The Physics of Music
UNIVERSITY OF CALIFORNIA, IRVINE

Lecture 14

- Percussion Instruments
- Keyboard Instruments

Instructor: David Kirkby (dkirkby@uci.edu)

Miscellaneous

Office hours this week are Wed 9-10am, 3-4pm.

Office hours next week are Wed 2-4pm.

There is a typo in 2(b) of Problem Set #6. The length of the clarinet to use should be 0.6 m, not 0.6 cm.

The final is scheduled for 10:30-12:30 on Friday Dec 13, in this classroom.

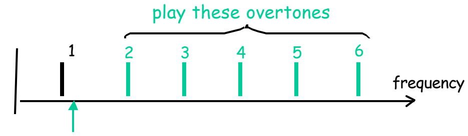
The final problem set will be handed out on Thursday and due 2 weeks later.

Do you prefer:
- another 50 point Problem Set, or
- a 75 point Problem Set (since you have 2 weeks)?

Do you prefer a final exam that covers:
- the entire course, or
- Lectures 9-18 in more detail.

Review of Lecture 13

We discussed the air reed instruments and the brass instruments. We will start today with a demonstration of the trombone. Some features to listen for:
- The inharmonic fundamental
- The pedal tone (an example of virtual pitch)
- Change of pitch and timbre during slide glissando
- Shock waves



Percussion Instruments

Unlike the strings, woodwinds and brasses, the percussion instruments do not share a common method for producing sound.

Instead, they share a common feature of the timbre: the percussion instruments are significantly inharmonic.

Some of the common resonators occurring in percussion instruments that we will discuss are:
- Bars and rods
- Membranes
- Plates

Energy is usually delivered by striking the resonator with a solid object, resulting in a characteristic decay envelope.

Vibrations of Bars and Rods

Bars and rods are solid objects, made of a single material, whose length is much greater than their other dimensions.

Bars and rods have two types of resonances that are musically useful:
- Longitudinal
- Transverse

We already saw an example of longitudinal resonance in an aluminum "singing rod". The resulting sound had a definite pitch with harmonic timbre.

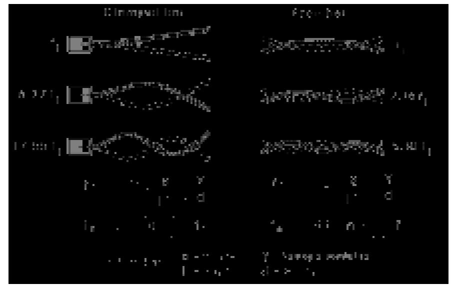
To a good approximation, the standing waves of longitudinal vibration are analogous to the (longitudinal) standing waves of an air column and the (transverse) standing waves on a string.

Therefore, the resonant frequencies for longitudinal vibrations do not depend on the other dimensions of the bar/rod or even its cross-sectional shape.

However, most percussion instruments exploit transverse vibrations. These are significantly more complex since they do depend on the transverse dimensions and shape.

Transverse Modes of Vibration

The standing waves depend on the boundary conditions:

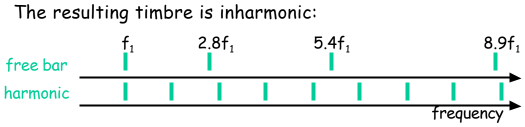


http://hyperphysics.phy-astr.gsu.edu/hbase/music/barres.html

The formulas given on the previous slide reveal the main differences between longitudinal (or any simple 1-dimensional) standing waves and the 2-dimensional modes of a bar/rod:

- The fundamental frequency depends on the resonator's thickness (a) and length (L) according to $f_1 \sim a/L^2$
- Overtones are related to the fundamental by $f_n \sim n^2 f_0$, with n = 3,5,7,...

The resulting timbre is inharmonic:



Listen to this sound morph from harmonic timbre to the timbre of a bar free at both ends:

Your perception of an inharmonic sound is usually an absence of a definite pitch.

However, most of the percussion instruments using a bar (e.g., xylophone) have a definite pitch.

We will see that each instrument has adopted a different strategy to minimize the effect of its inharmonic spectrum.

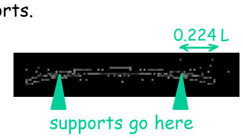
Glockenspiel

The Glockenspiel (or Bell Lyra) is the instrument with bars closest to the ideal we have been discussing:

This instrument resolves the problem of inharmonic overtones by producing a sound that is mostly due to the fundamental frequency. The resulting timbre has a definite pitch, but is thin because it lacks overtones.

Higher-frequency overtones of the Glockenspiel are suppressed with a combination of two strategies:

- Bars are made short enough that the overtones are at frequencies where human hearing sensitivity is starting to decrease.
- The bars are supported at the locations of the two nodes of the fundamental standing wave. All higher-frequency overtones are damped to some extent by these supports.



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Marimba, Xylophone, Vibraphone

The marimba, xylophone and vibraphone are the most common bar percussion instruments:

xylophone

vibraphone

marimba

Marimba and xylophone bars are usually made of rosewood or a synthetic material with similar properties. Vibraphone bars are usually made of aluminum.

All three instruments have tubular resonators (usually open at one end, closed at the other) below each bar. The lengths of the tubes are chosen to resonate at each bar's fundamental (lowest) vibration frequency.

Restoring Harmonic Timbre

These instruments restore an approximately harmonic timbre with two strategies:

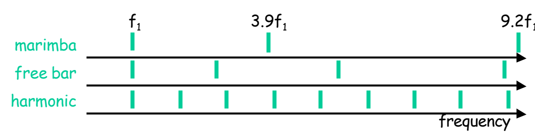
- Remove material from the middle underside of each bar to alter the overtone frequencies, and bring the second overtone close to a harmonic frequency.
- Reinforce the fundamental frequency (and in some cases also the first overtone) with a half-open air-column resonators below each bar.

Removing material here lowers the fundamental's frequency

Shaped Bar Overtones

The marimba and vibraphone have their bars shaped so that their 2nd overtone matches the frequency of the 4th harmonic of their fundamental.

Xylophone bars are shaped so that their 2nd overtone matches the frequency of the 3th harmonic of their fundamental. Listen to this sound morph to a marimba:



Resonator Tubes

Recall that a pipe with open+closed boundary conditions has standing wave frequencies of f_1, $3f_1$, $5f_1$,... (no even harmonics).

As a result, the pipe reinforces the 2nd overtone of a xylophone, but not of a marimba or xylophone.

Question: why do the pipes get shorter and then longer in some instruments?

Answer: it is purely cosmetic. The long pipes under high notes are blocked near their top.

Vibraphone

A unique feature of the vibraphone is that its aluminum bars vibrate for a long time.

As a result, the instrument is equipped with a pedal-controlled damper (bar with felt lining) to allow short-duration notes to be played.

Vibraphones also often have motor driven discs installed at top of each resonator tube. When the disc is closed, the tube is no longer coupled to the bar (by sympathetic vibrations). The rotation of the discs give the vibraphone its characteristic amplitude vibrato.

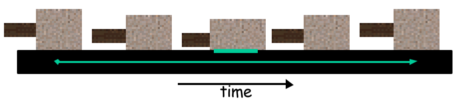
Mallets

The source of energy for a bar instrument is the impact of a mallet hitting the bar.

Mallets come in a variety of sizes and hardness.

http://www.vicfirth.com/

Even for hard mallets, the mallet head is deformed when it strikes the bar. As a result, the mallet makes contact over some area, for some period of time.



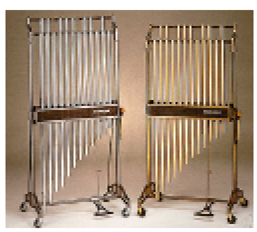
Some general principles for mallets:

- A mallet transfers the maximum amount of energy to the bar when its mass is equal to the bar's dynamic mass (about 1/3 of its actual mass).
- If the mallet remains in contact with the bar for a time T, then frequencies above ~2/T are damped.
- Striking at any point excites each natural mode in proportion to how much that mode moves at that particular point. In particular, a mode with a node at the strike point is not excited at all.
- The effect of the mallet striking over an area can be analyzed using the Principle of Superposition.

These principles apply equally well to mallets and drumsticks used to play other percussion instruments.

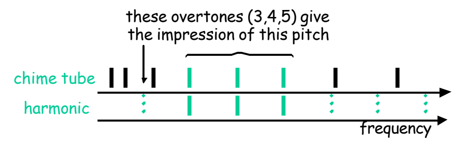
Chimes

Chimes (or Tubular Bells) are made from hollow tubes (usually brass) that are closed at their top end and open at the bottom. The sound of a chime is mostly produced by transverse vibrations of the tube walls, and not by the air column contained within the walls.



The overtones of a chime tube are close to those of an ideal free bar, except that the lowest modes are shifted down in frequency by the end plug.

The resulting spectrum has overtones 4,5,6 approximately in the frequency ratio of 2:3:4. As a result, the pitch you hear is 1/2 of the 4th overtone's frequency. Listen to this sound morph to a chime timbre:

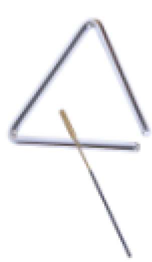


Triangles

Triangles are an example of a simple rod (usually steel) whose overtones are not adjusted to sound harmonic. The resulting timbre is inharmonic.

The bending of the triangle does not alter its sound: a straightened triangle would have essentially the same sound (just like a straightened brass instrument).

Supporting a triangle at one corner favors modes with a node near this location.



Vibrations of Membranes

A membrane is an elastic object whose thickness is much smaller than its other dimensions.

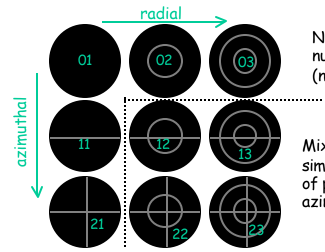
Membranes used for percussion usually have a circular boundary that is fixed (I.e., a node for all standing waves).

The source of energy for a membrane instrument is a mallet or drumstick hitting the membrane.

All of our comments about mallets hitting bars also apply to mallets and drumsticks hitting a membrane.

Standing Waves on a Membrane

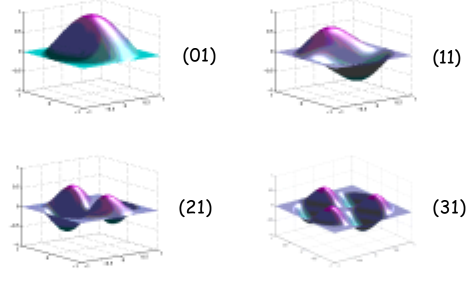
In two dimensions, nodes become lines instead of points (remember the Chladni patterns of violin and guitar plates). The standing waves can be organized according to how many azimuthal and radial node lines they have:



Nodes are numbered (n_{rad} n_{az})

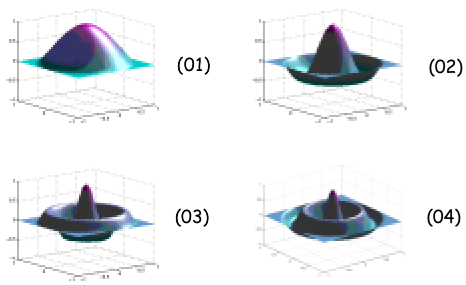
Mixed modes are not simple superpositions of pure radial and azimuthal modes!

Azimuthal Modes of a Membrane



http://www.matbham.ac.uk/C.J.Sangwin/Teaching/CircWaves/waves.html

Radial Modes of a Membrane



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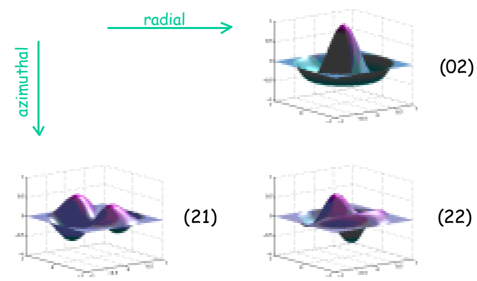
A Radial + Azimuthal Mixed Mode



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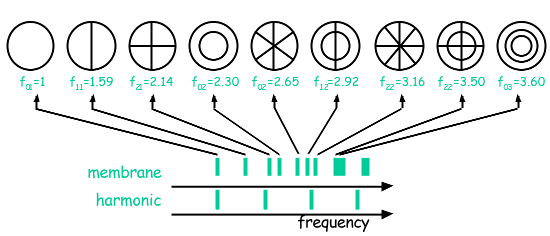
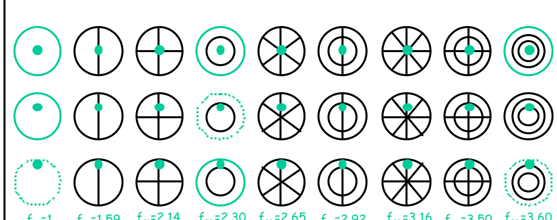
Membrane Timbre

The resonant frequencies of a membrane are not harmonic. Just as for the transverse resonances of a bar/rod, the fundamental reason for this is the two-dimensional nature of the object.



The location where a membrane is struck determines the relative proportions of each mode to the resulting vibration. In particular, nodes with a node line at the strike location are not excited.

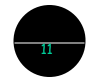


The amount of time T that the mallet/drumstick makes contact with the membrane will also influence the contribution of each mode: frequencies above ~2/T will be damped.

A soft mallet/drumstick head will generally make contact for a longer period of time than a hard one, and therefore produce a sound with less high-frequency overtones.

Timpani

Timpani (or Kettle Drums) consist of a membrane stretched over a hollow enclosure. The dominant mode of vibration that you hear is (11).



The otherwise inharmonic overtones are coaxed into a more harmonic relationship primarily by the air trapped under the membrane.

Timpani have a pedal that adjusts the membrane tension enough to raise the fundamental frequency by about a fourth interval (4/3).

Bass Drum

The bass drum consists of two membranes on a hollow cylindrical frame (with air trapped inside).

The bass drum is capable of making the loudest sound of all the instruments in the orchestra!

Striking one membrane causes the other to vibrate because of the strong coupling through the air trapped between the membranes.

The drum's timbre can be varied by increasing the tension of the struck membrane (batter) relative to the other membrane (carry).

Snare Drum

A snare drum is essentially a small (33-38cm) version of a bass drum (50-100cm).

Except for one important difference: the snare…

Wires stretched on the carry membrane add a shimmering sound to its vibrations.

The snare can be separated from the membrane to change the timbre.

Other Drums

There are many other types of drums, but they are mostly variations on the theme of bass and snare drums…

Vibrations of Plates

A plate is a solid object whose thickness is small compared with its other dimensions.

A plate has the same relationship to a membrane as a rod/bar has to a string: tension force is replaced by stiffness and other dimensions (e.g. thickness) influence the sound.

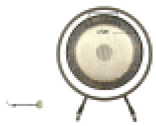
The standing waves on a flat circular plate are similar to those of a circular membrane, but tend to be higher in frequency.

Plates are not necessarily flat in their resting position (unlike membranes).

Cymbals, Gongs and Tamtams

Cymbals are circular plates, usually made of bronze, with an almost flat saucer-like shape.

Gongs and tamtams are similar to cymbals, but with more curvature at their edges.

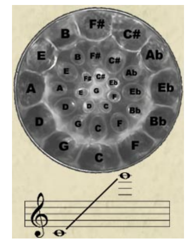


Steel Drums

Steel drums are a recent invention, developed by trial and error using the 1000s of oil drums left on the beaches of Trinidad & Tobago by the British Navy after World War II.

The playing surface (pan) of a steel drum is hammered into a concave shape with individual note areas.

Listen to an example…

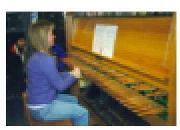


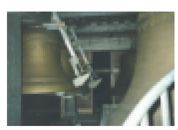
Bells and Carillons

Bells are another form of vibrating plate: in this case the plate is curved into a bell shape (!)

A carillon is a set of tuned bells controlled from a keyboard. Listen to an example…

Handbells were developed to allow church bell ringers to practice without disturbing the whole neighborhood.



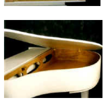


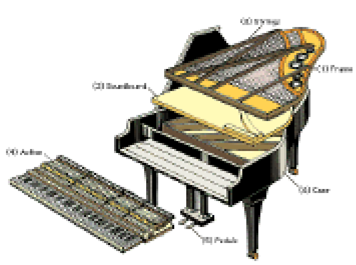
Keyboard Instruments

Keyboard instruments consist of tuned strings coupled to an air-filled cavity. Strings are struck or plucked by a mechanical action which is controlled from a keyboard.

Pianos, clavichords and harpsichords are all examples of keyboard instruments.

Piano Construction





http://www.concertpitchpiano.com/GrandPianoConstruction.html

Piano Strings

Piano strings are made from high-strength steel and usually stretched to about half of their breaking strength on a metal frame.

The strings of a piano are almost ideal one-dimensional strings, but have some inharmonicity that gets worse at higher harmonics.

Pianos cover the frequency range from 27.5 Hz (A_0) to 4186 Hz (C_8) with 88 keys (a ratio of 152:1).

Rather than have the longest strings 152x longer than the shortest ones, the tension and mass are varied in different ranges.

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Piano Tuning

A piano sounds best in tune when its octaves are stretched to match the inharmonicity of the string overtones.

Most notes on the piano have three corresponding strings. The piano sounds best when these strings are slightly out of tune with each other: this deliberate mistuning allows the vibrations of the string to last longer (otherwise, they transfer their energy too efficiently to the soundboard).

When the strings are too far out of tune, the result is a "honky-tonk" piano sound.

Hammer-String Interactions

The mechanical action that translates a key press into the hammer hitting the string is surprisingly complex:

http://www.concertpitchpiano.com/AnimatedGrandAction.html

This mechanism has 3 main purposes:

- to provide a lever action so that the hammer travels faster than the key,
- to provide an escapement action so that the hammer moves independently of the key,
- to raise and lower a felt damper that allows the string(s) to vibrate freely.

Piano Pedals

A piano usually has 2 or 3 foot-operated pedals.

The right-most pedal raises the dampers on all strings so that they continue to vibrate after a key is released, and are also free to vibrate sympathetically when other notes are played.

The left-most pedal makes the instrument quieter by either shifting the hammers to miss one string, or else by moving the hammers closer to the strings.

A center pedal, if present, usually sustains only those notes being played.

Piano Soundboard

The sound board plays a similar role to the front and back plates of a string instrument, and is responsible for producing most of the sound that you hear.

Vibrations of the strings are transmitted to the sound board via a bridge.

Although the metal frame hold the strings does most of the work, some of the string tension is transmitted to the sound board via the bridge. This force totals ~300 lbs.