SOUND

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Chapter I. The author begins a discussion of audio subjects with a simple description of the nature of sound—musical or otherwise.

IT IS COMMON KNOWLEDGE that the generation of sound is associated with mechanical vibration, although the exact nature of this vibration, and the way in which it communicates itself to our ears, is not as widely understood. Newton referred to sources of sound as "tremulous bodies". This is an apt expression, because it implies a to-and-fro motion which is small, fast, and constantly repeated.

The vibrations of stretched strings, reeds, or membranes are familiar examples of such motion. When the vibrating body advances it pushes against the air with which it is in contact, compressing the molecules in front of it. Force applied to a rigid body would cause the whole body to move like a piston, all parts in unison, but an essential characteristic of an acoustic medium is that it is elastic. The molecules of air, therefore, are instead propelled against the neighboring particles, which in turn transmit the pressure to *their* neighbors, and a pressure impulse moves out with a definite speed from the original disturbance. When the source retreats it draws the nearby air towards it; the resulting partial vacuum is filled in by particles further out, and this time a rarefaction impulse travels out from the source.

Thus we have an impulse, alternately of compression and of rarefaction, which moves out from the oscillating source and which controls the behavior of the particles in its path, causing them first to crowd together and then to spread apart. A given particle imitates the to-and-fro motion of the source, but with a time lag, like that between the leader and followers of a "Simple Simon says" game. The time lag grows progressively greater with distance, and since the pressure changes are spread over an increasingly larger area, as the sound impulse moves out the imitative vibrations of the air molecules become weaker.

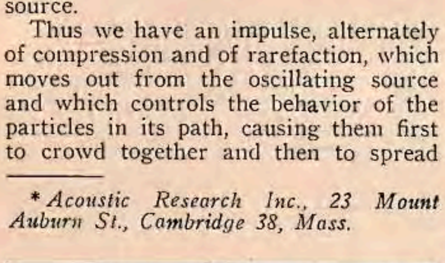

Fig. 1-1 (A) Alternate compression and rarefaction of air caused by sound. (B) The physical picture of (A) represented symbolically by a graph.

The vibrations of a source of sound are small: they may cover as much as a sizable fraction of an inch. But the human ear can detect particle "excursions" of microscopic distances—as little as .0001 inches—and it can detect changes of pressure of the order of magnitude that would be created by raising or lowering a body in the earth's atmosphere about one foot.

Sound travels as a "wave," and hence the transmission is accomplished without permanent displacement of air. This transmission can only take place through an elastic medium, a fact which was finally demonstrated by the classical experiment in which a bell and clapper were placed in an evacuated glass jar. The bell's vibrations were made inaudible, as sound could not be transmitted through the vacuum. (The apparatus had to be constructed many times by different experimenters before sufficiently refined techniques were developed to completely isolate the vibrations of the bell from the world outside the jar.) If the moon is ever visited one feature of the environment will be known beforehand with certainty; the wastes will be noiseless except for vibrations transmitted through the solid surface. Since there is no gaseous atmosphere there can be no tread of footsteps heard, no rustle of clothing, and if an obstruction is dynamited the débris will fly apart silently, as in a dream.

When a stone is dropped into a pool of water, waves travel out in all directions. This phenomenon is often used as an analogy to the action of sound waves. The force of the dropped stone is sent out through the water, but the particles of water merely vibrate in orderly sequence and do not travel with the force. There is an important difference, however, between this type of wave motion and that of sound. The particles of water vibrate up and down, in a direction transverse to the direction of wave travel, rather than back and forth along the path of the wave (as they would if they were transmitting sound). The water wave is thus called *transverse*, the sound wave *longitudinal*.

It is easy to draw a picture of a transverse wave which will reveal its characteristics; we merely take a cross-sectional side view of the medium at any particular moment. It is more complicated, however, to make a pictorial representation of a longitudinal sound wave. We would have to show the particles alternately compressed and rarefied, as in (A) of *Fig.* 1–1, and since we could only show a few particles the picture would be a crude one. Therefore we abandon pictorial representation and substitute a symbolic graph, as in (B) of *Fig.* 1–1. Where the graph line crosses the horizontal axis the medium is in its normal, undisturbed state; where the graph reaches its peak height the medium is compressed to a maximum degree; and where the graph reaches the bottom of its "trough' the medium is at maximum rarefaction.

This graph represents the pressure state of the medium at a given point, as it varies over a period of time. We must always remember that these graph "wave forms" are not pictorial, and that, unlike ocean waves, sound waves do not physically look like their graph curves. The ocean wave actually forms such a pattern in space because of the fact that its particles vibrate transversely.

The Characteristics of a Sound Wave

The adoption of the above method for graphically representing sound waves makes an analysis of the quality of a sound much easier. A person would never mistake a buzz-saw for an oboe, but the differences can also be detected by an oscilloscope and stated in purely quantitative terms. The graph of pressure *vs.* time will tell the story if we know how to read it.

First, consider the height of the graph, from peak to trough. The greater the vertical distance the more the air is being compressed and rarefied, the greater the excursion forced on the ear drum, and the greater will be the intensity of the sound. This characteristic is called *amplitude*.

The second significant characteristic of the graph is the number of times per second the complete sequence of vibratory events, called *cycles*, occurs. This characteristic is referred to as the *frequency*, and the sensation of pitch depends on it. The higher the frequency the higher the pitch. But all sounds do not have pitch, as is evident from listening to many of the everyday sounds of the street. The existence of a definite pitch requires that a number of successive cycles of the same frequency be

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quantitative terms. The graph of pressure *vs.* time will tell the story if we

repeated. Regularity of this nature makes the sound a *periodic* one. Nonperiodic sounds are produced by automobiles, by leaves in the wind, or by the jangle of keys on a ring, and are referred to as noises rather than musical tones. Periodic sounds are produced by musical instruments—middle *C* on the piano, for example, represents a string vibration whose frequency is approximately 261 cycles per second (abbreviated as 261 cps). The frequency range of audible sound for a normal young person is about 20 cps to 20,000 cps.

The third feature which must be taken into account is the shape of the graph, or the *wave form,* which determines timbre. The graph of *Fig.* 1–1 is that of a sound created by the simplest of vibrations. It is called a sine wave. It is found relatively rarely in nature and has a tone which has little interest musically. The tone produced by blowing across the top of a bottle is of this type, except for its noise component. The characteristic timbre of various musical sounds is associated with a characteristic wave form, and it is this element which will immediately allow us to differentiate the oscilloscope pattern of one sound from another.

The reproduction of the tones of a whole symphony orchestra by a single vibrating speaker cone becomes less of a miracle when we understand the full significance of the wave form of sound. The wave form graph, besides representing the instantaneous pressure state of the air, may also be thought of as representing the instantaneous position of the human ear drum receiving the sound. It is obvious that, no matter how many sounds from how many instruments are being heard at the same time, the ear drum can be in only one position at any particular instant. Since we are able to hear and distinguish many sounds at once, evidently the single, complex vibration, and a single complex wave form can represent a combination of many different sounds. An oscilloscope picture of the wave form of the total sound of a symphony orchestra would be formed by a complicated but single line, and a headset diaphragm could theoretically reproduce exactly the same ear drum vibration as 75 musical instruments playing together.

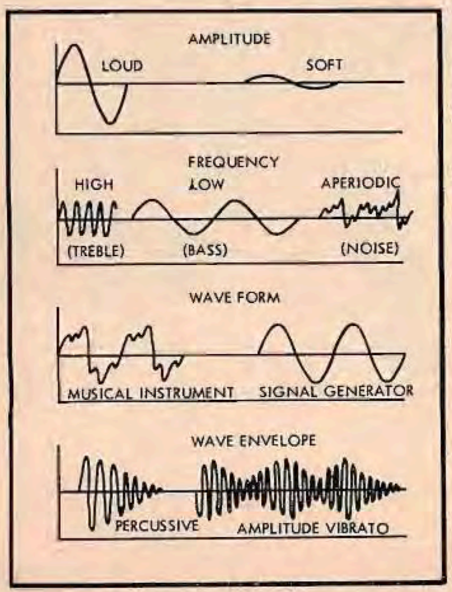

Fig. 1-2 The four physical characteristics of sound.

A fourth characteristic of sound is more subtle but not of less importance. It has to do with the instantaneous changes of volume which take place, especially those involved in the starting and stopping of the sound. The wave characteristic which defines this element is called the wave envelope, and it describes the transient attack and decay of a tone, one type of vibrato, and crescendo and diminuendo.

The physical characteristics of sound listed above—the amplitude of the pressure changes, the frequency, the wave form, and the wave envelope—are associated with the sensations of loudness, pitch, timbre, and the sensation inspired by instantaneous amplitude changes, in that order. This is illustrated in *Fig.* 1–2.

Although these associations are primarily correct the sensations are not each determined exclusively by one physical characteristic. Loudness is also affected by pitch, pitch by loudness, timbre by wave envelope, and so on.

Musical Instruments

The sound quality of a musical instrument, which we describe with subjective terms such as "fiery," "melan-

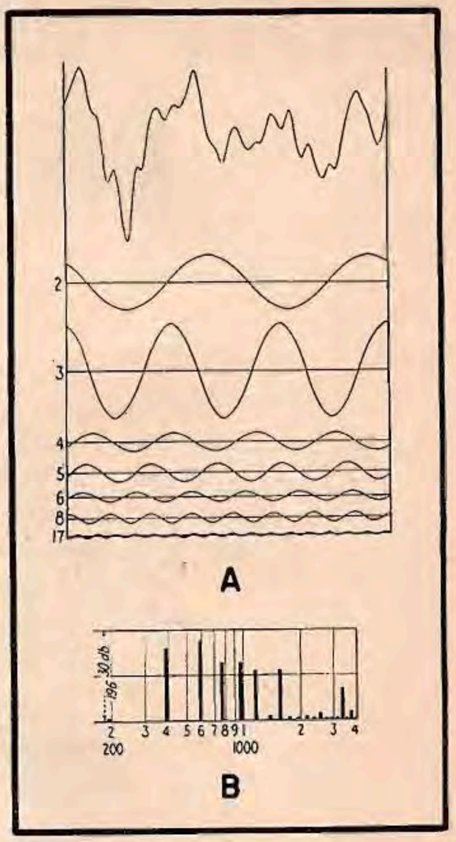

Fig. 1-3 Wave form and harmonic composition of a violin tone (G below middle C). (After Seashore)

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choly," "brilliant," etc., can also be described in terms of the four physical characteristics of sound referred to above.

The most dramatic characteristic of an instrument is its *timbre,* which we have seen is primarily associated with wave form. Musical instruments vibrate in complex ways; in addition to vibrating at the frequency corresponding to the musical note on the score, they also vibrate simultaneously at many other, higher frequencies. The basic tone which identifies the pitch is called the *fundamental,* while the higher frequency components are called *overtones.* It is the particular combination of fundamental and overtones, in number, kind, and relative amplitude, that determines the wave form and the timbre.

In most musical instruments the overtone frequencies are simple multiples of the fundamental frequency. Such overtones are called *harmonics.* Thus if the fundamental tone is *A* above middle *C,* 440 cps, the second harmonic will be 880 cps, the third harmonic 1320 cps, and so forth. The general musical term for any component of a sound, whether fundamental or not, is *partial.*

The wave form and make-up of the complex musical tone of a violin, showing both the fundamental and harmonic overtones, is illustrated in *Fig.* 1–3.

Not all musical instruments, however, have overtones that are harmonic. Certain instruments of the orchestra, as a matter of fact, simultaneously produce such a varied assortment of harmonically unrelated frequencies that there is no definite sensation of one pitch. Strike tones and inharmonic overtones make up a large part of the sound of such members of the percussive group as the triangle, the bass drum and cymbals.

It is also true that certain musical tones, with harmonic overtones, have weak and even inaudible fundamentals. The lowest strings of the piano are examples. We nevertheless clearly identify the pitch correctly, because we recognize the harmonic structure and we respond to the *difference frequency* between harmonics (which, of course, is always the fundamental frequency). This phenomenon of hearing accounts for the fact that tones from the double bass or organ pedal pipes, when reproduced by table-model radios which are incapable of vibrating at the low fundamental frequencies involved, can still be recognized musically.

Musical instruments also differ widely in relation to the three characteristics of sound other than timbre. The majesty of the full pipe organ is partly due to its ability to pump very large quantities of vibrating air from its pipes, and to achieve tremendous volumes of sound. Some instruments, such as the pipe organ and piano, cover the entire musical range of fundamental frequencies, while others are specifically designed for bass or treble passages. The attack and decay of musical instruments may be characterized by sharp attack and slow decay, giving the sound a percussive quality, or by a gradual rise and fall of volume.

Units of Measurement

There are two units of measurement in sound that should not be omitted from this discusion. One is the musical pitch interval—the octave, whole tone, etc.—and the other is the engineering unit used to measure sound power, the decibel. Both are basically the same in concept.

A piano keyboard seems to be divided up evenly as far as pitch is concerned. The same apparent rise in pitch is produced by going from middle *C* to the next higher *C,* then to the *C* following, and so on, or from *C* to *D* to *E.* The first mentioned musical interval is called an *octave,* the second a *whole tone.* From *C* to *C* sharp is a *half tone.*

This apparently even division does not correspond to a similarly uniform physical division of frequency. As we increase the musical pitch, octave by octave, we are not adding equal increments of cycles, but are instead multiplying the frequency by two. Starting at 440 cps, one octave up will take us to 880 cps; two octaves up will take us not to 1320 cps but 1760 cps. A musical interval thus represents a geometric *ratio* of frequency, not a given number of cycles. An octave at the bottom of the keyboard covers only 27.5 cps, while an octave at the upper end covers 2093 cps. The range of musical pitch, however, is the same for the two, because this is the way we perceive sound.

The decibel is a similar unit of ratio, except that it refers to sound power, and the basic multiplier in the db system is 10 rather than 2.

We could construct in our mind's eye a special keyboard instrument in which all keys played the same frequency, and where ascending the "scale" increased only the volume of the sound. This hypothetical instrument could be calibrated in decibels by designing it so that every ten keys increased the sound power ten times. For example, if .01 watt were produced by a given key, ten keys further up would produce .1 watt, and ten keys further, 1 watt. Each such group of ten keys would correspond to a power ratio of one *bel,* while each adjacent key would increase or decrease the power by one *decibel.*

The decibel, or db, represents, under certain conditions, the minimum difference in sound power that the average human ear can perceive. There are conditions (such as at the lower frequencies) when several decibels of change are required for a person to notice the change of volume, and there are also conditions in which a small fraction of a decibel can be perceived.

The main reason for the adoption of the decibel system is the same as the reason for the octave system in music: that's the way we hear, in terms of geometric ratio rather than arithmetic increments. Thus if we want to plot the performance of an audio component over the frequency spectrum, and require a graph which lays out the ranges of fre-

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and ten keys further, 1 watt. Each such group of ten keys would correspond to

quency with the proper importance assigned to each range, we imitate the piano keyboard and use a geometric scale. When we describe the output of this component at different frequencies we state variations in relative db units, rather than in absolute units such as watts. The former is more accurate in terms of perception, and hence more meaningful.

The similarity between the layout of a piano keyboard and of frequency response graph paper used in audio work is illustrated in *Fig.* 1–4. A comparison between a linear (arithmetic) and decibel (geometric) scale of power is illustrated in *Fig.* 1–5.

We have discussed the decibel as a unit of relative sound power; it is also used as a unit of relative electrical power, or it can be applied to such quantities as voltage, current, sound pressure, and sound intensity (power per unit area). When a level of sound is described in db a reference level is always given or assumed.

Let us make a simple application of the decibel system in order to see how it affects the significance of absolute values. Suppose we own a ten-watt amplifier, and are not satisfied with the power capability of our system for the room in which it is used. We substitute a twenty-watt amplifier. How much have we increased the volume of sound that we can call on? A power ratio of two to one is represented by 3 db, not a very damatic increase. Forty watts will give us a 6 db increase over the original ten watts.

Resonance

Resonance is the basis of musical instrument design; it also plays an important but usually unwelcome role in sound reproducing systems.

If we pluck a stretched piano string it will vibrate for a while at a certain frequency. It we try it again we will find that the fundamental frequency is the same. This frequency is its natural or *resonant* frequency.

When the string is first released it is in a position of stretch, and it springs back. But when it has straightened itself out it is moving transversely at high speed, and momentum carries it beyond its neutral position, into a position of stretch on the other side. The overshoot is stopped by an opposing elastic restoring force, and the same half-cycle of events begins again, this time in the opposite direction.

It may be seen that the original energy injected into the system is not absorbed by either the elastic or the mass element, but is stored temporarily by each in turn, and is poured back and forth from one to the other like a Bromo-Seltzer being prepared at a drug counter. The rate of interchange of this energy, which is to say the resonant frequency of the system, is determined by the relative values of mass and elasticity of the string. This is why the strings of the piano become progessively heavier as the pitch decreases, and why tightening the strings of a violin, which increases their elastic restoring force, raises the frequency of the tone produced.

The vibrations cannot go on indefinitely, because energy is lost with each excursion—partly through mechanical and acoustical friction, and partly through the energy represented by the radiated sound. If no new stimulus is given to the string, each overshoot becomes less than the previous one, until the system has come to rest. The process of energy absorption which brings motion to a halt is called *damping.* Heavy damping stifles the sound quickly, while a relatively undamped system allows the tone to continue for a long period of time.

The restoring force of a freely vibrating mechanical system may be supplied by gravity as well as by elasticity, as it is in the case of a suspended pendulum or of water sloshing about in a washbowl.

Forced vibrations are of a different character. The stimulating energy cannot be a one-shot affair but must be applied continuously, and the vibrating element follows the dictates of the stimulus rather than of its own resonant tendencies. But all mechanical systems have mass and restoring force to some extent; there is no such thing as a massless body or perfect rigidity. The loudspeaker, too, has its own resonant characteristics which we cannot exorcise even though we might like to. A system subjected to forced oscillation acts differently when the frequency of the stimulus comes close to or coincides with the natural frequency of the system itself. It offers much less resistance (technically the term is impedance) to being vibrated, and as a consequence the oscillatory excursions are very much greater than they are at other frequencies, even though the magnitude of the stimulating force has not changed.

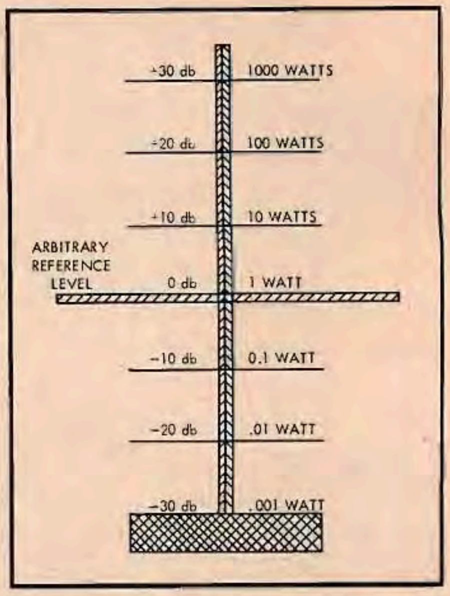

Fig. 1-5 Comparison between a linear (arithmetic) and decibel (geometric) power scale.

Thus when a recorded bass viol sounds a tone which happens to be at the resonant frequency of the phonograph's loudspeaker there is a tendency for that particular tone to "boom." Fortunately there are ways to mitigate and even to completely overcome this tendency.

A dramatic example of the results of resonant behavior is given in the description, according to one theory of geophysics, of the formation of the moon. The entire surface of the originally molten earth, it is stated, followed a tidal ebb and flow created by the gravitational influence of the sun, which alternately, according to the rotational position of the planet, caused the surface to lead and lag its spinning core. (The day was then about four hours instead of twenty-four). We can readily recognize the situation as one of forced oscillation of an inertia-gravity system, whose frequency was controlled by the velocity of rotation of the earth about the sun. This veloctiy began to decrease, due to frictional losses incurred with each tidal shift of the surface. It is reasoned that at some point the frequency of tidal oscillation coincided

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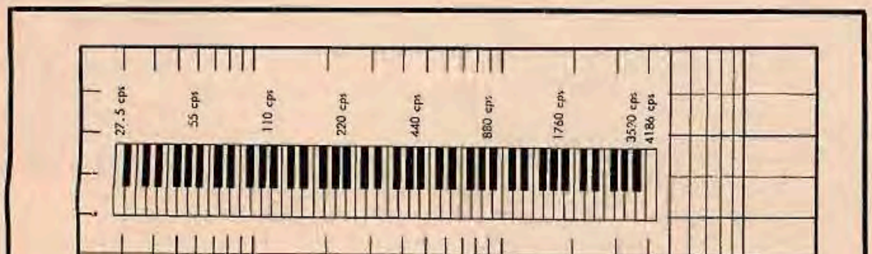

Fig. 1-4 Comparison between the frequency scale of a piano keyboard and that of an audio frequency response graph.

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A dramatic example of the results of

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(*from page 34*)

with the resonant frequency of the terrestrial mechanical system or of some part of it; the surface excursions reached their peak of violence, and a part of the surface was broken loose and hurled into space.

Another example of the effect of resonance on forced vibrations is the "wolf-note" produced in certain stringed instruments such as the cello. The body of the instrument, forced into vibration by the bowed string, has its own natural modes of oscillation, which help form the characteristic tone of the instrument. An unfortunate design may cause the excursions of belly and back to over-vibrate at their primary resonant frequency. Pieces do not fly off, but the howling sound produced has the unpleasant connotations of its name.

Acoustical Resonant Sources

There are also sources of an acoustical nature in which free vibrations may be induced. These fall into two types; the air column, such as exists in the flute, pipe organ or "acoustical labyrinth" loudspeaker enclosure, and the Helmholtz resonator, illustrated by the empty bottle, the ocarina, or the bass-reflex speaker enclosure.

The simpler of these two is the Helmholtz resonator. It consists of an enclosed body of air with an opening or duct to the outside. If the longest acoustic path within the enclosed space is small relative to the wave-length of a stimulating oscillation, the internal pressure state at any instant will not vary significantly from one point to another, and the entire bulk of the imprisoned air will be compressed and rarefied as a unit.

The enclosed air supplies elasticity, and the requirements of a freely oscillating system (restoring force and inertia) are completed by the acoustic mass of the air in the port or duct. A close mechanical analogy would be a weight on a spring.

The Helmholtz resonator is characterized by the fact that it produces no harmonics, and that its natural frequency is determined by the dimensions of the port and the *volume* (not length) of the enclosure.

The resonant frequency of the air column, on the other hand, is determined precisely by the length of the column, and it is rich in harmonic overtones. The air can pulsate longitudinally as a whole, in sections, or in both modes simultaneously. It should be clear from the comparative characteristics of these two resonant devices that the air column is the one most suitable for musical instruments.

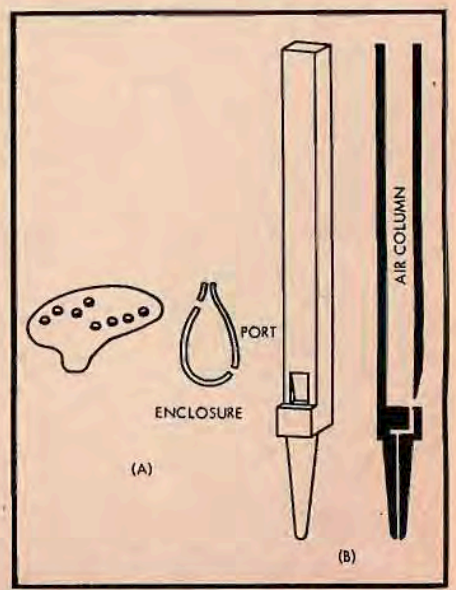

Fig. 1-6 Helmholtz and air column resonance, illustrated by simplified diagrams of ocarina and flue organ pipe.