Part 6

More Auditory Effects, Voice and Vocal Tract, Vocal and Instrumental Formants

Missing Fundamental and Periodicity Pitch

Consider a sustained complex tone containing several harmonics. If you leave out the fundamental N = 1 and play only higher harmonics from the overtone series, you may hear the "missing fundamental". The missing fundamental is composed in the brain from nerve impulses.

Example

N = 1	f = 200 Hz	Fundamental - not played (missing fundamental)		
N = 2	f = 400 Hz	Octave	400/200	Difference 200 Hz
N = 3	f = 600 Hz	Fifth	600/400	Difference 200 Hz
N = 4	f = 800 Hz	Fourth	800/600	Difference 200 Hz, etc.

The frequency differences between successive harmonics are 200 Hz in this example. If you hear a tone with a pitch of 200 Hz, you are "hearing" the missing fundamental. This effect also is called *periodicity pitch* because the pitch and period of the tone are obtained from the harmonics.

Question

Two successive frequencies in a harmonic series are 1000 Hz and 1200 Hz. What is the frequency of the fundamental?

Answer: f = ______Hz

Challenge Question

Can two frequencies of 300 Hz and 500 Hz be *successive* harmonics in an overtone series?

Answer: Yes, for a closed tube having only the odd harmonics 100 Hz, 300Hz, 500 Hz etc.

Demonstrations

1. Play some CD tracks demonstrating missing fundamentals.
2. Bow the lowest empty C2 string on a cello. The fundamental (C2 = 65.4 Hz) is very weak or non-existent in the Fourier spectrum. Nonetheless, the note C2 sounds loud because of the missing fundamental frequency being put together in the brain from the harmonics.
3. Play Beethoven's "Ode to Joy" on the piano to become familiar with the melody. Then play "Ode to Joy" from a recording where the first four (!) harmonics in the melody are missing. Most people nonetheless can "hear" the melody by tracking the fundamental.
4. Play C2 on the keyboard. The fundamental may be missing from the spectrum, but the higher harmonics are visible. As a result of *periodicity pitch*, the note C2 is "heard" with its pitch.

Fundamental Tracking

In the preceding demonstrations, especially in "Ode to Joy", we hear the missing fundamental and how it is *tracked* as the music plays. This is called *fundamental tracking.*

The fundamental of the lowest notes on the piano is very weak because the soundboard responds poorly below 50 Hz. Nonetheless, you "hear" the notes because the missing fundamental is tracked from the harmonics.

Missing Fundamentals from a Bassoon and Bass Tuba

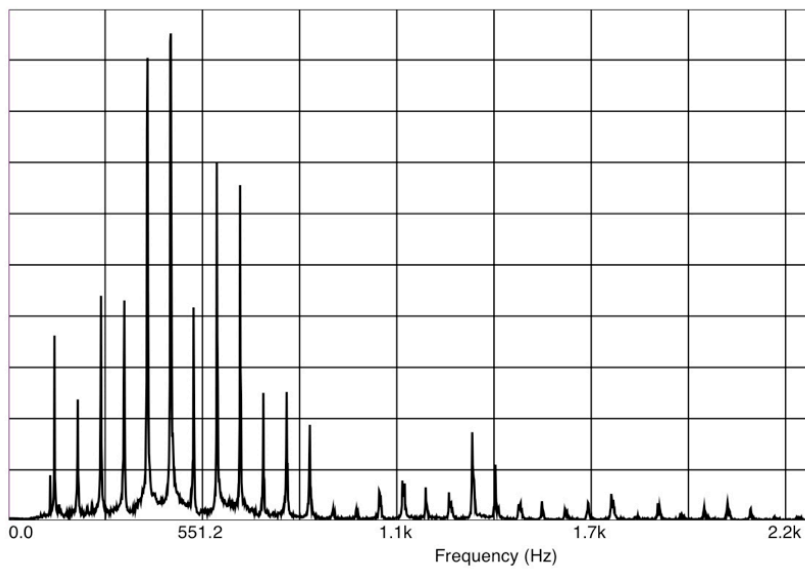


Figure. Sound spectrum of the note C2 = 65.4 Hz from a bassoon played by Professor Richard Meek, Texas Tech University. The fundamental at 65.4 Hz (harmonic number N=1) is missing. The lowest harmonic is C3 (N=2) an octave above C2.

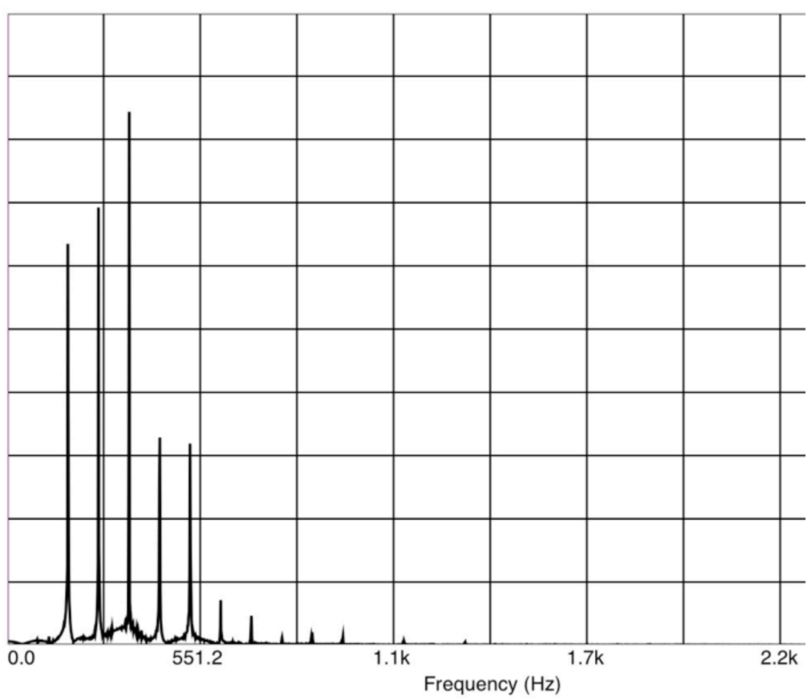


Figure. Sound spectrum of F2 = 87.3 Hz from a bass tuba played by Professor Kevin Wass, Texas Tech University. The fundamental at 87.3 Hz (harmonic number N=1) is missing. The lowest harmonic is F3 (N=2) an octave above F2.

Aural Harmonics

The response of the ear to sound intensity is *non-linear*; it is in fact approximately logarithmic. A *loud* sine wave of frequency *f* will thus sound distorted. The distorted wave "heard" still has the same fundamental frequency f, but it is now a complex waveform. According to *Fourier's Theorem*, it consists of a fundamental *f* and harmonics *2f, 3f, 4f*... These additional harmonics are called *aural harmonics*. They become more and more pronounced with increasing intensity of the fundamental. The tone still has the same pitch, but it sounds "spicier" or more "brilliant".

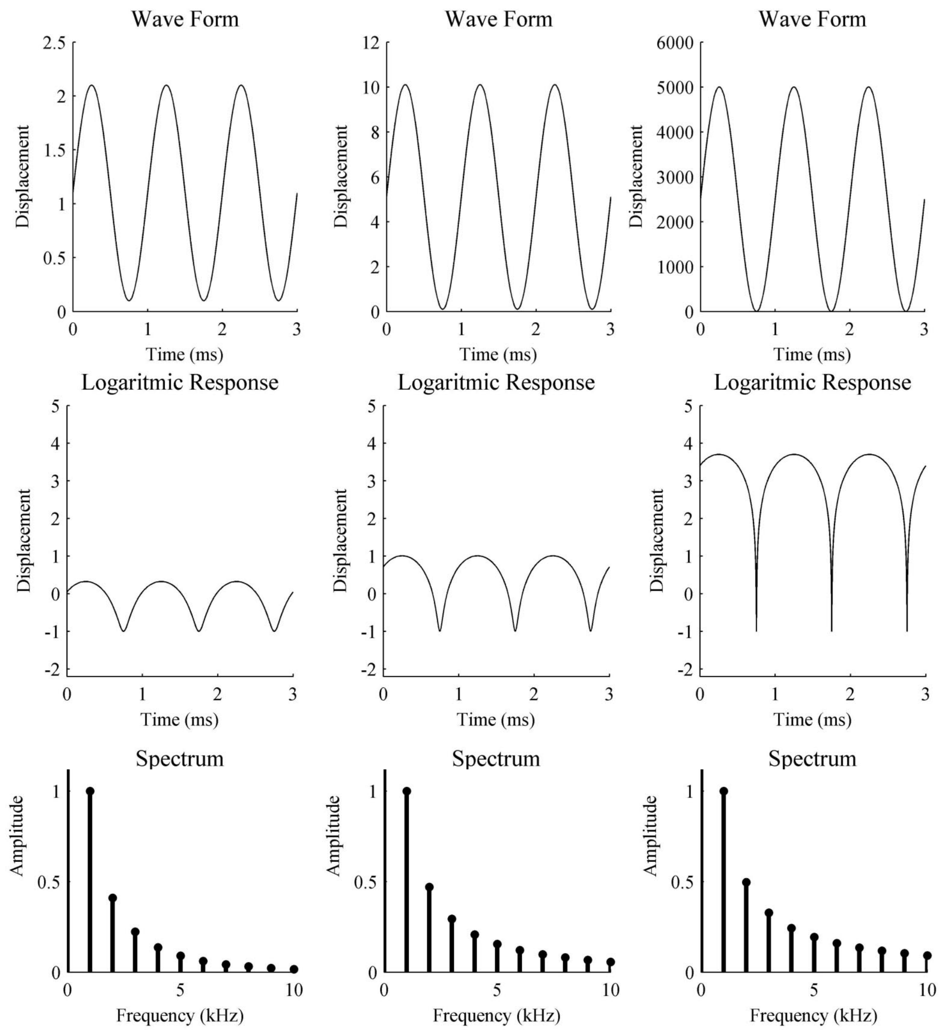
Question
Why does the timbre change?
Answer: ____

Demonstration
Play a pure sine wave, first softly, then increasingly louder. Listen to the change in timbre arising from more and more higher harmonics "sneaking" in.

Intensity Increase of the Aural Harmonics
For a 1 dB increase in the intensity of the fundamental of frequency *f*, we have the following intensity increases in the aural harmonics:
2 db increase in the 2^{nd} harmonic 2f (N = 2)
3 db increase in the 3^{rd} harmonic 3f, (N = 3)
4 db increase in the 4^{th} harmonic 4f, (N = 4)
…………………………………………….etc.
Question
For a 2 dB increase in the fundamental, what are the dB-increases of the 2^{nd} and 3^{rd} harmonics?
Answer: ____

On the next page we show a simulation of the increasing presence of higher aural harmonics as the amplitude, and hence the intensity, of the sinusoidal wave is increased. As a consequence, the timbre of the tone, as "heard" by a listener, has changed from a pure sine tone to a complex tone with higher harmonics. Of course, the tone arriving at the ear still is a pure sine wave!

Simulation of Stronger Aural Harmonics with Increasing Intensity



Top Figure. Three sine waves of the form **y(t) = Asin(2πft) + B** are shown, where the amplitude A of the waves increases from left to right, and B is a constant chosen to provide non-zero signal bias of the basilar membrane (so that a logarithm may be taken).
The three sine waves have a frequency f = 1000 Hz = 1 kHz (fundamental frequency).
The pairs of constants A and B chosen for the sine waves are, from left to right:
A = 1.0 and B = 1.1 A = 5.0 and B = 5.1 A = 2500 and B = 2500.1
Middle Figure. The logarithm curves of the three sine waves from the top row are shown. This is intended to simulate the logarithmic, non-linear response of the cochlea of the inner ear to sound intensity.
Bottom Figure. The Fourier spectra of the three log-response curves from the middle figure are shown. In addition to the fundamental frequency, with an assumed amplitude 1, higher harmonics or simulated *aural harmonics* now appear. It is seen that with increasing sound

intensity, higher harmonics become more and more prominent. The tone quality or timbre thus becomes increasingly “spicier” or more “brilliant”.

Aural Combination Tones, Difference Tones, Sum Tones

When two tones of fundamental frequency f_1 and fundamental frequency f_2 are played simultaneously with comparable intensity, additional tones, called *combination tones*, are produced. These are a result of *aural harmonics* caused by the non-linear response of the ear to an external auditory stimulus. The origin of this non-linearity originally was thought to be in the outer and middle ear. Hermann Helmholtz ascribed the non-linearity to the curved eardrum (tympanum) connected to the hammer of the middle ear. However, more recent experiments on animals indicate that the frequencies of combination tones are not present at the oval window. Instead, they come from distortions of the original waveform in the cochlea of the inner ear. The combination tones have frequencies that are a combination of the two frequencies f_1 and f_2 and their aural harmonics, i.e. $2f_1$, $3f_1$, $4f_1$…. and $2f_2$, $3f_2$, $4f_2$…. as follows:

$$\mathbf{f = |nf_1 \pm mf_2|},$$

where n and m are the integers 1, 2, 3, … The *minus* sign produces *difference tones* and the *plus* sign *sum tones.* The sum tones usually are very difficult to hear, and may not have been heard at all so far, because they have higher frequencies, are masked by tones of lower frequency, and have smaller amplitudes. On the other hand, difference tones can be heard more easily. Guiseppe Tartini (1692-1770), Italian composer and violin virtuoso, used difference tones for tuning double stops on his violin while performing violin concertos.
The most easily heard difference tones have the frequencies

$$\mathbf{\Delta f = f_2 - f_1 \qquad \Delta f = 2f_1 - f_2 \qquad \Delta f = 3f_1 - f_2}$$

where $f_2 > f_1$. The 2nd and 3rd difference tones here are best heard when $1.1f_1 < f_2 < 1.3f_1$.

Demonstrations – Missing Fundamentals and Difference Tones

1. We can demonstrate difference tones with the same experimental setup used for beats. Play two pure loud tones of similar amplitude and frequency. We hear beats if the two frequencies are within about 10% of each other. If you increase the frequency separation further, the sound becomes rough. Eventually the two frequencies can be distinguished, and the coarseness between them becomes a low frequency tone in the audible range. This tone is the *difference tone.*
Start with $f_1 = f_2 = 700$ Hz. Increase f_2 until you hear the coarse difference tone.
2. Use a third frequency generator and play a sine tone of the difference frequency. Does the sine tone have the same frequency as the coarse difference tone in the preceding demonstration?
3. Consider the pure harmonics in the harmonic series

A3	A4	E5	A5	C$^{\#}$6	E6
220	440	660	880	1100	1320 Hz

Use two frequency generators and play two loud sine tones with $f_1 = 1100$ Hz and $f_2 = 1320$ Hz. Can you hear a tone with $\Delta f = f_2 - f_1 = 1320 - 1100 = 220$ Hz = A3?
The frequency Δf in this case is both a difference tone and missing fundamental.
P.S.: On a piano the difference Δf will not be exactly equal to the frequency of the missing fundamental because the piano is tuned to "equal temperament" rather than to pure harmonics. On the piano we have E6 - C$^{\#}$6 = $\Delta f = f_2 - f_1 = 1318.5 - 1108.7 = 209.8$ Hz, but A3 = 220 Hz.

4. Use a third frequency generator to notice the difference tone more clearly. Set the frequency to the difference $\Delta f = 220$ Hz. Listen and decide whether this is the pitch of the difference tone from the preceding demonstration. If you are having trouble hearing the difference tone, slightly vary the frequency of the third audio generator and listen for beats between its frequency and the 220 Hz of the difference tone A3. If you hear beats you are "hearing" the difference tone.

5. Use available sound files and play the intervals B^b6-G6, B6-G6, C7-G6, D^b7-G6, D7-G6.
a) Can you "hear" missing fundamentals from these intervals?
b) What are the fundamentals corresponding to these frequency differences?
Partial answers: B^b6 – G6 = E^b4, D7 – G6 = G5.

Question for Musicians
Consider pure harmonics and show that the difference between B^b6 and G6 is the note E^b4. From the piano keyboard we know that E^b4 = 311 Hz but for pure harmonics B^b6 – G6 = 297 Hz. Why does this not equal 311 Hz?
Answer: From "equal temperament tuning" of the piano we have 311 Hz, from exact Pythagorean intervals (pure harmonics) we have 297 Hz.

6. **Difference Tones from a Contrabass**
Professor Mark Morton from the School of Music at Texas Tech University played his contrabass in class. When he played with high loudness the notes $C^{\#}5$ (550 Hz) and E4 (330 Hz) together, some could hear the difference tone (here also missing fundamental) A3 = 220 Hz.

Distinction between "Missing Fundamental" and "Difference Tone"
Difference (and sum tones if they ever can be "heard") are caused by the non-linear response of the ear to sound intensity. They are produced by the waves in the cochlear fluid and are physically real. On the other hand, "hearing" a missing fundamental comes from the frequency differences between harmonics. The resulting missing fundamental seems to be created in the brain from electrical nerve impulses. It does not originate as a physical phenomenon in the ear.

Difference Tones, Fundamental Tracking, Small Loudspeakers and Cell Phones
Bass notes may be "heard" from small speakers of transistor radios and cell telephones in spite of the fact that such low frequencies cannot possibly be reproduced by these speakers.
Two phenomena act together and provide an explanation:
1. *Difference tones* produce a low frequency due to the non-linear response of the ear.
2. The *fundamental tracking mechanism* in the brain analyzes intervals of harmonics and adds the missing fundamental.

Note on Sum Tones and Research Project
We have only been able to "hear" difference tones in class, but not so-called "sum tones" from two sine waves. An interesting research project would be finding beats between an anticipated sum tone and a nearby frequency from a signal generator. Hearing such beats would be a clear indication for the presence of sum tones.

A Test for Difference Tones and Missing Fundamentals

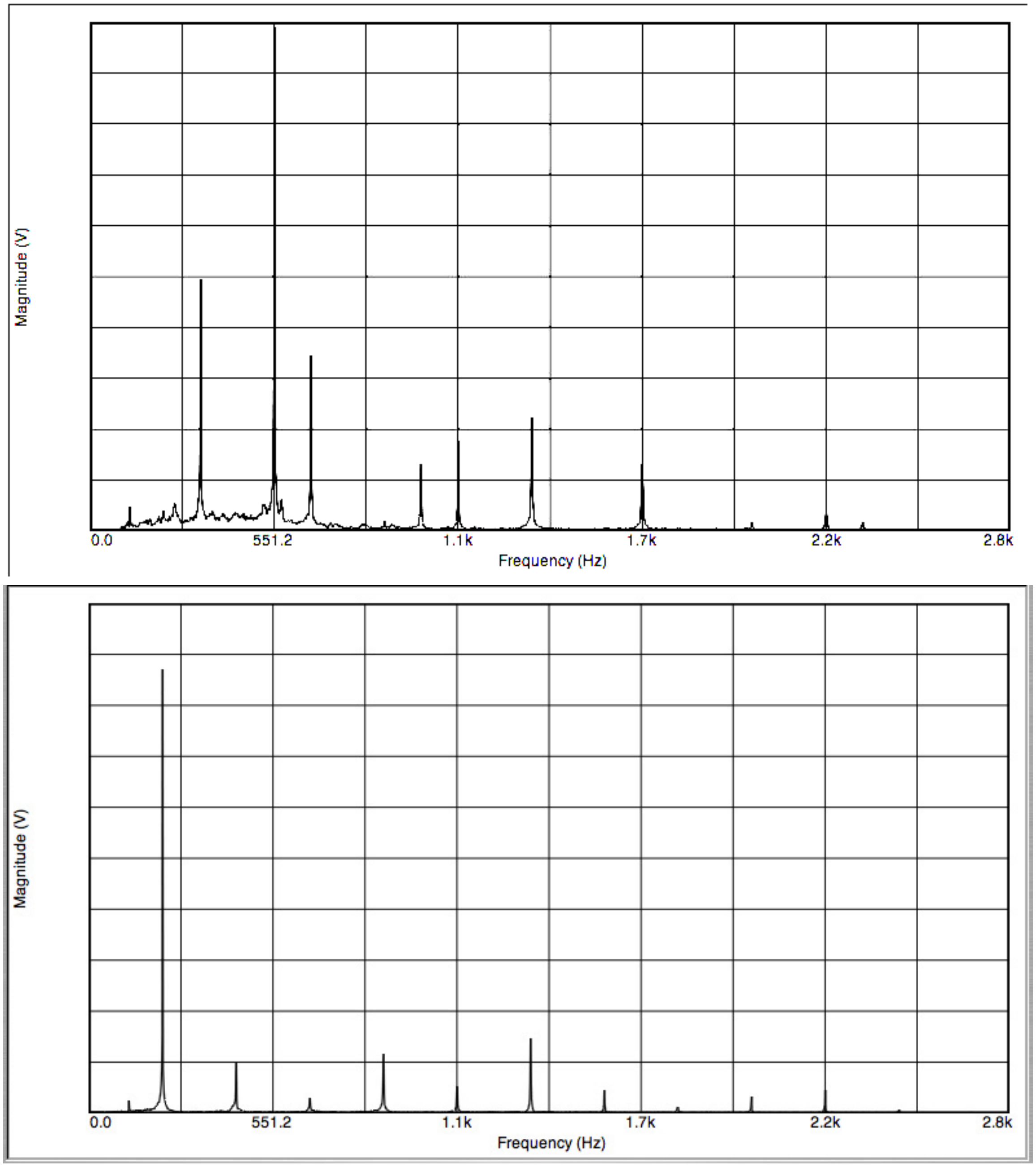


Figure. Top panel: Notes E4 (330 Hz) and C5# (550 Hz) were played simultaneously at high intensity on a double bass by Professor Mark Morton, Texas Tech University. The fundamentals and harmonics of the two notes are seen. The difference at 550 - 330 = 220 Hz (A3) was absent in the recording, but it could be "heard" by several students in the classroom.
Bottom panel: The note A3 (220 Hz) was played separately to show where the difference tone or the missing fundamental would have been. It is absent from the recording at the top but rather was produced within the auditory system.

Ohm's Law of Hearing, First and Second Order Beats

Ohm's Law of Hearing : "The timbre of a complex tone is given solely by the amplitude spectrum of the harmonics. The relative phases between the harmonics are unimportant."

First Order Beats or Primary Beats

These beats are consistent with Ohm's law. The phases between the two beating tones do not matter in what you hear. It makes no difference when you start the tones. They interfere with each other and produce a tone with a slow amplitude modulation that varies with the beat frequency $\Delta f = | f_2 - f_1|$. The frequency we hear is the average $f = (f_2 + f_1)/2$ of the two frequencies. The timbre or sound quality of the beating tone does not change with time.

Second Order Beats or Quality Beats

When the frequencies of two pure tones are about one octave apart, so-called second order or quality beats may be heard at the beat frequency $\mathbf{\Delta f = |f_2 - 2f_1|}$, where now $\mathbf{f_2 \approx 2f_1}$. For good audibility $f_1 < 1500$ Hz is needed. *The phase of the resultant waveform changes continually*. The ear can detect changes in the waveform and thus in the phases as the sound quality changes with time. The amplitude does not change significantly. Ohm's law no longer applies to this rather subtle effect. Second order beats can be heard when playing soft tones where non-linearities in the ear are unimportant. Hence these beats are not created from aural harmonics that are caused by non-linearities in the ear. Rather, quality beats appear to be created directly in the brain.

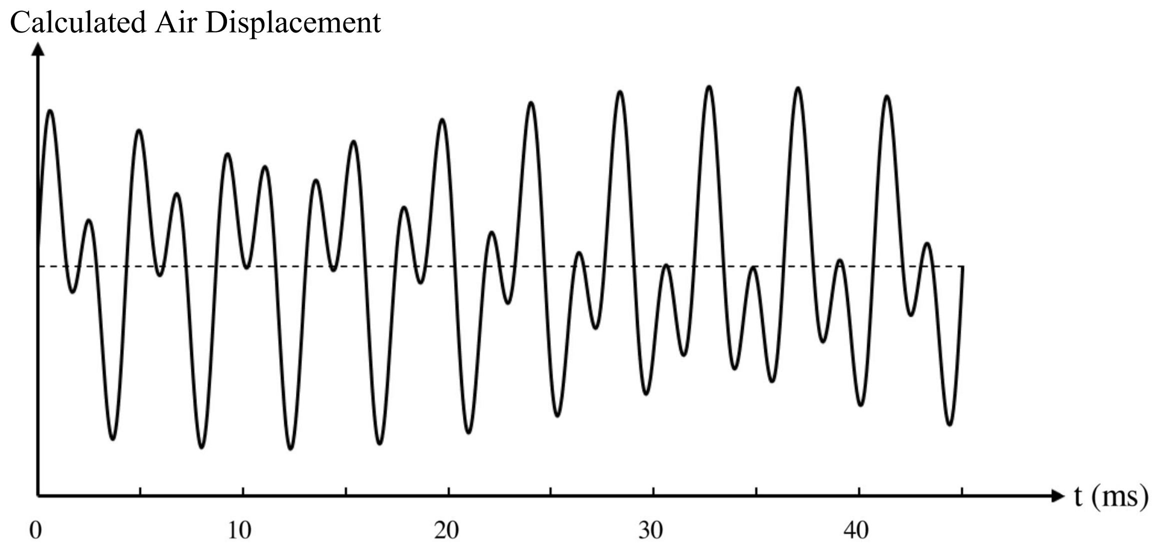


Figure. Calculated second order or quality beats. The waveform shown is the combination of a 222 Hz sine wave and its 2nd harmonic (444 Hz) mistuned to $f_2 = 466$ Hz. The amplitude of the two component sine waves is the same. The beat frequency is $\Delta f = |f_2 - 2f_1| = 466 - 444 = 22$ Hz. Shown is one full cycle of second order beats with a period of about 45 ms.

Question

Find the frequency of the 2nd order beats from the graph. Compare with the calculated result.

Answer: From graph: $\Delta f =$ ________ Hz, calculated: $\Delta f =$ ________ Hz

First and Second Order Beats (continued)

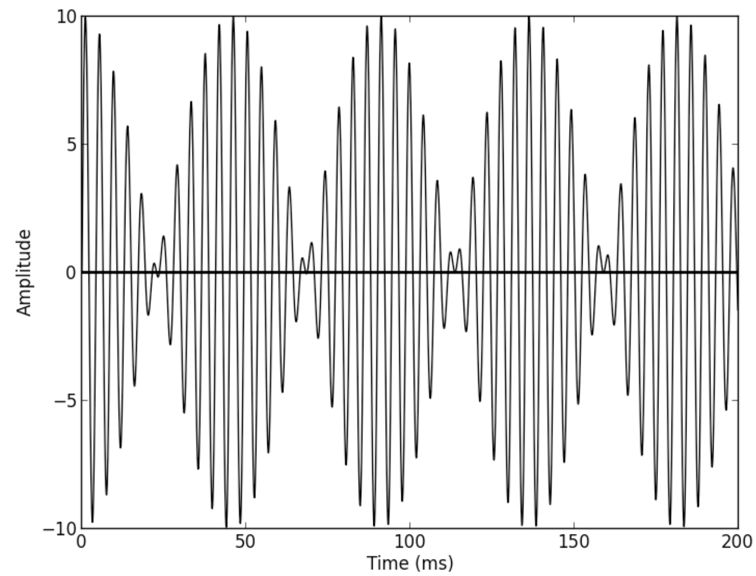


Figure. Waveform of first order beats between two sine waves of equal amplitude, with $f_1 = 222$ Hz, $f_2 = 244$ Hz, $\Delta f = f_2 - f_1 = 22$ Hz.

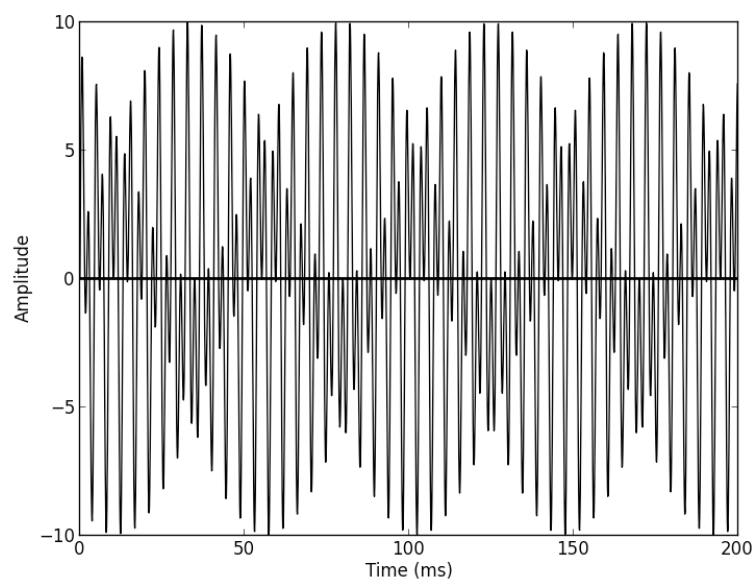
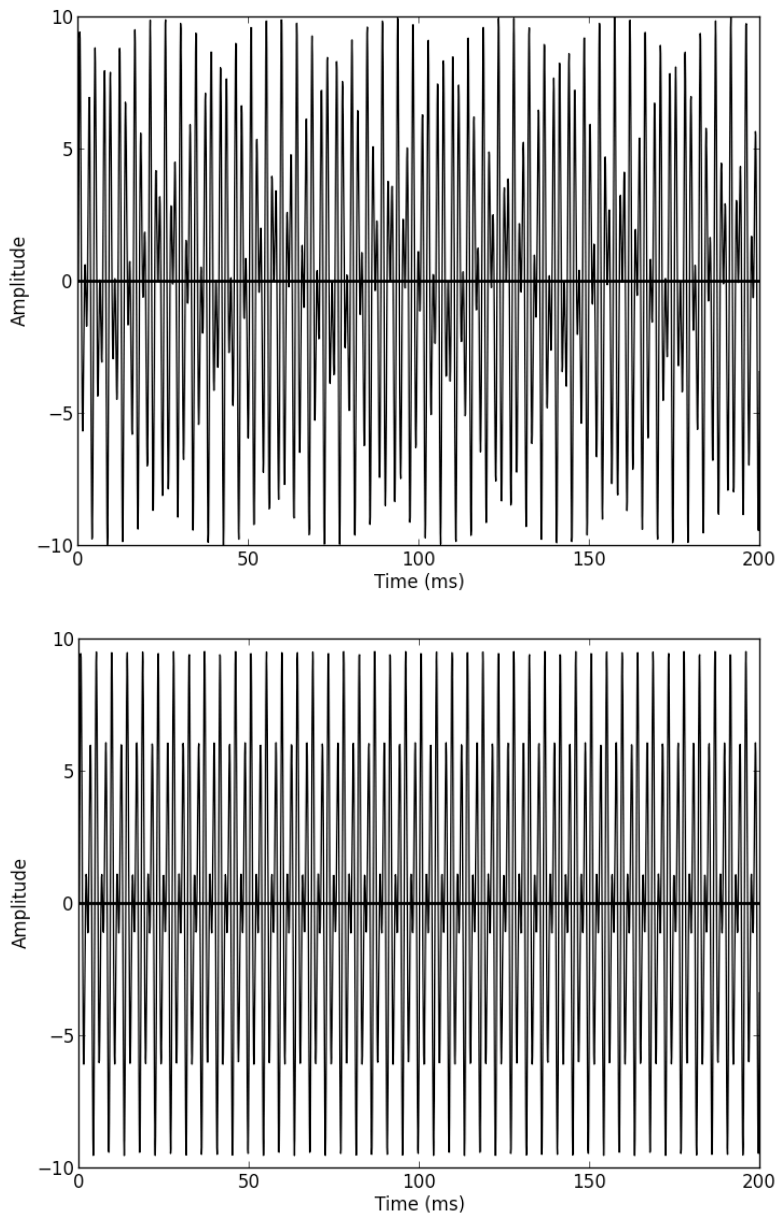


Figure. Waveform of mistuned octave. Second order beats are shown between two sine waves of equal amplitude, $f_1 = 222$ Hz, $f_2 = 466$ Hz, and $\Delta f = f_2 - 2f_1 = 466 - 444 = 22$ Hz.

Second Order Beats (Quality Beats) and Mistuned Consonances
Quality beats not only occur between mistuned octaves as described above, but more generally between mistuned harmonics. As an example of mistuned fifths we consider the open violin strings A4 (f_1 = 440 Hz) and E5 (f_2 = 660 Hz). The first figure below shows the waveform for a highly mistuned E5 string at f_2 = 675 Hz, the second figure shows an exactly tuned fifth.



Top Figure. Simulation of the waveform of a mistuned fifth and resulting second order beats from a violin. Two sine waves of equal amplitude are assumed, with f_1 = 440 Hz (A4 string), f_2 = 675 Hz (mistuned E5 string), and $\Delta f = 2f_2 - 3f_1 = 1350 - 1320 = 30$ Hz.
Bottom Figure. The waveform of the exactly tuned fifth shows no beats ($\Delta f = 0$ Hz).

Demonstrations

1. Use two frequency generators with $f_1 = 360$ Hz, the other at $f_2 = 362$ Hz, with loudness about the same. Listen to the first order beats having a beat frequency of $\Delta f = 2$ Hz. Note the intensity variations without a change in timbre.
2. Use two frequency generators, one at $f_1 = 360$ Hz and the other at a mistuned octave of $f_2 = 720 + 2 = 722$ Hz. Listen to the quality beats with a beat frequency of $\Delta f = f_2 - 2f_1 = 722 - 720 = 2$ Hz. Note the second order beats without much change in intensity. Choose the intensity of the higher frequency about equal to half the intensity of the lower-frequency tone. Furthermore, choose $f_1 < 1500$ Hz.
3. Listen to tracks demonstrating beats on the CD "Auditory Demonstrations" by the American Acoustical Society (Track 62, track 63).
4. Set two sine wave generators to the frequencies 222 Hz and 466 Hz as in the preceding figure and show the resulting waveform on the computer monitor. Can you hear the 2nd order beats?

The Importance of Ohm's Law in Sound Reproduction

Sound recording and reproduction systems change the relative phases of harmonics in many ways. Luckily, Ohm's law still applies and one can hear music sounding like the original, because we are not sensing the phase distortions.

Question

Good recordings do not sound distorted in spite of the many phase distortions in the electronics. Why is this so? (Hint: Which quantities in Fourier's theorem generally do we not "hear"?)

Answer: ____

Mistuned Consonances

Second order beats also may be heard between *mistuned consonances* such as mistuned fifths and fourths. These can be used in tuning pianos and string instruments. Good tuning is achieved once second order beats have been eliminated.

Demonstrations

1. Mistuned fifths: Play two tones with $f_1 = 360$ Hz, and $f_2 = 540 + 2 = 542$ Hz. Do you hear beats? What is the beat frequency? Does this work with sine waves or only complex waves?

Answer: The beat frequency is $\Delta f = 4$ Hz, not 2 Hz as we might think! Explanation: Consider the harmonics and take $2f_2 - 3f_1 = 1084 - 1080 = 4$ Hz

2. Play two tones with $f_1 = 200$ Hz, and $f_2 = 301$ Hz. The beat frequency is $\Delta f = 2$ Hz!
3. Play two tones with $f_1 = 201$ Hz, and $f_2 = 300$ Hz. The beat frequency is $\Delta f = 3$ Hz!

Explain these two puzzling results similar to the explanation given for the first demonstration.

Binaural Beats

Use earphones to play a soft tone into one ear and another one of similar frequency and loudness into the other ear. The resulting beats move "around the head" and are called *binaural beats*. No physical mixing of the two waves can occur in this case, the only mixing occurs in the brain. Binaural beats have been used for therapeutic purposes, specifically in "music therapy".

Demonstration

Listen to CD track 71, binaural beats, from "Auditory Demonstrations". Unfortunately we cannot do this in class, because earphones need to be used for this effect.

Auditory Masking

Auditory masking occurs in the presence of two or more tones, when one tone "drowns" out or *masks* the other.

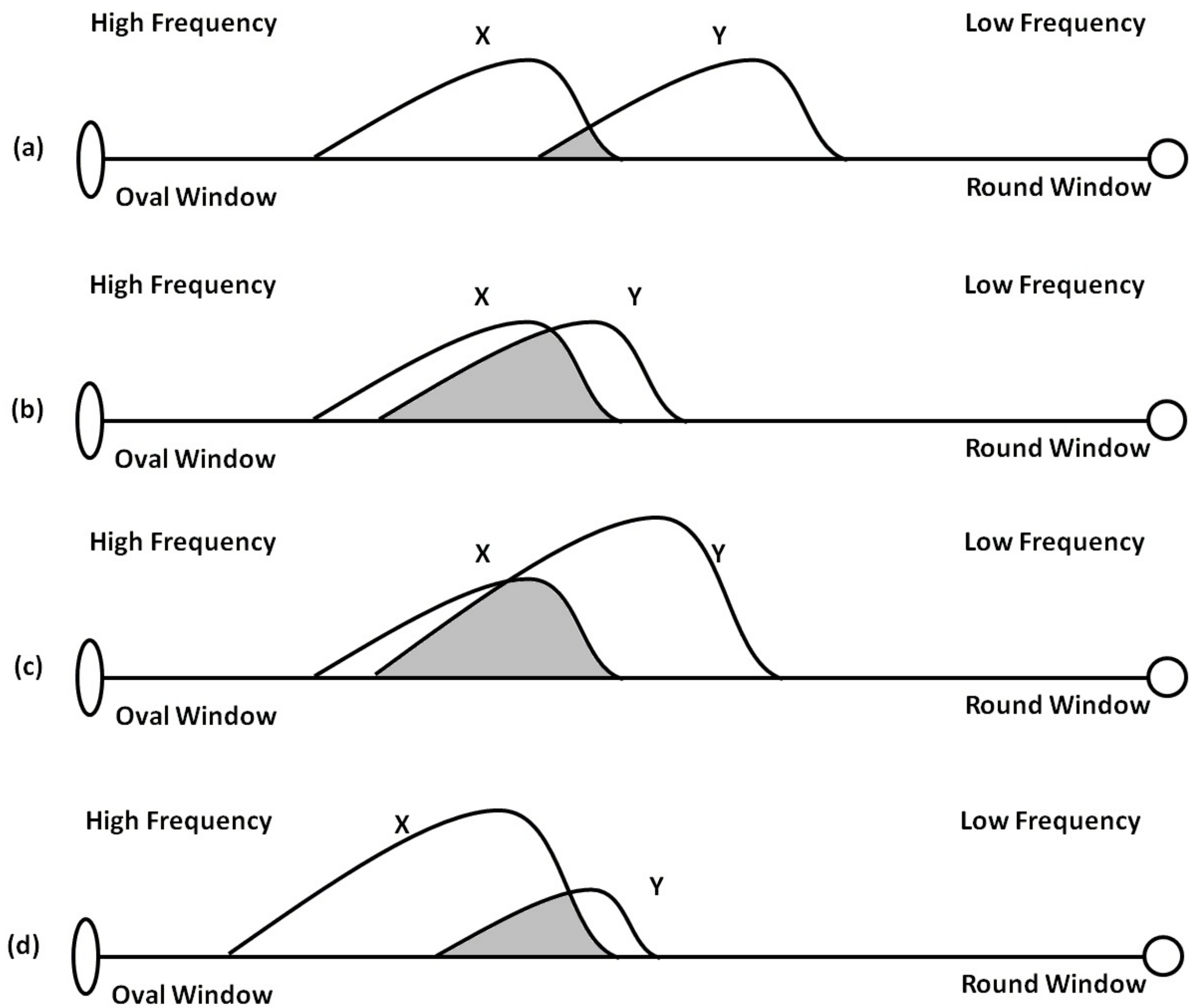


Figure. Masking explained schematically with the overlap of critical bands for two pure tones X and Y on the basilar membrane.
(a) The two critical bands hardly overlap. Little masking occurs.
(b) The two curves have appreciable overlap. The lower frequency tone Y masks the higher frequency tone X somewhat more than X masks Y.
(c) The lower frequency tone Y is more intense than the higher tone X and almost completely masks X.
(d) The higher frequency tone X is more intense, but does not completely mask the lower tone Y.
(Figures partly adapted from Thomas D. Rossing, The Science of Sound, 3rd edition Fig. 6.10, p. 114, Addison-Wesley, 2002.)

Exercise
Shade the regions of overlap between tones A and B in the figure to understand better the masking effect in the four cases (a), (b), (c), and (d).

Masking and Masked Tone
The *masking tone* is the tone drowning the *masked tone.*

Masking Level
The masking level is the minimum sound intensity level (SIL in dB) to which the masked tone has to be raised to become audible. Masking strongly depends on frequency.

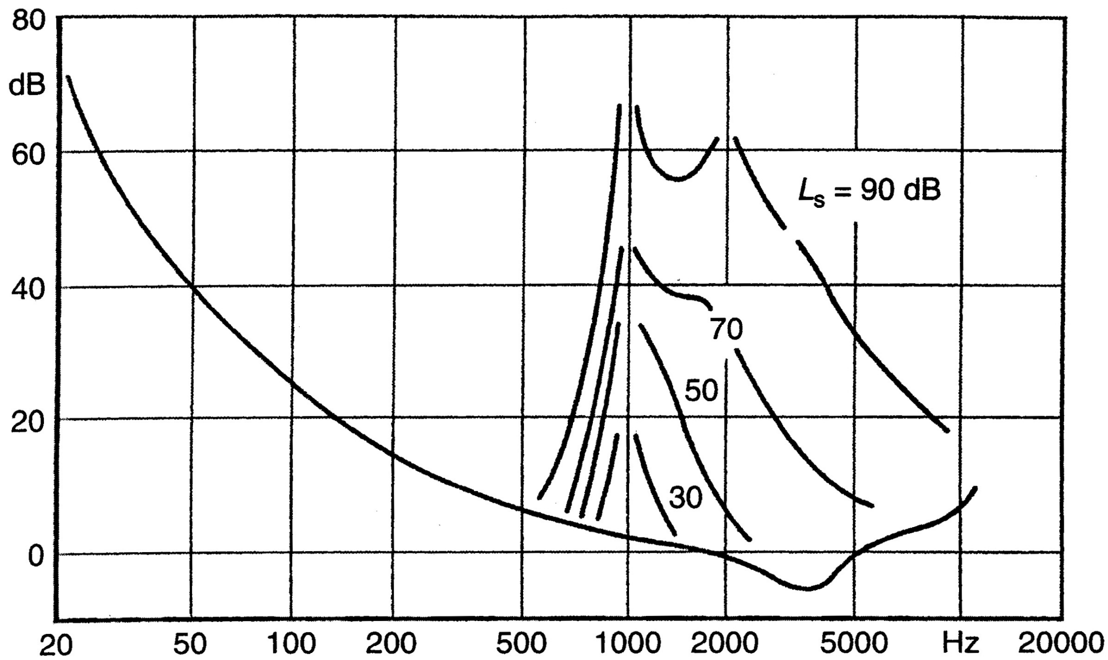


Figure. Masking by a 1000 Hz masking tone at sound intensity levels of 30, 50, 70, and 90 dB. The SIL on the ordinate and frequency on the abscissa are for the masked tone. In the absence of the masking tone, the threshold of hearing is given by the lowest curve. This threshold is raised in the presence of a masking tone as shown by the four labeled masking curves. The asymmetry in these curves, with a steeper rise at lower frequencies, indicates that low frequency tones below the given masking frequency of 1000 Hz are masked less than above. A tone is inaudible below the masking curve and becomes audible only above it. For instance, for the 1000 Hz masking tone at 70 dB, a masked tone at about 1500 Hz becomes audible only if it exceeds 40 dB. (From: Jürgen Meyer, Acoustics and the Performance of Music, 5th ed,. p. 11, Springer, 2009.)

Case 1. Special case: The frequencies of the masked tone and masking tone are the *same*. Masking is very effective. We know that the intensity JND (Just Noticeable Difference) is about 1 dB = 26%. Hence for a masking tone having an SIL = 70 dB, the masked tone must be raised to 69 dB to become audible. This masking level of 69 dB is high.

Case 2. The masked tone has a lower frequency (800 Hz) than the masking tone (1000 Hz). Masking is not very effective. For example, if a 1000 Hz masking tone has an SIL = 70 dB, the level to which an 800 Hz masked tone has to be raised and heard is only about 25 dB. The masking level is 25 dB. In other words, it takes a high intensity of the higher frequency masking tone to mask a low frequency tone. Low frequency tones easily mask high frequency tones.
Case 3. This is the opposite case to Case 2. The masked tone has a higher frequency (e.g. 1500 Hz) than the masking tone (1000 Hz). Masking is more effective. For example, if the 1000 Hz masking tone again has an SIL = 70 dB, the level to which a 1500 Hz masked tone has to be raised to become audible is about 40 dB. Thus the masking level is 40 dB. This is 15 dB higher than the masking level in Case 2.

Demonstrations on Auditory Masking
Case 1. Special case: Take $f_{masked} = f_{masking} = 1000$ Hz. Play the masking tone at moderate intensity while raising the intensity of the masked tone until you hear it. Now play both tones separately. They sound almost equally loud and are separated by about 1 dB, which as we know, is the intensity JND. Thus the masking level for the masked tone is almost as high as the intensity of the masking tone.
Case 2. Use two signal generators and select 800 Hz $= f_{masked} < f_{masking} = 1000$ Hz. Raise the level of the masked tone until it becomes audible. Take a mental note of the intensity of the masked tone and the masking tone (by ear is sufficient).
Case 3. Select 1200 Hz $= f_{masked} > f_{masking} = 1000$ Hz on the two signal generators. Raise the level of the masked tone until it becomes audible. Take a mental note of the intensity of the masked tone and the masking tone (by ear is sufficient).
Question
In which case, Case 2 or Case 3, did we have to raise the masking level of the masked tone more in order for this tone to become audible?
Answer: ____

Other Demonstrations
Play sound tracks of “Masking Differences” from the CD entitled “Auditory Demonstrations” by the Acoustical Society of America (ASA).

The Significance of Masking
1. Polyphonic Music
Johann Sebastian Bach’s polyphonic fugues sound more transparent when played softly, because the masking effect decreases with decreasing loudness. Furthermore, when the melodic lines in polyphonic music are close in frequency, a single melody with rich harmonies may be heard. When the melodic lines move farther apart, the individual melodies can be heard.
2. MP3 Sound Files
Motion Picture Experts Group, Audio Layer 3 (MP3) files are compressed audio files. In the compression process, data are discarded that would be inaudible due to efficient masking of closely spaced frequencies. This results in a reduced file size of about one tenth of the original. However, some of the nuances in the music may be lost and this may be noticeable to a connoisseur.

Subjective Loudness. What is "Twice as Loud"? Phons and Sones

When you increase the loudness level of a tone 10-fold, for instance for a 1000 Hz tone from 40 phon to 50 phon, the perceived loudness is not 10-times higher. Instead, many people will say that the sound is about "twice as loud".
In order to express loudness quantitatively, the unit of *sone* was created.
By definition, **1 sone corresponds to 40 phons for a 1000 Hz sine tone.**
For a loudness level of 50 phon, the loudness is 2 sones, for 60 phon it is 4 sones, for 70 phons it is 8 sones, for 80 phons it is 16 sones, etc. The sone number thus doubles for every 10 phon increase in loudness level.

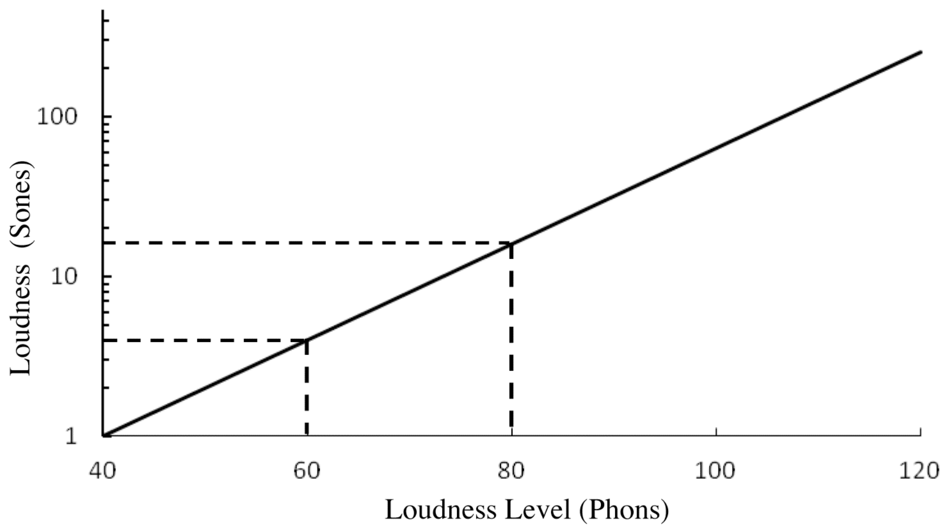


Figure. Subjective loudness in *sones* versus loudness level in *phons* for a 1000 Hz tone.

Questions
1. What is the perceived loudness in sones for a 1000 Hz tone at 70 phons?
Answer: This is a 30 phons increase from 40 phons, so the loudness is $2^3 = 8$ sones

2. The loudness of a motor increases from 16 to 32 sones. What is the loudness level and the change in loudness level in phons?
Answer
The loudness of 16 sones corresponds to 80 phon, 32 sones correspond to 90 phons, i.e. the loudness level increases by 10 phon.

Example
A quiet bathroom fan may have a noise rating of 1 sone, a rather loud one may produce 4 sones.

An improvement to the straight line dependence between loudness and loudness level in the preceding figure shows that the loudness depends significantly on the frequency for a given sound intensity level (see following Figure).

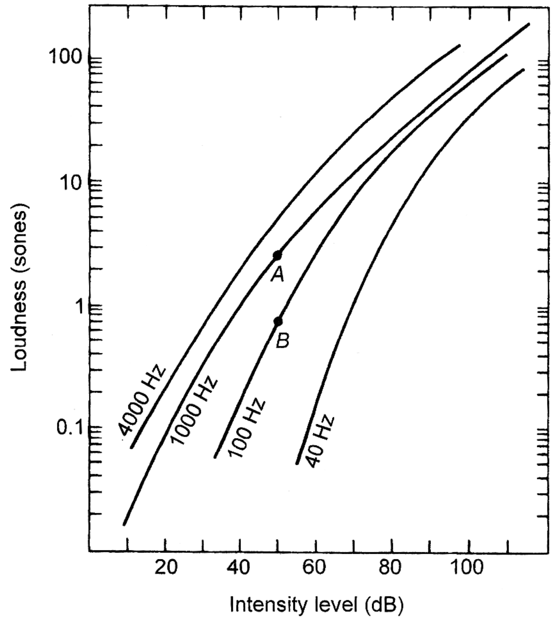


Figure. Subjective or perceived loudness in sones versus sound intensity level in dB for sine waves of different frequencies. A doubling in the number of sones means "twice as loud". (From Donald E. Hall, Musical Acoustics, 3rd edition, Fig. 6.10, p.102, Brook/Cole, 2002.)

We have for a 1000 Hz sine tone at 40 phons a loudness of 1 sone and SIL = 40 dB by definition. At point "A" in the Figure, the loudness of a 1000 Hz tone with SIL = 50 dB is about 2.5 sones. "Twice as loud" in this case (i.e. 5 sones) means SIL = 60 dB, which is the 10 dB increase stated earlier. For the 100 Hz curve we have 0.7 sones at 50 dB. "Twice as loud" or 1.4 sones is reached at about 56 dB, corresponding to an increase of only 6 dB. All four curves shown become parallel above 90 dB, and "twice as loud" means a 12 dB increase from then on.

The curves shown are an improvement over the older definition where a 10 dB-increase in the SIL was said to be "twice as loud" at all frequencies. We now see that the dB-increase for "twice as loud" depends on both frequency and SIL.

Exercise
Show from the 1000 Hz curve that "twice as loud" means an increase of about 6 dB at low intensity levels, and about 10 dB at high levels.

Demonstration
Increase the intensity of a tone and ask at what point it sounds "twice as loud".
Is your answer closer to an increase of 6 dB or 10 dB?

Challenge Question
Show that the intensity of a sound decreases by a factor of 4 with a doubling of the distance from the source according to the inverse square law. Show that this means a 6 dB decrease in the SIL and thus a sound about "half as loud".
Answer: ____

The Human Vocal Tract and Voice

The human vocal tract can be considered as a group of Helmholtz resonators acting together:
Larynx

Oral pharynx	Nasal pharynx
Oral cavity	Nasal Cavity

Other anatomical parts of the vocal tract playing a role in sound production are the lungs, trachea, vocal folds/cords, epiglottis, tongue, mouth, lips, teeth, soft palate, hard palate, and nostrils.

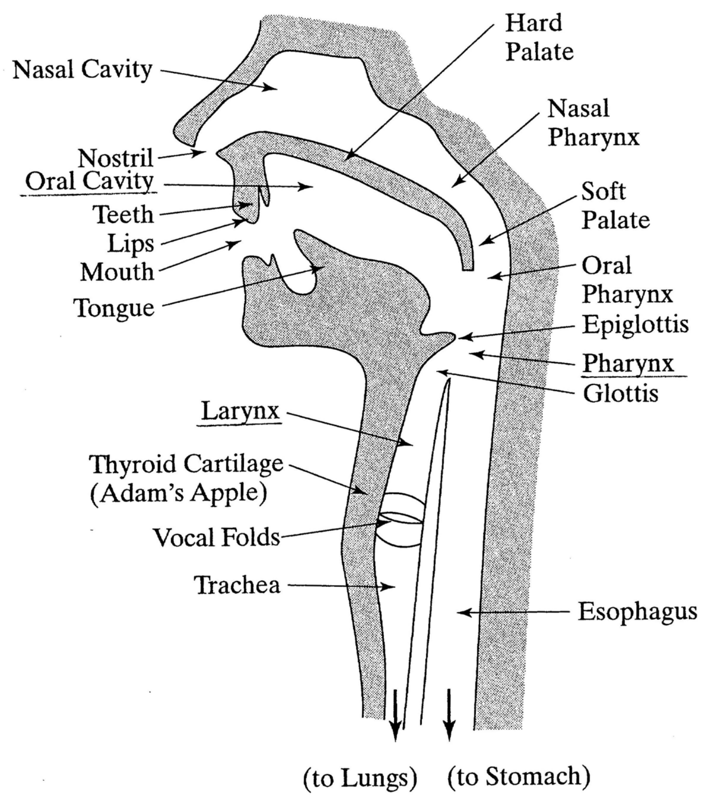


Figure. Schematic diagram of the human vocal tract. (From Berg & Stork, 3rd edition, Fig. 6-8, p. 167, Pearson/Prentice Hall, 2005.)

As the air pressure from the lungs builds up, the vocal folds open. A buzzing sound ("noise") is produced by the air rushing through the folds. This is similar to the functioning of the reeds in woodwind instruments. After a short time, the pressure decreases and the folds close. Then the cycle repeats itself. The cavities of the vocal tract act as a filtering system to the broadband noise from the "buzz". The overall response of the vocal tract causes the sound we hear. It may be musical (singing) or non-musical (speaking).

Bernoulli Effect

The closing and opening of the vocal folds when the air rushes through can be explained with the *Bernoulli Effect*. When the air velocity is high (low), the pressure is low (high) in the flow, and the vocal folds close (open). After the air pressure from the lungs rises again, the vocal folds open. This cycle repeats and produces a noisy buzz that enters the larynx and excites the air resonances in the cavities of the vocal tract.

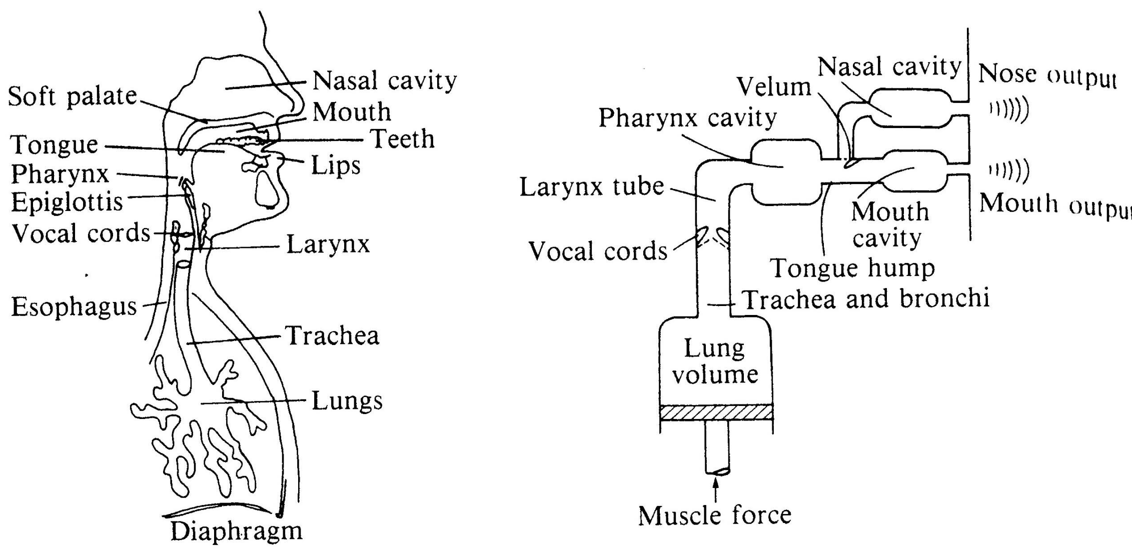


Figure. Human vocal tract and simplified schematic of the acoustical parts.
(From Thomas D. Rossing, The Science of Sound, 3rd edition, Fig. 15.1, p. 337, Addison Wesley, 2002.)

Lecture Demonstration – Bernoulli Effect
Hold two sheets of paper close together with a small gap between them. Now blow air between the sheets. They will move closer together rather than apart, because the air pressure is lower at the higher flow velocity that exists between the sheets compared to outside. When the sheets finally touch, the pressure increases and the gap opens again. As a result a buzzing sound is produced while air is blown. This simple experiment simulates the action of the vocal folds.

Vocal Formants and Singing Formant

The human vocal tract, with the oral cavity the major part, can be approximated as a tube of length L = 17 cm, with an "open" end at the lips and a "closed" end at the vocal folds.

Exercise

Calculate the first four existing resonance frequencies for a closed tube of length 17 cm.

Answer: Use the formula $f_1 = v/\lambda = v/4L$ and find the frequencies $f_1 = 500$ Hz, $f_3 = 1500$ Hz, $f_5 = 2500$ Hz, $f_7 = 3500$ Hz. These frequencies define the peaks of the so-called *formant regions.*

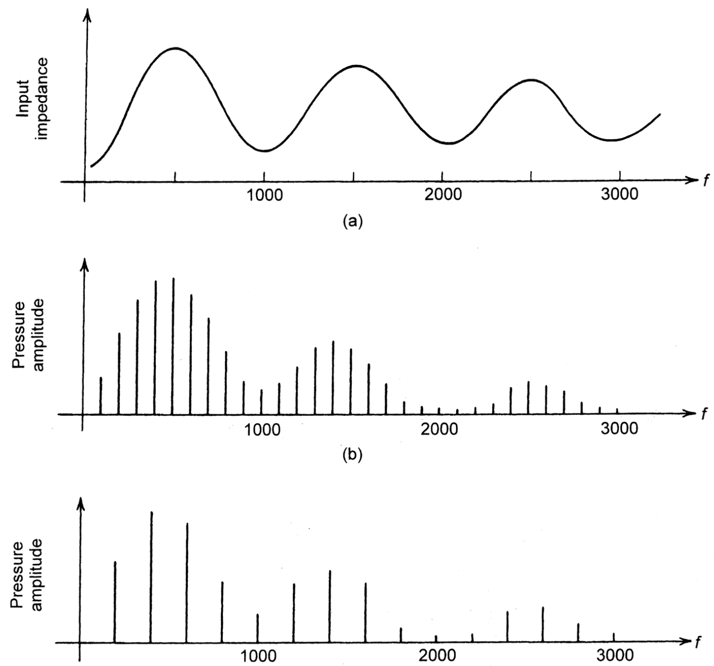


Figure. Top: Response curve of an idealized cylindrical "vocal tract" with three formant regions. Middle: Harmonics from the vocal folds with fundamental f = 100 Hz after passing through a cylindrical "vocal tract".

Bottom: Harmonics with a fundamental frequency of 200 Hz. (From Donald E. Hall, Musical Acoustics, 3rd edition, Fig. 14.8, p. 303, Brooks/Cole, 2002.)

Formants, Pitch and Harmonics

Note that the formants of the vocal tract define the overall frequency response of the resonating cavities. The formants are not sharp spikes at 500, 1500, 2500 Hz, as we would expect from a 17 cm long closed tube with rigid walls. In reality the resonances are weak and broadened because of the elasticity and softness of the cavity walls. The soft walls absorb much of the vibrational energy. This causes a broadening and lowering of the peak amplitudes. The broad maxima giving the overall response of the vocal tract are called *formants or formant regions*.

The *harmonics* in the formant regions come from the vocal folds and not from the oral cavities. The frequency with which they vibrate is controlled by muscle tension in the larynx. For the male voice the fundamental frequency of the vocal cord for speech ranges from 70 to 140 Hz, with integer multiples for the harmonics. For the female voice the range is 140 to 400 Hz plus harmonics. Good singers can extend these ranges by more than an octave when singing.

The vocal folds act as hard reeds whose frequency and sound output are adjusted by the cord tension, mass, and separation, not by the cavities of the vocal tract. When a male sings the note G2 at about 100 Hz, the vocal cords vibrate at this fundamental frequency and harmonics. When this sound from the vocal folds enters the vocal tract, the latter acts as a filter. This modifies the amplitudes of the individual harmonics (but not their frequencies) according to the shape of the formants. The broad formants can be adjusted in height, width, and frequency of the broad maxima by varying the geometry of the vocal tract.

Summary - Speaking and Singing

1. Harmonics from the vocal cords enter the vocal tract.
2. Broad resonances in the cavities of the vocal tract define the formant regions. The harmonics from the vocal tract excite the formants. The formants act as filters for the harmonics. Each formant region may contain several of the closely spaced harmonics.
3. Adjustment of the pitch of a tone is accomplished primarily by adjusting the tension in the vocal cords. The formants themselves are adjusted by varying the geometry of the cavities in the vocal tract.

Singing Formant

Accomplished singers have strong vocal and singing formants that can be louder than the accompanying orchestra. This applies, for instance, to operatic tenors with their strong singing formant around 2500 Hz. (The 2nd and 4th formants at 1500 Hz and 3500 Hz may be weaker.)

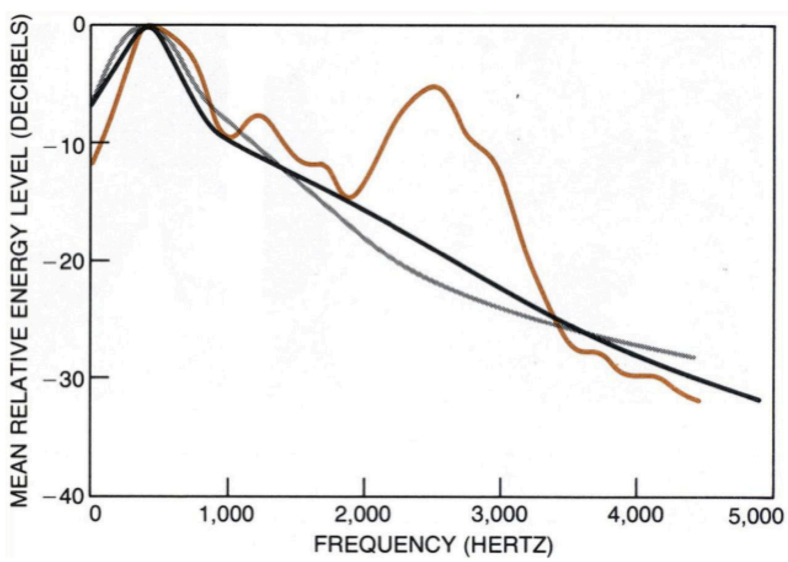


Figure. Intensity spectra in sound are shown from a good singer (brown curve), ordinary speech (light curve), and orchestral accompaniment (dark curve). The curves are normalized to 0 dB at about 500 Hz, which is the peak of the 1st singing formant. The pronounced 3rd singing formant around 2500 Hz enables the singer to be heard well above the orchestra.
(Reference: Johan Sundberg; The Acoustics of the Singing Voice; Sci. Amer. March 1977.)

Research Project

Compare the singing formants of male and female singers and write a report.

Singing Formants

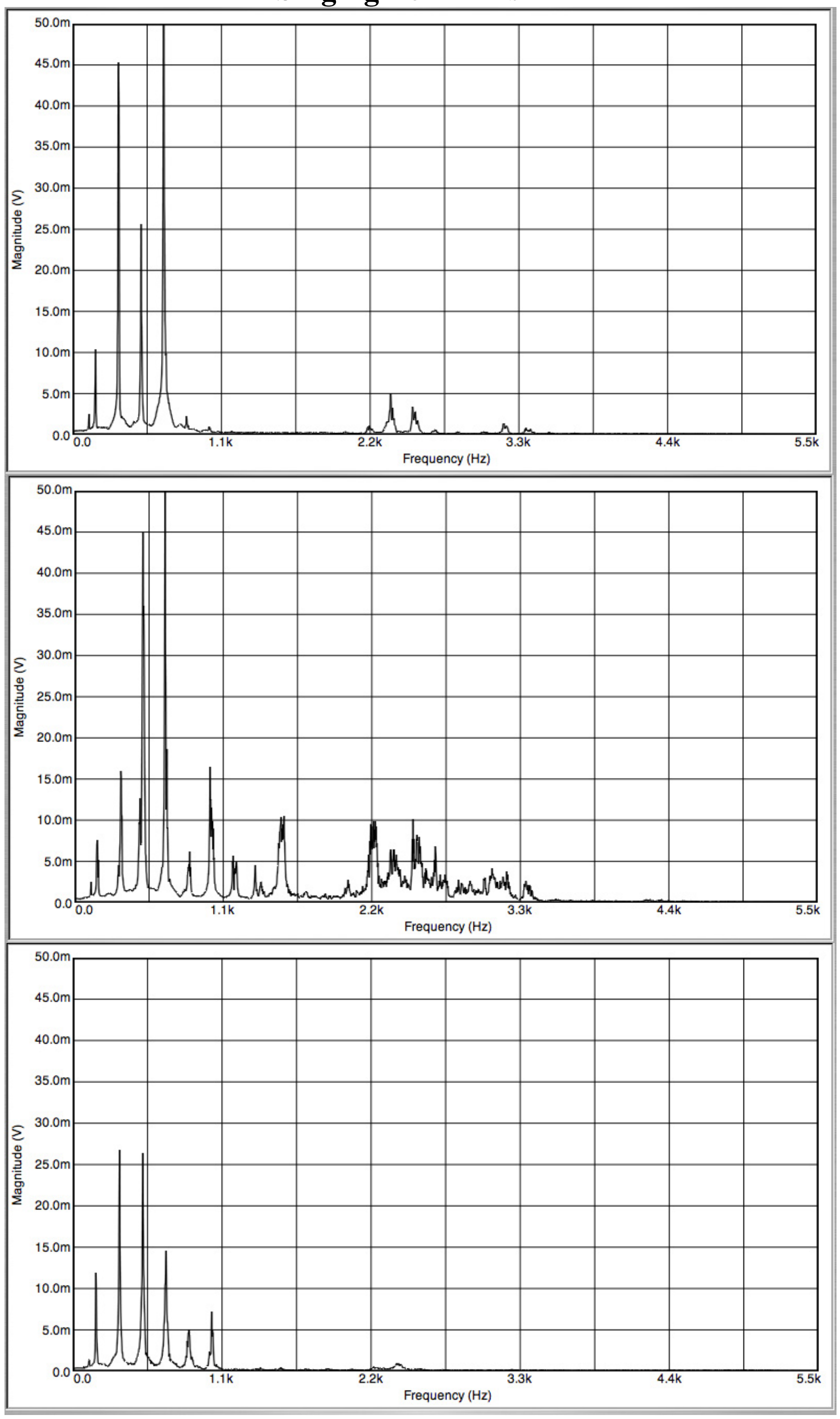
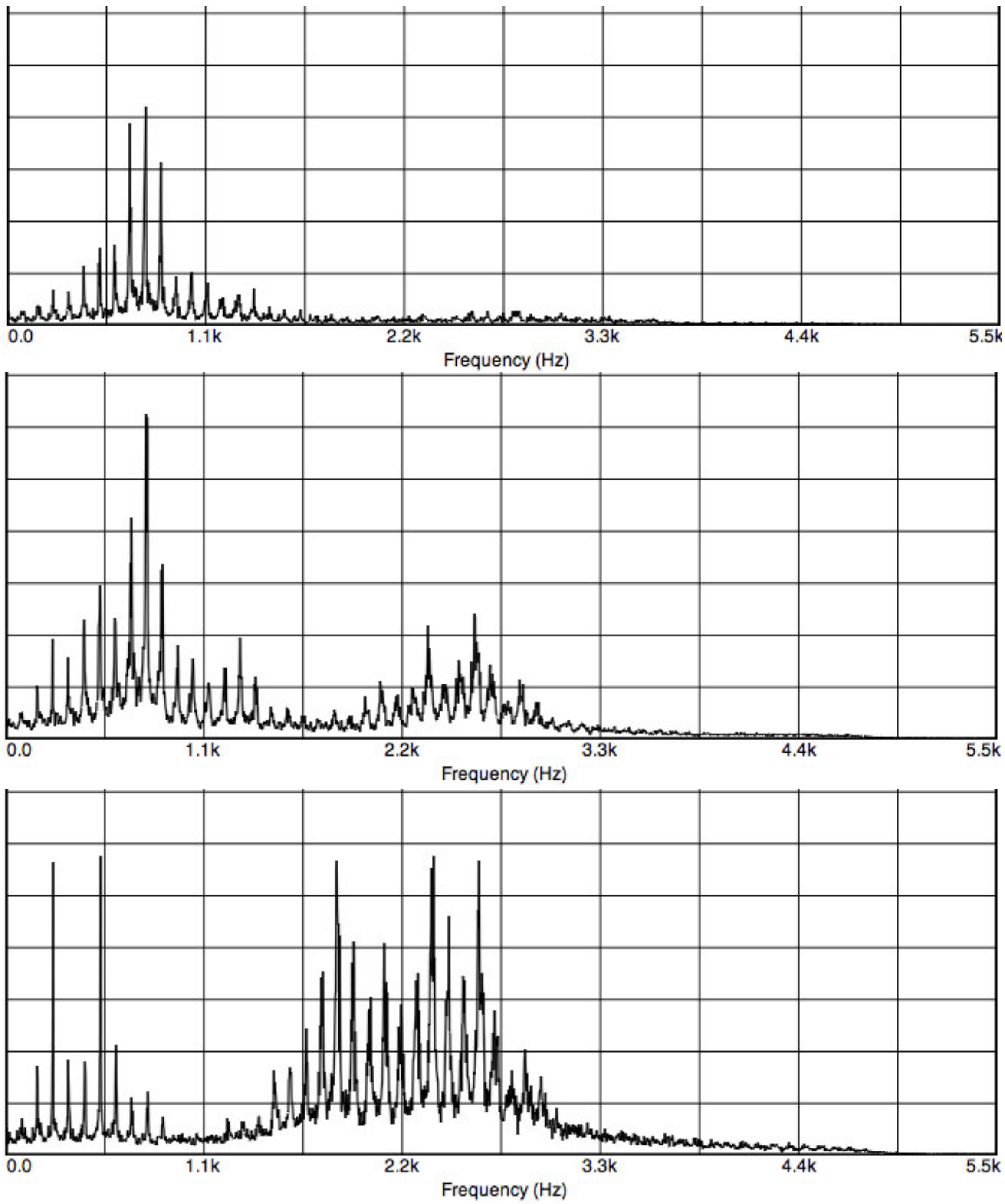


Figure. Vowel sounds at pitch a F3 = 175 Hz. Top: “oh”. Middle: “ah”, both sung by Professor Gerald Dolter, School of Music, Texas Tech University. Three formant regions are seen around 500, 1500, and 2500 Hz. Bottom: Vowel “ah” from an untrained voice. Only the formant region around 500 Hz is seen, no singing formant.

Singing Formants (continued)



Singing formants of a bass-baritone (Professor Gerald Dolter, Texas Tech University),
Note sung: F2 = 87 Hz
Top: Vowel sound “ah”, controlled shouting, without singing formant.
Middle: Vowel sound “ah”, singing formant between 2 and 3 kHz.
Bottom: Vowel sound “eh”, very strong singing formants between 1.5 and 3 kHz.

Overtone Singing

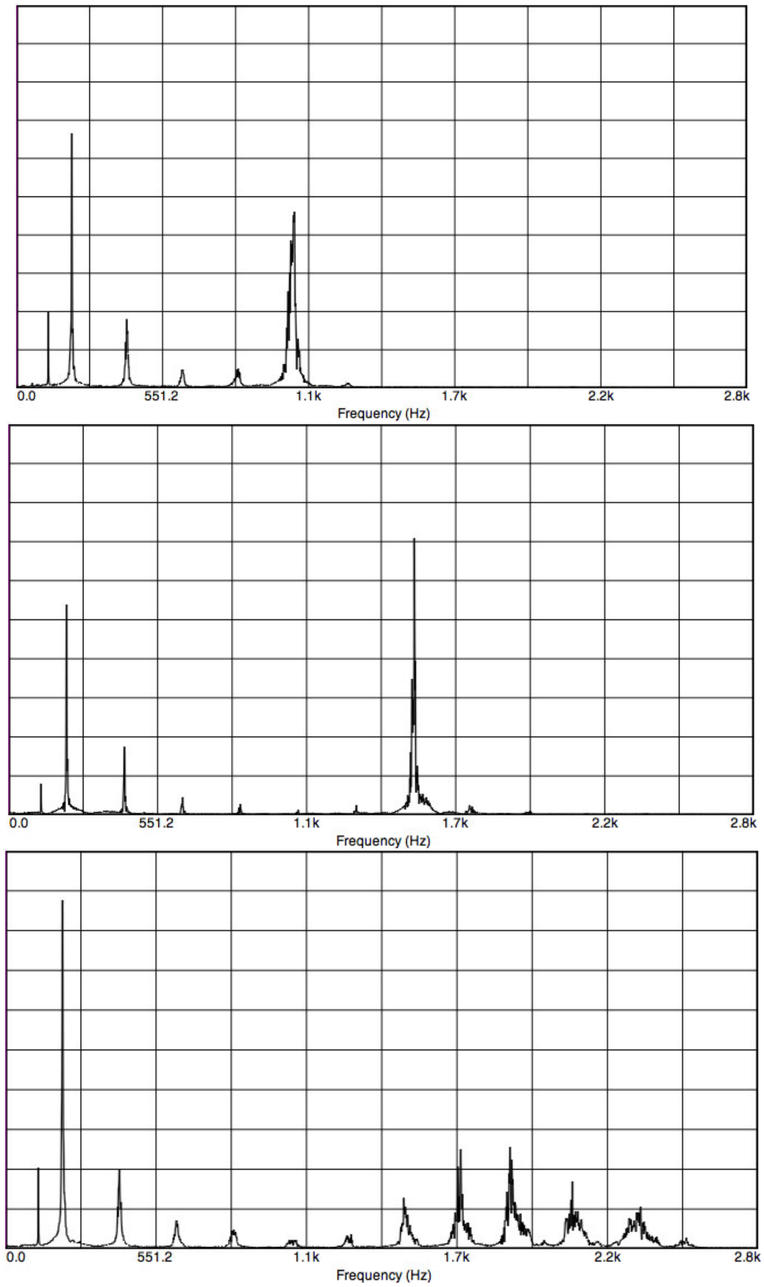


Figure. Harmonic or overtone singing by Dr. Stuart Hinds. Fundamental frequency
f = 208.6 Hz or about G3$^{\#}$. (The lowest spike at 120 Hz is ambient noise from a fan.)
Top: Harmonic N = 5 stressed.
Middle: Harmonic N = 7 stressed.
Bottom: Harmonics N = 7, 8, 9, 10, 11 stressed.

Formants of Musical Instruments

Formants also exist in musical instruments. They show frequency groupings where the overtones are strong.

Formants of a Krummhorn

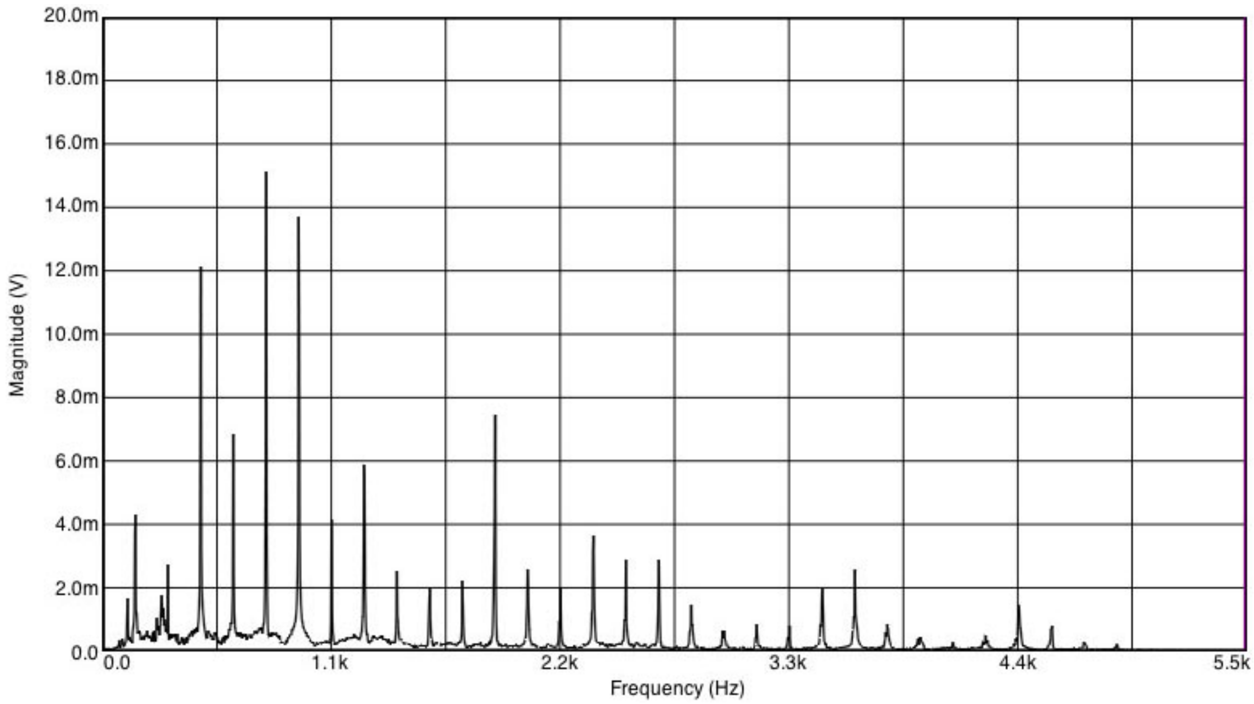


Figure. Fourier spectrum of the note E3 = 164.8 Hz from a Krummhorn (played by Professor Richard Meek, School of Music, Texas Tech University). Three formant groups of harmonics can be seen, centered around 600 Hz, 2400 Hz, and 3600 Hz.

Exercises

1. Draw a curve over the Fourier spectrum of the Krummhorn to highlight the formants. Read off the peak frequencies of the broad formant maxima.

Answer: Formant maxima at: _____ Hz, ______Hz, _____Hz, _____Hz, _____Hz

2. How many harmonics do you see in the overtone spectrum of the Krummhorn?

Answer: Number of harmonics: _________

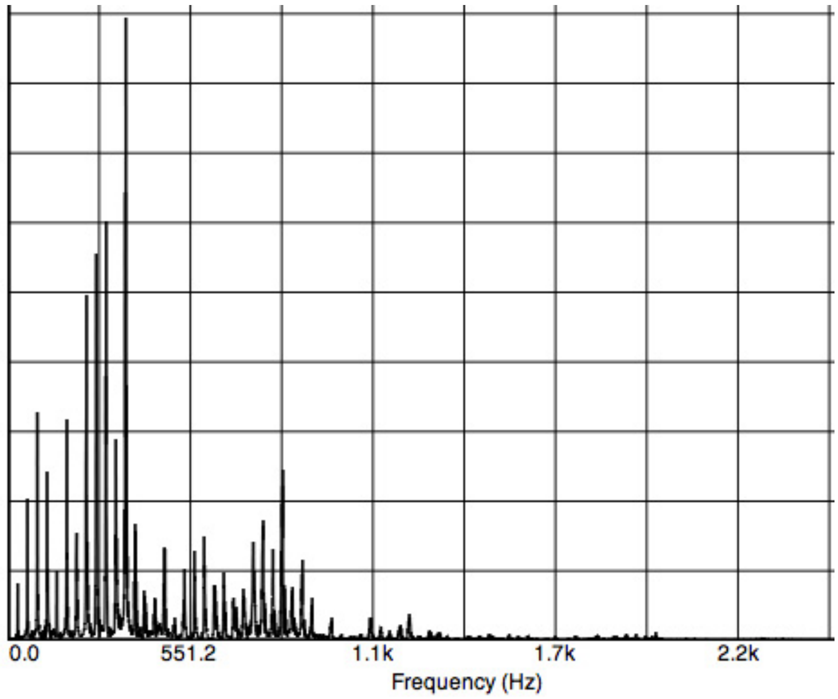
Demonstrations

Observe some formant regions in the Fourier spectra of instruments:

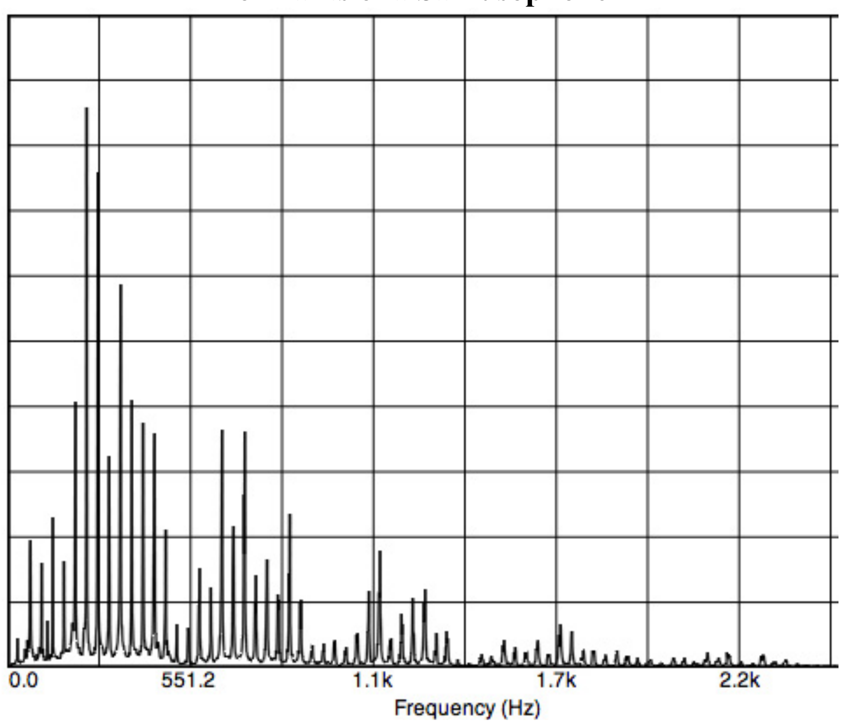
1. Krummhorn
2. Harmonica
3. Bassoon
4. Clarinet
5. Singing voice

and other available instruments.

Formants of a Contrabassoon



Formants of a Sarrusophone



Top figure: Two pronounced formant regions from a contrabassoon for the note $B0^b$ (29.1 Hz). Bottom figure: Four pronounced formant regions for the note $C1^\#$ (34.0 Hz) from a sarrusophone, a saxophone-like instrument. The amplitudes of the harmonics are shown on a linear scale. (Instruments played by Professor R. Meek, Texas Tech University.)

Intensity-Frequency Boundaries of Hearing, Music, and Speech. Presbycusis

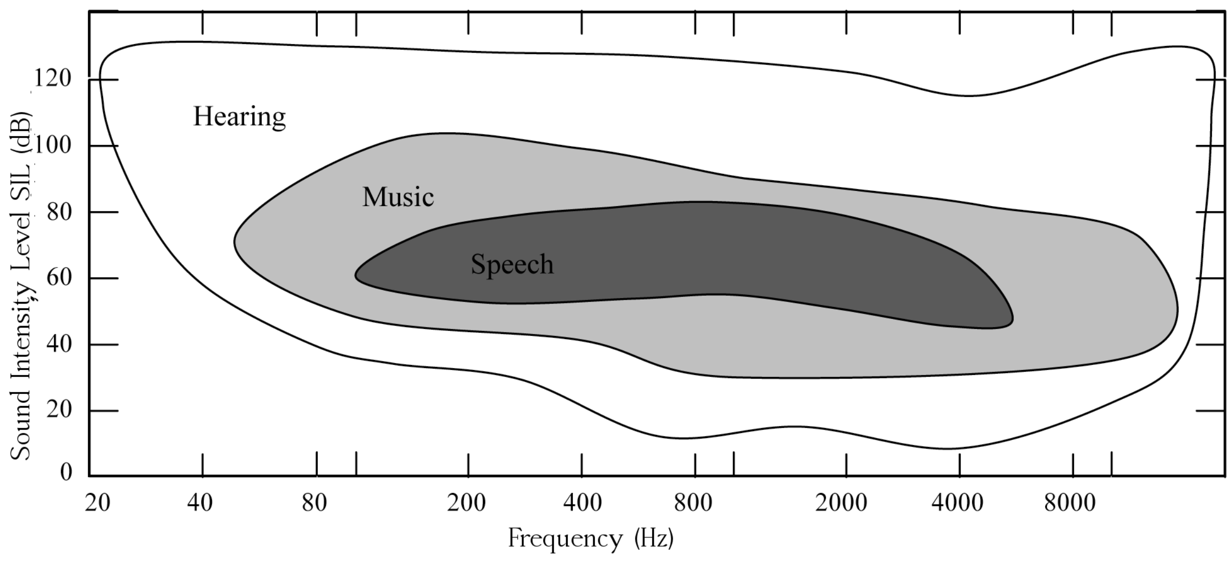


Figure. Intensity boundaries versus frequency boundaries for normal hearing, orchestral music, and speech. (Adapted from Irving P. Herman, Physics of the Human Body, Springer Verlag Berlin, 2007, Fig. 10.30, p. 594.)

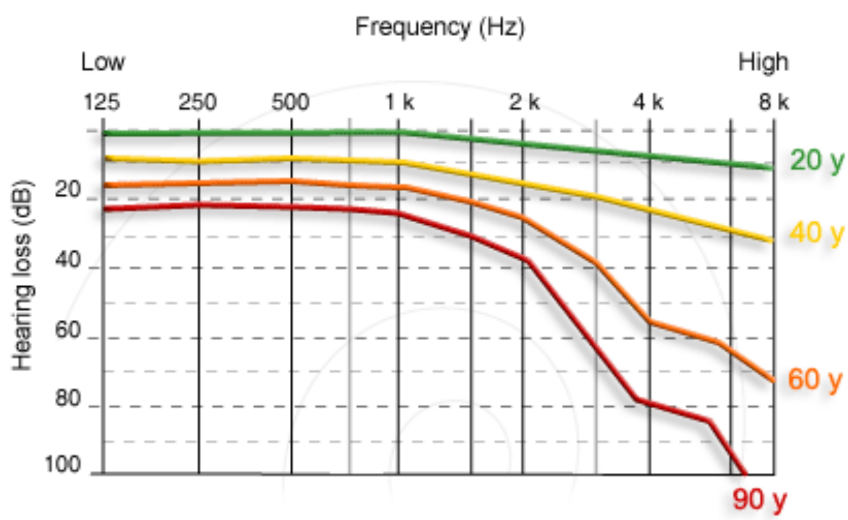


Figure. Age-related hearing loss (presbycusis) in decibel (dB) as a function of frequency, with age as a parameter on the colored curves. The loss can be severe beyond age 60 (or earlier).

Human Pain and Infrasonic Vibrational Frequencies

The human body may suffer certain pains and discomforts in the infrasonic range (below 20 Hz):

Chest pain	5-7 Hz
Jaw pain	6-8 Hz
Abdominal pain	5-10 Hz
Back pain, e.g. lumbar region	8-12 Hz
Headache	13-20 Hz

(From: Irving P. Herman, Physics of the Human Body, Springer Verlag Berlin, 2007, p.617.).)