Handbook of Sound Reproduction

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Chapter 5—Musical Instruments and the Human Voice

A discussion of the methods by which sound is produced by various familiar musical instruments. The author shows how air is set in motion by vibration of some part of the sound producing device.

MOST SOURCES of musical sound, including the human voice mechanism, are complex systems, containing a primary vibrating source plus a system of resonators and acoustical couplers. The primary vibrating element —reeds, strings, and air streams flipping back and forth across hard edges are common types—provides the initial oscillatory energy for the fundamental tones and a spectrum of harmonics. In the case of the triangle, the cymbal, and a few other percussive instruments, the primary source comprises the entire system, but ordinarily this source is coupled to and partly controlled by resonators which selectively emphasize certain harmonics and give the sound its characteristic timbre. The majority of instruments, with the notable exception of members of the flute family, also have a sounding board or horn to increase the efficiency with which oscillatory energy is coupled to the air.

The various instrument families will be discussed along the lines of the general functional breakdown indicated above.

The Bowed Strings

The primary vibrating source of a bowed string instrument is the mechanical mass-elasticity system formed by a stretched string, which is normally set into vibration by drawing a rosin-coated hair bow across it. The bow tends to drag the string along with it, and succeeds in displacing it transversely until the elastic restoring force of the system exceeds the frictional coupling between bow and string. At this point the string is released and springs back, and the bow does not catch again until the string has exhausted its momentum in the opposite direction. Since the friction between moving surfaces is less than that between surfaces at rest with respect to each other, the resonance characteristics of the string are able to determine the period of time required for the bow to regain its grip and to carry the string on a forward journey once again.

It can be readily seen that the vibrations induced in the string will not be of pure sine form; the stimulating force has a saw-toothed wave shape and is applied over a very small part of the total length, causing a deformation far different from that which would be associated with a pure sine-wave fundamental vibration. The multiresonant properties of the string create a primary tone with strong harmonics which reach into the higher orders.

The various intercoupled mechanical and acoustical resonant systems of the body of the instrument respond to this stimulation rich in harmonics, producing a tone such as the typical violin wave form illustrated in *Fig.* 5-1. The belly, back, and ported enclosure serve a dual function as resonators and as air couplers.

Although the resonator formed by the enclosure and the *f*-holes (so named because of their traditional pattern) is of the Helmholtz type, without overtones, it is highly damped due to the viscosity of its internal surfaces, and it tunes broadly and reinforces the tone of a large band of frequencies in the lower range. In addition the dimensions of the body relative to the wave lengths of the sounds produced is such that various air column resonances also come into play. The distribution and relative strength given to harmonics are what determine the difference between a high-quality instrument and a poor one.

If the main body resonance is a sharp one the instrument may vibrate so violently at the corresponding frequency that it produces a very unpleasant howling effect called the "wolf note." Measures taken to counteract this effect include damping and careful adjustment of the resonant frequency of the body. There is a clear parallel between this difficulty and similar troubles occurring in loudspeakers.

The design differences between the different members of the bowed string group are along the lines that we would anticipate from the earlier discussion of principles governing freely vibrating systems. We would expect the low-frequency double bass, for example, to have strings of high mass and low stiffness, for its Helmholtz enclosure to have large volume, and for the sounding boards formed by the belly and back to be great in area. The last expectation follows from the fact that the excursion of air molecules must be increasingly greater, for the same sound power, as the frequency of vibration is decreased. Since the vibratory excursion of the instrument's belly and back is obviously limited, the radiation of sound power at low frequencies is kept up by moving a larger number of air molecules over the shorter path. This is the equivalent, from the point of view of power transferred to the medium, to moving a smaller number of air molecules over a longer path, and results in the relatively strong and deep fundamentals voiced by the bowed or plucked double bass. The same principles applied to speaker systems make possible the efficient reproduction of bass.

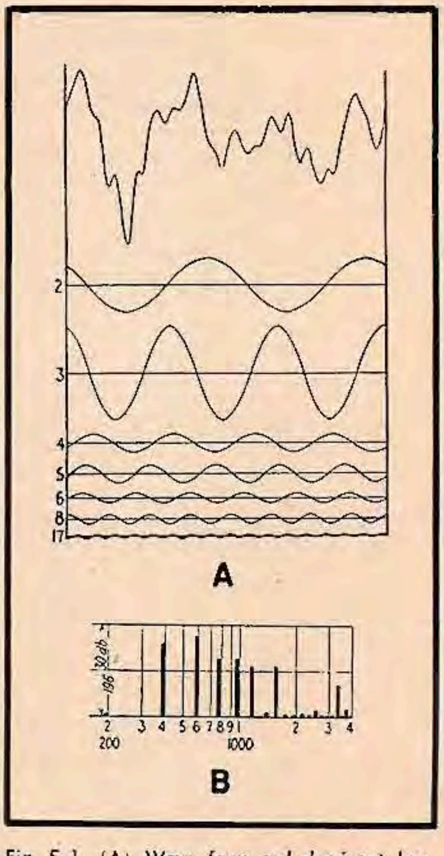

Fig. 5-1. (A) Wave form and dominant harmonics of typical violin tone at 196 cps. (B) Relative intensity, in db, of components of the tone. (Courtesy McGraw-Hill Book Co. from Psychology of Music, by Carl E. Seashore.)

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Instruments of the bowed-string class allow the performer to control timbre by different techniques of bowing which deform the string in different ways. In addition the player, by changing the length of string left free to vibrate, has exact and continuous control of pitch. He is able to use natural pitch intervals and can apply frequency and amplitude vibrato.

Plucked Strings

The plucked string group includes the guitar, the harpsichord, and the harp.

The harpsichord is a keyboard instrument similar to the modern piano, but with a lever-actuated plectrum of leather, fiber, or tortoise shell which plucks rather than strikes the strings. The harpsichord proper, also called the *clavicembalo*, ordinarily has two manuals or keyboards. Occasionally a third keyboard and a pedal board are included. Each manual has more than one set of strings, and each set of strings is controlled individually by a stop, as on the organ, so that the timbre of notes is under the control of the player, who can introduce or delete sets of resonating strings. In all models the coupling between the vibrating strings and the air is aided by a sounding board with which the strings are in contact, greatly increasing their effective area of radiation surface.

The harpsichord was the principal solo keyboard instrument, and held an important place in the orchestra, until the close of the 18th century. At that time it was superseded by the piano. Recently, however, there has been a rebirth of interest in this instrument, which has ceased to be regarded as an old-fashioned piano and is accepted as an instrument of unique quality in its own right. The timbre of the harpsichord includes a much more extended range of higher-order harmonics than that of the piano.

The modern harp is a multistringed instrument in which the strings are plucked by hand, and in which the effective length of each string can be shortened in two semitone steps by a system of pedals. Although the harp is one of the most ancient of musical instruments, having been used by the Egyptians of the 13th century B.C., the modern pedal version is less than 250 years old. Its characteristic "ethereal" quality is largely a function of the relatively small sounding board which forms its base. The decreased area of the radiating surface, compared to that of the keyboard stringed instruments, does not couple as much air resistance back into the vibrating system; the amplitude of the tone is decreased, and the poor damping allows the tone to persist for a longer period of time.

Struck Strings

The piano and the clavichord are members of the group of stringed instruments which operate by a striking action. The piano has more than one active string for each key (except for the lower bass notes); the five upper octaves use plain steel strings, while the strings of the lower notes are wrapped in order to secure the greater mass required by a low-frequency vibratory system. The vibrations of the strings are coupled to the air by a sounding board.

The key mechanism of the piano works as a launching device. When a key is depressed the hammer is driven towards the appropriate string, but is released from its driving mechanism, like a projectile for a sling, before the key has reached its bed. The hammer is thus free at the point of striking, and it rebounds and remains poised a short distance from the string as long as the key is kept depressed. At the same time that the string is struck its damper is removed. When the key is released the hammer returns to its normal rest position and the damper is again brought to bear on the string.

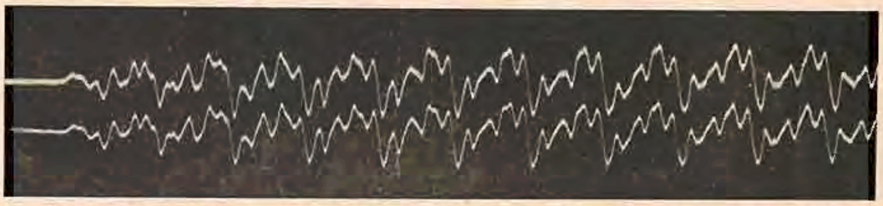

Fig. 5-2. Single piano tone produced by a concert performer, compared to the tone produced by allowing a weight to fall on the same key. (Courtesy J. Acous. Soc. Am.)

The piano tone may be controlled in a limited manner by pedals. These operate by adding or removing dampers, by reducing the length of the hammer stroke, or by shifting the position of the hammers so that fewer strings are struck.

The mechanical system of a piano is such that the player can exert no control over the action of the keys other than determining when, how hard, and for how long the key will be depressed. There is no such thing as artistic "touch" relative to a single note.[1] *Figure* 5-2 illustrates the identity of tones produced by a concert performer striking a key and by a weight falling on the same key. Descriptions of the quality of a piano performance which employ terms referring to the artist's "tone" or "touch" are not fallacious, however, because the overall quality of the sound of a piano is formed by the relationships, in intensity, timbre (as a function of intensity), and duration, between the individual notes. A particular performance may be thought of as having a "brittle" or a "singing" tone, but these qualities are not based upon the wave form produced by the individual strings, which at a given intensity is unchangeable.

The vibrations of the piano string do not have a large content of higher-order harmonics because of the nature of the hammer, which is felted and which has a rounded striking surface. The strings are thus not deformed to as angular a shape, and do not produce a wave form with as much high-frequency content. The richest timbres are in the bass (the energy content of the very low notes consists almost exclusively of harmonics), while the higher notes contain a progressively weaker harmonic structure. Like the violin, the piano may be plagued by a wolf note, which in this case is more properly called a clang tone. The bass strings may form standing waves at relatively high frequencies (stimulated by the initial hammer impact) which are harmonically unrelated to the fundamental.

In contrast, the brass strikers of the clavichord produce a tone which resembles that of the plucked harpsichord. The clavichord is a smaller instrument, sometimes made as a table model, and does not have as intense a sound as either the piano or the harpsichord. The striking of the strings of the clavichord is achieved with an entirely different mechanical system from that of the piano; the brass tangent which strikes the string simultaneously marks off the length of the vibrating section, and the key does not lose control of the string as it does in the piano. The player thus "makes" his own notes, like a violinist or guitar player, and the introduction, from the keyboard, of subtle variations of pitch and of vibrato are possible.

Reedless Wind Instruments

The flute, piccolo, and pipe organ are the main instruments of this category. The fife, flageolet, and recorder are similar to the flute in that they make use of air-column resonance, while the ocarina (sweet potato) and police whistle use enclosure resonators which are of the Helmholtz type.

All of the instruments mentioned receive their stimulating energy from a steady stream of air. This stream is directed against a hard lip, and eddies of whirling air currents are formed, alternately on each side of the lip, as illustrated in *Fig.* 5-3. The effect is the same as that of an actual reed vibrating back and forth; for this reason these instruments are sometimes referred to as belonging to the *air-reed* class.

The primary, non-sinusoidal oscillation thus produced is called the edge tone. By itself the edge tone would have a natural fundamental frequency determined by the velocity of the air current in relation to the diameter of the edge, but the primary vibratory system does not operate independently. It is strongly influenced and almost controlled by the air resonator to which it is coupled, whose fundamental–harmonic resonances force the frequency of vibration of the "air reed." The frequency of oscillation of the air column or cavity is also pulled

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[1] The pianist can contribute a greater noise component to the tone by a percussive stroke, and there is a trick, of no artistic significance, in which partial damping is attempted by momentary release and a second stroke.

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slightly towards that of the independent edge tone, and the final resultant frequency is a compromise between the two, with the air resonance very much predominant. The influence of the edge tone, however, cannot be disregarded. For example, the natural periods of the edge tone and of the air column in an organ pipe must be similar in value, or a relatively long time will be required for energy to build up in the column vibration, and the pipe will not "speak" promptly. (Adjustment of the pipe's edge-tone frequency is one of the problems of the "voicer.") Another example of the influence of the natural frequency of the edge tone may be seen in the control of pitch which the flutist can exert by varying the intensity of his blowing.

The resonant frequencies of an air column, as we have seen, depend upon its effective length rather than its physical length, and the end correction, a function of the diameter of the pipe, also varies with the order of harmonic. The pipe is thus slightly mistuned for some of the harmonic overtones, producing a discordant note. This effect may be counteracted by using a narrow pipe with a much smaller end correction, or by suppressing the higher-order harmonics in the pipe and using separate pipes with high-frequency fundamentals to inject the desired overtone directly.

The resonant frequency of an air column is dependent on the speed of sound in the enclosed medium. Since this speed varies with the temperature it is important that the flue pipes of an organ are not distributed over parts of a building which are likely to maintain temperatures different from one another. A change of 20° Fahrenheit will increase the general pitch about half a semitone. In this connection it is interesting to note that in certain types of organ pipes the primary sound generator is a reed. The vibration of the mechanical reed is not nearly as much a slave to the air column as is the edge tone, with the result that a rise in temperature which affects all of the flue pipes in the same way has less effect on the reed pipes. The reeds may therefore seem to go sharp or flat as a group when the temperature changes.

The reed organ stops are used to create the sharper timbres. In the older organs the reed was allowed to strike the aperture which released the air stream, so that air current stoppage was both sudden and complete, and the upper harmonics were very prominent. This produced a fiery, almost savage tone which may still be heard in certain recordings. Most modern organs curve the end of the reed in such a way that the air jet is not cut off as suddenly, and the tone is smoother.

Ordinary organs produce fundamentals down to perhaps 30 cps, but a few have been built for subsonic fundamentals as low as 8 cps.

Fig. 5-3. Eddies formed at the lip of an organ pipe. The original photographs were taken by mixing fine smoke with the air. (Courtesy Journal de Physique.)

The flute and its higher-pitched sister, the piccolo, work in a similar way to the flue organ pipe. In the former instruments the edge tone is created by blowing transversely across the blow hole, and the exciting stimulus for all frequencies must be produced at the same lip. The effective length of the air column is varied by opening holes in the tube through a system of levers and keys. When the player "overblows" he raises the edge tone in fundamental frequency so that it meshes with a har-

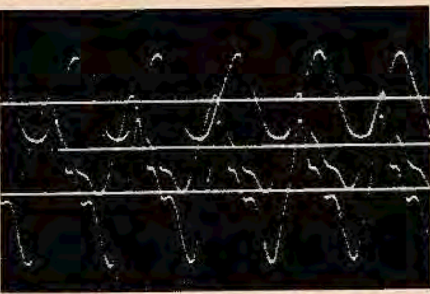

Fig. 5-4. Oscillograms of wave forms produced by a flute blown p **(top),** mf **(middle), and** f **(bottom).** (Courtesy Case Institute of Technology, from "The Science of Musical Sounds," by Dayton C. Miller.

monic mode of the air column resonance. The pitch thus jumps an octave on the first overblowing (since the second harmonic has a frequency ratio to the fundamental of two to one), and a fifth on the second overblowing (the third harmonic has a frequency ratio to the second of three to two).

The transverse flute is a very old musical instrument. In its primitive form the player blew across the end of a hollow reed, and later holes were introduced into the side of the reed to allow control of pitch. The immediate precursor of the modern transverse flute is the recorder, an instrument of the flute class whose edge tone is produced by blowing *into* the pipe, through a whistle head, rather than across it. In the middle of the 19th century Theobald Boehm developed the flute key mechanism and hole spacing which is used today. The Boehm system has also been adapted to the clarinet and oboe.

Flutes may be made of hard wood, brass, silver, or even gold. The material of the body of the instrument may affect its tone in two ways, by damping and by resonant vibration. *Figure* 5-4 illustrates the wave forms produced by a flute blown at different intensities. The higher notes of the flute are of almost perfect sine-wave form.

Reed Woodwinds

The clarinet, oboe (that "ill wind that nobody blows good") and saxophone are reed woodwinds. Like the reed organ pipe these instruments use a mechanical vibrator to generate their primary sound. The reed may be single, as in the clarinet and saxophone, or double, as in instruments of the oboe family. The latter group includes the bassoon and an instrument with the misleading name of English horn. *Figure* 5-5 shows the characteristic wave form of the oboe.

In all cases a steady flow of air is periodically throttled by a reed or reeds which vibrate in a direction transverse to the air flow. The stream of air first reduces the pressure between reeds or between the reed and the mouthpiece (an effect described by Bernoulli's theorem), forcing the passage to close; the reduced air flow of the constricted passage then allows the pressure to return to normal, and the reed springs back, inertia taking it beyond its nor-

Fig. 5-5. Characteristic wave form of an oboe playing *mf*, **at middle C.** (Courtesy of Case Institute of Technology, from "The Science of Musical Sounds," by Dayton C. Miller.)

mal position. This cycle of events is repeated as long as the air stream is continued, and the throttling action is characterized by a saw-toothed wave form containing all of the harmonics. The controlled air-column resonances of the tube dominate the vibration frequencies of the reed; the coupled system creates a tone of the desired pitch and with a rich, expressive timbre. "Quacking" noises are produced by inexperienced players when the reed vibrations are allowed to escape from their coupling with the air column.

Brass Instruments

The mode of operation of various types of modern horns is illustrated by that of the simplest, the bugle. The player's lips, which are pressed against the cup-shaped mouthpiece, serve as the primary generator of alternating impluses, acting in a manner very similar to the double reed. The Bernoulli effect causes the lips to throttle the breath being forced into the bugle with a saw toothed periodicity, and the folded air column is stimulated at several of its resonant modes. When the player changes tension on his lips he can force the fundamental frequency of the vibrating "lip-reeds" to mesh with some other resonant mode of the air column, and he therefore has command of a limited number of pitches. More complex brass instruments allow the player to change the length of the air column—by adding discrete sections of pipe through a system of valves, as in the trumpet, French horn, and tuba, or by sliding a telescopic assembly of tubes in and out, as in the trombone. It may be seen that the folded horn used for loudspeaker loading, in which a long, gradually flaring horn is made to occupy a reasonable space, is derived from the design of brass instruments like the tuba, in which a horn approximately 18 feet long is coiled into a fairly convenient shape.

In both reeds and brass the effective radiating surface is increased by the horn design.

Drums, triangles, cymbals, and like instruments are essentially mass-elas-

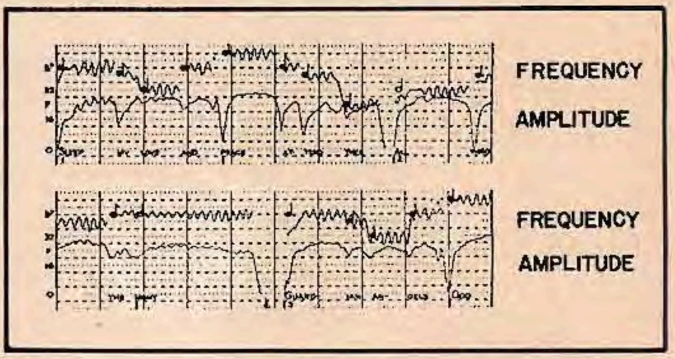

Fig. 5-6. Frequency and amplitude variation in the voice of singer Arthur Kraft performing a portion of "All Through the Night." Note that frequency vibrato is always present, but that amplitude vibrato is subdued and and often absent. (Courtesy University of Iowa and Harold Seashore.)

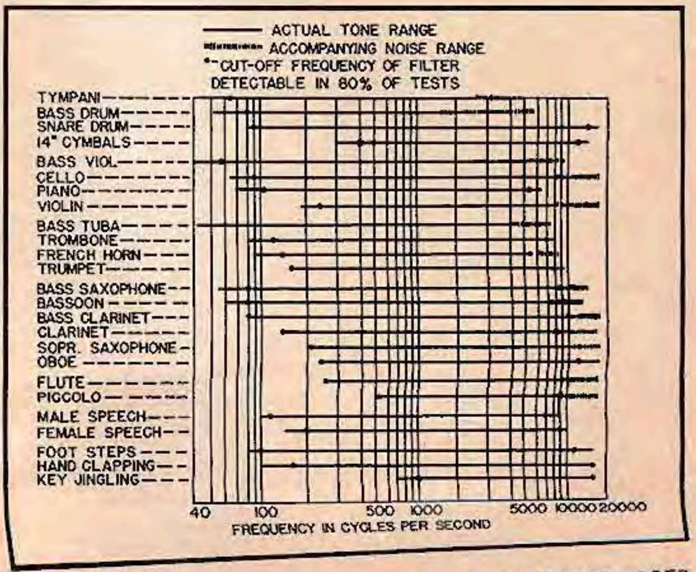

Fig. 5-7. Audible frequency range for music, speech, and noise, after W. B. Snow. (Courtesy J. Acous. Soc. Am.)

ticity devices which are shock excited by a single blow and then allowed to vibrate of their own accord. Instruments like the kettle drum are tuned, producing a note which may be varied by adjusting tension on the membrane. The triangle, cymbal, and bass drum produce sounds whose harmonically unrelated partials[2] are so diverse that no sensation of definite pitch is created; the tone can only be identified as belonging to a general frequency area.

The Human Voice Mechanism

The human voice is produced in much the same way as is the sound of a reed instrument. The vocal cords, stimulated by a steady flow of air from the lungs, provide an initial vibration which is sawtoothed in wave form. The resonating elements of the vocal cavities can then be controlled to pick off and reinforce various harmonics, giving the sound its tonal structure.

The crooner rejects the classical use of the full singing voice and substitutes a sort of moan, which is inadequate in intensity for a public performance, but of proper amplitude to serve as the input stimulus of a public-address system. The electronic assembly of microphone, amplifier, and loudspeaker may be considered as an intrinsic part of the crooner's acoustical mechanism.

Intelligible speech is produced by varying the transient and frequency structure of successive sounds through changing the shape of the vocal cavities, especially of the mouth. The dependence of vowel identification upon frequency content is easily demonstrated; the vowel sound "ah," occurring on a phonograph record, may be changed to "aw" by decreasing the speed of the turntable. Unvoiced consonants like the hiss of the sibilants do not involve the vocal cords.

The Vibrato

Instruments differ considerably in the type and degree of control given to the performer. Where the player has continuous and immediate control of pitch and amplitude he can introduce a musical effect called *vibrato*. This consists of periodic variations, primarily of pitch but also of amplitude, subsonic in frequency, which enhance the musical value of the tone. *Figure* 5-6 illustrates the frequency and amplitude vibrato used by a concert singer. The "tremolo" stops on organs provide a mechanically produced vibrato.

Frequency Ranges

Figure 5-7 is a chart of the audible frequency ranges of various sounds. It is of interest to note that the theory of discord referred to in an earlier chapter, based upon the beat effect of non-coincident harmonics, is supported by the fact that certain chords may sound acceptable when performed upon instruments with limited overtones, but become intolerably discordant when sounded by other instruments with strong harmonics extending into the higher orders.

[2] A partial is any simple component of a complex sound.