

Making Music Beautiful

Complex Musical Tones

Have you ever asked yourself while listening to a recording, or while at a concert, what it is that makes the music so appealing? There are, of course, many answers. The music may bring back memories, or make you feel warm all over, or let you drift off into space (at least it seems that way), or it may just be that it's pleasing to your ear. Regardless of what conclusion you come to, there's no doubt that music makes you feel good. So we have to ask, What is it that does this? Melody is certainly important, as is rhythm, but there's something else you might not realize. The "richness" and complexity of the harmonics also add to the enjoyment. When you play a single note on a piano, or any other instrument, you may think you're getting a single tone, or single frequency, but you aren't. Many different frequencies are striking your eardrum, and of course, the music coming from an orchestra is much more complex. In this chapter we will look at this complexity and explore why it helps make music more appealing.

"Seeing" Music

If you listen to a note—say middle C—played on several different instruments, such as a violin, piano, and a clarinet, you can easily tell which instrument it came from. All are vibrating with the same frequency, 256 Hz, but even if they all have the same loudness, they still

sound different. And we can easily hear the difference. But if they are different, there has to be a way to see this difference. And, indeed, there is. What we need is a way of looking directly at the sound so that we can actually "see" the music. And for this we need two devices: a microphone and an oscilloscope. Both are relatively complex, so I won't go into the details of how they work, but I will give a brief outline. Later in the book I'll talk about them in more detail.

The major part of a microphone is a pair of electrically charged metal plates. The outer one, which is referred to as the diaphragm, is thin enough so that it vibrates when an air pressure wave such as the one created by your voice strikes it. These vibrations cause tiny electrical currents to flow in an external circuit that are proportional to the amplitude of the diaphragm; the current is therefore a "coded" copy of the oscillations. In effect, the vibrating signal has been converted to an equivalent electrical signal.

This oscillating electrical current is then fed to an oscilloscope. If you're not sure what an oscilloscope is, you merely have to look in your living room or den; the heart of your television set is an oscilloscope. In a television set a beam of light sweeps across the screen thousands of times a second. After each sweep it moves down slightly so that it eventually sweeps the entire screen. This beam causes the screen to glow with a particular intensity, and since the intensity at each point is continually changing, we see a picture.

In the same way, the oscillating current from our microphone is fed to two metal plates in an oscilloscope (fig. 38). A beam passes through the region between these plates and is deflected according to the charge on the plates; in other words, it changes in the same way that the oscillating electrical current that is applied to it changes. Finally, as in the case of the television set, the beam is moved rapidly across the screen hundreds of times per second until it has covered the complete screen.

What we see is a "picture" of the sound wave that struck the microphone. If the sound is pure, such as that from a tuning fork, we get a perfect sine wave and can easily determine its frequency and wavelength by measurements made on the screen. But when the note from a musical instrument is projected on the screen, we see immediately that it looks quite different. And we can now answer the question: why does a note such as middle C sound different on a violin, a

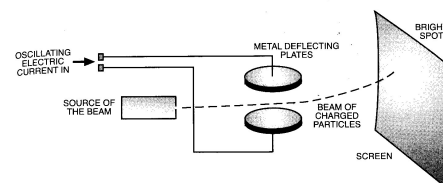


Fig. 38. A simple representation of an oscilloscope.

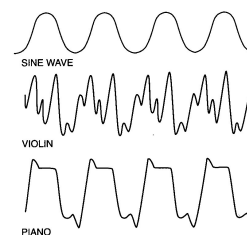


Fig. 39. The same note sounded on a signal generator, a violin, and a piano.

piano, and a clarinet. If we look at the sound from each of the instruments, we see that each has a frequency of 256 Hz, as expected, and each has the same loudness (with the height, or amplitude, of the wave measuring the loudness), but other than that their waveforms are quite different (fig. 39).

Timbre: The Quality of Music

The shape of these waveforms reminds us of the form we got earlier when we superimposed two pure signals of different frequencies, where one of the frequencies was double the other. Indeed, if we had continued this process with wavelengths that were multiples of the first, we would have made the wave more and more complex, but it would have continued to be periodic. What we can conclude from this is that any tone from a musical instrument, say middle C, is made up of waves of several different frequencies. We will, in fact, see that in most cases these frequencies are numerically related; in other words, they are multiples of the first frequency. And this is what makes the same note from various musical instruments different. Each of them has the same overall frequency, but they have other frequencies superimposed on this note that are different. We refer to these other waves as *overtones* or sometimes as *partials*.

In practice these overtones can be exact integral multiples of the first tone, which is referred to as the *fundamental*, or they can be arbitrary. If they are integral multiples, as shown in figure 40, we refer to them as *harmonic*; if not, they are *inharmonic*. For most instruments, overtones are harmonic; only such instruments as cymbals

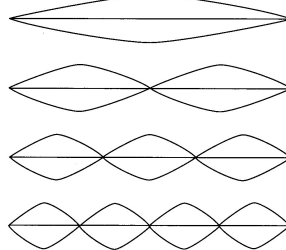


Fig. 40. Overtone. The top one is the fundamental.

and bells have inharmonic overtones. So we will direct almost all our attention to harmonic overtones.

The difference in the waveform of a note from instrument to instrument is referred to as the *timbre*, or *quality*, of the tone. Without thinking about it, you encounter timbre every day. The human voice is also made up of various overtones, and because of this, each voice is distinctive. This is why you can identify someone over the phone so easily, even though you can't see the speaker.

While the timbre, or quality, of a tone is mainly a result of overtones, other things also contribute to it. Consider a violin string, for example. You know that it sounds different when you pluck it, compared to when you bow it. We refer to this difference in the quality of sound as being the result of the *attack*, or method of producing the sound. Also important is the *decay* of the note—in other words, how long it takes for the sound to fade away.

Complex Tones: Analyzing the Music

Although a musical note is composed of many different frequencies, it can be broken down into pure tones or single frequencies in a process referred to as *analysis*. This is now relatively easy to do with modern electronic instruments. Also important in music is the converse process, namely the bringing together of many frequencies to produce a complex sound. The combining of frequencies is referred to as *synthesis* and is done by electronic instruments called synthesizers.

Let's look at synthesizers in more detail. A question that immediately comes to mind is whether it is possible to produce a waveform of any shape if we add enough harmonics together? The answer is yes. And the man that proved that it could be done was Jean-Baptiste Fourier of France. There is little indication that Fourier was particularly interested in music, or even sound; his major interest was in how heat flowed from one point to another, and he made many important contributions to the theory of heat. In the process, however, he formulated what is now known as Fourier's theorem; it applies to all waves, and since sound, and music, are waves, it applies to them.

Fourier's theorem can be stated as follows:

Any periodic oscillation curve, with frequency f , can be broken up, or analyzed, into a set of simple sine curves of frequencies f , $2f$, $3f$, ... each with its own amplitude.

In the case of sound, these "simple sine curves," or waves, are harmonics; and as we saw, we refer to the first as the fundamental, and the higher multiples of it as overtones. This means, for example, if the fundamental has a frequency of 200 Hz, the first harmonic is 400 Hz, the second is 600 Hz, and so on. All these frequencies are sounded at the same time, so that when a musician plays a single note, he is actually playing several frequencies. Furthermore, if the same note is played by two musicians, say, two violinists, the two notes will not be identical, even if the two violins are perfectly in tune. The reason is that no two instruments are exactly the same structurally; also, no two musicians bow the instrument in the same way. The result will be beat notes between the two violins; in fact, beats will even occur between the second, third, and higher harmonics. This, however, does not detract from the sound; the overall effect is called the chorus effect, and it is something that adds to the richness of the sound.

Harmonic Spectra

One of the best ways to show what overtones are present and what their amplitudes are, is by using a bar graph. It is a plot of frequency versus loudness, or amplitude, but since the tones are distinct, it looks like a series of vertical lines. Frequency is plotted along the horizontal, and relative intensity is plotted in the vertical direction. Usually the fundamental is assigned a value 1.0, and the overtones are compared to it. The plot of a pure tone is shown in figure 41. Most instruments, however, have relatively complex spectra, as seen in figure 42.

These graphs give us an excellent way of "seeing" musical notes. We can see immediately what overtones are present and also their intensities. Not only does the spectrum of different instruments differ,

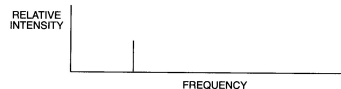


Fig. 41. Bar graph (spectrum) of a pure tone.

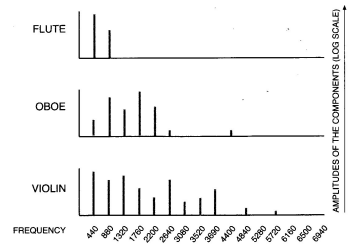


Fig. 42. Bar graph (spectrum of frequencies) of a flute, an oboe, and a violin.

but the spectrum within a single instrument depends on what note is played (the note C, for example, will give a different spectrum than the note F).

Formants

Since each instrument has its own distinct spectrum of harmonics, it might seem that the spectrum for a given type of instrument would always be the same. But this isn't so. Several things beside the spectrum of harmonics characterize an instrument. One of the most important is that the harmonic structure depends on loudness. Loud notes usually contain many more high-frequency harmonics. In addition, the musician playing the note makes a difference; each musician plays it slightly differently. And as we saw earlier, the attack and decay of the note also make a difference. Because of this, it is useful to supplement the harmonic spectrum of an instrument with its *formant*. The formant of a musical note is a frequency region where most of the sound energy is concentrated (fig. 43). It might seem that this region would consist of the frequencies near the fundamental, but this is not necessarily the case. Often, the high harmonics are louder and determine the timbre of the instrument.

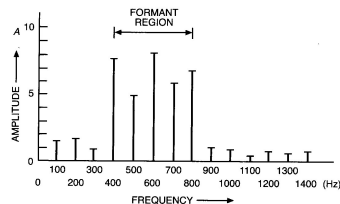


Fig. 43. Bar graph showing the formant region.

How Can It Vibrate That Way? Vibrational Modes of a Stretched String

When a string vibrates with several harmonics, they are all vibrating at the same time. This may seem like a difficult thing for a string to do. How can it vibrate in several ways all at once? Since several instruments, including the violin, the guitar, and the piano, have vibrating strings, it is instructive to look at the various vibrational modes of a stretched string.

Consider a string of a certain length that is vibrating at its resonant or natural frequency. Each natural frequency produces its own characteristic vibrational mode, or standing wave pattern, and it is these standing wave patterns that we will be looking at.

Let's begin by attaching the string at two points, as in the diagram shown in figure 44. The two ends are unable to move and are therefore nodes; in between these two nodes are one or more antinodes. If there is only one antinode, this harmonic is the *fundamental*; it is also sometimes called the first harmonic. This harmonic will have the longest wavelength; in fact, the wavelength will be twice the length between the two nodes (fig. 45).

The second harmonic, or first overtone, is produced when the string vibrates with a node in the center. In this case it will have three nodes and two antinodes (shown in fig. 46). We see from the diagram that exactly one wavelength fits between the two end nodes, so the

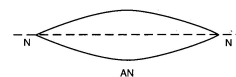


Fig. 44. The fundamental of a string.

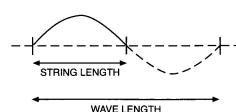


Fig. 45. Note that the wavelength is double the string length.

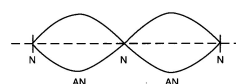


Fig. 46. The first overtone (or second harmonic) has one wavelength, with three nodes and two antinodes.

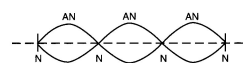


Fig. 47. The second overtone (or third harmonic).

wavelength (λ) is equal to the string length (L). For the third harmonic, or second overtone, we have to add another node; in all there will therefore be four nodes and three antinodes (fig. 47).

The length of each loop in the higher harmonics is the same. In

the case of the third harmonic, we have one and a half wavelengths along the length of the string, which means there is $3/2$ of a wavelength along the length of the string. With this we can see a pattern emerging: each higher harmonic introduces a half-wavelength. This means that the fundamental has $L = \lambda/2$, the first harmonic has $L = 2/2\lambda = \lambda$, and the third harmonic has $L = 3/2\lambda$ and so on, and we can easily solve each of these for λ . Our results are summarized in table 3.

So far we have said nothing about frequencies. It's well-known, however, that the frequency of a string—for example, a guitar string—depends on the tension in the string and the linear density of the string (the expression for it is complicated, and we won't get into it). This means that we can change the frequency by tightening or loosening the string. If we assume that we have a string of, say, 70 cm, we can tune it so that it has a frequency of 375 Hz by tightening it appropriately. We also know that there is a relation between speed (v), frequency (f), and wavelength (λ), namely, $v = \lambda f$. From table 3 we can write $\lambda = 2L/n$, where n is an integer, so we can calculate the speed of the waves:

$$375 \text{ Hz} \times \lambda = 375 (1.4) = 525 \text{ m/sec.}$$

But the speed of the wave is dependent only on the tension and density, and not on the properties of the wave, so all waves will have the same velocity regardless of their frequency or wavelength. We can therefore calculate the frequency of the second harmonic from $v = \lambda_2 f_2$ where $\lambda_2 = L$.

$$f_2 = v/\lambda_2 = 525/0.7 = 750 \text{ Hz.}$$

In the same way we can calculate the frequency of the third harmonic; it is 1,125 Hz. Again we see a pattern; it's easy to see that f_2 is

Table 3. Nodes and antinodes for various harmonics in strings and in tubes

Harmonic	Wavelengths	Strings		Tubes		Length-wavelength rel.
		Nodes	Antinodes	Nodes	Antinodes	
1	$1/2$	2	1	1	2	$\lambda = 2L$
2	1	3	2	2	3	$\lambda = L$
3	$3/2$	4	3	3	4	$\lambda = 2/3 L$
4	2	5	4	4	5	$\lambda = 1/2 L$
5	$5/2$	6	5	5	6	$\lambda = 2/5 L$



Fig. 48. All the harmonics vibrating at the same time.

$2f_1$, f_1 is $3f_1$ and so on; in other words, the upper harmonics are integral multiples of the fundamental, as we would expect.

It's important to remember that all these harmonics are vibrating at the same time, as shown in figure 48.

Listening to Overtones on a Piano

Since the harmonic series is the sequence of frequencies nf , where f is the fundamental and n is an integer, we can express this using musical staff notation. For example, for the harmonics of the key A_4 (the A above middle C) we have



The frequency of each note has been specified; you can see that they are integral multiples of 55 Hz.

You can actually play this series on a piano and hear the various harmonics. Begin by slowly depressing the key A_4 and holding it down. This lifts the damper for the key but does not sound it. Now go up one octave to A_5 and strike it hard (and staccato, or detached). After the sound from A_4 has died away, you will hear A_5 vibrating in its second harmonic. Then do the same thing with E; you will hear A_4 vibrating in its third harmonic. You can continue up the keyboard in this way, striking A, C#, E, and so on, for the third, fourth, and fifth harmonics.

Vibrational Modes of a Column of Air

We have seen the vibrational modes of strings, which are common to violins, guitars, and pianos, but many musical instruments make their sounds using vibrating columns of air. There are, in fact, open-end air column instruments such as the flute, the trombone, the sax-