# APPENDIX 1

# Some Fundamentals of Acoustics

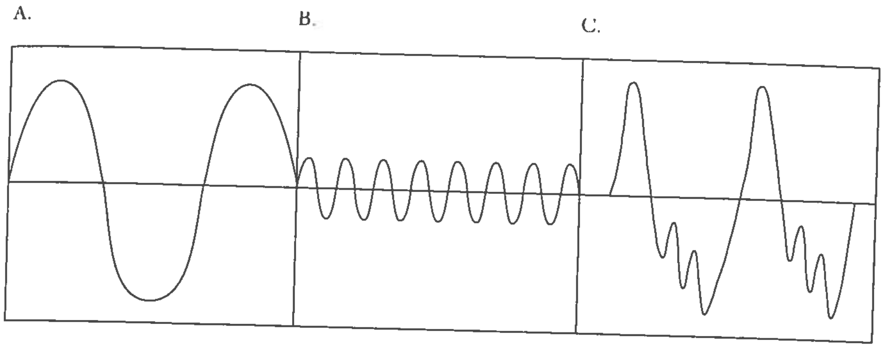
The field of music acoustics embraces a variety of subjects, including such diverse topics as tuning systems, room acoustics, sound reproduction, psychoacoustics, acoustical properties of musical instruments, and so forth. In this appendix we will limit our discussion to an examination of the four basic properties of a musical tone: (1) its frequency or pitch, (2) its intensity or loudness, (3) its vibration form or timbre, and (4) its duration or length. In each case we will distinguish between a musical tone's *physical* properties, listed first, and the *subjective* manner in which we perceive it, listed second.[1]

## Frequency and Pitch

Sound originates in the vibration of elastic or flexible objects. Included in this family of vibrating objects are stretched strings, blown reeds, vibrating lips, drumheads, and even the molecules of air in a wind instrument. Regular or periodic vibrations produce a musical tone. You can see the graphic

1. For material on other acoustical topics, refer to John Backus, *The Acoustical Foundations of Music*, 2nd ed. (New York: W. W. Norton, 1977) and D. W. Campbell and Clive Greated, *The Musician's Guide to Acoustics* (New York: Schirmer Books, 1987). Neither requires an extensive background in mathematics.

**Figure A1.1**




representation of such a tone on the screen of an oscilloscope, an electronic instrument used to view and evaluate waveform patterns. Three of these patterns are illustrated in Figure A1.1.

One complete to-and-fro motion, or vibration, of an elastic body is called a *cycle*. The *frequency* of a tone is determined by the speed of its vibrations, which is measured by the number of complete cycles per second (cps) or simply *Hertz* (Hz). For instance, $A^4$, which vibrates 440 times per second, has a frequency of 440 Hz. We perceive frequency as *pitch*—that is, the "highness" or "lowness" of a tone. The greater the frequency or the faster the rate of vibration, the higher the pitch; the lower the frequency or the slower the rate of vibration, the lower the pitch. Frequency or pitch is indicated on the horizontal axis of an oscilloscope screen. The frequency of the tone in the second pattern of Figure A1.1 is greater and its pitch is higher than that in the first, since the distance between the successive vibrations peaks is less. Doubling the frequency of a given pitch produces a pitch an octave higher; conversely, halving the frequency of a given pitch produces a pitch an octave lower. Therefore the *interval ratio* between successive octaves is 1:2; 1 represents the original note and 2 the higher octave. Thus frequencies of 220, 440, and 880 represent the pitches $A^3$, $A^4$, and $A^5$, respectively. Since each additional octave doubles or halves this ratio, we perceive pitch according to a *logarithmic scale*, or by powers of 2—$2^1$, $2^2$, $2^3$, $2^4$, etc.[2]

2. The logarithm of a number is the power to which 10 must be raised to obtain that number. Thus, if $10^2 = 100$, then $\log 100 = 2$; if $10^1 = 10$, then $\log 10 = 1$, and so on. As a number doubles or increases by a power of 2, its logarithm also doubles. For instance, $\log 2 = .301$ and $\log 4 = .602$. A logarithmic scale consists of the logarithms of each number in a given series: for instance, the logarithmic scale from 1 ($10^0$) to 10 ($10^1$) would consist of a series of numbers from 0 to 1.

The frequency distribution of fixed pitches within an octave on a keyboard instrument, for example, is called a *tuning* or *temperament system*. *Equal temperament* has been employed as the basic tuning system in Western music since about 1800. In this system, each of the twelve half steps in the octave are of equal size. This equality permits the use of enharmonic notation—F♯ and G♭ represent the same pitch. An equal-tempered half step may be expressed mathematically as $12\sqrt{2}$, or 1.0595, and occurs on a continuum, in which 1 is the lower note and 2 is the note an octave higher. Therefore, if we increase the length of tubing in a woodwind or brass instrument, or the length of a string on a stringed instrument, by 5.95 percent, or from 1 to 1.0595, we lower the pitch by one tempered half step.

## Intensity and Loudness

The energy or *amplitude* created by the displacement of vibrating objects carries through air to reach our ears. Amplitude is expressed as a measurement of *intensity* compared to absolute silence and is represented on the vertical axis of an oscilloscope screen. The intensity of the first pattern in Figure A1.1 is greater than the second, since the extremities of its vibrations are higher and lower on the vertical axis. In order to avoid extremely large or small ratios, intensity is measured on a logarithmic scale of *decibels* (dB). Intensity may range from the background noise of a quiet room, about 30 dB, to the threshold of pain, about 120 dB. Since each additional increment of 10 dB represents a tenfold rise in intensity, this decibel range involves an increase of about $10^8$, or one billion times.

Our ear is more sensitive to the frequencies of the top notes of the piano, about 4000 Hz, than to those of its lowest octaves, below 100 Hz. Therefore, in softer passages the bass must be boosted either electronically or acoustically to achieve a better balance.

Another unit acousticians use to measure relative loudness is the *sone*. Each sone is equivalent to an increase of 10 dB at the frequency of 1000 Hz. Based on an average of numerous individual responses, two sones sound twice as loud as one sone, and four sones sound twice as loud as two sones, and so on. Assuming that each violinist played the note $B^5$, approximately 1000 Hz, with the same intensity, it would take ten violins to sound twice as loud as one instrument, because in order to be twice as loud to double the sones, there must be an increase of 10 dB. In order to have an increase of 10 dB, the intensity must increase ten times, which means that ten violins are necessary.

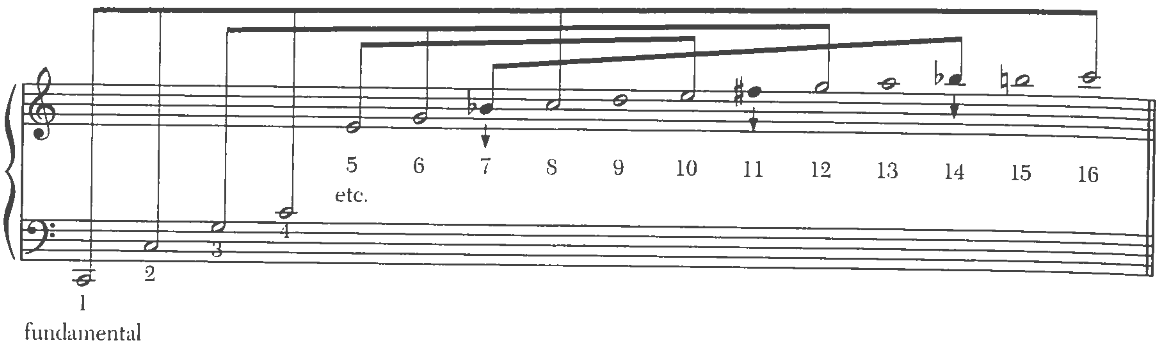
Because musical dynamics are so subjective, we employ the approximate Italian terms *piano* and *forte* and the prefix *mezzo-* and suffix *-issimo* to distinguish relative loudness in music. Thus *mezzo-piano* indicates "moderately soft," while *pianissimo* indicates "very soft." *Crescendo* and *diminuendo* denote a gradual rise and fall in loudness.

## ιATIONS FORM AND TIMBRE

The tone quality or *timbre* of a musical tone is dependent on its physical *vibration form* or characteristic waveshape. A pure or *sine tone*, the simplest waveform, sounds quite uninteresting to our ears. The sound used by doctors to check a patient's hearing is a sine tone. Its characteristic wave pattern is shown in the first two diagrams of Figure A1.1. Pure tones are rare in most musical situations; we sometimes hear them in the tones of a tuning fork, the low register of a flute, or the highest notes sung by a soprano. Most instruments produce what we call *complex tones*, whose waveforms are more complicated. A typical example is given in the final diagram of Figure A1.1. The diverse pattern produced by a complex tone results from the interaction of a series of simultaneously sounding pitches, of which we actually perceive only the lowest. This pitch, called the *fundamental* or *first partial*, is overlaid with a series of *overtones* or *harmonics*. Although we do not hear these overtones as distinct or separate tones, they are physically present and serve to color the sound of the fundamental. The relative strengths or intensities of the various harmonics add a distinctive sound or timbre to the fundamental tone. For instance, the particular combination of differing harmonic strengths in a tone such as $A^4$ produced on an oboe, violin, or trumpet allows us to distinguish one instrument from other. If we turn the treble knob on a stereo amplifier to the left, the upper harmonics of each tone in the music being played are gradually attenuated and finally eliminated by means of a filtering system, changing their timbres by causing them to lose their "brightness."

This blending of natural overtones on acoustical instruments (except for some percussion instruments) is caused by the predictability of a series of numbers that form numerical ratios between the various harmonics, numbers that theoretically extend to infinity. The successive interval ratios of these numbers are arithmetic—1:2:3:4:5:6:7:8, and so forth. That is, the interval ratio between the first two harmonics (the first harmonic is the fundamental) is 1:2, and that between the next two harmonics is 2:3. The interval ratio may be calculated by dividing the frequency of a higher tone by the frequency of a lower tone. For instance, $A^4 = 440$ divided by $A^3 = 220$ equals the interval ratio 1:2 or an octave. If we take $C^2$ as the fundamental or first harmonic, this *harmonic series* produces the pitches shown in Example A1.1. Only the first sixteen harmonics are given. Thus the ratio of a perfect 5th ($C^3$-$G^3$) is 2:3, and that of a major 6th ($G^3$-$E^4$) is 3:5.

**Example A1.1**




The harmonic series not only affects the timbre of each musical tone but also lies at the basis of our Western theoretical and tuning systems. For instance, if we consider the ratio of each harmonic to the fundamental, or the ratio of one harmonic to another, we can identify most of the diatonic intervals that are familiar to us—1:2 = an octave, 2:3 = a perfect 5th, 3:4 = a perfect 4th, 4:5 = a major 3rd, 5:6 = a minor 3rd, and so on. Each of these ratios represents a pure harmonic interval, expressed in its simplest possible relation. Music theorists of the medieval and Renaissance periods based their distinction between the so-called "perfect and imperfect" consonances on these numeric ratios. The ratios for the perfect octave and perfect 5th are based on the indivisible and therefore simpler numbers 1:2:3. The ratios for the imperfect intervals incorporate the more complex, mostly divisible numbers 4:5:6:8. We can produce the harmonic series as separate tones on certain musical instruments—on a flute or trombone by overblowing, on a violin by natural harmonics, and on an organ by mixture stops. On a piano, press a key which would be a harmonic down silently and strike a fundamental note loudly below it; you will hear the harmonic ringing. Or lightly touch a piano string at a point that divides it either into halves, thirds, fourths, etc. and then strike the key of that string; the harmonic will sound.

Attempts to produce a workable musical scale and tuning system using the natural tones of the harmonic series have proven unsuccessful, since its intervals produce two different sizes of melodic major 2nds—8:9 (C-D) and 9:10 (D-E). In addition, in this so-called *just* tuning system the perfect 5th D up to A is not a pure 2:3 ratio. As a result, Western musicians eventually devised the system of equal temperament, in which the distances or ratios between major 2nds and all other intervals remain constant. The tones of the harmonic series are indicated with black note-heads in Example 1.1 seem severely out of tune in relation to our equal-tempered scale. Now have some of your fellow students demonstrate the harmonic series on their instruments. Which tones sound in tune and which ones out of tune?

## Duration and Length

The duration of tones used in music is fairly short. Even a whole note in slow tempo will rarely last longer than four seconds. There is, however, an aural limit to a tone's brevity. If tones occur at a rate faster than twenty per second, the human ear can no longer keep them distinct one from the other. The notes will then fuse together, giving us the sensation of a single sustained tone or a sliding glissando between two tones.

On an oscilloscope, most musical tones exhibit a characteristic shape consisting of intensity or loudness and duration that is called an *envelope.* An envelope normally consists of an initial *attack* followed by a *steady state* or sustained sound, and concludes with its eventual *decay* or release. The envelopes of a typical piano tone and a clarinet tone, given in Figure A1.2, show that a sound sharply expands in intensity just after the initial attack and usually takes much longer to decay. The difference between these two envelopes results from the fact that a piano tone cannot sustain itself once the key has been struck, while it is possible to sustain a clarinet tone.

**Figure A1.2**