Building a Xylophone, Part 1: Xylo-troduction

Kate Salesin ∷ 11/12/2020

Kate Salesin

Feb 28, 2018

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2 min read

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One day, I woke up and decided to build a xylophone. There wasn't a whole lot of rhyme or reason to this decision — it just seemed like a fun project to occupy a month-long lull in my schedule, and easy enough for a woodworking beginner. I had played xylophones, bells, vibraphones, and other auxiliary percussion growing up, and I thought it would be nice to build an instrument for myself. Little did I know, it would be a long descent into a rabbit hole of acoustics, structural engineering, and programming.

'Beginner,' though, might be a wild understatement, because I had never done any woodworking before in my life. I've shown many a salt-crusted boat dooflicker some love, but that was limited mostly to sanding and varnishing. Luckily, I had a fountain of knowledge nearby in my dad, who has been a woodworker for a long time, and who has cultivated a small armory of a woodworking tools in our basement.

He also had a large block of padauk given to him by his brother over ten years ago. Padauk happens to be one of the woods commonly used for xylophones (along with rosewood) due to its hardness, which gives it a bright ring when struck. It is also a very pretty purplish-red color, though this piece was dark on the outside due to its long exposure.

Ready to come out of hibernation

With a block of wood in hand, a small wood shop at home, and access to a bigger wood shop at the art school nearby for a couple weeks, I was ready to get started. My first step was to research how one would cut the blocks to the right pitch, and I quickly fell down the rabbit hole of music math, which plopped me into a rambling stream of simulation software.

Next Up: Xylo-brations

Building a Xylophone, Part 2: Xylo-brations

Kate Salesin ∷ 1/7/2019

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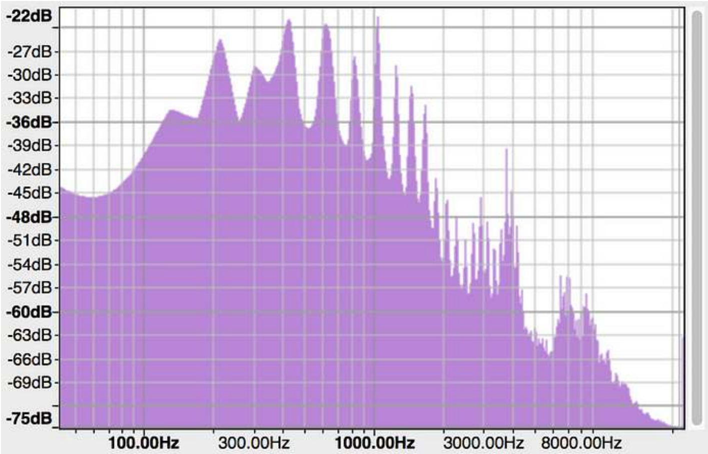
5 min read

Once I decided to build a xylophone, the first question I had to answer was how I would tune the bars. I didn’t expect a simple answer, but initial searches bombarded me with an avalanche of physics gobbledygook like ‘antinodes’ and ‘Fast Fourier Transforms.’ I suggest you put on a hard hat before we proceed.

Here’s a snowball to ease us in: the variable that affects frequency most for a bar or tube is **length**. If you brush a set of wind chimes from short bars to long, it clearly descends in pitch. The same tenet holds for organ pipes, glockenspiels, and xylophones, along with many other percussion instruments. For my xylophone, then, could tuning simply be a matter of cutting the bars to the right length?

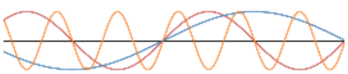
Of course it couldn’t be that easy. It turns out that when an object resonates, it does so at multiple frequencies. The lowest, and generally loudest, frequency is the **fundamental frequency**, which is the note that we primarily hear. The other resonant frequencies are called **modes** or overtones, named the second mode/first overtone, third mode/second overtone, etc. in order of increasing frequency. The fundamental frequency is the first mode. If those overtones happen to be integer multiples of the fundamental, they are called **harmonics**, and sound particularly… harmonious.

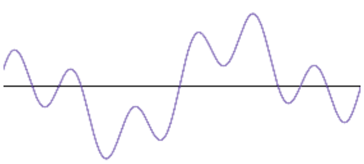
For any sound, we can identify the modes, or resonant frequencies, by plotting all frequencies present in that sound against their power level in decibels (by using software that performs the above-mentioned Fast Fourier Transform). Such a plot is called a **power spectrum**, and the peaks in the spectrum are the different modes within the sound.



Power spectrum for Star Wars opening chord

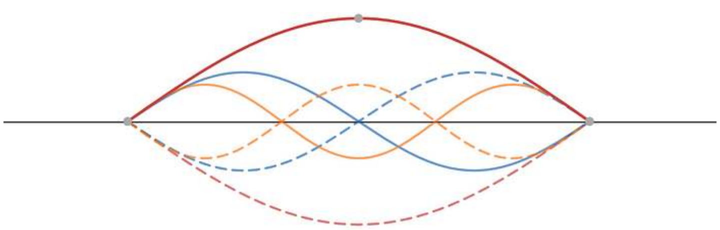
One interesting aspect of power spectra is they can give us clues as to the tone or quality of the sound. For example, a spectrum with a very dominant fundamental frequency might have a crystal clear, pure quality, and might have been produced by a flute or violin. Conversely, a spectrum with many modes vying for top billing might have a fuzzy, woody, or even cacophonous quality, and might have been made by a bassoon or bagpipes. The plot above has a particularly high number of peaks because there are many instruments playing different notes simultaneously.



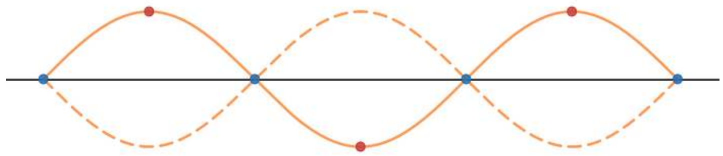


Three simple waveforms (left) combine to create a complex waveform (right)

Each mode has a waveform associated with it, which describes the oscillating vibration of the air molecules that propagate the sound. When the waveforms from each mode are added together, they create a single complex waveform that reconstructs the original sound. In some cases, we can easily visualize the waves being created in the sound-producing instrument, such as a guitar. When you pluck a guitar string, it vibrates strongly in the middle, which creates the fundamental frequency, and also activates other modes.



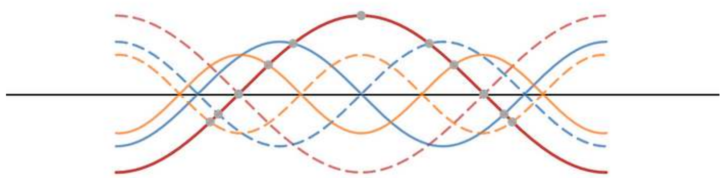
First three vibrational modes for a fixed guitar string



Nodes (blue) and antinodes (red)

The **antinodes** of the wave are the points along the string that move the most, and the **nodes** of the wave don’t move at all. In a string instrument like a guitar, the two ends of the string are fixed, which forces the wave to have nodes at those points. If you were to pluck the guitar string directly in the center, that would favor the modes that have an antinode there (odd modes) and dampen those with a node (even modes). This is likely why it sounds better to strike the string off center—that way all modes can be excited.

In a xylophone, the bar itself acts like the string — it physically vibrates, albeit less dramatically. However, the ends of a xylophone are not fixed, which means the natural nodes of the fundamental frequency are located about a quarter of the way into the bar.



First three vibrational modes for a xylophone bar

Because of the free nature of the vibration, the second and third modes of a xylohone bar produce frequencies that are 2.76 and 5.4 times the fundamental. You may have noticed those are not integers— if you didn’t, then take a moment to observe so. This means the sound of a struck block of wood is naturally discordant, which begs the question, how do we make the block of wood sound more pleasant, and perhaps more importantly, do we care?

It turns out we do, though interestingly, people didn’t care about tuning the higher modes of xylophones and marimbas until the 1920s. A marimba is like a xylophone but with larger bars and a wider range. Another key difference, I discovered, is that the second and third modes of a xylophone are tuned to multiples of 3 and 5 times the fundamental, whereas a marimba is tuned to 4 and 10 times the fundamental, which creates a deeper, richer tone.

The trick to tuning higher modes is to carve out the underside of the bar, which affects the shape of the waveforms when struck. In commercial instruments, this tuning is done first by machine, then by xylophone tuning prodigies who meticulously guess and check. Being fluent in computer and not a xylophone tuning prodigy, my next question to research was, how can I get a computer to do the work for me?

Next Up: Xylo-speriments

medium.com /@kas493/building-a-xylophone-part-3-xylo-speriments-951105bf9f16

Building a Xylophone, Part 3: Xylo-speriments

Kate Salesin ∷ 1/7/2019

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4 min read

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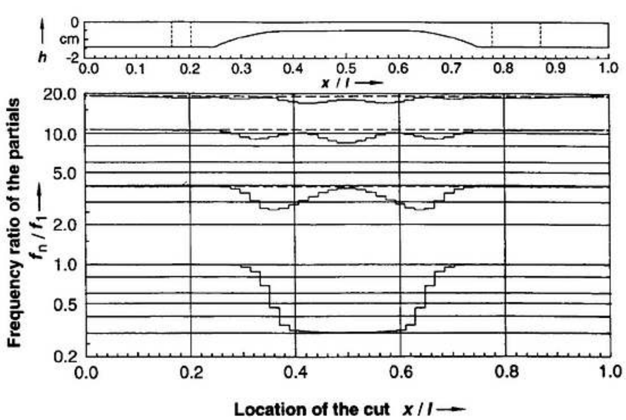
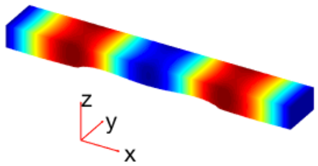
My first stop along the research highway was to find studies on how cuts along the bar affect its resonant frequencies. It is known that cutting at the center of the bar causes it to be more flexible and therefore lowers the fundamental frequency, but the relationship between cuts and higher modes is more nebulous. General tuning strategy is to make cuts progressively toward the outer ends of the bar to tune higher and higher modes.

In his 1995 experiment "Practical Tuning of Xylophone Bars and Resonators," Ingolf Bork elucidated this relationship by discovering that cutting the bar at the antinodes of a mode had the greatest effect on lowering its frequency, while cutting at a node had minimal effect.



Results of Bork's experiment

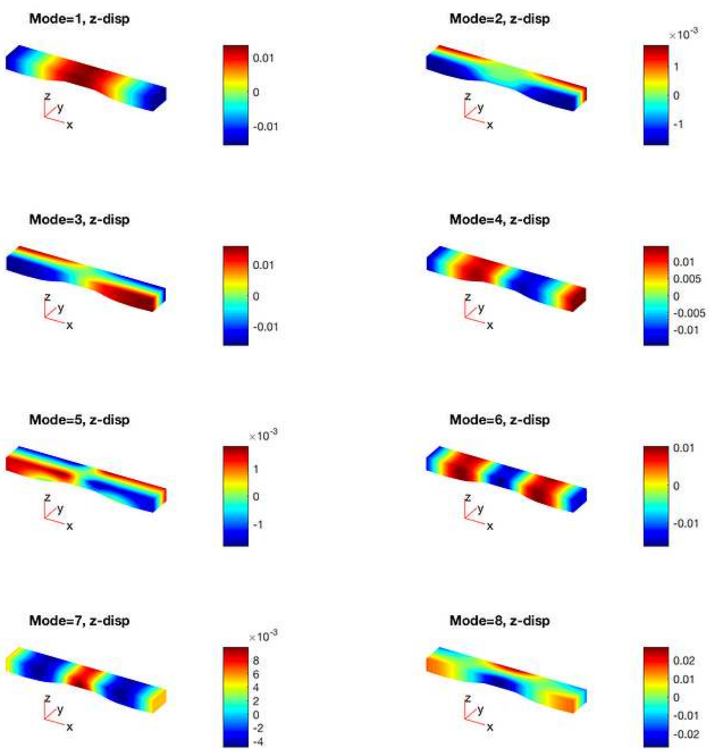
Next, I turned to the optimization problem of carving the bars to match desired frequencies. The batch of papers I ultimately decided to emulate used Finite Element Analysis to tackle this problem. At first those words, coupled with 'partial differential equations,' struck a primal fear into my heart. But upon deeper inspection, I found they were code for stuff the parameters into a computer and let magical, colorful results pop out.



Magical!

Finite Element Analysis is essentially a process where a computer breaks down a 3d model into very tiny pieces ('finite elements'), analyzes their tiny little reactions to force and disturbance, then combines all that data together to predict the reaction of the whole model. It is used often in structural engineering and industrial design to measure stress and potential breakage points, heat transfer, and resonance frequencies.

Why would structural engineers care about resonance? Often they are trying to avoid it. The classic example of a resonance problem is the ill-fated Tacoma Narrows Bridge in Tacoma, Washington — the bridge collapsed in 1940 when high winds caused it to vibrate violently at its resonant frequency. Even in small scale examples, like a machine part, the vibrations caused by resonance could cause the part to wear and weaken over time.



First eight vibrational modes of a xylophone bar, z-displacement

We can visualize the results of a Finite Element Analysis with a plot for each mode/resonant frequency showing the displacement, or movement, of the system under vibration as colors — red and blue here correspond to areas of high displacement, green zero displacement. Since the model is three-dimensional, you would need a separate plot for each dimension or a 3d animation to get a full picture of the movement for each mode.

For our purposes, we care about only the **tranverse** modes along the length of the bar, which have high displacement in the *z*-direction independent of *y*, and are modes 1, 4, 6, and 7 in the above diagram. As you can see, the analysis finds many other modes, some of which are transverse in other dimensions or **torsional/**twisting motions. Technically, those other modes could be tuned to a desirable frequency as well, but since we tend to hit a xylophone bar along the central axis of the length and not, say, on the side or the edge, those modes are unlikely to be excited.

Having reviewed the literature, there was clearly a precedent for my experiment, but there was one key distinction that threw a spooky minor chord into the works. All the FEA studies above used aluminum for their bars, creating a metallophone, not a xylophone. Aluminum is **isotropic**, which means its properties are the same regardless of direction, whereas wood is **anisotropic**, or directional. Not only that, but wood has curves, twists, and inconsistencies within the grain due to its organic growth, making it inherently unpredictable. The studies also used very precise computer-guided machines to carve the final aluminum bars.

Results of Kirkland's experiment, aluminum bars carved by CNC machine

My xylophone, on the other hand, would be hacked together by me, someone who has literally never used a saw before. I've sanded some crusty boat bits in my day, but that's about the extent of my experience. So I went forward knowing that even if I could manage to get a computer result that claimed to produce heavenly frequencies, it would unlikely be replicated in reality. My mindset toward the computer phase was to see if I could implement an algorithm that predicted optimal bar shapes to a reasonable accuracy, and then use the results as a guide when actually cutting the bars.

The paper I decided to base my experiment on was a Master's thesis by Brandon Kirkland, though I diverged in how I modeled the underside curve. In the next section, I describe my ultimate experiment setup, along with some failed strategies I littered along the way.

Next Up: Xylo-gorithms

Papers of Interest

Bork, I. (1995). Practical Tuning of Xylophone Bars and Resonators. *Applied Acoustics*, 103–127.

Kirkland, W. B. (2014). Topographical Optimization of Structures for Use in Musical Instruments and Other Applications. Master’s thesis, University of Alabama at Birmingham, Birmingham, Alabama.

Building a Xylophone, Part 4: Xylo-gorithms

Kate Salesin ∷ 1/7/2019

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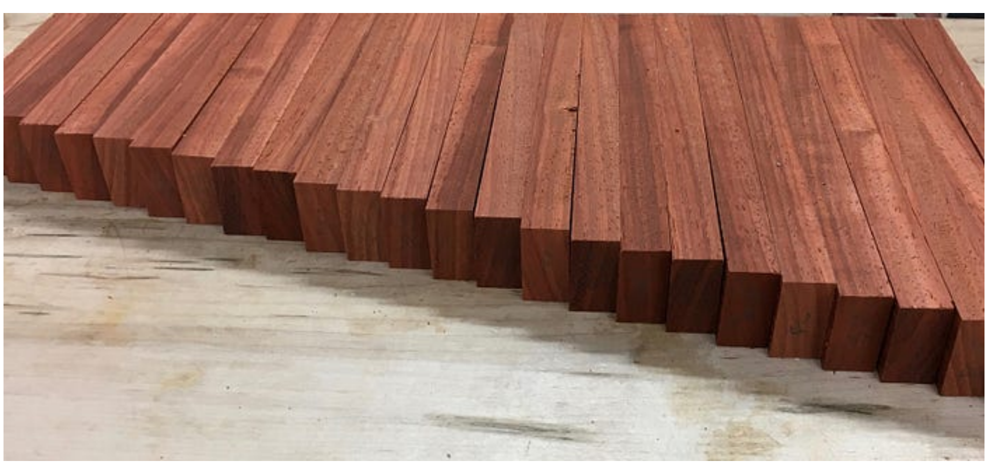
6 min read

The first step in my process was to get a Finite Element Model working. Most of the software structural engineers would use for FEM is either proprietary or expensive, so I shopped around a bit to find a free option. I ended up using MATLAB and its Partial Differential Equation Toolbox, since I already had a student license and knew the language.

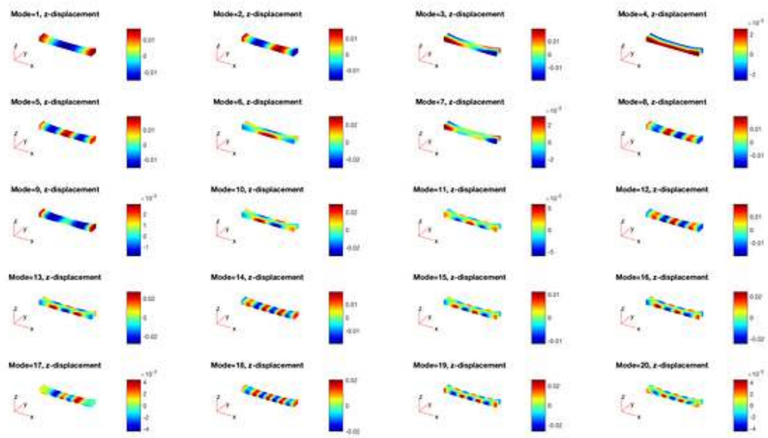
With the canvas staring blankly before me, all I had left to do was paint my masterpiece, right?

Actually, I had to give the program a palette of colors and it was going to do the painting for me. Finite Element Analysis needs three colors: the model, the material, and the constraints. The model was the trickiest part, and was redrawn each iteration based on the results of each analysis — we'll address that later.



The material can be described with a set of properties: the elastic modulus, or how bendy the wood is; the poisson ratio, or how stretchy the wood is; and the density, or how likely it is to hurt if you drop it on your foot. Since wood is anisotropic, or directional, the properties change depending on which direction you measure, but since we only care about the direction aligned with the grain (also called the longitudinal direction), we can use those properties. Luckily, that's generally the direction people care about for wood, and I found the corresponding elastic modulus and poisson ratio for padauk wood online. I calculated the density of my own block with a tape measure and food scale.

We didn’t have any constraints for our FEA because the bar will be moving as freely as possible — there will be no outside forces or restrictions on its movement. With the properties set, I ran my first FEA on a plain rectangular block. Being a graphics nerd, it’s always a euphoric moment when your code runs without errors for the first time and a pretty picture pops out — like a pixel baby.

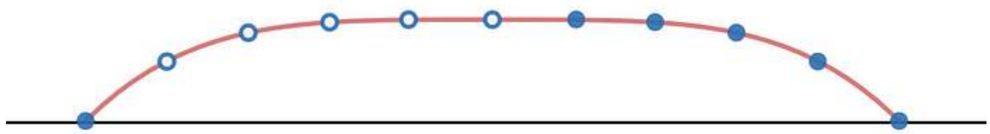


First twenty vibrational modes for a plain wood block, z-displacement

However, our bars were not going to be boring rectangles, so we had a lot of work ahead. Our bars needed a curve cut out from the underside (an ‘undercurve’) in order to match the first three desired resonant frequencies. To accomplish this, I tried to emulate Kirkland’s experiment as closely as possible, but I also wanted to simplify since I had a time restraint.

I based the width, thickness, and lengths of my bars on this Yamaha marching xylophone, which had dimensions listed in the specs. I chose this one because it was particularly small, which meant I could cut the maximum number of bars out of my padauk block.

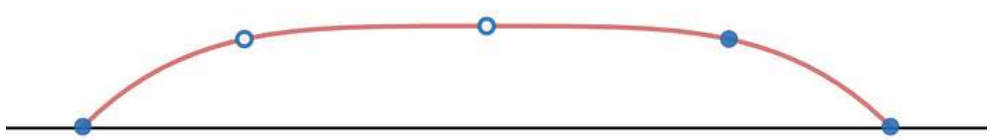
Kirkland’s set up was to keep constant the width, length, and thickness outside the undercurve for each bar, while varying the thickness within the undercurve (matching what xylophones generally do). Specifically, he used eleven equally-spaced points along a spline to model the undercurve, with constraints that the curve be symmetrical and the two end points be at full thickness. This left five variables to optimize: the cut depth of five inner spline points (one point in the center, four pairs of symmetrical points).



Example undercurve (11-point spline) showing variables (open circles) and constants (closed circles).

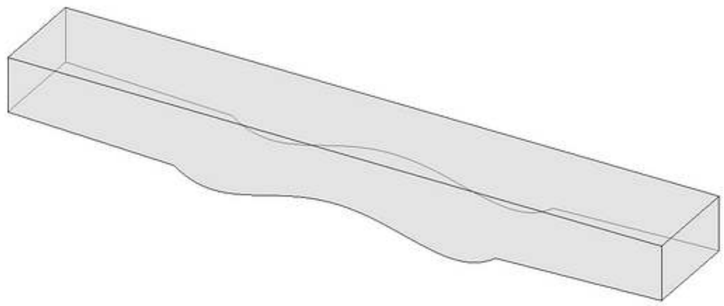
I generally stuck to his experiment set up (more details of which are in his paper), except in how I modeled the undercurve. I knew I wanted to decrease the number of variables in order to decrease the time it would take for the optimization to run. In retrospect, I think decreasing the variables did limit the algorithm and increased the overall error of the results, but I knew the errors the program reported were unlikely to be translated to reality anyway, due to the unique swirly nature of the wood.

My first approach to optimizing the curve was based on Bork's 1995 paper, which found that cutting at the antinodes of a mode had the greatest effect on its frequency. The location of antinodes for a plain rectangular block are known (as a proportion of its length), so I used those to approximate the antinodes of my block. To start, I only bothered with the first two modes, which meant I could model the undercurve with five points: a center point for the first antinode, two inner points for the second antinodes, and two end points. Since the curve had to be symmetrical, this left me two variables: the cut depth at the center and inner antinodes. Since there were five points, the curve could be modeled by a unique quartic polynomial (found by solving a system of linear equations).



Example undercurve (quartic polynomial) showing variables (open circles) and constants (closed circles).

I made my own simple optimization algorithm based on Bork's results: find the frequency most out of tune, cut its antinode more if too sharp, uncut its antinode if too flat, rinse and repeat. Though simple, this strategy sometimes produced impossible geometry.



Not as captivating as Escher

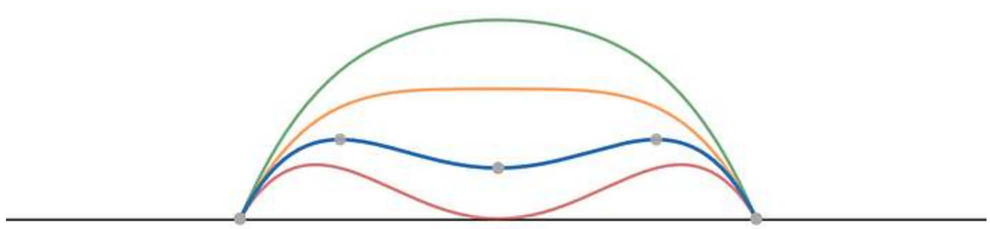
Since that clearly wasn't working, I turned to a new strategy. I knew that a polynomial curve to describe the undercut had to be at least fourth-degree in order to produce the range of shapes typically seen in a xylophone, from round to *w*-shaped. Generally, a quartic polynomial has the following form, with five coefficients *a*, *b*, *c*, *d,* and *e*:

$f(x) = ax^4+bx^3+cx^2+dx+e$

I wanted to find a more specific form for my quartic, given the constraints that the curve be symmetrical and the end points (or roots) be at specific locations along the *x*-axis. In math-y words, the quartic would be biquadratic (or have odd-degree coefficients of zero), have two real and two imaginary roots, and it would be a frowny face. I derived the new quartic equation and found it could be described with two coefficient variables instead of five:

$f(x) = –a(x^4–(–t^2+s^2)x^2–t^2s^2)$

where *s* is a constant — the *x*-coordinate of the real roots, or the start and end points of the undercurve. This gave me two variables to optimize, *t* and *a. t* essentially corresponds to the location of the imaginary roots, or the curve's '*w'*-ness, and *a* refers to the slope.



Example undercurves for a range of t and a values

With variables in hand, I set up the optimization as closely as possible to Kirkland's using MATLAB's Optimization Toolbox. The optimization algorithm tried to minimize an **objective function** while also satisfying a set of nonlinear **constraints**. Our objective function found the mass of the bar, which meant the algorithm tried to minimize the bar's mass. Our constraints limited the algorithm to accept only solutions that satisfied our desired frequencies within a certain error tolerance.

To recap, given the algorithm's guess of the variables *t* and *a* at each iteration, we:

1. Created a 3d bar model with an undercurve shaped by and
2. Ran a Finite Element Analysis on that bar
3. Found the frequencies we cared about (the first three transverse modes)
4. Set a nonlinear constraint that the error of each of those frequencies was less than 0.25%
5. If those constraints could be satisfied, ran the objective function, which found the bar's mass

Based on the results of each iteration, the algorithm picked new variables *t* and *a.* The error tolerance of 0.25% was chosen because humans apparently cannot detect changes in pitch within that range.

How well did it work? Instant gratification.

Building a Xylophone, Part 5: Xylo-nalysis

Kate Salesin ∷ 1/7/2019

Kate Salesin

Feb 28, 2018

4 min read

I soon discovered that the optimization algorithm was very sensitive to the initial guess. Recall that the inputs to this algorithm are two variables that define the quartic curve for the underside, and we have to provide the algoirthm with a first guess to get the ball rolling. To recap, the algorithm’s goal is to minimize the output of an objective function while also satisfying all constraints. In our case, the objective function found the mass of a bar shaped by a quartic curve, and the constraints were errors of the frequencies found by Finite Element Analysis.

You can think of this algorithm like a blind skiier. Our objective function is like a very wavy ski slope with lots of ups and downs, and your initial guess places the algorithm-on-skis at some starting point along the slope.

The algorithm-on-skis, like I said, is blind. It makes a guess as to which direction is downhill and takes a tentative step in that direction. If it turns out that direction is uphill, it tries taking steps in other directions until it finds downhill. Once it finds downhill, it lets gravity drag it down the slope until it settles in the nearest valley.

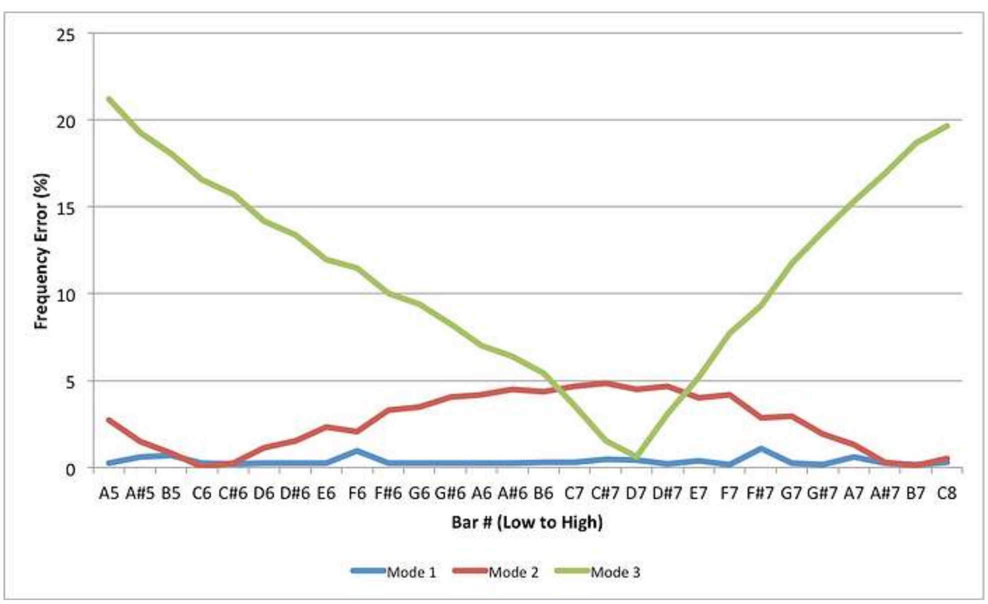
This skiier is also pretty lazy. Once it finds a valley, it decides it has conquered the slope and calls it a day. There might be a really warm, comfy ski lodge with hot toddies down at the very base of the ski resort, but it doesn’t bother to look over the next ridge.

Very technical illustration

In math-y words, the algorithm finds a local minimum, which may not be the same as the global minimum, or the very lowest value the function can produce. In our case, I found the algorithm tended to converge to a solution that was very close to the initial guess, suggesting there were many local minima for the objective function. In other words, there were many possible solutions.

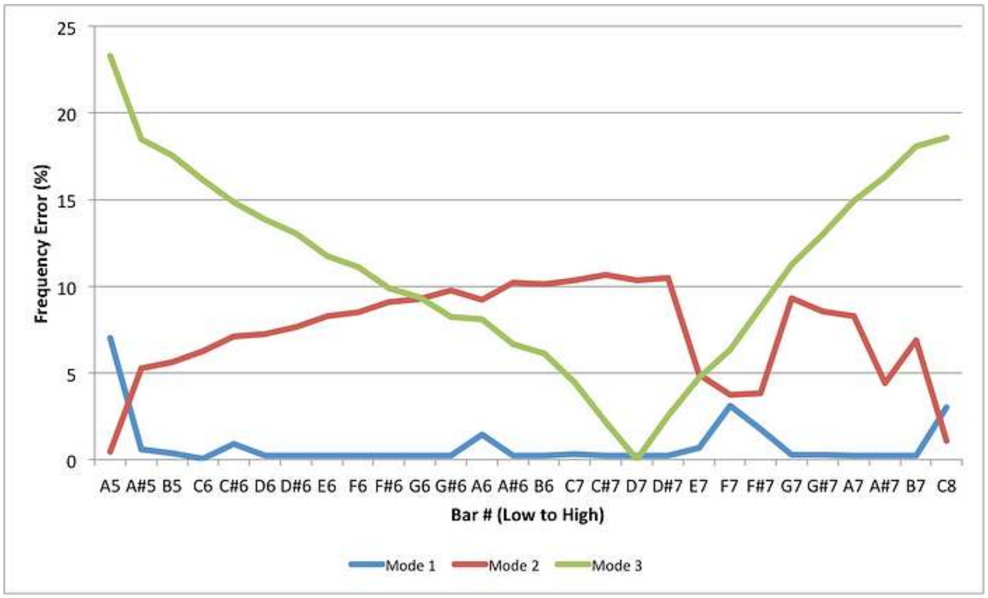
These are the error results for two different initial guesses, one creating a round profile, and the other a w-shaped profile. The *x*-axis refers to each bar in the xylophone's range, and the *y*-axis to the frequency errors for the algorithm's final solution. It took roughly three hours for the algorithm to run on all twenty-eight bars, or about six minutes per bar.

Round profile



Frequency error for round profile initial guess

W-shaped profile



Frequency errors for w-shaped profile initial guess

The algorithm was pretty reliable in converging to a solution of less than 0.25% error for the fundamental frequency (blue line), but it had trouble converging for the second and third modes (red and green lines). It was interesting to see how the guesses worked better for some parts of the note range than others — both struggled toward the extreme ends of the range on the third mode.

After running many, many trials with different initial guesses and parameters, I decided to move forward with the set that produced the best results (the round profile from above), given that I had a limited time frame. I also knew from reading blogs about xylophones that it was very difficult to tune the third mode effectively in practice, and even commercial 'tuned' instruments were often way off in that regard, so I would not worry about trying to tune the third mode.

If I were to ever revisit this project, I'd probably experiment with adding more variables into the mix and trying to reduce the error.

Finally, it was time to put the computer away and bring out the power tools! Vroom vroom.

Next up: Xylo-sculpting

Building a Xylophone, Part 6: Xylo-sculpting

Kate Salesin ∷ 1/7/2019

Kate Salesin

Mar 25, 2018

6 min read

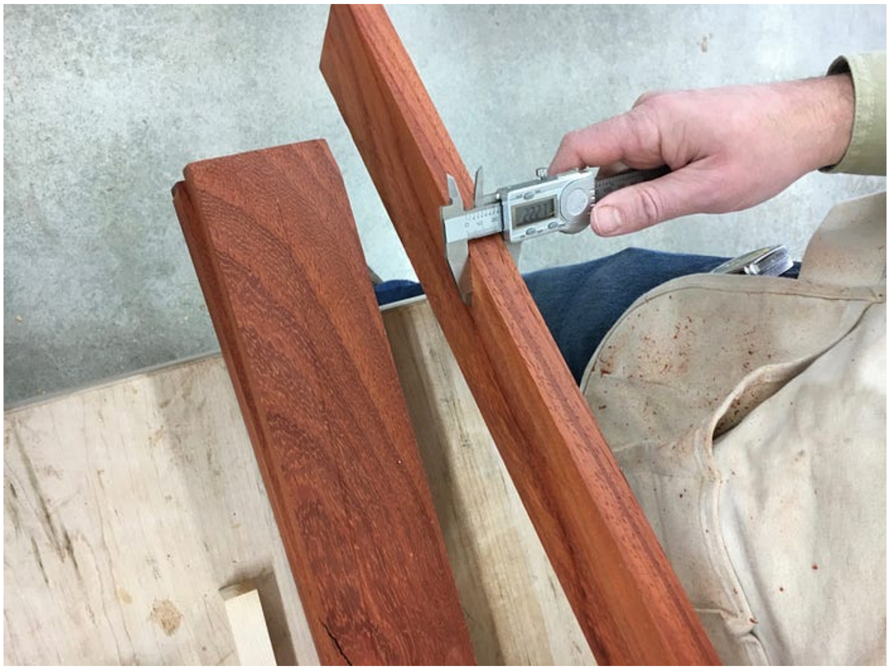
After a couple weeks of computer time, I was ready for some hands-on work. Before even thinking about the undercurves, though, we had to chop up the big block of padauk into bars of the correct width, thickness, and lengths. Like Michaelangelo, I just visualized the rectangular blocks within and chipped away delicately until the ultimate form was slowly and spectacularly revealed.

Just kidding, we used a lot of big saws.

After planing the large block of wood on all sides, the vibrant red color underneath the dark aged crust was revealed, and I was pretty excited to see it for the first time. Unfortunately, it also revealed a substantial crack running through the block. I was at first worried this would force me to downsize the xylophone, but with careful cutting and organization, we managed to cut out not only all the bars I had originally planned, but also three extra high notes.

Large crack down the center

Here is a compilation of shots from the cutting room floor.




FastCap
16FEET


Final bars after cutting

Like peanut butter and jelly, what is sawing without sanding? We had cut the lengths of the bars a bit generously, so I sanded down the ends to the correct length.

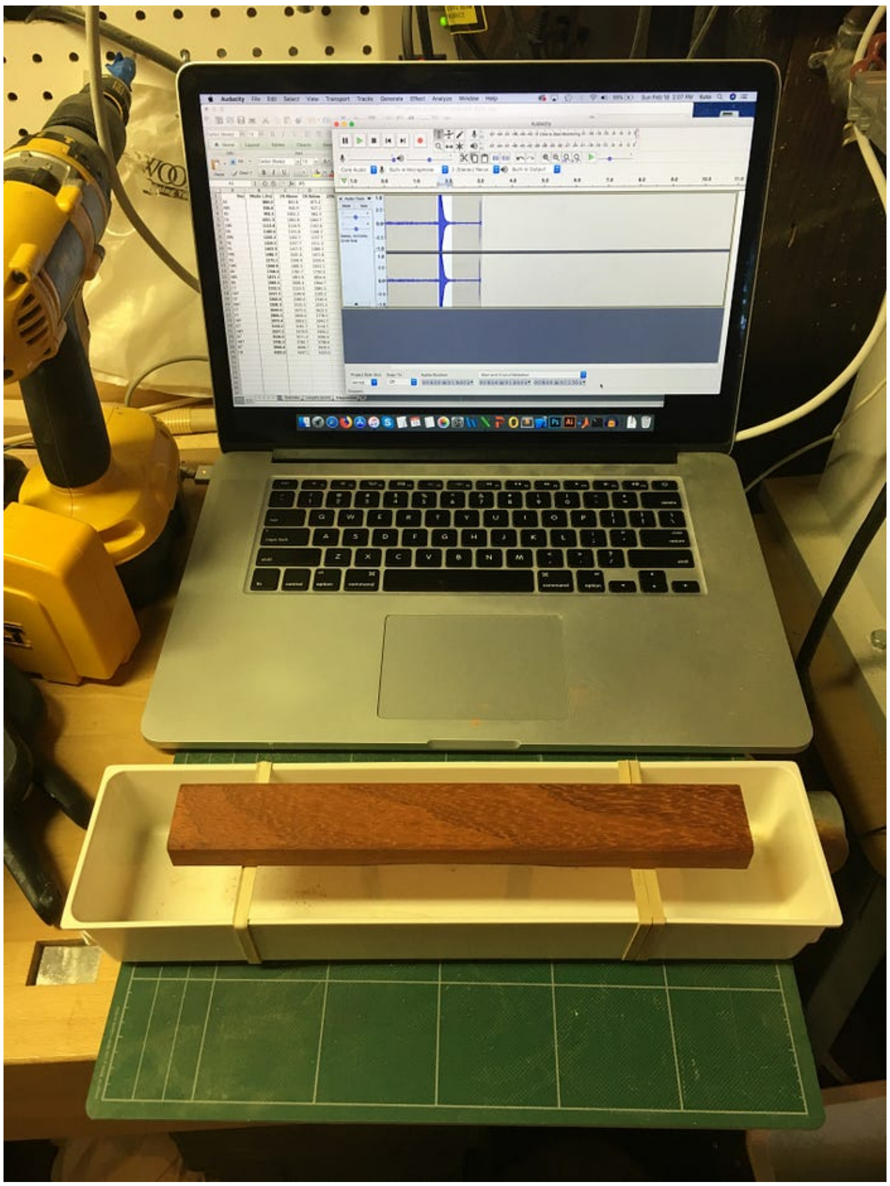
Band-Aid may or may not be due to sanding off part of my fingernail

Happy xylophone butts

It was then time to sand the undercurves, which meant incorporating my computer results. There were several ways I could have done this, but I decided to go the simple route: I printed out the profiles of the desired undercurves, cut them out, clamped them onto each bar, and colored the curve onto the bar with a marker.

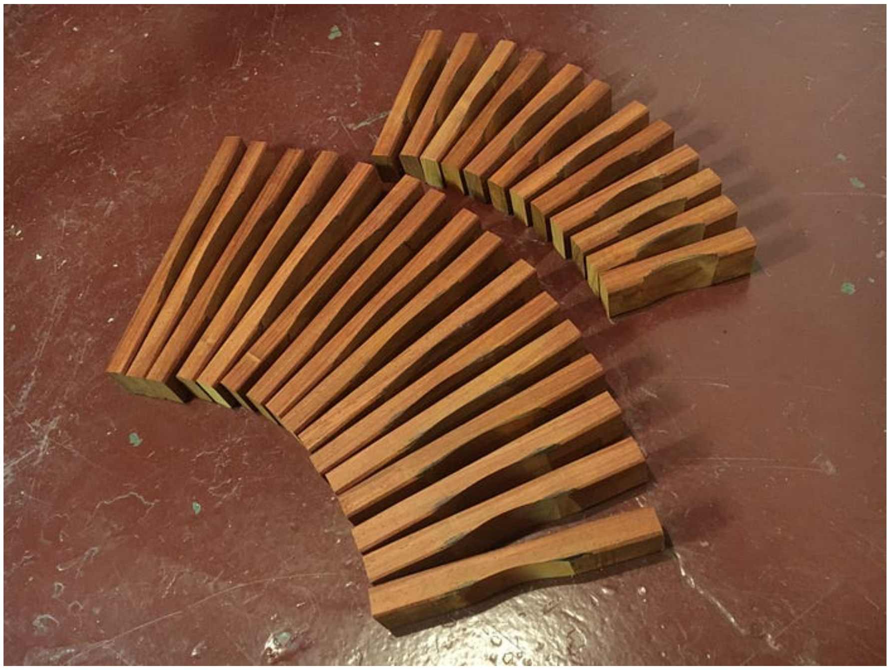
Using the marker guide, I sanded the bars down to the curve with a belt sander. Given that I was unsure how accurate the computer results would be, I started by sanding to about a millimeter short of the prediction, then went to my computer and analyzed the frequency. I used Audacity to perform a spectral analysis on the sound of the bar being struck. I then made trips back and forth between sander and computer until I got the fundamental frequency and second mode to within 1% of desired. I left some error since I knew drilling and further sanding would affect the frequency unpredictably.

I decided to neglect tuning the third mode, since I had read it was very difficult to achieve in practice and often not accurate even in commercial instruments. Also, my computer predictions were not particularly accurate with that mode.



Testing the bar's frequency

I found the computer predictions were helpful as a starting guide, but were not perfectly accurate. Interestingly, it was most helpful with low notes and got progressively less accurate as the frequency increased. I found tuning the second mode was especially difficult as I moved up the scale, and eventually I began tuning the second mode to twice the fundamental frequency instead of the desired three times, since that's the way the bars seemed to lean. I knew as long as it was an integer multiple, it would be harmonious (in this case, the second mode would be the same note as the fundamental but one octave higher).

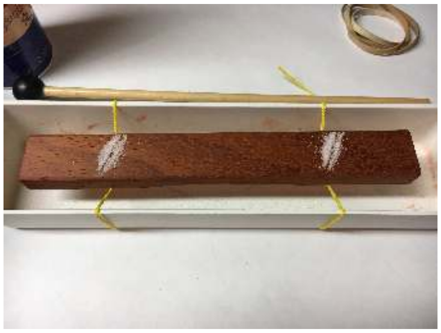

Bars after initial sanding

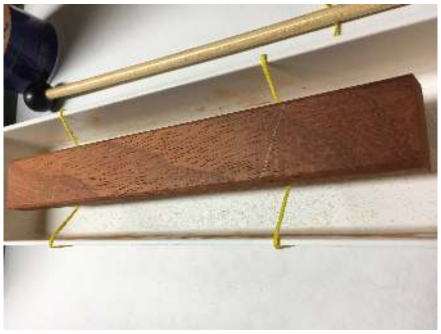
After this rough sanding, I drilled the holes where the taught string would run to support the bars. The string has to run through the bar in two places in order to support it, and the natural choices for their locations are at the nodes of the fundamental frequency. Recall that the struck bar vibrates as a wave with maximum displacement at the center, and the nodes are the locations of minimum displacement (roughly a quarter of the way in). If you were to run a fixed string through the center of the bar, that would restrain the bar from vibrating as forcefully as it would like and dampen the sound. Therefore, drilling at the nodes should have little damping effect on the bar, or allow it to be as loud as possible.

There is a clever test to find the nodes of an object, which would make a fun elementary science project. If you sprinkle salt all over the bar, then strike it repeatedly to cause it to resonate, the salt will congregate at the nodes of the object, since the bar does not wiggle at all at the nodes.

Salt test in action

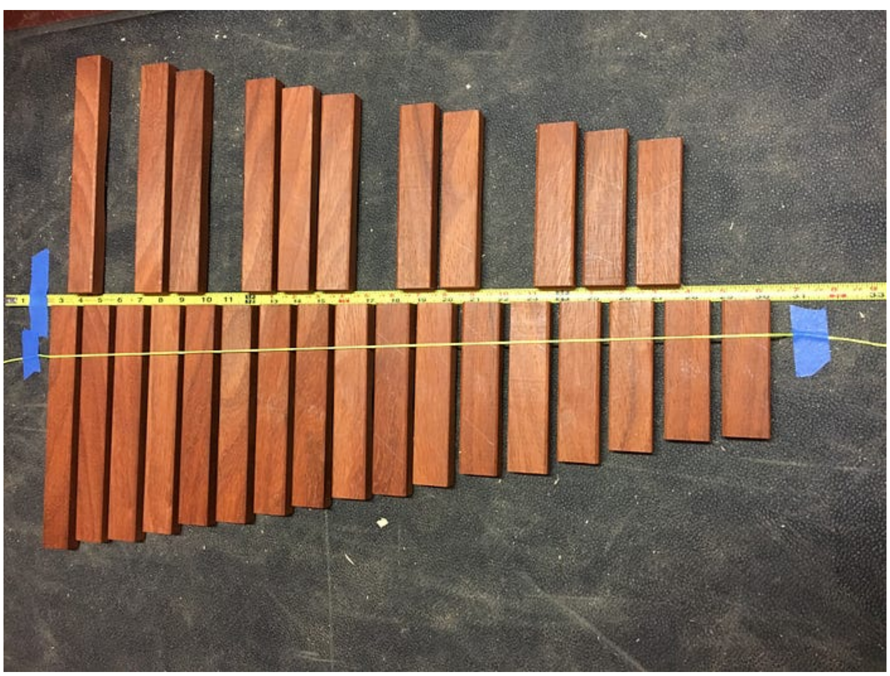
Once the salt had congregated into two lines, I drew a best-fit line in pencil through the salt in order to mark the nodes. Some lines were relatively straight across (perpendicular to the length), and some were quite diagonal, speaking to the swirling grain of the wood.



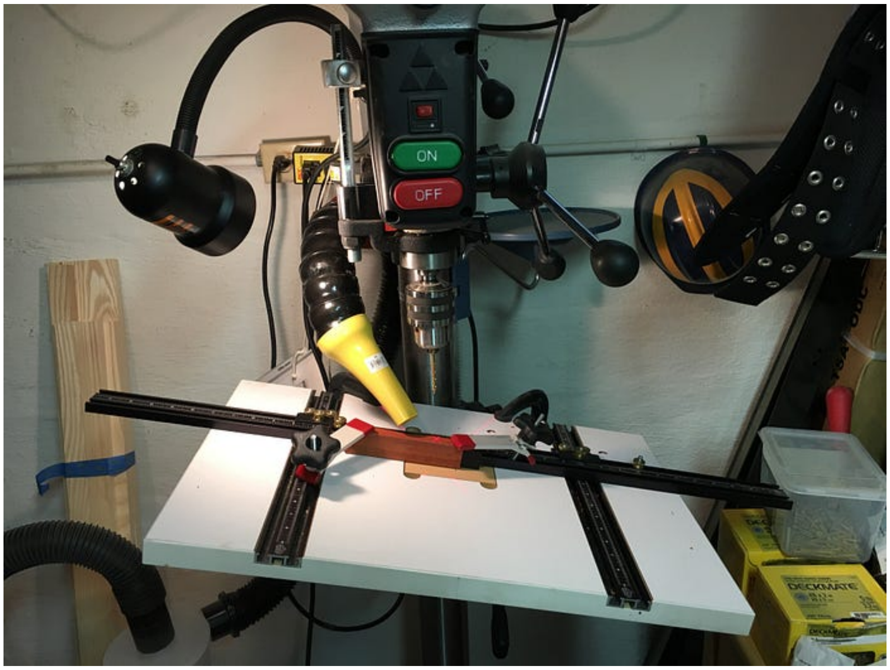


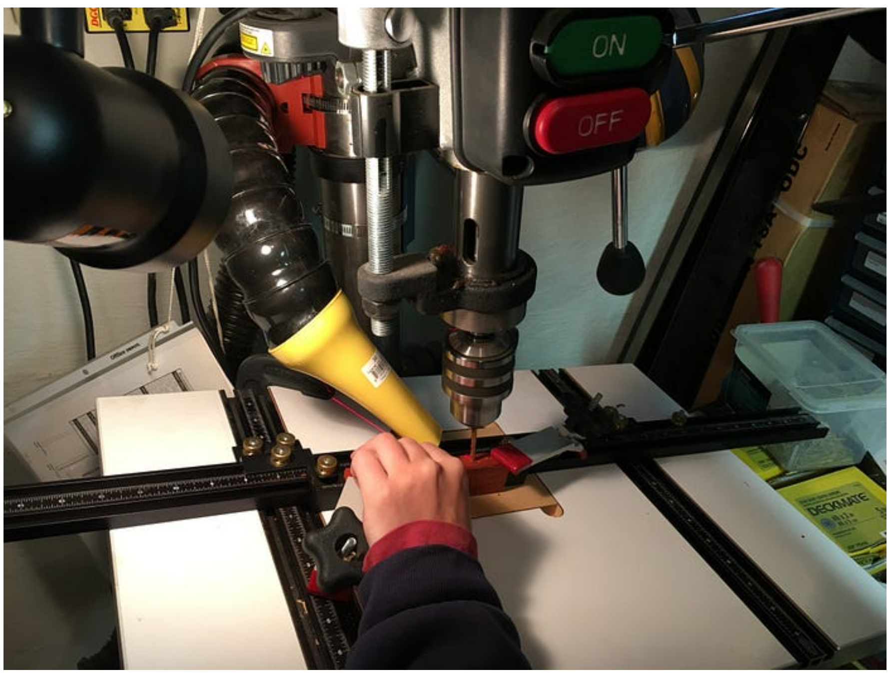
Given the unique nature of each bar, the node lines did not necessarily match up neatly from bar to bar. So I lined up all the bars in their final configuration for the xylophone, leaving 5/8" space between each for some hardware that would guide the strings. This was the first time I had a clear picture of what the xylophone might look like!

I then used the very scientific method of 'eyeing it' to find a line of best fit through all the bars with some string. I redrew the node lines along the string to mark where I would drill through the bars.

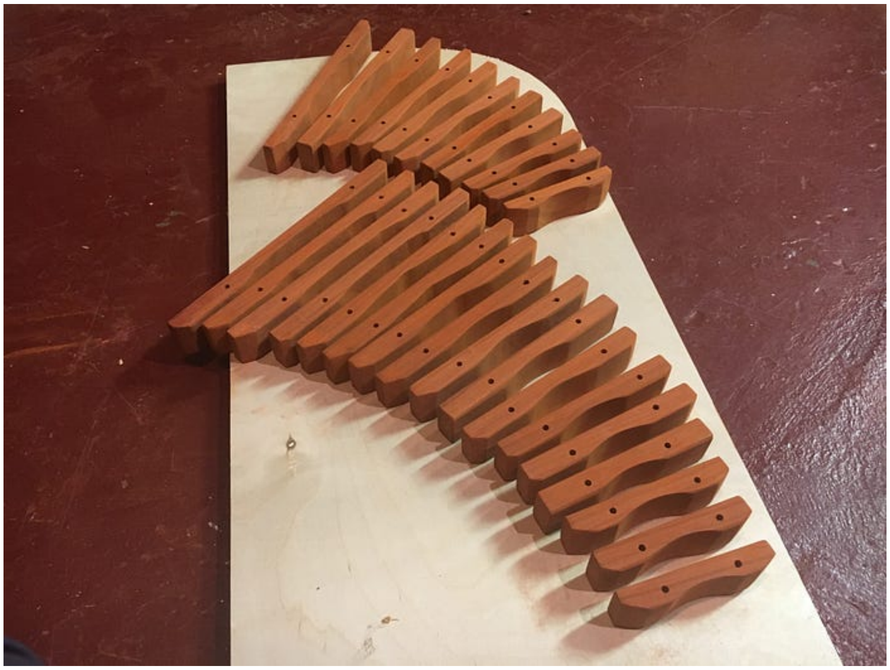


Then it was time to drill. The photo below is not tilted — we actually tilted the drill table to match the angle of the node line for each bar. Since the string method created node lines with identical angles, though, we only had to change the angle of the table four times (two for the 'white keys', two for the 'black keys').





After drilling the node holes, I did a few rounds of hand sanding on all faces of the bars. Then, I did a round of spot sanding the underside with a Dremel to get the fundamental and second mode within 0.25% of desired. This process was quite tedious, with lots of pausing to check the spectrum in the computer. I found that some bars had remained accurate, some were too sharp, but most were too flat. I corrected for the flatness by shaving wood off the underside of the ends of the bars, which I had read was general practice. This led to some rather extreme shapes. Though part of me wishes the butt ends could all have been neat little matching rectangles, I can also appreciate the wonky, unique nature of a handmade wood piece.


Bars after final sanding

The final step in the bar-making process was finishing. We used two coats of a light varnish oil, which really brought out the rich color and grain variation.


Drying after varnish oil

With the bars finished, the last piece of the puzzle was building a frame to hold them.

Click here for the thrilling conclusion to the xylo-saga!

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Building a Xylophone, Part 7: Xylo-coda

Kate Salesin ∷ 1/7/2019

Kate Salesin

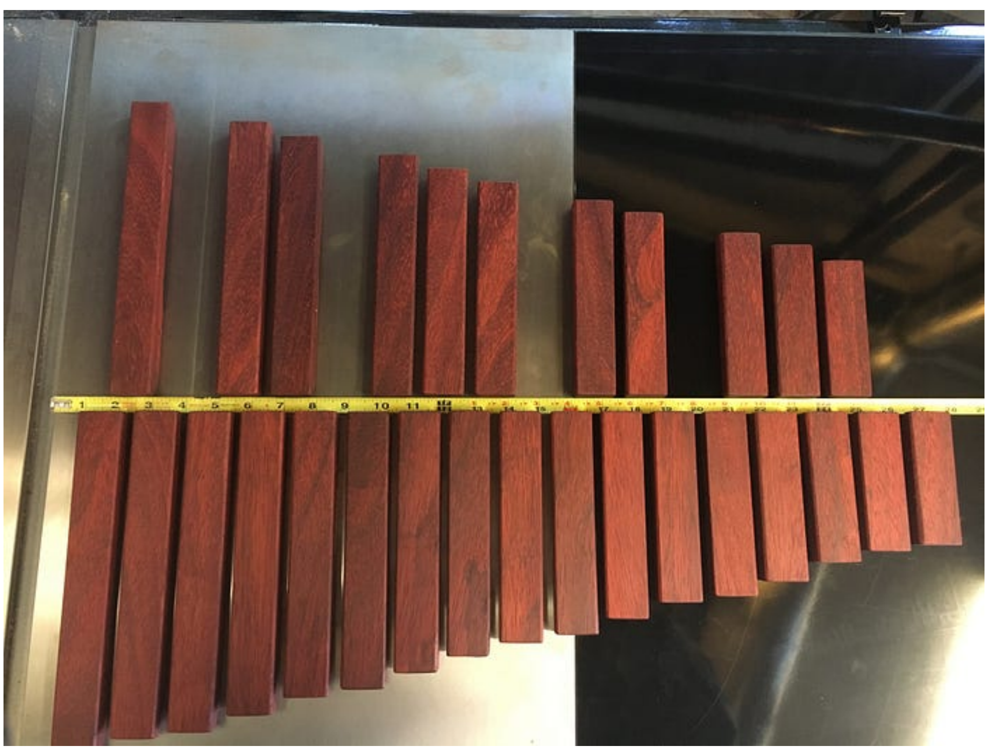
Jul 23, 2018

4 min read

The final piece of the puzzle was to create a base to hold the bars. This phase of the project took by far the longest, not due to difficulty (in fact, it was probably the simplest), but due to my only visiting the project once every few weeks. In the end, it was not a sprint to the finish, but a crawl.

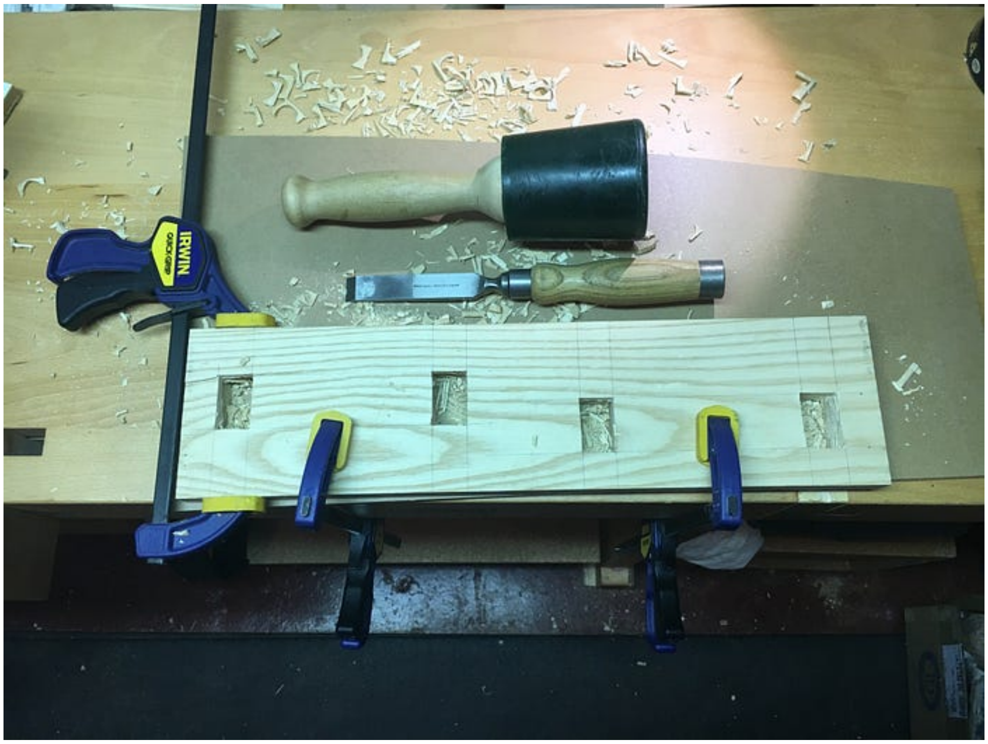
I made the base out of some spare ash in my dad’s shop. In all, the base is composed of four support beams running beneath the bars (two each for naturals and accidentals) and two end blocks to hold the support beams.

To start, I had to line up the bars with their final spacing to see how long the four supports running underneath (one for each set of nodes) needed to be.



All the ducks in a row

I decided to have the support beams pass completely through the end pieces and let them jut out a bit. This required me to chisel through the end pieces at four precise angles, corresponding to the angles of the drilled node holes.



The longer end piece, post-chisel

This was only a mildly successful endeavor, since the chiseling caused the end pieces to crack, especially the smaller end. It had broken into six separate pieces by the time we were done, but we just glued it back together.

Next, I marked where each hardware support would go to hold the line running through the bars. We got some eye lag screws for ceiling grids from Home Depot to serve this purpose, and they worked perfectly.

Marking the placement of the hardware (pencil dots)

Visualizing the end result (and double checking my measurements)

We drilled guide holes for the screws, then glued the base pieces together and finished them with varnish oil. After the base had finished drying, I installed each of the 66 screws.

Stringing the line through the bars was the final step, and probably the most enjoyable part of the experience, as it was exciting to see the whole thing finally (…finally) come together. For line, I used braided nylon para cord. Although we had drilled the node holes with its diameter in mind, we perhaps erred on the side of too tight, as getting it through the bars was a challenge. In the end, though, I think this was much preferable to the opposite problem, which might have caused the bars to droop and rattle.


Glamour shot

To tension the line, I used a couple of baby turnbuckles.


Babies!

And, drumroll please, here is what it sounds like! (I guess that was kind of the point?)

I’m really pleased with how it turned out. In the videos, it seems cute and dinky, but in person, it is quite ear-piercing. I scared away all members of my household (including my cat) while playing it. That’s what we call a feature, not a bug.

Was it worth the effort? Yes, absolutely. Will I do it again? Not in the near future.


‘Xylonaut’ overlooking his new home

The end.