10.3.5: Stringed Instruments

There are probably an infinite number of ways to connect a string to a resonating body to form a musical instrument and any number of body shapes. Here is Wikipedia's list of stringed instruments with links to information about each one. There are also several variations in how the string is excited and how the string vibration is coupled to the body of the instrument. It is also possible to turn the vibrations into an electronic signal for amplification, as we will see later.

Stringed instruments have strings with string harmonic resonances connected to a surface which has additional overtones, some of which are not harmonic. Most stringed instruments also have a hollow body with an opening (called the ***f hole*** or sound hole in a violin and some guitars) so there are air resonances associated with the body cavity; the Helmholtz resonances we saw in Chapter 4 and mentioned above. The shape of the hole developed over time by trial and error to provide the most sound as explained in this article.

It is this combination of string, surface and Helmholtz resonances that make each type of instrument, and in fact each instrument unique. A primary difference between expensive violins such as a Stradivarius build in the late 1600s, early 1700s (worth millions of dollars) and a cheaply made modern violin is that the resonance frequencies of the Stradivarius are more distinct, have a larger amplitude and are closer to the frequencies of the notes played by the string. These resonances make it easier to reach a given note and the note being played sounds louder. (It should be noted, however, that blind listening tests can rarely distinguish between a Stradivarius and a well made modern instrument selling for tens of thousands of dollars.)

For most stringed instruments the ***bridge*** transmits vibrations from the string to the body of the instrument (electrical pickups will be discussed later). Many guitar and violin bridges are carved with interesting shapes. This makes them more flexible so that they are closer to the resonance frequencies of the string and body. This also means, however, that they can act as filters since they do not transmit some frequencies as easily. Some bridges are slightly rounded so that the length of the string changes slightly as the string vibrates. This will also affect the frequencies emitted by the instrument. In the picture on the left below the bridge of a double bass is the light colored piece. On the right is the bridge of a modern guitar.

Figure 10.3.5.1

Figure 10.3.5.2

One problem that occurs for some stringed instruments, particularly the cello, is an unwanted resonance of the bridge, string, and body called a ***wolf tone***. The result is an unpleasant, wavering note. For certain notes, energy from the string causes a resonance in the bridge and body that feeds back into the string, making the string hard to control. Beginning performers often have more trouble controlling these unwanted resonances than experienced musicians. Various design changes have been tried to avoid this problem but it is very difficult to construct an instrument with resonances only where desired and no others.

When the string vibrations are up and down relative to the bridge, energy is transmitted to the body more efficiently so the sound dies away more quickly. If the string is plucked in a direction parallel to the body the sound is softer but lasts longer because the bridge is less efficient in transmitting the vibrations. The schematic below shows the effect of the direction in which the string is plucked or bowed (blue arrows) relative to the body surface of the instrument.

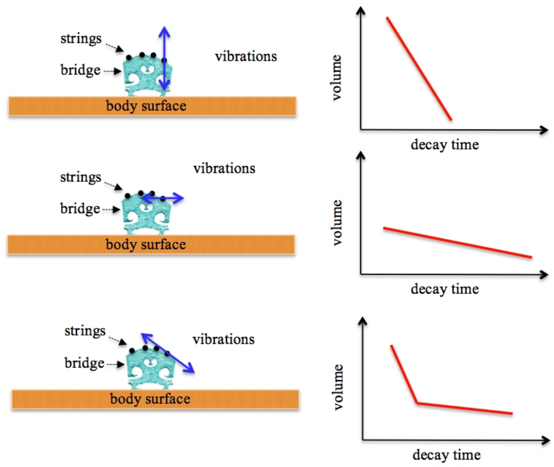

Figure 10.3.5.3

The top surface of most stringed instruments is smooth and flat but guitars, violins and other instruments have reinforcing bars on the inside, that strengthen the top and carry vibrations from the bridge area to the rest of the surface. For guitars this is called ***guitar bracing***, for violins the reinforcing bars are called ***bass bars***. Instrument makers generally try to construct these so that they do not cause unwanted resonances while reinforcing desired frequencies in the instrument but this is largely a trial and error process. The knowledge gained from this process has been handed down over many generations and there are at least half a dozen major bracing styles for guitars with many small variations of these. The following picture shows the bracing inside a guitar.

Figure 10.3.5.4

Many hollow bodied stringed instruments also have a ***sound post***. This is a small dowel inside the instrument wedged between the top to the bottom surfaces. The purpose is to conduct vibrations from the top surface to the bottom. Placement and size of the sound post is also determined largely by trial and error. Both sound bars and sound posts affect the resonance frequencies and overall sound of the instrument. Placing the sound post closer to the neck of a violin makes the tones louder; moving it further from the neck changes the tonal quality to be more rich by transmitting more overtone frequencies from the top to the bottom of the instrument. The sound post transmits lower frequencies more effectively with the result that high frequencies are emitted mostly by the top of a guitar or violin but low frequencies are emitted from both sides.

In the schematic below the cross section of a violin is shown. The bass bar runs the length of the violin and the sound post connects the top to the bottom surface. Notice that bass bar and sound post are positioned so that as the bridge rocks back and forth due to vibration of the strings the bridge will transmit energy to both the bass bar and the sound post. The asymmetric location of the sound post also means the top surface is more likely to vibrate with the left side out of phase with the right side (left side going up at the same time the right side is going down). This affects the Helmholtz resonances of the cavity inside.

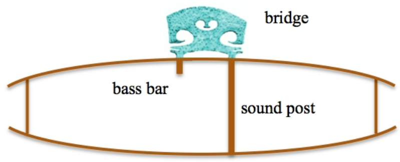

Figure 10.3.5.5

The Helmholtz resonances affect the volume of certain frequencies being produced. If the air is coming out of the f hole due to a Helmholtz resonance at the same time the instrument body top is vibrating downward (the two motions are 180 degrees out of phase), the exiting air will end up at a higher pressure and thus a higher volume. This effect is stronger for lower frequencies because the Helmholtz resonances tend to be lower frequency, around $270\ \mathrm{Hz}$ for a violin.

Another factor that affects the sound of a string instrument is the material of which it is constructed and the finish. More expensive guitars and violins are made from wood that is picked to be very dense and have very uniform and fine grain. The more uniform the wood grain the less likely there will be an unwanted resonance. It has been claimed that the famous Stradivarius violins have a special sound in part because the wood was treated with special chemicals. The process of how they were made was a secret that was lost hundreds of years ago and has not been replicated.

Strictly speaking keyboard instruments such as the piano, harpsichord and clavichord are classified as percussion instruments because there is a mechanism that strikes or plucks the string. In the clavichord, developed in the 15th century, a small metal piece called the ***tangent*** hits the string (sometimes two strings) when a lever is pressed by the performer. The harpsichord was developed in about a century later and uses a quill (originally from the feather of a bird) called the ***plectrum*** to pluck one or two strings when the key is pressed. A spring mechanism moves the plectrum out of the way while the mechanism returns to its starting point (see Wikipeda for details).

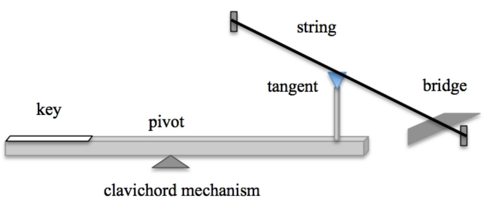

Figure 10.3.5.6

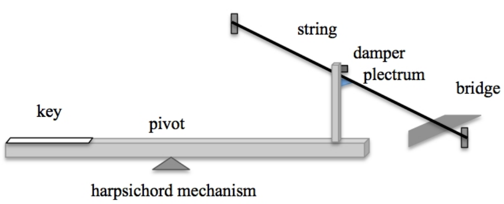

Figure 10.3.5.7

The piano was developed in the early 1700s This instrument overcame several limitations of the earlier harpsichords and clavichords. Because it was significantly louder it was originally called the 'piano forte' (forte is Latin for loud). Below is a very simplified diagram of the mechanism of the strike action of the piano (more details can be found in this animation of a piano mechanism). When the key is pressed a series of levers acts to throw the hammer upward so that it hits the string. The back check keeps the hammer from bouncing back and striking the string twice. As long as the key is held down another set of levers keeps the damper off the string.

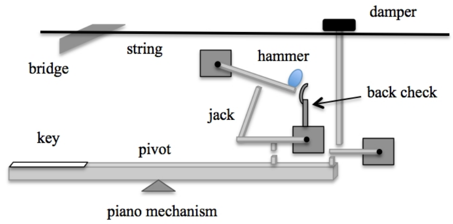

Figure $10.3.5.8$

The clavichord, harpsichord and piano sound different in large part because the strings are set into vibration by different mechanisms. As we saw above, the initial shape of the string when it is plucked or struck determines which harmonics are more present. For the piano the harmonic that has an anti-node where the hammer strikes is dampened out because the hammer contact prevents the string from vibrating at that location, forming a temporary node. The piano also has a number of other innovations that give it a distinct sound. The mechanism of the piano allows the hammer to strike the strings at a different angle depending on how hard the key is pushed. The surface of the hammer is made of felt and different regions have slightly different stiffnesses of felt. So pushing a key harder not only causes the hammer to strike harder, it also causes a stiffer part of the hammer to strike the string, giving a louder sound and activating other harmonics.

Pianos also have multiple strings for some notes the piano plays. The treble pitches have three identical strings, the tenor range uses two strings, and the bass notes have only one string. There may be more than 230 strings used to produce the usual 88 notes on a piano. For treble notes all three strings are usually struck by the hammer but when the left foot petal is held down the hammer shifts so that only two strings are struck. In this case the third is activated by vibrations traveling from the other two through the frame that holds the strings. Since the strings can vibrate in different directions at the same time, transmitting energy at different rates and to different resonances in the piano body, the sound of a piano is much richer than instruments that sound only one string at a time. In the first picture below the strings are all moving up at the same time. In the second picture the third string is moving down while the other two are moving upwards. In the third picture the third string is moving in a direction perpendicular to the motion of the other two strings. Obviously there can be other combination of vibrations.

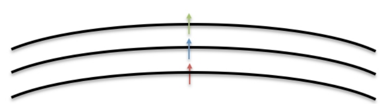

Figure $10.3.5.9$

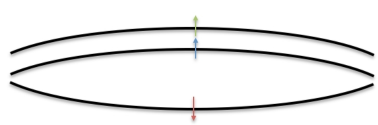

Figure $10.3.5.10$

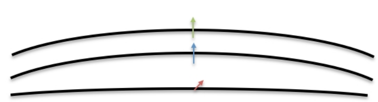

Figure $10.3.5.11$

The piano also plays a larger range of notes than the harpsichord or clavichord. To archive the high notes the tension must be very high in the strings, as much as 1000 N for some strings. To withstand these forces the strings in a piano are attached to a cast iron frame. For strings under this much tension even slight displacements from equilibrium (when the hammer strikes the string) cause a significant change in the tension. This means that striking the note harder changes the pitch slightly because the string is stretched more. The effect is greater on higher harmonics because a higher harmonic has more bends along the length of the string, increasing the tension even more. The result is that the overtones are no longer exactly harmonic.

A second problem for a stringed instrument that plays very low notes is that for a given string density and tension, the strings have to be unreasonably long to play the lowest notes. In order to shorten the length of string needed for low notes the strings are made more dense by wrapping them either once or twice. Even with these adjustments a grand piano is quite large. Upright pianos put the strings into layers so that more strings can be packed into a smaller space. The wires shown below are double wrapped piano wires.

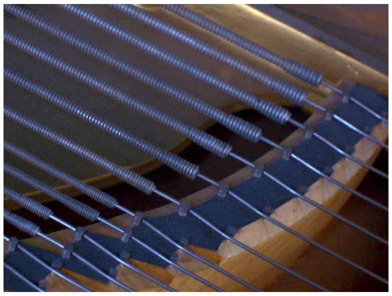

Figure 10.3.5.12

As with all stringed instruments the body of the piano acts as a resonator to amplify the sound of the vibrating strings (of course, at the cost of having the string vibrate for less time so that conservation of energy is obeyed). Pianos have a ***soundboard*** attached to the frame that holds the strings. Much like guitar bracing, the soundboard also has bracing that helps transmit the sound through the entire surface. The top of the piano serves two purposes. One is to reflect sound from the soundboard out towards the audience. The piano top also has resonant modes, just like those of a guitar or violin body that affect the frequencies being transmitted.

Video/audio examples:

- Information from Wikipedia and YouTube on a few well known stringed instruments:
  - The violin family.
  - The violin.
  - The guitar.
  - The harpsichord.
  - The clavichord.
  - The harp.
  - The following web sites have pictures, sound samples and information about modern musical instruments used in bands and orchestras: one, two, three.
  - Viola de gamba performance.
  - Clavichord performance.
  - Harpsichord performance.
  - Piano performance.
- How a guitar is made.
- Chladni patterns of a violin shape.
- Helmholtz resonance in a guitar body.
- Animation of violin vibration modes.
- Violin wolf tone.
- Project for class by Kelsey Krueger on the cello wolf tone.
- An NPR report which says that tests show even experienced musicians can't tell the difference between a Stradivarius and an ordinary violin.
- Animation of a piano mechanism.
- Simulation of a piano hammer hitting a string from Wolfram (you may need to download their plug in to play with this demonstration). Notice that the seventh harmonic is missing in the Fourier spectrum. This is because the hammer itself dampens this harmonic by touching the string where the anti-node would be.
- Frequencies of Piano notes.
- Formula for piano string frequencies.
- Some information and YouTubes about aeolian harps. Two examples: Ordinary harp in the wind and an aeolian harp in a fan. Why does this happen? Vortex shedding. More than you want to know. Notice that there is a natural frequency of the air oscillations going past the cylinder that depends on air speed and viscosity, and size of the object. If this vortex shedding frequency equals a natural frequency of the string, it will drive the string to vibrate (resonance). Here is another explanation of and demonstration of vortex shedding.

Summary

Strings have harmonic resonances at multiples of the fundamental frequency. The bridge of a stringed instrument transmits these harmonics to a surface that has its own resonance frequencies which are usually not harmonic. The surface can move more air than a string and so acts to amplify the sound of the string (at the expense of a shorter vibration time for the string). If the instrument has a hollow body the Helmholtz resonances of the cavity contribute to the frequencies that are present. The particular combination of string, surface and body cavity resonances give each individual instrument its timbre.

Questions on Stringed Instruments:

1. What are the three parameters that determine the fundamental frequency of a vibrating string?
2. What is the relationship between the speed of a wave on a string and the fundamental frequency?
3. What are harmonic frequencies?
4. If you have a fundamental frequency of 102 Hz, what are the next three harmonic frequencies above this?
5. What is the distinction between a node and an anti-node?
6. How many nodes and antinodes are there in the 3rd harmonic? The 6th?
7. Explain the difference between harmonics and overtones.
8. What is the relationship between the fundamental frequency of a vibrating string on a stringed instrument and pitch?
9. What effect does plucking a string at different locations have on the harmonics that are formed?
10. What is the difference in vibrational modes between a string that is plucked and one that is bowed?
11. Why is it that a vibrating string in air doesn't produce as much sound as a vibrating string attached to a surface?
12. A string attached to a surface is louder than if it is not. How does this fit with conservation of energy?
13. Strings have harmonic overtones but surfaces typically do not. How does this effect the sound produced by a stringed instrument?
14. What is holographic interferometry and how does it show the vibrational modes of a surface?
15. Are Chladni plate resonance frequencies harmonic? Explain.
16. Explain Q-factor in terms of surface resonances for a stringed instrument.
17. Why do you want the body of a stringed instrument to have low Q resonance frequencies?
18. Why is uniformity in wood grain for a stringed instrument such as a guitar important with respect to resonance?
19. What does the bridge of a stringed instrument do?
20. What is the purpose of the sound post in a stringed instrument?
21. What is the purpose of bracing in a guitar?
22. What is the purpose of the bass bar in a violin?
23. What is the Wolf tone, and what causes it?
24. Which can play a note longer, a harpsichord or a piano and why?
25. Why is the piano louder than the harpsichord?
26. Using a reliable source, find out how much tension do the strings of a piano have. Using this, explain why pianos had to wait until the development of cast iron before the first piano was created.
27. What is a Helmholtz resonance? Explain what this has to do with acoustic string instruments.
28. Why do acoustic stringed instrument have hollow bodies with holes?
29. Find a reliable source and discuss the history of the f-hole.
30. Violins and guitars are both stringed instruments with hollow bodies and can play some of the same notes. Why is the timbre different between these two instruments?
31. On the Indian instrument, the sitar, why are there strings that are not plucked? Explain how this works.