore.

A thin pipe with a slippery (fast) bore is doubly bright.
A fat pipe with a rough (slow) bore is doubly dark.

So if a shak's AR is a little low we could polish the bore and come out about right. How to polish a bore? A good coat of varnish, lacquer, polyurethane, etc. is a quick, easy way. Part of the reason for the tradition of pouring water down a Didge at corroboree is to "polish" the bore a bit. A wet surface is smoother to air molecules. Slop some water down the bore of an untreated rough wooden shak and it's tone will brighten.

How to roughen a bore? There are the obvious ways--steel wool, etc. Affix a big wad of coarse steel wool to the end of a rod and then use an electric drill. Gluing sand on the bore surface is an extreme possibility and probably should only be used for instructional purposes. Mix up a diluted mixture of wood glue and water, coat the inside, fill with dry sand, leave overnight, then drain the sand out. But there are other more interesting and subtle possibilities.

To get and/or increase that nice mellow, breathy, woody, dark timbre we need to increase air friction in the bore. But this doesn't necessarily mean **on** the bore wall. To get a feel for the effects of air friction, snake a strip of cloth down the bore using string tied to the ends. It's a simple matter to experiment with different materials inserted in the bore to alter the air friction. Make sure they're fairly thin or their cross-sectional area will alter the AR of your tube. Try adding friction in the top half of the tube, the bottom, the middle. You get the picture.

What surface do we want? The one which **coupled with the Aspect Ratio** produces the tone we like. These two: **AR and surface friction** need to be complimentary and balanced. So it's quite possible to have a very rough bore and a fairly bright tone or a glassy-smooth bore and a dark haunting tone. One of the woodiest, darkest tones I ever got was from a polished Plexiglas tube--but it's AR was quite low.

For some precise hole measurements and instructions leading to some great practice shaks visit PVC Shakuhachi. The Aspect Ratio's role in the sound of the shakuhachi becomes clear in these examples.

At a meta-level, the fundamental thing a shak (as well as other woodwinds) does is **constrain air movement** in subtle, interesting and useful ways. There's a lot of talk about impedence--just think of it as resistance. **Everything we've talked about in this page (and the others) can be boiled down to messing around with the ways and means of creating and lessening air resistance.** That's what the tube does, what the holes do (both in size and location), what the bore shape does, what the Choke Point does, what the inner wall surface does and so on. Air is tricky stuff--light, elastic, very quick and the most frustrating part is that you can't see the stuff.

It helps to begin thinking of the air as moving at Mach 1 speeds instead of the speed of the airstream. There's an F-16 aircraft in the bore when you play and the instrument is a wind-tunnel. This wind-tunnel can be shaped differently, doors can be opened and shut along its length. We can put in baffles, wedges, carpet--whatever we want. We can paint the walls of our wind-tunnel or leave them raw--whatever. And all of these changes have an effect on the resultant sound. Some more pronounced than others. **Why taper a bore? To increase its air resistance.** But now you know other ways to accomplish that. Once you move your mind to the concept of air resistance; many, many possibilities suddenly open up. Repeat this Mantra often: **Friction and Constriction create Resistance.** We're just fiddling with air--there's nothing holy about it. A shak is just an example of what you can do with one breath of air and some resourceful uses of friction and constriction. Lengthening the tube or thickening the wall both lead to an increase in constriction thus air resistance. Begin thinking of the air-load on a butterfly's wing--that subtle.

So we're left with the debate of tapered vs. straight-walled. Which way to go? Since we've separated out tuning the debate can now be seen a little clearer. With a straight-walled tube the timbre is easily selected and is more uniform across notes. With a taper, between the low and high notes in each octave, timber shifts--the Aspect Ratio (thus the timbre) undergoes a bigger shift with a taper than in a straight-walled tube. Remember, when the holes are opened you are in effect cutting off the tube, so with a taper you're leaving the choke point behind. The problem with tapers can be boiled down to trying to compute the Aspect Ratio for each note. It's not an easy proposition. Figuring out the true Aspect Ratio for the fundamental note is hard enough. Do you use the Choke Point? That's not quite right. Average? Maybe, but still not right. If you were to really try and figure it out you'll appreciate that the whole thing is a non-linear problem.

Since a straight-walled tube doesn't have a Choke Point the shift in Aspect Ratio is more linear and gradual. **So at the end of the day it's what you want the timbre of your shak to do, how you want it to vary while playing. More constant or more change? Kind of a Three Bears deal. Too much, too little and just right. I hope the foregoing will be of some aid in**

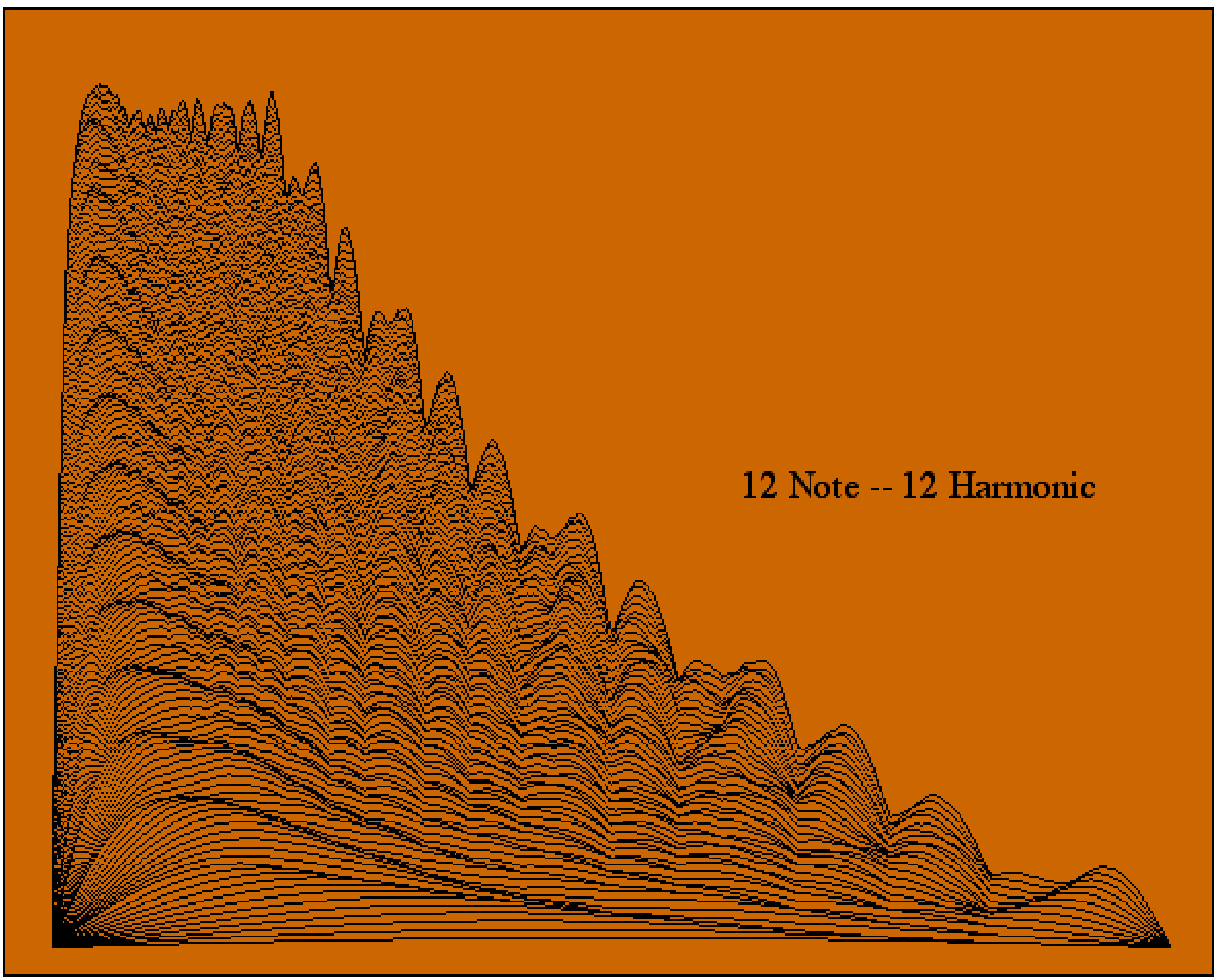
achieving your 'just right'.

Ultimately, the perfect flute would change internal diameter as you played it. Figure out how to achieve that and you'll have something.

There's a strange paradox to the Shakuhachi. If you sell someone a wonderful sounding shak, what are you selling? Some cleverly shaped emptyness--that's about all. Designed nothingness--that moves at the speed of sound.

For a book that's something like this discourse read The Structure of Delight.

For your visual enjoyment following is a graphic generated by the algorithm--a 'dimensional' view of the waveform created by plotting the values as they're computed and added up.

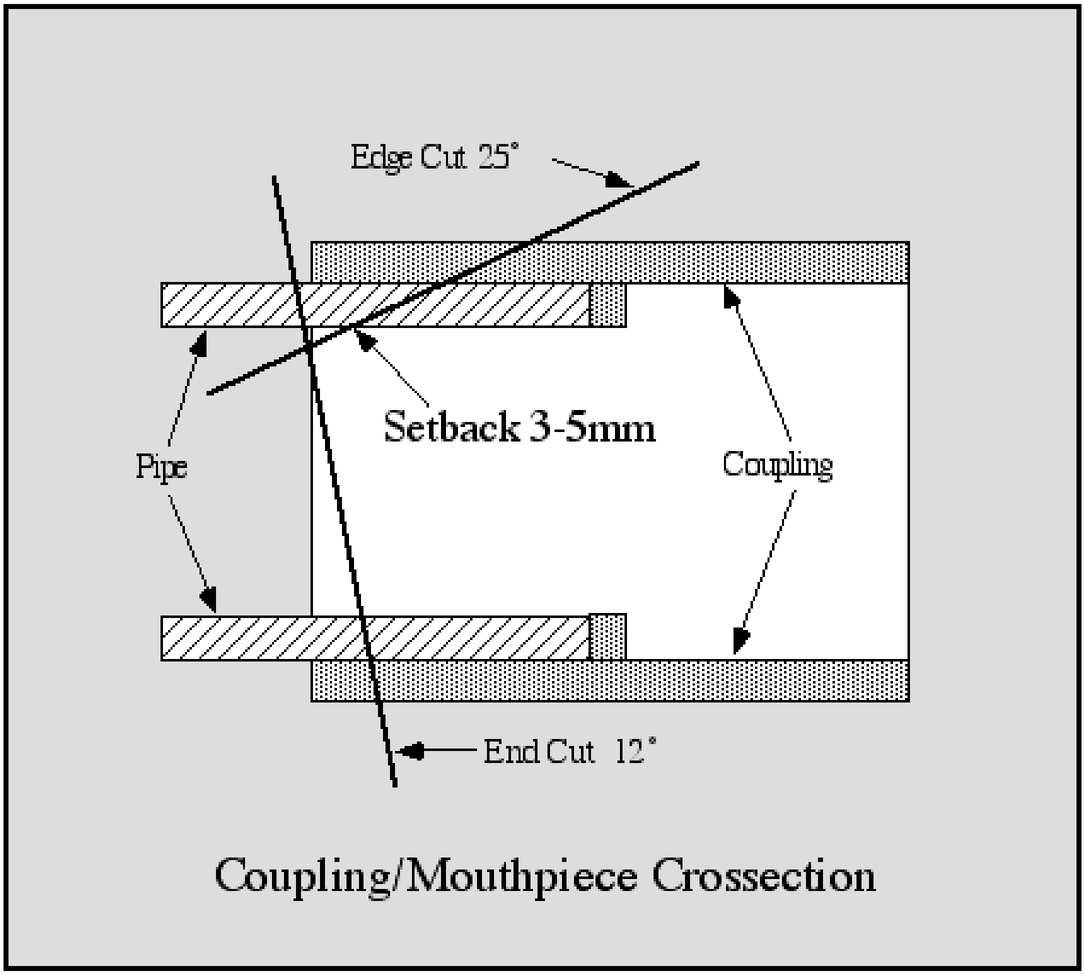


Shaku Design	PVC Shakuhachi

Go Back Home Shakuhachi Email Friend

Updated 1/15/04

Following up on the bore page we can further explore the subtleties of Aspect Ratio in the production of some fine practice PVC Shakuhachi. PVC is the acronym for Poly Vinyl Chloride which is used in the manufacture of plumbing pipe. 3/4" Schedule 40 PVC plumbing pipe is white, comes in 20' lengths and costs around $4. If you're a little careful in cutting you can get 9-10 flutes per length. The actual measurements are OD 1.050"--26.7mm and ID 0.815"--20.7mm. The pipe is not always perfectly circular or uniform in thickness--varying a few thousands of an inch. For this project make a removable mouthpiece from a 3/4" pipe coupling as shown in the following figure. Or if you're more ambititious create an integral mouthpiece.



Cut about an inch of pipe and glue it into the coupling with pipe dope. Make sure it's seated against the inner flange. Complete the **Edge Cut** first and be sure the **Setback point** is at least as great as you want. The blowing edge will have a nice curve in it and the center of that curve is the setback point. Then make the **End Cut**. If the setback point is initially a little too great you can make it right with the End Cut. Sand the sharp corners (not the blowing edge) and smooth to your satisfaction. Use acetone on a rag or paper towel to smooth and clean PVC. The pipe will have printing along its length and acetone will remove it leaving a white shiny, smooth surface. Now you have a mouthpiece which can be applied to any of the tubes we'll make.

Although this mouthpiece works fine it doesn't look like much, but there are more aesthetically attractive alternatives.

Getting Tubular

But first, let's review: Aspect Ratio is the bore's length divided by its diameter or width. It's a measure of how thin or fat the bore is. We're using a standard diameter

(20.7mm) available to all so the only variable is tube (hence bore) length.

We're going to explore **Aspect Ratios between 28 and 31** using a hole size of 11.5mm (29/64"). All holes distances are calculated using the **Factors** (factor times length equals hole distance) and measured in millimeters **from the flute's foot to the center of the hole**. The measurements in the table below are experientially derived and are true for 3/4" PVC Schedule 40 tubes, 29/64" holes and the mouthpiece described. The factors apply to these conditions and length ranges and are optimized for an Aspect Ratio of 30. **You can choose any length between 560 and 680mm and apply the factors to calculate hole distances.**

Hole	Factor	28 580mm	29 600mm	30 621mm	31 642mm	C# 555mm	C 588mm	B 623mm	A# 660mm
1	**0.2077**	120	125	129	133	115	122	129	137
2	**0.3092**	179	186	192	199	172	182	193	204
3	**0.3961**	230	238	246	254	220	233	247	261
4	**0.5169**	300	310	321	332	287	304	322	341
Thumb	**0.5781**	335	347	359	371	321	340	360	382

1) Make a clean cut on the section of pipe, seat the mouthpiece and measure from the side of the mouthpiece (not the blowing edge) to the length you've selected from the table above. **The length is the total length of the flute.**

2) Cut the tube to length.

3) Draw a pencil line lengthwise on opposite sides of the pipe for radial hole placement. This is greatly helped by placing the tube in a section of 3/4" angle iron (either iron or aluminum or make something out of wood)--tubes like this are hard to wrestle down and hold steady.

4) Measure the holes and drill.

5) Chamfer the inner edges of the holes and both ends of the tube. I use the edge of a half-round needle file as PVC is easier to scrape and cut than file.

Using the factors will make the flute play in tune with itself. Should you also want your flute in tune with other instruments use the right most four columns. The C flute's Aspect Ratio is a little above 28 -- B is close to 30. **Aspect Ratio probably has a greater effect on tone quality than any other single factor.** **Making tubes with Aspect Ratios of 28, 29, 30 and 31 will give you a very clear picture of Aspect Ratio and the Shakuhachi.** Another important element is how easily a shak will play the higher registers. Notice the difference in jumping to the second octave with a 560 and a 680mm tube. High Aspect Ratio make the upper registers much more available--low Aspect Ratio is generally considered the better sound. Go figure.

With the removable mouthpiece and tube selection you'll have a wide range of shaks to test-drive, study and enjoy!

See The Synthesis for a final flute design.

Read about craft from the Japanese perspective in *The Unknown Craftsman* by Soetsu Yanagi.
Sabi, wabi and the directness of Korean craft.
This is the deepest book on craft I know of--get it from Amazon.

Don't worry--be Hopi!

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Shaku Design	Tale of the 2.2 Shakuhachi

Updated 6/6/06

Everything was fine in the village, music reigned and life was simple. Then one day the Even Tempered Scale showed up and the numbers started proliferating.

Numbers, numbers, numbers. A shaku is a Japanese unit of length, just a hair less than a foot. Traditionally, shakuhachi have been made in 1/10 shaku variations from, let's say, 1 to 3 shaku--the 1.8 shaku (THE shakuhachi) being the most popular and the unofficial standard.

Once Western music settled on 12 notes per octave, the question became how the twelve notes would be spaced. They could have equal spacing or various other schemes. The Even Tempered Scale, which won the day, employs a simple and unique spacing method--the twelfth root of two. What number multiplied times itself three times equals 27? It's three, the cube root of 27. What number multiplied five times itself equals 3125? Five or the fifth root of 3125. The spacing of the Even Tempered Scale reduces to finding what number when multiplied twelve times itself equals two. We want to fill the interval between one and two (an Octave) with twelve **regularly**, but not necessarily equally, spaced notes. That's what the twelfth root of two does. Numerically it equals 1.059463094. Multiply that number times itself twelve time and you'll end up with two. As the twelfth root of two steps through an Octave it slowly ‘picks up speed’. The first spaces are smaller than the last-- the first divisions are shorter than the last, but the ratio is constant.

Further, the frequency of any note on the scale (think piano) multiplied or divided by the twelfth root of two will be the frequency of the next or previous note. Thus any two keys which are 12 notes apart on a piano comprise an Octave. The Even Tempered Scale spacing is close to equal but slowly and steadily increases as the frequency rises. Its a percentage deal, each note is about 6% bigger or smaller than the previous or next.

With the tenth-shaku system each flute is 1/10 shaku longer or shorter than the next. We've got two systems going on here--one is mathematically linear (shaks) and the other isn't. But we can ask: At what point do the two systems coincide? This is the same as asking at what flute length does 1/10 shaku equal 5.9463% of the whole? It's the inverse of 6% or the 1.6817 flute. Either side of that length the two systems of measurement start getting out of step.

So the 1.7 flute is very close to the length where the two systems match. Let's double that length to 3.4. Should play one octave (12 notes) lower, right? But according to the shaku system it should be 17 notes lower. There's the rub--12 notes verus 17. The two systems match up best the closer you are to 1.7--the further away the worse.

Back to the Village. What to do? They wanted to retain the tenth-shaku system **and** have the flutes in tune with Western musical standards. Two irreconcilable systems--obviously they're going to have to fudge a little. After considerable contemplation the Gray Beards decided. The tenth-shaku system will remain in name only, not as a actual literal system of measurement. For literal measurement they'd switch to the metric system or do shaku fractions and be done with it. The tenth-shaku system will be retired and elevated to a ambassadorial position, the Even Tempered Scale holds its own and the metric system or shaku fractions will be used for measuring the length of flutes.

""Our flutes played just fine before the notes came to town.", exclaimed the villagers.

"How do these three systems relate? What's the deal?", they asked.

Well, flutes aren't usually measured in tenth shaku anymore, they're just named that and their length is such to create the note we want. Thus the name and length may be, and often are, independent. Monty Levenson reports that most of the D shakuhachi he has seen fall in the range of 54.5 cm plus-or-minus one cm as a host of factors can and do effect pitch--bore volume, air temperature and, most importantly, the method and habit of playing. Monty goes on to explain the phenomena of 'leap flutes':

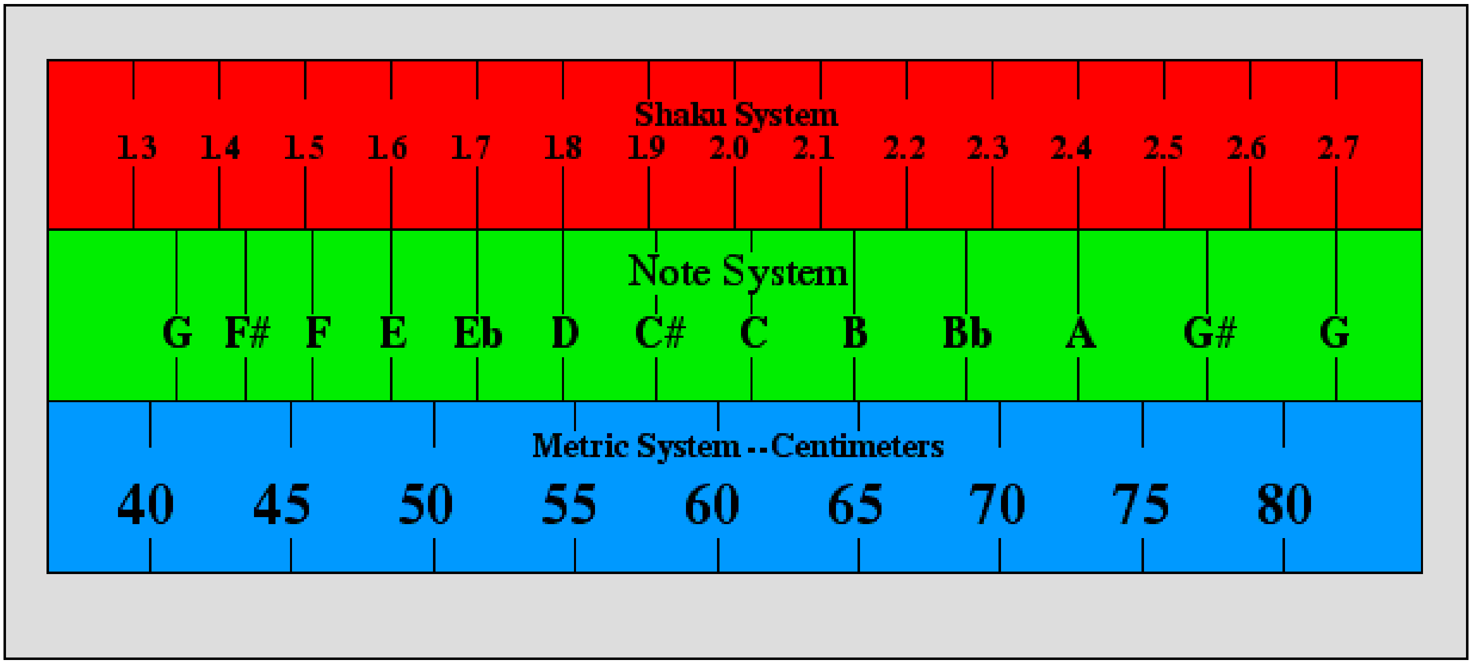
It is analogous to the Earth's annual trip around the sun. Each calendar year is a bit out of phase with the actual rotation necessitating the addition of an extra day every four cycles. In this case, the shakuhachi "leaps" at 2.2'. Starting with a 1.3' (Key of G), each sun added to the length of the instrument lowers the pitch one semitone. This convenient pattern, however, *breaks down when we get past the 2.1' (Key of B).* ***Hence, a Key of B-flat shakuhachi can be 2.2' to 2.3' in length. Often, shakuhachi made in the Key of A (called 2.4') are actually closer to 2.5'.*** *Add to this the different overall bore diameters used by shakuhachi makers as well as the relative thickness of the bamboo and resulting chimney heights (i.e. finger hole depths). These variations in bore parameters will determine the volume of air column inside the bamboo and account for small changes in pitch. Makers deal with this issue by slightly varying the overall length of the bamboo used. I would venture to guess that, upon close inspection, very few 1.8' shakuhachi exist that are exactly i shaku ha sun. The same is true for other lengths.*

Tom Deaver in Japan, offers this:

Just now I'm finishing the cosmetics on some 9-sun flutes which were made at just 1 shaku 9 sun. They play a bit high. ***2 shaku are made here at 2.03 shaku = C, 2 shaku 1 sun at 2.15 shaku = B, 2 shaku 3 sun at 2.3 shaku = B flat and 2 shaku 4 sun at between 2.43 and 2.46 shaku = A.*** *The next time any 9-sun flutes are made here I will just make them a bit longer. It all seems to get worked out in the long haul. 8-sun flutes are now, and have always been, made at 1.8 shaku even though they seem to play lower or higher as the current fashion demands. People just kari up or meri down to the currently popular fashion.*

Tom further mentions:

All the shakuhachi making folks I know here use the shaku system for the lengths and the metric system for bore measurements. There are two shaku systems in common use in Japan. One, called "kujira shaku" (same pronunciation means whale) which is about 20% longer than the other one, is used exclusively for kimono and cloth and every "wasai" (Japanese seamstress) knows it internally. The other, called "kane shaku" (kane means metal) is used for everything except kimono and cloth.



The first column, in the following table, is the flute model, then the note it should play and the frequency, then length in centimeters using a progression factor of **1.0594** (the twelfth root of two) and the length in shakus with the same factor. The last column uses a heuristically arrived at factor (**1.0632)** taking into account the comments of Deaver and applies most directly to his flutes. This is closer to reality (the builder's experience) than the twelfth root of two used in the progression of the notes. **If this holds, notes and flute lengths progress at different rates--that is, using different factors.** See Equivalent Timbre for more.

Tuning and Lengths

Model	Note	Frequency **1.0594**	Cm **1.0594**	Shaku **1.0594**	Shaku 2 **1.0632**
1.3	G	392.0	40.8	1.35	1.325
1.4	F#	370.0	43.3	1.43	1.409
1.5	F	349.2	45.8	1.51	1.498
1.6	E	329.6	48.9	1.60	1.592
1.7	Eb	311.1	51.4	1.70	1.693
1.8	**D**	**293.7**	**54.5**	**1.80**	**1.800**
1.9	C#	277.2	57.7	1.91	1.914
2.0	C	261.6	61.2	2.02	2.035

2.1	B	246.9	64.8	2.14	2.163
2.3	Bb	233.1	68.7	2.27	2.300
2.4	A	220.0	72.7	2.40	2.445
2.6	G#	207.6	77.1	2.55	2.600
2.7	G	196.0	81.7	2.70	2.764

Shaku = 30.303 cm = 11.93 in

So what's the length of the Model 1.8, the D flute or any other for that matter? As Monty rightly points out, it depends on the bore profile and other factors. Aside from the note system not correlating with the shaku system there are a host of other factors complicating the correlation of frequency to length. So measure your D flute when you play 'D' on it--that's how long a D flute is. Or more correctly, that's how long ***your*** D flute is. Levenson makes it clear when he points out that shakuhachi these days are measured by frequency rather than length.

Measuring the instrument linearly made sense when the shakuhachi was essentially a solo flute used as a tool for mediation. Later on, when it evolved in a secular, i.e. "musical", direction and was used in ensemble with other instruments, an acoustical standard became paramount. The impact of western forms and paradigms no doubt reenforced this shift after Japan was forcibly opened after three-hundred years of isolation before the Meiji Restoration. The confluence of traditional and modern always makes for an interesting, if somewhat baffling, amalgam.

So the moral of this story is beware when new standards are implemented.

You, like the 2.2 & 2.5 shakuhachi, may get squeezed out.

For some thoughts on flute length and ergonomic hole location.

The traditional system of weights and measures (Japan) is called shakkan-ho, from shaku, a unit of length, and kan, a unit of weight. This system had been widely used in Japanese life for centuries, affecting the formation of Japan's traditional culture. It was in 1891 under the modern Meiji Government that the metric system was officially introduced. The shakkan-ho was repeatedly modified to cope with internationalization and technical innovation and was finally banned in 1966 for use in contracts and for certification. Despite being banned, it is still used at worksites involving traditional wooden architecture or for handicrafts where the tools are still based on the old measures. It is also the basis for paper sizes for books and bills. Thus the ancient system of measure remains alive, coexisting with the metric system.

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Shaku Design	Hole Placement

Updated 1/15/04

Where should the holes go?

They can be placed with any number of criteria in mind: handability, aesthetic appeal, sound, etc. This page will look at hole placement from the point-of-view of 'Flat Spots'. It might be helpful to review the subject of nodes and tuning to get a grasp of why it might be advantageous to position the holes at certain locations and not others. Right between the flow and pressure nodes is what we might call a flat spot--a point of dynamic quiescence along the air column.

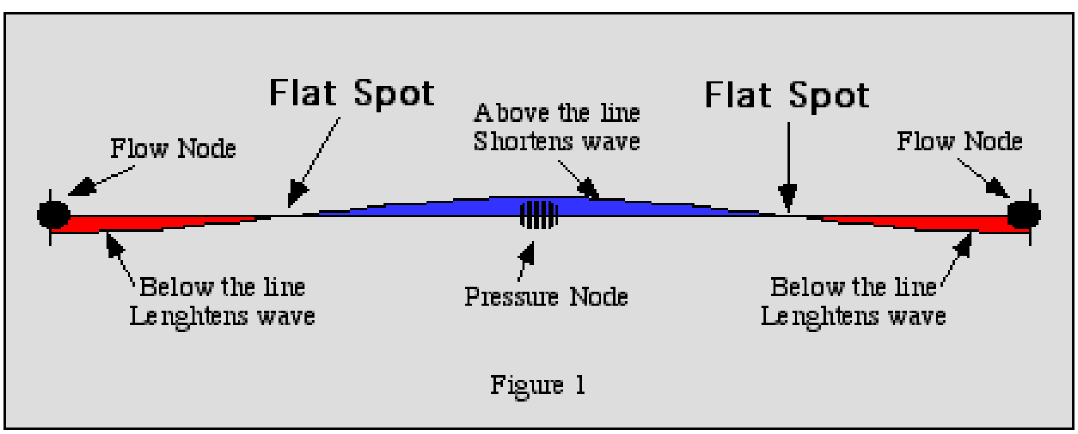


Figure 1

These locations present opportunity for hole placement because what happens in the vicinity of a flat spot has the least effect on sound. By 'happens' I mean any change in the geometry of the bore. If you want to do something to the bore (widen, narrow, drill a hole through the wall, etc.) and want your modification to have the least effect--do it at a flat spot. **All of the following is intended to be applied to a tube--a straight non-varying bore.** If the cross-sectional area of the bore varies then all bets are off as it becomes a harder problem to identify locations suitable for holes. That being said standard flat spots are a good place to start with any bore.

So where are these Flat Spots?

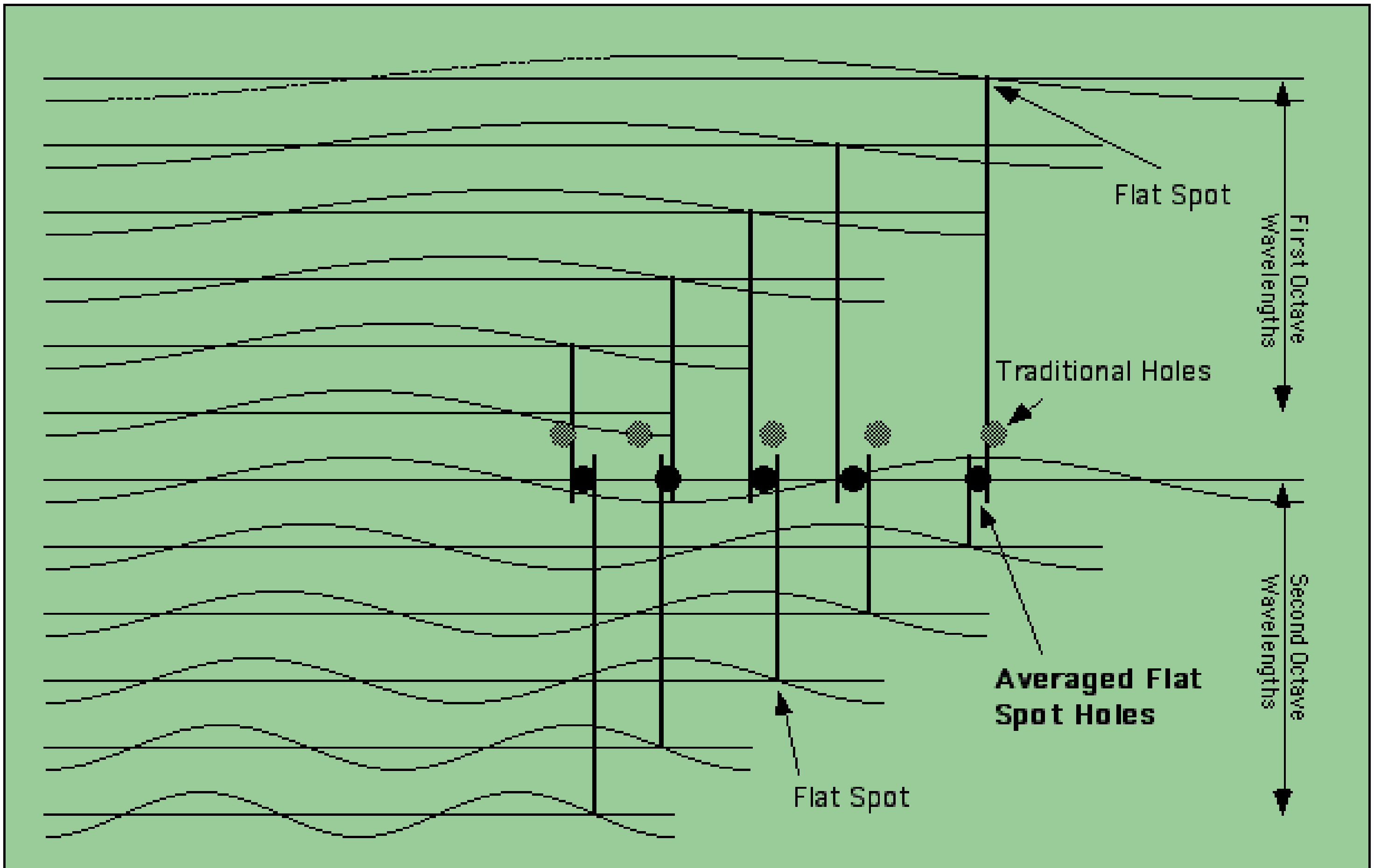
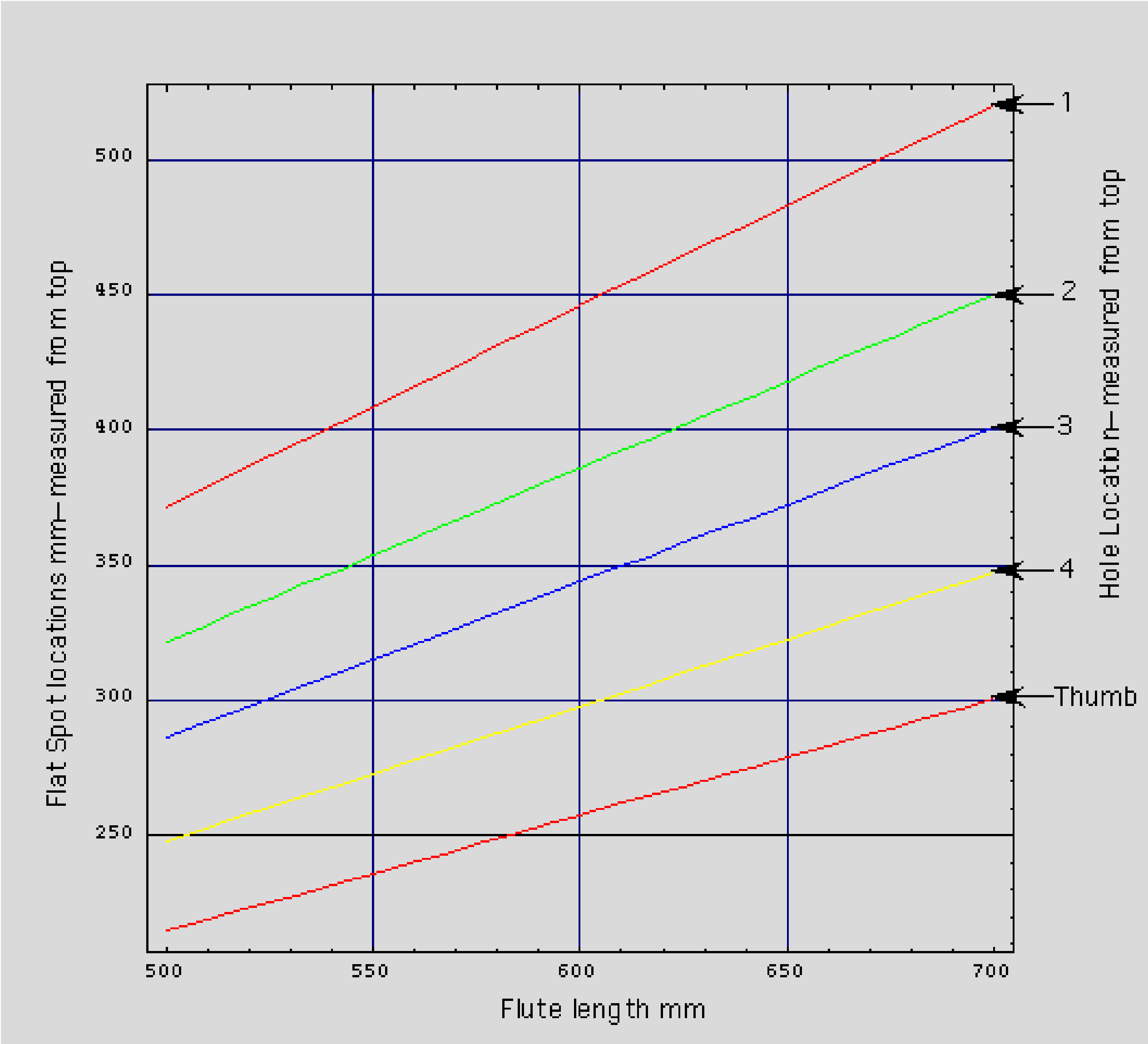


Figure 2

Figure 2 is a detailed 'map' of the acoustical properties of an air column, identifying the flat spots of the first and second octaves that are closest to the foot of the flute. Although the flat spots don't line up exactly, they're close enough to locate the holes between the two octaves. 'Traditional Holes' (above) indicates the hole location of traditional shaks--if there's such a thing as an average traditional shak. Relative to traditional, the first, second and third flat spot holes **move up** and the fourth and fifth holes are **lowered**. Placing holes in these locations will ensure the least adverse effect on the sound.



The idea implicit in Flat Spot Hole placement is that holes can have precise locations which correspond to the flat spots of the air column. Tuning is accomplished by sizing a hole rather than moving it. It doesn't work out that the holes are all the same size. The first three will be smaller and the last two larger. With this hole placement method, holes have an absolute location but not an absolute size. **Flat spot holes have a tighter grouping that more traditional layouts which makes their use in longer flutes attractive.**

For some related thoughts on ergonomic hole location.

And another page about the effects of hole size.

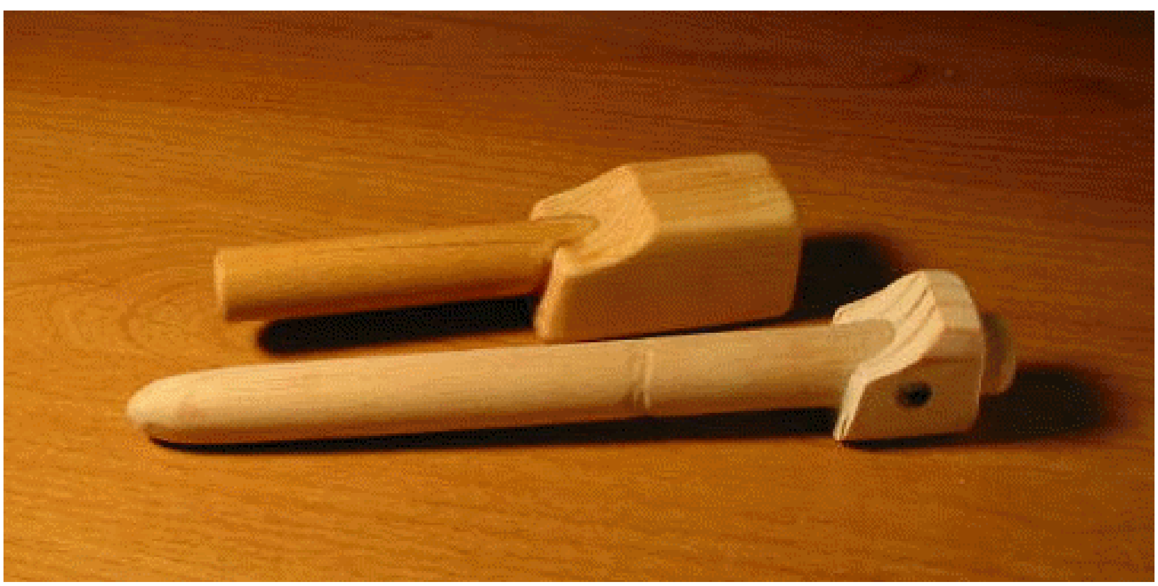
See The Synthesis for a final flute design.

Shaku Design	Mouthpieces

Updated 1/15/04

Part of the reason PVC shaks haven't met with wider acceptance is because of the standard coupling-mouthpiece. Mouthpieces made from pipe couplings work fine but they don't look so good. They don't tend to make you want pick up the flute and play it--something akin to contemplating kissing a toad. We'll try and rectify this by demonstrating how to fashion an integral mouthpiece from the end of the pipe. **See below for molded polyurethane mouthpieces for both Shak and Didge--that odd duo.**

Creating a **Integral Shak Mouthpiece** is pretty simple, you'll need a few tools and a Flaring Mandrel. The mandrel is the key and can be constructed from wood with a little patience and whittling ability.



Looking at these prototype Flaring Mandrels will give you the whole concept.

It's a dowel to fit inside the tube, with a radiused flare, set at the correct cut-off angle.

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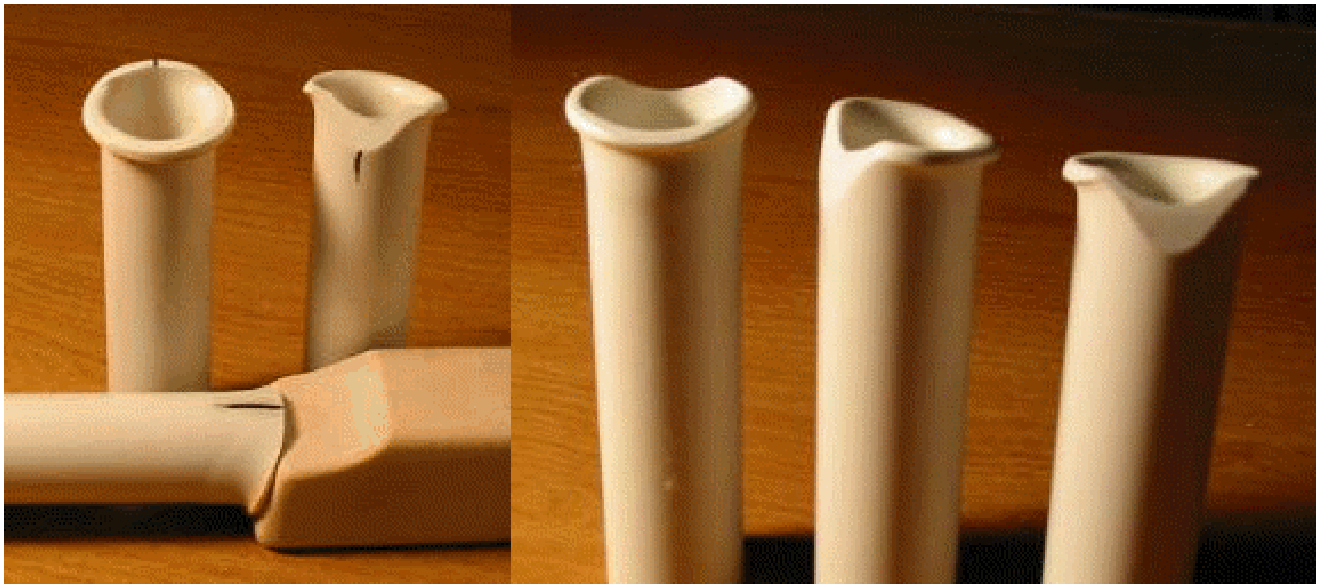
1) Just heat the rim-edge of the pipe with a heat-gun. Try and limit the heat to the portions you want deformed.

2) Insert the flaring mandrel, **twist** and press. Wait for the PVC to cool and set.

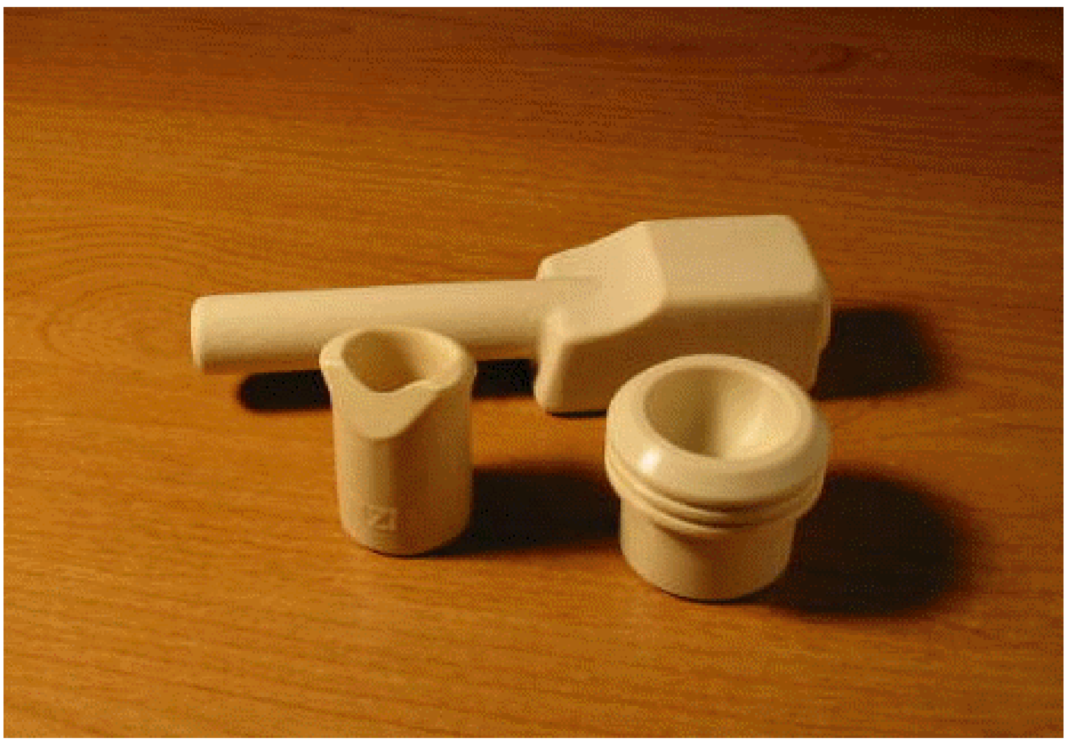
3) Fashion the blowing edge. Sandpaper around a short length of 3/4" PVC pipe will produce a suitable curve in the blowing edge.

4) Clean up the mouthpiece with files and sandpaper.

5) Smooth and polish with Acetone and you're done. That's it!



Removable mouthpieces.

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Shaku Design	PVC Hochiku

Updated 1/15/04

The Japanese flute called a Hochiku is similar to a shakuhachi and is often lumped in with the shakuhachi. But Tom Deaver, in Japan, points out that the two are different and explains this difference.

Hochiku, or as some write, Hocchiku, flutes are always (except for the exceptions) one piece flutes, without the familiar connecting joint near the center of the length. Shakuhachi are almost always made in two pieces with the joint near the center of the length. Any shakuhachi made in one piece is called "nobe". The "be" of "nobe" sounds like the "ba" of "baby". "Nobe" can be translated into English as "total".

Hochiku are usually much thicker (fatter) and longer than shakuhachi so are commonly heavier than shakuhachi.

More often than not hochiku have no inlay material (buffalo horn, ivory, plastic, whatever) at the mouthpiece. NOTE: Instead of "mouthpiece" we'll say "utaguchi". The angle of the utaguchi plane of hochiku is closer to perpendicular to the length *of the bamboo than utaguchi angles commonly seen on shakuhachi.*

The size of the hole at the top of hochiku varies widely and can be quite large while the size of the hole at the top of shakuhachi is very nearly the same for all shakuhachi regardless of the length. The hole at the utaguchi end of shakuhachi varies a bit among shakuhachi makers but nowadays there is some consensus that things are generally easier when these open ends are all nearly the same in internal size. The external size varies widely, of course, depending on the fatness of the bamboo. What this means is that for shakuhachi with large bores there will be a thin wall partially closing the open end at the very top of the flute in the area where the shakuhachi is placed against one's chin. This little wall is called "iki kaeshi". "Iki" means breath and "kaeshi" means return. On some shakuhachi, and even hochiku, a thin ring of bamboo is inserted into the utaguchi end to replace part of the removed membrane and is then filed out in the area where the breath is blown over the edge, leaving a sort of crescent shaped partial ring of different color and texture. Sometimes material other than bamboo is used to reduce the size of the opening at the utaguchi, car body putty, resin, whatever.

Hochiku are mostly bamboo bores that have grown while shakuhachi are bamboo and some other material bores that have been made. 0n certain occasions for whatever reasons filling material is added to the grown bore while on other occasions for perhaps other reasons bamboo material is removed from the grown bore.

The membranes at the nodes of hochiku (on the inside) are removed to a lesser degree than the membranes at the nodes of shakuhachi. The node membranes of hochiku are usually visible while the node membranes of shakuhachi are almost never visible.

The frequency of the lowest normal note (neither meru nor karu), Ro, of hochiku is not adjusted to any specified frequency. The frequency of the lowest normal note of shakuhachi is, these days, nearly always adjusted so some specified frequency of the equal temperament scale.

The frequencies of the fingering positions for all notes, other than Ro, of the open hole hochiku scale (Tsu, Re, Chi, Ri, Japanese Inakabushi Yosenpo) are not adjusted to conform precisely to any musical scale, nor are they adjusted to sound a specified musical distance from the basic tone (Ro). These same notes of the *shakuhachi are almost always adjusted to conform to the the musical scale currently in vogue, nowadays, the equal temperament scale with A4 somewhere between 440 and 445 hz, depending upon with whom one is talking.*

Finger hole location determination is about the same for both hochiku and shakuhachi, being in most cases a sort of good guess full of hope.

Hochiku, as bamboo flutes and as a term used and understood by Kodama, are as long as or longer than about nishaku-gosun or rokusun. Some of the shorter big fat flutes used by Watazumi would not be hochiku according to Kodama. Further, what might be called semi-hochiku which have some but not a lot of filler in the bore (some call them "ji-nashi" = without "ji" or filler), could not be classes as hochiku by Kodama because of the added filler.

So, hochiku are a simpler, more natural flute than the shakuhachi. It could well be that 'improvements' to the hochiku resulted in the shakuhachi. Anyway, hochiku makers fiddle with the nodal membranes-- selectively filing them away to achieve certain desired tonal properties. Unfortunately, the process isn't easily reversible. You're working down the bore with special tools and if you go a little too far in the filing then what?

Well, you can probably see where this is going. The obvious answer would be tunable nodal membranes--and that's what we're going to build. Using gray 3/4" schedule 40 PVC we'll fashion a hochiku with special adjustable 'nodal membranes'.

Where do the nodes go? Many years ago, XELO, a radio station streaming out of Chihuahua, Mexico sold live baby chicks through the mail. Part of the spiel was, "You can grow 'em up, bash 'em on the head, eat 'em if you want. You can do anything you want wit 'em, cuz they yo' chickens." The nodes is yo' chickens.You can put a node any place you want. And put in as many nodes as you want.

Generally there are four nodes if we count the closely spaced nodes at the foot of the flute as one. Since a shakuhachi usually alters the location of the fourth node when the top section is cut and reconfiured this node location is based on aesthetics rather than the natural growth pattern. What are the natural growth nodal locations? Hard to say because culms for hochiku are selected by at least partially aesthetic criteria. But we're really only talking about one node--the fourth (see table below). Where should it go? It will be closer to the mouth than it's located in a shakuhachi. Let's say 24 mm. Again, you can put any and all nodal membranes wherever you wish. Make up your own natural nodal algorithm or measure a prized piece of bamboo and use those ratios.

Tunable PVC 1.9 (576mm) Hochiku

Holes 3/8"	Nodes Shakuhachi	Nodes Hochiku
1 -- 451	544	544
2 -- 400	484	484
3 -- 344	363	363
4 -- 283	**216**	**192**
Thumb -- 246	--	**--**

All measurements in millimeters and from the top.
This length (576 mm) with an integral mouthpiece plays C#.
So you can skip the nodal business
and just build a C# flute from these measurements.

Cut the pipe, fashion the mouthpiece, drill the holes 3/8" and mark the node holes along the underside of the flute. Drill and tap the node holes to accept 1/4" inch bolts. Insert the bolts and you've got a tunable hochiku--just screw these 'nodal membranes' in and out as you wish. That's the concept. You can easily alter location and number of nodal membranes along with their size and material. Small Parts, Inc sells nylon setscrews of different sizes and lengths. Air seal the bolts with Vasoline or wax.

There have been claims that adding outer 'nodes' to PVC will improve it tone. The theory is that PVC needs stregthening at nodal locations to achieve full resonance. If that's true then hose clamps would do the trick. We're all little more inclined to believe that adding mass at selected points along the course of the flute might effect it's resonance. In any event, the size and material of the bolts lend themselves to an investigation of the role of mass in this mysterious subject of 'resonance'.

Screwing bolts in and out at selected locations changes the volume of the bore which has a direct effect on sound and tuning. It's called perturbation and that's what filing natural nodal mebranes does. One interesting aspect of this design is that with a partner you can actually hear the shift in tone as the bolts are being adjusted during play--real time feedback.

These hochiku are inexpensive, simple to build and lend themselves to learning about nodal membrane tuning--besides worrying the neighbors. A different kind of adjustable flute is on the Throated Flute page.

See The Synthesis for a final flute design.

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Shaku Design	How long is your D flute?

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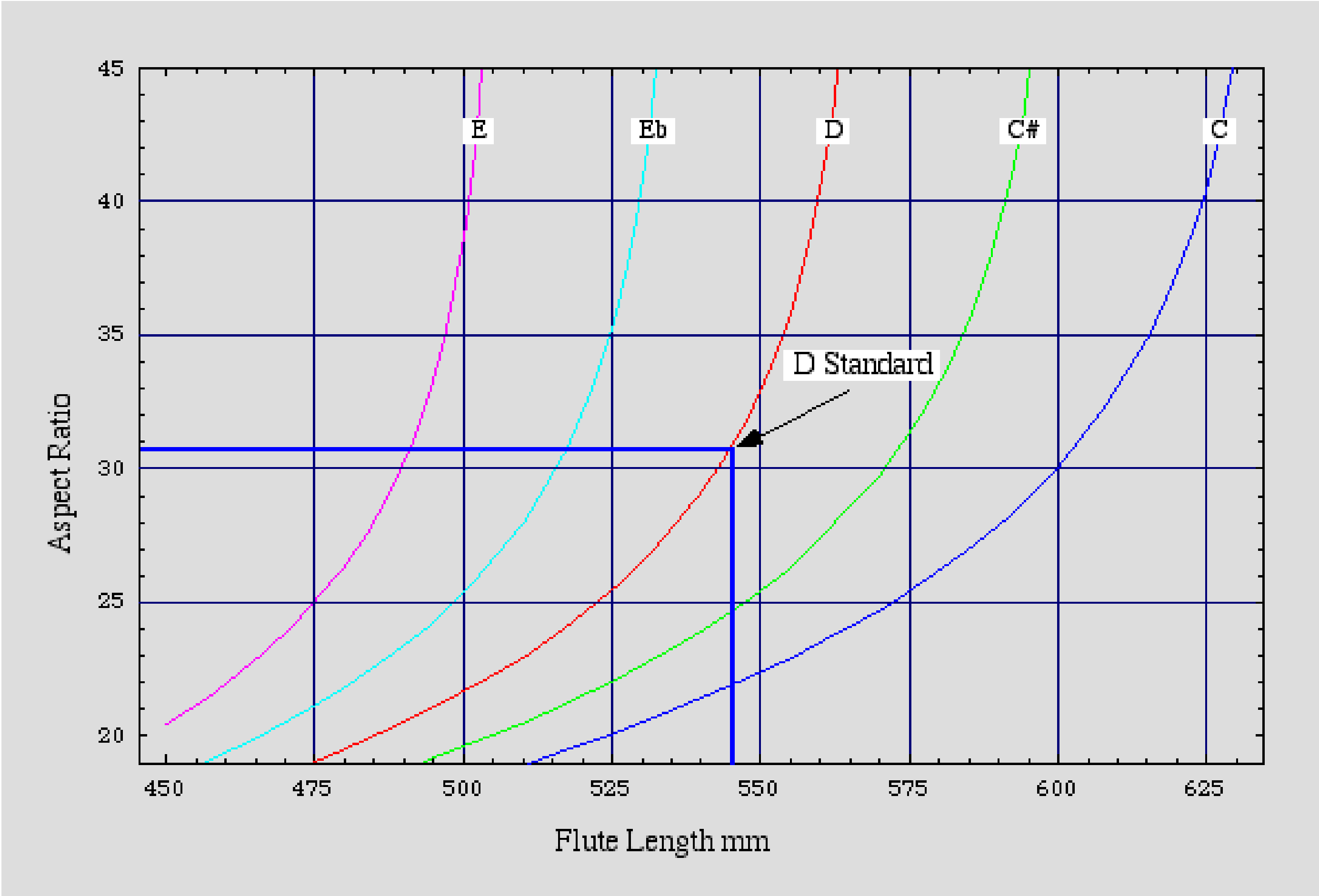
Updated 1/15/04

With flutes, there's a strict relationship between length, bore and frequency. The standard D shakuhachi is 545mm long--that's 1.8 shaku. Thus the standard shak has a specific effective bore size which means a specific Aspect Ratio, which means .... Well, let us show you.



This graph ties it all together--**Note, Length and Aspect Ratio** (length divided by bore). If your flute is 545mm long and plays D then it's AR is not quite 31. Every shak which is 545mm long and plays D has this Aspect Ratio. **All D shaks 545mm long sound pretty much alike because they all have essentially the same Aspect Ratio.** A D flute with an AR of 25 will be about 520mm long--it's that simple. (Another method of determining Aspect Ratio)

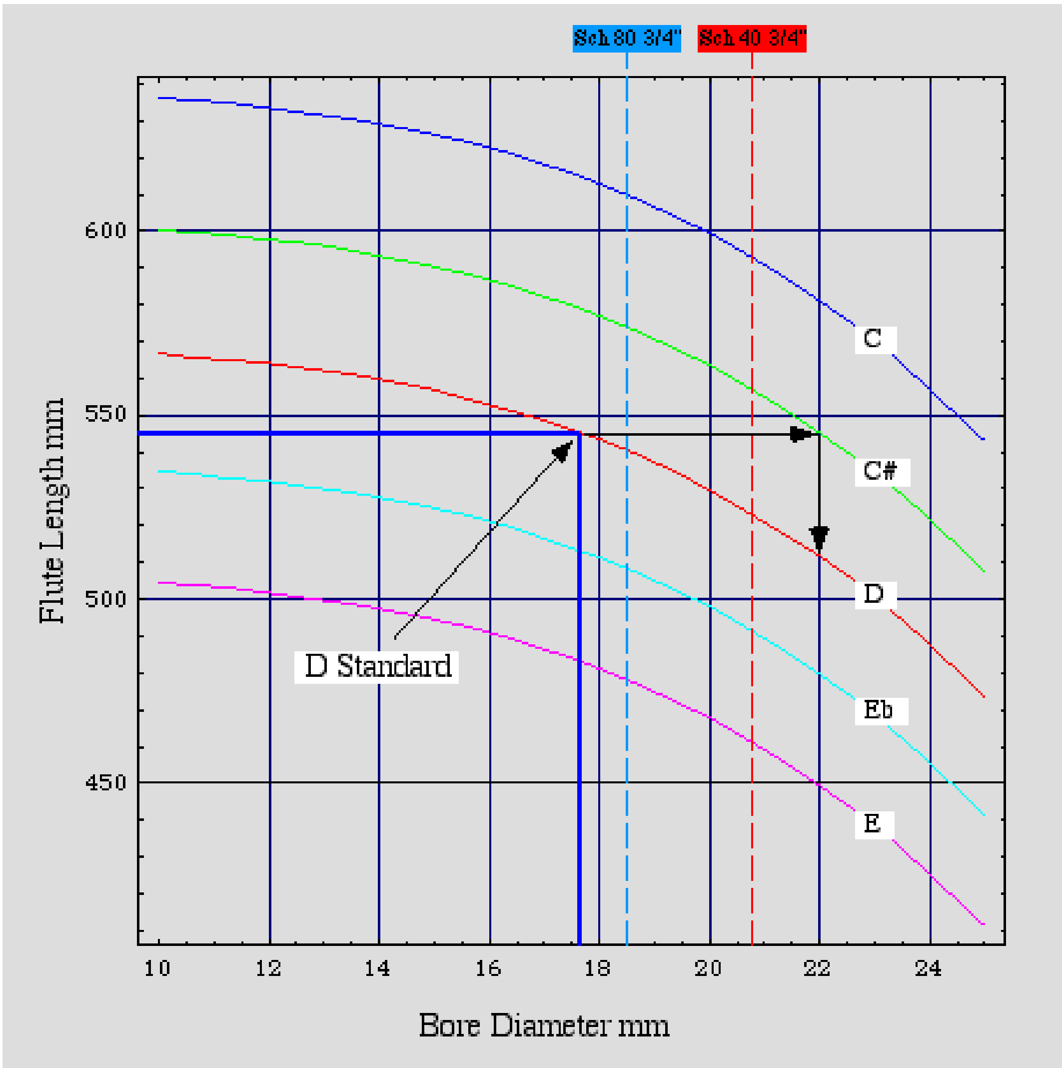
Yes, there are things (bore finish, etc.) which can shift Aspect Ratio...a little. But the basic geometry of the bore is the greatest determinant of Aspect Ratio--the timbre--of your flute. What the graph tells you is that for flutes tuned to specific keys the flute's length determines it's timbre. There should be D flutes around which vary in length from, say, 480 to 560mm. That's about a 17% variation in length. Outside that range they won't play too well.

It's obvious from the graph that length isn't the sole determinant of pitch--it's just one factor, Aspect Ratio being the other. At the end of the day it doesn't matter a whole lot about how a shakuhachi's bore is configured--as far as Aspect Ratio goes. **A fancy tapered bore with an Aspect Ratio the same as a straight pipe will sound pretty much the same.** The octave tuning may be a little different but the fundamental sound characteristics are very similar.

To have flutes made to standard lengths is the same as saying they have standard sound characteristics. If nothing else the graph demonstrates the impact of bore diameter. Aspect ratios above 30 are sharper, clearer, more piercing and favor the higher notes. Below 30 are mellower, softer and favors the lower notes.

So how long is your D flute? Or perhaps more importantly, how long do you want it to be?

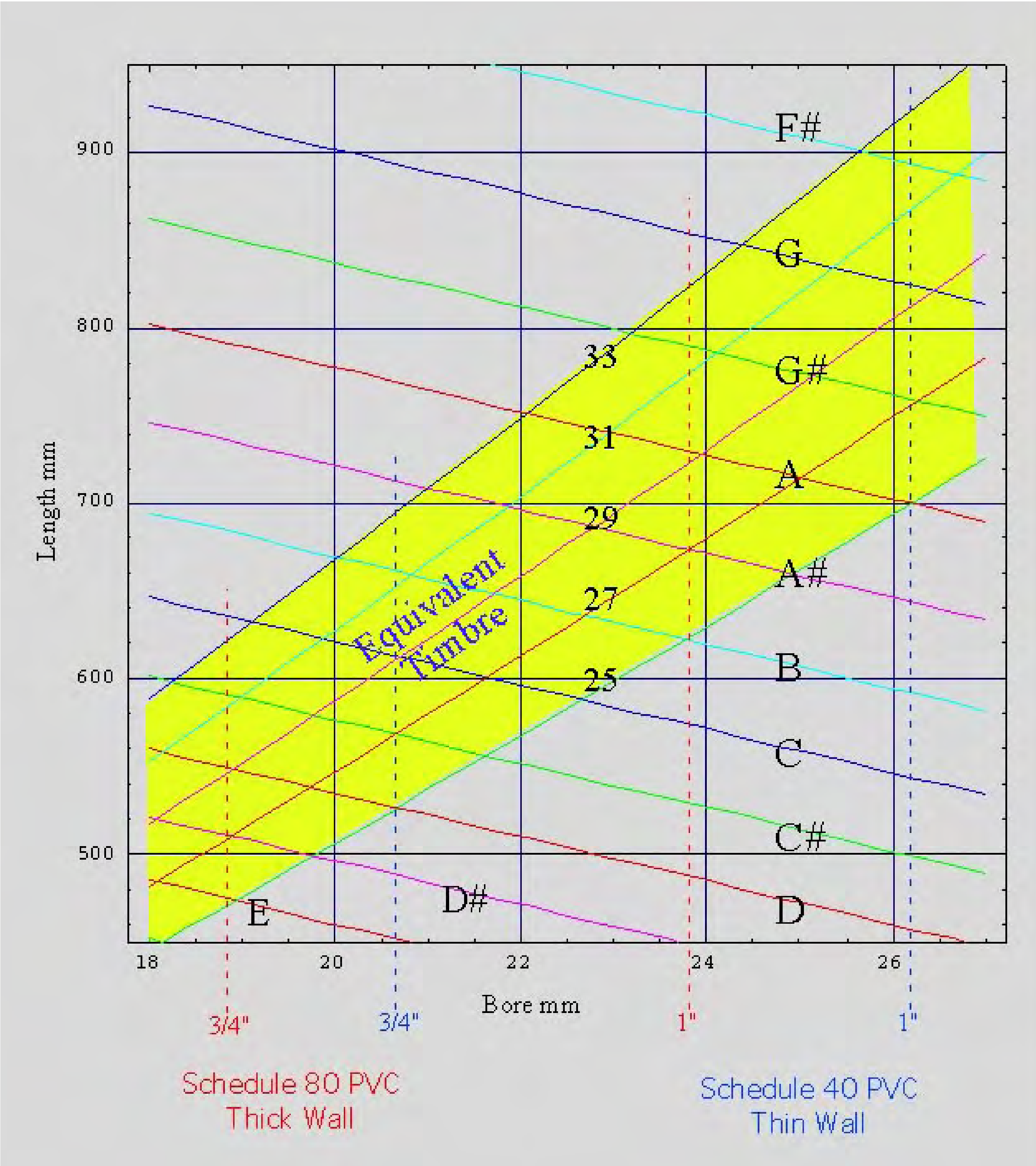
Graph of flute length vs. effective bore diameter.



Here's the dance. Suppose you have a D flute and it's average bore diameter is about 17.5mm. You want to open it up a little, lower the AR, get a mellower sound. So you do some filing in the bore. But then it doesn't play D any more--it plays flat. So you cut off some of the length to get D again. And so it goes, following the D curve in the graph above.

Notice that if you opened up the bore of standard D all the way to 22mm it'll play C# (see graph). D length but C# sound. Then if you cut off about 35mm you'd get it back to D. **Fat bores are shorter than skinny to produce the same note.**

The following graph attempts to make sense of it all.



The Yellow Zone (above) delineates lengths and notes for suitable PVC flutes.

The range of the Zone's Aspect Ratio is 25-33, but this is Equivalent Timbre.

Very playable flutes can be made of thick and thin walled 3/4" PVC, tuned respectively to D and C.

PVC pipe sizes •••• Convert English-Metric •••• 1"=25.4mm

See The Synthesis for a final flute design.

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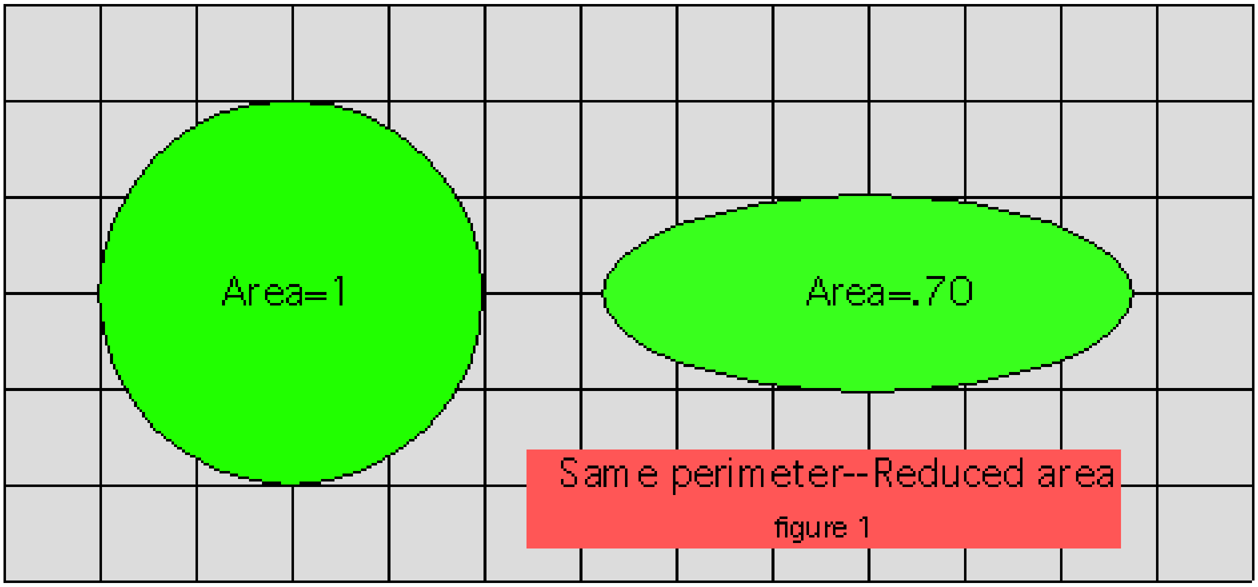
Shaku Design	Tapering PVC Pipe

Updated 1/15/04

Aside from PVC pipe not being bamboo, what's the primary objection to using PVC for making shaks? It's the taper thing. So let's solve that. Think about a garden hose and how the water flow is reduced by squeezing the hose. If a circle is turned into an ellipse, the area decreases. Same perimeter, reduced area. As the ellipse continues to flatten its area decreases to nothing. Tapering the bore is just a method (there are others) of restricting air movement by reducing the area of the bore.



That's what we're talking about in the tapered shakuhachi bore--the cross-sectional area of the bore decreases to the choke point and then flares to the foot of the flute. **So how can we easily alter the cross-sectional area of the bore of a PVC pipe?** Yes, you guessed it! We'll heat the pipe and squeeze it where we want the bore area decreased--gradually shifting the shape from a circle to a flatter and flatter ellipse.

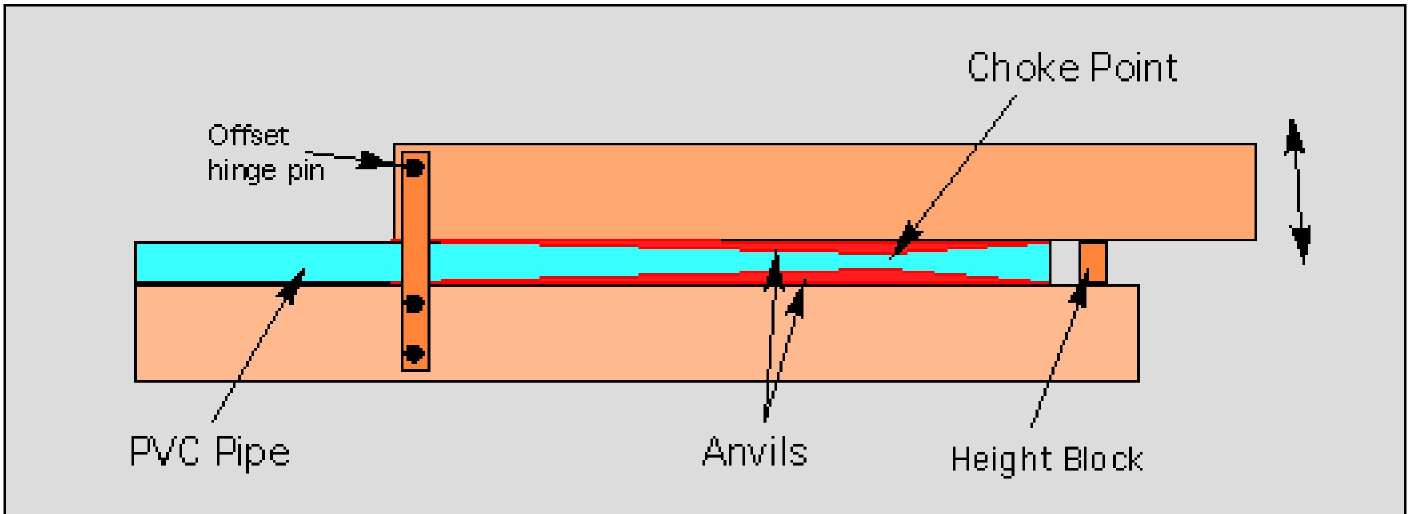
What bore shape do we want? For this exercise, let's keep things simple.

1) Start the taper between the second and third tenths of the flute's length. A quarter of the length is a good general starting point.

2) Continue the taper (squeezing) until about 86% of the length, then flare back to the foot.

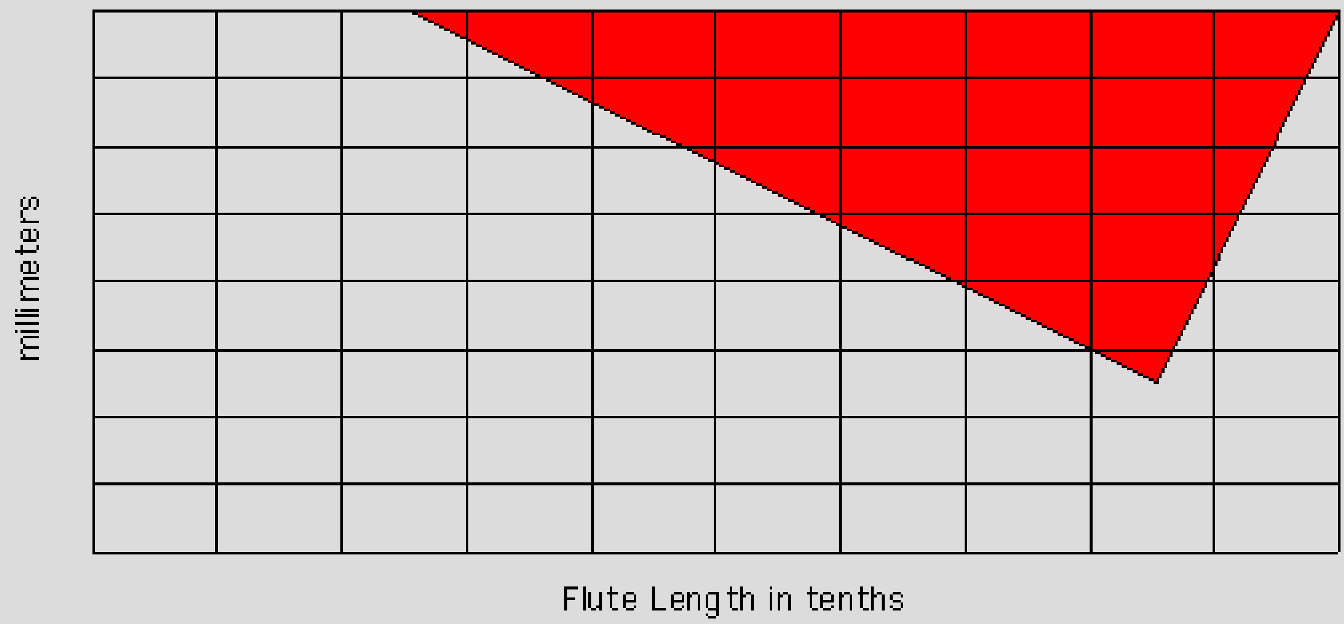
3) How much to squeeze? The choke point in some shaks is half the area of the mouth, but that's a pretty tight constriction. That's where the ellipse will be flattest.

There is another consideration: In woodwinds the cross-sectional shape of the bore **does** make a difference. **In a pipe organ, a circular and square pipe of the same area don't act (or sound) exactly the same.** A square pipe has more surface per area than does a circle and the same is true with an ellipse. Anyway, start by squeezing the diameter at the choke point to 1/2 that of the mouth as shown in figure 1. Using these measurements you'll be well within the ballpark for a tapered bore. The rest is just tweaking for the particular sound your ears enjoy.



PVC Pipe Tapering Clamp
figure 2

A simple clamping jig can be built from two-by-fours. You can make any number of squeezing anvils, each **pair** with a different geometry. Once the clamp is ready, make a PVC shak in your usual manner, then heat with a heat gun and clamp. In less than a minute, the PVC will set rigid and **you will have tapered the bore to the geometry of the anvils**. The anvils will be thinner than you might have imagined. For Schedule 40 PVC pipe the bore has a diameter of about 20.7mm. Squeezing that in half means the thickest part of each anvil will be 5-6mm. For a 1.8 shak the anvils will be approximately 410mm long, so they're long skinny suckers. We're talking 16" long and a quarter inch thick at the thickest point.

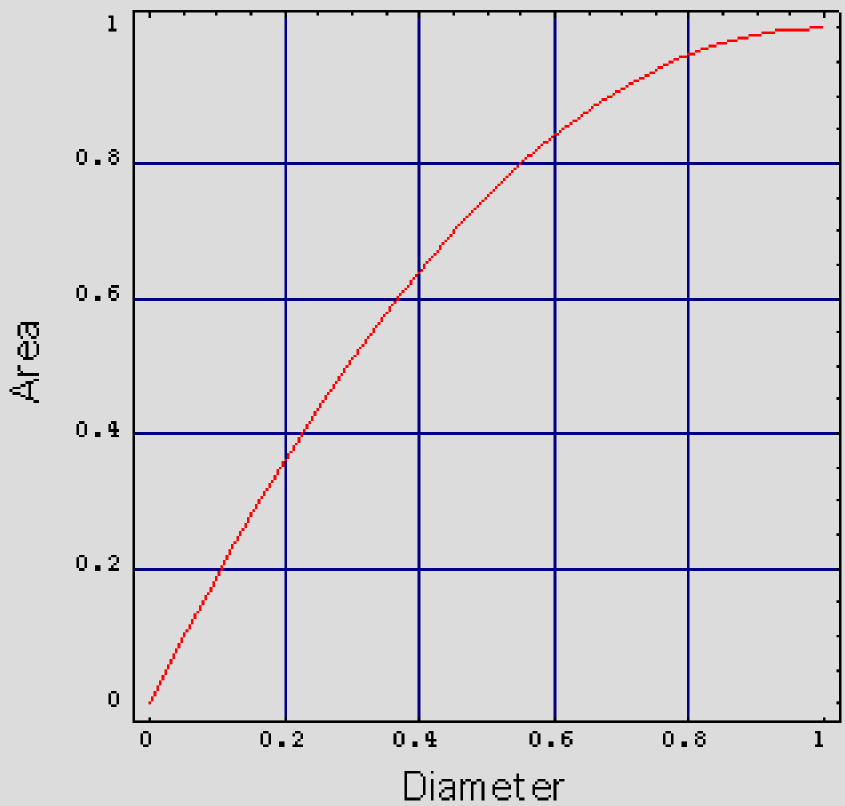


Anvil Shape for Schedule 40 PVC
figure 3

If you're handy with tools you don't have any excuse for not having PVC shaks with bores tapered to your own specifications. Another interesting part of this ellipse business is your flutes can begin to vibrate as an elliptical bore shape is the biggest single factor is the production of flute body vibrations.

This method of creating tapered bores is well suited to the investigation of bores in general. Because PVC pipe can be reheated and pressed back to a straight pipe this method lends itself to forming and reforming bores. It's a quick, easy, low-tech method through which one can learn a tremendous amount about the mysterious shakuhachi bore--aside from knocking out some inexpensive high quality shaks.

See The Synthesis for a final flute design.



Approximation of the ratio between diameter and area as a circle flattens into an ellipse

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Shaku Design	Lookin' for the Buzz?

Updated 1/15/04

Getting the body of a flute to vibrate is a fairly simple matter--if you like that kind of thing. John Singer, in a fine article, calls this phenomena "chikuin". To some, these vibrations are seen as evidence of a superior flute and perhaps it's true, but **they arise from purely geometric circumstances**.

Now for a little geometry. A circle is an ideal shape in that it contains the greatest area for its perimeter. Thus of any shape, a circle is optimal in it's area to perimeter ratio--a factor of 1/2. The ratio for a square is 1/4 and all shapes fall in the range 1/2 to 0. A line, which can be thought of as a completely squashed and flattened circle, has a 'perimeter' but no area--a factor of 0.

Now think of a soap bubble. Blow them up and they want to form spheres (three dimensional circles). Why? Because any other shape has a smaller area (in this case, volume) so the gas pressure is higher. By altering it's shape to spherical, a bubble reduces it's gas pressure. Water flows downhill and bubbles seek the lowest pressure possible.

A circle is already optimized and can't improve it's shape--it's already maxed out. So to get a flute to vibrate we have to seek a bore shape with a ratio lower than 1/2. We want a shape which can trade up to being a cirlce. And that's where the oval comes in.

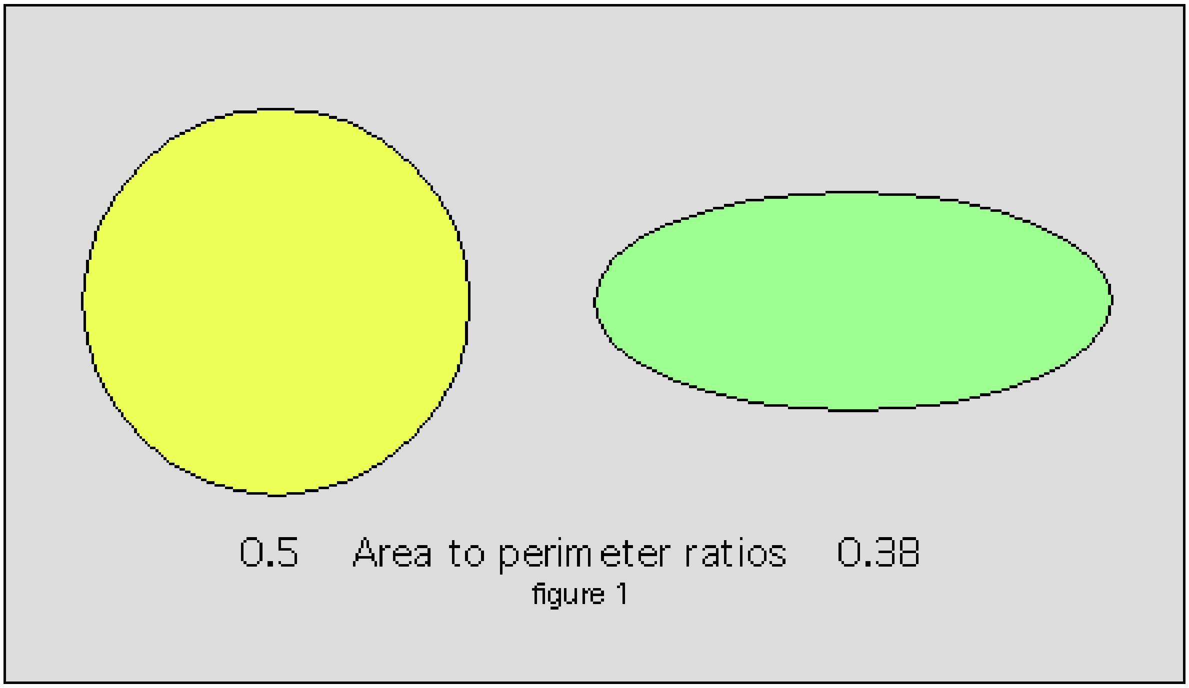

figure 1

For the purposes of this discussion, **an oval is an unhappy circle**. It wants to be a circle and given the change it'll change it's shape toward that of circle. You haven't been blowing many ovaloid soap bubbles lately, because given a choice they all instantly assume the spherical shape. In the case of a flute, when an ovular bore comes under pressure it seeks a circular shape but is restrained by the rigidity of the bore walls. So it moves just a little. When the pressure is released the bore snaps back to it original oval shape. But when a flute sounds, air pressure is applied and released a few hundred times a second. That's what sound is. **So hundreds of times a second an ovular bore strains toward a circle and then falls back--that's flute body vibration.** It's a matter of shapeshifting.

What your shak to buzz? Here's how.

The task of creating a vibrating flute is two fold: 1) Pick a shape which wants to be a circle and 2) Make it easier for it to get closer to being a circle. Do that and you've have a fine vibrating flute. We've got to make it easier for the oval to deform toward a circle. And to do so we will reduce the strength and rigidity of the bore wall in both planes--horizontal and vertical.

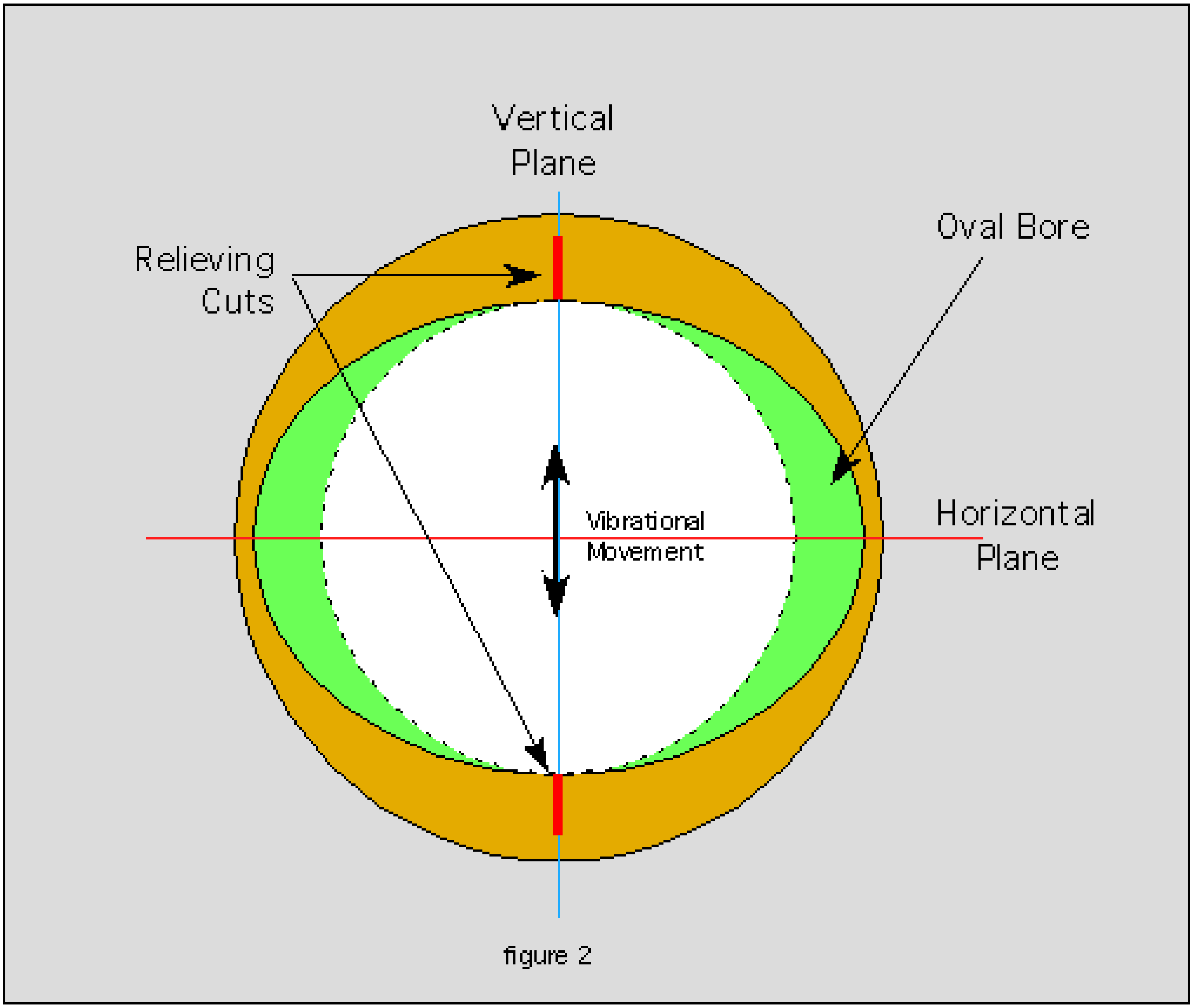

figure 2

Creating an oval bore will thin the bore walls in the horizontal plane in the process. Now take a hacksaw blade (or some such) and make cuts in the vertical plane, cutting inside the bore. The thinner the walls are in both planes the easier it is for the oval to shapeshift--thus the greater the vibrations. Vibration robs energy from sound volume so it's hard to have a LOUD and vibrating flute at the same time.

Anyway, for greatest vibratory effect: 1) make the bore ovular, 2) add relieving cuts which extend as far down the bore as possible. These two things reduce the thickness of the bore wall in both planes.

From a purely engineering standpoint there is a further consideration called mass-loading. When the mass of the bore walls is just right for the frequency; body vibrations will be greatest. Any smaller or greater mass will dampen the effect. Since flutes sound at different frequencies during play, mass considerations are difficult. There are other factors which effect vibration, rigidity of the bore walls and so on, but without the basic geometry nothing is going to happen in the first place.

Now here's the problem with all this 'flute body vibration' stuff. Play Ro, Tsu, Re--those three notes. Did the vibrations also change notes? Play Ro, Tsu, Re on a marimba. Did you play it all on the same bar? Of course not. A flute who's body will vibrate does so at a single pitch, so the sound arising from this vibration would be heard as a drone note as it's pitch would be unvarying.

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Shaku Design — Removable Tapers

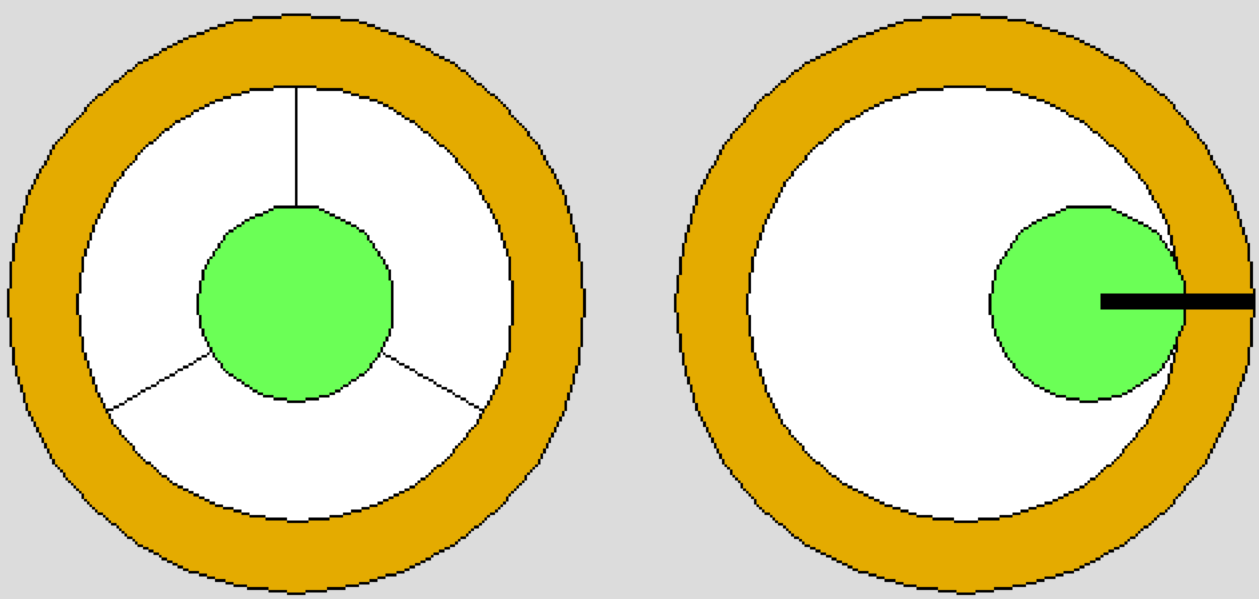
Updated 4/17/06

We're back to talking about straight pipes and tapered bores. Again. As was pointed out on an earlier page, material used in tapering the bore of shakuhachi doesn't have to be on the wall of the bore. A taper doesn't have to look like old plumbing pipes filling up with lime coatings. A tapered stick can be introduced into the bore which will fulfill the function of restricting the air space. And that's all tapers do anyway. **So the possibility arises of having shakuhachi kit:** a basic straight-walled pipe with blowing edge and holes and then maybe a dozen tapered inserts, each to optimize different aspects of the shakuhachi experience. Each would allow the pipe to play and sound differently. The tube and taper can (and maybe should) exist independently from each other.

As a starting point, obtain a dowel which has a cross-sectional area half that of your basic pipe and then by sanding/grinding/whittling/etc. shape it to change the bore volume into whatever configuration you want. The one nice thing about this approach is that you can remove the taper, work on it, reinsert and **test your addition or subtraction in a fast, easy and straightforward manner.** No more peering down the drain pipe and working like a surgeon, wielding strange homemade tools and waiting for things to dry/harden. About the only trick may be how you affix the taper inside your flute. Because there are holes on opposite side of the flute, the taper will likely have to go either in the center (supported by a wire bracket) or screwed on a side-wall as seen below.

Using this method you can create, test and finalize tapers in a couple hours. It's ideal for those 'what if' moments and you can try out about anything you can imagine. Tapers don't need to have any particular cross-sectional shape, they can be square, round, oval, half-round, rectangular---about anything you desire and find easy to work with.

Removable tapers would add a new and interesting dimension to the shakuhachi.



Methods of suspending Taper Inserts

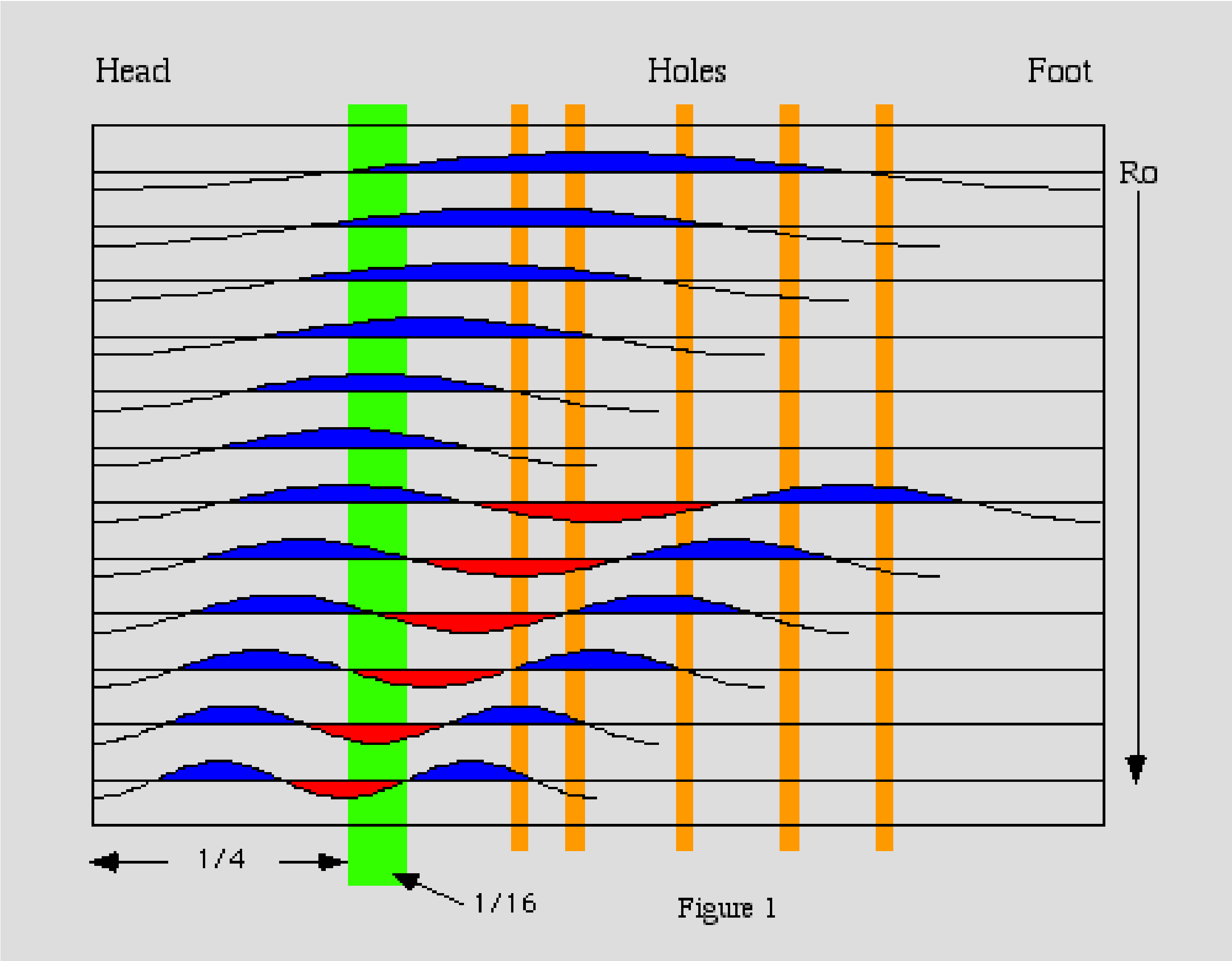
See The Synthesis for a final flute design.

Sharpening the Second Octave

Updated 1/15/04

You can take a straight tube, drill holes of the right size and location and the notes will be in tune--in the first octave. The second octave is another story. For physical/ acoustical reasons the second octave will play progressively flatter. If this weren't true we'd all play a straight tube and be done with it. But it's this fact that leads to much of the fiddling with the bore geometry of shakuhachi. In a previous page we talked about tuning by adding material to the bore. In this page we'll investigate **tuning by stock removal**.

Surprisingly, the location (within reason) of the holes doesn't make a whole lot of difference as far as tuning goes. And when tuning the second octave by stock removal, computer studies have revealed there's really only one location (the green strip in figure 1) which has a profound correcting effect. It makes sense that any effort toward progressively sharpening the second octave should take place above the holes so as to effect all notes--thus octave tuning should take place in the throat of the flute. And by happy coincidence there is a specific place that works.

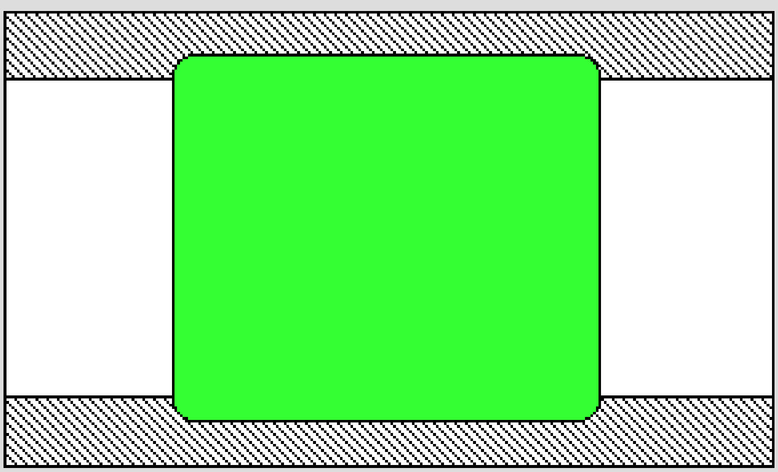


Both the orange (holes) and green stripes in figure 1 signify stock removal. Holes, even when closed, create a little 'bump' in the bore--an extra space. To some extent, the 'green' is offsetting and reversing the 'orange'--bringing things back into balance. With a straight tube the extra space created at the green strip can be located mathematically, but in an uneven tube (read bamboo) it's a little more difficult. In general, with bamboo it'll always be less than 1/4 of the total flute length. But the sonic nodes (hence the removal spot) in non-regular tubes can be determined precisely with a little extra effort and equipment. Red and blue in figure 1 signify sonic nodes and anti-nodes--see the general tuning page for more clarification if needed.

Here's the deal: **When material is removed from inside the tube, enlarging the bore at the green strip, the second octave will come into tune.** It's that simple.

Stock removal should begin 1/4 of the flute's length down the throat and proceed for another 1/16 of the length. So for a 600mm flute it'd start at 150mm and end at 188mm--a 38mm wide band removed from the inside of the flute. How deep? A depth of 10% of the wall thickness is usually sufficient. The depth is the one variable which isn't fixed and depends on hole size, wall thickness and other factors. Although the placement of the edges of the internal groove (figure 2) is sensitive, the depth is variable depending on the flute. This spot sometimes corresponds with the upper bamboo node in a non-jointed flute--and sometimes it doesn't. Depends on the bamboo. In any event, it's usually near the top bamboo node and there's a tendency to remove material at the node whether it's in exactly the right place or not. The location is sensitive and a few millimeters one way or the other changes things, not gradually, but somewhat catastrophically.

To go by the bamboo's nodes one has to believe a particular piece of bamboo intended to be a flute rather than a piece of furniture or just wanted to live a long life and die peacefully in the forest. Who knows what's in the mind of bamboo? And until we do it's best to measure.



Crossection of tube displaying stock removal

Figure 2

How to remove material from the inside of your bore? That's the trick. With PVC pipe it's simple to cut the pipe at the green strip and use a coupling to leave an internal space. Otherwise? You now know the place to start digging/filing/cutting/sanding/planing--how is limited only by your imagination.

For those who like numbers, measuring, etc., tuning can be improved slightly by adjusting hole locations. Generally, the thumb hole is about 42% of the flute length from the top. Progressing from the thumb hole downward, set holes at 48%, 58%, 68%, 78%. **The old prescription of placing holes a tenth flute length apart appears to have merit.** To gain even more tuning balance raise the thumb hole to 39%.

For what it's worth, the most theoretically perfect tuning is achieved by enlarging the bore at the green strip and placing holes at 39%, 48%, 58%, 68% and 78% of the flute's length.

See The Synthesis for a final flute design.

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Shaku Design	Peruvian Whistling Vessels, etc.

Updated 11/28/03

In the mid 70's, the psychoacoustic effects of certain Andean ceramics came to light. **Whistles built into Andean vessels could be played together, producing astonishing results.** The greater the number of whistles played simultaneously, the greater the result on the players. Players report 'sounds' which move about inside of their skulls. What makes these 'sounds' unique is they are different than what we ordinarily experience as aural sensation. They have a definite kinesthetic (felt) component and seemingly distinct physical locations within the skull. They're described as a low-pitched buzzing sensation which wanders around in one's head--often at dizzying speeds. It quickly became apparent that this phenomena was an example of binaural beats.

Binaural beats were first studied in 1839 by a German experimenter, H.W. Dove. The human ability to hear binaural beats appears to be evolutionary adaptation. Humans possess the ability to detect the subtle phase shift of sounds arriving at one ear slightly before arriving at the other ear. This phase difference normally provides directional information and is what enables us to determine the physical location of a sound. The difference in phase relationship can be detected when sound frequencies are below approximately 1000 Hz. It is more difficult for us to determine the physical location of a high pitched sound. At lower frequencies, the sound wave is larger than our head and 'wraps around' thereby strongly affecting both ears.

After 1980, interest in this phenomena grew quickly and produced 'consciousness raising' equipment, tapes, workshops and all the other excitement which tends to surround anything seemingly mysterious that has to do with the brain. In 1961 there had been an article on binaural beats published in *Scientific American.* 1981 saw an article in the same publication on the binaural hearing of Barn Owls. Owls hunt much more by sound than sight and binaural hearing allows them to locate prey very accurately in the dark. In 1993, a further article on owls delineated the neural pathways (in both owls and humans) necessary for the phenomena.

Want to hear the beats?

Want to get your Inca Shaman act together? Then round up a couple friends (the more the merrier) and some shaks which will play the same note--let's talk Ro here. For threesomes, seat the subject between two players, having them play the same note within 10-30hz of each other--close but not exactly the same tone. Let the tones waver slightly. Have the subject close her eyes, relax and **listen for that sound beyond sound**. The ability take a little practice and varies among individuals. Once everyone has been initiated (heard the beats), players can sit in a circle and induce the experience in each other. This isn't the same thing as tuning a piano by beats where what you hear is 'external'. You'll have the distinct experience of 'hearing' a third sound--one which resides **inside** your head. **The sound the Gods make.** Should you become an expert in the shamanic field of binaural beats the Owl will become you totem.

It could be that you've inadvertently heard this sound already and just thought you were having some kind of neural beakdown. Some kind of acid flashback/ short-circuit--or something. Anyway, hearing it means that you're functioning just fine and can now cancel that membership in the Rosicrucians.

Set of ceramic whistles made specifically for hearing binaural beats.

So, if you get bored playing the usual stuff on your flute use it to have some fun with your friends and give your consciousness/spirituality a boost in the process. The shakuhachi is ideally suited to generating binaural beats as its pitch can be adjusted so easily.

Shaku Design	Binding and other matters relating to the care and feeding of your Shakuhachi

Updated 1/15/04

by Liviu Burducea

In this article find information on the following:
- Binding
- Storage
- Transportation
- Glossary - Relating to Long Shakuhachi

If you live in a low humidity environment or use central heating in the colder months, it is advisable to have bindings on your shakuhachi, to lower the chance of cracking. Inlaid bindings are very time consuming to make, therefore their cost is very high. Not all makers offer the option of a lower cost binding.

You may want to consider doing your own surface bindings for the following reasons:
- saving money which you could spend on buying a better quality instrument with no bindings
- surface bindings preserve the structural strength of the bamboo, inlaid bindings weaken it to a certain degree
- adding a personal touch to your instrument
- learning skills that are useful later, when repairing a crack

Bindings are not difficult to make. For best results, you should approach this process with a can-do attitude and plenty of time and patience. If done right, the bindings will last the life of the

instrument.

Threads starting at the left: upholstery, rod building (size E), Bainbridge and nylon utility.
The thread burnisher at the top is made of nylon rod and was originally a tool for shaping wet leather

Materials

In the beginning it is easier to start with a thicker thread, preferably bonded, so that it won't unravel easily. As your skill improves you can move to thinner thread varieties. Thinner threads are preferable, because they are not as noticeable when sliding your fingers along the bamboo. As far as binding strength goes, thinner threads are just as effective as thicker ones, because you get more wraps in the same space. The main characteristics we are looking for in a thread, are high strength versus diameter and a certain amount of elasticity. This generally points to synthetics, which is also what most shakuhachi makers use for wrapping under inlaid rattan bindings. The threads should not come impregnated with wax or any other substance.

Below is a list of the commercially available threads I found most appropriate for the task. The mail order web sites are for the USA, but most of these threads are available worldwide.

1. **Nylon Upholstery Thread** -commonly available at sewing, craft, upholstery suppliers and leather working stores in basic colors. Mail Order: Van Dyke's

3. **Nylon Rod Building/Wrapping Thread**, size D or E (heaviest) - available in a wide variety of color choices from fishing rod building suppliers or fishing stores. Mail Order: Clemens and Angler's Workshop

3. **Bainbridge Hand Sewing/Whipping Thread -** for sailmaking, white color. This is actually relabeled Hemingway and Bartlett "Dabond" polyester bonded threat in size V69. I found this to have

the best blend of properties for making shakuhachi bindings. Mail Order: Boater's World Manufacturer/ Distributor Contact: info@bainbridgeint.com

4. **Nylon Thread** for Fishing Nets - available at commercial fishing supply retailers.
Note: nylon thread from your neighborhood hardware store is also usable, but it is most likely not bonded, so it will unravel easier. Best if you want to have a rougher looking binding, since it is available in larger diameters Mail Order: Jann's Netcraft

All of the above can be colored by using fabric dyes. Don't forget that once dry, colors will look lighter than when wet. The best shades are obtained by mixing several colors in various proportions. Always dye twice as much thread as you think you will need.. There are no rules as to what color a wrap should be, this is where your personal taste enters in, but I find shades of tan and brown to be the least obtrusive.

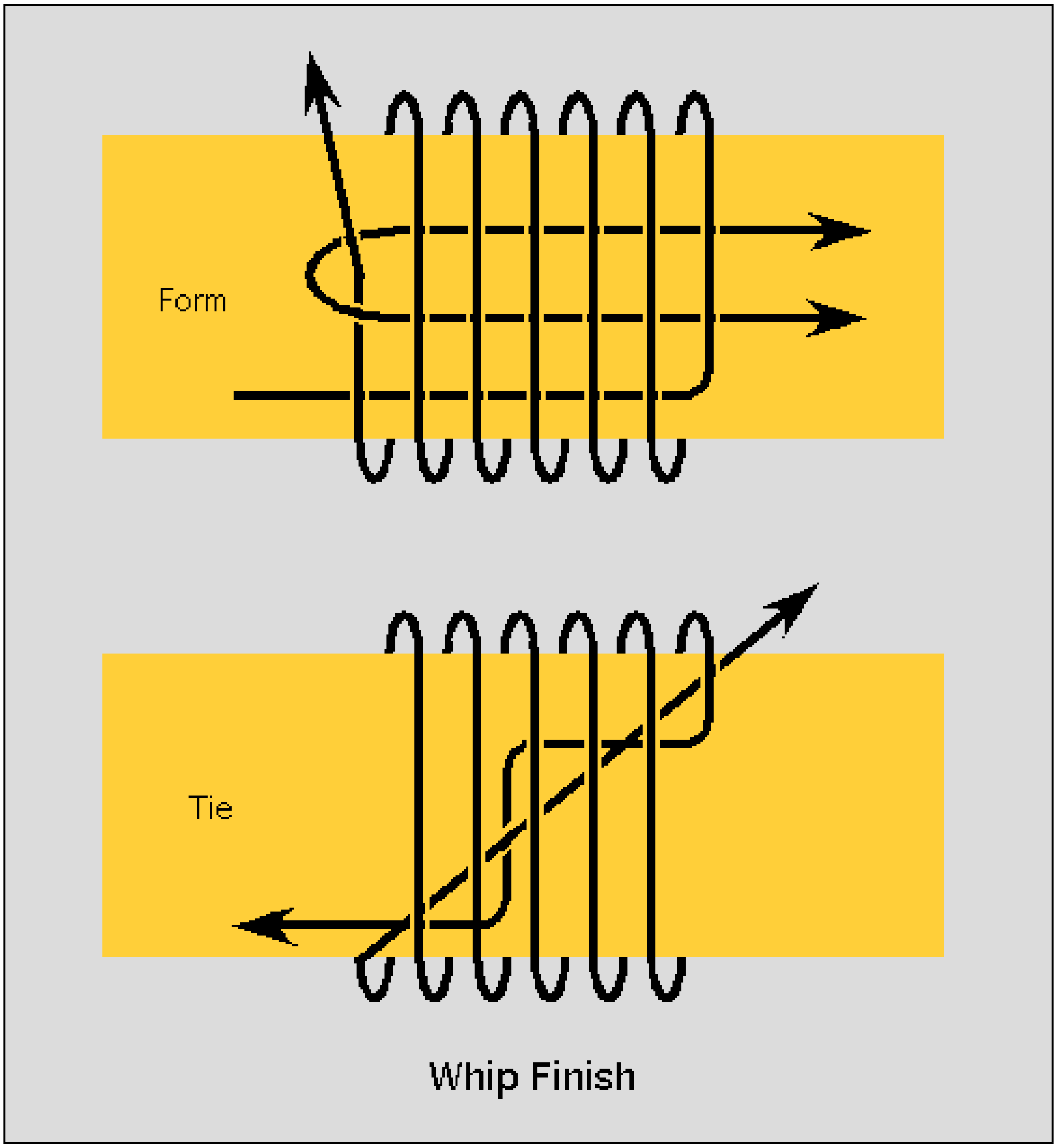
Where to Place the Wraps

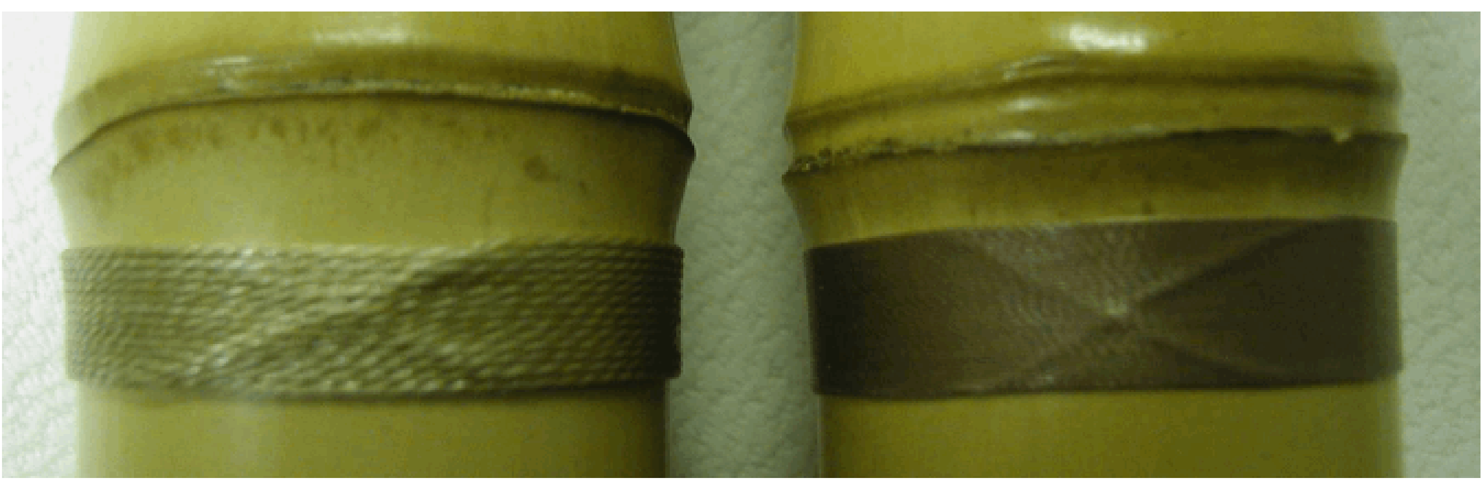
There are no strict rules as to where the wraps should be placed or what their width should be.

Some ideas:
- a wrap must be placed under the utaguchi, because cracks frequently appear in this area
- space the wraps evenly between finger holes, even if overall the wrap spacing will not be uniform. This way you will get better clearance space for your fingers.
- if near a bamboo node, get the wrap as close as possible to the node
- if there is an area with damage to the bamboo skin, try to place a wrap on it or nearby.
- generally the root end is not wrapped, unless there is a crack in this area.
- most people find it more pleasing if the wraps are all the same width. Use a ruler with mm divisions or pair of dividers to measure.
- more wraps are better than too few.

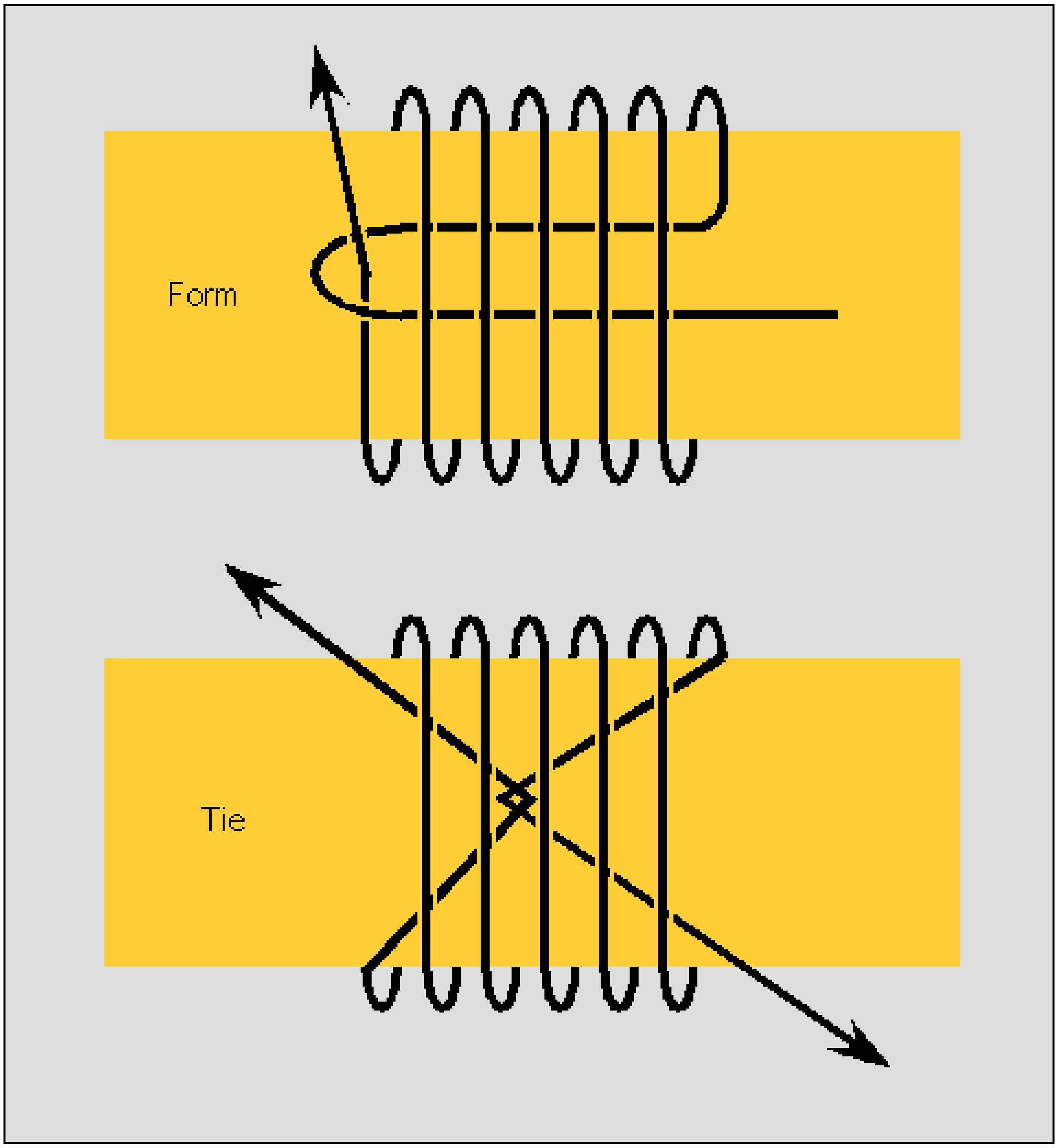
Wrapping Technique

No matter how you do your wraps, you should start by completing several just for practice, before starting on your shakuhachi. As a support, you can use any round hard object, such as a plastic tube or a wood dowel. Lay down the loop first, making sure it's plenty long. Hold the string with your thumb and start wrapping toward the loop. After a few turns friction will hold things in place and you can begin to apply more tension.





Dyed nylon thread binding on the left, upholstery thread on the right

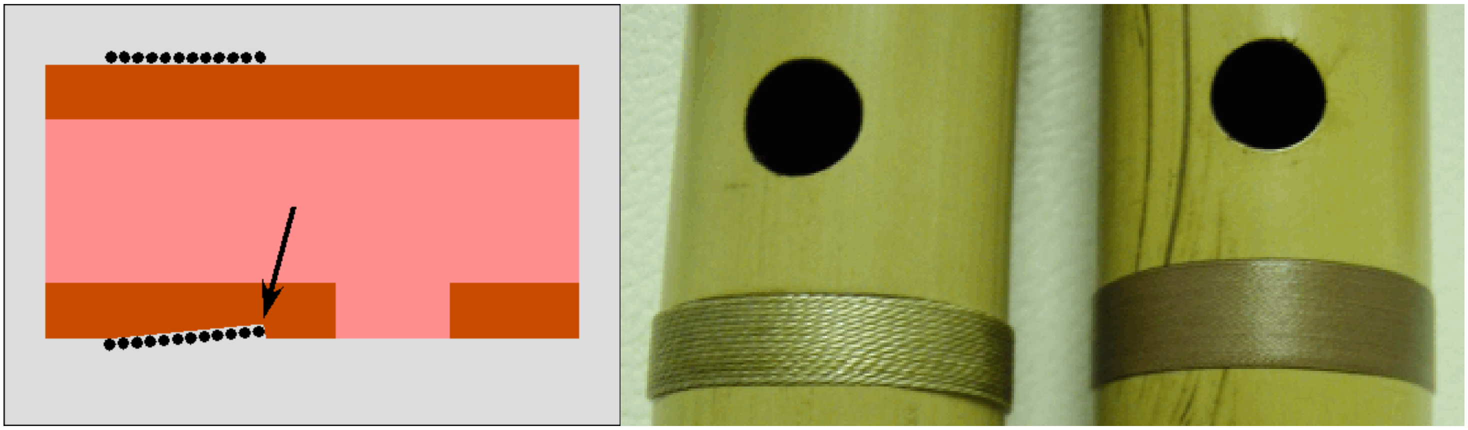


Always wrap with the highest thread tension you can handle. The ends can be pulled either parallel to the strand coming from the other side, so they form a slightly diagonal bump in the wrapping, or at a right angle, so that the resulting bump has an "X" shape. Other than the overlap, there is no knot to fasten the thread ends, they are held in place by the tension of the wraps.

Once the wrapping is done, pull on the thread ends to increase the tension to just below breaking. You learn when this occurs from experience, don't be worried by having to redo a wrap. As you pull, you will see several of the wraps slide and tighten. Watch the skin on your fingers for cuts. If you do this over a period of several days, you will develop calluses that will protect you. If not, just tape over the stress points.

Use a plastic burnisher (or a smooth object such as a round plastic pen or round hardwood chopstick) to distribute the wraps evenly and push the wraps together as tightly as possible. When you feel the wrap is as nice as possible, trim the ends off with a sharp blade (single edged razor blade or Exacto knife), while keeping the thread under slight tension. Be careful not to cut into the bamboo. Should there be any fuzz, singe it off with quick touch with a cigarette lighter flame. Go over the wraps with the burnisher one more time.

For the wrap between hole 4 and 5, if you use a thicker thread, you may want to do a partial inlay of the thread wrap, to have a smooth surface under your thumb. Use a square file, medium cut, 6-8" long, to file a sloped depression the width of a wrapping. The edge near hole 5 would be as deep as the thread is thick. At the other edge, it would blend into the bamboo surface. Do this inlay only in the area where your thumb would be, symmetrical on the left and right side. Leave the rest of the surface as is. Finish the binding with the knot on the opposite side of hole 5, i.e. on the front of the shakuhachi..



Views of binding near the fifth hole.

Please don't think twice about redoing a binding in case that it is not even, if the knot did not work out or there is a problem with the finish.

Finishing

The bindings should be saturated with a substance which will keep the tension from loosening and the binding from slipping and unraveling. In fact, as the finish soaks into the thread, its tension increases.

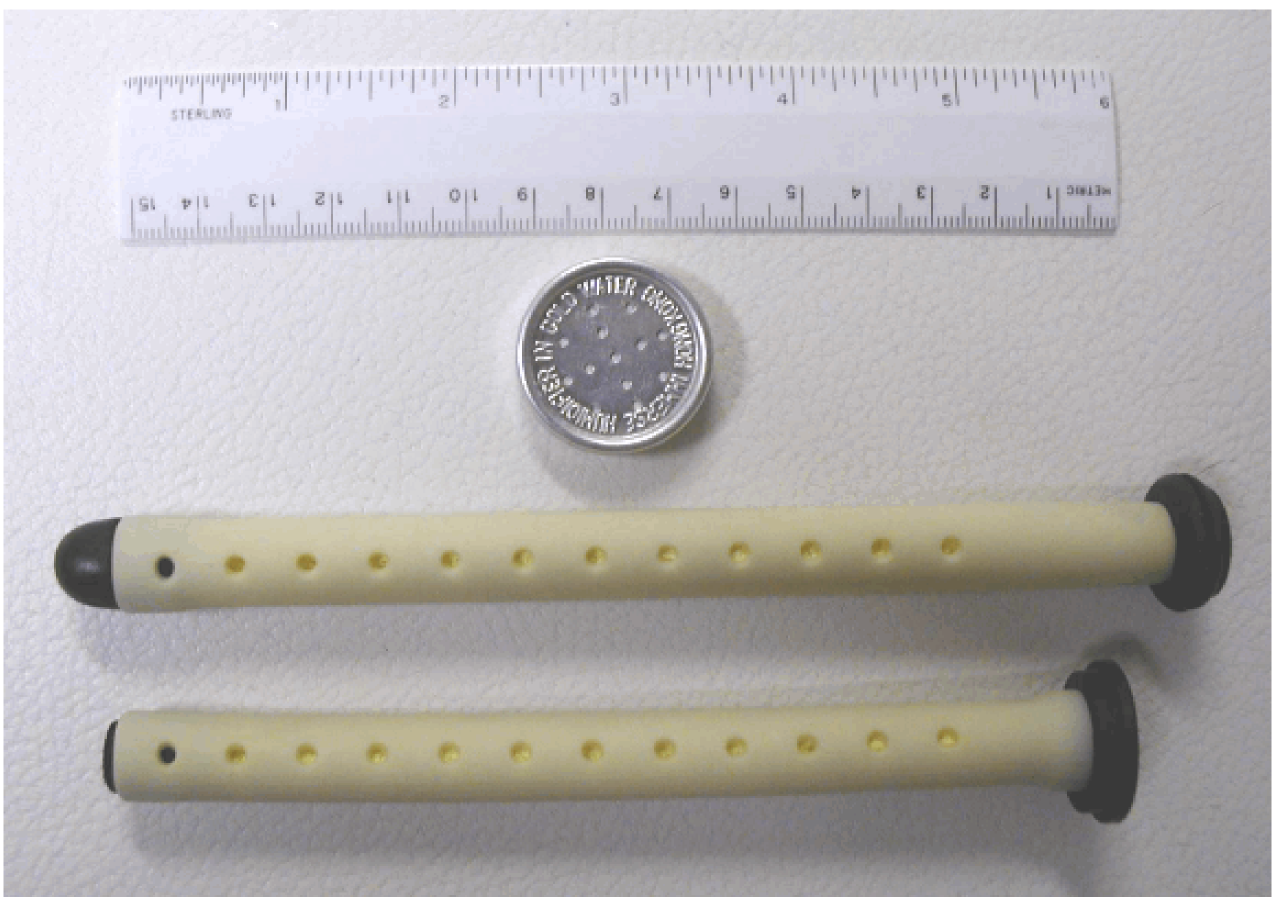
Here are the options I have found to be most practical. However, feel free to experiment if you do not have these finishes available:

- Urushi - best from a traditional point of view and for working with wrappings on wet bamboo that is being repaired
- Slow Cure Epoxy - best from the point of view of wear, ease of working and cleanup (use rubbing alcohol)
- Super Glue (cyanoacrylate) - fast drying, but short working time does not allow it to soak into thin thread under tension. Best to use with thicker nylon thread. Cellulose in paper napkins acts as an accelerant for this glue. You can use this to your advantage to speed up drying or wipe with synthetic tissue to avoid this effect. Superglue cures in the presence of water or alcohol, which it absorbs in the form of vapors from the air and the surface of the objects being glued. A moist breath can act as an accellerator. Too much moisture can produce a white, uneven glue surface, not desirable for our purposes. Clean up with Acetone.
- Polyurethane - commonly available wood finish, very durable but does not take a polish
- Color Preserver (clear acrylic) **-** soft but sufficiently durable if applied with no buildup, cleans up with water, definitely non-traditional.

Some tips:
- apply thin coats and avoid bubbles.
- saturate the whole binding with the finish of your choice, but avoid any buildup.
- do not apply any finish to the bamboo.
- clean off any drips on the bamboo immediately.
- occasionally rotate the shakuhachi while it is drying, so that the finish will remain evenly distributed.
- when finished without applying a color preserver (clear acrylic), certain thin nylon threads turn translucent. This can be an interesting visual effect, but you must make a very neat wrapping.

Storing Your Shakuhachi

Bindings reduce the likelihood of cracks, but they are not a guarantee. A shakuhachi is best stored individually in a waterproof bag (nylon), with the open end folded over. This is sufficient if you play it every day, even if only for a few minutes. If not, you can include a very small humidifier in the bag, such as available from cigar stores. This is a very small aluminum can (1" diameter), with perforated top and bottom, which contains an absorptive material similar to chalk. This type of humidifier releases moisture very slowly. If you can't buy it, you can make your own version from a small plastic container, but check occasionally to make sure that no molds grow inside.



Metal case is a pipe tobacco humidifier, the others come from off-the-shelf humidifier from the music store, cut in two pieces

Remember that too much moisture applied suddenly can crack bamboo. For a shakuhachi, humidifiers designed for Western musical instruments can release too much moisture, too quickly. Avoid these or cut them back to a smaller size and squeeze them out well after soaking.

Long nylon bags can be recycled from various products packed in these and are sometimes available separately at kite or fishing stores. The thicker ones last longer. You can also make your own from larger waterproof sheets and tape.

Transporting Your Shakuhachi

Now that you have gone through all this trouble to prevent the shakuhachi from cracking, you probably want to protect it while it's outside your house, as well. The idea is to use a case that will protect your instrument against bumps and sudden temperature changes. For cases which are not padded, wrap your flutes individually in a towel or foam sheet.

Cordura is a low maintenance, wear resistant nylon fabric. Lengths refer to single piece flutes, two-piece flutes are. of course, easier to accommaodate.

Following are some affordable and commonly available solutions (at least in N.America and W. Europe).

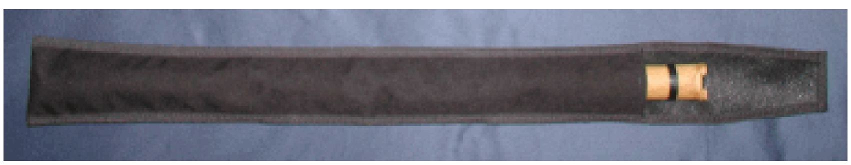
- fishing rod tubes - available in diameters up to 4" and various lengths (20 inches to 7 feet), metal, plastic and cordura covered PVC, with screw-on, snap-on and zippered lids, wide variety of colors, not padded. Best for transporting one or 2 shakuhachi per tube. Can be purchased at outdoor/sports stores.

- takedown shotgun cases - available in hard plastic or padded fabric, Cordura or leather, in a wide variety of designs. Prices start low, but can range to very high. Can hold several shakuhachi, at least up to a 2.6 shaku. If you choose the right color and shape and remove the labels, some of them will not look like a gun case at all. Can be purchased at outdoor/sports/gun stores.

- guitar effect and MIDI keyboard carry cases - made from black padded synthetics, usually good for lengths up to 2.1 shaku and multiple flutes. Available at specialized music stores.

- tripod carry cases - made from Cordura in several colors and lengths but not padded. Smallest sizes suitable for several 1.8 shaku. Can be purchased at photo and outdoor stores.

- **kite bags** - made from nylon fabric, in many colors and lengths but not padded. Usually best for holding several longer shakuhachi. Can be purchased at kite specialty stores.
- golf club cases - available in soft or hardwall construction, in various diameters, with or without wheels. Best suited for transporting several long shakuhachi. Can be purchased at golf specialty stores.
- folding saw pouch - to hold your 1.8 shaku or shorter (not root end), made from black Cordura, no padding. Good as an all around storage bag, but don't forget to use a plastic bag inside. Can be purchased at outdoor/sports stores.



Following is a glossary of Japanese terms I hope will help those interested in longer shakuhachi and their construction or in ordering one of these instruments. Romanized spelling of the terms varies depending on the source, I have listed the commonly seen variations.

- Tuning -

Seiritsu - tuned to a specific frequency on the western equal temperament scale, i.e. exact pitch

Seisun - made to a specific length (measured in shaku and sun), tuning reference accuracy is secondary

- Construction -

Urushi - East Asian lacquer, made from the refined sap of the urushi tree (Rhus vernicifera D.C. or Rhus verniciflua Stokes). It is available in several forms, in both raw and refined states. Mixed with mineral pigments to produce red, black and vermillion colored lacquer. Other colors are also possible, but generally not used in shakuhachi construction.

Ki Urushi - raw, filtered urushi, dries translucent brown

Shu Urushi - vermilion urushi

Kuro Nakanuri - black undercoat urushi

Honguro - black finishing urushi

Tonoko - powdered claystone

Ji - paste commonly made from raw urushi, tonoko and water

Jiari - with ji, in other words bore constructed with ji paste, flute can be of any length

Jinashi - without ji in the bore, but could have a coat of raw or refined urushi to seal the bamboo, flute can be of any length

Nobetake or Nobekan - one piece flute

- Flute Names -

Chôkan, Chokan, Choukan or Joukan - long pipe or flute, one might call anything longer than 2.4 chokan, whether it is a jiari or jinashi

Hôchiku, Hochiku, Houchiku or Hocchiku - way of the bamboo, dharma bamboo, bamboo of the law, religious bamboo, seisun, frequently (not mandatory) a longer flute with bare bamboo bore and no utaguchi inlay. Term originated by Watazumi.

Kyotaku - empty bell, term used to refer to a shakuhachi type instrument used in a spiritual context

Dôgu - tool, instrument (for the way), term used by Watazumi to designate a shakuhachi type instrument used in a spiritual context

Dong Xiao - historic predecessor of shakuhachi from China, thin diameter, 6 finger holes, various lengths, still played today

Hitoyogiri, Kodaibue, Tenpuku or Tempuku - historic flutes of the shakuhachi family, no longer in use today

Recommeneded Listening: A Collection of Unique Musical, Music of Japanese People Series, King Records KICH 2030--CD featuring various rare Japanese flutes.

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Shaku Design	Searching for Control

Updated 1/15/04

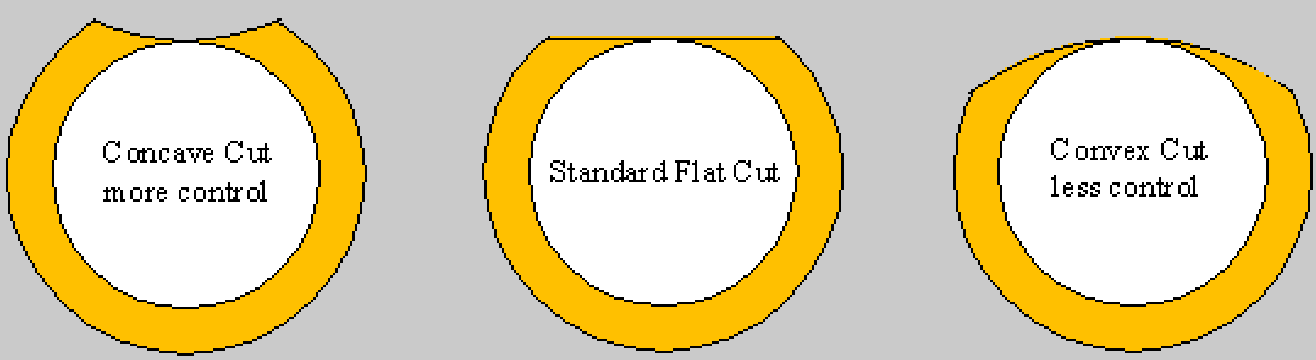
Let’s you and I go out and shoot some hoops. Best of ten. I make two and you…eight. Other than you being the better shot, what are we to make of this? What percentage of completion would, for each of us, be the most engaging? What this involves is the issue of control, which varies widely between individuals. Would you be happier and more engaged in a circumstance where your percentage of success is high? Medium? Low? Do you want to make 10 for 10 from the free-throw line or would that get boring. If you could consistently make 100 shots in a row would shooting hoops still engage you? Or would it be deeply satisfying? Let’s try another sports metaphor. What if a hole-in-one in golf were much more common? Let’s say you can make a hole-in-one every other time, would you enjoy the game more and get more from it?

While it might not have occurred to you, the level of success in both games has been arbitrarily set. Take basketball, suppose I changed to a basket with a ten-foot diameter—I could probably go 100 for 100 any time I wanted. Suppose I made the golf hole 200 feet across—well, you get the picture.

The diameter of a standard basketball is 9.5” and the hoop is 18” (slightly smaller in the Pros). Who decided this? **Who set the ball and basket diameters, thereby the percentage of success/failure?** Maybe you’d be happier and more engaged with a larger basket. Maybe a smaller one. Maybe you’d be happier with a hoop diameter such that the average hoopster would make a bucket once-in-a-thousand.

The issue of control is central to the shakuhachi. It's traditionally thought of as a difficult instrument to play or at least learn to play. For some people this is deeply satisfying—to be able to play an instrument that most can't. For others, it's endlessly frustrating. **What may not be apparent is that the degree of difficulty in playing a shakuhachi has been arbitrarily set for you.** It has mostly to do with the geometry of the cut that creates and forms the blowing edge. Yes Bucky, a shak can be made easier or harder to play. The standard edge cut is straight and flat. Making this cut concave gives the player greater control, making it convex results in less control. It's that simple. A few hundredths of an inch makes all the difference.

Organ pipes often have flanges called 'ears' which run parallel to the air stream—placed on either side. They constrain the air stream—box it in a little. The edge in a recorder is usually recessed, having sidewalls that serve the same purpose as 'ears' in organs. The point being that when an air stream is constrained along its sides, greater control is achieved and maintained by the player. The standard flat-cut of the shakuhachi provide a certain amount of side constraint just by the fact that there is air there and it has to be pushed aside for the air stream to spread out. A convex-cut lets the air stream spread out quicker—thus the player has less control. A concave-cut forms a groove that tends to hold the air stream together until it's well past the edge. The geometry of the cut is the subtle part of a shakuhachi and has a direct bearing on the amount and degree of player control.



View of the Air Stream approaching the Blowing Edge

There have been studies about the failure/success ratio for optimum learning, but they don't usually allow for the peculiarities of the individual. Do you do better when things are hard in the beginning or easy? Do you respond well to a high failure rate or a low one? Needless to say, people are very different in their response to control. What kind of shakuhachi do you want to present to your children for them to learn on? Easier, average, harder? This is a decision you can now make.

Absolute motor control is not possible. For example, you can't hold your hand absolutely still. The blood coursing through your veins and your heart pumping will always induce some movement. But we can consider the outer limits of motor control, where it begins to approach physiological limits. **And right in that zone where motor control is approaching physiology, right where the central nervous system runs up against the autonomic is where we find the shakuhachi.** Control, in the sense of this discussion, has to do with control of the air stream, which is mediated largely by the lips. Thinking of the air stream as a flame puts things in the proper perspective, as by its very nature an airstream is dynamic and chaotic. And we're talking about control of maybe 6-8mm of the first part of this air-flame. To a large extent, what happens in the first 6-8mm of your air-flame determines the quality and consistancy of your play. Much, if not most, of the shaku-drama takes place in the first quarter to third of an inch--right under your nose, as it were.

Tom Deaver passed on the following from Joe Wolfe, the researcher in Australia:

Unfortunately, we shan't be on the shakuhachi again for a while. Partly because of pressing other things (things that we're actually paid to do: the shakuhachi was out of interest) and partly because we're having a lot of trouble dealing with the jet of air itself. It's properties change so much as one changes the length and angle that it's difficult to model other than purely empirically.

The standard shakuhachi is, in essence, a feedback device. Control of the instrument is limited to the extend that states of physiology have a considerable impact on the play and sound. It's perhaps easier to know the state of a player's 'soul' while listening to shakuhachi than other instruments. It shouldn't be surprising that the shakuhachi got picked out as a (the?) Zen instrument. Zen really likes things which are near the limit of motor control—they can serve as accurate and instantaneous feedback devices. Want to know your current state of being? Go blow some notes, the flute doesn't lie.

Anyway, now you know—**the degree of difficulty, the level of control, the ratio of success/failure of a shakuhachi can be adjusted.** It might make sense to have different flutes for different times. Certainly different flutes for different people.

Often American shak players have a Calvinist streak in them—pain and struggle is good, cleansing and admirable. For them, exploring the convex model makes sense. To try out the concave (more control) model, take your straight-cut shak and with a little wax/modeling clay etc. build up the sides somewhat like the drawing above. What you're fashioning is a groove or channel for the air. To create a convex model, try PVC or something expendable before filing down your favorite flute. There's a lot that can be done just by fiddling with the shape of the cut. The point is to get the flute that really serves your purposes and temperment.

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Shaku Design

Sine Waves and Timbre

Updated 1/15/04

Timbre (pronounced tamber) is variously defined as 'tone color' and or the characteristic of sound that distinguishes one voice or musical instrument from another. **It is determined by the harmonics of the sound and thus is distinguished from intensity and pitch.**

To understand timbre we first need to make a side-trip into mathematics. Interestingly, many mathematicians are musicians, while few musicians are mathematicians. A greater percentage of mathematicians have a substantial understanding of, say, Bach and Mozart than musicians who are conversant with the Riemann Hypothesis or the Dirac delta function.

One of the trigonometric functions is called sine, which is often written as Sin to distinguish it from sin, which is a religious term. Sine and Sin are both pronounced 'sign'. In 1822 Jean Baptiste Joseph Fourier proved that any function of a variable, whether continuous or discontinuous, could be expanded into a series of multiples of that variable. Moreover, of course, the series now bears his name. He understood that when waves act independently of one another the displacement of any particle at a given time is simply **the sum of the displacement that the individual waves alone would give it**. It's what is now called 'superposition'. The importance of the superposition principle physically is that it makes it possible to analyze a complicated wave motion as a combination of simple waves. And the simple waves that Fourier specified are sine waves. **In short, Fourier said all music is made from sine waves.** In fact, almost all sounds are made of sine waves. **The character of a sound's particular tone is directly related to the sine waves that compose it.** Doesn't matter whether it's a tuba or a violin.

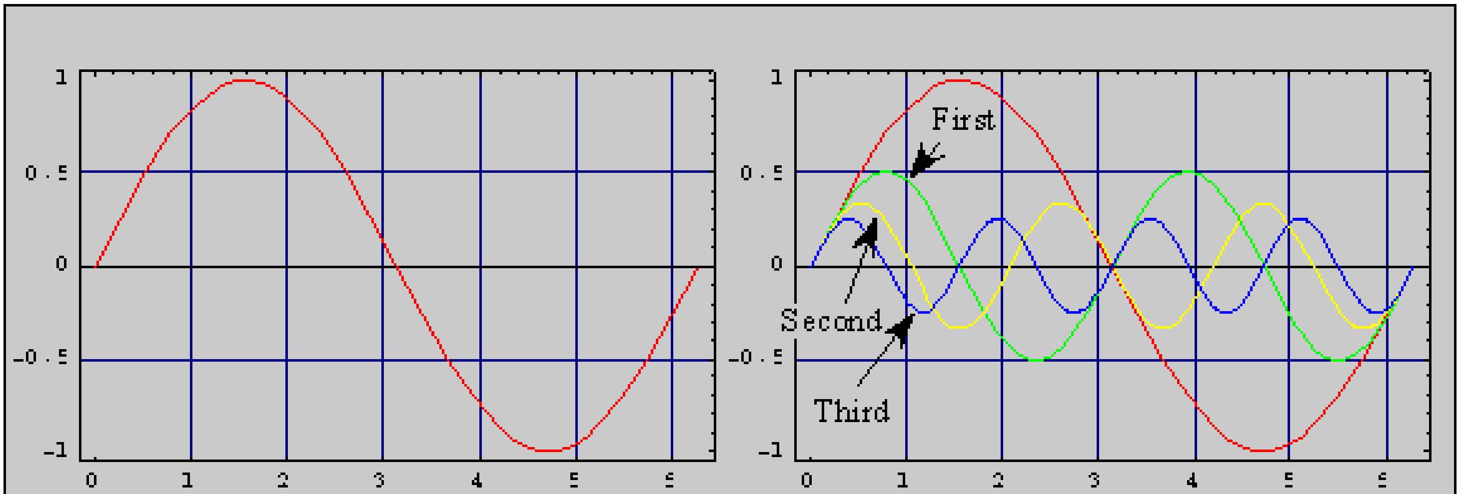

Figure 1 - The basic Sine Wave

Figure 2 - Fundamental with Harmonics

So, Fourier made it clear that musical sounds are simply combinations of sine waves (figure 3). And it turns out that the basic structure of one sine wave is identical to every other sine wave (figure 2). Timbre is the resultant sound envelope of the combination of various sine waves (figure 3).

As all sine waves are basically alike, how can we distinguish one from another? Sine waves can be varied in two ways: by varying length and/or height. Changing the length of a wave is identical to changing it's pitch and varying the height (amplitude) is identical to varying intensity (loudness, volume). **The three major components of musical sound are pitch, intensity and timber and all relate directly to sine waves.**

We now know what a sine wave looks like (figure 1) and how they can be changed—by varying length and amplitude. The next step is to introduce the concept of harmonics (partials). The fundamental (prime) wave is the longest that can fit into the tube. It's the absolute base note; the lowest pitch one can get from a particular tube. Harmonics are just divisions of that length (pitch).

So we've got the fundamental. Let's introduce the first harmonic. What's its length? It's 1/2 of the fundamental. And the second harmonic is 1/3, the third 1/4 and so on. But what this really means is that the first harmonic is an octave above the fundamental. The second harmonic is 1.5 octaves above the fundamental, etc. See figures 2 & 3 and notice that the length of each harmonic's **wavelength** is a whole-number fraction of the fundamental. Notice also that the **amplitudes** of the harmonics are arbitrarily (could be any value) graphed also as whole-number fractions of the fundamental's amplitude.

In a New Agey, feel-good-kind-of-way it can be said that any musical sound contains all octaves thereby all sounds. And it's probably true. But the higher harmonics are so small in amplitude as to be safely ignored. Since harmonics are higher and higher multiples of the fundamental we are out of the range of hearing pretty fast.

One last potentially confusing bit: The first harmonic is an octave above the fundamental, the second harmonic is musically called the Fifth. The third harmonic is two octaves above the fundamental. The fourth harmonic is called the Third and the fifth harmonic is a Fifth of the first harmonic. Unless you're familiar with musical nomenclature you can safely forget you ever read this paragraph.

Now you know the layout (lengths) of the harmonics, the **pitch** of each is just a whole number multiple of the fundamental. Most musical instruments work this way. Drums don't; with them the harmonics scale up in what's called an Eigen fashion, which for the terminally curious, is somewhat similar to the way quantum physics works.

But what about the amplitude (volume) of the harmonics? That's what the whole timbre business is all about. The harmonics have fixed pitches (in relation to the fundamental) but the amplitude of each is determined by the instrument, technique of the player, etc.. Violins, for example, have a large amplitude fifth harmonic—that's how we identify the sound. And in fact, the usual nomenclature for timbre uses the names and materials of instruments to refer to particular timbres. We say a timbre is 'brassy' not because brass sounds like that but because horns with very high aspect ratios are usually made of brass. They could just as well be made of cement. A timbre which is 'woody' is so called because it's identified with wooden instruments of lower aspect ratio which could have just as well be made of brass. **Timbre is the resultant sound envelope of adding all the sine waves together--**fundamental and harmonics (figure 3). The timbre of a tuning fork is close to the sound of a single sine wave**--**just the fundamental and few if any prominent harmonics so it should look like figure 1. Speaking or singing the vowel oo (as in too) comes close to producing a pure tone with few harmonics.

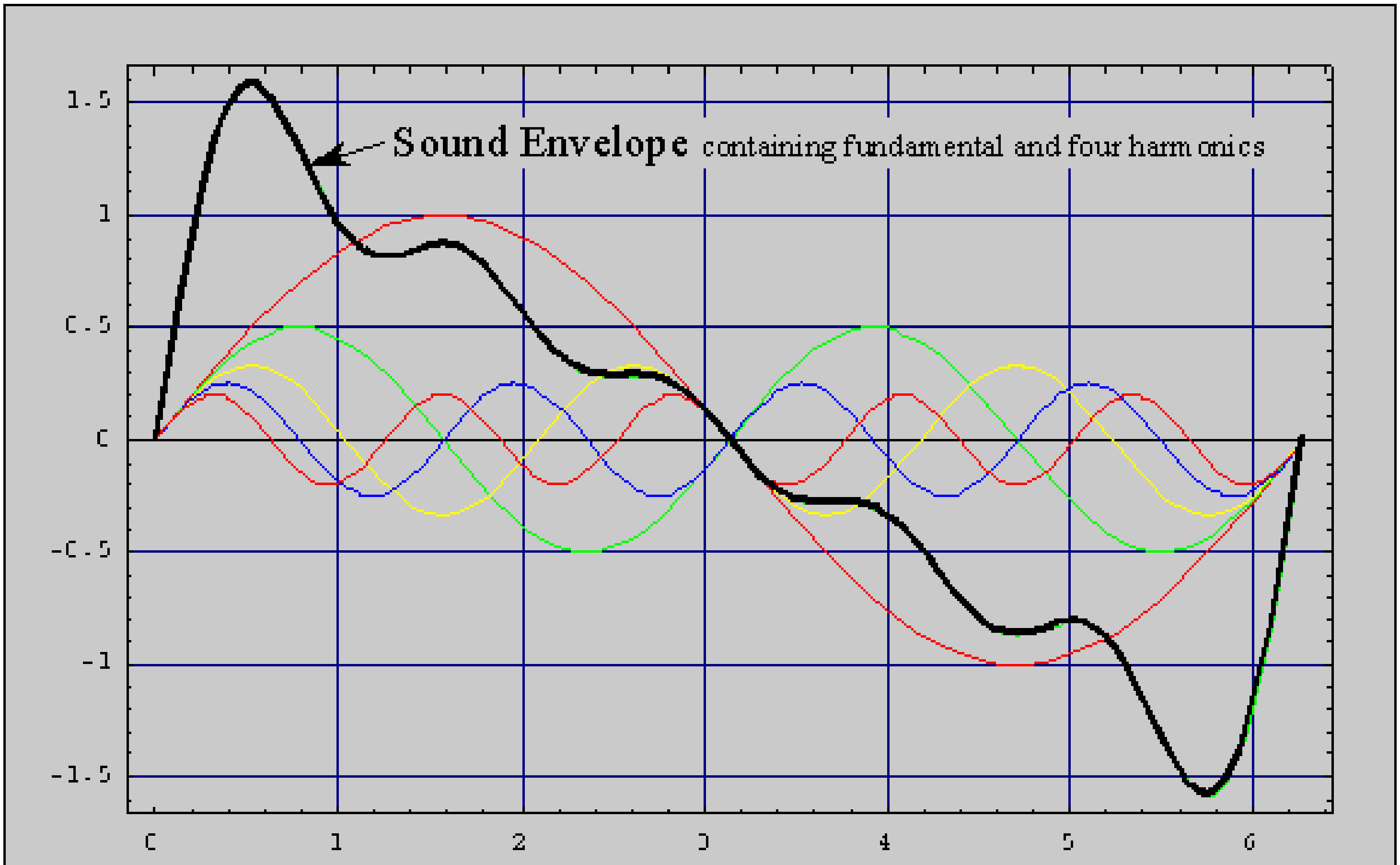

Figure 3

The distinctive timbre of the shakuhachi has a lot to do with the fact that it's end blown. **The differences in timbre BETWEEN shakuhachi has to do with geometry of the bore and aspect ratio—mostly aspect ratio.**

The biggest difference in timbre between shakuhachi and hochiku, for instance, is simply a matter of aspect ratio. **High AR tubes favor the upper harmonics and lower AR tubes favor the lower harmonics.** In high AR tubes the upper harmonics have greater amplitudes (relative to the fundamental) than do low AR tubes. What qualifies as upper and lower as far as harmonics are concerned? For the most part, the timbre of a shak is contained in the first dozen harmonics and its major elements in the first half dozen. So we can make an arbitrary distinction and place the dividing line between upper and lower as between the third and fourth harmonic--or there abouts. **Whether particular harmionics are present is really just a question of their amplitude--a question of how strongly they are present.** Adjusting the bass/treble knob on electronic equipment changes the amplitudes of respective harmonics. **Your preference with the tone knob is a direct indication of the AR you'd be happy with in flutes.**

Let's switch to looking at half-waves rather than full-waves for two reasons: the second half of a sine wave is just the inverse of the first half (figure 1) and the wavelength of a shakuhachi is twice the length of the tube. So looking at half-waves is representative of looking at the length of a shakuhachi bore.

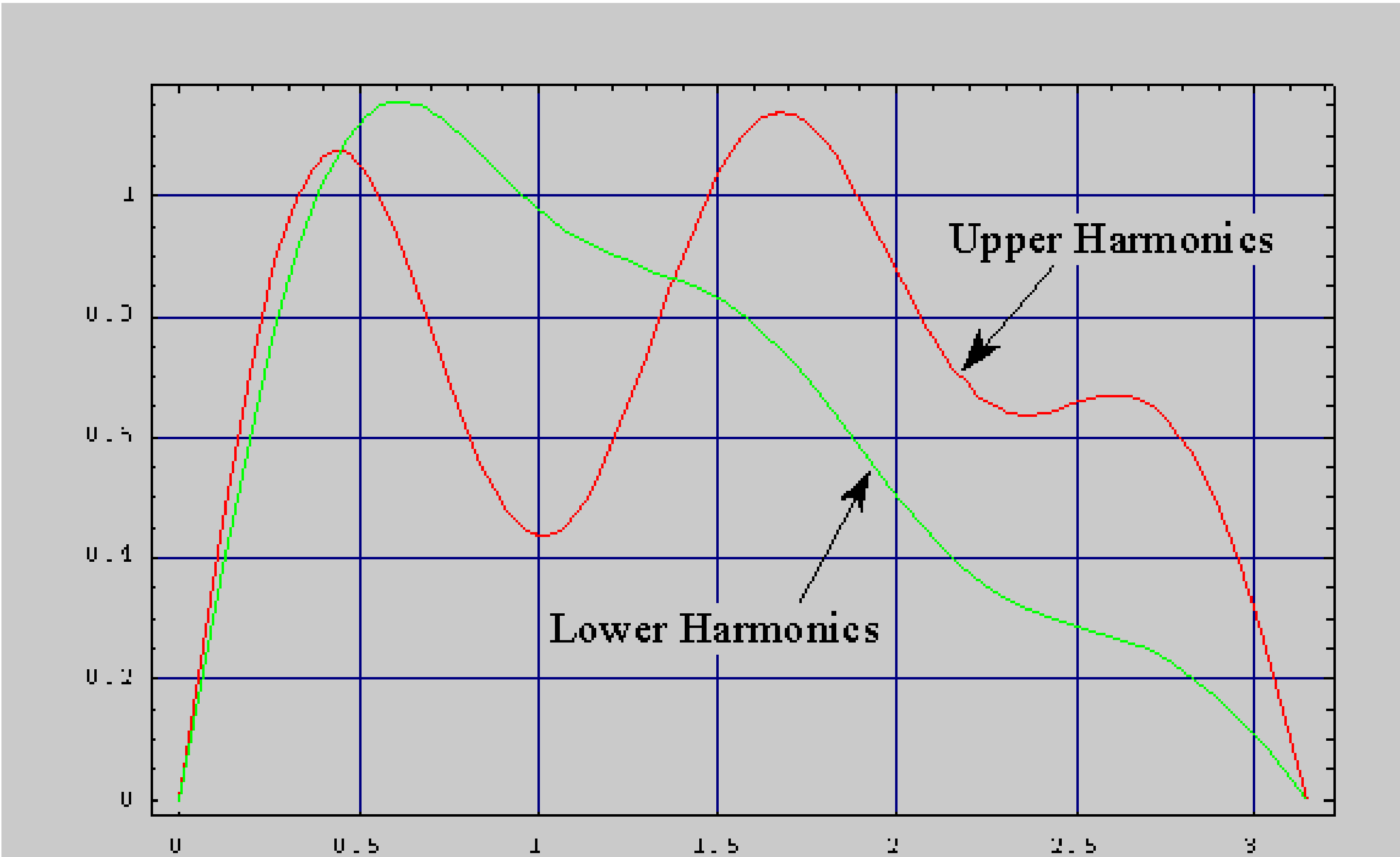

Figure 4

Graph of the difference in the Sound Envelopes of lower and upper harmonic emphasis.

With a flute which plays second octave easily it shouldn't be surprising that the timbre is comprised of upper harmonics--it's a flute more favorable to higher pitched sound whether it be harmonics or fundamentals. All around, the flute just plays 'higher'. And the converse is true of a flute which strains to get second octave--it will be more comfortable with lower harmonics and fundamentals. **It's mostly a case of aspect ratio.**

One other thing. The area of the opening at the blowing edge does effect things in these regards. A smaller AREA (between lips and blowing edge) favors the upper harmonics, a larger opening--the lower harmonics. So you could have a tube with a low AR and by making the blowing notch shallow and narrow, boost the upper harmonics...some. Or go the other way and with a tight tube lower the harmonics by opening up the blowing area.

That's really what meri-kari is about--changing the area of the opening. Not only does it change pitch but timbre as well by shifting the emphasis in the harmonic register.

If you want 'bright' timbre tighten up everything except the holes--they work the other way round. Big holes favor brighter timbre, small holes, darker. For that dark moody flute loosen up the bore, the blowing opening and tighten the holes.

The shakuhachi as a 'musical' instrument is built to boost the higher harmonics--thus it's particular bright timbre. The hochiku as a 'spiritual' instrument is designed to emphasis the lower harmonics and so it sounds darker. Apparently in the shakuhachi world a skinny tube is 'musical' and a fat tube 'spiritual'--it's a simple matter of timbre, which is largely a matter of aspect ratio. Play both and you've got it covered.

Bore and timbre

Hole size and timbre

Utaguchi and Timbre

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Shaku Design	Scaling Factors

Updated 1/24/05

Suppose you came upon a outstanding D shakuhachi, it sounds just like you want and you love the thing. Suppose further that you want to make a replica but tuned to a lower pitch. To make this story easy to understand, suppose you want to make it exactly one octave lower. So you measure very carefully and double the measurements—twice the length and twice the bore diameter. And then the day comes when you first play your new flute—but it doesn't sound quite right! What's up with this? An octave lower is twice the length, thus it should be twice the bore diameter, right? Well, not quite.

As with a lot of things concerning flutes there is always some grit between theory and practice. The organ builders of Europe ran into this problem centuries ago. On the face of it, it would appear that the scaling principle for pipe organs should result in a doubling of the pipe radius every octave, 'doubling on the 12th pipe' as builders often call it. This makes all pipes geometrically similar. But it doesn't work, as the timbre across a rank of pipes begins to shift and the organ sounds funny. For a satisfactory scale the **bass pipes must be narrower and the treble pipes wider**.

The problem of finding a scaling rule that gives **tonal coherence and balance across a rank of pipes** is of central importance in organ building and one to which the great builders have found satisfactory empirical solutions. A scaling with doubling at the fifteenth to eighteenth pipe is generally satisfactory for pipe organs.

Now back to our shak. To make a replica pitched an octave lower and having the same timbre, how much should the bore be increased? **Not 2, but 1.78 times.** This is about the same as doubling between the fourteenth and fifteenth pipe. **When scaling shakuhachi down one note change the length by 1.0595 and the bore by 1.0493.** To scale to higher pitches use the inverse of these values. The length changes by about 6% per note and the bore about 5%.

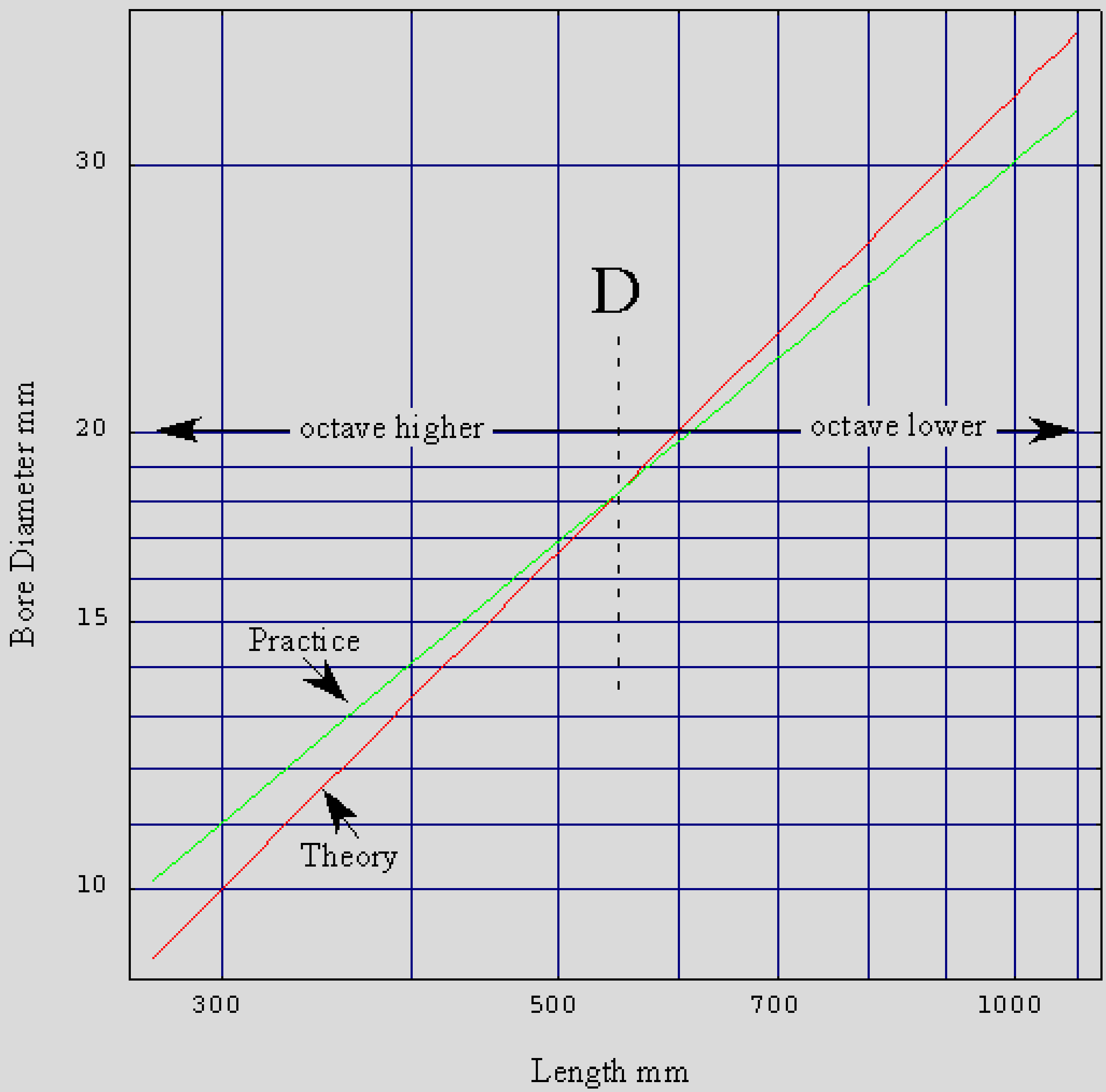
For the mathematically curious: 1.0595 is the twelfth root of 2 and 1.0493 is the twelfth root of 2 raised to the 5/6ths power. 1.78 is 1.0493 raised to the twelfth power.

Anyway, the point is that shakuhachi scale using different factors for length and bore.

The need for a separate bore factor arises because a flute loses energy in two ways: out the end of the pipe and into the walls. The loss out the end of the pipe is affected by frequency, while loss to the walls isn't. So what we're really talking about is the fact that frequency effects one loss more than the other. And of course length is what determines frequency, so doubling the length cuts the frequency in half, effecting the end loss more than the wall loss.

Let's bring this discussion closer to home. It may not have occurred to you or perhaps you've never really listened but **the timbre of the first and second octaves isn't the same.** Same flute, same length, same bore diameter, so what's different? The frequency. The second octave is the same as building a replica with measurements divided by 2. From above we already know that it would play with a brighter timbre, so we know that the timbre of the second octave is brighter than the first. How much brighter? We can measure it indirectly. If the aspect ratio of our flute is 30, the second octave would sound as if it had an AR of 33.7. **For the second octave to have the same timbre as the first, our flute's bore diameter would have to magically expand by 12% whenever we shifted to second octave.**

The following graph plots the theoretical relationship between length and bore diameter in red and the practical in green. It extends an octave below and above D. **The green line indicates proper bore diameters which will result in a timbre matching that of our D shakuhachi.**



Measurements for similar timbre across a two octave range

In this example the pitch (D) and aspect ratio (30) were arbitrarily chosen.

For more specific info on Aspect Ratio and timbre.

See The Synthesis for a final flute design.

Shaku Design	Various Bits

Updated 11/23/03

A collection of various bits of information and factoids applying to shakuhachi and flutes in general.

Boundary Layer

There is a thin layer of air on the surface of the bore which tends to stick to the bore and as such isn't acoustically active. This layer's thickness (about 0.1 mm or 0.004") is the result of the viscosity of air and is present regardless of the bore material or it's smoothness. To give an idea of this thickness, a sheet of paper for your printer is about 0.003" thick. The effects of bore roughness become significant only when the roughness itself is significant on the scale of the boundary layer. Should you want to finish the bore in a way which doesn't encourage a greater boundary layer, the finish should either be finer or rougher than about 150-120 grit. Either way takes you out of the range of the layer and doesn't contribute substantially to it. Conversely, if you want to mess around with increasing the boundary layer then sand or line the bore with 150-120 grit material.

The upshoot of all this? It probably makes no acoustical difference whether the bore is finished to a slick, reflective surface. Whatever the final surface, there will be a few thousands of an inch of air sitting on top. A thin boundary layer of air is the final finish (air varnish?) regardless of whatever else you may do to the bore. A smooth shiny bore looks nice--but that's about it.

Flute Material

There is a common belief that the material from which a flute is constructed defines the character of its sound. This misconception has been put to rest by countless studies and experiments. The quality of any particular flute sound is the result of the geometry of its air column--including the holes and blowing mechanism. The sound of a flute comes from the shape of its air, not the material from which the flute is constructed.

The large tone holes of a silver Boehm flute give it a much brighter tone than that of a Baroque wooden flute with its necessarily rather small finger holes. In the case of these two flute examples, it's hole size (see Cutoff Frequency below) which accounts for different timbre rather than material. Its common to ascribe this tonal difference to the difference between silver and wood as bore materials, but this is erroneous.

There are those who will persist in the "material equals sound" belief as it's the result of associative thinking. Mistaking the menu for the meal, the map for the territory. Bamboo flutes don't have a 'bamboo' sound, they have 'bamboo' geometry. Change the geometry of a bamboo flute and you can make it sound like any 'material' you want. As one example, in shorter shakuhachi hole size begins to catch up with bore and so they are often characterized as 'brilliant'. (See Wall

Vibrations below)

Cutoff Frequency

In woodwinds, there is a correlation between relative hole size (and hole spacing--the lattice) and the highest frequencies of which the instrument is capable. There is a definable cutoff frequency above which most sound production is suppressed. For clarinets, oboes and Boehm flutes it's between 1200 and 2000 hz. The cutoff frequency limits the highest note that is readily playable on the instrument.

Because of the traditional way in which shakuhachi are constructed (fingered holes, etc.) they will forever retain a diminished cutoff frequency. The longer the shak the more diminished as the ratio of hole size to bore size steadily declines. Employing bigger hole sizes helps the situation slightly but at the expense of other acoustical characteristics. If you want a higher cutoff frequency go with shorter shaks.

The cut-off effect has it impact primarily on the high overtones. Large holes and smaller spacing increase the cut-off frequency and harmonic content.

Acoustical Length

Every flute has two lengths: its physical length and the acoustical length. And they are not the same. A 1.8 D shak usually plays a base tone somewhere near 294 hz., depending on tuning standards, etc. The unencumbered tube length require to support such a frequency is Length = Speed of Sound / (2*Frequency), in this case about 564mm. 1.8 shaku is 545mm, so acoustical length is 19mm longer than physical length. Where is this extra length? Conceptually, you can think of it as sticking out the bottom and top of the flute. About 0.6*Bore sticks out the bottom, the rest out the top.

For a properly proportioned shak, acoustical length always runs 3-4% longer than physical length. With varied blowing (airstream speed and thickness, etc.) and playing methods (kari-meri, etc.) the acoustical length is varied, thus the acoustical properties of the flute are modified. The particular charm of the shakuhachi exists because of this extra length and what one can do with it.

Other Length Stuff

A one percent change in length will change the pitch by 17 cents. To change a full semitone change the length 5.9%.

Flute Efficiency

Flutes convert pneumatic energy into acoustical energy with an overall efficiency on the order of 1%. That's a big fat ONE percent. On engineering grounds, one would be hard pressed to find a more inefficient, indulgent device. The 'Zen' of this situation isn't immediately apparent.

Runway Time

How long does it take a flute to settle into a particular note? How long on the runway before taking to flight? Something like 30 periods of the fundamental, which for a D flute is about 1/10 of a second. Longer flutes take longer--shorter, shorter.

Bending Bamboo

Surprisingly, bamboo bends (with heat) more readily at the nodes than in between.

Tapered Bores

Acoustical science can find no compelling acoustical reason for the reverse tapered bore. There is nothing of consequence which can be done with a tapered bore that can't be done with a straight bore. It's now generally felt that the shift to tapered bores in Europe during the Sixteenth century had more to do with construction methods than anything else. The shakuhachi probably never had a straight-bore period so, in Japan, the question is moot.

Hole size/placement

Roughly speaking, a 10% change in hole diameter, or a 1% positional change relative to the (acoustical) top of the tube, causes a frequency shift of 10 cents.

ToneVolume

The loudness of flutes is most directly related to hole size. The bigger, the louder.

Wall Vibrations

There is strong evidence that wall vibrations (if any) do not contribute perceptibly to the total of radiated sound; the material of the wall therefore has no influence of the timbre. Frequency, initial transient, stability, ease of blowing and timbre of a note are solely determined by the inner geometry of the entire instrument, including the player's mouth.

John Singer, in a fine article, talks about something called "chikuin" which he implies contributes significantly to the sound of certain shaks which possess this quality. A simple experiment will clear up a lot of the misconception.

Play Ro, Tsu, Re--those three notes. Did the vibrations also change pitch? Play Ro, Tsu, Re on a marimba. Did you play it all on the same bar? Of course not. A flute who's body will vibrate does so at a single pitch, so the sound arising from this vibration would be heard as a drone note as it's pitch would be unvarying. Those who insist on the idea that flute body vibrations contribute in any meaningful way to the sound of a shakuhachi would have to have flutes that, first of all, do vibrate and second, the length of the vibrating medium must change length in order to create different pitches. Thus, what they're claiming is that their flutes somehow magically change length while being played. Now that would be something to witness!

A flute who's body could (somehow) create audible sound would be deemed

inferior as a strange drone note would be in the background of all play.

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Updated 9/24/03

It’s obvious that before the introduction of the Western scale into Japan there was a musical scale in place used to create shakuhachi. But what was it?

This story starts, as good stories do, with a legend. Chinese writings claim that in 2697 BC the emperor Huang Ti sent a scholar, Ling Lun, to the western mountain area to cut bamboo pipes that could emit sounds matching the call of the phoenix bird, making possible the creation of music properly pitched for harmony between his reign and the universe. Lun did so and returned with a pitch pipe which emitted a sound called the yellow bell pitch. The length of the yellow bell pipe became the standard measure and the amount of rice which filled the pipe became measures of weight and volume. Thus Lun made an early measure of Aspect Ratio.

By way of some clever iterative math Lun generated, from the yellow bell pipe, 12 notes—the Lu notes. Although their exact frequencies are not known their relationships are. And these, handed down and over time, made their way to Japan where they became the foundation for the scale of the shakuhachi. Anyway, that’s the way one version of the story goes.

Was the scale used to create the old flutes and was the original honkyoku based on the Lu notes? Circumstantial evidence tends to indicate that it likely was. If so, this means that modern flutes and modern playing of the original music has departed from the old ways. The sound of that played by the Komuso was different than that which is played today. How much? You'll have to decide. Below is a table giving the difference in cents.

Note	**Lu Ratios**	**Chinese Lu Scale** cents	**Western Scale** cents	**Difference** cents
	18/17	98.955	100	
	9/8	203.910	200	
Tsu	6/5	315.641	300	**+16**
	54/43	394.347	400	
Re	4/3	498.045	500	**-2**
	27/19	608.352	600	
Chi	3/2	701.955	700	**+2**
	27/17	800.910	800	
	27/16	905.865	900	
Ri	9/5	1017.596	1000	**+18**
	36/19	1106.397	1100	
Ro	2/1	1200	1200	**0**

If shakuhachi tradition, authenticity and/or pitch are important

to you
this table gives the cent differences required to recreate the Old Flutes.

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Shaku Design	3.6 Chokan

Updated 7/31/06

Brett Breitwieser wants to play a Watazumi flute. Barring that he wants to play a flute like Watazumi's. He wants the Watazumi experience. Dave McCullen was already experimenting with novel long flutes. Dr. Gene Neill wanted to try his hand at making a big flute of PVC. Peter Riley had made attempts at chokan and was disappointed with the results.

So we pooled resources and began

The Breitwieser/McCullen/Neill/Riley/Watazumi Project

in order to find out more about designing and building long flutes (chokan) and long flutes with big bores.

Watazumi in action

Brett's 2.6 (785mm Length, 23.25mm Bore, made by Dave Mason) with 10mm holes has a Equivalent Aspect Ratio (EAR) of 31.77. He wanted a BIG flute so he tried a 3.6 out of 2" PVC.

Dave's 3.2 (965mm Length, 20.1mm Bore, made by himself) with 9.5mm holes has a Equivalent Aspect Ratio (EAR) of 43.65.

Gene wanted a chokan, but wanted the holes placed in the traditional locations as his hands are large enough to play a long flute. He picked 1" PVC (ID 26.2mm) and a length of 933mm.

Peter went with the 3.6 and a 1 1/4" bore.

Equivalent Aspect Ratio (EAR)

$$\text{EAR} = \frac{2.858\ \text{Length}^{5/6}}{\text{Bore}}$$

(the 2.858 part comes from the sixth root of 545 which is the length of a 1.8 shak, which is the referent length.)

You can do these calculations at Google. Just put it into the search box and click search.
Example: Enter **((545^(1 / 6)) * (1090^(5 / 6))) / 26.24** into the search box, click and you'll get the the EAR for a 1090mm length of 1" schedule 40 PVC--37.0076068.
For more Google calculator instructions.

A 3.6 (1090mm) made from:

1" PVC has a EAR of 37.0

1 1/4" PVC has a EAR of 28.03

1 1/2" PVC has a EAR of 24.02

2" PVC has a EAR of 18.67

All pipe used this these experiments was Schedule 40.

PVC pipe sizes

10 foot lengths of gray PVC electrical conduit in 1 1/4", 1 1/2" and 2" from Ace Hardware came to $20.82 with tax and will provide enough tube for a dozen heavy duty flutes.

For a 3.6 chokan, cut the PVC at 43" which is a millimeter longer than 3.6 shaku. (a shaku is 303.03 millimeters)

It's an under-appreciated fact that with standard shakuhachi the hole span (distance from center of thumb hole to center of first hole) is 36% of the total flute length. **This figure stays constant over the entire range of shakuhachi and is independent from hole size, bore diameter or length.** Only when we get to long flutes (chokan) does this figure change. On long flutes, special considerations have to be made to accommodate hand size--that is, the holes are configured differently in order to make the flutes playable. With chokan the span percentage drops below 36% and so we could turn things around and define chokan as any flute in which the span figure drops below 36%.

Brett cut his big (2") tube to length (3.6) and then got fascinated with its Ro:

The main thing I did was cut a piece of milk carton plastic to span the upper end and tape it in place... I trimmed it off so that the upper (flat edge) was big enough to stick my big fat (lower) lip into the flute but keep my chin out... this serves the practical purpose of giving me a way to exactly set my chin in the same place EVERY time... which gives me a remarkably consistent RO.

For now the end guard is just taped on with electrical tape, but my sister has dropped off her hot glue gun and I think I'll glue it in place as soon as I'm sure the end cap is exactly the way I want it. One of my family members has suggested that I use a slightly heavier piece of Teflon-coated plastic as the milk carton plastic seems a little thin and is prone to disintegration in the Arizona heat/UV... I should point out that the plastic end cap is slightly concave (dips into the tube slightly) so my chin position is right.

As far as trimming the ute... I originally had it narrower (about 38 mm) and was getting very good volume but was slightly out of tune... I widened it to your recommended 40mm+ by slowly sanding it down and deepened it slightly (almost to 9mm+) and now am almost exactly in tune but noticeably "windier" with less volume as far as the note goes but still adequate.... I think this is to be expected with the wide utaguchi.

I'm going up to Canyon de Chelly next week and will take the big tube with me (as well as my smaller bamboo flute)... maybe I will raise apparitions of the Ancient Ones that way. I hope to somehow buy or reproduce one of the Ancient Ones' flutes eventually. I have heard that they may be hard to play. But it seems like a natural fit for my "buffalo boy zensufi" style. Using new technologies to rediscover and recreate the past.... But hey, I want to build a solar pithouse too...

I've been pretty much a one note man all along, even when I still owned the Levenson flute (which I since have given to a more deserving student with a formal teacher) my style is not performance but to sit in solitude and RO RO RO the boat.... "merrily all the way, life is but a dream"....

Dr. Gene Neill writes:

Eureka! My big, low, 933 mm, "F", PVC shakuhachi is finished and magnificent and in perfect pitch.

I simply marked off the hole locations according to the factors, adjusted them right or left for ergonomics and then drilled them quite small. And, by the way, I do not have any great difficulty reaching all the holes.

Then, with my Yamaha electronic tuner, I first verified that my RO was a solid 440 - 442 "F". Then TSU of course, with the small hole, came in flat, but I opened up the top of the hole and got my hoped-for perfect "G#" (this tuner does not show flats, only sharps). Moving on up to RE, the small hole was again - thankfully - flat, but when I opened it up at the top, it came out a perfect "A#". And, after opening up the tops of each of the rest of the holes, I got a perfect "C", "D#" and, with everything open, another "F".

Your calculations could not have been more flawless, and they also worked out perfectly for this huge flute.

And wait'll you hear it!

I can see now why Watazumi-Do got so turned on with his mammoth hochiku - this thing rattles the windows in my room, and does not require the exorbitant volume of breath which I anticipated!

Peter Riley reports:

IT WORKED, Great God Allmighty, it worked!!! The 3.6 page plus The Utaguchi page did the trick. Until now the utaguchi proportions I have tried have been wrong. I have fooled around for years with these "big suckers" and have always been defeated. I used a 3/8" brad point drill on the first holes as it doesn't grab the PVC on the way through. Utaguchi from 1.25" pipe coupler and removable. The hard part, for me, was in the tuning as the development of a new embouchure and the low hooting sounds were unfamiliar. I am not at all sure that I have it now but what I do have is certainly worth messing with i.e. further experiments with utaguchi. There are two workable octaves which is better than ever before. So the point is, your splendid offering moved me into the "it's possible" mode for which I will remain grateful as will the great trees out back that have to listen to me hooting away.

Peter then wanted uniform, large holes:

In multiple tries at 3.6 I find the first hole consistently wildly sharp. Not surprising as it's a long way to the bottom from there. ***I have stubbornly opted for 11mm holes for their open sound.*** *To flatten hole #1 pertubation (globs of kids modeling clay on thin wire) caused as many problems as it solved) The solution was to build a chimney, like a flute around the hole. Pieces cut from a coupler and glued onto the barrel with PVC cement solved the sharp problem wonderfully. If clever the hole can be stacked in an upward angle further helping with pitch. Bamboo in these large dimensions must thicken appreciably at the bottom as PVC does not. The other area that I found helpful was careful carving of the "chinage". If you are Dick Tracy it has one shape and Mortimer Fudd another.*

And he went even further:

The chimney, ala Boehm and his flute, was first made from modeling clay. When this solved the sharp #1 hole I opted for pieces of PVC from a coupler of the right radius as a more permanent solution. If I modeled around it with epoxy paste it wouldn't even look bad. Rather than whittling both the coupler and the tube inside into the utaguchi I opted to extend the tube beyond the coupler so now only the tube has to be shaped. My bench top is covered with 2'" long pieces of tubing with curves whittled in them. It dawned on me that I should experiment with utaguchi made from modeling clay. This would come close to "adjustable" and later replace my first efforts with something more permanent.

Here's the deal:

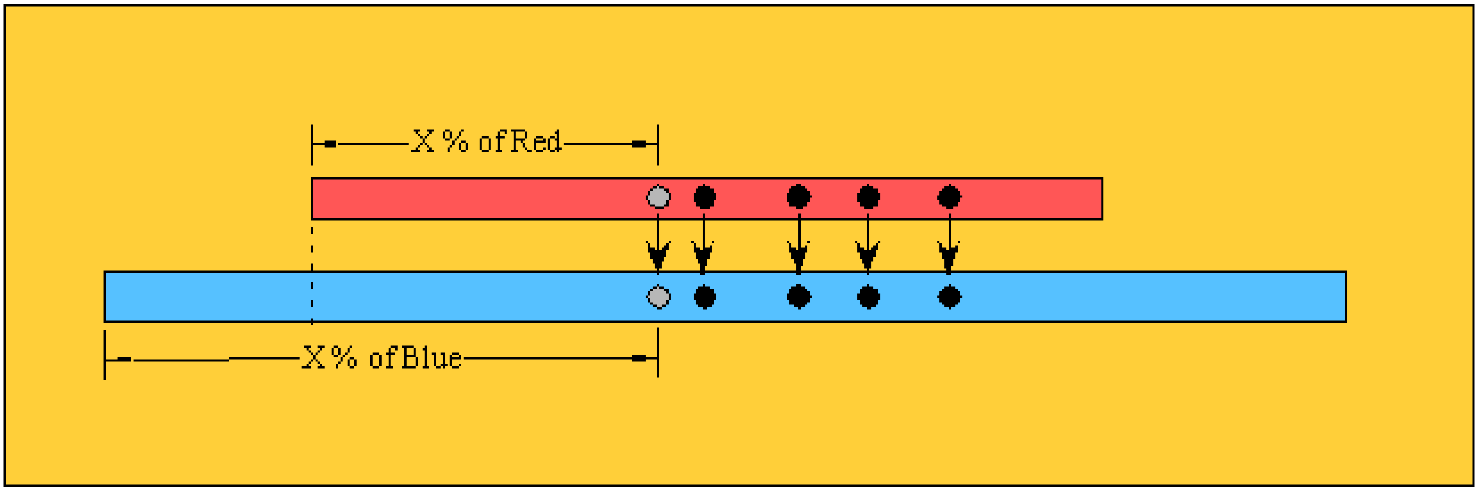
Pick a favorite flute and measure from the center of the thumb hole to the center of the first hole, call this the SPAN. Use a flute where your hands are not unnaturally stretched. (as a point of interest divide the SPAN length by the length of the flute--the result should be right at 36%).

1. Measure from the head of the flute to the center of the thumb hole. Divide this by the total length of the flute. It should be somewhere between 0.40 and 0.45. This is the X % of RED as seen in the graphic below.

2. Multiply the length of the chokan you're building by X % of RED, the result is the X % of Blue. Same percentage, different lengths. So the thumb hole in both flutes is the same **percentage** distance from their heads. Mark the Blue thumb hole.

3. Transfer the hole locations from Red to Blue, either by physically aligning flutes and marking off the holes or by measure/math. If measuring, mark the Blue at the dotted line seen below and measure from there.

The whole thing is about matching up the thumb holes of the two flutes, once that's done the rest follows.



To create a chokan by math alone, we need to create a Virtual Red Flute. Pick a comfortable SPAN. Say 250mm. Divide it by 0.36 and get the length of our virtual flute. (250 / 0.36 = 695) Use the table below for the hole locations. This table can be used for any Virtual length which is generated by any SPAN.

Hole	Hole Percentages for Virtual Red
Thumb	**0.4417**
4	**0.5036**
3	**0.6173**
2	**0.7022**
1	**0.7986**

The 'thumb' percentage (0.4417) is the X % of RED in the graphic above. Mark the rest of the holes, remembering to multiply times the Virtual Red Flute length (695mm).

Now that the chokan holes are located proceed with drilling. Start with hole #1. Drill small and enlarge until hole #1 starts to come into tune. The holes may not be the same size, increasing from #1 to Thumb. The trick here is not to drill #1 too big at the beginning. Always error on the small side, it's much easier to enlarge than to shrink.

Below is a table (built on a SPAN of 250mm) which lists the hole measurements for a 3.6 chokan--the math is all worked out, just measure from the head and mark the holes. Fiddle with the holes until the flute is in tune.

Some readers were put off by the discussion above about choosing a 'comfortable' hole span for Chokan flutes. 'Proper' hole placement (on any flute) creates a hole span of about 36% of the flute's length. Normal to large hands start to get strained with a span of around 240-250mm. What this means is that you can't play a flute of over about 700mm (2.3 shaku) with proper holes. A hole span of 250mm is about 10 inches, meaning that all the holes on any flute you will ever play fall within a 10 inch range--maybe a little more if you have very large hands.

Should you pick the greatest span you can UNCOMFORTABLY play? That way the holes will be closer to 'proper'. Or, since the holes aren't going to be proper, should you pick a more comfortable span? What this boils down to is whether you want to play the flute or not. Yes, you can design your flute to be closer to proper and torture yourself every moment you play or you can accept the fact that flutes over about 700mm will by necessity have 'improper' hole placement.

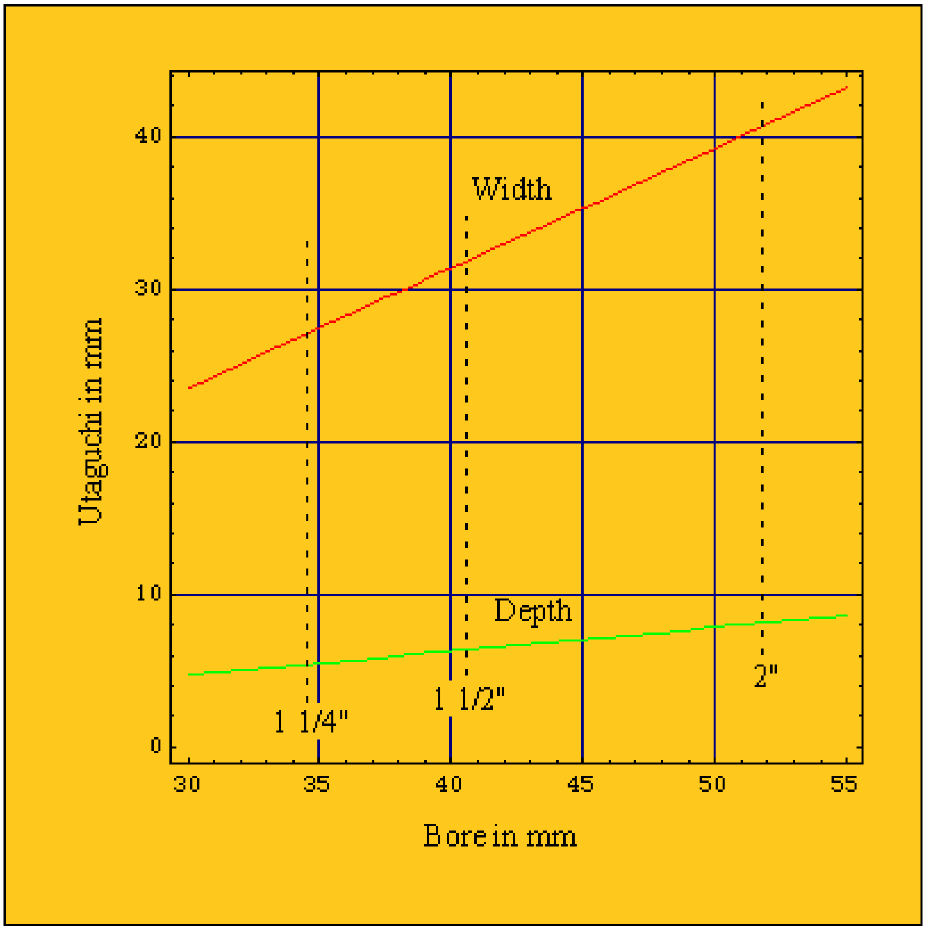
Flutes in the 2.3-2.4 range often create the greatest damage to the hands because there is a strong temptation to stretch the hole span just a little more to achieve hole propriety and it's probably a bad idea in the long run. With flutes of greater length, the holes will be so far from 'proper' that one might as well concentrate on making the flute very playable. Since you'll have to live with the impropriety of hole location, attend to other features you can do something about.

There's no compelling reason to have a hole span on any flute that's outside the range of your personal hand comfort. What would be the point?

For a page on Big Bore Flutes.

And see The Synthesis for a final flute design.

Hole	**Hole distances for 3.6 Chokan** 1090mm
Thumb	**481**
4	**524**
3	**603**
2	**662**
1	**729**



Approximate Utaguchi sizes for Big Flutes

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Shaku Design	End Blown Flutes

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Updated 11/17/03

The beauty of PVC is good instruments from a trip to Home Depot and five bucks. I think the trick is to keep the concept within the ability of the determined hacker. --Peter Riley

Hack the Shak. --N. Zink

An end-blown flute is a variety of flute in which the airstream is directed against the sharp rim of the open upper end of a pipe by the player's lips. Despite its unsophisticated appearance it is very difficult to play. The pipe is often fairly long and the number of finger holes is frequently only two or three. The main materials are bone, horn, wood, bamboo, or occasionally metal, and the bore is usually cylindrical. The angle at which the instrument is held varies according to the style of the upper rim. End-blown flutes are found in every continent but especially in South America and Asia, and examples exist dating from the Stone Age. In examples of modern end-blown folk instruments wood or bamboo are the most usual materials, though in some countries a length of metal tubing is used. Made from bamboo, the Japanese shakuhachi has an uncharacteristic wide bore that is internally lacquered. –Musical Instruments of the World

Types of Blow Hole:
The simplest blow hole (a) is often modified to create a sharper edge against which to direct the airstream. Common types are the beveled blow hole (b) or blow holes with notches that are V-shaped (c), squared-shaped (d), or rounded (e).

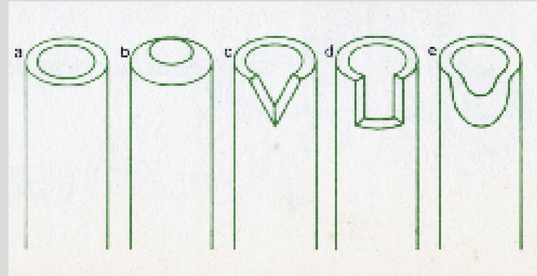


Figure 1

Note: As we're a little hazy on nomenclature, on this page we'll use the term 'utaguchi' to mean mouthpiece--including, but not restricted to the actual blowing edge.

Generally, end-blown flutes have an aspect ratio somewhere in the range of 40, thus the shakuhachi is unusual in that its aspect ratio usually centers around 30. Why 30? One conjecture is that at or near the aspect ratio of 30 the amplitudes of the even and odd harmonics are roughly equal. The shakuhachi has staked out the sonic ground right between first and second octave. Through playing techniques the shakuhachi can emphasis either even or odd harmonics (timbre bending) and thus it is an instrument of great psychoacoustic range.

The ratio of the amplitudes of even and odd harmonics can be varied in two general two ways: By changing the basic aspect ratio of the bore and/or by varying the ratio of the area of the blow hole (utaguchi) to the area of the bore. The first is fixed, being set by the instrument maker, the second is constantly manipulated during play. The ratio of blow hole to bore area which best explores the border between first and second octave is usually between 20% and 30%. Painting with a broad brush, let’s call it 1/4 or 25%.

Any end-blown flute with a blow hole ratio of 25% and an aspect ratio of about 30 will sound pretty much like a shakuhachi. If a shakuhachi is defined by its acoustic properties rather than particular construction techniques and materials, then any end-blown flute with the proper ratios IS a shakuhachi.

The design of the shakuhachi blow hole (utaguchi) provides for and encourages the considerable effects of pitch bending. In end-blown flutes pitch and timbre bending are inseparably bound together and, in a way, two different aspect of the same thing. So, a flute with considerable pitch bending capabilities makes precise hole tuning somewhat irrelevant and perhaps impossible. In such flutes, the question of whether they are “in tune” is somewhat meaningless.

In traditional shakuhachi the utaguchi is ill-designed as far as accommodating the player's lips and mouth. The design conforms much more to the parameters of the bamboo and the general criterion is aesthetic rather than practical. In short, the utaguchi is built more for looks than play.

Problems with the traditional utaguchi:

1) It's not designed to facilitate a good air seal as Peter points out:

The bane of the woodwind instruments is air leaks. Fingering, joints and keys all conspire. The saxophone with its big keys that must seat squarely is a prime offender. ***The simple elegance of the shakuhachi does not escape leak problems.*** *In small bore instruments the soft, pliable, fleshy lower lip (provided it is hairless) works well as a gasket to close the area below the utaguchi. As the bores become bigger i.e. 1"-2" and the radius starts to reach down into the chin area. Closing off to be airtight becomes virtually impossible. Very small leaks in the mouthpiece area will quickly stop resonance. In experiments with large bores I made a gasket for this lower area from modeling clay. This was simply a worm of clay pressed onto the edge of the tube. When pressed against my chin it formed a tight seal. I was startled to find many of my "playing failures" dying out. I found that if I made a small leak with a toothpick in the clay resonance stopped completely. The problem is that a clay gasket is short lived and needs to be repeatedly pinched up and reseated. Now, the soft wax seal of the didgeridu makes a lot of sense. It seems to me that the shape of this lower area needs to be an oval such that the lower lip makes the seal not the chin or chin/lip transition. In PVC instruments, I found that the coupler concept tended to leak. If the assembly will not hold a vacuum it leaks! When I gave up the PVC coupler and simply joined the short mouthpiece/utaguchi section to the barrel of the rest of the instrument with tape a great deal of the mystery disappeared. Cosmetics can come later with a Turks Head knot or a glued, leak proof version of the PVC coupler covering the seam.*

2) It's not designed for good control. The distance from the lower edge of the mouthpiece (where it rests on your chin) to the blowing edge is usually about an inch. To institute finer control this distance needs to be shorter.

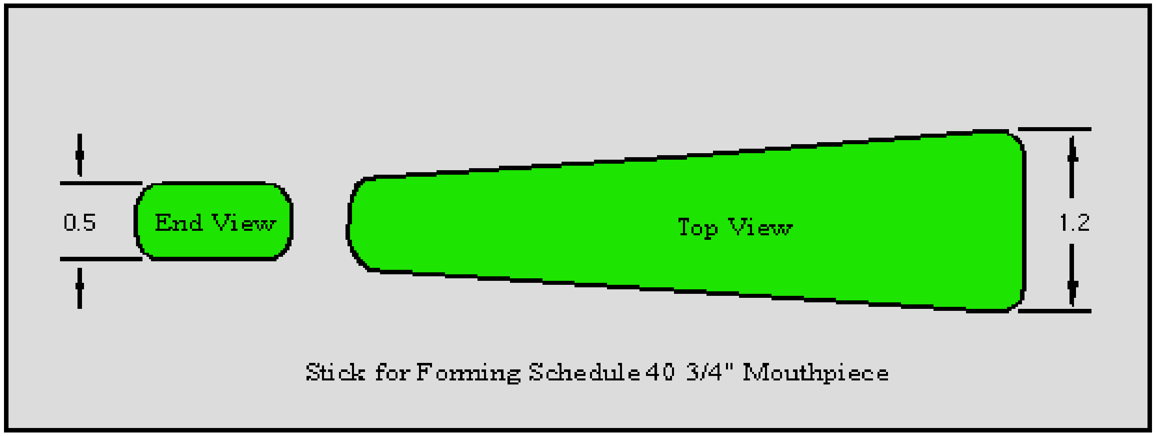
3) In a previous page we explored the role of the lower lip in forming a hole with the blowing edge and with standard utaguchi the lower lip is wedged into the uppermost part of a circle. **A more sensible utaguchi would accommodate the entire lower lip and allow it a wider range of mobility.**

Reducing the utaguchi to its fundamentals, we need a structure which positions the lower lip in respect to the edge**--*this is the first thing that needs to be achieved. Without proper lip placement the rest is irrelevant***. The utaguchi need not be larger than the lower lip in its relaxed and uncramped state--say 1/2" x 1".

The blow holes in Figure 1 all conform to the shape of the material from which the flute is constructed. With PVC a new generation of flutes can be constructed as, with a little heat, PVC is malleable. Thus, all manner of utaguchi can be designed and constructed.

The Oval Utaguchi

See below for a drawing of a stick to form a suitable mouthpiece in 3/4" schedule 40 PVC using the principles we've set forth. Simply heat the end of a PVC pipe with a heat gun and insert the tool until the tube conforms to the tool. Let cool and withdraw the tool. Put a slight curve in the bottom edge to fit just below the lower lip. The blowing edge will have to be cut deeper than usual because the lip is now comfortably within the end of the tube. Make the blowing edge about 5/8" wide and 1/4" deep. Depending on your lip thickness file the blowing edge with an overcut or an undercut. Or somewhere in between with a little of both.



Yesterday my wife spirited me off to Wally World (Walmart) and there, can you believe it, a heat gun fairly sprang out at me! The first try at an oval mouthpiece, a 1 1/2" worked better than anything so far! When I first looked at it I thought the oval was too big and would reach around to my ears but not so. My only caveat is that this technique requires knowledgeable carving. ***I had to chase the sound with my knife.*** *Also there is no way I can describe the multiple curves that are required. --P.R.*

Oval Utaguchi

This design is easier and more interesting to play than the traditional utaguchi as it addresses the three problems outlined above. It provides a good air seal, gives the player about twice the control of a standard shakuhachi, and allows the lower lip greater latitude during play.

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4) The fourth problem with the standard utaguchi is that it 'stalls' easily.

The Reynolds Number (Rn, which is proportional to inertial force/viscous force in fluids), named after Osborne Reynolds, should be of interest to flute players. The Reynolds Number of air changes according to air speed. In recorders the number is typically in the range of one to two thousand and the air jet remains laminar across the width of the instrument mouth. For large organ pipes, and the high notes on flutes, however, the Reynolds Number can exceed 3000, and turbulent noise makes a significant contribution to the sound. Most end-blown flutes have that distinctive air-rush sound and it’s an indication of a higher Reynolds Number.

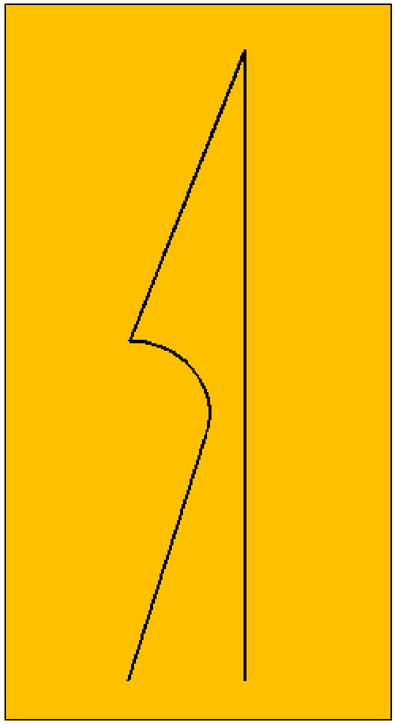
Air streams change dramatically with different speeds (Reynolds Numbers). Within the range of most flute playing there are three phases: At very low speeds the air stream is steady and quiescent, like a candle flame. A little faster (Rn—40 to 2000) and the flow is laminar. Even faster (Rn>2500) the air stream becomes turbulent and generates a particular quality of sound.

There isn't a smooth transition from one phase to another, it's rather sudden and the sound of the shakuhachi (and most end-blown flutes) is distinguished by the rapid transitions from laminar flow to turbulent and back again. These shifts are generated by changes in air-stream pressure/speed. Want more of that air-rush sound? Pump up the pressure. Less? Drop the pressure. What you're really doing is shifting the Reynolds Number of the air stream.

In avionics, the wing can do something which is referred to as 'stall'. When a wing stalls the lift characteristics suddenly collapse and the craft begins to fall from the sky. This is usually caused by the 'angle of attack' becoming too great. If the angle of attack is kept within a certain range everything works fine, but if it goes over a critical value then turbulence ensues, the wing quits lifting, and quick thinking and/or a parachute is needed.

When a flute suddenly loses sound it's because the blowing edge has stalled. The angle of attack of the air stream to the edge is out of synch and the resonance and whole sound envelope vanishes. The edges of end-blown flutes have a narrow range of angle of attack and thus are considered hard to play. There isn't as great a latitude as with other instruments.

This condition can be rectified and to do so we need to look at airfoils which are harder to stall. In particular, the Kline/Fogelman Airfoil. By adopting some anti-stall geometry we can expand the sweet spot of the end-blown edge, making it easier and less frustrating to play. What we'll attempt to do is create an edge which is more tolerant of swings and variation in angle of attack. Adopting the design below will substantially improve your flute's stability (blowing edge stall characteristics). **As a demonstration, you should be able to jog and play your flute at the same time.**

Cut away (blue) showing anti-stall geometry on the inside of the tube

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There is nothing quite so fine as messing about with utaguchi. --Peter Riley

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Putting it all together:

C Flutes 262 hz. 606mm

Hole Locations (in mm) for Various Sizes

Schedule 40 (thin wall) 3/4" PVC & the Oval Utaguchi

Hole	**9.5 mm** 3/8"	**9.9 mm** 25/64"	**10.3 mm** 13/32"

5	258	260	261
4	295	297	298
3	364	366	367
2	416	418	419
1	475	476	478
Ro	606	606	606

Since they're all the same length, hole size will define the character of the sound of your C flute. Smaller holes will make it soft, quiet and mellower--larger holes do just the opposite. If you want to do a fine job then drill holes one size smaller and carefully expand (file) the holes (starting from the bottom) until they come into tune. 606mm is the TOTAL length which pitches the flute to C. The aspect ratio of these flutes is 29.5 which makes the Equivalent Aspect Ratio 28.9--putting them on the mellow (dark) side of things.

For extra credit, slightly undercut the holes along with the foot opening. Use acetone on a folded paper towel to smooth, clean, and finish.

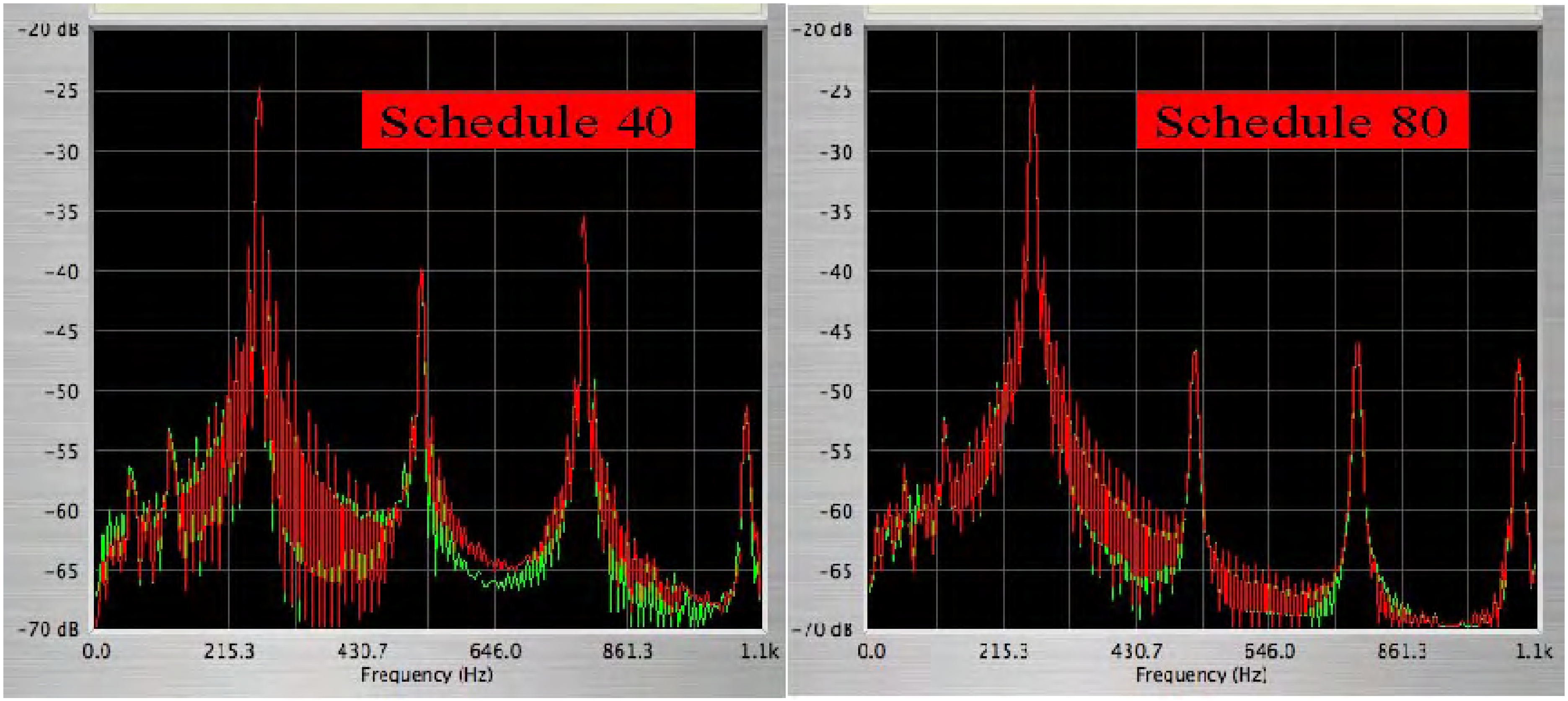
Schedule 80 (thick wall) C Flutes 611mm

3/4" PVC & the Oval Utaguchi

Hole	**9.5 mm** 3/8"	**9.9 mm** 25/64"	**10.3 mm** 13/32"
5	272	273	274
4	309	310	311
3	377	378	379

2	428	430	431
1	486	487	488
Ro	611	611	611

The aspect ratio of these schedule 80 C flutes is 33.2 which make the Equivalent Aspect Ratio 32.6--placing them on the bright side.



Acoustical comparison of the two pipes

See The Synthesis for a final flute design.

Shaku Design	Register Holes

Updated 9/3/06

This from Tom Deaver:

I've noticed over the years that, in some cases, when the sound of ro (kan) changes when opening the 4th finger hole, the change can be eliminated with adjustment between the second and third finger holes. ***It seems that most people prefer flutes such that opening or closing the 4th finger hole causes no change in the sound of ro.*** *I have no idea what's going on but know that the area between the second and third finger holes is about a third of the length of the flute. It's also easy to mess up Chi and chi working in that area. It's probably near the end of the half-length of the Chi sound wave.*

Tom has developed a self-referential test for well-balanced shakuhachi. You can now test your own and any shakuhachi you might play. Simple, quick, definitive--the best of analytical feedback.

To achieve this balanced condition, the fourth hole needs to be placed and sized to also serve as a register hole. To make a register hole work on a traditional shak it has to lie at the flute's acoustical center. This may not be at the linear center as the bore of a traditional shak varies along its length, but with PVC we can step around this problem and investigate the whole idea of a register hole and general sonic balance.

So what does the Deaver test achieve? **What it's really about is determining the proper hole size in relation to bore.** In Tom's description, he can work the other way round from what we will. As do all traditional makers, Tom has the option of adjusting the bore to match the holes he's already located and drilled. In our example, we'll select hole size based on a preexisting wall thickness and bore diameter. Since the wall thickness and bore diameter of PVC is uniform we can place the fourth hole exactly at the acoustical center of flute length and be done with it.

So the problem we need to solve is what sized holes to use in order to have the fourth hole at the acoustical center of the flute length? Smaller holes migrate toward the head of the flute and bigger holes toward the foot. "Hole size", in this context, is not just the size drill you use. What we're talking about is the effective hole size--how easily the hole vents. And that is also dependent on wall thickness. In this example we'll use 3/4" Schedule 40 PVC, so the question is what hole size will make the fourth hole in Sch40 PVC fall at the acoustical center of the flute? And the answer is 9.5mm or 3/8"

If you'll notice on a previous page, the dimensions for the Sch40 9.5mm C flute places the fourth hole right at the acoustical center. So, for any length Sch40, 9.5mm sized holes will create the balanced condition we're trying to achieve.

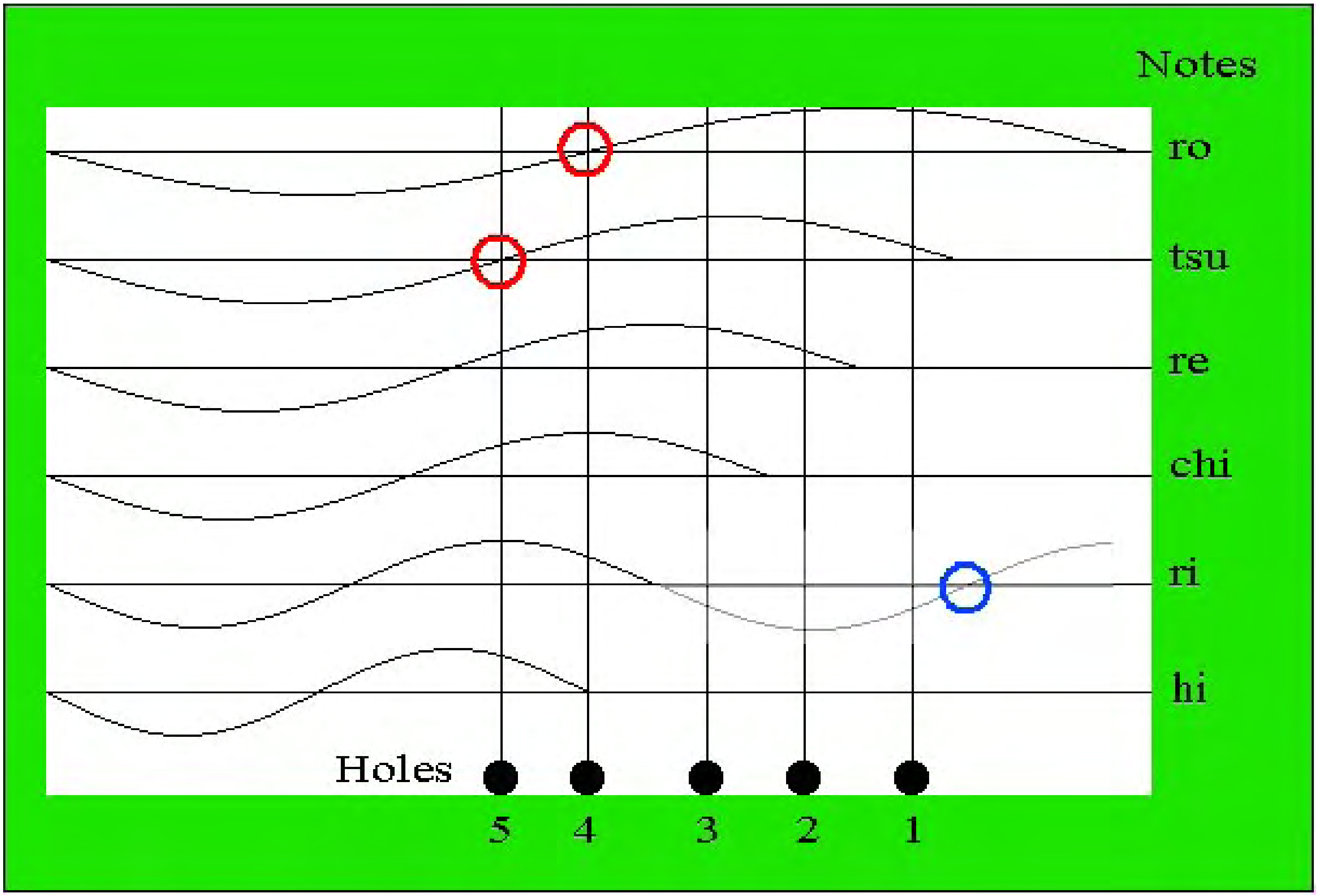
Since lower pitched flutes are often preferred while playing honkyoku, let's make this one a 2.1, pitched to B

B Flute 247 hz. 642mm

Schedule 40 (thin wall) 3/4" PVC &
the Oval Utaguchi
with **9.5mm (**3/8") holes
Aspect Ratio--31.2 ** EAR--30.36

Note	**Hole**	Distance (mm) & Percentage
Hi	5	275 -- 0.428
Ri	4	314 -- 0.489
Chi	3	388 -- 0.604
Re	2	443 -- 0.690

Tsu	1	504 -- 0.785
Ro		642 -- 1.000



The fourth hole can serve as a register hole for ro. By moving the fifth hole up slightly it could also serve a register hole for tsu.
The wavelengths signify the effective length of the flute while playing second octave notes.

Deaver continues:

There is another little sort of test. Do you know the fingering technique called "kara-kara" in Tozan notation? Don't see it so much but believe it is repeatedly striking the 1st finger hole while playing ha meri in kan. (That's a ha without the capital letter so its kan, not Otsu. Did I get my personal notation switched around? Hope not...Otsu has capitals and kan does not.)

This repeated striking might also be noted as ru again and again quickly.

What happens is that the pitch goes to a higher frequency while the first hole is momentarily closed. Now, play chi and chi meri and apply the same technique, ru, in rapid succession. Aren't these fingerings called cross-or forked-fingerings, closing a hole below other open holes in the lattice? Benade touches on this in his textbook, saying that the pitch of the forked fingering may go up or down depending upon the situation. ***Well, on a preferred shakuhachi, the pitch always goes up.*** *You can imagine that not all the flutes in the house now work this way. Some flutes send the pitch up, others send it down. I'd be happier if the shift was always up.*

So, what's going on when one plays chi and then ru and the pitch goes down rather than up? Hole placement, as one might suspect, seems to have an effect.

If the first hole is a little lower than usual it can be close enough to the nodal point (see the blue ring above) to create the effect described.

Along these lines there's another trick.

Suppose you want a single-piece flute with the utaguchi cut at the node AND want it tuned to a specific note. If you are very lucky and find a correctly dimensioned culm it'll all work out. Otherwise, you can **raise** the pitch with a **tuning hole**(s). Native American flutes have used this technique for a long time. Drill a very small hole (usually on the back side) about halfway between the first hole and the foot. Place it in the bamboo node to hide it if you want or proudly put it on the front of your flute between nodes. Drill it just like you would a finger hole--straight into the bore. Start the hole small (1/16") and slowly enlarge until the flute raises to the pitch you want. Then place finger holes and finish in a regular manner. **What a tuning hole does is allow the flute to vent a little more than it would ordinarily--thus raising the pitch.** In different flute cultures these holes are often called Devil holes and/or Ghost holes.

See The Synthesis for a final flute design.

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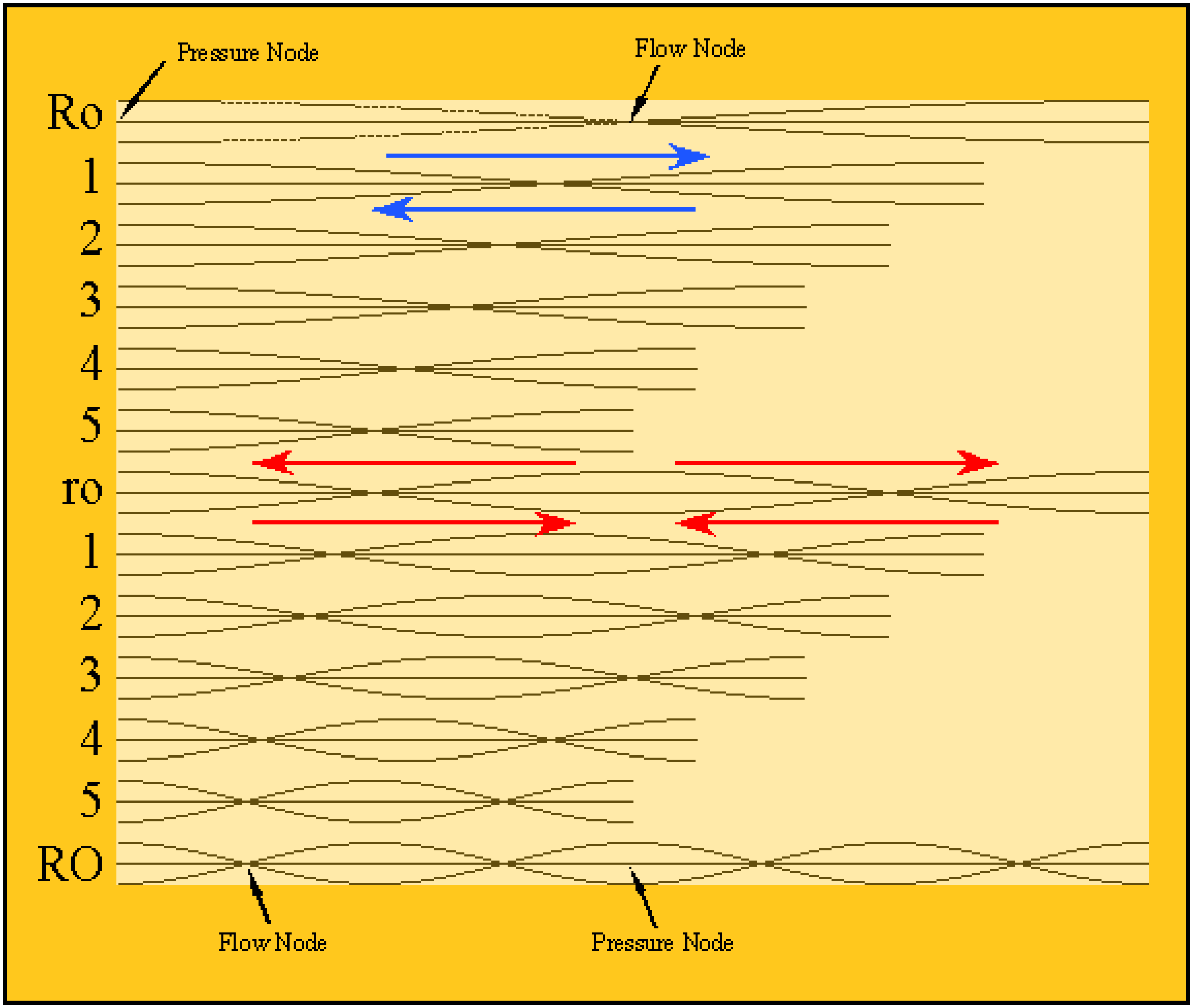
Shaku Design	Nodes

Updated 12/23/06

Nodes, antinodes, pressure nodes, flow nodes, displacement nodes? What gives? The perturbation nodes are different than the air nodes which are still different from the bamboo nodes. We'll try and sort it all out. Below is a graphic of **Standing Wave Patterns** in a flute bore.



In the first octave, pressure nodes (where the air pressure fluctuates) are at the ends of the effective flute length. In between, the air flows (flow node) back and forth from one pressure node to the other (Blue arrows). All first octave notes have two pressure nodes separated by one flow node.

All second octave notes have three pressure nodes interspaced by two flow nodes. Red arrows signify the air movement. The movement of air between pressure nodes is what's perceived as sound.

Benade writes:
The interlacing of pressure nodes and flow nodes allows us to deduce the following general principle, which was first enunciated a century ago by Lord Rayleigh: A

localized enlargement of the cross section of an air column (a) lowers the natural frequency of any mode having a large pressure amplitude (and therefore small flow) at the position of the enlargement, and (b) raises the natural frequency of any mode having a flow node (and therefore large flow) at the position of the enlargement.

This is the whole basis for perturbation. The effects are just reversed for an area of constriction. This explains the great mystery of the shakuhachi bore and what people are trying to accomplish while adding and subtracting from it. Benade goes on to describe how curves called **Perturbation Weight Function Curves** ('W' waves for short) can be deduced from the standing wave patterns and Rayleigh's principle. These are presented on the tuning page.

Following up on the principle governing shifts in frequency by way of perturbation, let's look at the facts. Perturbations have different effects depending on where in the bore they're placed. For this example, let's pick the most effective location. Perturbation length is likewise conditional--let's pick the most effective length. With these two optimal conditions **the maximum percentage change in the frequency (up or down) is equal to the percentage change in the total air volume produced by the perturbation.** Take the total air volume of a 1.8 flute as somewhere around 135cc. Now, let's take the volume of a 25mm square of newsprint--0.0476cc. Placing it in the most auspicious location, we'll get a frequency shift in Ro of plus or minus 0.104hz. That's a shift of 0.6 cents or about 1/3 of the threshold of just being able to hear a difference. **The point is that all the talk about micro adjustments to the bore making significant differences is just that--talk.** When somebody tells you that adding a thousandths of an inch somewhere suddenly turns a clunker into a wondrous flute you can be assured that they don't know what they're talking about. Another myth bites the dust. Micro bore adjustments make micro difference.

Have you ever wanted to see the air pressure nodes within a flute bore? Well you can. It's a simple proposition. Make a flute of clear PVC, cool it and then play Ro. The humidity from your breath will condense on the inner wall of the tube at both ends of the flute--the pressure nodes. Play ro and you'll get three areas of condensation. Pressure nodes is where the air is static and at flow nodes it's moving (oscillating) and thus is dynamic.

The bamboo nodes have nothing to do with the air pressure nodes or the perturbation nodes except when they are left partially exposed in the bores of jinashi flutes. Then they create perturbation as they are bore constrictions. That bamboo grows with its nodes in the correct placement for tuning constrictions is very fanciful thinking.

See The Synthesis for a final flute design.

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Updated 1/12/07

Let's face it, the shakuhachi is an acoustical kludge.

Its look, feel and history make the shakuhachi a very attractive instrument--but as a efficient sound making device? In the last couple centuries musical instruments have been vastly improved with application of acoustical knowledge. But the shakuhachi harkens back to a time before the physics of air columns was understood. And tradition has kept it firmly entrenched in it's anachronistic ways. Myth and player's enthusiasm for the instrument mixed in with the Old Ways have kept it from the harsh light of reality. The shakuhachi is so idiosyncratic as to resist development. It remains an overwrought folk flute.

Where to start? We've covered problems with the mouthpiece on a previous page. Three other things stand out--the bore taper, the holes and octave balance.

The Bore Taper

What's up with the shakuhachi bore? It's hard to say. It isn't at or near optimal by any acoustical standard and in the end attains it peculiar shape because of the perturbation necessary to make manageable it's many problems. It ends up being perturbation on top of perturbation--kind of an endless regression. Only two classes of Bessel curves provide suitable bore profiles--straight cylinders and straight tapers. Cylinders and cones. The standard bore profile of the shak is an oddly curved taper.

In *Horns, Strings and Harmony* Benade is quite specific:

The familiar cylindrical pipe...and the simple cone...are therefore the only musically useful bore shapes for use in woodwinds.

In *Fundamentals of Musical Acoustics* Benade continues:

Further inquiry into the properties of air columns shows that any straight sided air column, cylindrical or conical, will have it's input impedance dips arranged in the desired way.

By the 17th century European flutes had switched over to straight conical bores and over a century ago evolved to the straight cylinder. Both Fletcher (*The Physics of Musical Instruments*) and Nederveen (*Acoustical Aspects of Woodwind Instruments*) speculate that the baroque adoption of conical bores was more a matter of practical constructive advantage than anything else.

Nederveen states:

In the absence of compelling reasons, the simplest possible bore is preferable to any other shape because of easier manufacture and perhaps because of a decrease in sound energy losses.

The central difficulty with the shak bore is that it's shape is **unique** to the particular bore diameter, hole size/ placement, wall thickness and utaguchi depth/angle/thickness, etc. of the flute in which it resides. Change any one of these factors and the taper should also be adjusted. **To say it plainly, every shak's bore profile is unique to that flute and the idea of achieving a universal unique profile is a chimera.** Fiddling with the bore is how makers adjust for all the other factors. And people wonder why the shak might be considered idiosyncratic.

Go with cylindrical pipe and save yourself an immense amount of grief. It will produce notes with greater acoustical balance than any other bore shape.

The Holes

Let's examine the effect of wall thickness. There are those who like flutes made of Madake bamboo with thick walls, but what are the consequences? As walls thicken the effective hole size shrinks. **A 11mm hole in 1mm and 10mm wall material are 'different' sized holes by about a third.** It'd be the same as 11mm and 7.26mm holes both in a 1mm wall. In standard shakuhachi, the wall thickness varies from thicker at the foot to thinner toward the head and usually the physical hole diameters are constant. What this means is that the **effective hole sizes** are smaller at the foot and expand toward the head.

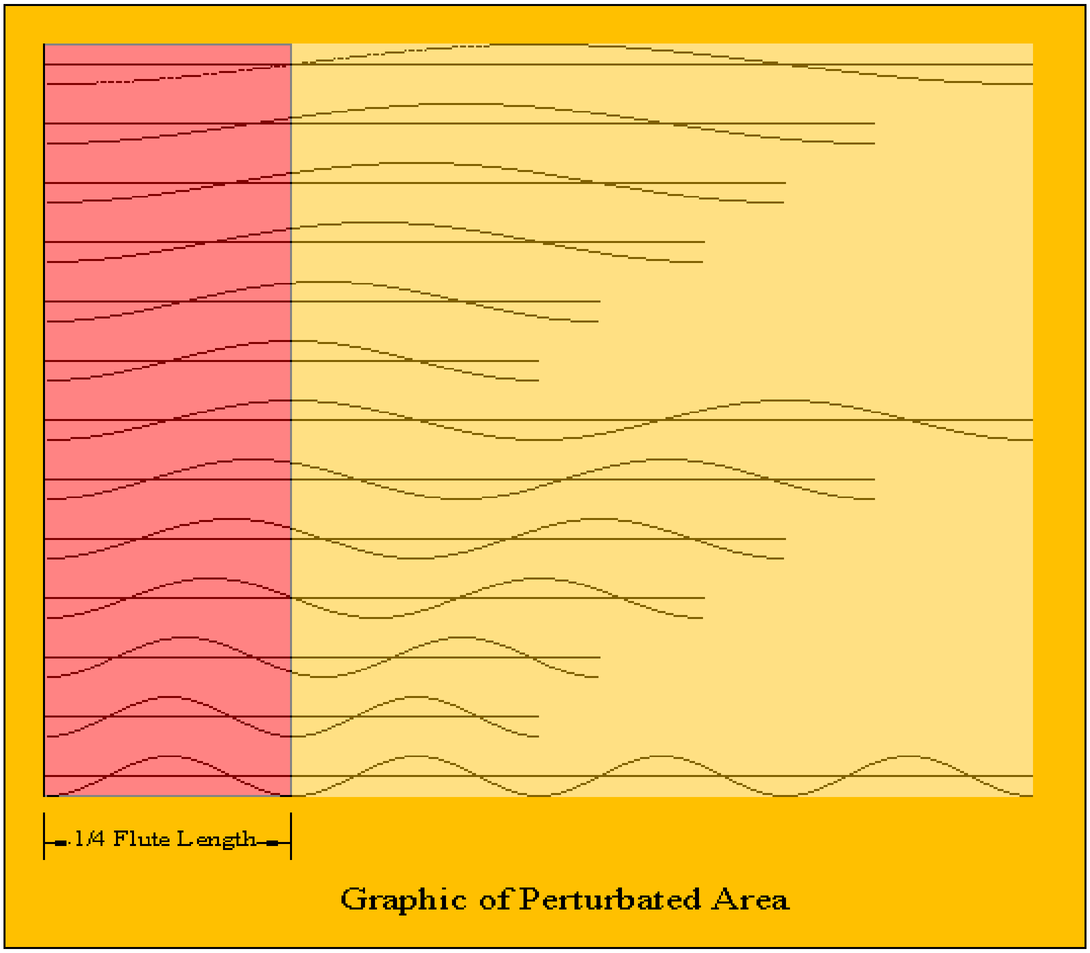
In general, flute acoustics are best with thinner walls. Deep holes (thick walls) create a myriad of acoustical difficulties and particularly if the wall thickness varies. **Flutes work best if the holes all have the same effective size.** For a traditional shak to be acoustically balanced it should have graduated hole sizes to compensate for the graduating wall thickness. That hole openings aren't graduated indicates that makers are unaware of the sonic consequences or at least unwilling to put the way the flute sounds ahead of how it looks. Tradition keeps them trapped.

Say again, go with cylindrical pipe and save yourself an immense amount of grief. It will produce notes with greater acoustical balance than any other bore shape. **Pipe has uniform wall thickness which is huge simplification in hole size/placement.**

Octave Balance

The biggest reason for messing with tapers at all is that a straight cylinder doesn't produce higher registers quite in tune with the fundamental. The higher notes become progressively flatter. We've introduced a couple of ways to compensate and now we'll present a third. It's really just an extension of the Oval Utaguchi. For a page on single octave flutes.

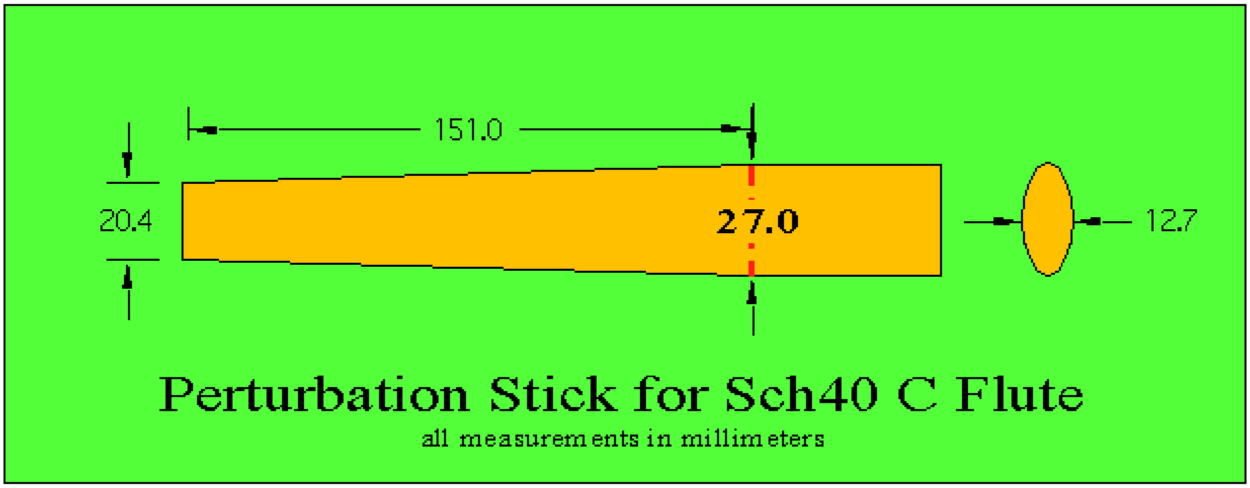
'W' waves of the notes of the first two octaves.



Benade writes:

*Mathematical analysis tells us that the frequency of the lowest vibrational mode is determined **jointly** by the shape and volume of the cavity, while the frequency ratios of the various registers to the lowest **are determined by the shape alone**. A great deal of time has been wasted by instrument makers and laboratory workers in musical acoustics who are either ignorant of this theorem, or are unappreciative of its importance. We base our understanding of **all** wind instruments on this point.*

What we'll do is narrow the first 1/4 of the flute's length by flattening the pipe's circular shape into a gradual oval terminating at the utaguchi. And to do that we'll create a special tool for a Schedule 40 C flute.



Heat the end of the PVC pipe with a heat gun, insert the tool to the red dotted line, let cool, tap out with a dowel from other end, finish the utaguchi and drill the holes. That's all there is to it! The registers of your flute should now play in balance.

Clear PVC (above) will milk up a little while hot but clears on cooling.

And yet a third time, go with cylindrical pipe and save yourself an immense amount of grief. It will produce notes with greater acoustical balance than any other bore shape. Pipe has uniform wall thickness which is huge simplification in hole size/placement. **An extremely simple and effective alteration to the shape of the end of a pipe balances the octaves AND creates the mouthpiece.**

The biggest problem with the shakuhachi is that its acoustical concerns haven't been understood and separated out such that they can be addressed in a straightforward manner. Timbre, tuning, note balance, volume, cut-off frequency, octave balance, hole lattice effects, etc.--all can be addressed somewhat individually with flute designs which necessarily deviate from the standard. And that, Grasshopper, is the rub.

For a page on bamboo jinashi flute design.

Better sounding/playing flutes can be achieved in the following ways:

1) Proper placement/size of holes using the Deaver method

2) Using a cylindrical tube with uniform wall thickness.
For experimental purposes and for 'proof of concept' I've used Schedules 40 & 80 PVC, however, many other possibilities exist.

3) Improve the mouthpiece

4) Adopt less expensive, more durable/available materials
Gray and white PVC is available at most hardware stores. There is also Clear PVC and 6061 Aluminium available in Schedule 40--both for under $2/foot. Phenolic tubes are a promising possibility. Watazumi made shaks of PVC and paper tubes (among other things), so the door is open to many different materials.

5) Achieve octave balance in a straightforward simple manner (see above)

Using the perturbation and mouthpiece specified above, a C flute (262hz) out of Schedule 40 3/4" pipe will be 606mm long. The wall thickness is 3mm as opposed to a bamboo wall thickness of maybe 6-9mm. For our holes to have a similar effective size they need to be smaller than those generally used on bamboo. *For those interested in raising the cut-off frequency of their flute, thin-walled PVC is a good choice because large holes and thin walls create a larger effective hole size than can be obtained with large holes on bamboo with it's thick walls.*

The Deaver Point is located at 295mm. 9.5mm holes should create near optimal timbre--use 9.1mm for a slightly darker, mellower flute and 9.9mm for a slightly brighter one. Roughly speaking, a 10% change in hole diameter, or a 1% positional change relative to the (acoustical) top of the tube, causes a frequency shift of 10 cents.

Synthesis Flute

Aspect Ratio--29.45 ** EAR--28.94

Measure (millimeters) from top of flute

Hole	**9.1 mm** 23/64"	**9.5 mm** 3/8"	**9.9 mm** 25/64"	**General Percentage**
5	257	258	260	**0.4258**
4	293	295	297	**0.4868**
3	363	364	366	**0.6013**
2	415	416	418	**0.6870**
1	473	475	476	**0.7833**
Ro	606	606	606	**1.0000**

After you've set up and made a couple flutes

you'll be able to make and finish a flute in a leisurely hour.
Files, twist drills and Dremel burrs for the utaguchi are suitable tools.

Soften (chamfer) edges where air flows (holes, mouthpiece, foot opening)
then rub with Acetone on a paper towel to remove the printing, clean and finish.
Attention to these edges will make a noticible acoustical difference.

To make flutes of other lengths, **locate** the holes using the GENERAL PERCENTAGES in the table above. Drill small and then, starting from the bottom, **increase hole size** until each note comes into tune. The PERCENTAGES are optimized for cylindrical pipe but should be suitable for irregular bamboo and other bore sizes as well.

Mark Sheperd has come up with a clever device to quickly lay out the holes of a 'percentage' flute. He stretches out elastic and marks the percentage locations on the elastic. Then it can used to locate the holes of any length flute.

Embarrassed by the look of PVC?

SEM Vinyl Dye does a good job and comes in a variety of colors. Firethorn Red, perhaps? Another look at various automotive vinyl dye colors. You can get a Vinyl/Fabric Dye in spray cans at AutoZone.

But a more interesting approach is to use Rit dye--you know, the original Tie-Dye stuff that you get at the Super Market. Mix about half and half liquid Rit dye and water, immerse the flute(s) inside a metal pipe and bring the temperature up to near boiling--you want it hot. The dye doesn't take in a uniform manner--something about the micro-surface I suppose. Anyway, you'll get subtle (see Wabi-Sabi below) variegations. Make some tests with PVC scrap and a pan on your stove top. Rit color chart PVC comes out of the Rit dye bath with a flat finish. Slap on some furniture wax or Deft Clear Wood Finish (it also comes in spray cans) and you've got a winner.

Krylon now has a new fusion spraypaint for plastic! The stuff is pretty tough.

* Bonds to Plastic
* No Sanding or Priming
* Dries in 15 Minutes or Less

* Features the EZ Touch Fan™ Spray Nozzle
* Available in 16 Colors

The obvious answer to pipe color is to have it custom extruded with a specified internal diameter and colorant dispersed throughout the RPVC matrix. That's what we've done and are now offering custom built flutes.

Another Urban Myth perpetuated by the North American shakuhachi community is that PVC is toxic, that dioxin is released should it burn, that PVC dust will lodge permanently in your lungs and so on. MSDS (Material Safety Data Sheets) for PVC don't support any of these fears.

Embarrassed by the fact of PVC?
Asked another way: Does PVC have Buddha nature?

There's a great Sound Color Analyzer and Tuner for Shakuhachi.

It's a free download for Mac(PPC only) or Windows 95, 98, 2000, NT.

Shareware for Mac OS X:

For a more detailed look at your sound get SignalScope the award-winning real time audio spectrum analyzer and oscilloscope.

iSpectrum is an easy to use audio spectrum analyzer that allows the user to view live audio in a standard frequency plot, a stereo oscilloscope view and a waterfall display. The user can adjust the display resolution, center frequency and save images to disk.

Amadeus II is a very powerful sound editor for Macintosh. It runs on MacOS 8.6 and up, as well as natively on MacOS X. The most recent version of Amadeus II is 3.7. Besides all the functions you would expect from a high-quality sound editor, Amadeus II has four main features that distinguish it from other similar products.

Paul Cohen discovered a Japanese study (The Influence of Material on Tone of Shakuhachi by Toshiyuki Sasaki, Dept. of Aerospace Eng., Nagoya University, 1999) which finds little difference between the sounds produced by tubes of four different materials, including bamboo. Figure 3.1 (in the study) is from transparent acrylic pipe, figure 3.2 aluminum alloy, figure 3.3 iron, and figure 3.4 bamboo. Overlaying the acrylic and bamboo graphs produces a virtually identical match.

Urushi lacquer (for the bore) is highly toxic (considered a biohazard in shipping), the red colorant (cinnabar) is a mercury based compound and yellow is an arsenic compound. Madake bamboo groves suitable for traditional shakuhachi are disappearing at an alarming rate. The shakuhachi seems to attract those with heightened environmental sensitivities and quite how they overlook these facts is a little strange.

Bamboo cracks and serious players make an obsession out of attending to the moisture needs of their finicky flutes. Some makers try to get around this defect by placing string bindings from head to foot. Then what's the point of using bamboo in the first place if what you're mostly looking at the 'patches' employed to overcome bamboo's defects? The mere existence of binding should tell you something.

Bamboo for shakuhachi, once an common material, is now scarce and expensive. That it is then encased with lacquer and oils, that a durable material is needed for the utaguchi edge tells you that bamboo's inherent properties aren't up to flute requirements. **Throughout the shakuhachi other materials and techniques have been pressed into service to overcome the fact that bamboo is a poor material choice for flutes.** The humble bamboo flute took on unnecessary levels of complexity in the form moisture-proof lacquer and oils, inset buffalo horn, various bindings, etc. and become the shakuhachi. And all of these were adopted to circumvent the simple fact that bamboo isn't suitable for flutes.

Over time, the shak became a design kludge--endearing, but a kludge never-the-less. The idea of unpretentious elegance is lost beneath an overlay of various 'fixes'. Much of the time, energy, and cost that goes into building a shak goes into these 'fixes' rather than the fundamental instrument. Why should there be an occupation such as Shakuhachi Repair? A material which is waterproof, crackproof and has the integrity to maintain an edge should be a minimum beginning requirement. A basic flute consists of an edge, a resonator and some holes--anything more is extra.

Among a sizable portion of advocates, the 'Zen' aspects of playing seem to amount more to a decision about lifestyle than economy, efficiency and simplicity. A resurgence of the ethic of the original Komuso has yet to take hold. The concept of simple tools and simple methods being strenuously applied is overridden by the current fixation with suizen fashion.

To find out where you fit in all this ask yourself, "Does Suizen serve me or do I serve Suizen? Just why am I wearing this literal/figurative basket on my head?" Can worthwhile principles of Suizen be separated from the cultural background from which it arose? Or do shakuhachi and their accoutrements remain fetish objects to fascinate oneself in the remembrance of and identification with a different time and place?

Get the whole outfit at Mejiro

The previous 38 pages and this Synthesis has been the result of 2 years of thinking and experimentation done in the evenings for relaxation and to satisfy my curiosity. **This information is intended to serve as a suitable base for those wishing to make and play their own flutes.**

All thirty nine pages are presented in the order in which they were developed and written, so they reflect the directions my understanding took as it deepened. At the onset this project was two-fold: 1) to understand the acoustics of end-blown flutes and the shakuhachi in particular and 2) to design a general purpose utility flute which was simple to make, easy to own, and had superior acoustical qualities--a true Zen flute as it were. I wanted something which exemplified the abundant spirit of resilience.

Each note on a shak has a different tone color (timbre) from the others. This wasn't a design decision, it's a consequence of the bore. So the Japanese turned around and made use of this imbalance to give the music additional 'character'--making the best of a bad situation. But this opens up an interesting area--designing for even greater individual note character. In terms of the flute design I'm proposing on this page, designing for and developing tonal 'character' is a much more straightforward and simple proposition. So we're talking about wabi-sabi sound (yet another wabi sabi book). From a Western point-of-view, we're talking about sound degradation. A first and most obvious approach is to abandon the concept of identical hole sizes. Beyond that, you're limited only by your imagination, creativity and spirit of discovery. Some people seem to have a natural intuition for this kind of thing, some don't.

The first evening Zen master Momataki arrived at Rain Mountain Monastery the monks requested their new master show them the way. When Momataki assented with a nod and pointed to the rising moon all but two of the assembled looked at his finger.

What do you make of this story? You've probably heard it before, innumerable times. The story becomes about as concrete as it can get in terms of the shakuhachi. The 'flute' isn't the container, it isn't the bamboo and lacquer, it's the empty part. So it's not surprising that the early monk makers and players (Komuso--the Monks of Emptiness) picked the name they did. Those who object to PVC on aesthetic and related grounds are still looking at the finger, not the moon. They're more interested in style than substance. The wrapper the emptiness comes in has a vanishing small influence on the emptiness itself. Only when the emptiness is shaped/sculpted properly will the true sound take up residence and manifest itself. So flute makers are Sculptors of Emptiness. And they have to keep their eye on the moon and their ear open for the sound. Because sound is the only guide to emptiness in terms of the end-blown flute.

By applying the information above you can create a end-blown flute that's a pleasure to play. It's very stable sonicly, offers much improved control and has greater pitch/timbre bending *potential than any shak you've encountered before. It's waterproof, crack-proof, dent-proof, lightweight (less than 200 grams for the thin wall model), comfortable, and costs but a few dollars (few worries about damage or theft). And by selecting thin or thick walled PVC and hole size you can set the acoustical character (timbre) to suit your own character. Beyond that, it'll come from your hands--you can stamp your own name on it and start on the path toward being a Sculptor of Emptiness. Let's call it katachizen--the zen of shape.*

At some point the shakuhachi will come to terms with it's inherent limitations in design and construction methods/ materials. Since the Sixties makers have universally begun to pay attention to tuning standards. In the last decade new construction methods and materials have been pioneered by Monty Levenson to good reception. Interest in end-blown flutes seems to be growing world-wide. The shakuhachi may be at the beginning of a revolutionary period of evolution.

To be included, send construction feedback, improvements, photos, etc.

Fabrizio Signal applied the principles above in the construction of his shakuhachi.
"I've built several flutes in bamboo, PVC and polypropylene and the sound is always great :)"
His splendid musical compositions are available for download. Check out 'Shakuhachi Tales I'.

Top of Page

Download

Shaku Design

as a PDF file

Updated 9/11/05

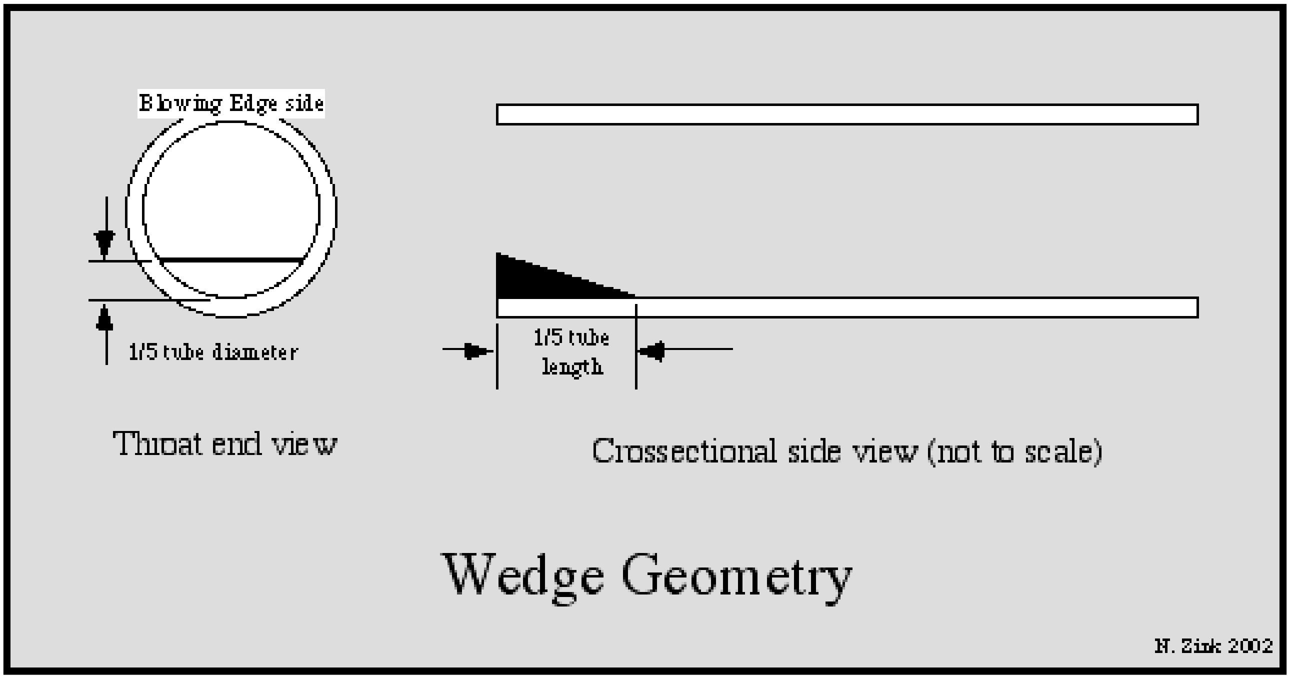
The entire Shaku Design website (up to 2004) is now available as a PDF file. All 209 pages of it, weighting in at about 2.4 meg. You'll need Adobe Reader 6.0 to read it which is also a free download.

Download Shaku Design as a pdf file.

Shaku Design	Kudado: The Way of Pipe

Updated 6/30/05

With this page we're starting to close in on a suitable flute design made from PVC pipe. It utilizes gray 3/4" PVC (schedules 40 & 80), the Integral Mouthpiece and a special Wedge in the flute's throat. This 'wedge' is the key element so we'll get right to it. The biggest, and perhaps only, problem with straight-pipe flutes is what's called octave flattening. What this means is with a straight pipe the notes of second octave and beyond play progressively flatter. It's just the nature of the physics of straight pipe. Switching to a tapered or conical tube is the standard solution to octave flattening. Flutes and recorders went through this change in Europe from the Renaissance to Baroque period. The natural growth geometry of root end bamboo culms leads naturally to tapered bores in shakuhachi. But a properly tapered bore is a tricky and costly thing to create. The Wedge can be fashioned from wood or other suitable materials or cast in place using polyurethane, epoxy, etc. Here's the basic geometry:

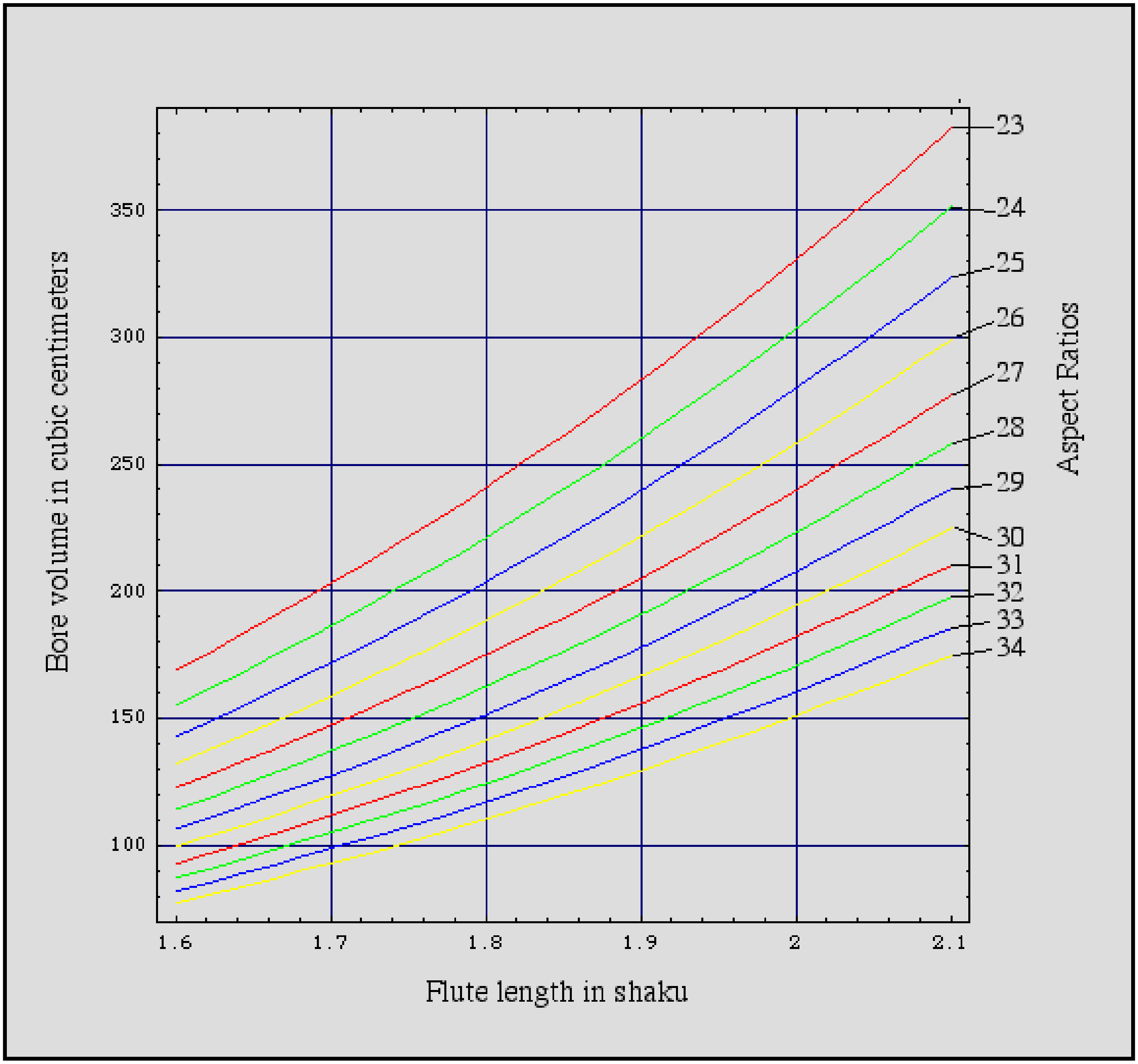


That's it. Stick a properly dimensioned Wedge into the blowing end of your flute and the octave flattening problem is taken care of. It straightens out octave flattening through perturbation. **An insertable Wedge opens up a whole new area of tonal experimentation as you can fashion subtly different Wedges to install in a single flute.** Slightly convex or concave, grooved, thicker, thinner, longer, shorter--the possibilities abound. For a page on tuning by stock removal follow this link.

Only three design factors remain:

Aspect Ratio (tube length divided by internal diameter), hole size and the blowing edge.

Since most shakuhachi have irregular shaped bores the Aspect Ratio can't be calculated from the throat and length measurements. **As most shak owners have little idea of the Aspect Ratio of their flute we'll include a method.** It can be determined by measuring the volume of the bore in cubic centimeters. Tape the holes and foot opening of your shak and fill with water (sugar or sand for the less intrepid), then measure that amount in cubic centimeters (cc). The graph below will compute the Aspect Ratio of your flute. High AR is a skinny bore, low AR a fat one. **Aspect Ratio determines the playability and character of a flute more than any other single factor.**



Since we're using manufactured pipe the internal diameter is fixed. So we can only adjust the Aspect Ratio by changing the length of the tube. Aspect Ratio **directly** effects how the flute sounds--it's timbre. Higher AR produces brighter tones while lower AR creates darker, 'woodier' tones. **Higher AR uses less air to play, very low AR will leave you gasping**--which is a not so subtle matter in playability. Higher AR favors the higher notes and the opposite is true with lower AR. **Typically, what's identified as 'resonance' correlates closely with high Aspect Ratio.** When players have a strong sensation that the flute body is vibrating it's invaribly assocated with an AR over 29. Jack up the AR and the suckers start to pound. Get into the low to mid-thirties and it feels like driving at 55 with the tires badly out of balance.

Another flute characteristic closely tied to Aspect Ratio is attack--the time it takes for the flute to speak. Describing a flute as having a quick attack is synonomous with saying it has a high AR.

Determining the AR of your flutes will give you a very good idea of the correlation between AR and timbre and will reveal the Aspect Ratio to which your ear is partial.

Hole size is a subtler matter:

Generally, hole sizes can range from 8mm to 12mm. Smaller holes favor micro-tones and 'shading' as the holes work more in concert. Smaller holes favor 'softer' sounds somewhat the same way lower AR favors darker tones. Larger holes favor a louder, sharper sound as the holes compliment or interfere (however you want to think of it) with each other less than smaller ones. It's generally felt that larger holes allow for a higher cutoff frequency--meaning more sub-harmonics are produced. **Larger holes increase the sensation of resonance as they expose more of the finger-pad area to the air-column vibrations, hence the player has a stronger tactile sensation of vibration.** So, for resonance go with high AR first and big holes second. It should be obvious that the air-column vibrates--that's the origin of the sound. That IS the sound. Seen on an oscilloscope the sound wave has a profile--a shape. And shape determines how much 'punch' a wave can deliver. High AR produces a taller, narrower wave--one with more punch and bigger holes deliver a larger amount of impact to the tactile nerve endings in the fingertips.

Think of the whole thing like tsunami. When at sea these waves are often just a few feet tall and sailors are unaware when a wave passes. But as the wave approachs land and the depth of the ocean begins to diminish the wave starts to stand up. A tsunami wave's height is directly related to the depth of the water--the ocean's Aspect Ratio so to speak. When it hits shore the tsunami's power is evident. **Shoreline to a tsunami is like a skinny flute is to resonance.**

Before leaving the subject of resonance, let's go a step further. Accepting that the receptors for resonance are in the fingertips (and lips); the index fingers are the most sensitive. So if you're going to do anything special to (or near) holes to boost resonance do it to the second and fourth holes. These are the index finger holes and the fourth hole is probably closed a greater percentage of the time than the second--thus that index finger will be in position most often to detect resonance. **If there's a single hole to concentrate on in terms of resonance, it's the fourth.**

For the following flute prototypes we've settled on the hole sizes in the chart below, if for no other reason than they are somewhat average. Should you vary the hole sizes you'll need to adjust the hole locations from the values listed. For a wealth of other flute measurements and possibilities see the Scales and Intervals page. For a prototype computer program to find the correct acoustical location of holes.

3/4" PVC Kuda Flute Measurements

Multiply hole fraction times length for hole placement
For lengths 1.8 to 2.0 Shaku

Pipe Schedule	Hole in.	Hole mm	Thumb Hole	Fourth Hole	Third Hole	Second Hole	First Hole
40	3/8"	9.5	0.4149	0.4792	0.5955	0.6806	0.7760
80	27/64"	10.7	0.4296	0.4939	0.6070	0.6922	0.7913

1" PVC Hochiku Flute Measurements

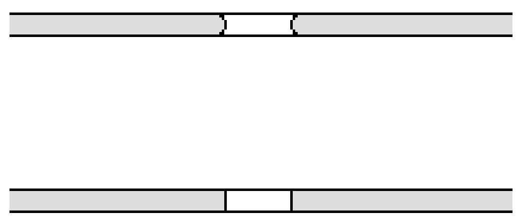
Schedule 80--27/64" holes
Fourth and fifth holes will need opened up a little

Length Shaku	Aspect Ratio	Thumb Hole	Fourth Hole	Third Hole	Second Hole	First Hole
2.0	25.6	249	289	349	409	469
2.2	28.1	284	324	384	444	504

Let's Talk Edges:

While playing a shakuhachi (other than with all the holes closed) all the 'action' is taking place across two edges: the blowing edge and the edge of the last uncovered hole. Air molecules crosses those edges at the speed of sound and reverse hundreds of times a second. The blowing edge is maybe 15mm long and the hole edge some 31mm for a total of 46mm. If we throw in a few mm of other holes (as one hole doesn't act entirely on its own) we end up with maybe 50mm. Call it two inches. The sound a flute produces is broadcasting from those two inches. Does the profile of those two inches matter? Let's find out.

Cut a tube 8" long and drill a hole all the way through the tube about 3" from one end. So you have two holes--on either side of the tube. Leave one hole rough (with the edges sharp and square) and smooth and round the edges of the other hole (both inside and out). Plug the end of the pipe nearest the holes and blow first one hole and then the other. Just blowing air throught the pipe and out one hole and then the other. Hear any difference? Put your lips around the pipe to ensure the same intonation with each hole. Rotate the tube to ensure that hearing differences between your ears doesn't effect your perception. The sound of the smooth hole is ....well, smoother. The raw hole produces greater hiss and white noise. You might be able to get it to whistle some, while the smooth hole stays steady. Listen carefully and you'll notice that the pitch of the smooth hole is slightly higher.



Crossection of edge profile of double holes

Now, make a flute and drill just the first hole and drill it all the way through the tube--again we have two holes on opposite sides. We're essentially doing the same experiment as above but doing it with playing conditions. One hole raw, one smooth--now play each hole. Plug the flute and play each hole again. With the flute plugged you'll notice a dramatic difference in the flute's ability to play the base note. With the smooth hole the tone is much steadier and eaiser to sound. The raw hole is more fickle and breaks up more easily. With these two experiments any number of hole edge conditions and profiles can be tested. The point of drilling through the tube, making double holes, is to isolate the differences in edge profiles and make them stand out clearly by direct comparison.

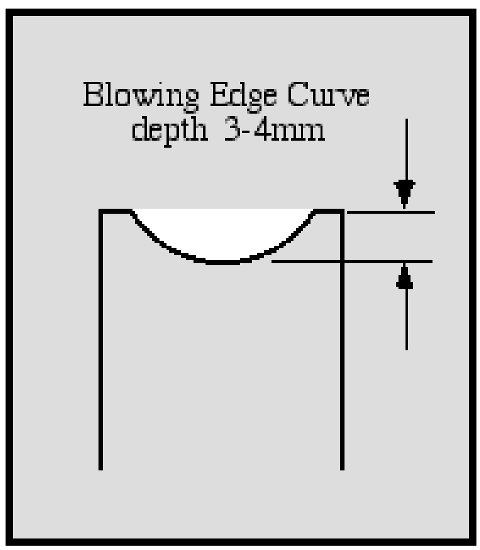
Now for the Blowing Edge:

For most people, instinct tells them that the blowing edge should be sharp. It cleaves the air-steam, right? Well, not exactly, in fact it's a little difficult to tell exactly what's going on at the blowing edge. But we can experiment with the sharpness issue. Make a flute but don't cut the top angle for the blowing edge. Give the blowing edge a nice curve, but no sharpening--leave it square. Will it play? You bet. Now round and smooth that edge like you did with the smooth hole. We've built flutes with blowing edges of up to 3/16" (4.76mm) thick--almost half a hole and they'll play. Go figure.

Attention to edge profile give flutes distinct playing characteristics. Squarer profiles favor the lower notes and lend a darker timbre while rounded profiles do just the opposite.

Sharpening the edge and using a thin slant sharpens the sound, making it clear and penetrating. **A sharp, thin edge brings out Ro and adds to resonance.** The opposite softens the sound and adds mystery.

Cut the top angle at 45 degrees because: 1) you can do it on a table saw and 2) that angle makes the edge a little beefier, thus stronger. Cut the edge about 3mm (about the width of the saw blade) deep on the table saw and then file it down maybe half millimeter more to round and smooth it. Increase the depth of the curve to deepen the register of the flute--decrease the depth to raise the register. If your design intention is to favor the low notes make the curve deeper, high notes just the opposite. Here is the perfect example and design application of kari/meri. Differences in curvature depth is **one** of the reasons flutes playing the same base note can be different lengths.



Should you want an edge that isn't as fickle as the standard shakuhachi edge, file the slant on the inside of the tube rather than the outside. Just that one difference. Same curve, same curve depth--just reverse the location of the slant. **Acoustically, it's a much more stable design** besides producing a strong Ro.

Contemplating Mouthpiece Cuts:

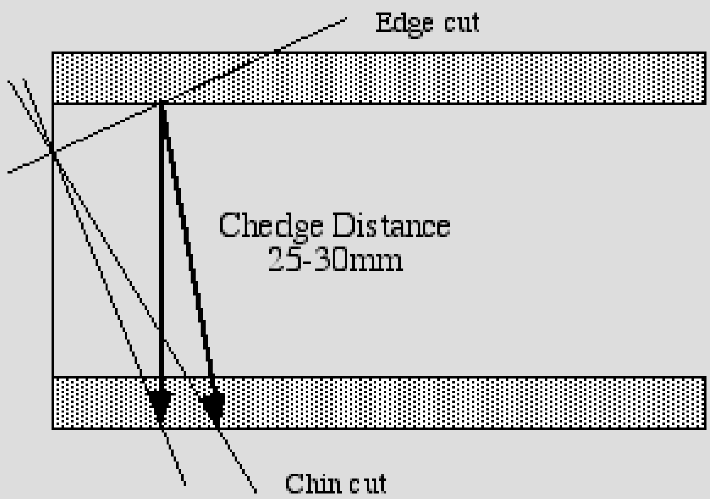
The mouthpiece of the shakuhachi is achieved with two cuts: edge and chin. The angle of the edge cut depends on the throat diameter. With a smaller bore the angle of the cut is more oblique to achieve a nice curve in the blowing edge and conversely for a larger bore the cut is sharper. Once the edge-cut has been completed (producing a satisfactory blowing edge) the chin-cut is made. But what should the angle be? Here is where we need to understand the structure and geometry of the mouthpiece.

Primarily, the mouthpiece does one thing: position the edge at the proper height to meet the airstream and it does so by resting on the 'chin bone'. So the **chin to edge (Chedge) distance** is the critical dimension. Every tube has a minimum Chedge, a distance that can be no shorter--throat diameter plus one wall thickness (see graphic below). The Chedge can be lengthened by increasing the angle of the chin-cut and theoretically Chedge has no upper limit. Usually Chedge is between 25 and 30mm depending on the chin structure of the player--Jay Leno being a special case. Measure the mouthpiece of a flute that fits you perfectly. Measure from the center of the blowing edge to the outside of the chin rest on the opposite side of the tube. Yes Bucky, actually do it! That's your personal Chedge. Remember it, write it down. MEASURE the Chedge of any flute you're contemplating buying lest the attractive finish get you distracted.

Back to the question of the angle of the chin-cut. The angle should be that which is required to produce the proper Chedge. Often the chin-cut angle is selected to set the slope of the flute when played. But that's a secondary consideration. If the Chedge isn't right it doesn't much matter what the slope of the flute is as playability will be adversely effected. Get the Chedge right and the rest will follow. **As far as playability goes Chedge is the most important dimension, if it isn't right you'll struggle from now to eternity--every moment you attempt to play.** Want to know where that sore chin comes from? The flute you're struggling to play has a Chedge that's too long for you. Either get another or get out the file. Here is where a millimeter makes a big difference.

The two numbers we'd like to see attached to flutes are Chedge and Aspect Ratio. These two will tell you whether you can play a particular flute and whether you'd want to play it.

Minimum Chedges for 3/4" PVC are: Schedule 40--23.5mm and Schedule 80--22.5mm, meaning that the Schedule 80 pipe will need a greater chin-cut angle to achieve the same Chedge.



Crossection of generalized Mouthpiece

Casting Wedges in place:

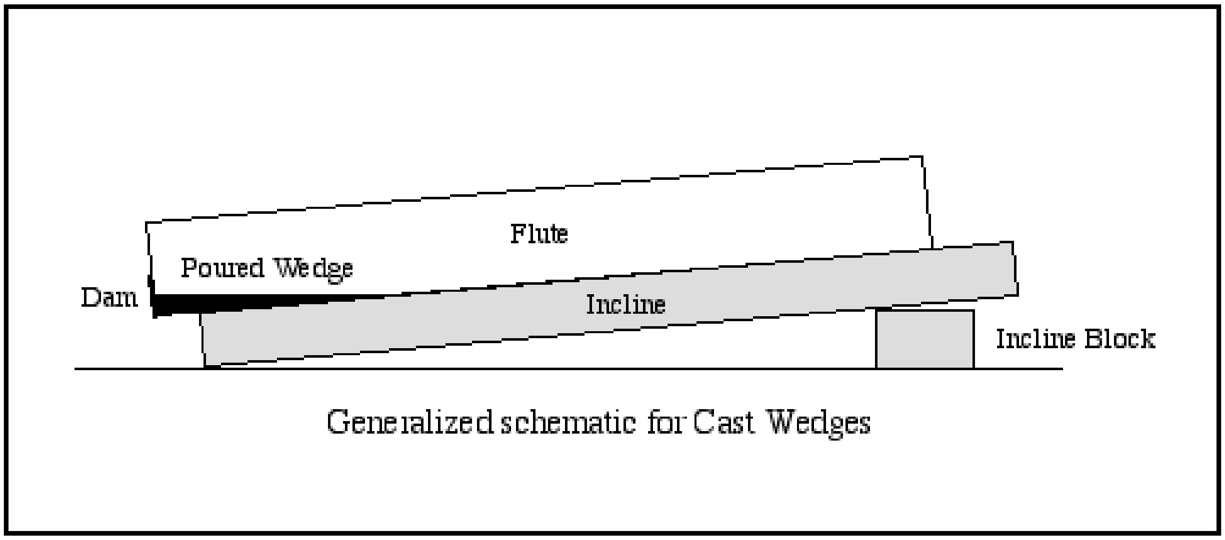
The following schematic pretty much says it all. The flute needs to be set at the proper angle which is adjusted by moving the Incline Block. Drill 9/64" holes through the tube wall to allow the resin to anchor. Tape the anchor holes and place a 'dam' (black electrical tape) across the lower part of the mouth opening and then introduce the resin, letting it seek it's own level. SmoothCast 315 polyurethane resin has a low viscosity and is UV resistant. It's naturally white but can be colored to about any color you desire. After mixing, the resin is injected into the tube with a 10cc syringe from your pharmacy. The syringe allows you to place the resin precisely and more importantly, gives control over the volume of the Wedge. The 'proper' Wedge thickness is 1/5 of bore diameter and varying the injected volume varies thickness--another place for experimentation.

Since the Wedge is proportioned both to the internal diameter and the length by the same factor (one fifth) we're really talking about the ratio of Length/Bore. **Thus, the Wedge is directly related to and is a manifestation of the Aspect Ratio.** To set the proper angle of the Incline divide length by bore (L/B--the AR) and set the length to the Incline Block and the height of the Incline Block to that ratio.

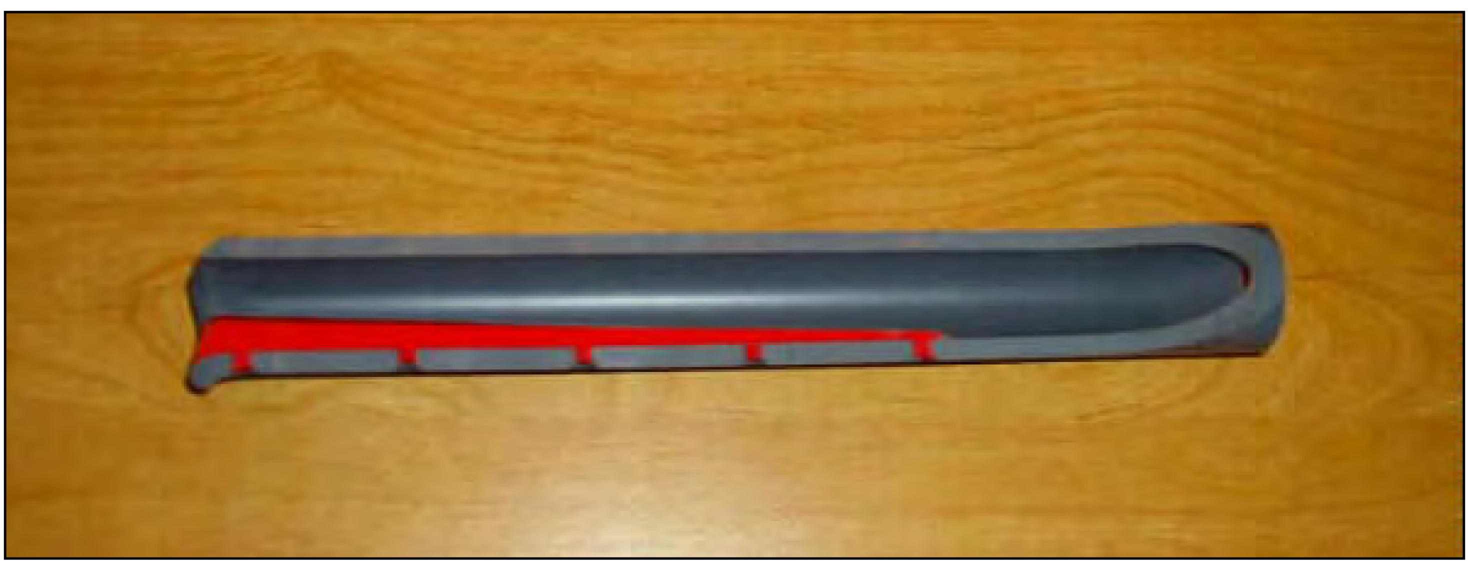
Example:
545mm length tube with 20.5mm bore. 520 / 20.5 = 26.59
Set one inch Incline Block 26.59" from beginning of Incline.
Or set 3/4" incline Block 19.94" from the beginning of Incline.

Or set 20mm Incline block 532mm from the beginning of Incline.
The point being that the **ratio** of the **height** of the Incline Block and the **distance** from the beginning of the Incline is **the same ratio as the Aspect Ratio.**

For the flutes specified in the first table (Kuda) above use about 3.5 to 4.5 cc of resin to construct the Wedge. The basic difference between schedules 40 and 80 pipe is wall thickness--80 being thicker. The internal diameter of 40 is 20.5mm and 80 is 18.5mm--outside diameters are the same. So in general, use schedule 80 for high AR flute and schedule 40 for low. With our local suppliers there's also a difference in color and outer texture between the two schedules. Schedule 80 is often easier to find at electrical supply (rather than plumbing supply) as it's used as electrical conduit.



Generalized schematic for Cast Wedges



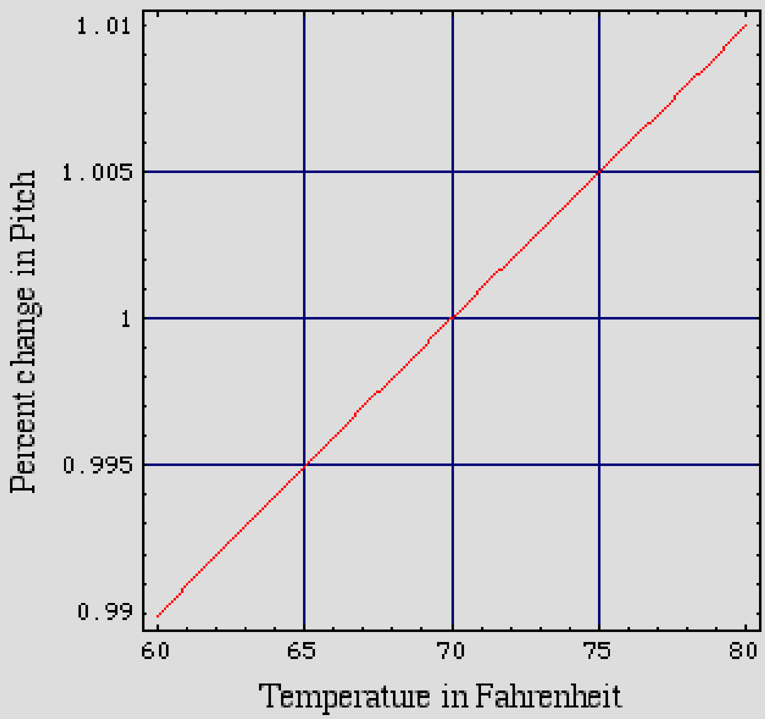
Use Acetone on a rag to clean and smooth PVC--it's semi-miraculous. Rub all the places you filed and sanded and any roughness will vanish. Add a thin coat of mineral oil (baby oil) for a little shine or use fine steelwool for a satin finish. Following these design specifications will produce a decent practice flute. Durable, simple to make, water-proof, little upkeep, inexpensive--what a deal!

All the design examples on this page have been built using the measurements given. They all play. **Feel free to adapt any and all of the information on this page to your circumstance and preference.**

See The Synthesis for a final flute design.

Flute Performance:

Altitude affects the pressure/density of air which by 14,000 feet (4267 meters) had dropped by over 40%. Each 1000 foot (305 meters) change in altitude results in about a 3% change in pressure. But altitude makes no difference on the pitch of flutes and humitity has only a small effect. It's temperature that has a direct and significant impact. The only variable in atmospheric speed of sound is temperature and pitch is directly related to speed of sound--if it changes so does pitch. There's some evidence that altitude affects the timbre of flutes and especially those with lower Aspect Ratio. Rising in elevation decreases the effective Aspect Ratio.



Each degree change in temperature results in a 0.1% change in pitch.

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Shaku Design	Scales and Intervals

Updated 4/9/06

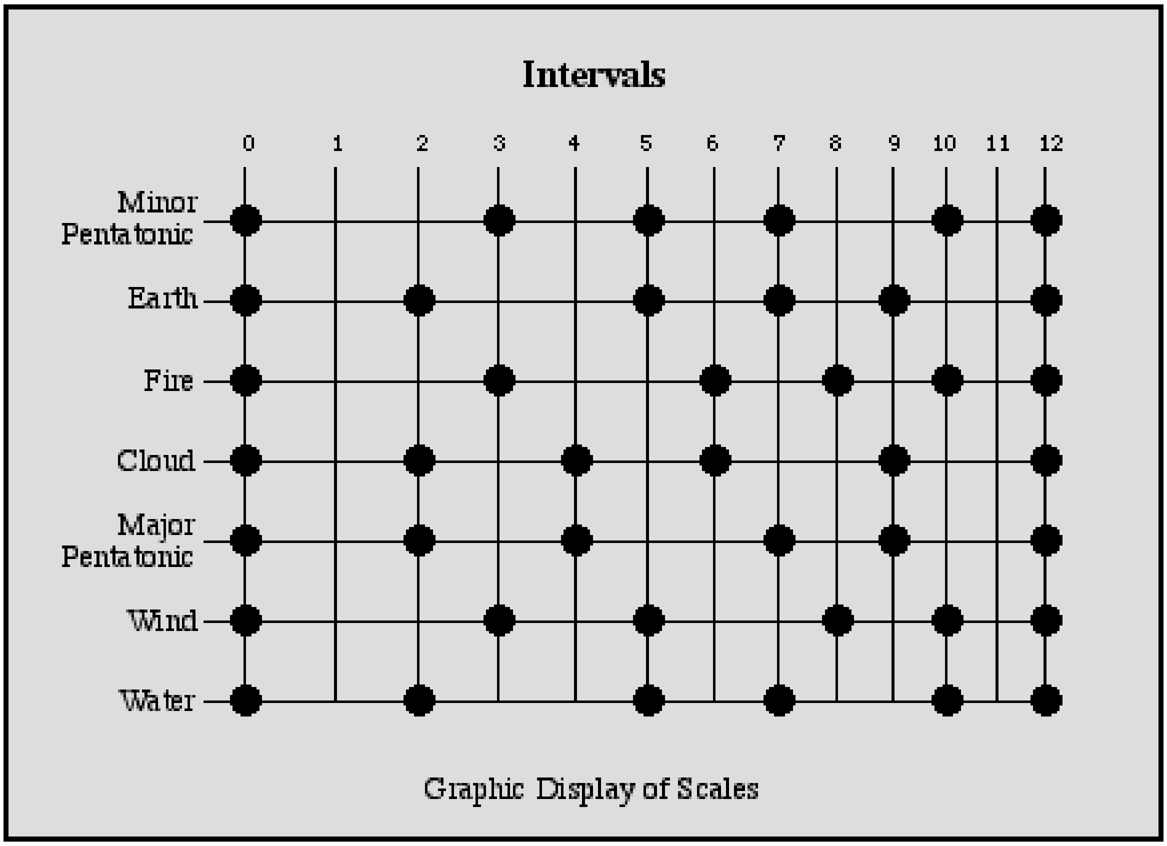
The shakuhachi plays the pentatonic scale--right? But that's the Minor Pentatonic scale--there's another one. Anyway, if you're tired of pounding out the same notes and/or are curious about other five note scales you've come to the right place. To make it simple (and understandable to non-musicians like us) let's think of scales in terms of the intervals between notes. In the key of D, the minor pentatonic is DFGACD'. Since there are 12 notes in an octave, the minor pentatonic goes from D to F (three notes), F to G (two notes), G to A (two notes), A to C (three notes) and C to D' (two notes). So we can write the minor pentatonic in terms of the 'intervals' between the notes--32232. Once we have this 'interval' notation we can make up all kinds of scales. Another useful feature is that the notation is independent of key--just start in any key and it all fits. **For what we're doing with this adventure there are only two rules: Five notes and the interval string must add up to twelve (one octave).** That's it! Be the first one on your block to create your own scale, name it, build it into a flute and then play the music of the spheres. It should be as rewarding to have flutes of different scales as to have them in different keys. **It seems cruel to restrict shakuhachi to a single scale.**

There's something else we can do with this scale business. We can make flutes tuned to different keys and play them together--kind of. And we'd do this by making them in different scales. We've got the standard D flute Minor Pentatonic (32232) and if we made a C flute with a scale of 23223 they would play the same notes except for the C's Ro and the D's Ri--the rest would match up. Or a B flute in the scale of 33222 would match a D 32232 except for Ro and Ri. Get the picture? **Flute duets of different keys and scales--the sound of three hands clapping.** Cross-scale alignment--strangeness abounds!

Tonehole Placement for Various Scales

For 3/4" Schedule 80 PVC--27/64"(10.7mm) holes
Employ the fractions for other lengths.

Scale	Interval	Key	Length mm	Thumb Hole	Fourth Hole	Third Hole	Second Hole	First Hole
Minor Pentatonic	32232	D	533	230 0.4315	263 0.4934	324 0.6079	369 0.6923	420 0.7880
Earth	23223	C	598	259 0.4331	319 0.5334	365 0.6104	415 0.694	508 0.8495
Fire	33222	B	634	277 0.4369	318 0.5016	363 0.5726	413 0.6514	503 0.7934
Cloud	22233	Eb	503	215 0.4274	264 0.5249	325 0.6461	371 0.7376	425 0.8449
Major Pentatonic	22323	F	448	189 0.4219	235 0.5246	268 0.5982	329 0.7344	377 0.8415
Wind	32322	D	533	230 0.4315	264 0.4953	301 0.5647	369 0.6923	420 0.7880
Water	23232	C#	565	245 0.4336	280 0.4956	344 0.6088	391 0.6920	479 0.8478



The Earth, Fire, Cloud and Major Pentatonic scales will all **play with the Minor Pentatonic** and are configured in the table to do so. All the scales are perfectly respectable by themselves and play very well alone. They can be made into an assortment of flutes by combining **any key length** with **any scale fractions** above. **The six key lengths and seven scales will produce 42 different flutes**--plenty for an interesting flute exploration. Visit the Synthesis page to learn how to make PVC flutes--it's not rocket science.

The scale we're calling Earth appears to be used by one of the oldest flutes ever found. Want to hear what they were playing 50,000 years ago? Now you can.

The Blues scale is just the Minor Pentatonic with an extra note stuck in--321132. You can get that extra note by cross-fingering--third hole open with first and second closed.

Using Interval Notation it's simple to make up any scale you want and with the five note system they all sound surprisingly good! With a modicum of programming skill each of these scales (or any others) can be programmed to play randomly--note, duration and time between notes. Random shakuhachi is in some ways more satisfying than written music--it flows in ways that reminds one of bubbling brooks and that kind of thing. There's something about five note scales that guarantees fundamental coherence, so you can't hit a 'bad' note--it all fits.

When the notion of random flute music is broached many players grimace. However, it's ideal for those interested in the 'spiritual' aspects of shakuhachi. Random flute is music without agenda, without authorship or intention. There's no beginning and no end. One exercise for those interested in the Path of the Spirit is to generate random music and play it. Generate randomly by computer or with a single die. Cast a die (ignoring sixes) to determine the note. Cast again for duration and yet again for pause until next note. Write down these three parameters as the instructions for playing a single note. Repeat the process for as many notes as you want. Then play the composition. Want more parameters? Just add them. Fewer? And so on.

The point of learning to play randomly is to free oneself from presuppositions of melody and technique, etc. The goal is to play until random notes sound melodious--and they will. Along the way one develops vastly increased attentional skills as one can't think ahead because there's no melodic structure through which to anticipate coming notes. It's all NOW and THIS note. There's no point in memorizing the music as the truly random can't be memorized. The whole point of this 'spiritual' exercise is to eliminate **content** and concentrate totally on **process**--the playing of the notes. It's surprising to many that random music has any melodic properties at all, but with Five Note Scales it does. You just have to play it to hear it.

A little reflection is enough to realize all songs come from random music. Songs are just the conscious selection of specific random notes from the Random River. **So what we're proposing is that one learn to play the source itself--learn to play the Random River.** This is the first song, the last song, the only song--everything we call 'music' is just a subset of this primal, beginingless, endless, constantly shifting stream of sound. This stream is the stream of possibility and it contains all.

---

507 Random Notes

445 - 512 - 553 - 445 - 123 - 554 - 543 - 435 - 354 - 434 - 112 - 123 - 551 - 413 - 545 - 551 - 113 - 252 -331 - 552 - 515 - 152 - 352 - 251 - 345 - 315 - 545 - 223 - 324 - 523 - 253 - 411 - 433 - 221 - 113 - 335 -122 - 542 - 241 - 243 - 423 - 444 - 231 - 113 - 251 - 231 - 244 - 551 - 322 - 311 - 335 - 233 - 241 - 115 -345 - 252 - 235 - 552 - 452 - 541 - 151 - 132 - 431 - 242 - 222 - 335 - 425 - 451 - 352 - 125 - 324 - 512 -334 - 233 - 131 - 241 - 454 - 421 - 412 - 423 - 254 - 515 - 441 - 453 - 114 - 151 - 152 - 542 - 434 - 445 - 215 - 512 - 313 - 441 - 354 - 543 - 313 - 252 - 444 - 535 - 212 - 543 - 553 - 455 - 432 - 451 - 343 - 523 -234 - 212 - 155 - 245 - 334 - 153 - 535 - 334 - 442 - 232 - 541 - 454 - 322 - 533 - 211 - 253 - 114 - 425 -244 - 342 - 242 - 244 - 215 - 442 - 515 - 144 - 225 - 512 - 411 - 344 - 242 - 322 - 244 - 412 - 453 - 342 -434 - 221 - 255 - 353 - 321 - 214 - 142 - 241 - 523 - 414 - 435 - 534 - 111 - 523 - 343 - 521 - 514 - 345 -355 - 243 - 321 - 354 - 423 - 141 - 522 - 553 - 151 - 353 - 424 - 115 - 533 - 554 - 223 - 342 - 152 - 442 - 212 - 344 - 314 - 415 - 431 - 411 - 532 - 445 - 233 - 311 - 313 - 223 - 424 - 433 - 115 - 424 - 225 - 124 -354 - 243 - 432 - 422 - 354 - 511 - 244 - 112 - 245 - 155 - 314 - 523 - 321 - 234 - 235 - 213 - 232 - 551 -154 - 224 - 211 - 522 - 243 - 413 - 321 - 555 - 125 - 422 - 213 - 353 - 242 - 335 - 431 - 235 - 434 - 353 -141 - 243 - 144 - 221 - 325 - 221 - 135 - 541 - 142 - 145 - 151 - 313 - 541 - 535 - 413 - 423 - 125 - 451 -555 - 425 - 331 - 321 - 421 - 325 - 321 - 124 - 325 - 155 - 515 - 124 - 432 - 254 - 412 - 532 - 412 - 133 - 131 - 144 - 234 - 253 - 344 - 154 - 413 - 543 - 215 - 511 - 312 - 411 - 454 - 542 - 114 - 154 - 135 - 451 -511 - 521 - 311 - 251 - 224 - 321 - 434 - 325 - 355 - 313 - 422 - 354 - 324 - 415 - 513 - 311 - 531 - 221 -324 - 422 - 241 - 212 - 145 - 152 - 422 - 225 - 211 - 413 - 531 - 252 - 433 - 533 - 115 - 512 - 443 - 532 -254 - 133 - 213 - 525 - 252 - 323 - 432 - 223 - 331 - 332 - 135 - 535 - 451 - 211 - 523 - 132 - 324 - 514 -351 - 232 - 455 - 434 - 254 - 423 - 332 - 151 - 145 - 331 - 321 - 225 - 414 - 251 - 451 - 351 - 212 - 535 - 434 - 412 - 515 - 311 - 552 - 453 - 532 - 131 - 333 - 414 - 153 - 254 - 214 - 543 - 411 - 351 - 355 - 153 -243 - 213 - 545 - 145 - 525 - 344 - 115 - 513 - 414 - 231 - 155 - 332 - 444 - 235 - 131 - 332 - 333 - 333 -221 - 143 - 435 - 122 - 125 - 234 - 231 - 414 - 355 - 211 - 423 - 545 - 243 - 251 - 235 - 211 - 441 - 332 -515 - 151 - 524 - 212 - 544 - 234 - 131 - 335 - 324 - 523 - 442 - 442 - 534 - 452 - 531 - 313 - 112 - 243 -212 - 214 - 435 - 555 - 421 - 535 - 413 - 422 - 551 - 114 - 152 - 551 - 521 - 512 - 155 - 445 - 124 - 331 - 122 - 511 - 212 - 153 - 445 - 121 - 253 - 444 - 554 - 453 - 441 - 254 - 532 - 155 - 244 - 235 - 323 - 132 -355 - 252 - 445 - 311 - 512 - 551 - 523 - 233 - 554 - 413 - 422 - 443 - 421 - 124 - 144 - 231 - 411 - 555 -522 - 212 - 534 - 235 - 411 - 543 - 534 - 455 - 131 - 213 - 323 - 324 - 433 - 554 - 435 - 321 - 424 - 332 -413 - 132 - 513

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Shaku Design

Some Ergonomic Thoughts

Go Back Home Shakuhachi Email Friend

Updated 1/15/04

There's a certain aesthetic to placing even-sized holes on a shak where they're 'supposed' to go--acoustically speaking. It's no great trick to write a little program that'll specify hole placement--but that's for an ideal world where hands are either nonexistent or very stretchable. Most other woodwinds have tricky levers to help fingers fit the holes, but the shakuhachi in all it's simple grace has none. So the problem arises, **should the shak be aesthetically pleasing or playable?**

Place your palm down on a table and spread your fingers. Measure from the center of the tip of your index finger to the center of the tip of your ring finger--check both hands. Now, take half that distance and you'll have the limit of the distance between the holes played by those fingers. For the sake of this discussion let's assume the **ergonomic distance is around 60mm**. This means that the distance between the first/second and third/fourth holes should be **60mm or less in order to play comfortably**. For the distance to the thumb hole take a third of your finger span--or 40mm. Now we have the limiting distances between all the holes except the second and third. Since the second and third holes are played by different hands there isn't any ergonomic limiting distance between them.

The greatest distance between holes in the 'correct' acoustical position is between the third and fourth. **As the shakuhachi grows longer this will be the first place to require stretching.** We can ask a simple question: **At what length do acoustically correct, even-sized holes become a problem as far as spacing?** But first, some background: It's makes little difference what sized holes your shak has. Big or small holes, the distance between holes is about the same. It's true! About the only difference big or small holes make (as far as placement goes) is whether the holes will be higher or lower on the shak. Big holes will be lower and smaller higher--but the distance between holes remains nearly the same! So at what length will a shak run into the 60mm limit set above? **Surprisingly it's about 1.75 shaku (530mm).** Yes Bucky, the standard 1.8 shak is already at or over the 60mm limit in regards to the span between the third and fourth holes. The limit between first and second will be achieved with a 2.06 shak (625mm) and the thumb limit will be maxed out at 2.14 shaku (650mm).

So what to do? **Aside from wrecking your hands there's only one answer--different hole sizes.** There goes the aesthetics. There are many ways to approach this design problem, but a simple straightforward way is to **keep the second and fourth holes at their correct acoustical positions** and original sizes. When the third/fourth holes hit the ergonomic limit place the third hole 60mm below the fourth and adjust its size smaller to compensate. Same thing with first/second. Keep the thumb hole within 40mm above the fourth. The size of the first and third holes will diminish, the thumb hole will expand.

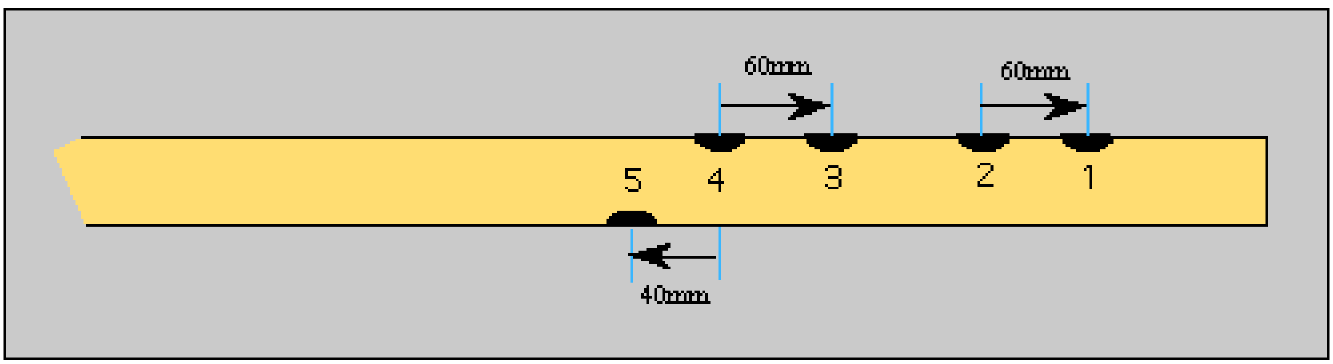
What does acoustically correct mean? The short answer is that it satisfies the Benade (or similar) equations. Does acoustical location really matter? The short answer is no--especially if it makes the flute unplayable. At the end of the day your flute will sound better if it's played better and that's only done with comfortable, unstretched fingers. **Despite what others may tell you, there is no acoustically compelling reason to place holes outside their ergononomic limit.**

Here's the deal. Place the index finger holes where they 'should' go. Place the ring finger and thumb holes where they 'should' go **UNTIL** they reach their ergonomic limits. Then hold them there and start changing the hole diameter to make things come out right. Not so hard.

It's much easier and more humane to fit flute to the hands than the other way around. If you know what the words 'carpal tunnel' mean from personal experience then it may be time for an ergonomically designed flute. Placing the holes in their ergonomically 'correct' location only happens once, if not, your fingers may be strained every note you play. It's more than a little bizarre that players will deform their hands rather than getting the right flute in the first place. Can't find one? Ask for it, demand it--makers will respond.

The downside of a ergonomically designed shak? The holes won't all be the same size and the spacing will be a little different than you're used to. The upside? Joy pervades the kingdom and the music to go with it.

Happy hands make happy music!



See The Synthesis for a final flute design.

Program for Acoustic Location of holes:

```
on mouseUp
ask "What flute length?" with 576
put it into TL --Tube Length
ask "What hole diameter?" with 10
put it into Dh --Diameter of holes
put 156521/TL into BaseNote
```

```
put 20.5 into Db --Diameter of bore
put 3*1.125 into Wt --Wall thickness
put Wt +(.75*Dh) into Te --Tonehole effective thickness
put 165674 into BigNum
put BigNum/BaseNote into TubeLength --Ideal tube length
put TubeLength-(.3*Db)-TL into MEL --Mouthpiece Equivelent Length
put "32232" into Interval --see Interval page for an explanation
----------------------------------
put empty into fld "Data"
put empty into temp
put TubeLength into LastLength

repeat with zz=1 to the number of chars of Interval
add char zz of Interval to temp
put BaseNote* 2^(temp/12) into Hz --frequency of hole
put BigNum/Hz into NewLength --Ideal tube length for note
put (LastLength-NewLength)/2 into S
put S*((((((TE/S)*(Db/Dh)^2)*2)+1)^.5)-1) into CF --Correction Factor
put round(NewLength-MEL-CF) into HoleLocation
put zz&"-- "&HoleLocation&" " into line (6-zz) of fld "Data"
put NewLength+CF into LastLength --moving to next hole
end repeat

ask "What's the ergonomic limit?" with 60
put it into ErgoSpan
set numberformat to "0.##"
put (word 2 of line 2 of fld "Data")-(word 2 of line 1 of fld "Data") into ThumbS
put (word 2 of line 3 of fld "Data")-(word 2 of line 2 of fld "Data") into TopS
put (word 2 of line 5 of fld "Data")-(word 2 of line 4 of fld "Data") into BottomS
if ThumbS>(ErgoSpan*2/3)then put " "&(word 2 of line 2 of fld "Data")+ (ErgoSpan*2/3) after line 1 of fld "Data"
if TopS>ErgoSpan then put " "&(word 2 of line 2 of fld "Data")+ ErgoSpan after line 3 of fld "Data"
if BottomS>ErgoSpan then put " "&(word 2 of line 4 of fld "Data")+ ErgoSpan after line 5 of fld "Data"

put TL/25.4&" in." into IInch
Put the short date&return\
&"Pipe Flute--"&BaseNote&"hz"&return\
&"Length--"&round(TL)&"mm "&IInch&return\
&"Aspect Ratio--"&TL/Db&return\
&"Schedule 40 3/4 in."&return\
&"Scale--"&Interval &return\
&"Holes--"&Dh&"mm "&return&return before fld "Data"
```

```
put return&return&ThumbS&" Thumb" after fld "Data"
put return&TopS&" Top" after fld "Data"
put return&BottomS&" Bottom" after fld "Data"
end mouseUp
```

Program output:

7/9/02
Pipe Flute--240.8hz
Length--650mm 25.59 in.
Aspect Ratio--31.71
Schedule 40 3/4 in.
Scale--32232
Holes--10mm

5-- 280
4-- 320
3-- 394 380
2-- 450
1-- 512 510

40 Thumb
74 Top
62 Bottom

Hole locations are in millimeters, measured from the top of the flute. The spans for acoustically located holes are at the bottom of the list. For any span outside the ergonomic limit a second hole location is given. **The program example above is set up for schedule 40 3/4" PVC pipe.**

Jeremy Bornstein has a page where one may perform the above calculations interactively.

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Shaku Design	Throated Flutes

Updated 1/15/04

A lovely page on the Nohkan flute includes a section on a 'nodo' or inner throat pipe fitted into the flute's bore. It's credited with creating the "mysterious and profound" sound of the Nohkan flute. Sounds interesting. Besides, the first step in making these flutes is turning the bamboo inside out. Amazing!

The shakuhachi already has a throat of sorts--the choke point near the foot. But it only effects the base note and maybe the first couple holes--after that (third, fourth and thumb holes) the lower portion of the shak is largely irrelevant as it doesn't play much of a part in sound production. But a constriction or throat placed **above** all the holes would effect the sound of the entire flute.

Off to the hardware store yet again. You'll need some **Schedule 40 PVC**: 3/4" for the flutes and a couple feet of 1/2" for the throats. Get a 3/4" inch hardwood dowel to tap the throats in and out. The outside diameter of 1/2" PVC is slightly larger than the internal diameter of the 3/4" PVC so here's what we'll do.

1. Make a flute of 3/4" PVC (see the Shak Index for some helpful pages) For this test flute it might be easier to make it **600mm** in length as most of the throat related measurements are fractions of the overall length.

2. Saw a couple sections of 1/2" PVC pipe for the throats. Cut them 1/16 of the overall flute length--or in this case about 37mm.

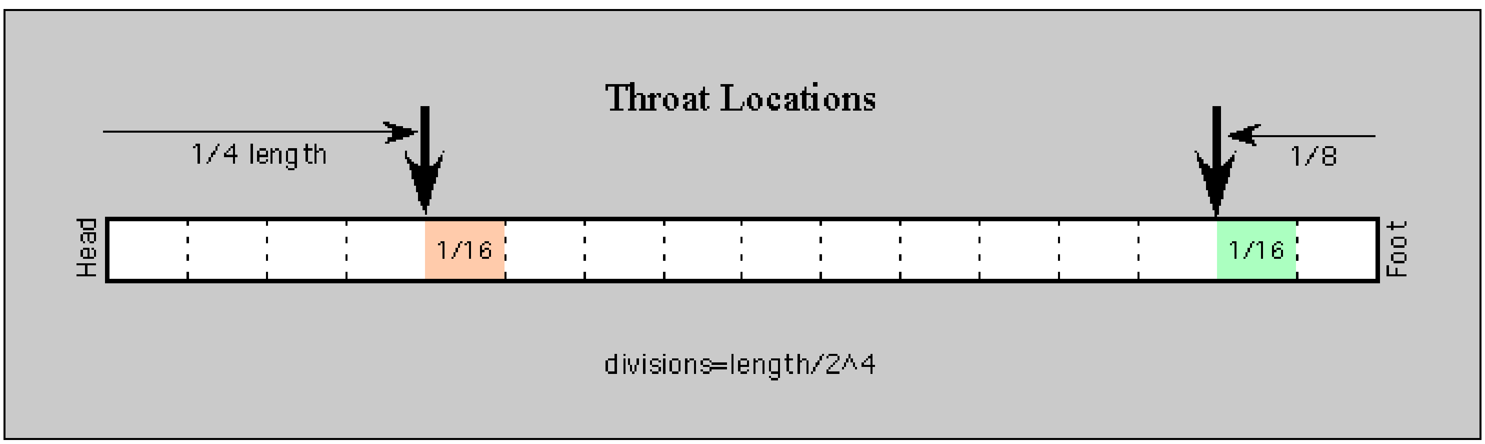
3. Cut through (lengthwise) **one** of the walls of the throat piece. This cut (or gap as it will be) should be about 3/16" wide. Ideally this is done on a table saw and the standard 1/8" saw kerf isn't quite wide enough so trim a little more. Since 1/2" PVC is too big to fit into the flute we're removing part of the throat's circumference and creating something of a spring at the same time. The finished throat will resemble what's called a 'tension pin'. Anyway, cut to these

instructions and the throat will fit tightly into the flute's bore.

4. Chamfer the end of the throats and use the dowel to tap (pound?) them into position. Friction being what it is, a little WD-40 (both bore and throat) won't hurt.

Where to place the throats? For starters try one at the head position and then the foot as indicated in the graphic below. If you want a PVC flute with a choke point, here's a way. Inserting both throats at the same time produces a Ro capable of a **natural tremolo** as it rapidly bounces between octaves. It's worth hearing.

From here on you're on your own. Try different lengths, different locations, etc. Put in as many throats as you want, wherever you want, any length you want. Since the basic function of the physical shakuhachi is the constriction of air in acoustically interesting ways, these throats are a natural learning and playing addition. Moving a throat a few millimeters often makes a dramatic difference. You'll end up with a lot of measuring marks on your dowel. Your flute suddenly becomes extremely adjustable. The approach used here is based on the wavelength (the length of the flute) and subdivisions thereof--which follow the formula 2 to the n. Create and explore any scheme you want.



If nothing else playing around with these nodo throats is very instructive. A tremendous amount which has been covered in other pages (timbre, Aspect Ratio, perturbation, tuning, nodes, etc.) can be experienced directly by fiddling with these throats--the theoretical made real.

Think seriously about making nodo throats (and the placement dowel) a permanent part of your PVC flute collection. With a single flute and a selection of throats you can achieve a large range of sonic effects to say nothing of a deeper understand of the whole affair.

See The Synthesis for a final flute design.

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Shaku Design	Bamboo/Humidity

Updated 1/22/05

Crackability

Will your flute crack? Who knows. It'll depend on a lot of things but mostly the **moisture balance** in the bamboo. If moisture gets too out of balance for that particular piece of bamboo, it'll crack. There's bamboo you can oven dry and it'll never crack, other bamboo will freak out at the first dry breeze. It has to do with how hard the wood is and how quickly it can transmit moisture. Since bamboo contains silicon, which is necessary for bamboo growth, hardness can vary greatly from culm to culm.

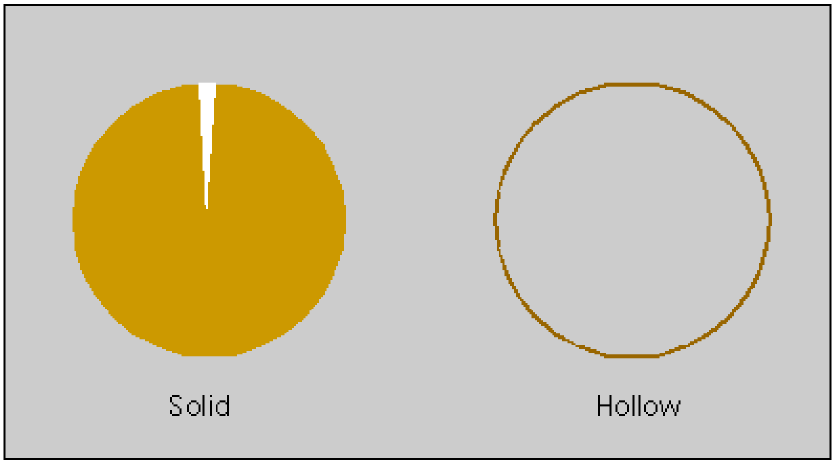
Although there are those who flinch at bamboo being referred to as wood, in most areas the two are very similar. Both can be heat bent, both are hygroscopic, both have similar cell structures, both contain lignin, both can crack and so on. As far the purposes of engineering go the two materials are similar. And perhaps more similar than the dissimilarities among woods. Although the physical structure of bamboo and trees is markedly different the material isn't.

Bamboo is somewhat analogous to people. Young bamboo is healthy and stupid. Old bamboo is smart and infirm. Culms grow old and die after maybe five to 8 years--figure 12 human years to a bamboo year. During a culm's life moisture content declines, the walls develop strength and much of the sugar converts to starch. So what's the ideal age for flutes? What's the ideal age for people? To further this analogy: Who do you want to have to depend on in a pinch? The person raised with a silver spoon in their mouth or the one from a more hard scrabble existence? Thusly, bamboo from poor soil, a cooler climate, etc. is probably better for flutes. The tougher culm makes the tougher flute. Since you probably had little to do with the selection of bamboo used in your flute the rest of this page has information which can used for your defense.

Below is information for the construction of a simple, organic Crack Meter.

Suppose it's your task to crack a flute, how would you do it?

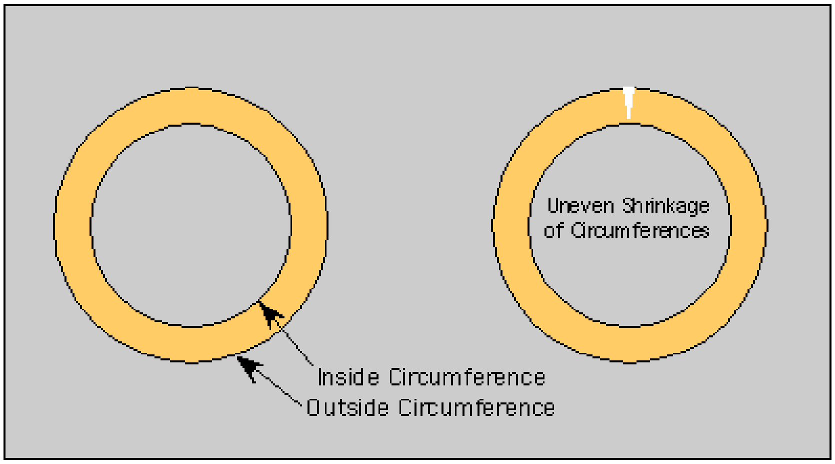
Let's start with a basic fact: **adding moisture to wood makes it expand, removing moisture from wood makes it shrink.** Now consider the two examples below: a solid stick of wood and a hollow tube of wood. With the solid, water vapor can only escape from the outside surface thus the outer surface is always shrinking at a greater rate than the interior surface. With the tube, vapor is escaping from both the inner and outer surfaces. If the wall of the tube is very thin the areas of the inner and outer surfaces are nearly the same, thus the contraction is nearly the same. The solid tends to split and the tube doesn't.



Notice that we've uncovered a principle here. The solid cracked and the tube didn't. In the solid, the drying (shrinkage) was very uneven and in the tube, inner and outer shrinkages were nearly identical. So here it is: **It isn't drying that creates cracks; what causes cracks is uneven shrinkage (or expansion).** Understand this single principle and most cracking problems can be avoided. **If the wood in your flute loses (or gains) moisture at a uniform rate it won't crack--it can't.**

Want to crack a flute?

Just insure that moisture loss or gain is as uneven as you can make it. How to do that? Make sure your flute has a vapor barrier on the inside of the bore (lacquer or some such), make sure the vapor barrier on the outer surface is either missing or insufficient and then stick the flute in a hot oven. Moisture will quickly leave the outer surface but be retained by the inner. The outer circumference will shrink and the inner circumference won't. Think of a standard piece of bamboo with an inner diameter of 20mm and an outer diameter of 32mm. The inner circumference is about 63mm and the outer about 100mm. Reduce the outer circumference by 1% while keeping the inner size the same and you've got a one millimeter crack. **That's where cracks come from--not from drying per say, but from uneven drying.**



How best to insure even drying?

Have both surfaces (inner and outer) transmit water vapor similarly. **An even better solution is to create inner and outer surfaces which are both strongly impermeable to water vapor.** That way it doesn't matter if your flute dries over time as the shrinkage will be very slow and therefore even. The best thing you can do isn't to buy humidifying stuff and fuss and worry, the best thing you can do is apply a good vapor barrier to the outer surface of your flute, while making sure the bore is either lacquered or has a finish identical to the outside. Then you can take your flute anywhere and not worry. It won't matter whether you take it into a hot seamy shower or to the Sahara in the summer. Both surfaces will transmit water vapor very slowly thus there will be no uneven expansion or contraction. You won't have to worry about dry air in the winter or any of the other things which torment those who attempt to monitor their bamboos's humidity. As long as the moisture content (whatever it is) is uniform throughout the bamboo it'll remain stable.

It's a far better method to control the rate of vapor transmission rather than trying to maintain a specific level of moisture in the wood of your flute. ***Don't try to control the humidity but flow with it, only at your rate--very slowly.*** What we're saying is don't worry if your flute dries out, worry if the moisture content of the wood in your flute becomes uneven--that's when it'll crack.

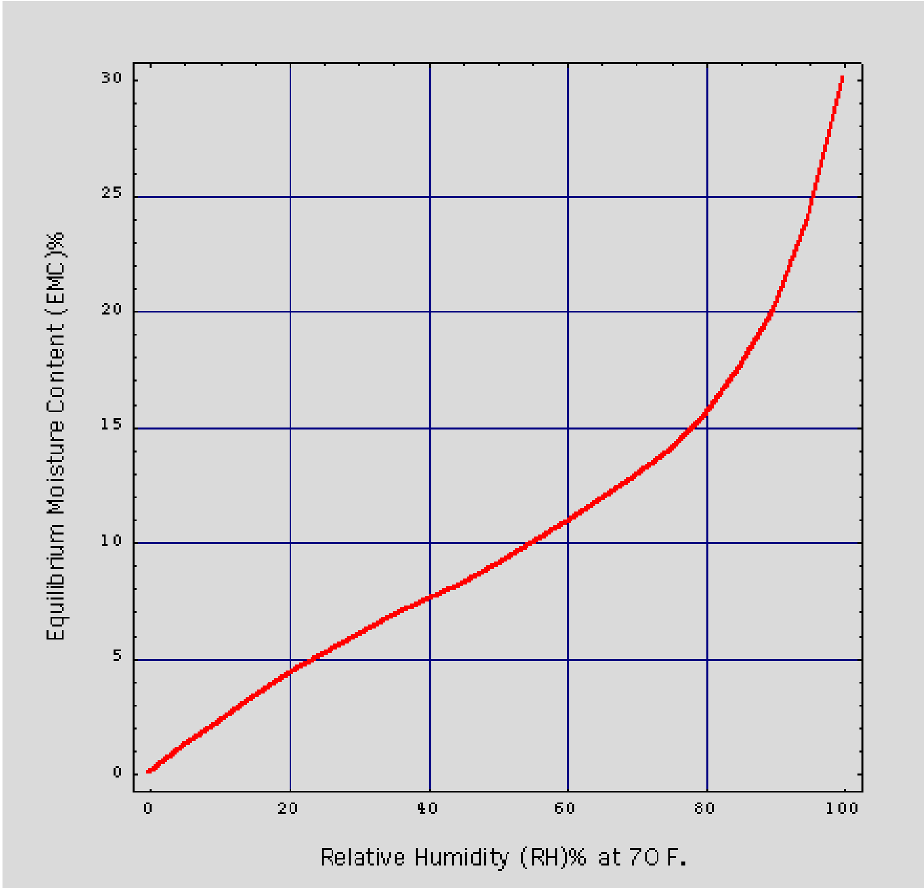
The goal isn't a specific moisture content, the goal is a uniform moisture content.

The whole concept of crack prevention is to apply a suitable vapor barrier to your flute. See the Oil Finish page for details.

The moisture content of unfinished wood kept indoors in most parts of the United States fluctuates seasonally (summer to winter) from 14% to about 4%. The moisture content of wood which has been well finished with lacquer or varnish oscillates in a much narrower range--7-9%.

It's a mistake to think that the moisture content of bamboo/wood is the same as the relative humidity of the air. Wood/bamboo **always** remains hygroscopic, which means that it responds to changes in atmospheric humidity. As the relative humidity drops, it loses bound water; as the relative humidity increases, wood/bamboo regains bound water. For a given RH level, a balance is eventually reached at which the wood/bamboo is no longer gaining or losing moisture. When this balance of moisture exchange is established, the amount of bound water contained in a piece of wood/bamboo is called the equilibrium moisture content of the wood.

At room temperature and a RH of 75% the equilibrium moisture content of wood/bamboo is about 14%. For 30% RH it's around 6% as seen in the graph below.



Science Fair Project

Let's do some experiments which might be suitable for the junior high science fair. Bamboo has openings (tubes) in its structure which run the entire length which the plant uses to transport water/sap. For the most part, sap is sugar water and the sugar is, for the most part, glucose (C6 H12 O6). As a point of interest, cellulose is glucose minus one water molecule (C6 H10 O5).

First Experiment: Demonstrate the tubes

Cut a couple pieces of bamboo 2” long.
Put 1/2” of water in one paper cup and 1/2” of alcohol in another.
Place bamboo sections in each cup.

Watch carefully, as the alcohol will make it to the top in a few seconds. The water will take minutes if at all.
Why? Water is more viscous than alcohol, but more importantly, the albumen in the cells hydrate and swell, closing the tubes.
Albumen is the clear stuff in eggs. And it can be hardened by heat, as in frying an egg. Albumen is present in almost all biological cells including bamboo. It is kind of a gel when hydrated (think egg again) and shrinks when dry.
Leave both samples in their cups for 30-60 minutes, then remove and examine the bottoms. The water sample swelled, the alcohol didn't.
The water sample started to soak in the ‘bark’ layer, the alcohol didn't—and never will no matter how long you leave it.
The top of the alcohol sample wetted almost immediately and the water sample didn't and probably didn't even after an hour.

Second Experiment: Evaluate water/alcohol as filling agents

Cut a couple pieces of bamboo 1/2” long. With an exacto knife or chisel, split one side of the bamboo. The sample

should spring open, leaving a gap in the bamboo. **The size of the gap tells you the degree of tension the bamboo was under just before you split it.** So, one can saw a small sample off the end of a culm, split it and have an immediate general indication of the tension the culm is experiencing, thus the crackability of the culm.
Put 3/4" of water in one paper cup and 3/4" of alcohol in another.
Place bamboo sections in each cup.

For bonus points, notice what percentage of the bamboo is below the water's surface when you first place it in the cup. This percentage is the bamboo's specific gravity. The specific gravity of maple is 0.54, oak 0.66, walnut 0.55, hickory 0.74. Getting the picture? Contrary to ordinary intuition, bamboo is a very dense material compared to woods. Place the sample in the upright position to get a good reading.

By watching the gaps of our samples we have a very good, real time indicator of what's going on in the wood. The gap of the water sample will expand for maybe 30-60 minutes and then begin to close. In a few hours it'll be closed. The gap in the alcohol sample will do very little and the gap won't close.
Should you want you can repeat this gap experiment with different solutions (acetone, mineral spirits, oil, etc.) they'll be about the same as alcohol.
The conclusion is that water is filling cells that other solutions don't and that as long as a gap remains the potential for cracking remains.
Now take the samples out of their solutions and watch the gaps during their drying cycles. This single experiment conveys a tremendous amount of information about cracking in general, the potential of any particular piece of bamboo to crack during service and the cellular structure of bamboo.

What's needed is some treatment of bamboo where the gap closes and remains closed. Once that's achieved, the bamboo will have no (zero, nada) propensity to crack.

Bamboo Flute Crack Meter

This gap method (as described above) is very instructive, but further, it can serve as an aid in keeping your flute healthy.

If your flute maker were to cut a small sample from the top of the culm of that root-end shak you paid thousands for and did the same (any treatments, lacquer, humid box, oiling, etc.) to it as the flute, you would have a real time indicator of the stresses in the flute. That the gap sample came from the same bamboo as your flute would guarantee identical bamboo morphologies—thus identical responses to treatments, moisture, humidity, etc. **The idea would be to keep the Crack Meter with the flute, thus it would experience and reflect the same conditions and indicate the same stresses.**

However, this isn't likely to happen as your flute maker doesn't want you to know the stress your flute is experiencing. But you can make your own crack meter and although it isn't from the same bamboo as your flute, it'll reflect ongoing humidity conditions--a glance at the width of the crack will let you know what's going on and the stresses your flutes are currently experiencing. **Wide gap indicates high cracking stresses, narrow gap lower stresses.**

Maybe it's never dawned on you but bamboo flutes are experiencing stress their entire lives. Some days are worse than others but the stress to crack is unremitting. Will your flute crack? A Crack Meter is probably your best indicator.

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Shaku Design	Oiling Bamboo

Updated 1/15/04

What oil to use on your shak? It's a perennial question.

But first, a more important question, why oil your flute at all? There is a mistaken idea that oil prevents a bamboo flute from cracking and it may but only indirectly. **Oiling a flute creates a barrier layer which slows the absorption and/or loss of moisture.** To be clear, what we're talking about here is a **vapor barrier**. What we're concerned with is water in vapor rather than liquid form.

Bamboo varies greatly in 'crackability' depending on growing conditions, time of harvest, soil nutrients and probably a host of other factors. Which is to say, bamboo varies greatly in it's dependency on **balance of internal moisture** to retain it's structure. So it's hard to know if your flute will crack until it does. A proper oil coat serves as a barrier to vapor transmission. Also it reveals and heightens the beauty of the wood, along with protecting it from stains, bumps, etc. A good oil finish makes your flute shine and has a wonderful sensual feel.

Daubing on some olive oil when your flute looks dry is probably a bad

practice. As you'll see below, olive oil is a poor barrier oil and oil in general doesn't replace moisture. It's a mistake to mentally equate moisture and oil. As far as oil and moisture go, oil is like a plastic raincoat--something to stop (slow?) the transmission of vapor.

A number of vegetable oils have the property of drying to form tough, adhesive films either by themselves or when assisted by the action of added ingredients (catalysts). These oils do not "dry up" in the ordinary sense of the evaporation of a volatile ingredient, but they dry by oxidation or absorption of oxygen from the air. The drying process is accompanied by a series of other complex chemical reactions, and the dried oil film is a new substance which differs in physical and chemical properties from the original liquid oil; it is a dry, solid material which cannot be brought back to its original state by any means.

The drying properties of most oils are due to the presence of glycerides of linoleic and linolenic acids, which have the property of combining spontaneously with atmospheric oxygen to start a chain of reactions which ends in the conversion of the oil to the tough, durable, insoluble, waterproof, plastic material know as linoxyn.

Oils:

The word 'dry' as applied to vegetable oils is a euphemism for hardening and oils differ in their ability to dry. In the table below oils are listed with their Iodine Value which is a chemical indication of hardening ability. Non-drying oils never harden satisfactorily and will remain forever soft and gummy.

Drying Oils	Semi-Drying Oils	Non-Drying Oils
Linseed --179	Corn -- 123	Grape Seed --100
Tung --168	Cotton Seed --106	Apricot --100
Walnut -- 145	Sesame -- 106	Almond -- 95

Safflower -- 141	Beechnut -- 104	Peanut -- 93
Poppy --135	--	Camellia -- 83
Soybean --130	--	Olive -- 81
Sunflower -- 129	--	Palm -- 54

For our purposes the top three oils are **linseed, tung and walnut**--in order of toughness, hardness, and reflectivity. Linseed is the shiniest of the three and is the primary oil used in artistic 'oil' paints and painting. It is the preferred oil in respect to art durability, luminance, and archival quality. Tung oil is used mostly as a wood and furniture finish. Our current home has soft pine flooring finished with tung oil which has held up admirably well over many years. Walnut oil is used in wood finishing and consumed as a salad oil. Wood finishing oils are usually sold with added catalysts (or as partially polymerized) which speed drying time.

Non-catalyzed oils: It takes some searching to find linseed in a non-catalyzed form. Tung oil is readily available in both forms and walnut oil is usually only available as non-catalyzed. Although all three oils are edible, walnut oil is the only one available in the oil section of your grocery store. Basically, the only difference between catalyzed and non-catalyzed oils is the time it takes for the oil to dry, harden and cure. Catalyzed oils dry in **10-24 hours**, non-catalyzed will take **75-90 days**. That walnut oil from Hain you may have been applying to your flute takes **three months to mature,** during which time oils go through sticky to gummy to semi-hard to hard phases. Should you have any doubt about the drying time of non-catalyzed oils pour out a thin layer into a lid (or other thin flat container) and observe the hardening process over its course.

These three oils can be mixed in any proportions you wish, both by type and catalyzation. If you're mixing catalyzed and non-catalyzed you may need to do some tests to determine drying time. The basic chemistry of all three oils is, for all practical purposes, identical.

Non-catalyzed oils **need light in order to fully polymerize**. Flutes oiled and then stored away will never mature. The ideal conditions are room temperature, normal humidity and substantial (but indirect) light--for three months. The presence of normal or diffused daylight is necessary for the correct drying of an oil, but any prolonged exposure to the direct rays of the sun is harmful, leading to cracking of the oil coat by reason of too rapid or violent drying action.

Applying oils with an Iodine Value of under 140 is an exercise in futility because the oil won't harden sufficiently to create a vapor barrier. Skin oil (sebum), for example, never achieves hardness. And without adequate hardness the oil won't be reflective enough to create a warm beautiful finish. Stick with the top three oils.

You know the old warning about being careful with oily rags--that they can spontaneously combust if stuffed in a drawer? Well, here's the reason: when drying oils dry (harden), the reaction is exothermic--it gives off heat as oxygen is being consumed. And with greater surface area in the rag and so on the stuff can ignite. Now you know--it's about oil polymerizing.

Now for the bad news!

Of the three oils mentioned, only tung oil comes anywhere close to creating a suitable vapor barrier and only after several coats. Even then it is substandard compared to other finishes. Linseed and walnut oils are both inferior when it comes to creating a vapor barrier--to the point of being essentially nonexistent. Both linseed and walnut oils will dry, but pass vapor easily. Compared to a varnish (alkyd, phenolic, or polyurethane) **oil finishes aren't even in the running as far as providing a suitable vapor barrier!**

So the question again: **Why are you oiling your flute?** For appearance or as a vapor barrier? Tung oil does admirably well for appearance and will provide some protection as far as vapor transfer. A good varnish will serve both purposes.

Buying new Shakuhachi

You should probably insist on a proper tung oil finish. Varnish is even better.

Getting a flute which was soaked in salad oil just guarantees problems latter. Even if you live in a high humidity locale such that dryness isn't a problem, your flute's sheen will diminish--it'll look dull and lifeless. And you'll start wiping various stuff on it and ... Well, you get the picture. A properly applied tung oil finish will remain hard, glowing and protective for years and is easily repaired in case of scratches, etc. Garret Wade is one of the best as far as quality and selection of different mix ratios is concerned. Two of these formulations were used on our floors and they've remained waterproof and held up to foot traffic for many years. Besides, drying tung oil has a wonderful smell!

Refinishing old Shakuhachi

OK, you were walking by the pawn shop and spotted a shak in the window. Went in and played it. Wow! And for $200--spectacular! But the thing is dirty, gummy and looks like an unloved stick. Now what? First you're going to clean it. Use mineral spirts and steel wool. Then decide whether you want a tung oil finish or a more substantial vapor barrier in the form of a varnish. If you're serious about your flutes get *Understanding Wood Finishes* by Bob Flexner. If you're going to use tung oil as your vapor barrier apply several coats. **The thickness of film has a direct relationship to vapor impermeability--whether it be tung oil or varnish.**

That stuff you just can't resist wiping on from time to time

I know, you love your flute and want to care for it and polish it. So what 'oil' are you going to use? Get some polymerized tung oil. When you apply, wipe on a coating. Let set for 10-20 minutes, remove all you can get off with a cloth, turning frequently. Let dry for a full day--reapply if there are 'dry' places. Then polish... and polish and polish with a soft cloth. Done right your flute won't need any new stuff wiped on it for a few years. But if you like the ritual then do it as often as you like--remembering to remove all the wet oil you can get off so as to prevent a buildup. What most people mistake as a DRY flute is just a DULL flute. It usually isn't dry (as in lack of moisture), it's just that the finish isn't hard and shiny. And using salad oils guarantees at some point in the future your flute will look dry and dull--keep salad oils in your salads!

Basically, if you feel the urge to apply oil to your flute more than once every few years, you're using the wrong oil and/or applying it incorrectly. A good oil finish, properly applied should serve well for a dozen years. So what's important here is to quit 'oiling' and to apply a proper oil finish.

However, if you're serious about the care of your flutes, apply a good varnish and all your problems will go away.

French Fried

For the adventurous, there's an intriguing wood treatment which bypasses most of the traditional bamboo drying/treatment processes and that's to french-fry the green culm in hot non-catalyzed tung oil. Cut the culm and drill out the nodes. Heat a tube of oil to about 350 F. Introduce the green culm. When all boiling and other activity ceases cut the heat and allow the oil to cool with the culm submerged.

Here's what happens: All moisture is expelled as it's turned into steam and escapes as bubbles. All lignin in the wood is hardened as the oil temperature is above its hardening point. All the surface waxes will be melted and removed. During the cool-down period any air which was greatly expanded at 350 F. contracts and atmospheric pressure drives the oil into the wood. Wipe all excess oil from your culm and submit to the standard 3 month drying period.

The result will be bamboo which has had it's starches and sugars stabilized, all moisture removed and be thoroughly impregnated with hardened linoxyn. The wood will be markedly hardened and strengthened--being waterproof, dent proof, etc. The modulus of elasticity will drop considerably and the material will become even more rigid and 'musical'. The major component of a Stradivarius violin is the treated wood of the top plate. It's acoustical properties are what we recognize as exceptional sound. Once the culm has cured, craft a flute in your usual manner.

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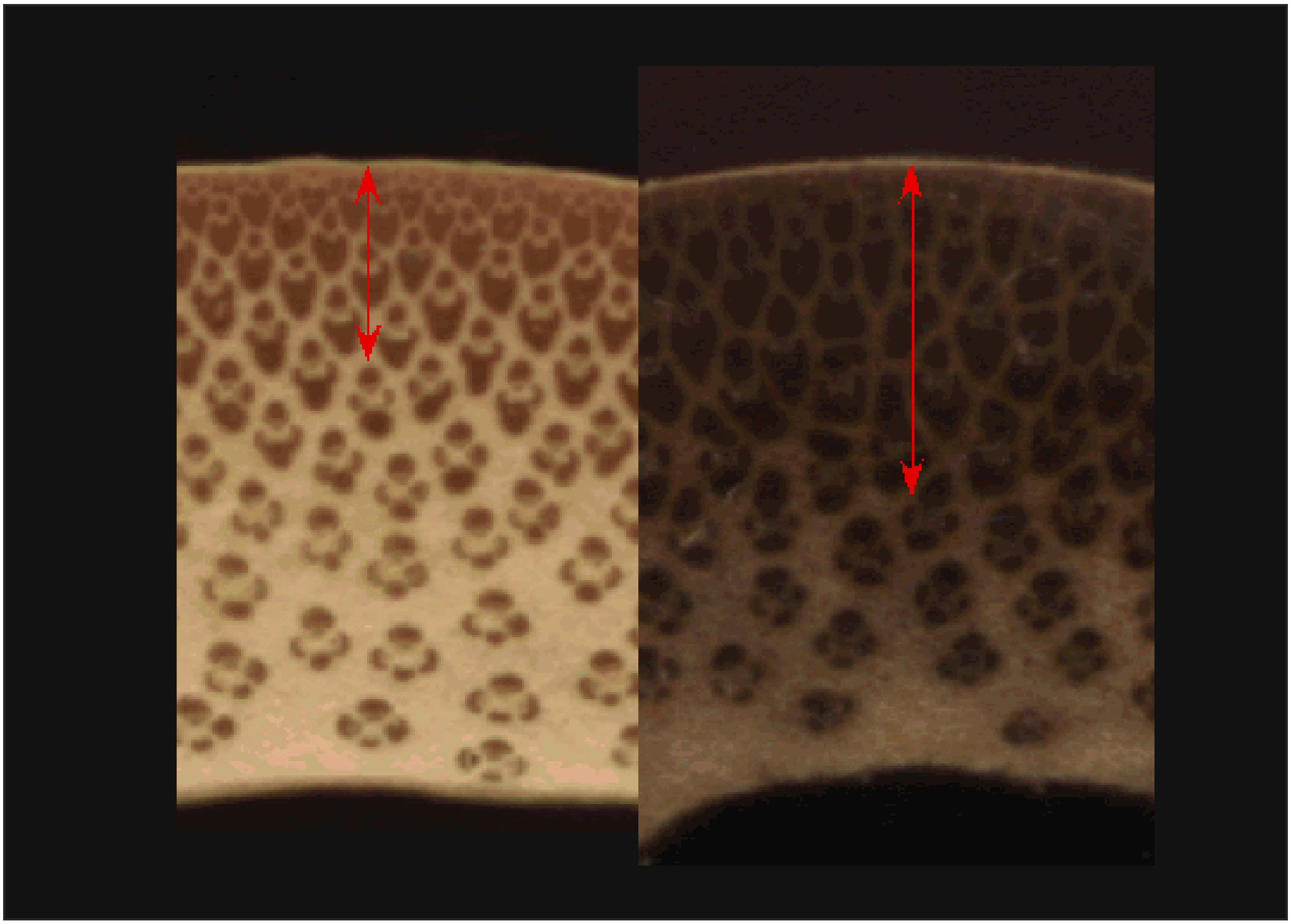
Shaku Design	The Structure of Bamboo

Updated 1/15/04

The growth structure of bamboo is entirely different than that presented by trees. The coarse, open cell structure so characteristic of the various woods is totally absent. In its place are found bundles of microscopic fibers laid parallel to each other, much like the strands within the sheath of a bridge cable. The spaces between adjacent bundles or cords of the bamboo are filled with lignin, a thermoplastic resin. Toward the outer surface of the hollow shell the number of these fibrous strands increases rapidly. Just below the outer protective enamel, bamboo is composed almost entirely of these cellulose fibers. Thus, considered from the outermost surface inwardly, the fiber structure, density, and strength of bamboo vary enormously.

There is no known method of infallibly appraising bamboo. Two factors, however, are readily apparent: (1) weight (density), and (2) appearance of the end grain. In viewing the end grain, notice in particular the character of grain and fiber structure at the outside edge, just under the enamel or cuticle. In most cases this is an exceptionally dense, close-grained substance. Taking note that the cut end does not occur in the immediate vicinity of a node, this dark amber-colored layer should extend, with slight diminution in density, inwardly at least one-third or more of the total wall thickness. Farther is better. If it is at all possible, examine a number of culms in order to gain a good degree of perspective. It is far simpler to isolate a single excellent specimen from a number of fair ones, than to appraise a single culm without reference to others.



The graphic above is two samples of end grain structure. The darker areas are the 'fibers' and the lighter areas comprise the matrix--primarily lignin. Notice the difference in distance, from the outer wall inward, measured to the point where the fibers begin breaking up into four segments. Thus the sample on the right is the **stronger, denser, harder piece of bamboo**. One can see these fibers exposed on the edge-cut of a shakuhachi and make a cursory assessment of the bamboo. It's a little harder to make an assessment on a slant cut rather than a cross-section, but as a general rule, one wants more of the dark brown fibers and less of the tan lignin.

Contrary to common intuition, bamboo is a very dense wood. It's density runs 2 to 3 times that of pine and usually is more dense than oak. On density alone bamboo would be listed well up in the hardwoods--above teak, mahogany, maple, walnut, oak and ash. Some bamboo will exceed ebony and lignumvitae in density. In general, bamboo has about the same density as hickory. Density is the single most important indicator of strength in wood and may, therefore, predict such characteristics as hardness, ease of machining, and resistance to penetration. Dense woods generally shrink and swell more and usually present greater problems in drying.

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Shaku Design	Kumihimo

Updated 1/20/05

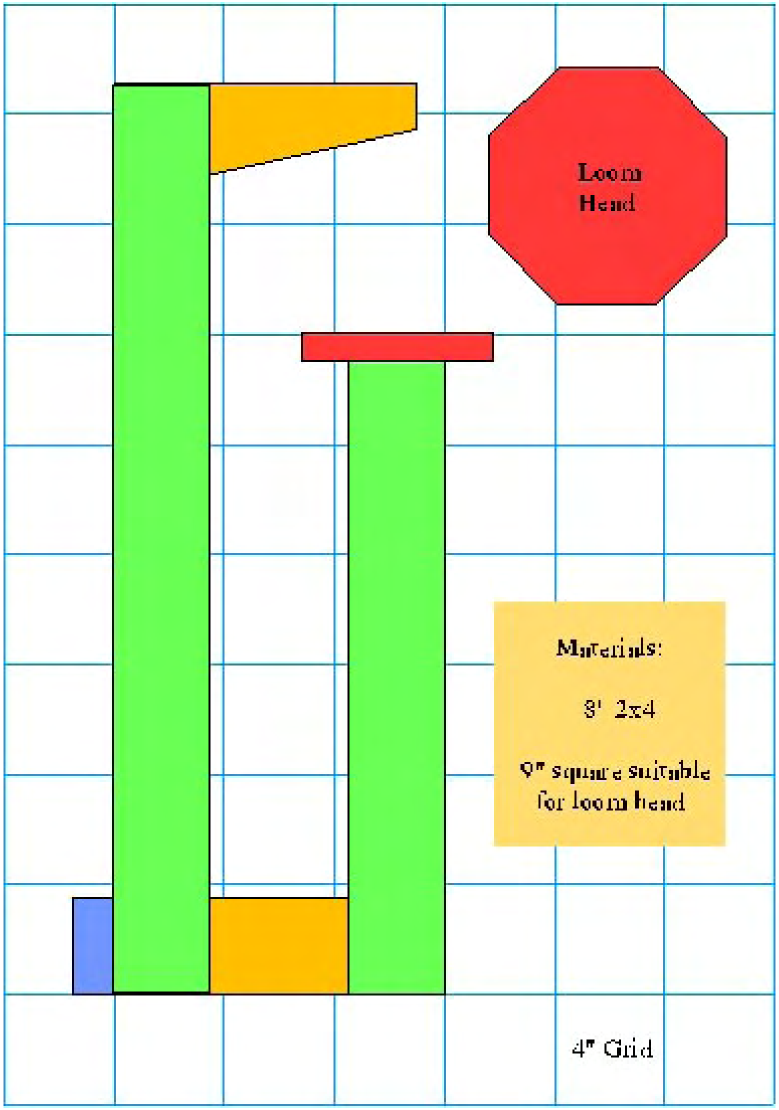
Kumihimo is the ancient art of Japanese braid making. Samurai armor required yards of exquisitely dyed and braided hand-made cord to hold it together. After the Samurai period the craft of kumihimo went into decline, but it's returning now. Flat braid, round, twisted, honeycomb, hollow, square--kumihimo is only limited by your imagination. The craft requires only the simplest of equipment and looms can be constructed in a variety of configurations.

Want to weave cords and braids for your flutes and flute bags? Kumihimo is the way to go.

Beginner's Guide to Braiding is a good instruction manual which includes the design for a very simple loom. This book alone will have you turning out beautiful braid and cord in no time at all.

The World of Japanese Kumihimo Braiding delves more into the aesthetic and historical aspects of kumihimo.

Below is the design for a simple loom we've developed. Bobbins are made of 3/8" bolts 3 1/2" long and 1/2" nuts. Wrap the thread on the bolts and then once around the nut. Herrshners is a good source for thread--look at crochet threads.


Loom Head
Materials:
8' 2x4
9" square suitable for loom head
4" Grid

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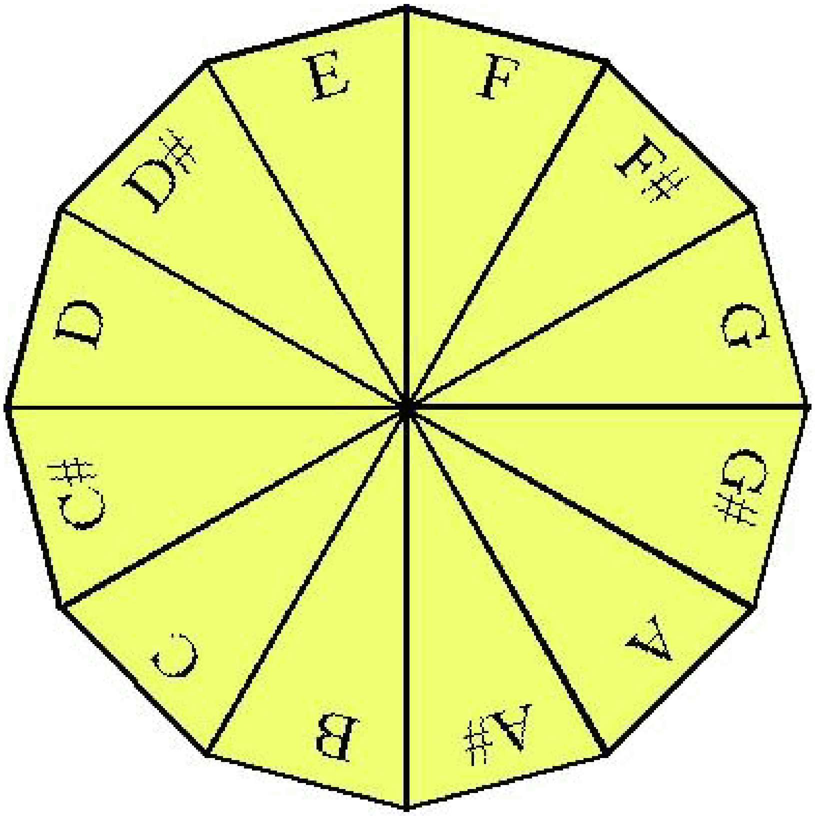
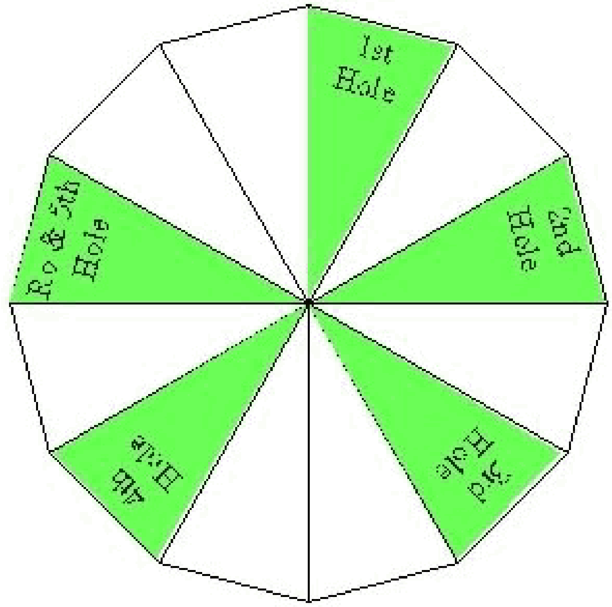
Shaku Design	Pentatonic Interval Gauge

Updated 5/8/06

The musical scale employed by the shakuhachi is pentatonic, which means it steps through an octave in five jumps. Three notes, then two, and two again, then three and finally two--returning to the key you started in but an octave higher. Pretty simple really, but kind of a pain if you have to write out the notes and tick them off. So, below is a interval gauge (set to the pentatonic scale) which will allow you to instantly see all the notes your shak will play. What notes will a bass F shakuhachi play? Just dial them up. (For a somewhat relevant page)

Move the graphic to your desktop to recover as a jpeg
then Print out, Cut out, Place little on big and Pin centers.





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Shaku Design	Equivalent Timbre

Shaku Design

Equivalent Timbre

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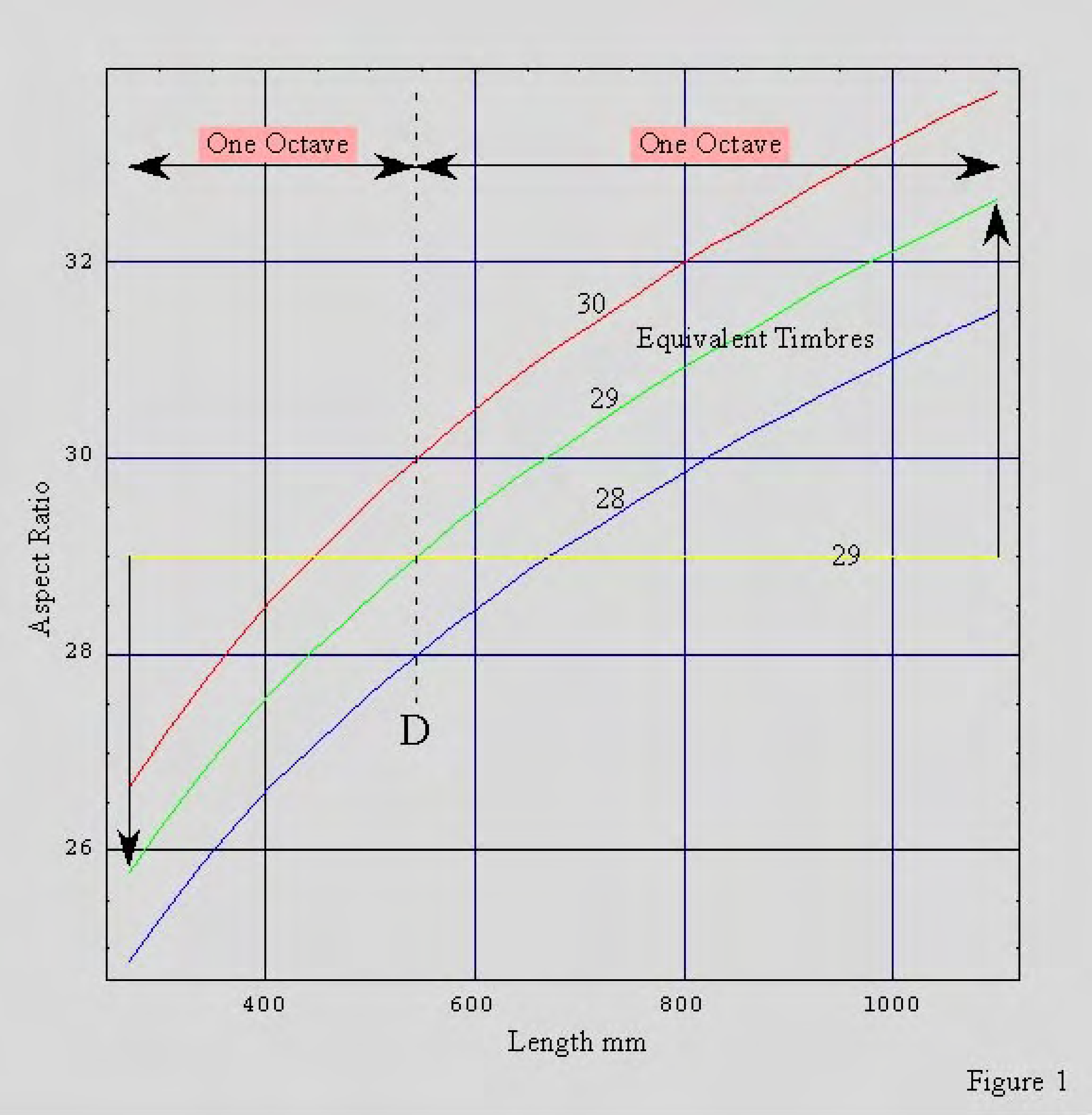
Updated 7/31/06

In a previous page we discussed the fact that bore and length don't scale at the same rate. What this means is that Aspect Ratio doesn't have a whole lot of meaning other than being the ratio of length/bore. By itself, Aspect Ratio won't tell you how your flute will sound. But we can define something called **Equivalent Timbre** which will. The idea is this: let's adopt the D shakuhachi as our standard and figure out what the AR is for flutes of other lengths--such that they will have the same timbre as our D standard. A little math is involved, but the result is pretty straight forward, EAR is Equivalent Aspect Ratio.

$$\text{EAR} = \frac{2.858\ \text{Length}^{5/6}}{\text{Bore}} \qquad \text{Bore} = \frac{2.858\ \text{Length}^{5/6}}{\text{EAR}}$$

Measurements in millimeters

Figure 1 (below) contains most of the information--spend some time and study it to get a grasp of the notion of Equivalent Timbre.



In Figure 1 the yellow and green lines intersect at our D standard--an AR of 29. But one octave lower, the AR needs to be below 26 to have a timbre equivalent to the D Standard. An octave above D the AR rises over 32. The further from D (either way), the more the AR needs to be adjusted in order to have a timbre and playability similar to our D Standard. **Flutes should get skinnier as they grow longer and fatter as they shorten.** Nothing is straightforward with the shakuhachi--that's part of the enjoyment.

Everything on this page is computed assuming a straight, cylindrical bore. Should you want to estimate your flute's Aspect Ratio (thus it's Equivalent Timbre) see other pages for the volume method and the length method. Once your flute's AR is known, it's equivalent timbre can be estimated from the graph above.

The following two figures (below) graph bore and length relationships required to achieve suitable Equivalent Timbres.

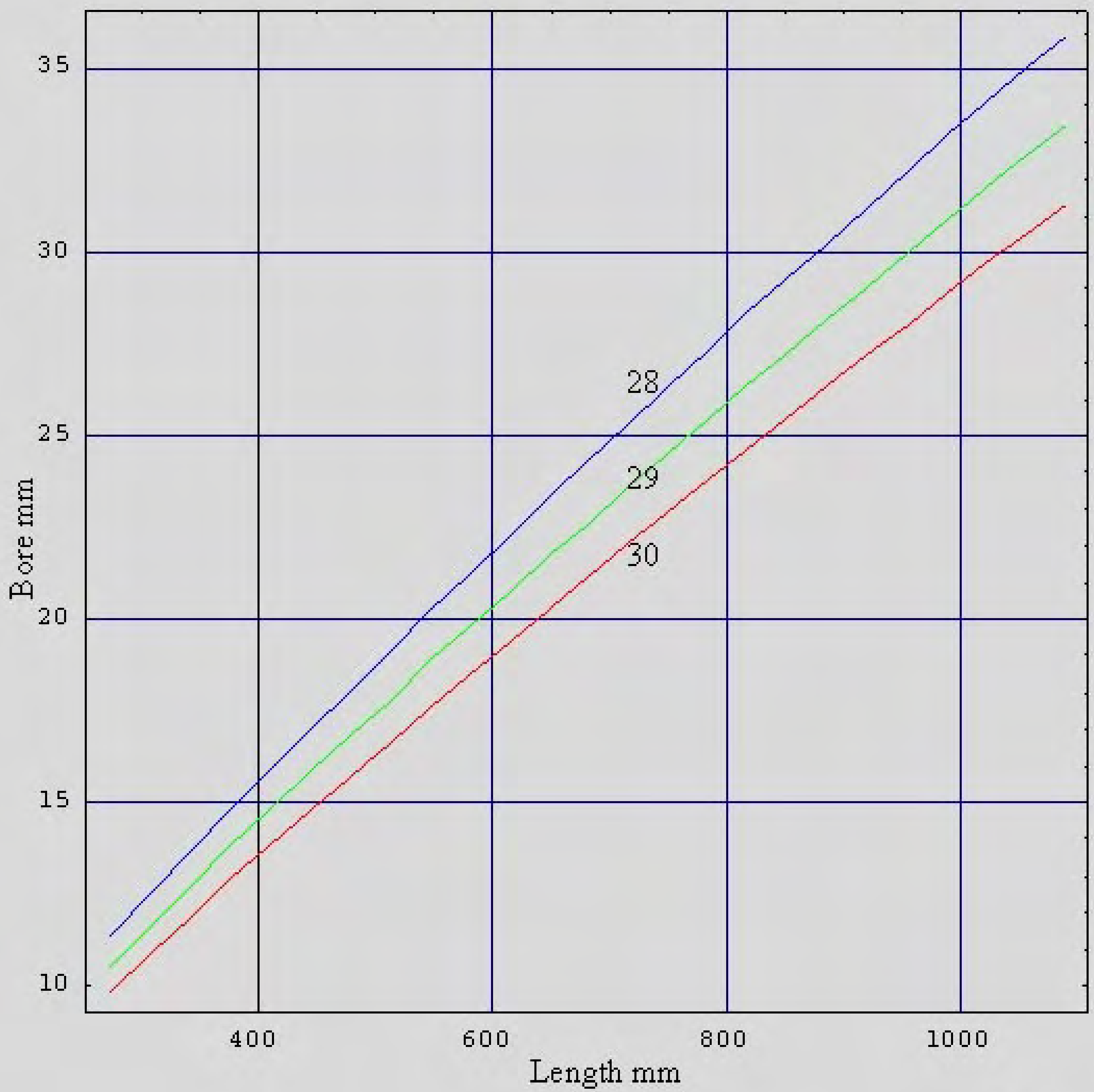
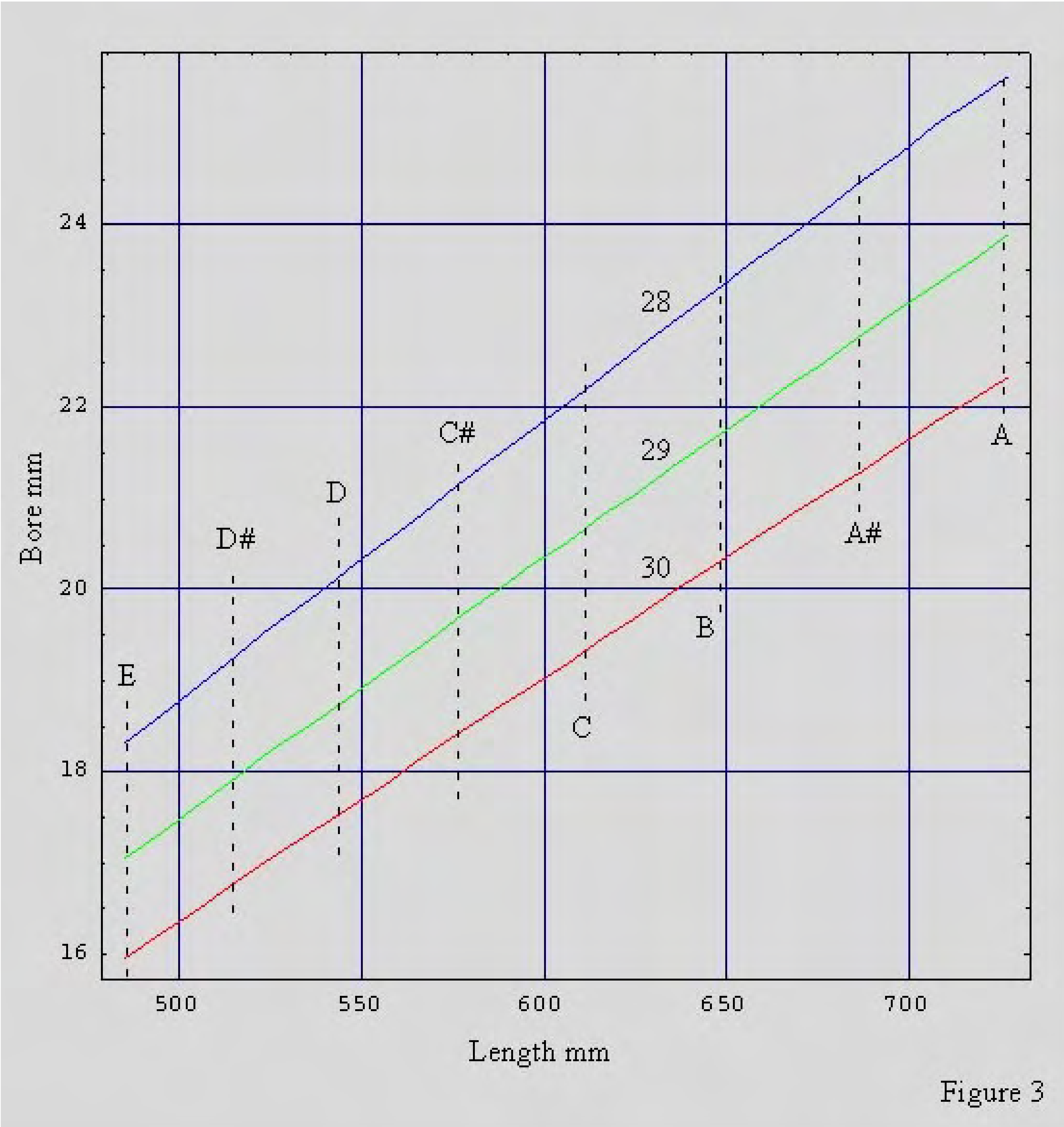


Figure 2



The EAR of end-blown flutes is the biggest determinant of the flute's ability to play second (and higher) octaves. So the timbre of a shakuhachi is largely determined by a playing balance between first and higher octaves. For the most part, this is restricted to first and second octave. These two octaves are fairly balanced with an EAR of 29-30 and hence the sound (timbre) of a balanced shakuhachi is about like that of any other balanced shak. An EAR of much over 30 makes the first octave fugitive. Much under 29 and the second octave becomes fugitive. For a page on big bore, low EAR flutes.

But suppose you wanted a shak which optimized the timbre of the first octave? Suppose you wanted the ultimate shak timbre? Medieval pipe organ makers settled on an EAR for standard midrange pipes of about 26.6. Since organ pipes only play one octave, the makers could concentrate on what they considered the ultimate pipe organ sound. In any event, the ultimate shak timbre will require a lower EAR than the balanced one of 29-30. Somewhere around 26 might be a good place to start your search. Essentially, you'd have a one octave flute, but what a great octave it will be. With this flute, second octave will be a constant effort and the second octave timbre will be thin whenever you achieve it.

Bore and Length Formulas

Hole Sizes

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Shaku Design	Magic Flute Formulas

Updated 1/9/07

We've finally derived formulas which incorporate much of the foregoing pages within simple mathematical expressions. When the energy losses in a flute (open end rate, wall losses, boundary layer, etc.) are balanced, a single formula appears. It's unique, in that, it strictly defines the length/bore/hole parameters over a huge range and at the same time contains an inherent equivalent timbre. Use of the formula guarantees your shakuhachi will operate with fundamental acoustical balance--a subtle, yet critical characteristic. Further, it's sound will be of the timbre distinctive to optimal bore geometry--at any length and in any key. **For metric measurements only.**

$$\text{Length} = 17\,\text{Bore}^{\frac{6}{5}} \qquad \text{Bore} = \left(\frac{\text{Length}}{17}\right)^{\frac{5}{6}}$$

$$\text{Hole} = \left(\frac{\text{Length}}{17}\right)^{\frac{2}{3}} \qquad \text{Hole} = \text{Bore}^{\frac{4}{5}}$$

General, all purpose metric (mm) equation:

Length = (186500/ Hz) - 5 Bore

You can do these calculations at Google. Just put it into the search box and click search.

Example: Enter **(545/17)^(5/6)** into the search box, click and you'll get the optimal bore diameter for a 1.8 shakuhachi in millimeters. (545 / 17)^(5 / 6) = 17.9868999

For more Google calculator instructions.

Note Range:

How many octaves should/could your flute play? Aspect Ratio (bore length divided by bore diameter) is the greatest determinate of note range.

AR / 12 = Range (in octaves)

So, a bore with an AR of 24 should play two octaves, an AR of 30 will support 2.5 octaves and so on. Consider this formula an approximation.

Here's another set of formulas--from the Dark Side.

These are approximations which will produce flutes a few percent darker (timbre-wise) than the equations above.

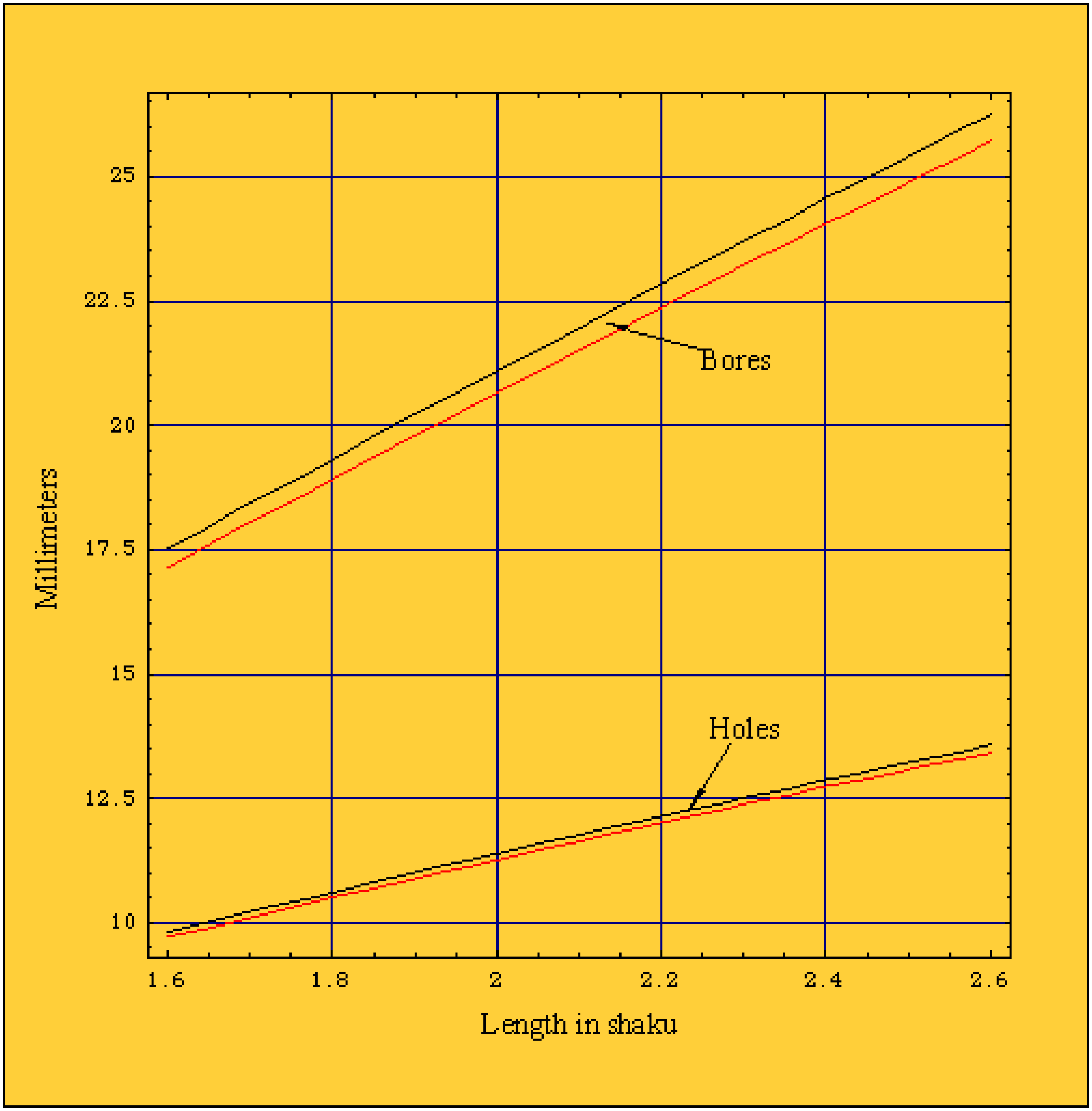
Make all measurements in millimeters.

$$\text{Bore} = \frac{\text{Length}^{5/6}}{\pi^2}$$

$$\text{Hole} = \frac{\text{Length}^{2/3}}{2\,\pi}$$

$$\text{Length} = \text{Bore}^{6/5}\,\pi^{12/5}$$

Comparison of the **'Light'** and '**Dark**' formulas



See The Synthesis for a final flute design.

Hole Size

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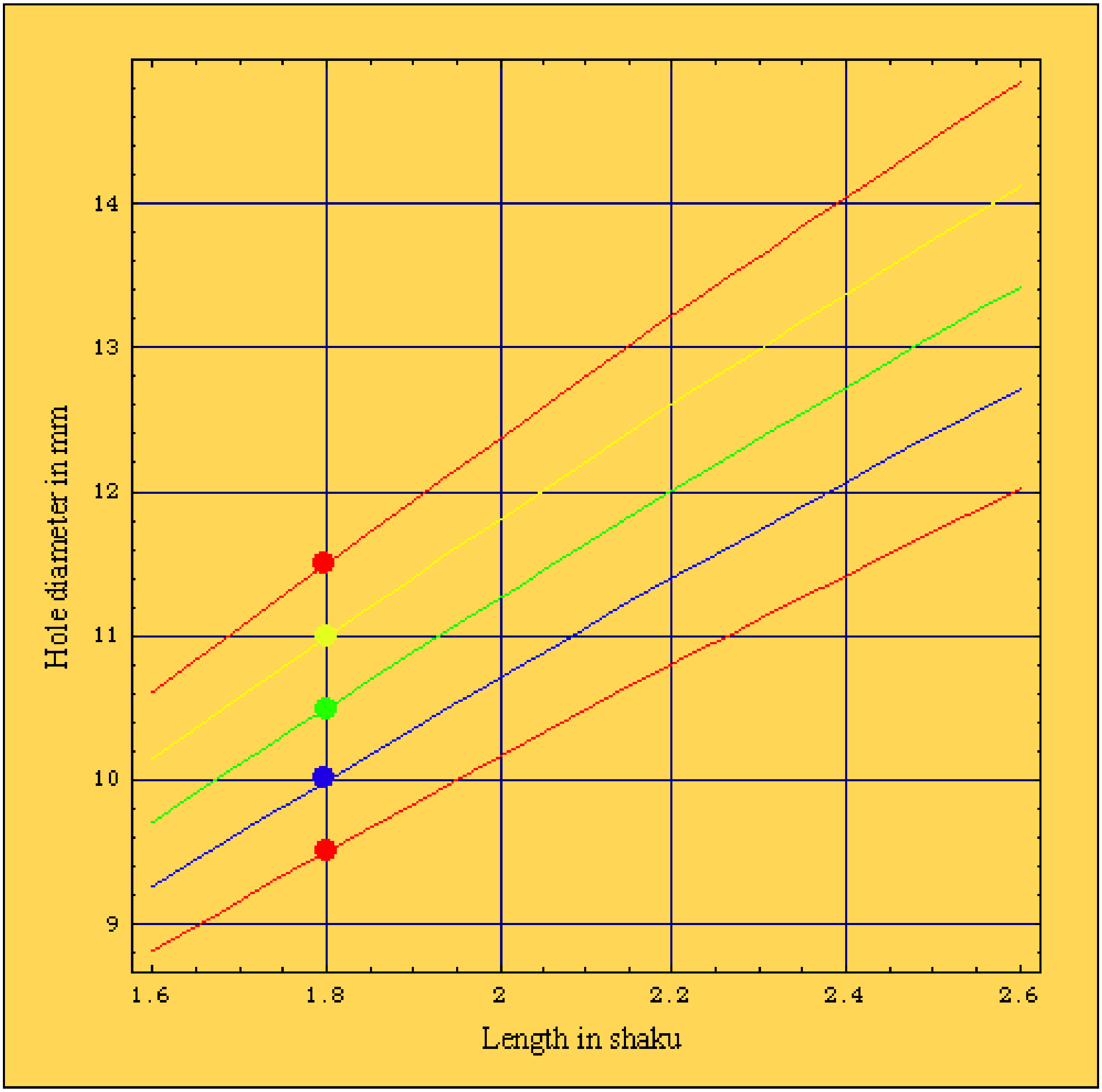
Updated 1/15/04

The subject of Equivalent Timbre isn't complete without an examination of the acoustical effects of hole size. Timbre is primarily dependent on two things: aspect ratio and hole size--the ratio of flute length divided by bore and the ratio of hole size to bore diameter. Classically, the standard 1.8 shak has 10mm holes, however in practice they are often larger. Bore diameter scales in a non-linear fashion with changes in flute length and so does hole size--in a doubly non-linear way. For superior flutes hole size should be balanced with bore diameter which, in turn, can be balanced with length by using the proper formulas. By employing the formulas and the following graph you can create flutes in which length, bore and hole size are all in balance. Much of the variation among shakuhachi exists because each of these factors can vary independently. For every flute length there exists a configuration where all factors are in balance.You now have a method for getting all the ducks in a row.



The graphic above plots hole size equivalent to hole timbres of the 1.8 shakuhachi. Examples are given in 1/2 millimeter steps from 9.5 to 11.5 mm. Each line depicts equivalent hole timbre across a range of flute lengths. For example, a 10mm hole size on a 1.8 (blue line) needs to increase to 12 mm on a 2.4 flute to maintain the same hole timbre and balance. With longer flutes the acoustical properties of holes run up against the limits of finger size and it shouldn't be surprising that these flutes are often characterized as mellow and mysterious as, generally, their holes are undersized.

For the sake of this discussion consider a 10.5 mm hole on a 1.8 to be optimal.

Increasing hole size to 11 or 11.5 mm will make the 1.8 flute sound louder, shriller, bright and brassy--the higher harmonics are accentuated . Decreasing hole size will sound mellow, quiet, and dark as fundamental harmonics are boosted. And, of course, changing hole size will move hole location along the barrel of your flute--smaller holes move toward the head of the flute and larger holes migrate toward the foot.

To use the graph, find the place on the graph which represents a favorite flute. The colored lines will automatically extend your hole timbre to different length flutes.

The point of this page is that using similarly sized holes across a range of flute lengths has substantial impact on timbre. To maintain similar timbre with different lengths, hole size needs to be matched to length--hence bore. Hole size doesn't change at the same rate as length, but the two are definitely related. Use of the proper formulas and this graph can aid significantly in designing and building flutes with chosen acoustical properties.

The formula for optimal hole size (listed on the Magic Flute Formulas page) produces a hole size of 10.507mm (green line in the graph above) for the 1.8 shakuhachi.

See The Synthesis for a final flute design.

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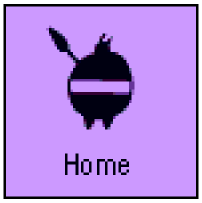
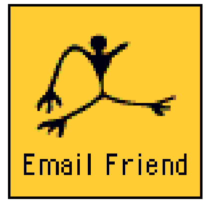
Shaku Design	Breathing





Updated 12/28/06

Within the North American shakuhachi community there's a persistent Urban Myth that PVC dust once inhaled will remain lodged in your lungs forever. This view contemplates the lungs as something like the collection bag on your vacuum cleaner. It takes about 5 seconds of consideration to realize this is total rubbish. Our lungs have a self-cleaning system, otherwise you wouldn't be reading this. A combination of lung cilia and mucus production continually clean your lungs--to the tune of several liters a day. Here’s a simplified explanation/demonstration.

Breathing is the process of moving air into and out of the lungs. Thinking of the chest cavity as a cylinder, one can increase its volume by one of three means:

1. Extending the diaphragmatic floor of the cylinder downward
2. Expanding the walls outward
3. Moving the top of the cylinder upward.

These three types of breathing are termed:

•Diaphragmatic
•Thoracic
•Clavicular

In the first your belly expands, the second your chest expands and the third raises your shoulders. Infants and small children use their diaphragms exclusively for breathing. Chest breathing cannot occur until considerably after birth, not until the bony chest matures. Diaphragmatic breathing fills the lower part of the lungs. Chest breathing fills the middle and upper portions. During normal activity clavicular breathing only comes into play when the body’s oxygen demands are very great or one is agitated.

Once the lungs are filled to their capacity, how are they emptied? What results in exhalation? Relaxation! Everyone has had the experience of sighing, or letting a deep breath out in a completely relaxed passive motion. **In normal breathing no muscles contract to push the air out.** It is as if the lungs themselves are pulling the diaphragm up and chest wall in. This is in fact, what happens. The lungs are elastic, and they shrink back to their original size once the forces which expanded them are released--much as a balloon shrinks back to its normal size once the end is untied. In forced exhalation, the stomach muscles contract to force the diaphragm upward as it relaxes.

To get this breathing thing down, think of an imaginary ball about the size of a coconut in your midsection. All you're doing when breathing diaphragmatically is moving this ball. If you need, place your hand on your stomach, pretending you have the ball in your hand, then press it in and up--then let it come down and out. Congratulations! You've just mastered a year of Prana yoga.

Usually when someone is asked to take a deep breath they will raise their shoulders slightly, indicating clavicular breathing which, paradoxically, is the shallowest form. To experience this take a deep breath now. If your shoulders don't rise slightly then take several breaths in very rapid secession and you'll notice your shoulders moving.

The three zones of breathing:

•Upper
•Middle
•Lower.

And there are natural sounds which coincide with these zones. Correctly pronounced, the mantra Om moves through the zones--that's it's purpose. AAAAUUUUMMMM. Another way to learn and appreciate this is by using distinct sounds. For our purposes we'll use the sounds of four different exclamations.

Ee as in fr**ee** --When one is very thrilled or frightened.
Ah or Aw --When one is surprised or startled.
Oo as in br**oo**m --When one is suitably impressed.
Oh --When one is engaged in acceptance.

The sound Ee is the highest (Clavicular breathing), Ah or Aw--mid-range (Thoracic breathing) and Oo and Oh --the bottom (Diaphragmatic breathing). With these three it is possible to make up a breathing-language which can have startling physiological effects. **There is a direct link between vowel sounds, breathing and physiological states--thus the whole subject of mantras.**

For example:

•Oo Aw (Homa) Moves from Lower to Mid breathing.
•Oo Ah Ee (Huame) Moves from Lower to Mid to Upper breathing.
•Ee Oh Ah (Eoma) Moves from Upper to Mid to Lower breathing.

These and any number of other breathing-language words (mantras) can be created and used to direct and modify breathing, thus physiological states. Adding a consonant (H, for example) to the beginning of words makes them smoother to remember and pronounce. As does the Mm or Nn sound at the end. The core of many mantra systems, for example, is Oo and Ah. However, pronouncing OoAh is a little clumsy and disjointed. Making it Hh Oo Nn Ah creates a flow and a memorable word--Huna. It could be Buna, Cuna, Buma, Cuma, etc. Saying (and/or thinking) the word HUNA moves one's physiology from lower to mid breathing. **Chanting Om (Ah Oo Mm) is to repeatedly invoke the sound equivalent of shifting from mid to lower breathing.** The warrior mantra (who-ahh, as heard in the Marines for example) shifts from lower to mid breathing.

Exercise 1:

Practice each breathing zone until you have them well differentiated. Use of the seed sounds will speed up this process. **Since the lungs are under both involuntary and voluntary control you have a way to consciously teach the non-conscious.** Get a good kinesthetic, auditory and visual sense of each type of breathing and your resultant physiology. Which zone someone uses while breathing (and/or the vowels they tend to emphasize) tells you what their emotional (physiological) state is.

Exercise 2:

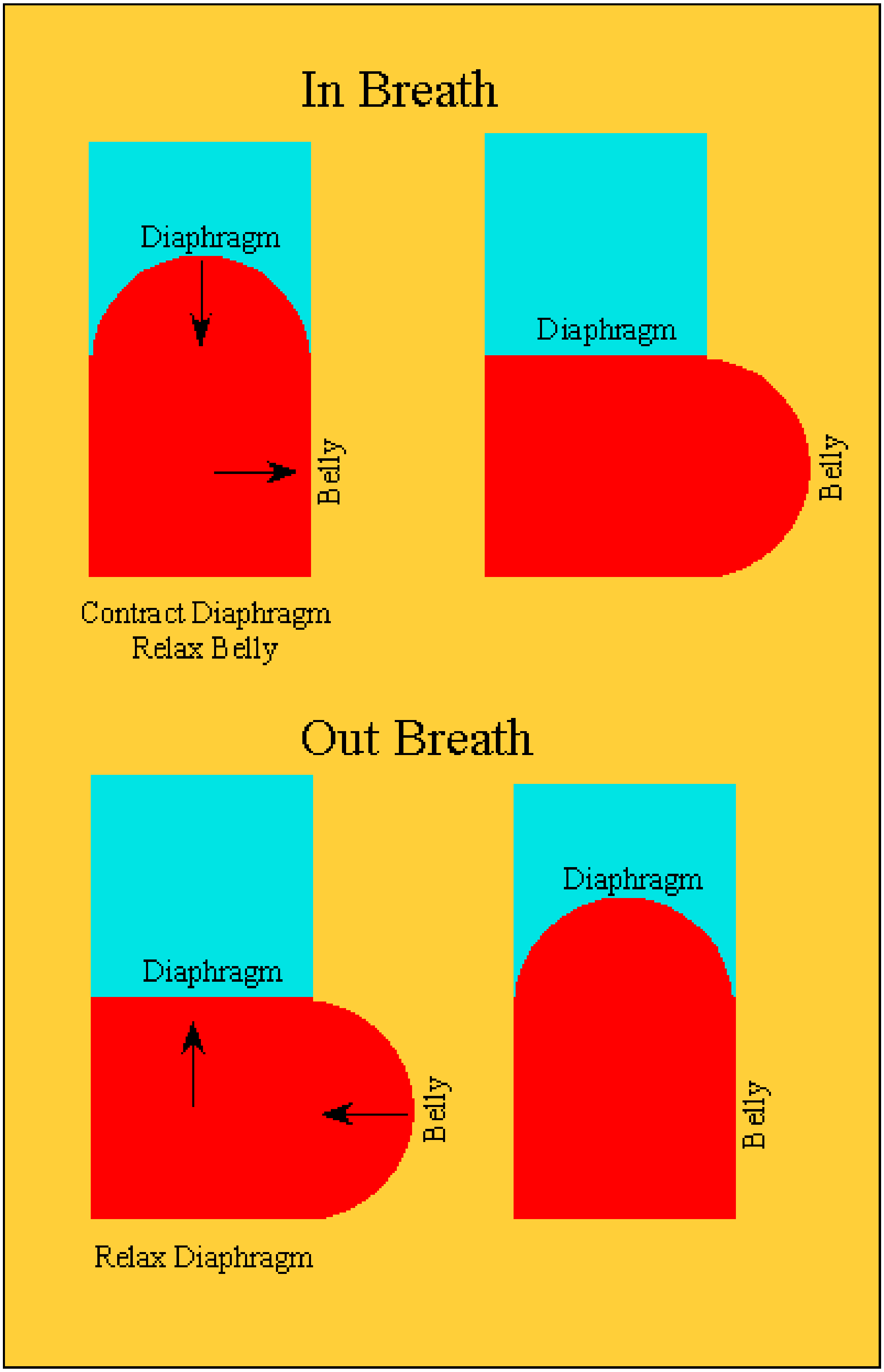
Develop a set of breathing-language words for your own use. They will serve as meta-anchors--directing your physiology in the direction you desire. When used quietly or sub-vocally your 'breath' words can automatically shift your breathing hence your physiology hence your mood and resoucefulness. You can now create your very own 'power' words!

Exercise 3: **FORTY BREATHS A DAY**

Inhale slowly for four beats, hold it for four beats, exhale for four beats, hold for four beats. If there is difficulty, start with three beats. Five beats for the Pro-exercise. One of the effects of this exercise is a reduction of your normal heart rate.

Now let's directly explore the subject of breathing with the intention of playing woodwinds. First off, most people's voluntary and involuntary breathing focusses on the abdominal muscles--that's the thing we've got to change. Most people's breathing focusses on the OUT breath instead of the IN breath. As noted earlier, by and large, the OUT breath takes care of itself. For the flute player, the whole trick to proper breathing centers entirely on the IN breath. It's all about the diaphragm (which is a muscle). So breathing is muscular--flute breathing is about switching from abdominal to diaphragm. Forget the abdominal muscles, they should remained relaxed during flute play. When people get tense one of the first muscle groups to tighten is the abdominal. Relax the belly!

So what's the deal with the diaphragm? As seen in the graphic below, diaphragmatic breathing is just about contracting and relaxing this single muscle. It's a muscle sheet which lies beneath and supports the lungs. In its relaxed state the diaphragm arches upward forming a semi-dome. Remember again, the OUT breath takes care of itself, naturally. It's the IN breath which requires attention. This is when the diaphragm constricts. It's length shortens and as a consequence the lungs fill. When the diaphragm constricts the volume of the lungs increases. It's counter-intuitive, but that's the way it works. In the schematic below, blue signifies lung cavity and red is intestinal cavity.



There are a couple of good ways to get in touch with your diaphragm and strengthen it. The first, is to lift weights. Remember that set of weights you got for your New Year's resolution, the one in the garage? Well, round up some of the flat weights (or something like them), lie flat on your back and pile up a stack on your belly. Now push them upward, as far as you can, full extension. A-one and a-two .... Now notice something and go over it until it sticks in your brain. You pushed the weights upward by taking an IN breath. **You pushed the weights upward by contracting your diaphragm. There's no other way to do it.** An IN breath pushed the weights upward. Even if you think you know how breathing works actually do this exercise, actually lie down and pump some iron on your belly. Doing this single exercise for less than a minute will clear up any misconception you have about breathing. If you want to strengthen your diaphragm then pump some belly iron on a daily basis. Keep increasing the load.

Let's be doubly clear. You lifted the weights by contracting your diaphragm and that muscle alone. Constricting your abdominals will interfer with lifting the weights. Go over it until it's really clear--the learning part of this exercise is kind of like learning to ride a bike, do it until you 'get' it.

The second exercise is a little stranger. Go to the hardware store and get 5-6 feet of clear, flexible tubing, somewhere around 1/4" ID. Place a bowl of water on the floor. With an IN breath draw water up the tubing as far as you can. You should be able to do at least 3 feet, call it a meter. Practice until you can draw water at least 4 feet (1.22m). This exercise is a very good way to measure the strength of your diaphragm. A standing column of water generates about 1/2 psi per foot, so 4 feet is equivilant to about 2 psi. Your diaphragm should have a rating of 2 psi (or higher) to handle the shakuhachi with ease. The strength training? Draw a column of water 4 feet or more, maybe 50 times a day. In a certain sense this is the perferred exercise: less equipment and measurable feetback.

Let's do a little math. 2 psi, that's two pounds per square inch. So a square of about 7.07 inches on your belly would be around 50 square inches, at 2 pounds each means you should be able to belly press 100 pounds without much difficulty. Or to make it simple, place a thick book on the floor, lie on it belly down and press yourself --same difference.

To play a shakahachi well you'll need to be able to breathe well. If you'll give as much attention to your breath as you do to your shak, things will improve rapidly. So, if you want to be a power breather you'll need to focus only on the IN breath and give your diaphragm some strength training. The diaphragm is a muscle like any other and will respond to resistance training.

The other part of flute breathing? Relax the belly--it'll do its thing naturally.

More:

Science of Breath, Swami Rama, Rudolph Ballentine M.D., Alan Hymes M.D.
For a clear explanation of 'spiritual' breathing read *Zen Training* by Katsuki Sekida--chapters four and five.

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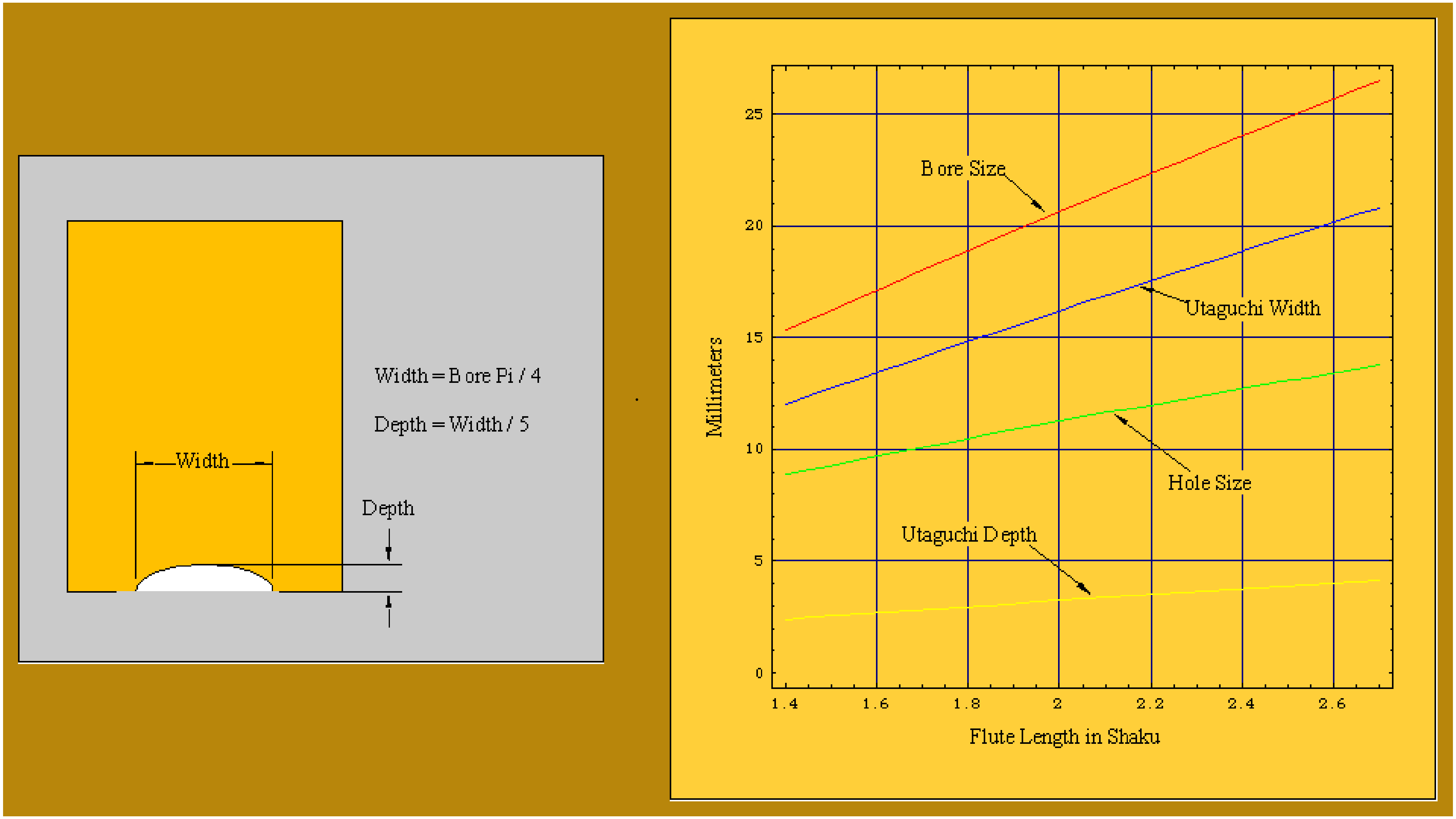
Shaku Design	The Utaguchi

Updated 5/9/06

It's advantageous to think of the utaguchi (the blowing edge) as a hole. Because while the shakuhachi is played, in fact, a hole is formed by the utaguchi on the flute and the players lips. And this hole, the Sixth Hole as it were, produces the soul of the shakuhachi. Why? Because the utaguchi hole is adjustable and during normal shakuhachi play the shape and area of the utaguchi hole is constantly varied. That's what meri-kari is--the most obvious sonic effects of changing the shape and size of the utaguchi hole. Make the hole smaller and the pitch drops, larger and the pitch rises. So again, as with many things shakuhachi the action is defined by what isn't there instead of what is. The emptiness rather than the object. So focus on what's beyond the utaguchi rather than the edge itself. The edge defines one half of a hole, your lips the other half. And the shape and size of that hole is vitally important to the sound quality of your shak. If the utaguchi isn't right, the rest of the flute is vastly under utilized.

While creating some Watazumi flutes (you know, those *big long* suckers) difficulties developed immediately while trying to get a good Ro. And they were traced to the utaguchi--the blowing edge. After some research, it was realized that proper utaguchi design requires the width to be about 1/4 of the circumference of the bore **average** and utaguchi depth should be about 1/5 of the width. For the size pipes (the Watazumi models) we were using, lips couldn't create an airstream wide enough for a proper utaguchi. So adjustments have to be made on extreme utaguchi widths, otherwise the graph below will suffice.



In general, the utaguchi hole's area is about two-thirds that of any other hole. And area is where the action's at. The utaguchi doesn't cleave the airstream so much as form one side of a very supple and adjustable hole. Sharpening the utaguchi doesn't help anything particularly and can create unwanted noise the same as any other shape edge. For optimum operation the hole created by the utaguchi must be correctly coupled (by area) to the air volume in the bore. So the size of the utaguchi naturally increases as flutes lengthen. When area is properly matched to volume, bamboo sticks start to sing.

A narrow and/or shallow utaguchi favors the harmonics and upper registers and *lowers the pitch*. Until we got the shape and size right one of the Watazumi pipes was playing third octave and only by extreme coaxing would first octave and the fundamental appear. A wider deeper utaguchi favors the lower register and the fundamental portion of the sound envelope and *raises the pitch*.

There seems to be some confusion about the size of the utaguchi hole and its effects on harmonics and pitch. Here's the thing: Imagine that the hole got smaller and smaller until it finally closed (ignoring for the moment that the flute is driven by air passing over or through the hole). Closing the end of a tube cuts the frequency (pitch) in half. So smaller hole is lower pitch. Something else happens with a closed tube, the even numbered harmonics drop to zero and vanish. **So the shakuhachi is somewhere between an open and closed tube and by varying the degree of opening (the size of the utaguchi hole) the sonic and acoustic qualities of the flute are altered.** Meri closes the hole thereby lowering the pitch and reducing the intensity of the 2nd, 4th, (etc.) harmonics. In particular, reducing the second harmonic makes the tone sound thin. Kari opens the hole, thereby raising the pitch and boosts the even numbered harmonics for a richer, fatter sound--thus a fuller Ro. That's what happened with the Watazumi pipe--it's pitch rose a full note. And utaguchi size and shape sets the degree of your flute's inherent kari-meri--the point from which literal kari-meri deviates. The utaguchi determines the inherent degree of open/closesness a flute possesses--thus its sonic properties and capabilities.

Contrary to ordinary intuition, it's possible to design a flute where the first and third octaves play better than the second--in a relative sense. How is this possible? By clamping down on the size of the utaguchi hole, the first and third harmonics remain and are strengthened, while the second harmonic is depressed. And second octave is just shifting the flute to second harmonic. If it's naturally weak, so to will be second octave. That's what we stumbled onto with the Watazumi tube and its undersized utaguchi. So it follows that a flute which has a strong third octave does so at a cost to the second. And that's the charm and penalty of flutes with high Aspect Ratios--improved upper register and weak mid-register (second octave). In the end, much of the talk about harmonics and fundamentals comes down to the ratio of the amplitudes of second and third harmonics. A strong second tends to be described as a flute with a good fundamental. A weak second, thus a strong third, tends to be described as a flute with good harmonics as its sound is the result of higher harmonics. (see more about Harmonics) Also the Harmonic Series.

The sound quality and playability of a flute can be altered dramatically by changing the utaguchi's geometry--thus the hole size and shape. To such an extend that it's surprising that someone has offered flutes with adjustable utaguchi. A utaguchi which could be extended and retraced could change a simple flute into a racehorse. This is the place where a millimeter make a big difference. An adjustable utaguchi would give your flute several personalities or allow them to be revealed, however you want to think about it.

Ever wonder why the same flute sounds different when played by various people? One of the reasons is the variation in lips, thus variations in the size and shape of the utaguchi hole thus differences in the sound. Flutes usually achieve optimum performance only with lips exactly like that of the maker. But what percentage of the population does that encompass? An adjustable utaguchi would put a lot of myths and misinformation to rest.

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Shaku Design	The Shakurina

Updated 5/8/06

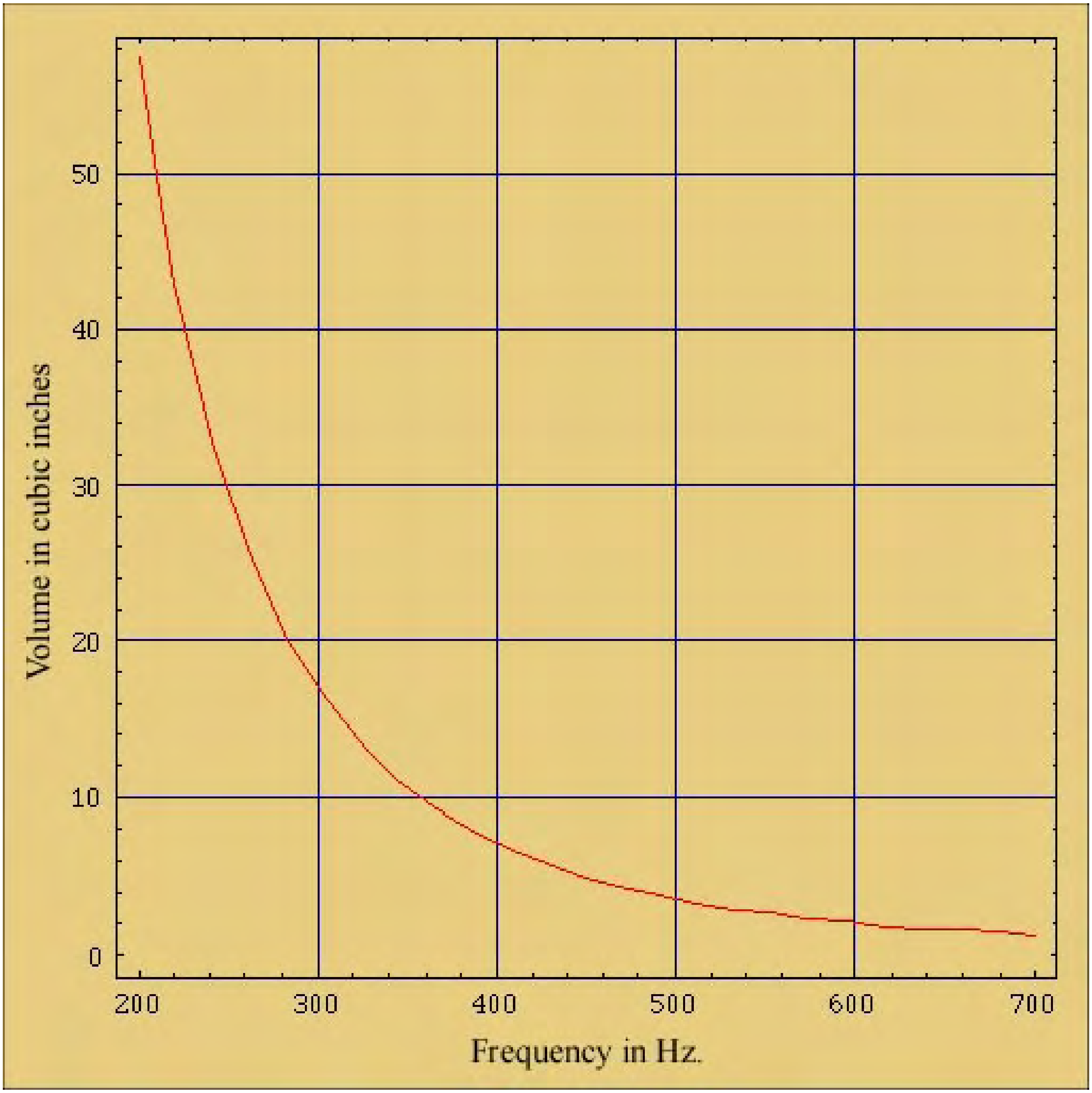
This page reflects an ongoing attempt to build ultra-low-pitched shakuhachi. G is about the lowest pitched shak normal humans can play. Beyond that it's a matter of arm/finger length. Below G, various problems conspire to make the flute more and more unplayable. A D3 shak (one octave below the standard 1.8) is probably not possible except for players who could compete in the NBA (long arms and BIG hands).

By capping a tube (think panpipes), the frequency is halved thereby dropping the pitch one octave. Thus, capped tubes and vessel flutes (Helmholtz resonators) are low pitched. Along with this drop in pitch is the loss of higher harmonics from the sound envelope. Closed volumes resonate primarily in the fundamental harmonics. However, shape of the volume does play a role in harmonic generation and somewhere between a capped tube and a sphere may lie a region where there are enough harmonics to play a second octave. This would be a ultra-low-pitched shakuhachi with a weak second octave or an ocarina which has second octave capabilities--a Shakurina.

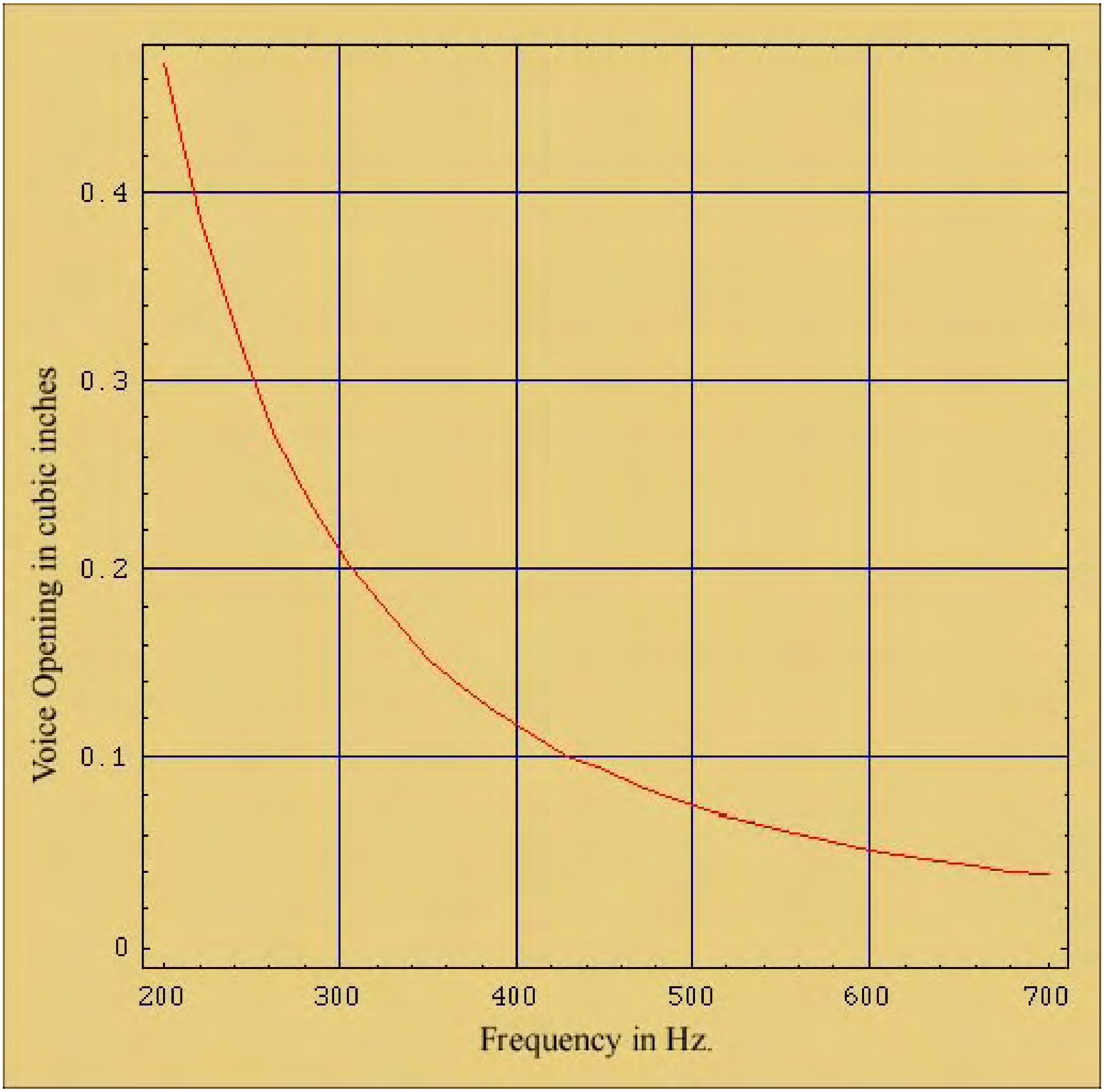
D4 Pentatonic Oc

Ocarina fundamentals:

The frequency of a standard ocarina (Helmholtz resonator) is governed largely by it's volume. The size of the Voice Opening contributes to the extend that sizing the voice opening can facilitate tuning of the fundamental and setting the timbre.



Ocarina Volume



Voice Opening size

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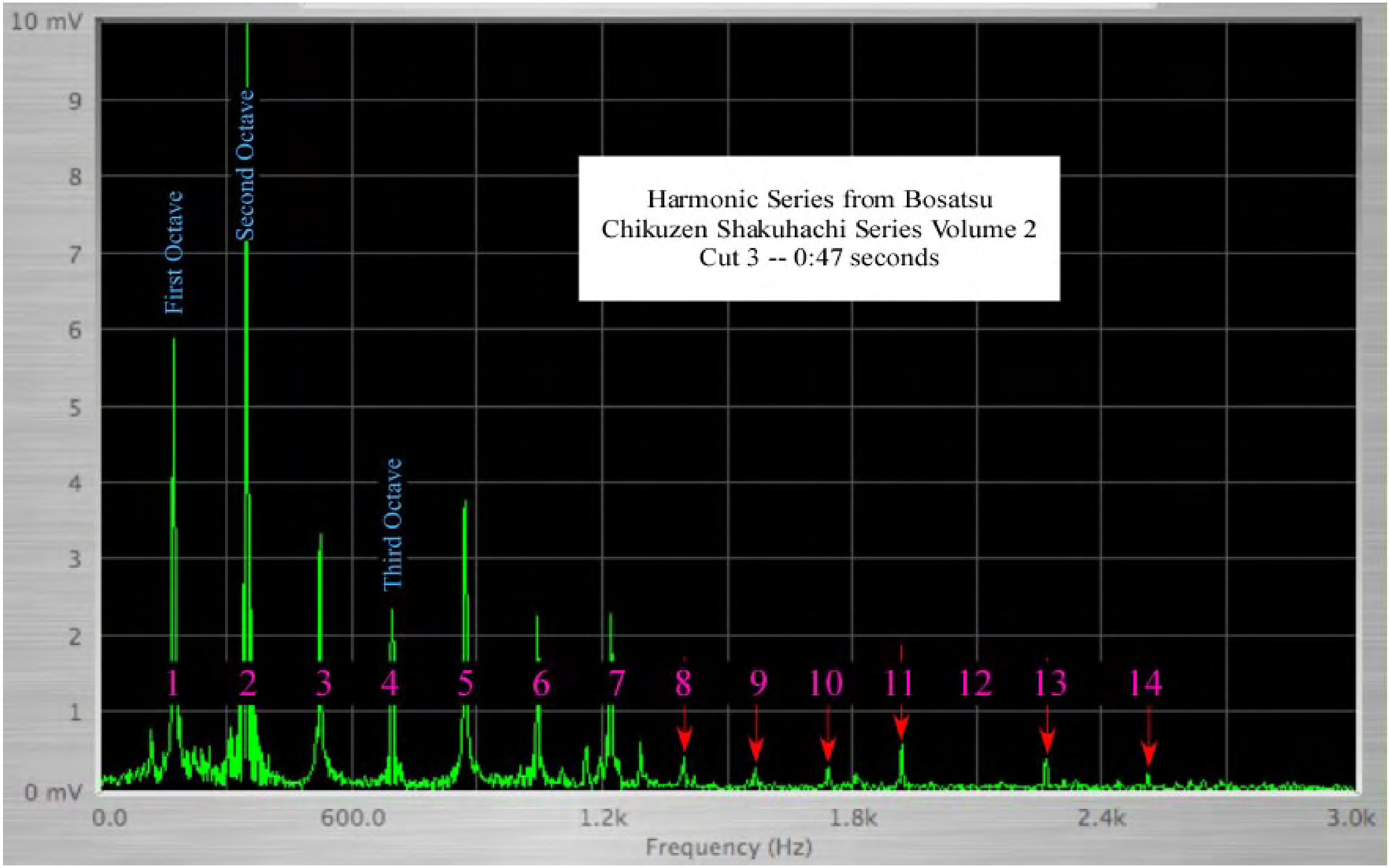
Shaku Design	The Harmonic Series

Updated 1/3/07

Shakuhachi bores resonate starting with the fundamental (the lowest note the tube can support) and then every integer value of the fundamental (nF). Octaves are every successive doubling of the fundamental (2nF).



FFT (Fast Fourier transform) analysis using SignalScope Pro Software

In this snapshot (47 seconds into the piece), Yoshinobu Taniguchi is playing in second octave (it's amplitude being dominant) and all the harmonic series up to the seventh are fairly prominent. After that, all (except the twelfth) harmonics up to the fourteenth are in evidence. It looks like the cutoff frequency of this flute is around 1300hz, anyway, that's about where the harmonic series is depressed.

Every shakuhachi bore has the potential to produce the harmonic series—and that's any length, i.e. any note played. Yet, the series only appears as prominently as in the graphic above, somewhat fleetingly. It's definitely under the players control as to when the series is amplified.

With the cutoff frequency being what it is, the potential for harmonics is greater with low pitched flutes and notes. Playing a high note on a D flute (~600hz) puts the next step in the harmonic series at ~1200hz, and the next at ~1800hz--usually beyond cutoff, so we'd get the first two in the series (maybe three) but the rest would be dampened.

In general, the cutoff frequency is controlled by hole size. The closer hole size is to bore diameter the higher the cutoff frequency. That's why silver Boehm flutes sound different from simple bamboo/wooden flutes. It isn't the flute material, it's that Boehm flutes have huge holes compared to shakuhachi and correspondingly have a higher cutoff frequency which means more harmonics in the sound.

What's required of a flute to produce the harmonic series? The biggest (and perhaps only) requirement is a geometry which can sustain some backpressure. When a player increases pressure, the series is amplified and appears. Is anything required of the bore other than the ability to sustain backpressure? I don't know, but think it'd be of far less importance than the backpressure requirement. And if we're talking backpressure we're talking aspect ratio.

The harmonic series appears any time a player pushes the flute. What we perceive as the flute ‘ringing’ is the sound of higher harmonics. I'm sure there's a Japanese word for this, but to me it sounds like I imagine wind-shear sounds. I hear it as having a tearing quality—something being torn or ripped. Since the harmonics only appear at higher pressure there's usually some wind-rush associated with them. Played at low pressure, flutes tend to suppress everything except a single frequency and have a sweet, pure, sin-wave sound.

Want more harmonics? Engineer in more backpressure and make the holes bigger.

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Shaku Design	Designing Your Own Shakuhachi

Go Back Home Shakuhachi Email Friend

Updated 1/9/07 Additions are made on a continuing basis as information warrants.

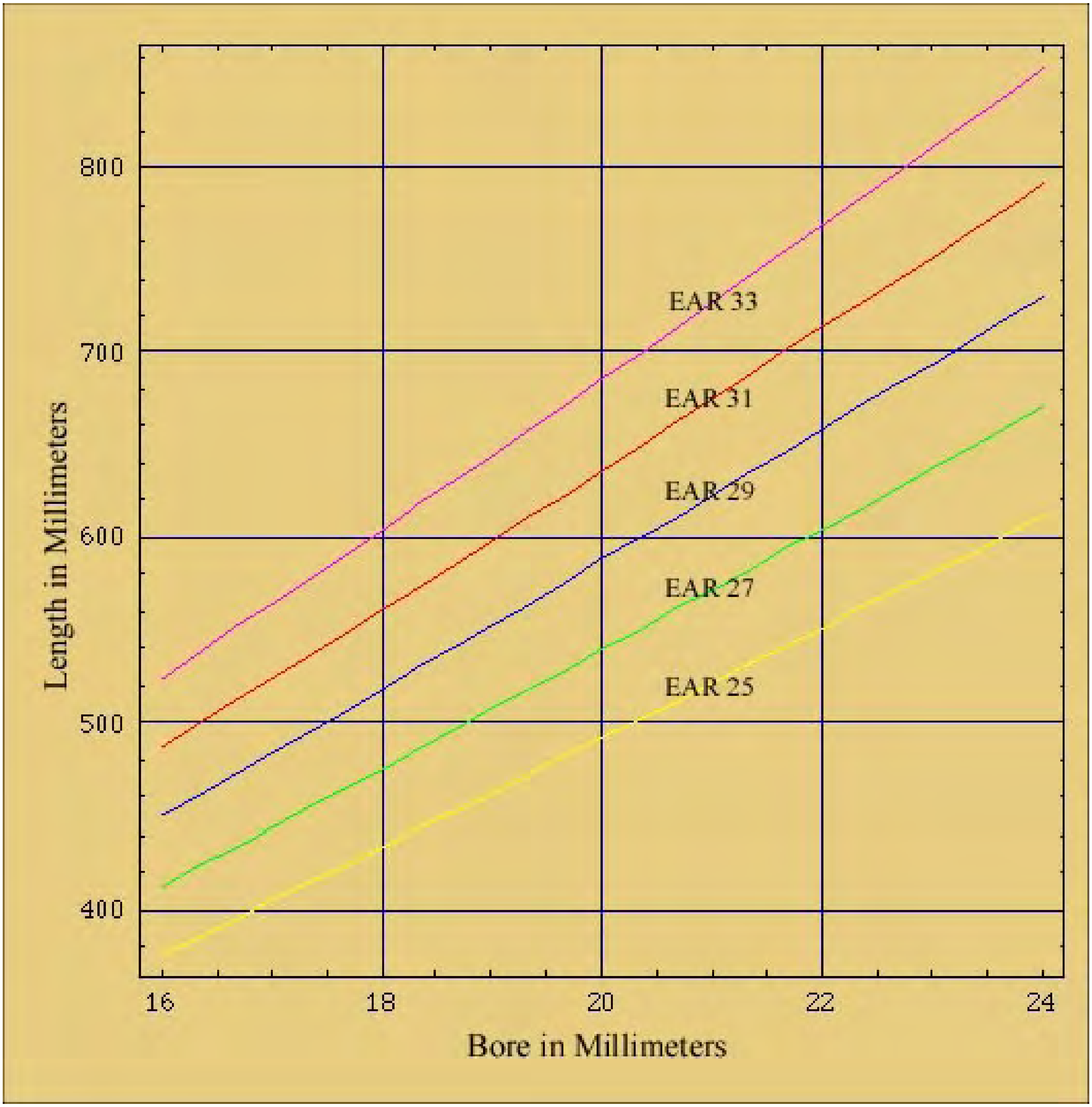
Suppose you were to design a car to get good gas mileage and suitable performance. How would you go about it? What parameters would you attend to first and what things would you pay attention to later? Having a clean windshield will improve both mileage and performance, but expending most of your efforts on the windshield won't work out too well. The gas efficiency of a ten-ton vehicle with a 1000 horsepower engine won't improve substantially after cleaning the windshield. The point being to focus on the things which make the most difference first--get the basic parameters right and things will go smoothly.

This page is intended for jinashi flutes, flutes who's bores are left natural.

The Boring Part

In designing a shakuhachi, **the biggest thing contributing to the overall performance and sound of the flute is aspect ratio**--which is the flute length divided by bore diameter. If you don't get this right, the flute will never do what you want no matter what you do subsequently. See Equivalent Timbre (Equivalent Aspect Ratio --EAR). An EAR of 29-30 is the mean for a shakuhachi, higher numbers brighten the timbre and make the higher registers more available and playable. Lower numbers favor the lower registers and make for a mellow sound. What is commonly referred to as a big bore flute has a lower EAR. Numbers outside of 25-35 start placing you beyond the acoustic range that defines the shakuhachi. Jinashi flutes tend to have EARs under 30 and often much lower. What is often identified as 'the sound of bamboo' is the result of a lower EAR, just as flutes start to sound 'brassy' when the numbers get substantially above 30.

As a point of interest, the word shakuhachi *is both singular and plural. One sheep, a herd of sheep. One shakuhachi, an armload of shakuhachi.*

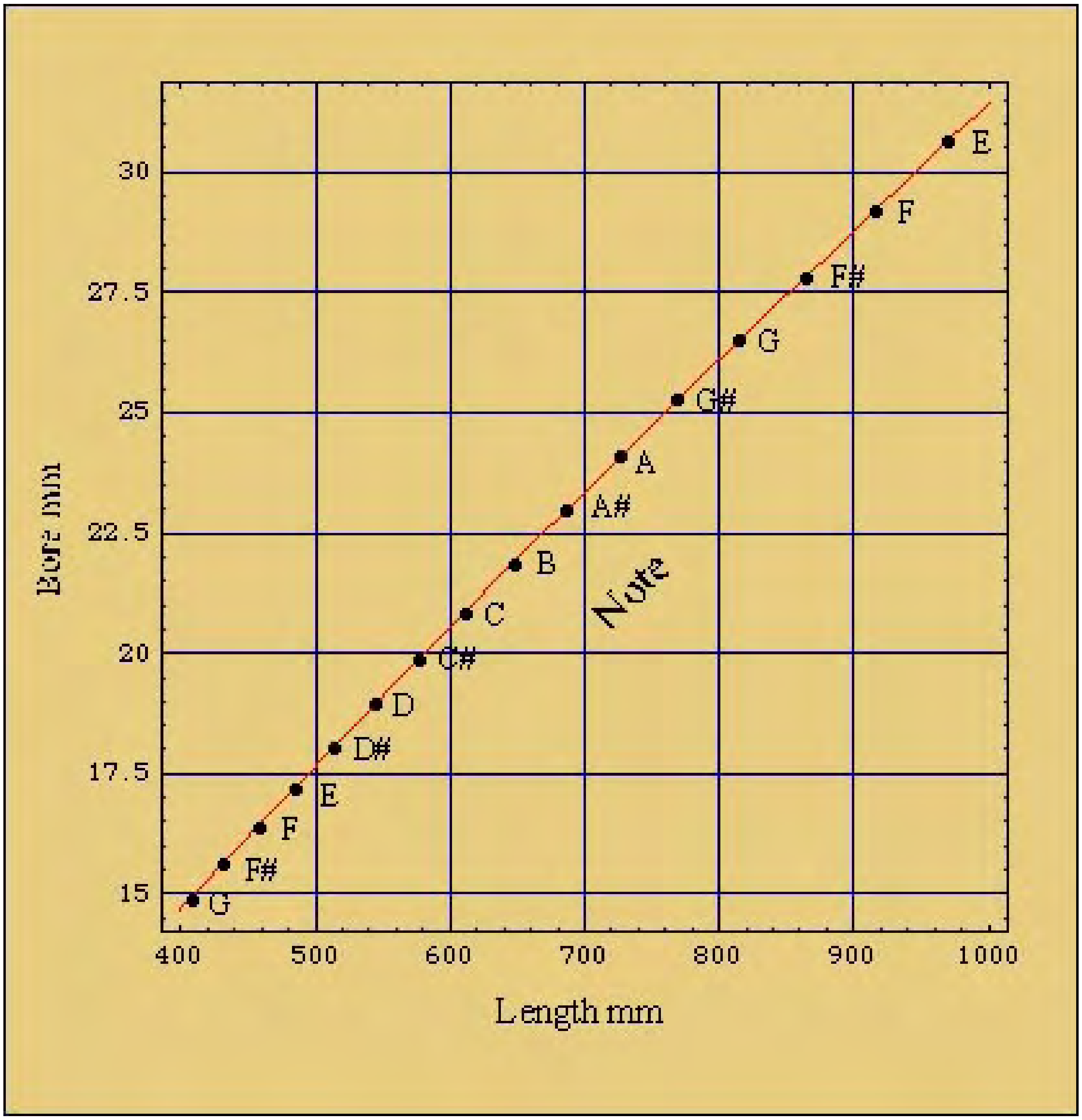


Measure/calculate bore size, then decide on an EAR number and consult graph to determine length.

Be aware that you might not be able to build a flute (from a particular piece of bamboo) which has BOTH the timbre (EAR) and pitch you want. Given a piece of bamboo, the bore is set and you should cut the length to achieve a desired timbre, which may result in a pitch that's not anywhere near the one you wanted. Suffice it to say, for example, that it's not possible to have a balanced D flute with a 25mm bore.

There's a story about an emperor in China who came into possession of a remarkable jade boulder. He summoned the royal jade cutter and commanded him to release a dragon from the jade. So the cutter set to work and every year the Emperor would send word, inquiring as to how the carving was coming along. Finally, the piece was finished and the Emperor came to see it. "Where's my dragon?", he asked. The Jade Cutter drew back a silk cover, "There was no dragon, just five butterflies."

Often, this is the way it is with jinashi (natural bore) bamboo flutes. And as such, jinashi flute making (subtraction method) is a much higher art than jiari, where bore subtractions AND additions are made to achieve a standard bore shape. Because each piece of bamboo is different, jinashi construction becomes a problem solving adventure with each and every flute. Those who enjoy solving puzzles are often drawn to and excel at jinashi flutes as they present an endless supply of riddles. Each flute is a new and unique challenge. The jiari method is based on solving the puzzle once and for all time and applying that bore shape over and over. Jiari is mainly an exercise in craftmanship, jinashi is largely an intellectual endeavor. Dragon or butterflies, you never quite know how it'll turn out.



Length-Bore-Note Relationships for EAR=29.5

Don't start your first shak with some impossibly big or long piece of bamboo. Get something with a bore of 18-20mm and a length of 20-24 inches (500mm-600mm) for your first attempts. One end of the bamboo bore will be larger than the other, **blow into the big end.** Yes, it may seem strange but much about the shakuhachi is strange.

Don't be surprised that your D flute (1.8) isn't exactly 545mm long. Length isn't the only determinant when tuning to a key, bore size contributes, but to a lesser extent. Big bores make flutes shorter, small bores, longer. A flute made of 3/4" Sch40 PVC (bore 20.4mm) with a fundamental of D will be around 533mm long. Methods for determining average bore diameter with irregularly shaped bores: the volume method and the length method.

Cutting the length raises the pitch. Cutting a flute by 6% will raise pitch by one note. Cutting off 1% boosts the pitch by about 15 cents. Often flutes are tuned to themselves rather than an external standard--kind of the sonic equivalent of a free range chicken. What flute holes really do is provide a virtual change to the flute's length. When playing your flute, what you're doing is making virtual cuts to it's length, pitch changes and it's called music. So instead of 'practicing', you could just as well say you are cutting your flute--sit and cut flute.

What the EAR really is, is a general measure of the degree of backpressure a flute will maintain. **Getting a flute to jump octaves requires a certain ratio of airspeed to backpressure.** Flutes with EARs above 30 have greater backpressure and the airspeed needed to jump octaves is less. With an EAR over 35 one blows quite softly in order to keep the airspeed down so as to remain in first octave. With lower EAR numbers this is reversed. An EAR under 25 (less backpressure) requires forceful blowing (high airspeed) to get an octave jump. The important point here is control of a flute is maintained with airspeed rather than air pressure. In texts on instrument acoustics this is called jet velocity and although velocity and pressure are wrapped up together **blowing hard should mean blowing fast.** Think of EAR as a direct expression of backpressure--higher number, greater pressure. Lower number, less pressure. Generally, somewhere around 30 is what's considered balanced (first and second octaves both easy to achieve and maintain) for a garden variety, vanilla shak. Other elements of backpressure.

The amount of 'air' a flute uses is determined more by it's EAR than it's general size. A short/small flute with a low EAR requires more air than a long/big flute with a high EAR. If the flute doesn't maintain sufficient backpressure you have to augment it with your blowing, thus low EARs take more 'air'. It follows that a given lungful (volume) of air will play more notes on higher EAR flutes than lower. Those really mellow flutes are breathless in more ways than one.

As a general rule of thumb within the realm of normal flutes, there is a 1 to 5 ratio between the effects of bore and length. If you wished to expand a bore by one mm and keep the same pitch, you'll need to cut five mm from the length.

General, all purpose metric (mm) equation:

Length = (186500/ Hz) - 5 Bore

Getting Holy

Probably the next most important factor is hole size. Consider 10mm on a 1.8 shak as the mean, smaller holes soften the timbre and larger holes harden it. Ending up with holes which are **nearly the same size** contributes to the holes working well together and a better overall result. Undercutting holes increases venting which is the same as drilling a larger hole. Undercut holes may appear to be the same size as regular holes but acoustically they are larger. Having to undercut a hole means it's in the wrong place and should have been higher on the flute.

Generally, hole sizes can range from 8mm to 12mm. Smaller holes favor micro-tones and 'shading' as the holes work more in concert. Smaller holes favor 'softer' sounds somewhat the same way lower EAR favors darker tones. Larger holes favor a louder, sharper sound as the holes compliment or interfere (however you want to think of it) with each other less than smaller ones. It's generally felt that larger holes allow for a higher cutoff frequency--meaning more sub-harmonics are produced. **Larger holes increase the sensation of resonance as they expose more of the finger-pad area to the air-column vibrations, hence the player has a stronger tactile sensation of vibration.** So, for resonance go with high EAR first and big holes second. It should be obvious that the air-column vibrates--that's the origin of the sound. That IS the sound. Seen on an oscilloscope the sound wave has a profile--a shape. And shape determines how much 'punch' a wave can deliver. High AR produces a taller, narrower wave--one with more punch and bigger holes deliver a larger amount of impact to the tactile nerve endings in the fingertips.

Think of the whole thing like tsunami. When at sea these waves are often just a few feet tall and sailors are unaware when a wave passes. But as the wave approachs land and the depth of the ocean begins to diminish the wave starts to stand up. A tsunami wave's height is directly related to the depth of the water--the ocean's Aspect Ratio so to speak. When it hits shore the tsunami's power is evident. **Shoreline to a tsunami is like a skinny flute is to resonance.**

Before leaving the subject of resonance, let's go a step further. Accepting that the receptors for resonance are in the fingertips (and lips); the index fingers are the most sensitive. So if you're going to do anything special to (or near) holes to boost resonance do it to the second and fourth holes. These are the index finger holes and the fourth hole is probably closed a greater percentage of the time than the second--thus that index finger will be in position most often to detect resonance. **If there's a single hole to concentrate on in terms of resonance, it's the fourth.**

The mouthpiece and edge isn't as critical as many believe. Again, we're talking ballpark figures. The edge needn't be particularly sharp, it doesn't 'split' the air stream, it just defines one side of a shallow 'hole'.

Location, location, location

Now for the perennial question--where do the holes go? It depends on hole size and somewhat on wall thickness. Thicker walls are effectively the same as smaller holes. What we're talking about here is the degree and ease of venting. Below is a chart of generalized percentages which will work fairly well with standard EAR and hole size. Smaller holes--smaller percentage, larger holes, larger percentage.

Hole	9mm 23/64"	9.5mm 3/8"	10mm 25/64"	10.5mm 13/32"	11mm 7/16"	11.5mm 29/64"
5	0.420	0.424	**0.427**	0.430	0.433	0.435
4	0.481	0.485	**0.488**	0.491	0.494	0.497

3	0.596	0.599	**0.603**	0.606	0.609	0.611
2	0.681	0.685	**0.688**	0.692	0.694	0.697
1	0.778	0.782	**0.785**	0.788	0.790	0.793

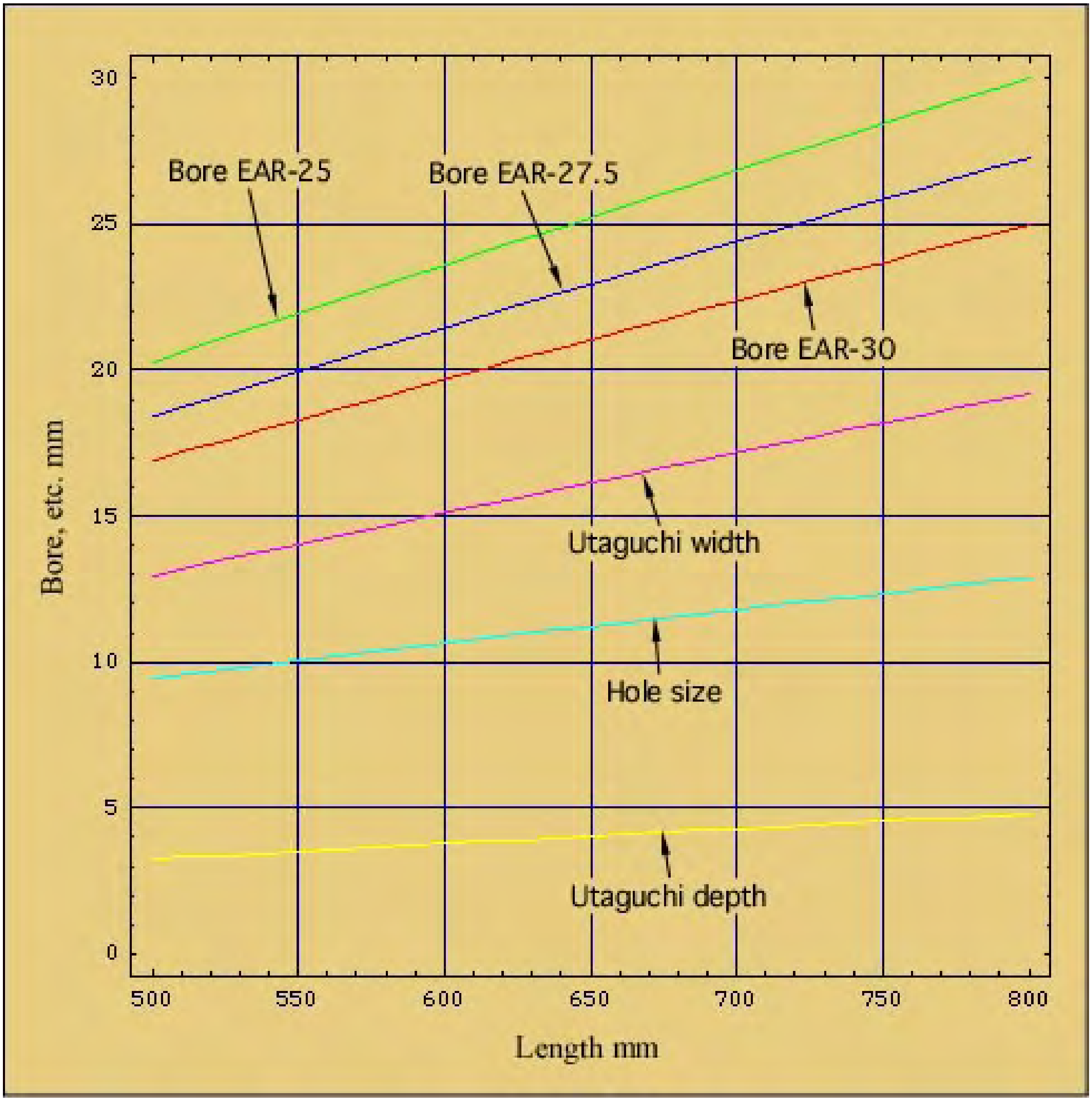
Measure percentage of flute length from top of flute

If you plan on designing more than a few shaks get a metric tape measure and a metric caliper from Ace Hardware.

25.4mm = 1" 1mm = 0.03937" 1 shaku = 303.03mm = 11.93"

For flutes with suitable bores (EAR~29.5) frequency can be calculated from length: Hz =160,045/Length mm and Hz = 528.59/Length Shaku.

Some years ago, Mark Shepard came up with a clever device to quickly lay out the holes of a 'percentage' flute. He stretches out elastic and marks the hole locations on the elastic. Then it can used to locate the holes of any length flute. It helps to epoxy small metal hooks on each end of the elastic so you can hook it onto the bamboo--top and bottom. Once you come up with a hole layout that works well, then transfer it to the elastic and hole layout is accomplished in a jiffy.



'Standard' Parameters

If you get:

1) the EAR about right
2) the hole size about right
3) the hole locations about right
4) and the edge about right--everything else will fall into place.

If you're too far out with any of the these four, finishing the flute in a satisfactory fashion will be an uphill struggle. Getting these four right will account for 95% of your flute's timbre, playability, etc. The rest is just fussing with the finer points.

For Nodal Tuning of Jinashi flutes.

For those who like the look of flute bindings, look to bow string material. High strength, low creep, assorted colors. If you have concern about cracking then a finish should be employed.

In general, both bore and holes should contribute toward the same result. If you want a mellow flute then increase the bore size (lowering the EAR) and go toward the small side with the holes. Having a big bore AND big holes creates a flute which is always operating at cross purposes.

If you can stay within 2% on EAR and hole size and under 1% with hole location things will work out pretty well. If these percentages start rising, expect problems and frustration. If you want a shak that will do all the tricks, jump through all the hoops, a flute that everyone will admire then stick to an EAR of 29-30 and standard hole size for the given bore.

If, on the other hand, you're interested in a particular type of sound then push the parameters in that direction. This flute won't do all things fairly well, but it'll do one or two things stupendously well. The standard balanced shakuhachi is by necessity a compromise--most things are suitable but not exceptional.

Construction PDF:

Making the Japanese Shakuhachi Flute by Ken LaCosse

Ken offers two methods for hole location--one in the text and the other in his drawing. The two methods are slightly different as noted in the table below.

Hole	From Text	From Drawing
5	0.412	0.414
4	0.478	0.480
3	0.578	0.583
2	0.678	0.678
1	0.778	0.778

Measure percentage of flute length from top of flute

Construction Manuals:

Blowing Zen: One Breath, One Mind by Carl Abbott

The Japanese Shakuhachi Flute: Notes on the Craft & Construction by Monty Levenson

Frank's Supply will sell you root-end culms by the dozen.

ShapeShifting Holes

Unless you have an extraordinary ear you'll need a tuner--some standard against which to adjust hole tuning.
The notes your flute should play depend on the basic key it's in.

Katsura Shareware has a Mac Universal Chromatic Tuner for 5 bucks.

Tuner for PC and older Macs.

Try SignalScope (Mac) for a look at waveform and harmonics.

To understand and benefit from the following you'll need to accept the premise that **every hole you drill is in the wrong place**.

Premise #1: It doesn't matter how much measuring and calculating you do, it doesn't matter how developed your intuition is, it doesn't matter how many hundreds of flutes you've made--the first drilling for holes will be in the wrong place. Maybe many millimeters, maybe a thousandth of a millimeter--but each hole will need to be adjusted. Think of this like golf, the point isn't to always shoot for a hole in one, the point is to complete a number of strokes, each of which advances you steadily closer to the hole. Following is a somewhat systematic method for arriving at proper holes.

Premise #2: Anytime you remove material (drilling, grinding, sanding, etc.) you're increasing venting. Venting and location, that's the thing with holes. It may serve you better to think of venting rather than hole size. Bigger holes vent more than smaller, deeper holes vent less than shallow. Cutting raises the pitch, whether it be the flute's length or holes. Cutting is a one-way street--always upward.

Expanding a hole or moving it upstream has the same effect--raising the pitch
Shrinking a hole or moving it downstream has the same effect--lowering the pitch.

Undercutting is the same as expanding a hole because both increase venting. Undercutting on the upstream or downstream sides move the effective center of the hole in that direction. So, undercutting on the upstream side is both increasing hole size and moving the hole upstream--both things raise the pitch. **Can you undercut and lower the pitch? No.** Undercutting on the downstream side does move the hole downstream (thereby lowering the pitch), but this is offset by the increase in hole size. It's the ratio of hole expansion versus hole movement and hole movement is smaller compared to hole expansion

Undercutting upstream doubly raises the pitch.

Undercutting downstream raises the pitch at a slower rate.

Because the bamboo bore isn't cylindrical and because the inside of all bamboo is different, accept that you're flying in fog, make your best guess and drill. What we're trying for here is to get within a few millimeters. To drill close enough to the correct location in order to be able to ShapeShift the hole into the right place. The trick is to drill a pilot hole of a size such that if it's in the right location it'll sound one note lower then it'll end up being.

Assuming a D Flute: Drill a pilot hole at the #1 hole location (the one at the bottom) where you think it should go, but drill it 1/2 the size you'll want on the finished flute. The first hole on a finished D flute will sound F. If you drill it 1/2 size and it sounds E then you know the hole is in the right location and you can go ahead and expand it. If the note is above E the hole location is too high and you should expand it on the downstream side. If the note is below E then the hole location is too low and expansion should only be on the upstream side. Drilling a pilot hole 1/2 size should sound one note lower (than the finished note) if the location is right. The method isn't perfect, but with a little practice this Pilot Hole Method will inform you about location and which way a hole needs to be shapeshifted. Use pilot holes on the remaining holes the way you did on the first. Pilot notes for a D flute: E, F#, G#, B, C#.

The outer hole edges are usually finished with a fairly crisp profile, inner edges should be chamfered more.

Premise #3: Holes don't exist in isolation, they work together. As hole size increases the less do the holes cooperate to create pitch. Small holes acoustically chain together more, so the effects of fingering and cross fingering becomes more pronounced. If you really like the sound and shades of tricky fingering then tend toward smaller holes. Larger holes favor half-holeing, smaller holes fingering.

Premise #4: Flute building is an exercise in compromise. Try as you might, you can't have everything in one flute. There is the issue of visual versus aural. Do you want the same identical hole sizes or equal hole spacing? Or should your flute follow more acoustical principles? Flute making is a matter of compromising, judgment, and intention.

Once you've gotten a grip on the four elements detailed above (EAR, hole size, hole location, edge) and are familiar with their effects, you can step out of the beginner category and start creating your own particular shakuhachi. For the most part, that journey will be about investigating the subtly of the interplay among the four elements. **The general concept of venting will serve you well in most circumstances.** For example, changing the slickness of the bore surface changes venting and changing the venting of the bore is the same as changing its size. So, by changing the surface roughness at the choke point (for example), one can effectively expand or shrink the bore at that location. Ordinarily, changing bore venting at particular locations along its course is done by adding material to the bore at these places and this is the way jiari flutes are built. It's not commonly realized that the pressure wave in the bore of a shak is moving at the speed of sound--Mach 1, so thinking like a supersonic designer could lead to any number of impressive effects.

Bamboo/Urushi Vibrations

There is a view that any flute material which is fairly stiff, hard, air-tight and used in thicknesses not given to incidental flexure produces about the same results as any other. So aluminum foil is out, being too thin. Pine isn't particularly hard, oak isn't air-tight. Foam-rubber's lack of stiffness makes it attractive for other purposes.

But let's look at the opposite belief, that the peculiar sound of the shakuhachi comes primarily from bamboo/urushi vibrations.

A quick review:

Areophones are instruments in which the sound is produced by the vibration of air. They are classified according to how the vibration is generated, and include flutes, reeds, cup mouthpiece instruments, and free areophones.

Idiophones are instruments made of naturally sonorous material, sounded in a variety of different ways. They include: xylophone, mirimba, gong, bell, glockenspiel, etc. These are the ‘percussion’ instruments.

Membranophones are instruments in which the sound is made by the vibration of a stretched membrane or skin--drums and mirlitons.

Chordophones are instruments in which the sound is made by vibrating strings. There are five basic types: bows, lyres, harps, lutes, and zithers.

Many in the shakuhachi world don't classify the shak as an areophone, they classify it as an **idiophone--an instrument who's tone derives from the material from which it's constructed, bamboo and urushi.** Further, they often posit that bamboo and urushi of bygone eras was of higher ‘quality’--implying that the sonorous qualities are superior in some way. This bamboo/urushi contingent sometimes classifies the shak as a chordophone by comparing it to violins, guitars and the like.

It's surprising that the bamboo/urushi group is generally made up of musicians and other experts who usually have wide exposure to different kinds and types of instruments. They, if anyone, should have a deep appreciation for the four general types of phonic instruments and the principles underlying each.

It's a mystery. If the shakuhachi isn't an areophone, what is it? Makers usually proceed with the idea that a shak is an areophone, but are repeatedly told that they're wrong in this assumption. If the shakuhachi world can't agree on the most fundamental principle of where the sound comes from, then there's something badly wrong with the whole endeavor. If the shak is an areophone this means that many of the leading lights in the shak world have been wrong their entire careers about the most basic fact of their instruments which implies that their opinions on other shakuhachi matters should be treated with caution.

If the shakuhachi is an ideophone or has important ideophonic qualities then the makers have been barking up the wrong tree the whole time and have never understood what they were doing.

The shakuhachi seems to attract and engender non-critical thinkers or this thing would have been settled long ago. It's kind of like clinging to the biplane era of flight after aeronautics moved on and insisting that flight itself arises because of the properties of canvas and wood. For a pilot to not comprehend or understand the basis of flight is worrying.

Some teachers steadfastly maintain that when, say, a wooden and bamboo flute sound differently, the difference is solely attributable to material. Why would they think so? Are the two bores identical? Same taper, same choke point, same hole size, same undercuts, same hole locations, same bore surface roughness, same chimney heights, and so on? Only after one has undertaken detailed measurements to guarantee similarity is he justified in making the pronouncement that disparate flute materials sound differently. Otherwise, it's just a case of very lazy thinking.

On the other hand, let's assume for a moment that the materials conjecture is true, that bamboo/urushi is at the heart of the shakuhachi sound. The people who believe this should already have done exhaustive resonant material tests. This should have become the Holy Grail, the search for the ultimate resonant flute material. But it hasn't happened. The Irish flute people swear that certain hardwoods are the best and won't even consider bamboo. Shakuhachi people believe only in bamboo and shun hardwoods. Go figure.

Where does the shakuhachi reside, in the flute or the activity? Shakuhachi collectors are compelled to believe in the bamboo/urushi theory, otherwise what are they hoarding? Object or activity? Settle that one for yourself.

Actually, the bamboo/urushi people don't really believe that the sound of a shakuhachi arises from the physical vibrations of bamboo/urushi. There are so many ways to test this that any moderately curious person would know it to be ridiculous within minutes. What the bamboo/urushi crew is claiming is much more subtle and profound. That the spirit of suizen only resides in bamboo/urushi and as such can only be called forth from bamboo/urushi. The idea that the soul of Honkyoku could happily reside in PVC (or any other disgusting equivalent) blows the lid off the whole belief structure surrounding the shakuhachi. Once cracked (no pun intended), the entire edifice would collapse. The bamboo/urushi crowd isn't claiming vibration on literal scientific grounds (otherwise, they'd demonstrate such), their claim is more quasi-religious and therefore faith-based. They feel vibrations in their finger tips and lips, they are touching bamboo/urushi--ipso facto, the bamboo/urushi must be vibrating. It moves, it's alive, and it sings. How could it be otherwise? They're really talking about what they percieve to be the spirit of bamboo/urushi. It's a subjective thing. Enlightenment from a single note?

Yeah, right.

The bamboo/urushi camp claims that bamboo adds an intangible quality essential for understanding shakuhachi and it's probably true in the same sense that context provides an intangible element to any experience. However, an 'intangible quality' is different from discernable tonal effects both by type and degree. Bamboo/urushi is doubtlessly REQUIRED to fulfill the traditional aspects of shakuhachi, but for little else. When bamboo/urushi is examined as an issue of fashion everything clears up. It's really the question of whether clothes make the man.

Suffice it to say that if you believe sonorous materials play a role in flute sound then little on this page is of much use to you for the purposes of flute building. The path would then be to develop tests to identify and quantify the vibratory qualities of bamboo/urushi and proceeding from the results.

Should you particularly care about this discussion of bamboo/urushi then contemplate ideophones and notice how different notes are created on an ideophone. That should clear it up.

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Shaku Design	Single Octave Flutes

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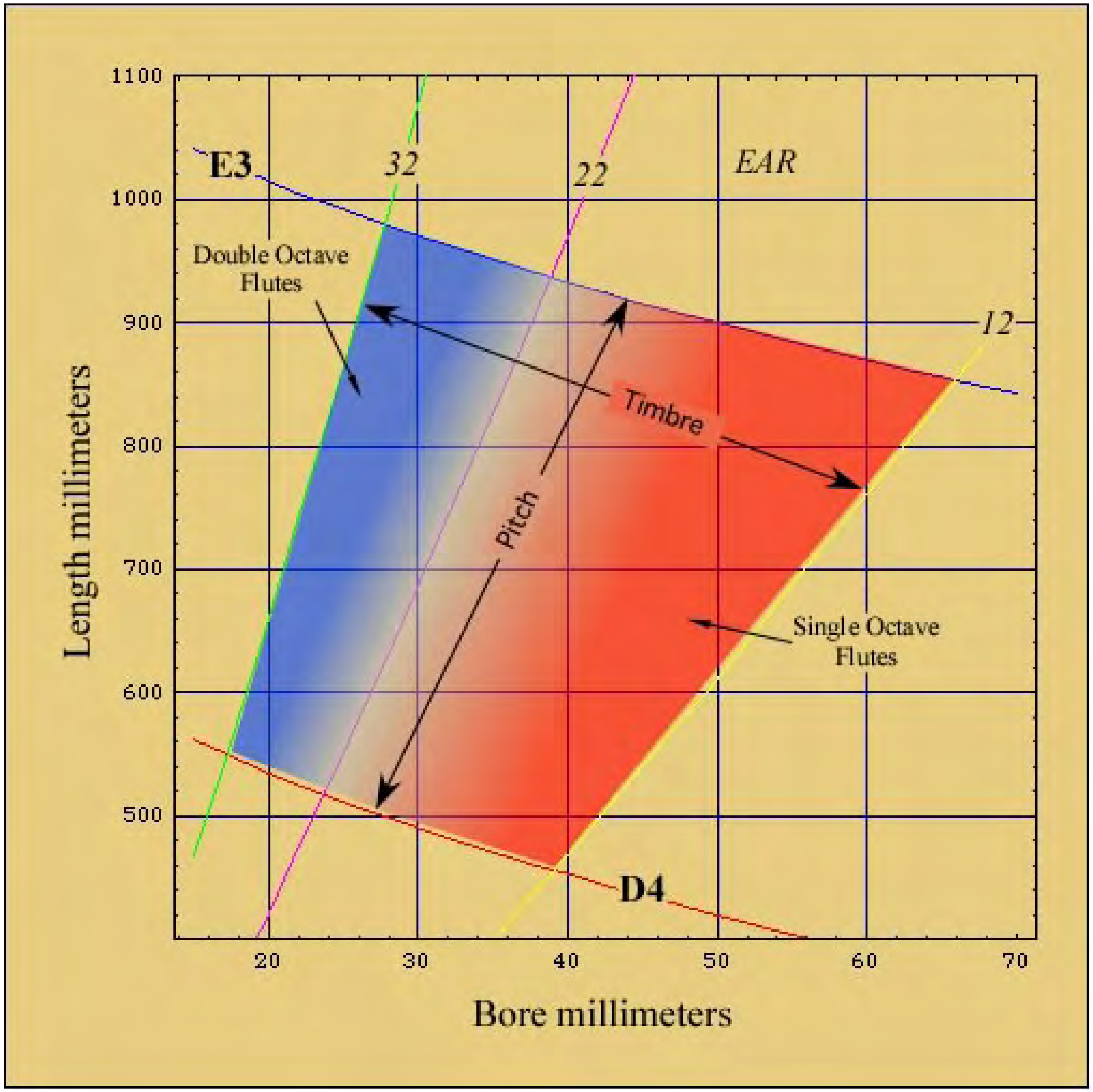
Updated 1/3/07

The desire for big bore, deeply pitched, rumbling, wheezy flutes must be hidden in the psyche somewhere and it never seems to go away. We've looked at long flutes, now let's investigate chubby flutes.

In the graphic below, the blue section indicates the dimensions of the vast percentage of shakuhachi. In general, these are 'balanced flutes', capable of playing both first and second octave. Most flutes are pitched between D4 and E3 (almost an octave lower). **For the most part, the blue section IS the world of the shakuhachi.**

As EAR drops, a flute's second octave becomes more and more fugitive to the point where the upper register is difficult if not impossible. Balance vanishes and it becomes, essentially, a single octave flute. That's the tradeoff--second octave for the big bore timbre. True big bore flutes are single octave affairs.

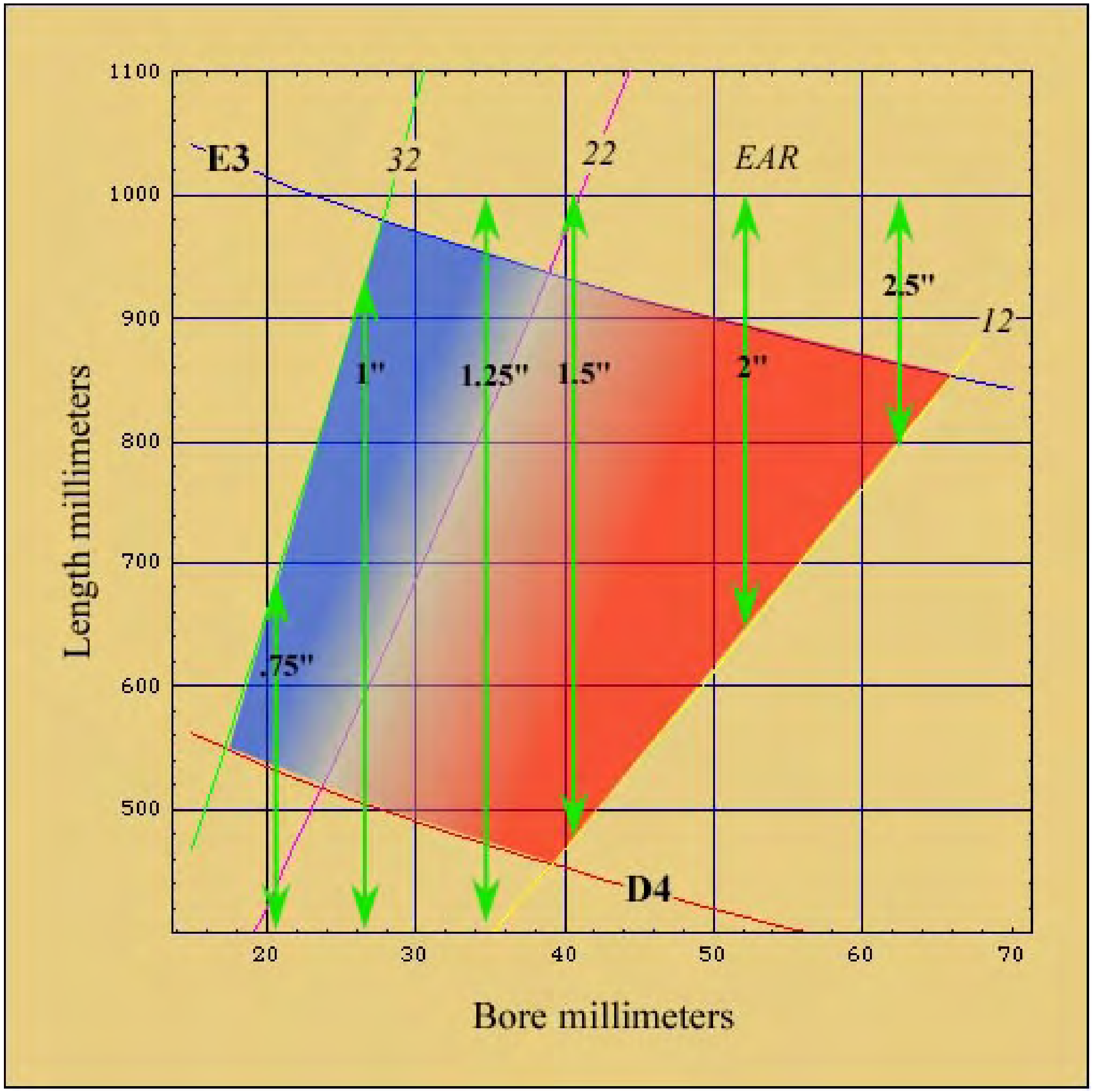


Dimensions for single and double octave flutes
with pitch and timbre elements denoted

There's an upper limit to the flute length that can be played. It's probably somewhere around 1000mm (one meter, 3.3 shaku), and beyond that depends on physical size and persistence. The standard 1.8 shakuhachi is pitched to D4 (294hz) and although there are flutes pitched higher, most shakuhachi exist in the range between D4 and E3 (165hz) in the blue part above. To the right (the red section) is the region of big bore flutes. EAR drops from 32 to 22 and then another 10 points to 12. The demarcation between single and double octave flutes is probably somewhere around EAR 22, but is defined by an individual's playing ability. As ability develops, this demarcation number decreases. Shifting a flute in the red direction makes second octave more tenuous and elusive. Moving in the blue direction brings a flute into better balance. The EAR you're satisfied with will be the result of what you like to hear and playing ability. The shift from double to single octave (blue to red) is gradual and can be noticed as the high second octave notes begin to fade and the flute's highest tonal reach slowly drops. In general, a flute's tonal range is a direct function of EAR. As an approximation: EAR / 12 = Range (in octaves).

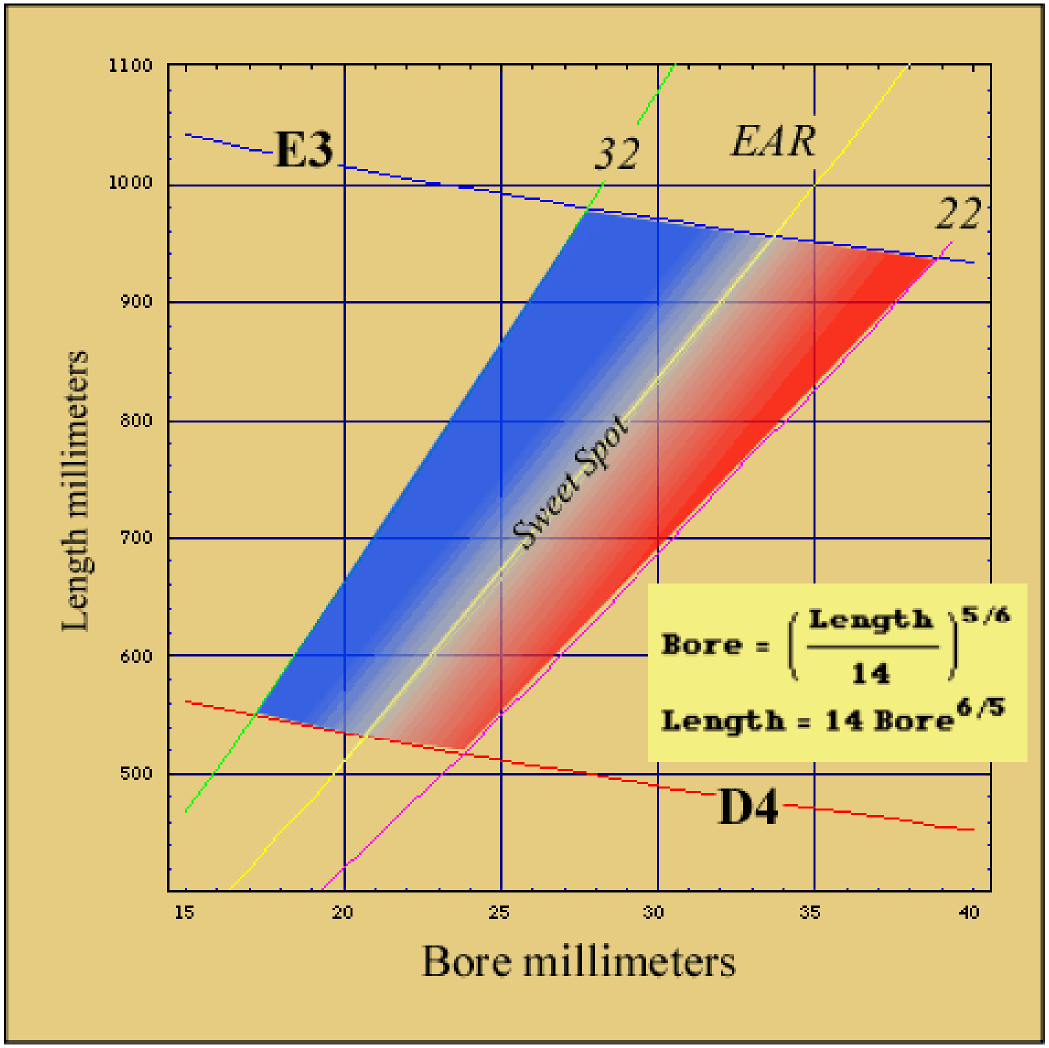
The EAR of pipe organs is usually down close to 12 and the pipes are prime examples of single octave flutes. One of the reasons is so that a pipe can't overblow into second octave even when air pressure is stiffened to accentuate volume. Since a pipe organ is just a collection of single octave flutes you can have an appreciation of the timbre of flutes with EARs approaching 12.

The five sizes of Schedule 40 PVC pipe noted in the chart below allow for rapid experiments with big bore flutes. Four of the pipe sizes represented in green will play lower than E3 and will do it at a playable length (under one meter). The 1.25" is interesting in that it will play all the way from D4 down to D3 and during the journey shifts from a single octave flute to a double. The 1.5" between 500 and 950mm makes a very suitable big bore flute. The 2" at 650 to 950mm is a similar arrangement. 1" pipe at about 505mm makes an interesting D flute--also E at ~ 450, C at ~565, Bb at ~635, and G at ~755. These One Inch flutes demonstrate the transition from single to double octave.



Nominal Pipe Size	ID Inches	ID millimeters
3/4"	0.804	20.4
1"	1.029	26.1
1 1/4"	1.360	34.5
1 1/2"	1.590	40.4
2"	2.047	52.0
2 1/2"	2.445	62.1

One way to get a feel for the whole subject is to cut a piece of 1.25" pipe to 1100mm. Fashion a utaguchi and play first and second octave. Then cut 100mm off the end and play again. Repeat until length is down to 400mm. With some couplings you can add/subtract to/from your flute at will. During the exercise the flute's fundamental pitch will change by over an octave and you'll get a clear sense of the single/double octave phenomena. One of the defining features of the big bore sound is diminished harmonics, it's a 'purer', simpler sound. The tonal migration revealed by this exercise moves from a 'musical' timbre (with harmonics amplified) to a windy, more natural sound. The sounds of nature aren't double octave.



Within the double octave segment there is a thin acoustical sweet spot depicted in the graphic above.
The formulas (metric only) will produce flutes which fall on the yellow line.

Try SignalScope (Mac) for a look at waveform and harmonics.

Once you've found the length/timbre/EAR you're happiest with, cut a new flute to that length and drill the holes. Ideally, hole-size should be about 50% of bore diameter but normal fingers can't cover much more than 12-13mm. But there are a couple things you can do to 'increase' hole-size: make the holes oblong (along the finger axis) and really undercut the holes to increase venting. Get the hole chimneys down under a millimeter.

As a point of interest, if you were to take an Optimal D flute (bore 18mm, length 545mm, EAR 30.3) and double the bore size its pitch would drop almost exactly two notes. Then you'd have a C flute (bore 36mm, length 545mm, EAR ~15). Increasing the bore by one and a half times drops the pitch one note to C# (bore 27mm, length 545mm, EAR ~21) . These two ratios hold fairly well for notes in the vicinity of D.

There is a well known experiment in which an organ pipe is constructed with an outer sleeve. Thus starts a perennial shakuhachi urban myth. *As the pipe is sounded, water is poured into the space between the pipe and the sleeve. Both timbre and pitch are affected by the water as it gradually fills the space around the pipe.* Drum roll .... and now for the finish. *So the material in a pipe has an effect.*

In 1909, D. C. Miller devised a demonstration that went something like the above. 'Organ pipe' is a misnomer as what he built wouldn't have been used by any organ builder. Miller intentionally built something that would amplify vibrations in the tube body and by pouring in water could dampen them changing the tube's tone quality--pitch, of course, staying stable. How did he do it? Miller built a square tube out of quite thin metal. He picked a geometry and material which would enhance wall flexure and drew the same conclusion as the urban myth above. Bad science with a rigged experiment.

Boner and Newman (1940) effectively laid to rest Miller's conclusion by showing little material effect even for pipes made of paper. A more thorough analysis by Backus and Hundley (1965) also confirmed this result.

Fletcher and Rossing in their 1998 volume *The Physics of Musical Instruments* note the foregoing and deliver, once again, the judgement that material is of vanishingly small importance for flutes.

C. J. Nederveen, *Acoustical Aspects of Woodwind Instruments* (1998), is even clearer, *"The material of the wall has no influence on the timbre. Frequency, initial transient, stability, ease of blowing and timbre of a note are solely determined by the inner geometry of the entire instrument, including the player's mouth."*

Actually, Miller could have done a half-way decent experiment had he made many square tubes out of different materials of similar thickness and seen how each reacted. But he didn't. Miller wanted to 'prove' a conjecture he already held, rather than wanting to know the truth of the matter. Anyway, nearly a hundred years later, Miller's deceit is still alive and going strong. It appeals to those who want 'evidence' to support their already made-up minds.

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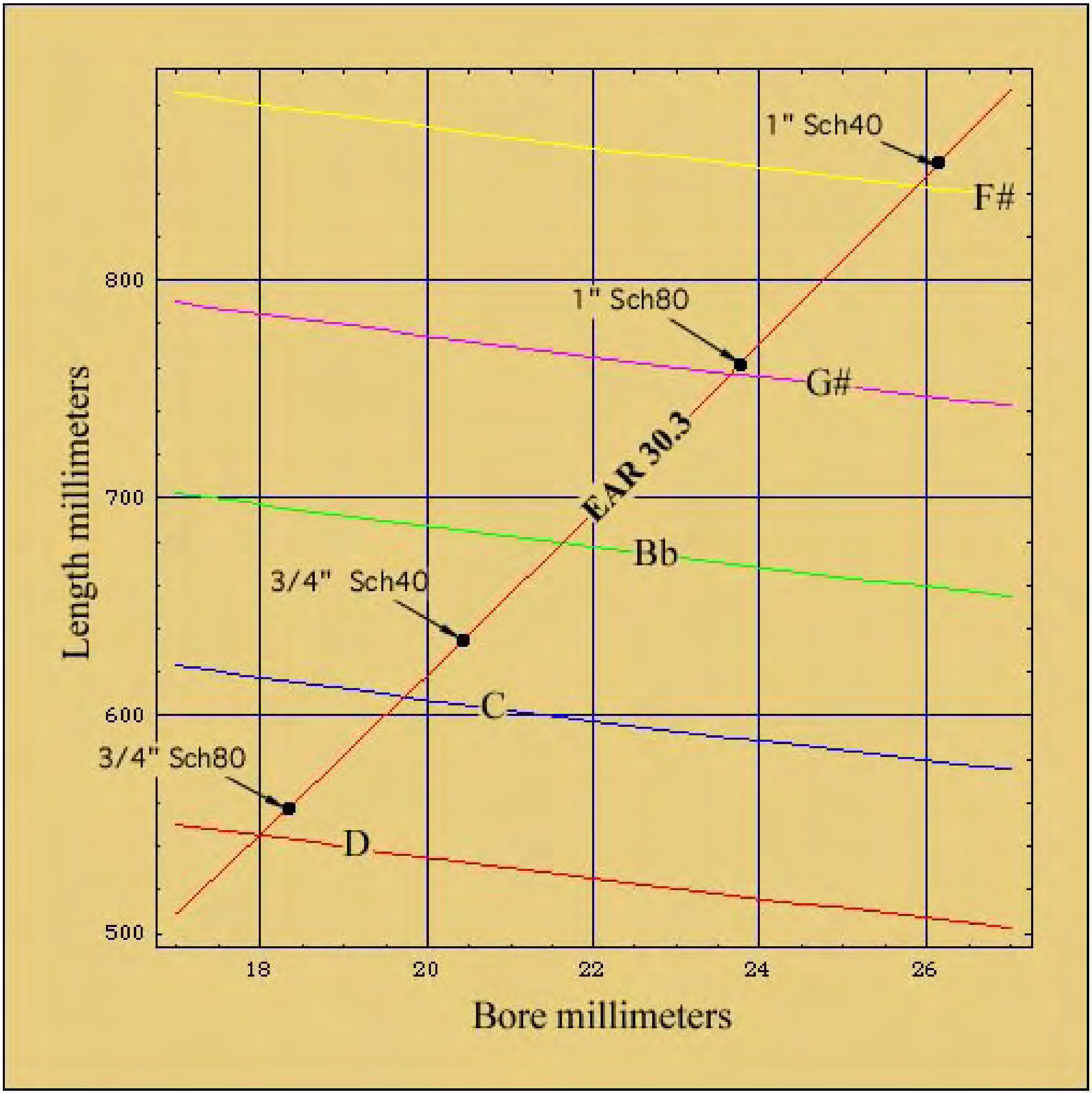
Shaku Design	Cutting to Length

Updated 9/2/06

What should a shakuhachi sound like? What is optimal shakuhachi timbre? Taking the 1.8 as the standard, because it *has a specific length and pitch it can only have one bore size which is right at 18mm. Given all this, the optimal timbre comes from an EAR of 30.3.*



Dimensions for Optimal flutes made from PVC

There is an optimal ratio between bore and length as graphed above, but are there optimal hole locations? Probably. By adopting the Deaver Test we can arrive at a set of hole locations which are optimal for all flute lengths that can be naturally played. Which means all but those really long flutes where the holes have to be moved to facilitate your fingers. Put the holes at the following percentages (as measured from the flute head): 0.43, 0.49, 0.60, 0.69, 0.78. 43-49-60-69-78, remember those numbers and you have the hole location layout for any flute (regardless of bore size and EAR) under about 2.3 or 2.4. Or, if your memory is quirky, adopt the slightly rougher Hermit Bamboo Cutter's layout: 43-50-60-70-80, it'll be a tad quirky but playable.

A one percent change on a 1.8 is, at most, a little over 4mm or half a hole. The rounding error of the blue set of numbers amounts to, at most, 2mm. The blue set of numbers is all you'll ever need while making anything less than chokan flutes. You don't need to run everything through a hole location calculator which can give numbers to a ten thousandth of a percent.

The blue set of numbers applies to all flutes because the same musical scale applies to all shakuhachi.

But how can a single set of hole locations apply to all but chokan flutes?--you ask. Here's the trick, don't change the location of the holes, change the hole size. There is an optimal hole location, don't fiddle with it. Use the blue set of numbers and tune your flute by adjusting hole size. In the end you'll have the optimal location AND optimal hole size for your particular flute.

If you want to know what an optimal flute sounds like, cut a chunk of Schedule 40 3/4" PVC to 634mm, drill 3/8" holes at the blue percentages, enlarge the holes (starting at the bottom) to bring the flute into tune. You'll end up with what the long tradition of Japanese shakuhachi making has arrived at as the optimal flute. You may notice it sounds a little different from some modern shakuhachi, it'll be a little softer and more subtle.

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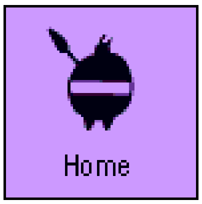
Shaku Design	The Missing Water



Updated 12/7/06

Get out your jinashi root-end D flute. It probably weighs somewhere around 300 grams and about 8-10% of that is water. There's nearly an ounce of water in your flute right now. When the bamboo was green it's moisture content was 100% or higher, so 250 grams of water had to evaporate to get it to the state it's in now. Back in

the day, your culm was green, plump, happy, and unstressed, but nearly 9 ounces of water evaporated and your flute has been stressed ever since. That's why it has already or may yet crack--the missing water. If the flute were submerged for awhile, it would swell back up, any cracks would disappear and it's weight would tend toward the original 550 grams and all stress would be gone.

Let's get a grip on how much water we're talking about. The volume of the bore is somewhere around 150 cubic centimeters. One cc of water weighs one gram, your flute is missing 250 grams of water, more than enough water to fill the bore--nearly twice. Now you know why flutes crack.

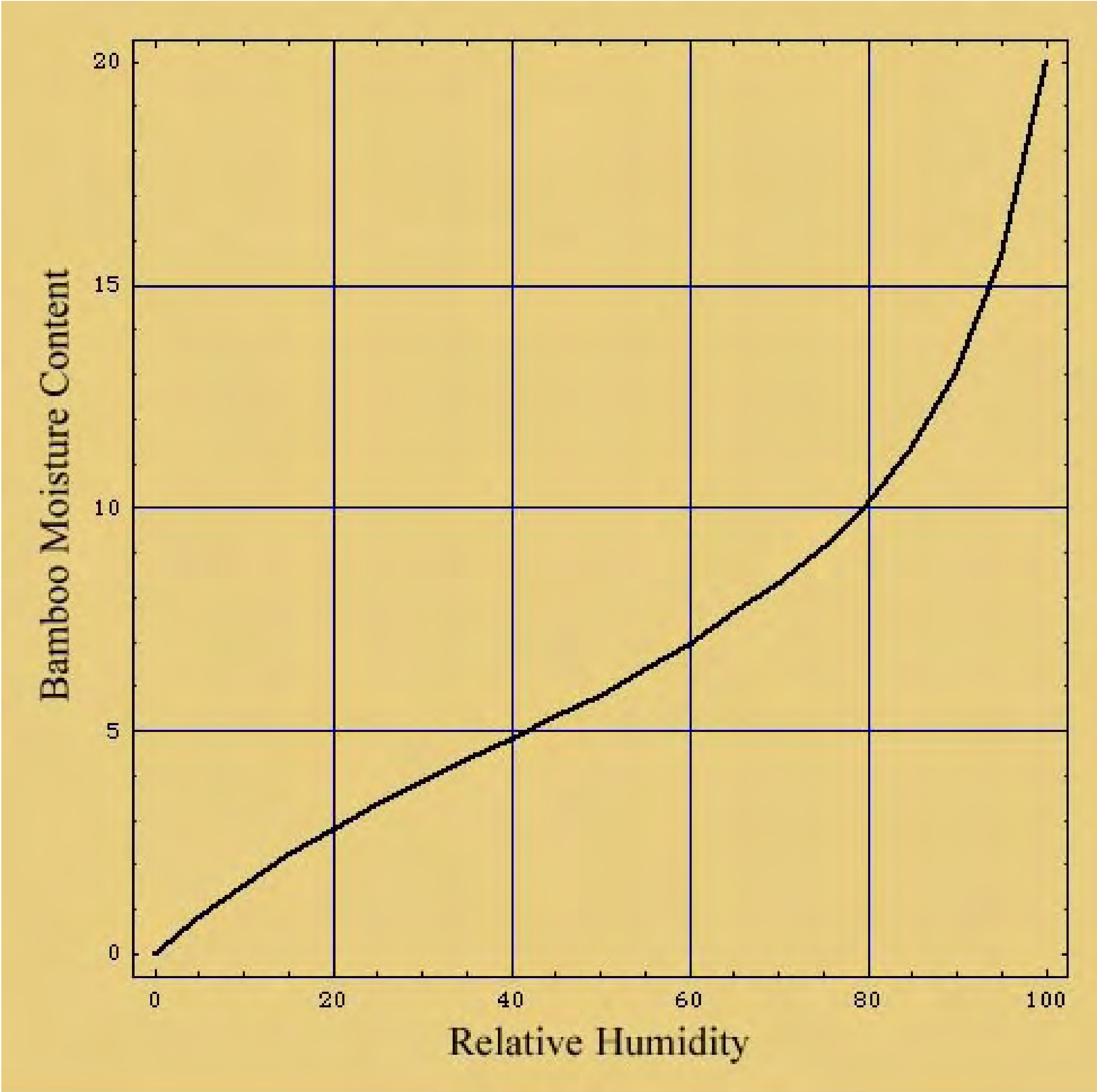
Moisture content (MC) is a little bit like talking about exerting 110% in terms of effort/commitment/etc. To calculate MC, divide the moisture weight by the dry wood weight and multiply by 100 ((M/W) x 100). So green bamboo often has a moisture content well over 100%.

Moisture in bamboo is divided into two parts: **free water and bound water.** Think of a wet sponge. You can squeeze out the free water but the sponge remains moist with the bound water. Something called the fiber saturation point (FSP) identifies the point between free and bound water, which in bamboo runs around 20%.

As bamboo dries the free water leaves first and the MC drops to 20%, at which point the bound water begins evaporating. An important point to remember is that dimensional changes (shrinking/swelling/cracking/etc.) only occur as bound water is lost or gained. **Placing dried bamboo in 100% humidity indefinitely will only raise the MC to 20%.** Once the bound water is replenished bamboo stops absorbing moisture from the air. To replenish free water the culm needs to be submerged. Bound water is held in the cellular walls in molecular form by forces of attraction, free water fills the cell cavities. Bound water is directly involved in the structure of bamboo, free water is just along for the ride.

The hydration graph below plots bound water versus humidity. All the moisture action you need be concerned with (in regards to a bamboo flute cracking) is contained in the graph--it's all about the bound water. To be clear, the graph (below 20% MC) only becomes operational after all free water has left the culm. Shrinkage doesn't begin until bound water starts evaporating.

The graph indicates the moisture content of your flute probably never rises much above 10-12%. Note also that varying the relative humidity surrounding your flute from 40% to 60% results is just a few percent change in the moisture content of the flute. 50% humidity (6% MC) is usually considered the minimum to remain crack free. Bamboo fishing rod makers need to keep the MC above a certain level in order for the glue to set and work right. Otherwise, the fishing rods start coming apart latter. For those particularly interested in the MC of their flutes, weighing a flute is probably the simplest and most accurate way to determine water gain and loss.



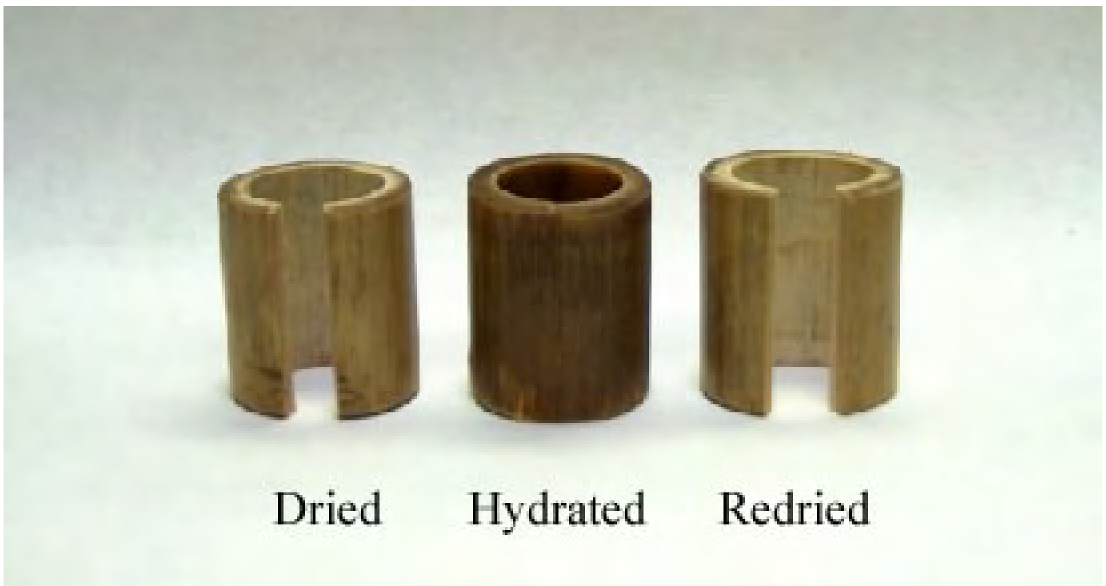
Here are two links with current US relative humidity: National Humidity and Regional Map.

Check your location and get a number for relative humidity
apply it to the graph above and derive the Bamboo Moisture Content that can be sustained.

Throughout the long history of the craft of Japanese flute-making one fact has remained true: bamboo is a poor material choice for flutes. Bamboo can't stand up to the demands placed on it by the rigors of flute playing, the material is too fragile and it cracks. Being a very linear material, only in a single direction is it strong and resilient. Radially (across grain), bamboo is virtually without merit. Which is a long way of saying it cracks.

At what MC a particular piece of bamboo may crack is dependent on many factors, chief among them, age/development of the wood structure and wall thickness--thicker walls being more prone to cracking. But for many flutes there is some point of moisture content where the stress becomes too great and the wall ruptures. If the MC of your flute is under 20% it is experiencing some degree of stress.

Samples are all from the same piece of bamboo.
They've been split to facilitate quick visual indication of stress.



If you were to band-saw a section from your flute right now and split it, it would spring open in the manner of the left sample above--indicating the amount of stress it was under. This desire to crack is perpetual and will reside in your flute as long as it exists. As can be deduced from the center sample, the stress level in your flute is directly related to its degree of hydration. When a hydrated sample (right) is left to dry the stress returns. We've taken bamboo dried to less than 5%, immersed it until the MC is above 20% and dried again, to demonstrate the absorption/desorpsion cycle. It also becomes obvious that the blond color associated with bamboo is largely the result of empty cells cavities filled with air.

There's a difference between the inner and outer portions of the bamboo wall and more of the vascular bundles (the water/sap carriers) are in the outer wall. Thus, as bamboo dries and the bound water evaporates, the outer wall shrinks proportionally more than the inner, creating stress which, if it becomes great enough, will lead to wall rupture and a crack.

In simple terms, the bamboo cell wall is a composite made of a rigid cellulose polymer in a matrix of lignin and the hemicelluloses. The lignin polymer is thermoplastic; that is, it softens upon heating. The glass transition temperature Tg of the lignin in the matrix is approximately 170C (338F). Above the matrix Tg, it is possible to cause the lignin to undergo thermoplastic flow and, upon cooling, reset in the same or modified configuration. This is the principal behind bending bamboo with heat.

The strength of bamboo is virtually unchanged while free water is leaving the culm. But once the free water is gone and bound water starts evaporating the values for strength, hardness, and stiffness begin rising and culminate at zero moisture content after having risen substantially. Oven dried bamboo is at it strongest with relation to moisture. Surprisingly, even greater strengths can be obtained by lowering the temperature. Dropped well below freezing the strength of bamboo continues to rise.

Speaking of temperature in general, the strength of bamboo falls as the temperature rises--about 5% for every 10F rise. So, placing your flute in a hot car such that the temperature goes from 70 to 100 degrees drops the strength about 15%. If the flute is under stress anyway, elevated temperatures could cause it to crack.

In the shakuhachi world there's a lot of talk about CURED bamboo. Curing is just a fancy word for drying. Expelling the free water can happen in weeks, if not days. Once the MC gets down to 20%, evaporation should be slowed a bit and dropped to 10% in a few months. Then the culm is dry-- it's cured, it's done. Nothing further is going to happen, even if it sits around for twenty years following the seasonal variations in humidity. The sponge by the kitchen sink doesn't 'cure', it just dries. In short, letting bamboo sit around for years doesn't facilitate any process which has any relevance to flute making. No time-dependent transformative process takes place--chemical, spiritual or otherwise. 'Curing' is simply drying green bamboo. CURED bamboo is a sales gimmick, about all it means is the bamboo is probably covered with dust.

Once the free water is gone bamboo begins shrinking in diameter as much as 10-16% as well as in wall thickness (15-17%). Such shrinkage is appreciably higher than encountered in wood. Which brings us to another myth. Since there is little dimensional change during free water absorption/desorpsion, it doesn't matter a whole lot how much free water bamboo contains. So it shouldn't make much difference when bamboo for flutes is cut. Water levels could be quite high, MC approaching 150%, but since free water has little to do with anything flute-wise it shouldn't matter. The tradition of cutting flute culms in the fall isn't a water issue, as many suppose, but a starch issue. Dry season is the best time to harvest bamboo when the culms are lowest in terms of starch content level making it less susceptible to powder post beetle attack. No shoot emergence also occurs during this time, hence shoot damage is evaded. In some areas of Japan, bamboo harvest is signaled by the yearly appearance of Pleiades (Subaru in Japanese) at dusk--around the first of November.

Another thing to realize. Since dimensional variations only takes place during bound water gain/loss, any time the MC of your flute changes, it's bore diameter and wall thickness also change. What this means is the sound of your flute is dependent on it's moisture content. And you thought the shakuhachi was simple! The difference between your 1.8 jinashi shak being at the Fiber Saturation Point and zero Moisture Content would be an average of 13% difference in bore diameter, which is about 3.5 EAR points. So with the normal variations in your flute's MC you can expect a one point shift in EAR. What does your flute sound like? It really depends on it's moisture content--which changes. This fact calls into question the comparison of different flute's timbre when moisture contents aren't known AND the MC at which each flute is intended to sound it's best isn't known. Any high-level pronouncement about ultra-refined tonal variation, made without knowledge of moisture content, should be treated with caution.

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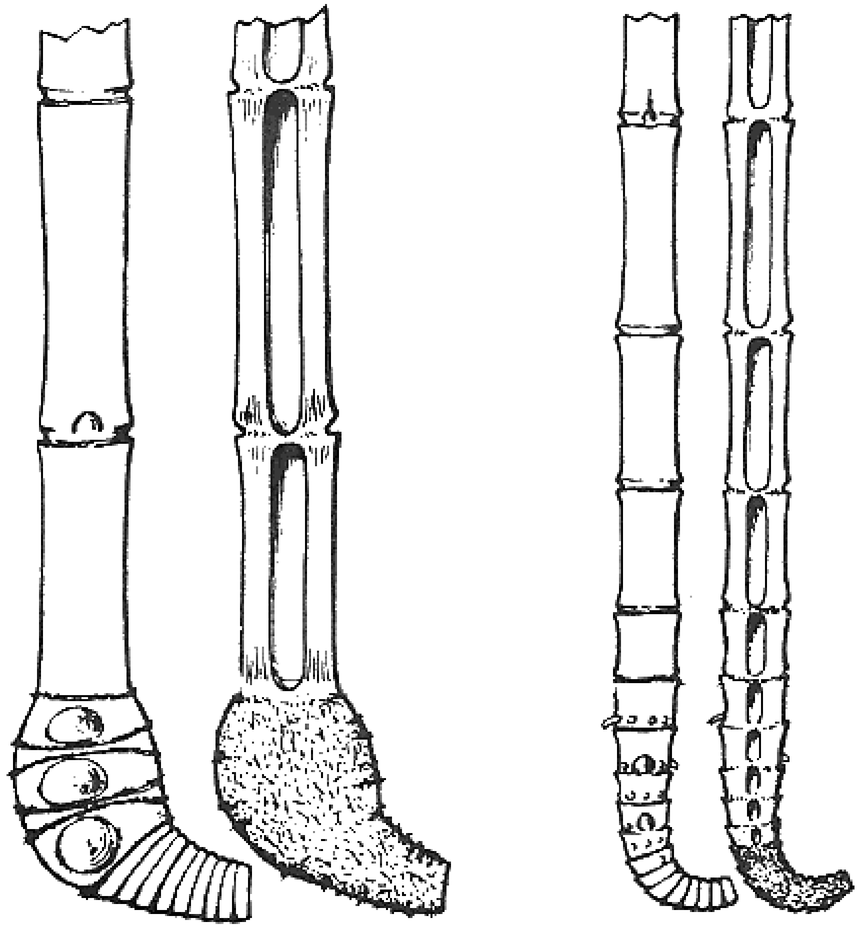
Shaku Design	Nodal Tuning

Updated 12/31/06

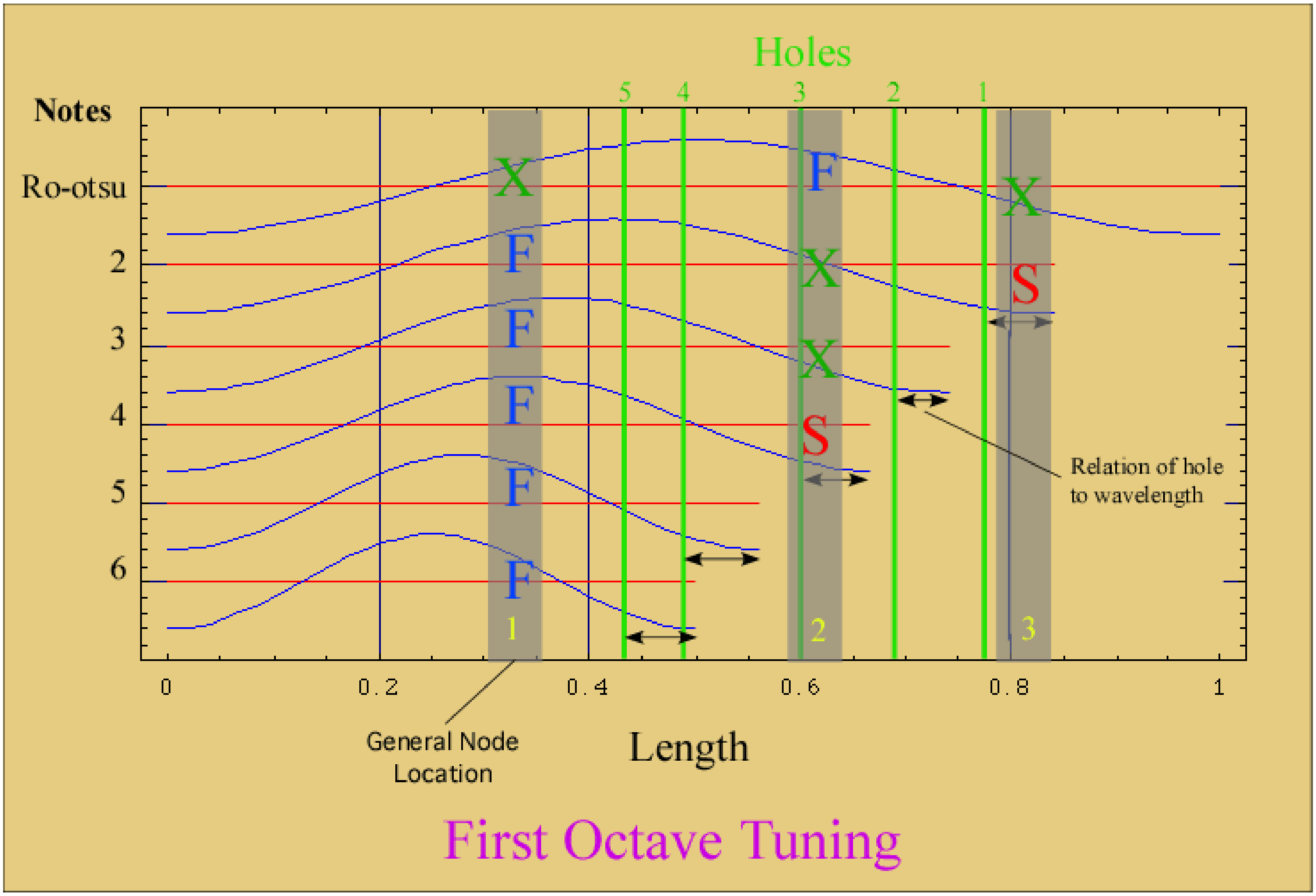
Bamboo flutes need to have the inner nodes (the diaphragms) removed in order to form a tube. Partial removal of the diaphragms allows for tuning opportunities by way of perturbation.

For root-end culms, nodal location is in the vicinity of 1/3, 3/5, *and 4/5 of the total flute length.*

Cutting/ sanding away partially removed diaphragms will affect a flute's tuning, hence the practice of Nodal Tuning.

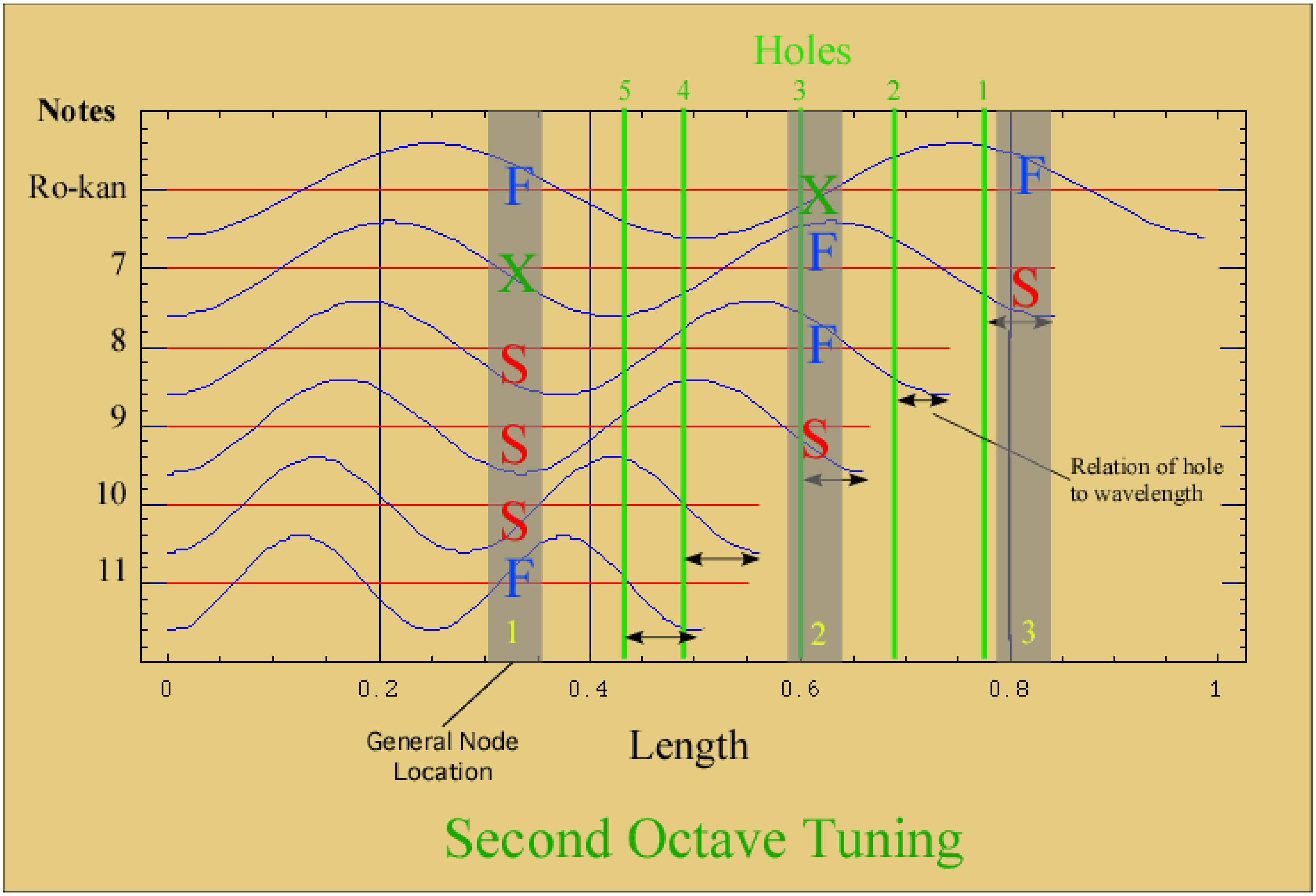


Often, tuning diagrams indicate that a note's wavelength ends at the hole, but it runs past the hole as indicated. To get an accurate picture, the wavelengths must be represented correctly as they are below.



Removing material where the blue wavelength is above the red line FLATTENS the pitch. When the blue wavelength is below the red line the pitch SHARPENS. When the blue wavelength is near the red line or crossing the red line little pitch change takes place (X). As can be seen in these tuning graphics, removing material sharpens some notes while at the same time flattening others. And to be clear, removing (or adding) material anywhere in the upper half of the flute affects ALL notes. In the upper half of the flute you can't adjust the bore just to fix one or two notes, they're all affected--some more than others and not always in the same direction.

Short wavelengths (higher notes) are affected more than longer wavelengths (lower notes). And the location (along the bore) of the diaphragms is of significant importance as can be seen after study of the tuning graphics.



The first node (the one closest to the head of the flute) affects all the notes as it's in the upper half of the bore. For nodal tuning it's the most important. Since the location of nodes varies considerably between culms each flute needs to be thought about separately. Apparently, it isn't bamboo's primary intention to become a flute.

	Ro otsu	2	3	4	5	6	Ro kan	7	8	9	10	11
First Node	**X**	**F-**	**F**	**F+**	**F**	**F**	**F-**	**X**	**S**	**S+**	**S**	**F-**
Second Node	**F**	**X**	**X**	**S**			**X**	**F+**	**F**	**S**		
Third Node	**X**	**S+**					**F**	**S**				

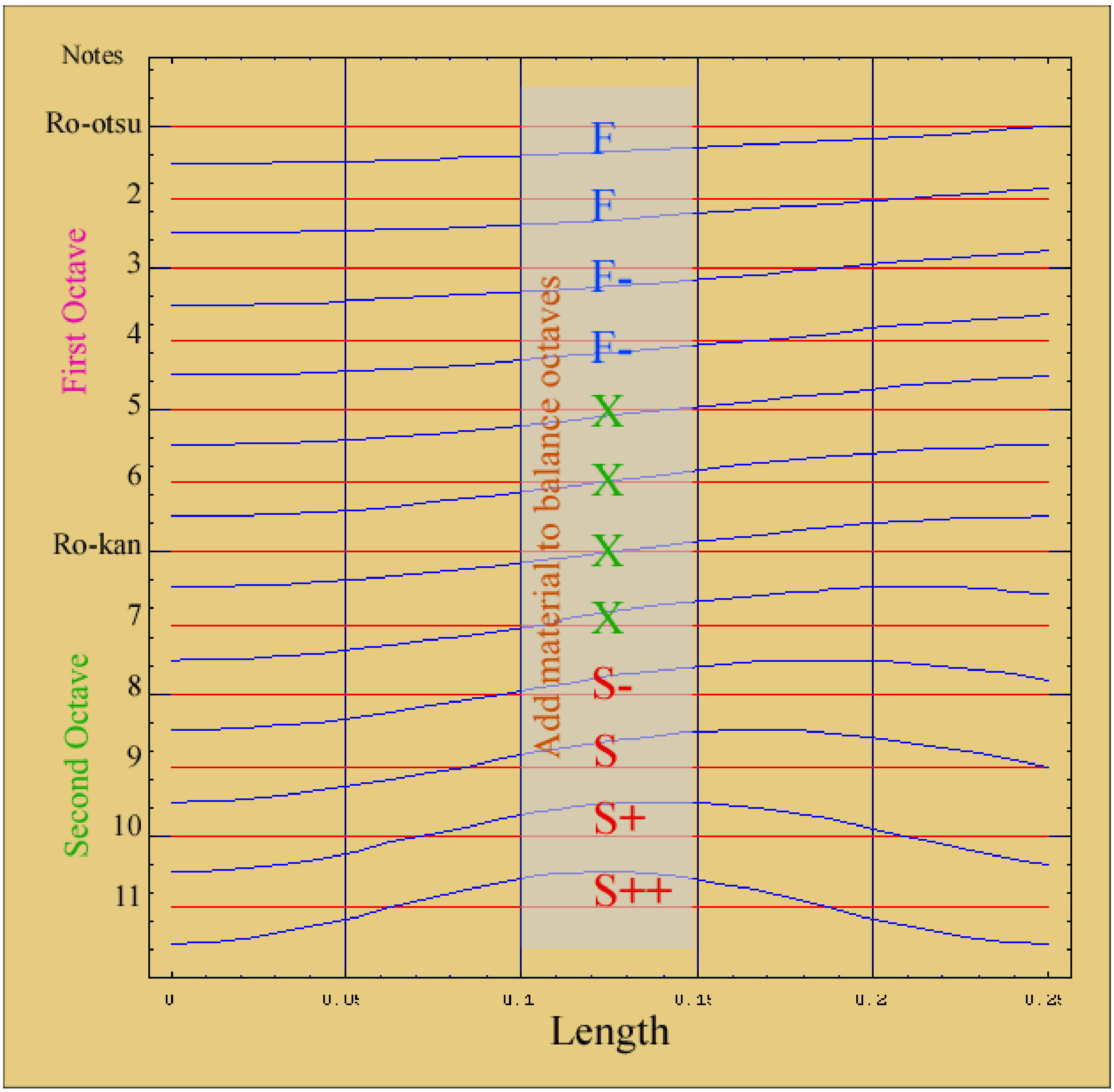
It's vitally important to know where the nodes are in relation to the bore length, which is to say, in relation to the wavelengths. Once the first node is marked on the graphic at the end of this page, the change in pitch for every note can be predicted and notated. Removing more of the diaphragm just moves each note further in the direction it was going. The degree of perturbation (both flat and sharp) is largely determined by how near to the center of the wave-crest the node falls.

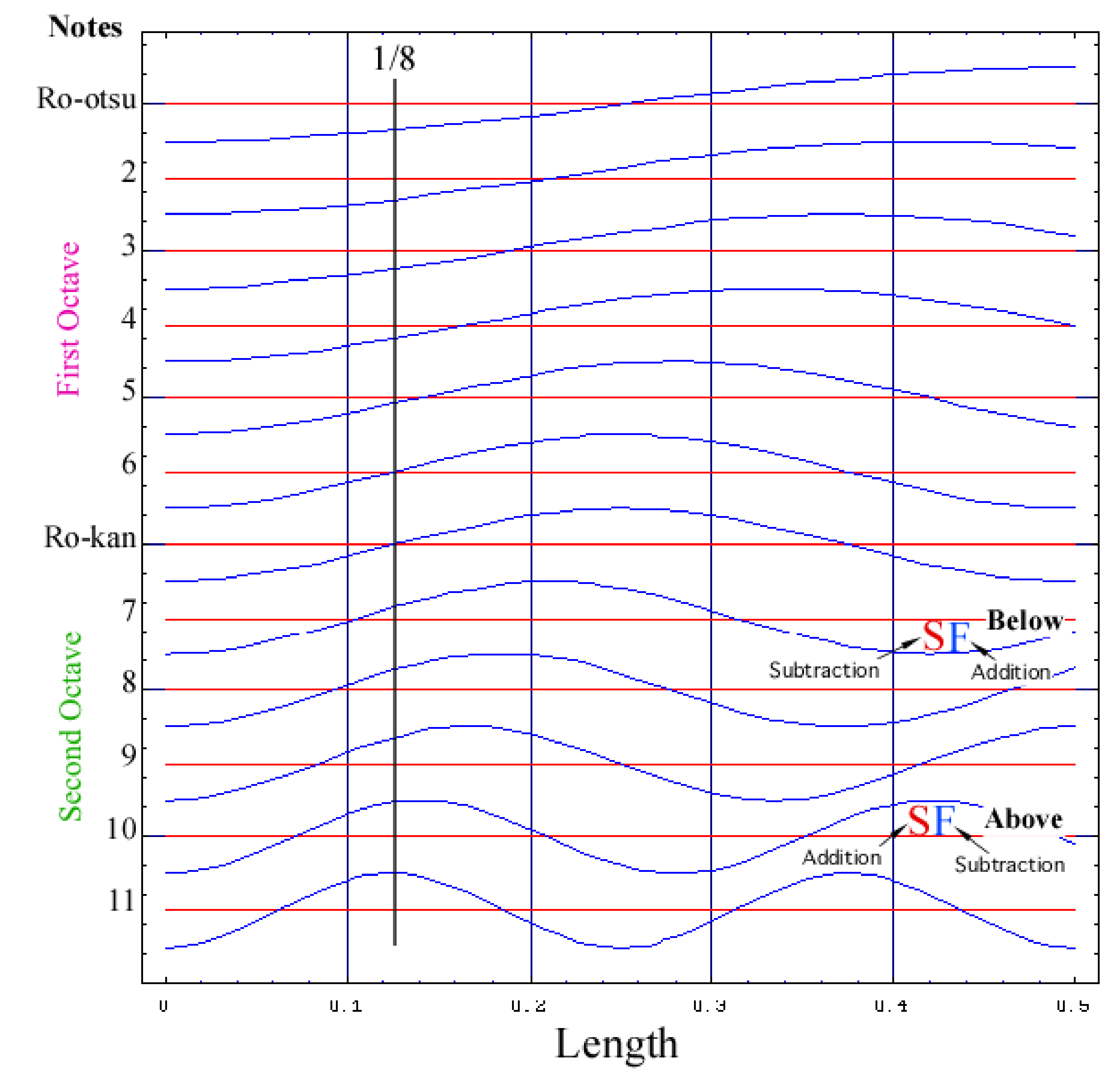
There is a way around the limitations inherent in nodal tuning:

1) Remove all nodal diaphragms until the bore wall is flush.

2) Tune the first octave slightly flat progressing upward from Ro-otsu. This is most easily done by working on the holes. Tip the first octave so that it gets progressively flatter.

3) There is a single place in the bore where perturbation affects all the notes in a smooth and progressive way--at 1/8 the length. Nowhere else in the bore is this possible. Adding material at this point flattens the low notes and sharpens the high notes, so Ro-otsu (etc.) is flattened and octave balance is achieved. Adding material at this special place tips the first octave back to where it should be and the second octave is progressivly sharpened, bringing it into balance. This spot can be up to an inch long so the bore addition should be from 1/2" to 1" long. Bore addition works backwards from bore subtraction as far as tuning goes, so the following tuning graphic below works differently (opposite) from the two above.





Download to desktop, print out and use to plan tuning.

There are four cases: Above, Below, Add and Subract.
On the Tuning Chart are reminders as to how the cases resolve to either Sharpen or Flatten.
Mark nodes or additions/subtrations and determine how each will affect the flute's scale.

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