America's Oldest Radio School

RCA INSTITUTES INC.

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75 Varick Street, New York

Sound Effect Machines Used In Broadcast Studios.

PHYSICS OF SOUND

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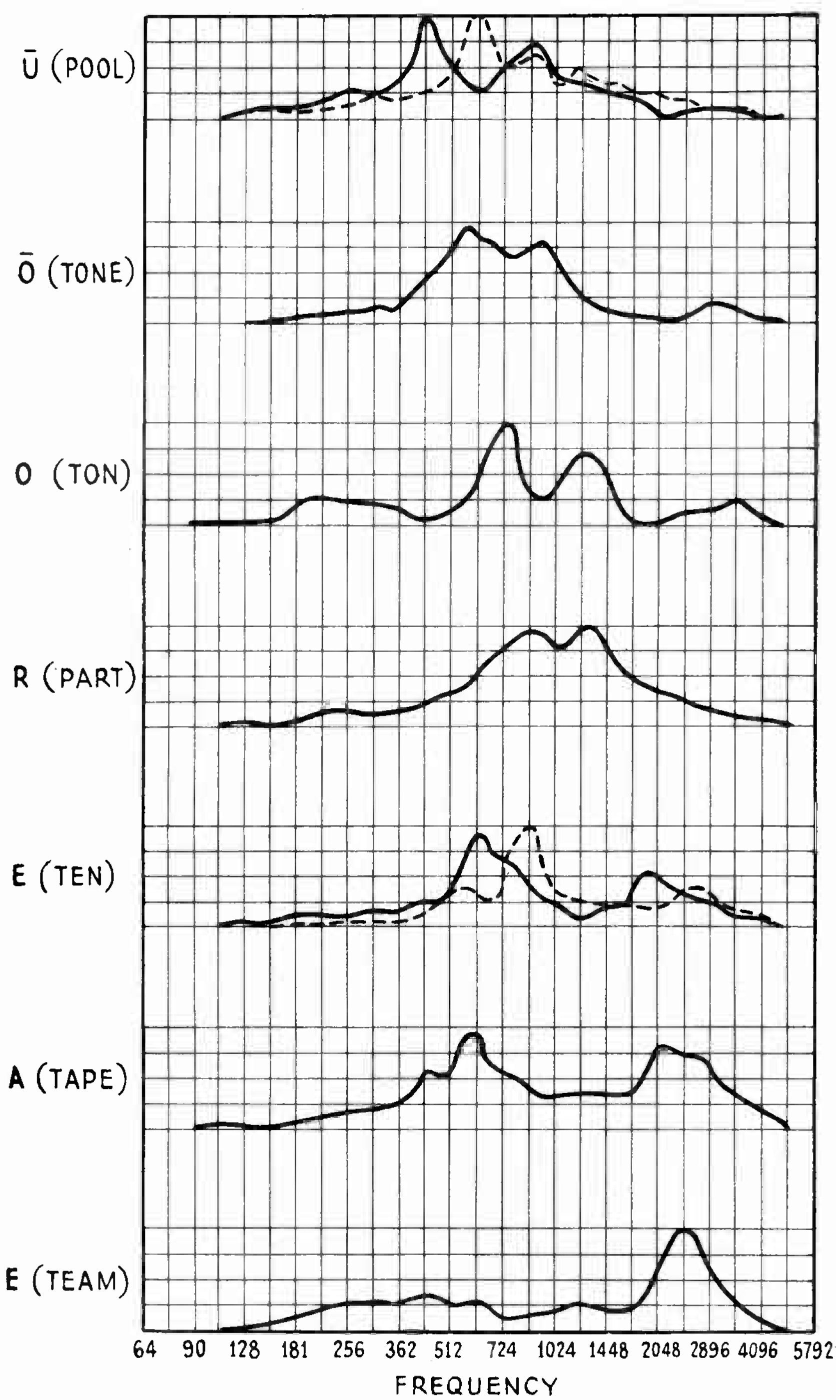

Chart showing frequency analysis of spoken vowel sounds

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PHYSICS OF SOUND

In our study of sound we are faced with the condition that has become prevalent in the allied industries of referring to it as "waves" instead of "pulsations". In this lesson, because it is accurate and more intelligible, we will use the latter term; then in later lessons, because of its popular use in the industry, we will return you to the use of the term "waves", hoping that such a use will not interfere with your continued understanding of the phenomena which you are studying.

In like fashion, we find that the term "sound" is used with two meanings. In the first place, it is properly used to denote the particular physical phenomena of producing air pulsations and propagating them through space. In the second place, if these pulsations produce the sensation of hearing on the part of some person or animal, the sensation is also referred to as sound. This is unfortunate, as we can readily see. In order to help you to clearly understand the text of this lesson, we will herein restrict the use of the word "sound" to denoting a succession of atmospheric pulsations which are capable of producing the sensation of "hearing". Furthermore, if these pulsations are too weak, too fast, or too slow to cause the brain response we call hearing, then we will not consider them as sounds. It will be left for other texts on the more advanced phases of atmospheric pulsations and phenomena, to consider these when they are beyond the ability of the ear to appreciate.

STRAIGHT-FORWARD THINKING OF AN OLD-TIMER

For simplicity and accuracy, we can do no better than go back to the plain words of a profound scientist who died over two centuries ago, Sir Isaac Newton. Writing in Latin, which was the scientific language of his day, he made a statement based on the common terms in use then, which might be translated: "Sound can be nothing else than pulses of air". Used in this way, the word "pulse" is meant to convey the impression of what we to-day would call "a pulsation". Perhaps your comprehension of this meaning will be helped by considering just what occurs when a succession of pulsations in the blood-stream of your forearm produces the collective effect we know as "the pulse".

A muscular contraction of the heart pushes a quantity of blood into arteries which are already filled with that fluid. Therefore the pressure increases at the heart end of the arteries, and this condition tends to right itself by an evening up of the pressure, which comes about either by an extension of the walls of the arteries to a greater diameter, or by the movement of fluid along the arteries. Actually both occur in this case. However, the expansion of the walls near the heart is not very easy. Therefore the pressure increase is chiefly taken care of by an actual forward movement of particles against those in front of them, increasing the pressure on these, while the pressure on the ones behind lets up a bit. This forms a pressure area which travels along the arteries.

Now at the forearm, close to the wrist, the artery is very close to the surface, and has rather thin walls. The pressure against the arterial walls is not very great at the beginning of a pulsation. The pressure increases then until it has reached a maximum value after which it declines again to the normal pressure value. The

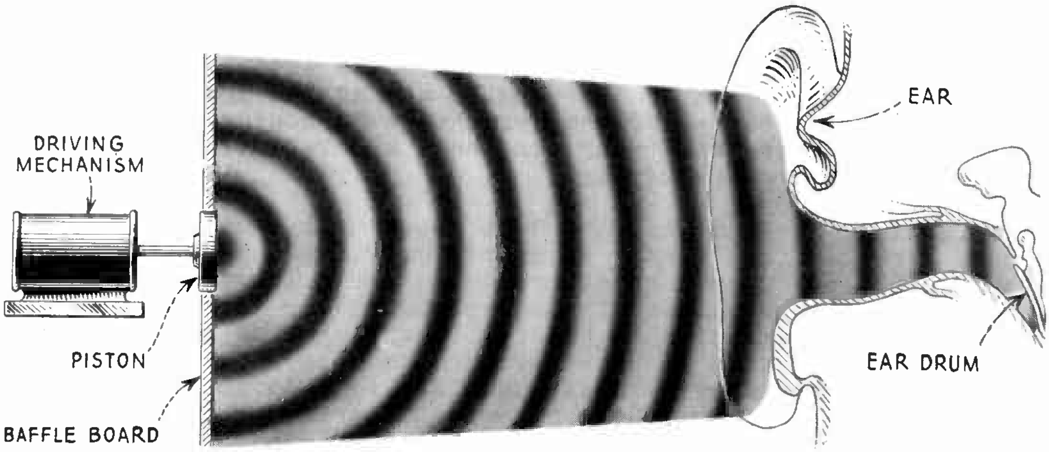

Fig. 1 – Device for creating sound pulsations in the air.

rise in pressure value during the pulsation is very slight, but the walls are so thin and resilient that they tend to expand, causing a definite pulsating movement of the finger applied to the forearm as an indicator.

If it were possible for a person to "feel the pulse" of the air which is the common medium for sound propagation, all would be easy. Since this is not so, let us continue with a direct comparison of the two ideas.

SOUND PROPAGATION

In Figure 1 is shown a simple device for causing pulsations in the air. In operation, the piston moves back and forth through the hole in the center of the baffle board, and on its forward motion (to the right) pushes the particles of air before it. This compresses the air into what is called an "area of compression". The particles are crowded together near the face of the piston, and their natural tendency is to find elbow room. This they do by pressing toward the air particles in front of them which were up to that time evenly located in space (steady uniform pressure), crowding these in turn until they are in succession crowded closer together. This displacement of the air particles has somewhat relieved the tension (pressure) among the crowded air particles against the hard face of the piston. Meanwhile, the feeling that "I'm being pushed, so I'm going to push you" has been communicated to the whole mass of air in the vicinity of the piston, and for some distance outward. This does not take the form of a riot, as would be the case if the air particles were human beings, with the struggle going on in every direction, and each person against every other person.

Nature has a more orderly way of doing things. When the pressure is applied on one side of a particle, it naturally gives way in the direction in which it has the greatest freedom to move, which is usually directly opposite to the applied pressure. This results in the area of compression expanding outward in all clear directions from the body that started the movement, namely the piston. When the piston has moved as far as the driving force makes it, and has returned to its position of rest, it starts compressing the air to the left of it, but causes a rarefaction of the air at its face. The term "rarefaction" is derived from the words meaning to "make rare". And that is just what happens at the face of the piston when it moves to the left. Where the piston was at the end of the stroke to the right, there would now be a vacuum, but for the tendency of the air particles to follow into the space left otherwise empty by the retreating piston. The normal air pressure causes the particles closest to the piston to follow it, and those still further away tend to follow these, because each in turn has a pressure exerted against it by all its neighbors. If the neighbors on one side give way in following the piston, a particle normally at rest will also give way due to the pressure exerted on its opposite side by the neighboring particles crowded together there. This leaves in the vicinity of the piston an area of rarefaction (but not a vacuum).

As the piston is made to move in and out continuously, in effect it repeatedly pushes and pulls the air particles. This causes alternate areas of compression and rarefaction to travel forward and outward, as shown by the dark and light bands of Figure 1.

It is well to realize here a difference between the action of the air driver and the heart. The latter has a true pumping action, in that the fluid is continually being supplied to it from one side through a valve, and driven forward by the heart into the arteries with an intermittent action. The periodical increases in fluid pressure which cause the pulse action at the wrist are accompanied by a movement of the fluid along the artery in spurts, but always in the same direction. On the other hand, the function of the air-driver which causes sound is not to deliver a fresh quantity of air at a distant point. Its only function is to cause the pulsation in air. The action of the piston is therefore forward and backward across a certain normal position of rest, causing an alternate compression and rarefaction of air. The compression must be followed by a rarefaction, because no new air is supplied to the piston, whereas the heart is always securing blood from one blood-stream, and passing it on to another. Its action is such that the movement of blood particles is always forward from a position of rest.

In Figure 1 the areas of compression are shown as circles expanding out from the central point which is the piston. This view happens to be a cross-section; the areas of compression actually are shaped more like spherical surfaces constantly expanding and becoming larger. This may be likened to the blowing of soap bubbles at a hole in a wall corresponding to the piston. The first air pulse would produce a half of a bubble expanding out from the hole, with its edges resting on the wall corresponding to our sound baffle-board. After the first half-bubble had gotten a short distance, the next forward movement of air (the next pulsation) would produce another half-bubble, shaped like the first one, which would follow it outward at a uniform distance.

Each bubble would consists of only a certain amount of soap and water, so as the bubble gets larger and larger, it has more surface, but becomes much thinner. This can be compared to the area of compression, like half the surface of a sphere, which expands outward, having a greater area, but has pressure change as the area moves outward. This is because at the surface of the piston we did a certain

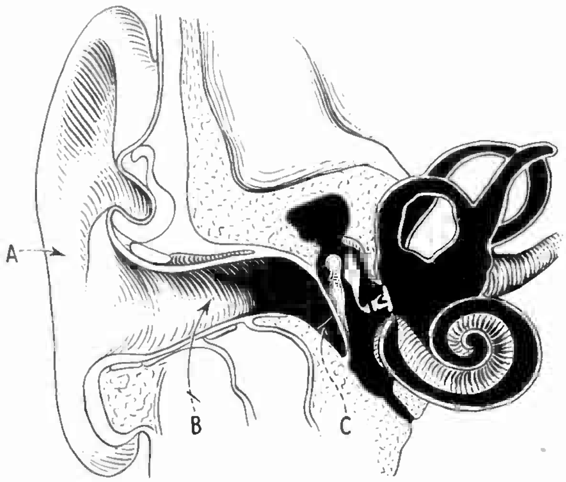

Fig. 2 - Construction of the human ear.

amount of work in increasing the pressure of air over the face of a piston having a certain area. As the compression area expands into an area greater and greater than the original compressed area at the piston face, it is evident that the particles of air at some distance away have much more room than those closely crowded together at the piston face, and therefore the pressure, or crowding of particles, at a distance is less than at the piston. As the areas of compression and rarefaction continue to expand, the compression or rarefaction becomes distributed over such a large spherical area that the actual change in pressure from the normal pressure at that point is negligible, and we say that the sound has "died out".

HEARING

In order to realize better the distinction we have made between air pulsations as sound and the sensation of hearing which is the effect caused by it, your attention is invited to Figure 2, which shows a cross-section of the human ear. The part of the ear (A) which is outside the skull is called the "pinna". The tube-like arrangement (B) leading into the head is called the "canal". The pinna intercepts a wide section of the areas of compression and rarefaction which approach it. It so directs the movement of air particles toward the canal that the compression at the canal entrance is greater than if the pinna did not exist. In like fashion, an approaching area of rarefaction tends to rarefy the air in the canal to a greater degree than if the pinna were absent. This is because the pinna prevents the air particles behind it from moving into the area of rarefaction as this approaches the canal entrance, therefore the particles in the canal itself tend to move backward into the approaching area of rarefaction to a greater extent than if the pinna were absent. The over all result is that the presence of the pinna makes an appreciably greater difference in air pressure between the compression and rarefaction areas, and we shall see that this means increased loudness.

At the end of the canal is a stretched tissue which we call the tympanic membrane. The space immediately behind the membrane contains air, and is connected to the back part of the throat by the Eustachian tube. When the air is still on both sides of the membrane, the pressure is the same on both sides. When an area of compression arrives in the canal the particles of air close to the outer side of the membrane are pushed together. This pressure pushes the membrane in against the normal steady air pressure existing behind the membrane. When an area of rarefaction approaches the membrane (called the ear drum), the pressure at the outside of the drum becomes less than the normal pressure on the inside, and the drum bulges outward. We see then that the ear drum bulges in and out for every pulsation consisting of an area of compression and an area of rarefaction.

The ear drum separates the outer ear from the middle ear, which is a chamber containing three odd-shaped bones. These bones form a system of levers to transmit the bulging motion of the ear drum to another membrane which separates the middle ear and an inner ear. Beyond this point we need not go, except to say that any movement of the membrane which acts as the door of the inner ear causes impulses to pass along certain nerves to the brain which interprets them.

This sensation is called "hearing". The greater the difference in pressure between the peak of compression and the peak of rarefaction of air at the ear drum, the greater will be the sensation of hearing produced in the brain, and we interpret this as loudness. That action should be fairly easy to understand because we can compare it with the sensation of feeling, for instance. We know that if something touches us lightly we barely "feel" it, but if the something that touches us exerts greater pressure the "feeling" increases up to the point where it may become painful. It is strange but the sensation of hearing has its pressure limit also, because as the pressure difference of the air pulsation becomes greater and greater a point is reached where the sensation of loudness of hearing is overpowered by an actual sensation of pain.

THE ELECTRIC EAR

A microphone has sometimes been called an electric ear, and there is some reason for this, as we can see by a study of Figure 3. Here we have an arrangement similar to that of Figure 1, with the ear replaced by the microphone. This also has a stretched diaphragm which can be compared to the tympanic membrane of the human ear. As an area of compression arrives at the front side of the diaphragm the air particles close to it will tend to bulge it inward, because behind the diaphragm the air is at rest and at the same pressure as the air in front would be if there were no pulsations. When an area of rarefaction approaches the diaphragm, the air particles close to its front move away slightly, decreasing the pressure on that side. The normal pressure of the air behind the diaphragm therefore makes it bulge outward toward the source of sound. This bulging of the diaphragm in and out causes an alternate compression and expansion of

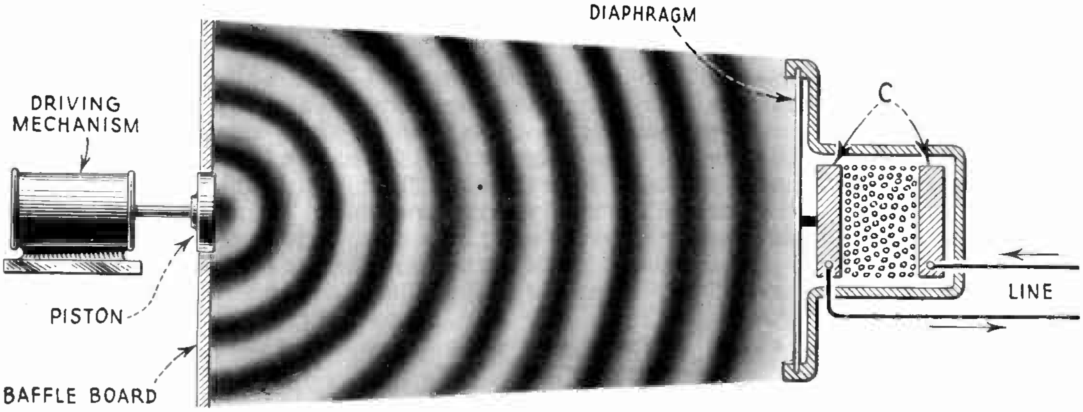

Fig.3 - A microphone responds to sound pulsations.

the carbon granules which lie between the two carbon contacts "C", because the left hand one of these is attached directly to the center of the diaphragm. The current pulsations along the line thus caused by the air pulsations can be compared to the impulses along the nerves connecting the inner ear and the brain.

This comparison is presented to you to emphasize the fact that the air pulsations can cause an actual movement in space of things such as diaphragms and other flat objects, which either are freely suspended in space, or which are supported on their edges, but flexible enough to bulge in and out easily. We can therefore expect that pulsations can be caused by making a generally flat body move back and forth in the otherwise still air, or by making a thin fixed body bulge in and out by applying mechanical forces near its center.

This is proved to be true by the complete telephone system shown in Figure 4. The microphone at the left changes air pulsations (AP) into pulsations in an electric current. A transformer (L) changes the pulsations into an alternating current which is passed through the coils (J) of the telephone receiver at the right. Here we have a round metal diaphragm (K) supported at its edge and which is attracted toward the permanent magnet (I). This attraction is a steady one, and the diaphragm does not move, just so long as no current passes through the coils around the magnet.

Such a current flow will occur whenever an air pulsation arrives at the microphone. The magnet then has a greater or lesser attracting power for the diaphragm. This results in the diaphragm bulging inward more or less from its normal position.

It is clear that this effect is the same as that of the piston used in preceding illustrations, and air pulsations (AP) are caused by the vibrating diaphragm.

SOUND PRODUCTION

The audible pulsations of the atmosphere which constitute sound are always produced by what Newton refers to as a "tremulous" body, but which we in modern times refer to as a "vibrating" body. This may be stretched skin, as in the drum; a thin metal plate, as in the cymbal; a pair of stretched pieces of flesh, as in the human voice; a string that is bowed, as in the violin; or a thin wooden reed, as in the clarinet.

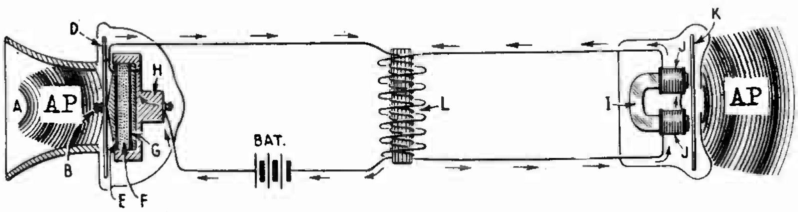

Fig. 4 - Sound pulsations and a telephone system.

Whatever the physical shape or composition of the vibrating body, its sole purpose is to cause those recurring pulsations of the air which we know as sound. The pulsations are useful to us only when they arrive at the ear as alternate areas of compression and rarefaction of air or some other gas or liquid which is capable of establishing an intimate contact with the surface of the ear drum.

A pulsation may be communicated along a solid substance such as a steel rod or a stone, but in general we may limit our consideration to the use of air and water, because these are practically the only gas and the only fluid which ever contact the ear drum.

A pulsation in air travels at the rate of about 1100 feet per second. A pulsation in water travels at the rate of about 4400 feet per second. The velocity of sound becomes important in some cases where we wish to measure the distance between a source of sound and the place where it causes the sensation of hearing. A case of this kind concerns the type of lighthouse or lightship in which a bell is struck below the surface of the water as shown in Figure 5. The pulsations travel through the water in all clear directions at a velocity of 4400 feet per second. If a microphone is placed close to the bell, the pulsations can also be changed into electric current pulsations with practically no time delay due to travel through intervening water or air. The electric pulsations are applied to a radio transmitter and received on a ship practically simultaneously with the striking of the bell, due to the high velocity of radio waves, about 186,000 miles per second. However, the pulsations through the water medium take an appreciable and measurable time to travel outward. It is not a difficult feat to measure the time between the arrival of the "sound" by radio substitution and the arrival of the actual sound pulsations by water. This time in seconds, multiplied by the velocity of sound through water (4400 feet per second) gives the approximate distance that the receiving ship is from the sound source.

The designers of certain musical instruments, particularly the organ, are greatly interested in the velocity of sound in air, because they must know the time required for a pulsation to travel along a pipe of a given length.

PERIOD OF A PULSATION

Any motion or action which continually repeats itself and always in the same time, is said to be periodic. The motion of the bob of a pendulum is periodic, and so is the motion of the earth around the sun. In either case the point on which we fix our attention describes the same path again and again; it furthermore completes its

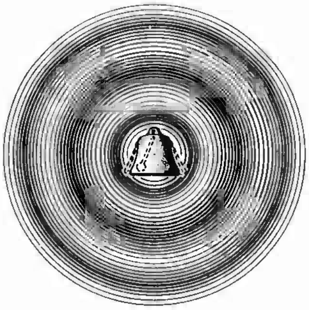

Fig.5 - Sound pulsations in water.

traversing of the path in the same interval of time. This interval of time we refer to as its period. For instance, consider the piston of Figure 1. If we give it a rapid motion to and fro at regular intervals of time the air pulsations produced will cause the sensation of hearing to appreciate them as a musical note. If the motion of the piston is irregular and non-periodic, we interpret the sound produced as noise.

The piston may move slowly at some points of its path and rapidly at others; it may even partially retrace its motion a bit. These peculiarities will affect the nature of the pulsation and also the sensation produced to some extent, but if the vibration of the piston, however complicated, is repeated regularly in equal intervals of time, its motion is said to be periodic. The ear drum will of course be made to have a motion that is periodic; the period will be the same as that of the piston. The number of complete to and fro vibrations executed per second by a body is called the frequency of its vibration. The maximum movement of the vibrating body from its position of normal rest is called the amplitude of its vibration. Let us not overlook the fact that, while the frequency of vibration of the ear drum is the same as the frequency of pulsation of the air and the frequency of vibration of the piston, the amplitude of pulsation of the intervening air decreases with increasing distance from the source to the ear drum. This decreasing amplitude of pulsation corresponds to a decreasing loudness in hearing the sound as the ear moves away from the sound source.

DOPPLER'S PRINCIPLE

When a source of sound is being carried toward or away from a person who is listening, there is an apparent alteration of the frequency of the pulsations produced. If the person is standing in a railroad station as a fast express rushes through with its whistle blowing, it seems that the pitch of the note changes as the engine passes. The same holds for the engine hum of a speedy motor car travelling along a road and passing a listener on the side of the road.

If the train is travelling toward the observer, the sound pulsations get crowded up into smaller space, and when the train is going in the opposite direction, the sound pulsations get spread out in space, as shown in Figure 6. On the approach, a sound pulsation leaves the whistle at a uniform air speed of about 1100 feet per second, and is well on its way by the time the next pulsation leaves the whistle. Meanwhile the whistle itself has been moved closer to the observer, so the second pulsation is appreciably closer in a forward direction to the first one than if the two pulsations had originated from an engine standing perfectly still. These pulsations travel at a uniform speed through the air, but more of them per second

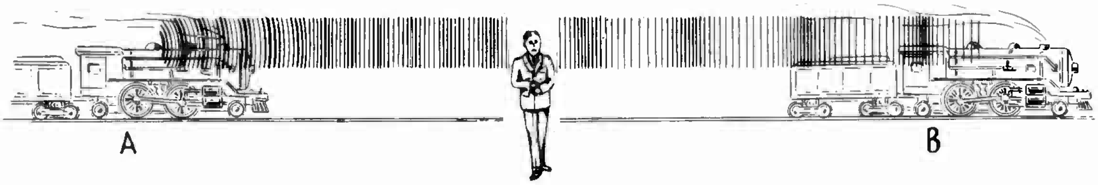

Fig. 6 - Pictorial representation of "Doppler's Principle".

arrive at the ear of the listener on the station platform than arrive at the ear of a person riding in the train at a fixed distance from the whistle. (See A in Figure 6.) The frequency of the whistle sound will remain the same for a person riding on the train, regardless of where the train is. Now when the train has passed the listener on the ground, each pulsation to the rear starts from the whistle at a point in space appreciably removed from where the preceding one started, and the distance between the successive areas of compression to the rear is greater than if the train were standing still. Therefore fewer pulsations will arrive at the ear of the stationary listener than would be the case if the train were standing still and pulsation had exactly the same distance to travel to him. (See B in Figure 6.)

The name "Doppler's Principle" is applied to this phenomenon. Since the frequency of pulsation is identical with the pitch of the musical tone which is sensed by an observer, we can see that there is plenty of room for argument between the best of friends as to the pitch of the whistle of an engine, if the engine is travelling rapidly between two nearby railroad stations at each of which one friend is standing. To the man at the rear station, the note will be of lower pitch than the true pitch of the whistle; to the man at the station ahead, the note will be of a pitch higher than the true one. And each would be right, because after all each is interested in what particular sensation of hearing is produced at his own ears.

GRAPHING A PULSATION

We have referred to an area of compression and a succeeding or preceding area of rarefaction as making up a single pulsation. This does not mean that in the first area the particles are crowded uniformly together and therefore at a uniform pressure. Nor does it mean that in the second area the particles are uniformly scattered from their normal positions, and therefore at a uniform pressure below the normal. There is actually a gradual variation in pressure throughout the pulsation, and it is easier to realize this by the use of graphs.

We have two quantities that are uniform as regards our purposes, and they are time and distance. The three quantities that are to be considered as variables are the position of a particle, the density of particles, and the pressure. The relation between these must be obvious. It would be possible for us to graph the forward and backward displacement of a particle from its position of rest with respect to a uniform time axis, but this is not customary. The density of particles and the pressure are directly related in the case of a gas, so we may consider either one as the variable whose action we wish to study. The uniformly changing quantity against which we will graph the variable can be either time or distance.

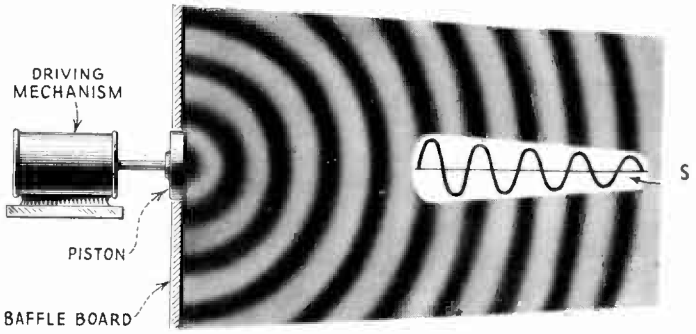

Fig. 7 - Graph of pulsation amplitudes at varying distances from source.

In Figure 7 is shown a cross-section of the air in which pulsations exist. As before, the compression of air particles is shown by the dark bands as contrasted with the light bands representing rarefaction. In the graph, the horizontal ordinate is distance, and the vertical ordinate is pressure. It could just as well be density, as the pressure is directly related to the density of air particles at the point where the pressure is measured. If we had sensitive meters to measure the air pressure along the straight distance line shown pointing away from the source, we would have values of pressure, at a given instant, which could be plotted along the line to form the graph which is shown. Pressures greater than normal would be graphed above the line; pressures less than normal would be graphed below the line.

If the measurements are made at points sufficiently close together, the resulting graph would look very much like a sine wave of alternating current. The area of compression corresponds to the positive half of a cycle, and the area of rarefaction corresponds to the negative half of a cycle. Actually there is no such thing as a negative air pressure. The pressure curve has as its reference line the value of air pressure. The pressure curve has as its reference line the value of air pressure existing in that vicinity when no pul setions occur, that is, when there is no motion of air particles with respect to each other. The pressure graph can be better compared to a graph of current in the plate circuit of an amplifying vacuum tube, where there exists a steady flow of current at all times when the proper voltages are applied, but which current rapidly increases somewhat and then decreases somewhat when an alternating voltage is applied to the grid input side of the tube. While operating as a linear amplifier, the tube plate current never decreases to zero. Likewise in the air which is the medium of sound transmission the rarefaction never even approaches the zero pressure which we call a perfect vacuum. In fact, the difference in pressure between the compression peak and the rarefaction peak is tremendously small compared to the actual normal pressure in the open air. Sound represents a very small percentage change in the air pressure, and therefore its measurement is always a difficult problem.

The fact that the maximum pressure change of a pulsation gets less and less as it travels outward from the source (piston) is shown by the decreasing height of the pressure graph peaks as the measuring point is moved along to the right, or farther from the source. It can be reasoned that when the areas of compression and rarefaction have proceeded a great distance the differences in pressure from the normal are so small that the ear cannot distinguish between them.

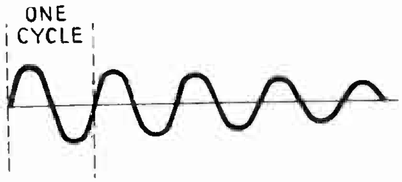

Fig.8 - Graph illustrating cycles of sound pulsations.

Thus the sound would become inaudible due to dissipation caused by length of travel.

THE BAR

Pressure is the total force exerted on an area divided by the number of area units. In sound we use a pressure unit called the "bar", and it represents a force of one dyne per square centimeter of area.

CYCLE

A "cycle" of the piston may consist of one forward movement, a return to center position, a movement backward from center and a return to center a second time. Observing Figure 8 it appears that the pulsation thereby produced constitutes one cycle of sound. This consists of a beginning point at normal air pressure, an area of compression, a return to normal pressure, an area of rarefaction, and a return to normal pressure again. This is shown by the section of the curve included between the dotted lines. Then another cycle begins. A single cycle may be considered to begin at any point on the pressure curve and end with the corresponding point which begins another complete repetition of the act.

The graph of Figure 8, it must be remembered, shows pressure values at various distances but for a fixed instant of time. We could just as well make a graph corresponding to the pressure changes at a fixed point in space but for different instants of time. This would be based on rapid readings taken of a pressure meter placed at a definite distance from the source. The readings would be timed accurately so the values of pressure could be plotted at the correct place along the time axis of the graph. This is based on an assumed ability of the meter to follow accurately the changes in pressure. Practically such a graph can be made only by a photographic record of pressure against time. This new graph would have a uniform height for all its peaks, because the amplitudes of succeeding pulsations would not differ at a fixed point in space, so long as the amplitude of vibration of the sounding body does not change. There will be no falling off in amplitude of succeeding peaks as shown in Figure 8, which occurs because that graph shows pressure at increasing distances.

An inspection of Figure 9 will emphasize this difference. In A of the figure there are indicated 20 areas of compression and 20 of rarefaction, and they alternate regularly, giving 20 complete pulsations. These are plotted against time in the graph above, showing that the frequency is 20 cycles per second. In B of the figure the corresponding information is given for a frequency of 40 cycles per second.

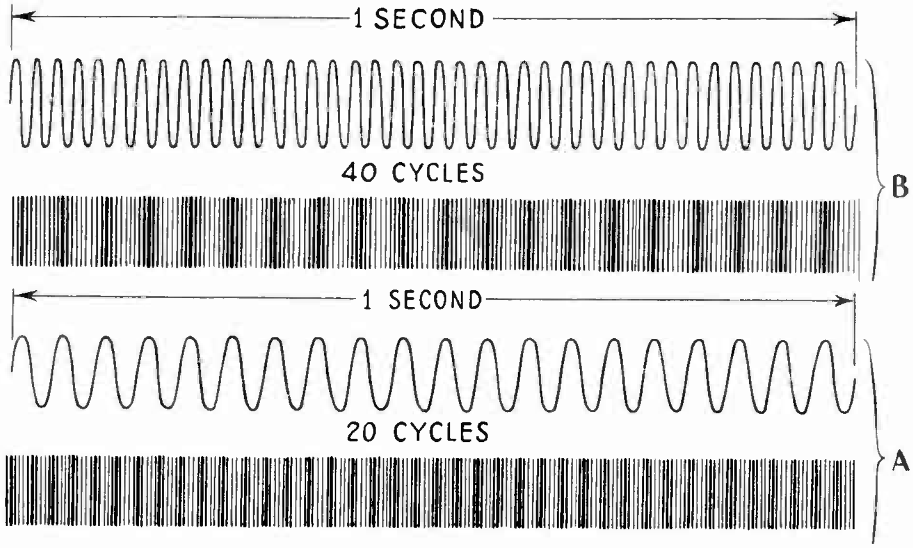

Fig. 9 - Graphs showing uniform amplitudes of pulsations.

INTERFERENCE - BEATS - RESULTANT TONES

In any elastic medium it is possible to have more than one periodic motion happening at a time. This applies to light waves, water waves, and even to air pulsations. Its occurrence in the case of water has probably been noticed by everyone, but will be explained here because of a certain similarity to sound.

Suppose that you have a quiet pond of water with a narrow channel leading out of it into another quiet pond. By dropping stones or using a plunger it is possible to start regular waves radiating from the spot where the plunger is working. Suppose we have two such plungers working at some distance apart, each developing a group of waves which move with the same velocity and are the same distance apart in their groups. If the waves are so timed that a wave-top of one group arrives at the exit channel at the same instant of time as a wave-top of the other group, the combinations of these elevations will produce a wave higher than either of the original waves. In the same way, the trough of one wave group will match with the trough of the other group to produce a resultant trough which is deeper than either. Now suppose that two equal waves, one from each group, arrive at the channel just one-half a wave-length apart. The elevation of the wave of one group will be offset by the trough of the wave of the other group. In the same way succeeding waves have their depressions filled up by the elevations of the other wave-group and the surface of the water will remain smooth. This shows us why the word "interference" is used to describe the phenomena.

The waves of one group may arrive at such a time with respect to the other group that the elevation of one wave occurs somewhere in between the elevation and the trough of the other group wave. In this case the combination will provide waves whose maximum elevation is something less than the sum of the two separate wave elevations.

Likewise the combination will provide a trough whose depth is less than the sum of the two separate wave troughs. Each wave system causes a motion of the area which is traversed by both. Sometimes the motions are in the same direction, and add; sometimes the two motions are in opposite directions, and the actual motion of a particle of water is equal to the difference of the two motions it would have had separately. When the channel, or common area, has

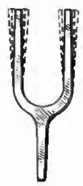

Fig. 10 - Tuning fork used to illustrate periodic vibrations.

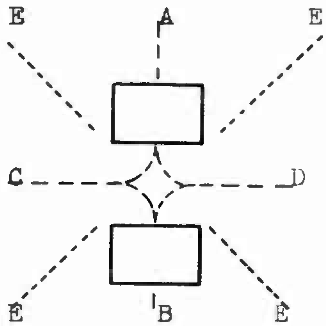

Fig. 11 - Top view of the prongs of a tuning fork showing lines of compression, rarefaction and silence.

been passed, each wave motion continues as it would have done if the other wave motion had never been present.

We have a good example of interference between sound pulsations in the case of a simple tuning fork, shown in Figure 10. If one or both prongs are plucked or struck with a padded hammer they will vibrate with a periodic motion for some time before coming to rest. Compressions are started in front of the prongs when they move, and rarefactions behind them. When the prongs move toward each other a compression will be formed between them and this will be propagated out to each side, at right angles to the direction in which the prongs are moving. A rarefaction is started behind each prong and this is propagated out from each prong in the direction opposite to which it is moving. Figure 11 will make this clearer, being a top view of the fork. When the prongs return to their normal positions of rest, their momentums carry them beyond and each compresses the air in front of it, causing compressions to be propagated in the direction in which they are moving. A rarefaction will then be created between the prongs which will be propagated sideways at right angles to the direction of motion of the prongs.

When compressions are being propagated along lines A and B, rarefactions are being propagated along lines C and D. When rarefactions are being propagated along lines A and B, we find compressions being propagated along lines C and D. We can expect to find that the compressions and rarefactions will combine to give us normal pressure along some lines which bisect the right angles formed by the lines A, B, C, and D. It is easy to prove the truth of this by causing the fork to sound, and rotating it about an axis parallel to the prongs. The sound dies out in four directions from the center of the fork, as shown by the lines each marked E.

The pulsation frequencies along lines A, B, C and D are identical because they are caused by the same vibrating body. The "lines of silence" consist of a series of points in space where an air particle is subjected to two equal and opposite forces, and therefore does not "pulse".

BEATS

Subjecting an air particle to forces of different directions is also done when two separate vibrating bodies are sounding close together. Their frequencies may of course be different. At any instant of time the pressure at some point will depend on the direction and amount the particles would have been displaced if the two pulsations had occurred separately.

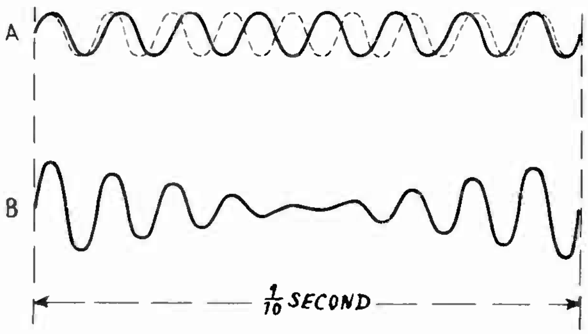

Fig. 12 - Graphs of two sound pulsations of different frequency and the resulting combined throb or beat pulsation.

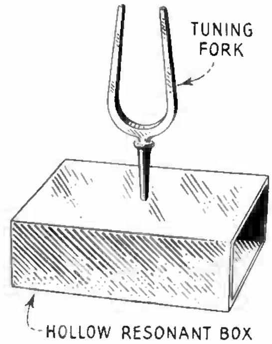

Fig. 13 - Tuning fork mounted on a hollow box to increase the amplitude of sound waves.

In Figure 12, A gives the pressure-time graph of an 80-cycle pulsation (dark line) and a 90-cycle pulsation (dotted line). In B is shown the net pressure effect due to the presence of both pulsations in a single medium. The left peak is due to the combination of the two pressure peaks at the left of A. The right peak in B is due to the two pressure peaks at the right of A. In the middle of B it is seen that the pressure wobbles weakly along for some time. This is caused by the fact that in A several peaks of the 80-cycle pulsation are nearly offset or cancelled out by several peaks, in the opposite direction, of the 90-cycle pulsation.

The effect is that the two pulsations at 80 and 90 cycles combine to cause a throbbing or alternate swelling and diminishing at the rate of (90-80) or 10 cycles per second. This is shown by B of Figure 12, where in 1/10 second, there is a gradual change in the peaks from maximum to minimum to maximum again. This represents one complete cycle of events in air pressure in 1/10 second. The frequency of the throb, or beat, is therefore 10 cycles.

We find the more general use of the term beat when the throbbing is at a rate which can be counted, as in tuning a piano. Here the procedure is to tune one string to the exact frequency of some portable frequency standard, such as a tuning fork. The tuning is accomplished by changing the tension on the string until its frequency is close to that of the fork. Then as the string is tuned closer, the number of beats between the string and the fork will grow less and less. When there is probably one beat per minute between the two frequency sources, they may be considered to have identical frequencies. The next step is to tune some second string to the first one; and this uses a definite count of beats between harmonic frequencies generated by the various strings. This will be better understood after you have covered the subject of tone quality and modes of vibration.

RESULTANT TONES

The term beat is used to apply particularly to the waxing and waning at very low frequency which compares with the beating of drums, etc., of which the ear recognizes each blow as a separate pulsation. This occurs where the pulsation frequency is less than about 15 per second. When the difference in frequency of two strong pulsations is more than 15, the increase and decrease in pressure at that frequency is sensed by the ear as a third musical tone. As far as the ear can sense, the third tone is there just as much as if it had been produced by a third vibrating body. This combination tone is referred to also as a resultant tone, a different tone, or a Tartini's tone.

RESONANCE AND DAMPING

A tuning fork is usually mounted on a hollow box or sounding board as shown in Figure 13. The effect of this is to reinforce the tone, that is, to increase the amplitude of the sound waves. It does this by presenting a larger surface to the air, and when the vibrations of the fork are transmitted to the sounding board and set it into vibration, it causes waves of greater amplitude to be sent out because it moves more air due to its greater surface. For this same reason stringed instruments are provided with a hollow, resonant body usually of wood and the sound waves which go out into the air really come from this vibrating body which in turn is set into movement by the vibratory motion of the strings. The piano has a large sounding board over which the strings are stretched and which vibrates when the strings vibrate. The comparatively large surface which the sounding board presents to the air produces a sound wave of considerable amplitude.

The part of a musical instrument which is the original source of the vibrations is sometimes referred to as the "tone-generator", and the body having a wide surface which acts to increase the pulsation amplitude is called the "resonator". This brings us back to the subject of vibratory periods and introduces us to an extension of that phenomenon.

SYMPATHETIC VIBRATIONS

It is a well-known fact that almost every object or body has a natural vibratory period, and this means that there is a certain frequency to which it responds more readily than any other frequency. This property of a body is forcibly brought to our attention at times by its action in a room where music is being played, for as notes of a certain frequency are struck, an object such as a vase or picture will suddenly commence vibrating and emit a loud rattle. This is due to the fact that the natural spring or resiliency of the body or object is such as to cause it to move back and forth at the exact moment when the areas of compression and rarefaction in the sound wave reach it and aid its backward and forward movement. This same effect of properly timed impulses is seen in the action of a person pushing a child on a rope swing, for the swing has a natural period of movement due to the length of its ropes. If it is given a slight push, allowed to swing back and is pushed again as it starts forward very little energy is required to get the swing into motion having a large amplitude or in other words to make it swing high. If the pushes are not applied at the right moment the motion of the swing will be retarded instead of helped.

This happens if the person on the ground pushes forward a fraction of a second before the swing has returned to the near end of its travel; the push is then opposite to the direction of movement of the swing. The energy in the pushing effort is partly wasted in stopping or slowing down the swinging. If the push is applied just after the swing has stopped at one end of its path, and has started forward again, the energy of a push will be effectively applied toward increasing the speed of the swinging child, which makes it swing higher than before.

If the pushing effort is stopped and the swing allowed to come to rest of its own accord, this happens because the energy of the swinging mass is slowly dissipated in overcoming air resistance and sometimes friction at the top of the ropes. If the child keeps his feet hanging low as he passes close to the ground, the dragging effect of his shoes on the ground increases the resistance, consuming more energy per swing, and bringing it to a stop much sooner. This decreasing of the amplitude of oscillation is called "damping". The damping is proportional to the rate of decrease of amplitude of successive swings.

The tuning fork shown in Figure 13 is mounted on the resonant box for a reason which should be clear. The fork itself vibrates very feebly. It also has a very low rate of damping, which means that the vibrations continue, after the first plucking or striking, for quite a length of time. A certain amount of energy has been stored up in it with the original distortion of its shape. If the mechanical energy can be transferred into sound energy at a faster rate, the amplitude of the early pulsations will be greater, but the vibrations of the fork will die out sooner. This is accomplished through the use of the resonant box. Its construction is such that its air column would naturally vibrate by itself at a frequency very nearly the same as the fork. The fork transfers some energy of its vibrations just by resting on the box. Energy is also transferred directly through the air, which should be clear from our study of the effect of a sound pulsation on the stretched diaphragms, etc. The walls of the box are made to bulge in and out slightly. Air pulsations are caused at the same frequency. The box resounds and is therefore said to be "resonant" at the frequency of the fork.

A well-known method by which this effect of sympathetic vibration in a body is shown is that of two tuning forks which have the same period of vibration or frequency. When one fork is struck and set into vibration it sends out pulsations which by means of successive tiny pushes and pulls start the other fork into vibration. This action of the areas of compression and areas of rarefaction in the pulsation is easily understood by reference to Figure 14 which shows pulsations produced by one fork acting upon another fork tuned to the same frequency. The dark bands represent areas of compression and the light bands areas of rarefaction. The sound is produced by fork A and travels through the air to fork B. The first area of compression to arrive at B pushes the prongs of the fork to the right and as the natural spring effect of the prongs returns them to normal, the area of rarefaction follows and pulls the prongs to the left, thus completing one cycle of movement. As the prongs start to return again to normal the next area of compression arrives and pushes them to the right past normal, and the succeeding area of rarefaction pulls the prongs again to the left. This continues as long as the sound wave from A exerts its force upon fork B. The latter is finally swung into visible vibration.

Suppose small pieces of metal or even of sealing wax are added to the ends of the prongs of fork B. This added weight or mass causes it to vibrate naturally, when struck, at a lower frequency than before. If fork A is now sounded, fork B will vibrate very weakly if at all. If more weights are added, fork B will not respond at all to the pulsations caused by fork A. The reason for this is simple. Perhaps the first few areas of compression and rarefaction would make fork B vibrate very slightly. Succeeding pulsations from fork A, however, would arrive so poorly timed with respect to the natural vibrations of fork B that the latter would be "stopped in its tracks". This compares with the poorly timed impulses given to the swinging of the child, previously described.

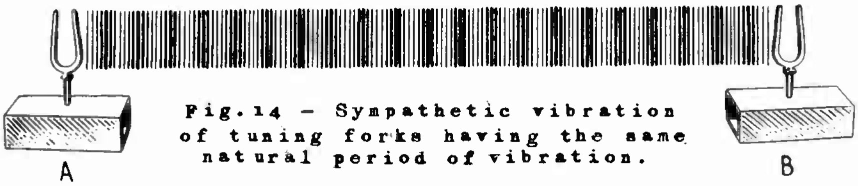

Fig.14 - Sympathetic vibration of tuning forks having the same natural period of vibration.

A tuning fork has a very low damping, which is to say that the energy imparted to it is expended very slowly in vibrating. The energy received from one pulsation lasts a long time, and if succeeding pulsations are not accurately timed to it the bucking effect results. The fork is therefore very sharply resonant.

It is interesting to note what happens if each fork is separately struck, when mistuned by the addition of weights to one. The energy given to each fork is imparted with a single blow, and is usually sufficient to keep it vibrating for some time, even though each fork is subjected to the air pulsations arriving from the other fork. The two forks now vibrating freely due to the hammer blows received will produce pulsations of different frequencies, and a listener would perceive the beats due to the phenomenon of interference.

If two forks accurately tuned to the same frequency are struck simultaneously, the sound waves of one will reinforce the sound waves from the other and a louder tone will be heard due to the fact that the areas of compression join each other to produce areas of greater compression; the areas of rarefaction join to produce areas of greater rarefaction thus creating a sound wave of greater amplitude and consequently greater sound.

This may not seem to fit in with the description of water waves in the paragraphs on INTERFERENCE. There it was stated that equal water waves of the same frequency might either add to their effects or might balance out and nullify each other. This would depend on whether the crests of the waves arrived at a point at the same time, or whether the crest of one arrived at the same time as the trough of the other. In the case of the water waves, we assumed that each wave group was being originated by a separate plunger that was being supplied with power which was so timed as to give it the same frequency as the other plunger, Therefore the plungers were not vibrating freely and one plunger would not be moved by water waves from the other.

In the case of the sound pulsations from the tuning forks, they vibrate due to single impacts of a hammer which immediately give up some energy to the prongs, and these continue to vibrate at the same frequency, but freely and independently of the hammers which have been laid aside. Each fork is resonant to the pulsations started in the air by the other fork. This transfer of energy from each to the other makes them "lock in", which may be compared to men marching along who not only make the same number of steps per minute (same frequency) but also keep step left and right (same phase).

FREQUENCY RANGE OF HUMAN HEARING

The sensitiveness of the ear to certain frequencies varies in different people so that sounds which are audible to one person cannot be heard by another at all. This failing makes itself evident in

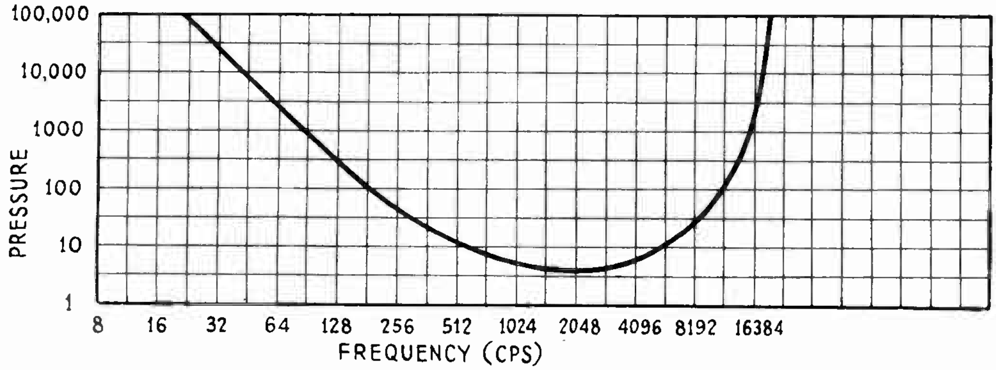

Fig. 15 - Sound pressure for human hearing depends on pulsation frequency.

the narrowing down of the band of frequencies that are audible. That is, a person with normal hearing can hear sounds with frequencies from 20 c.p.s. (cycles per second) at the lower limit to 16,000 c.p.s. at the upper limit. It is thus said that the audible band of frequencies for that person is from 20 to 16,000 c.p.s. It must be evident that the ability to hear well depends to a great extent on the elasticity or "limberness" of the ear drum, for if the eardrum is elastic it moves with the slightest movement of air caused by a sound pulsation. The eardrum is more elastic in youth than in old age, and in fact there is a gradual hardening of the eardrum with age just as most of the rest of the body hardens and grows less elastic with age. As age increases then the audible band of frequencies grows narrower and a person cannot hear sounds of as high or as low a pitch as he could when he was younger. The chart in Figure 15 serves to illustrate this point somewhat.

First let us say that in order to hear any difference between the volume or intensity of one sound as compared with another sound there has to be a certain difference in pressure that the sound pulsation exerts upon the eardrum. This difference in pressure must be great enough or the ear will not be affected to a degree sufficient to enable it to recognize that there is any difference in the loudness of the sounds. The difference in pressure necessary to make the change in loudness noticeable varies for the different frequencies so that while it takes a change of air pressure of only 3/10ths of 1 per cent to enable the ear to recognize a difference in loudness at frequencies from 500 to 4000 c.p.s. it takes many times as much difference in pressure at frequencies lower than 500 and higher than 4000 c.p.s. As seen by the chart in Figure 15 it takes almost 100,000 times as much pressure to make the ear notice a difference in loudness at about 20 c.p.s. as it does at 2,000 c.p.s. Now, inasmuch as the sensitiveness of the ear to sound depends to a certain degree on the flexibility and response of the eardrum to the pressure of sound waves, it is evident that as a person grows older and the eardrum stiffens somewhat, and thereby becomes less sensitive, the person will first lose the ability to hear the lowest and highest frequencies so that the audible band of frequencies for that particular person will narrow down from both ends. If a person is growing deaf through the action of age upon the eardrum, for instance, we would expect that as he grew older he would first fail to hear the frequencies at the lower and upper limits of normal hearing, say 20 to 30 c.p.s. and 20,000 to 15,000 c.p.s., then as he grew older possibly he would not be able to hear a range greater than from 60 to 6000 c.p.s. and so on until probably the last frequency he would be able to hear before he went entirely deaf would be about 2,000 c.p.s. at which frequency the ear is most sensitive. So much for the human ear and its normal range.

FREQUENCY RANGE OF THE HUMAN VOICE AND MUSICAL INSTRUMENTS

Figure 16 is a very interesting chart showing the frequency range of various musical instruments and the human voice. At the bottom is seen a representation of a standard piano keyboard with some dark keys added to carry the range beyond that of the piano. Immediately above the keyboard are letters by which the various keys on the piano are known, as A, B, C, D, E, F, and G after which they start all over again. The numbers directly above the letters refer to the frequency of vibration of each note and as can be seen extends from 26.667 cycles for the lowest key to 4096 cycles for the highest key on the piano keyboard and up to 8192 cycles for the highest note shown on the chart.

The pitch frequencies marked for the various piano keys are those based on the tuning of middle C to 256 cycles per second, which is the physicists standard of pitch. Pianos are actually tuned for ordinary playing to either the "international" or the "concert" pitch, which are respectively based on 435 and 440 cycles for the A note immediately to the right of middle C. The average organ range is from 16 to 4138 cycles although an organ pipe has been made that will produce a note vibrating at 15,600 cycles.

It is interesting to note the various ranges covered by singers. A base voice ranges from about 80 to 342 cycles; baritone from 96 to 384 cycles; tenor, 128 to 480 cycles; alto, 171 to 683 cycles and soprano from 240 to 1152 cycles. The chart shows how the ranges of these various voices overlap so that each voice is able to reach a considerable number of notes within the next range. In fact, there are several notes that are common to all the voices shown. Running up the left side of the chart are brackets labeled, "human voice", "stringed instruments", "percussion instruments", and "wind instruments." Each instrument has a clearly defined range of frequencies which it is able to produce and it is seen that there is considerable overlapping of ranges in this instance also. Now the thought probably occurs to you that if a certain note, say middle C which vibrates at 256 cycles, is in the range of several musical instruments and the human voice, there must be something else that takes place in order to make the various instruments sound differently. Following up from middle C at 256 cycles on the chart we find that it is in the range of the human voice, eight stringed instruments, nine wind instruments and the harmonica. Therefore there are nineteen sound sources which produce a note vibrating at 256 cycles and yet not two of the instruments sound the same. For instance, when middle

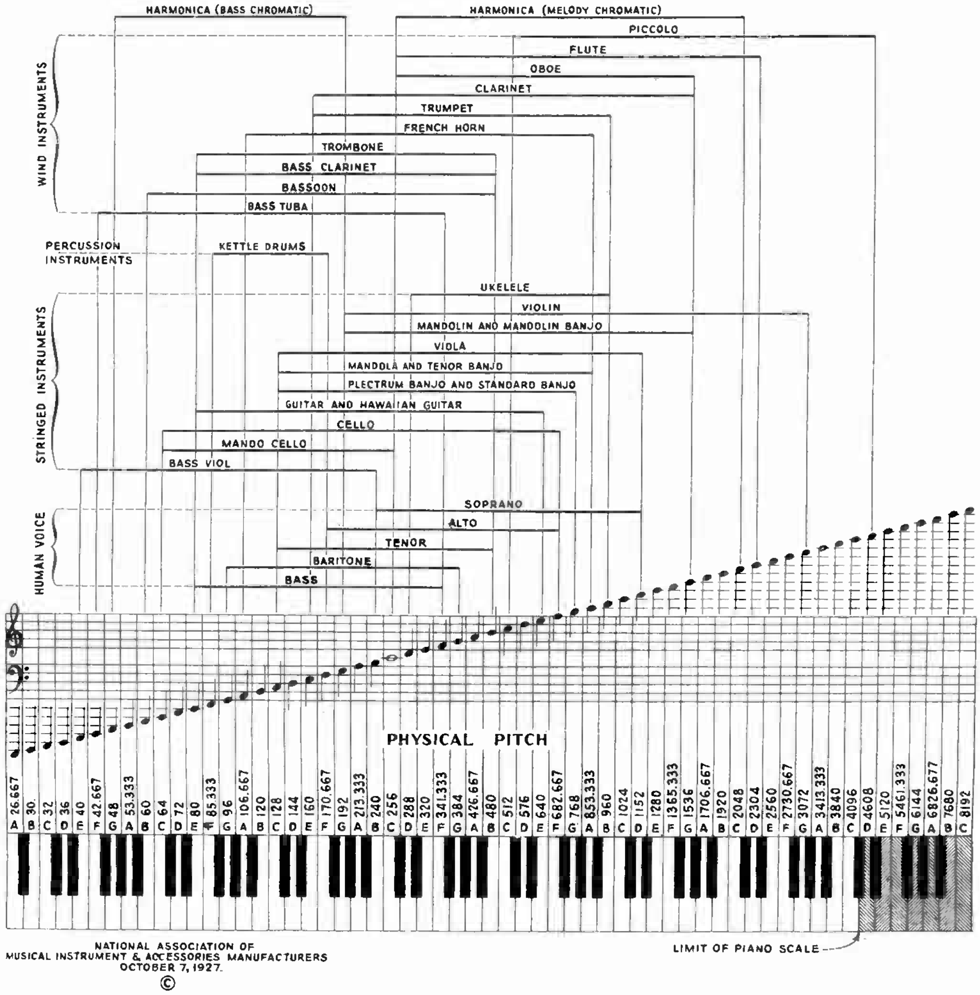

Fig.16 - Frequency range of the human voice and musical instruments.

C is struck on the piano you can tell instantly that it is a piano note and not a violin note although both are vibrating at 256 cycles.

MODES OF VIBRATION IN STRINGS AND TONE QUALITY

The answer is in the harmonics or overtones which accompany the fundamental frequency of every note and these harmonics differ for each instrument so that a distinct quality of sound is given to each note by the addition of the harmonics which are always present. This presence of harmonics is shown in simple form in Figure 17. If a stretched piano string is struck at its center point it will vibrate as a whole as shown in Figure 17(A) and produce the fundamental tone. If you now place your finger on the middle of the string and then strike each half separately the string will vibrate in two parts as shown in Figure 17(B) and will continue to maintain this form of vibration even after the finger is removed. The tone heard will be of a higher pitch than the fundamental, in fact its frequency will be just twice that of the fundamental as each half of the string vibrates twice as rapidly as the string would vibrate as a whole.

If the string is stopped at two places, dividing the string into three sections of equal length, the vibrations will be as shown in Figure 17(C) when each section is struck individually. Each section vibrates at a rate determined by its length; the common frequency will be three times the fundamental produced by the open unstopped string. In Figure 17(D) is shown the mode of vibration in five equal sections, the common frequency being five times the fundamental. The string can be made to vibrate at other frequencies which are integral multiples of the fundamental, such as four, six, seven, eight, etc.

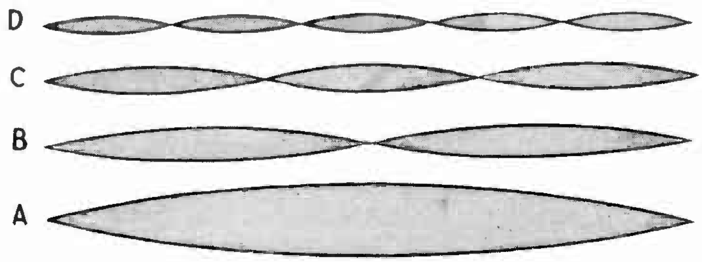

Fig.17 - Graphic representation of modes of harmonic vibration.

We find various names applied to the several frequencies which can be produced by a string or other vibratory body. It is unfortunate that there continues to be a disagreement between the purely artistic members of the musical profession and those other members, more far-seeing, who treat the production of music as a branch of science without losing their appreciation of the resulting sensation.

In the following table the contrast is shown between the various methods of naming the frequencies. As a concrete example a frequency of 220 cycles for the fundamental is assumed.

Shown in	Freq.	Ratio to Fund.Freq.	Terminology Used	
			Scientific	Artistic
Fig. 17A	220	1	Fundamental and 1st Harmonic	Fundamental
17B	440	2	2nd Harmonic	1st Harmonic 1st Overtone
17C	660	3	3rd Harmonic	2nd Harmonic 2nd Overtone
---	880	4	4th Harmonic	3rd Harmonic 3rd Overtone
17D	1100	5	5th Harmonic	4th Harmonic 4th Overtone
---	1320	6	6th Harmonic	5th Harmonic 5th Overtone
and so on				

Now these harmonics can be produced without the trouble of stopping the string movement at certain places. In fact, a string seldom vibrates in only the fundamental mode. This means that the string vibrates as a whole and also in sections at the same time. The difference between musical instruments lies largely in just what sections their vibratory bodies break up into, and at what relative amplitudes.

Let us consider the first three harmonics, shown in Figure 17, (A, B, and C) and draw the pressure-time graphs of the air pulsations produced. In Figure 18, let us assume that graph A is caused by a tuning fork which is producing sound pulsations at a certain frequency. Then we start a second tuning fork vibrating which produces pulsations as graphed in B, at twice the frequency of those graphed in A. These two sounds both exist in the air at the same time. The pressures combine to produce a pulsation which could be graphed as in D. If we now start a third fork vibrating which produces pulsa-

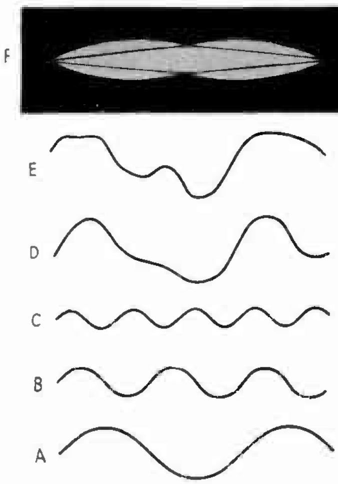

Fig. 18 - Composite effect of vibrations in several modes.

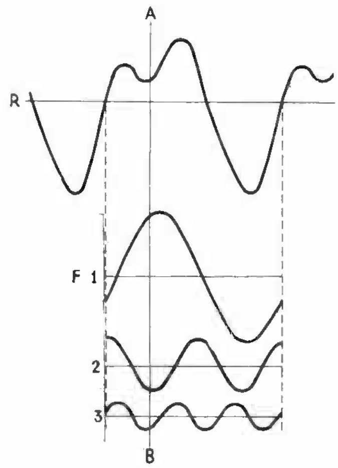

Fig. 19 - Graphic analysis of a violin note.

tions as graphed at C, having three times the frequency of those graphed in A, we find that the pressure conditions will be further modified and can be graphed as in E.

By careful inspection you will be able to see how the addition of pulsation B to pulsation A lifted or lowered the graph of A at certain points to make it as shown at D and how the added effect of pulsation C altered pulsation D in certain places to change its graph to E. The effect on the ear of such a pulsation as shown at E is that of a fundamental with the pitch of A and in addition added quality or "richness" of sound due to the harmonics. It should not require much of a stretch of the imagination to visualize in your mind a piano string vibrating with the effect of the fundamental and the second harmonic so that in vibrating it looks as shown at F. Thus, if this be the form a piano string takes when vibrating and you have learned to associate with it the sound produced by a piano then whenever any string vibrates in that particular form you will recognize by the quality of sound produced that it is a piano note. And so it is with the various string and wind instruments. The certain quality that enables the ear to recognize one from the other is brought about by various combinations of harmonics added to the fundamental. The tone pitch of a string is due largely to its length; the longer it is the slower it vibrates, which produces a low frequency sound wave. As the length of the string is decreased it vibrates more rapidly and the higher becomes the frequency of the tone it emits.

The action of pulsating air may be photographed to show the graph form which it produces. When a violin note is "photographed" by this process it produces a form as shown in R, Figure 19, which when analyzed into its component parts shows that it is composed of the fundamental F and the 2nd and 3rd harmonics designated as 2 and 3 in the same figure. It can be seen in this figure how the two valleys on the line A-B put a dip in the fundamental making it look as shown on the same line A-B in the resultant curve R. It is easier to see the effect of superimposing a harmonic on a fundamental pulsation by assuming that F in Figure 20 is the fundamental and H the harmonic. The resultant pulsation graph is seen to be in the form as shown at R.

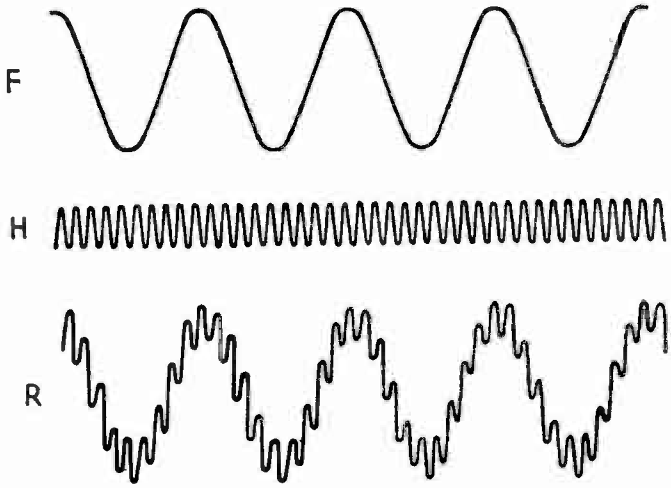

Fig. 20 - Graphic representation of a harmonic superimposed upon a fundamental pulsation.

Before going further the student should realize that the shape of the graph of a combined pulsation produced by several independent pulsations depends on three factors:

1. The frequencies of the component pulsations
2. Their relative amplitudes
3. Their phase relation.

The latter may be described as the relation in time between the occurence of normal air pressure (before compression begins) for the several components. In Figure 18 all three graphs (A, B, C) begin a cycle at the same instant of time. In Figure 19, for the period of time shown, the fundamental graph cycle begins at less than normal air pressure (below the line), the second harmonic graph cycle begins at a compression peak, (above the line) and the third harmonic graph cycle begin at normal air pressure (on the line). As far as the ear is concerned, there is practically no difference in the sensation produced with different phase conditions for these various harmonics. However, the photographed records may be radically different in shape. A resultant graph must be broken up into its components (analyzed) to determine what is the true cause of a musical effect.

MODES OF VIBRATION OF AIR COLUMNS IN PIPES

The production of air pulsations by wind instruments is due to the air columns within them which are caused to vibrate by various methods. In the reed type of wind instrument a slender flexible reed opens and closes the entrance to the air column admitting little puffs of air which set it into vibration. The clarinet, oboe, and saxaphone are instruments of this type while the cornet, trombone, and bass horn are examples of instruments that require the vibration of the lips against a cupped opening to produce a vibrating air column. To produce notes of various pitch, a variety of devices are used to vary the length of the air column. The slide trombone, for instance, lengthens its air column by means of a sliding tube, the cornet by means of keys which stop up certain sections of its tubular construction and the clarinet by keys which open new paths through which the air escapes. The particular quality which each wind instrument displays is dependent upon the fact that its air column vibrates as a

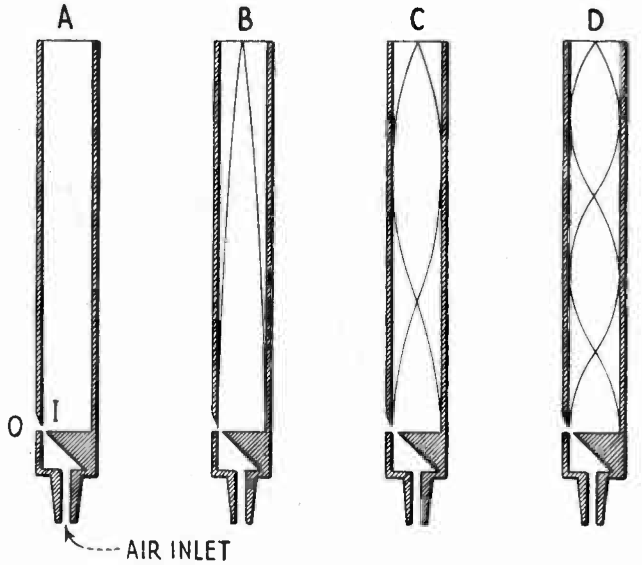

Fig.21 - Modes of vibration of air columns in organ pipes.

whole to produce the fundamental tone and also in parts to produce the harmonics. This is more clearly understood by referring to Figure 21 which shows how sound is produced by a closed organ pipe and how its air column vibrates as a whole and also in sections to produce the characteristic quality of tone which we recognize as organ music. In A the air enters through a pipe at the bottom and a puff of it passes through the opening into the tube at 1. This puff of air travels up the pipe as an area of compression and when it reaches the closed end of the pipe it rebounds or is reflected back down the tube. When it reaches the opening at I it pushes the jet of air which is entering the pipe out towards O causing an area of compression to be sent out into the air. When the compression area that pushed the jet of air out of the pipe has passed, a rarefaction area follows it, the jet of air again passes into the pipe causing another compression area to pass up the pipe where it is again reflected from the closed end, travels back and pushes the air jet out through O again.

This happens over and over again as long as air passes up through the inlet. The sound is caused by the intermittent puffs of air sent out at O and the frequency of the sound is determined by the number of puffs emitted per second. It takes a certain length of time for the compression areas to travel up the pipe to its closed end and back again and this length of time governs the frequency of the note which the pipe produces. Thus it can be seen that the longer the pipe the greater the length of time it will take the areas of compression to travel twice its length and the fewer puffs of air will be sent out per second at orifice O. It follows then, that the longer the pipe the lower the frequency of the sound produced by it. This conclusion is well demonstrated by the fact that an organ pipe producing a tone of 16 cycles is over 32 feet in length and weighs 1278 pounds while one of the smallest pipes ever made produces a tone of 15,600 cycles, has an effective sound producing length of $\frac{1}{4}$ inch, and weighs a matter of ounces.

The characteristic tone of a closed organ pipe is produced by the air column within it vibrating as a whole as shown in Figure 21(B) and in sections as shown for the third harmonic in C and for the fifth harmonic in D, and so on. If the organ pipe were open at the end opposite the air inlet, it would have been able to vibrate at all the harmonics, both even and odd; the closed pipe provides only the odd ones. Also the pitch of an open pipe fundamental tone is an octave above the pitch of a closed pipe of the same length.

The exquisite richness of the organ tone is due to the fact that in addition to the fundamental tone there are a number of harmonics. This condition is shown in graph form in Figure 22 where R is the graph of air pulsations, F is the fundamental and graphs 2 to 11 are the harmonics. The vertical dotted lines show the limits of one cycle of the pulsation R and the fundamental F. The proper way to look at this is that the pulsation R is the resultant form of the fundamental pulsation F when the ten higher harmonics have acted upon it to change its shape. It can be seen in this figure that the second harmonic is twice the frequency of the fundamental, the third harmonic three times the frequency of the fundamental and so on up to the eleventh harmonic which is eleven times the fundamental frequency. The set of curves shows also that in general the amplitude of the pulsations decreases as the frequency of the harmonics increases so that the amplitude of the eleventh harmonic is but a small fraction of the amplitude of the second harmonic. Any recurring graph, no matter how complex, may be analyzed by certain formulae and found to consist of a certain combination of fundamental and harmonics.

A COMPLEX TONE MEETS A DIAPHRAGM

Now you might very well say at this point that you don't understand how a body such as the diaphragm of a microphone or loudspeaker can move in two ways at the same time as it would have to do to follow or to make a sound pulsation as seen in R of Figure 20. Let us look at an edge view of a diaphragm as seen in Figure 23. The solid line represents the diaphragm at rest, while the dotted lines represent an exaggerated idea of the amplitude of movement of the diaphragm when a pulsation strikes upon it. The diaphragm is pushed out of its normal position by the area of compression and, in effect, pulled in the opposite direction out of normal by the area of rarefaction. A pulsation with a fundamental frequency of say 27 cycles, would cause the diaphragm to move back and forth to the dotted line positions 27 times per second. During the same interval of time let us assume that the second harmonic at 54 cycles per second is also acting on the diaphragm. Then, while the diaphragm is moving to the dotted line positions shown it will move backward and forward a little twice due to the 54 cycle pulsation while it is moving back and forth once due to the 27 cycle pulsation. Let us demonstrate the possibility of

Fig.23 - Edge view of a diaphragm.

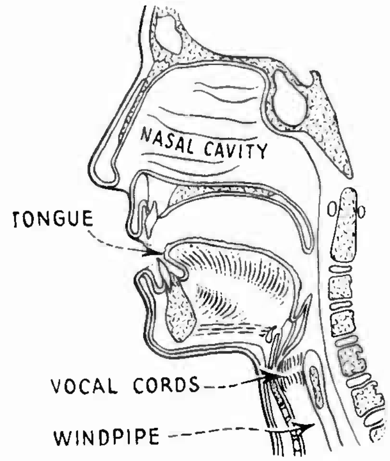

Fig.25 - Cross-section view of the human voice organism.

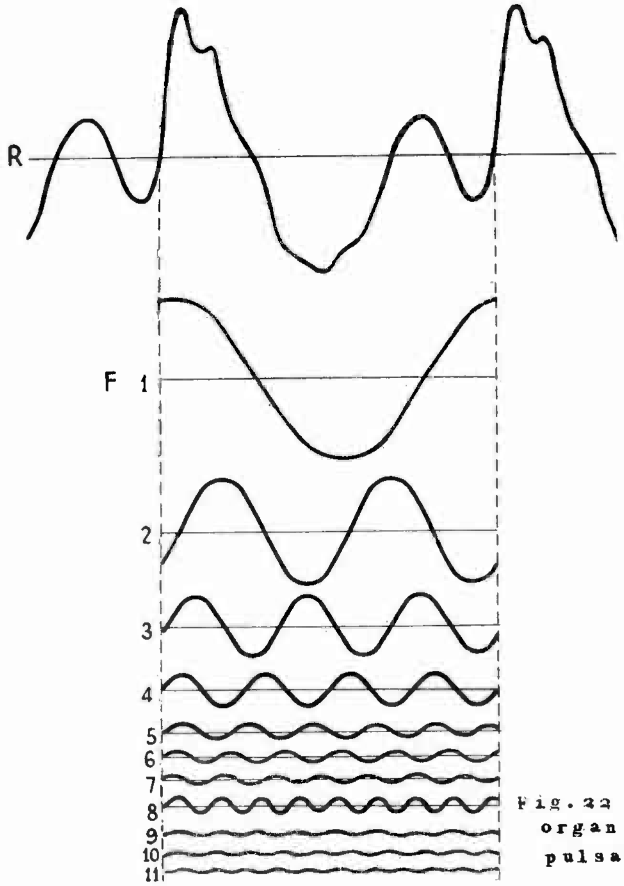

Fig.22 - Graphic representation of an organ note showing the fundamental pulsation with all the harmonics.

this by laying the diaphragm in a horizontal position as shown at A, Figure 24, comparing the movement of its center point with the movement of a man walking over a series of hills, as seen in B. We all know that due to the action of walking a person's body rises and falls a trifle as he walks so that if we looked steadily at his head as he walked along on smooth ground we would see it describe a path somewhat in the fork of a sine wave with an amplitude of say two inches. This would look like the line C in Figure 24 if the man were walking on level ground but if he were walking over a series of ridges as shown at B then the path his head would follow would look like the line in D which looks considerably like the resultant wave R in Figure 20. The center of the diaphragm A shown by the dot at the middle of the line can describe a path exactly as shown at D if the diaphragm were moved along at the same rate of speed as the man. The line corresponding to the hills could be produced by a 27 cycle pulsation and the line corresponding to the rise and fall of his head during walking could be produced by the 216 cycle pulsation which is its 8th harmonic. The resultant pulsation in air would provide the graph shown in D, and this would also represent the displacement in space of the center point of the diaphragm. The pulsation graphs we have studied so far have all been produced by musical instruments or tuning forks and most of them have been curves of simple sounds. A simple sound is one that has few harmonics as for instance the tuning fork whose tone is composed chiefly of the fundamental and approaches the standard of what is known as a pure tone because no harmonics are present. There are very few vibrating bodies that produce pure tones, most of them adding harmonics to the fundamental.

THE HUMAN VOICE

The voice is produced in a manner different from either the tuning fork or the organ pipe but it, too, requires something that vibrates in order to produce sound. The action by which a human voice is produced is easily understood by referring to Figure 25 which is a cross-section illustration of a human head. In the action of pro-

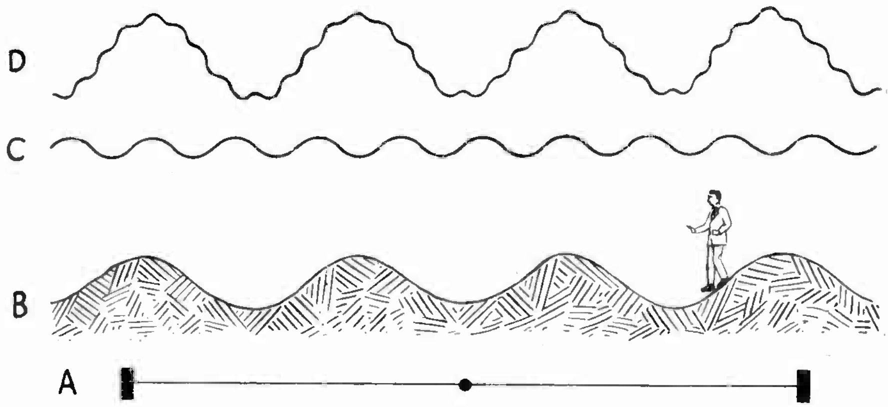

Fig. 24 - Graphic representation of composite pulsations of a diaphragm.

ducing sound, the air is forced up the windpipe by the lungs and passes by the vocal cords which are muscular ledges or flaps, setting them into vibration which causes air pulsations to pass up through the mouth and out into the air. There are cavities in the head that resonate with the component frequencies of the pulsations to provide a certain quality that makes one person's voice sound different from that of another person. By placing the tongue in various positions and changing the shape of the mouth and throat by muscular action words and sounds of different pitch and quality are produced. Each voice has a certain range of frequencies which it can produce and this range varies with different persons and between men and women. The range of fundamental frequencies covered by the human voice is from 80 to 1200 cycles, but it should be understood that this range cannot be covered by one person's voice. It includes the frequencies from the lowest note sung by a bass singer to the highest note reached by a soprano.

REFLECTION

Sound may be reflected from surfaces which are too firm to give way to the pressure changes of a pulsation. If the surface is far from the sound source so much time may have elapsed before the return effect that the direct sound reaching the ear from the source will have died out completely. The reflected pulsation arrives at the ear drum when the latter has ceased vibrating, and gives the impression of a separate sound; we call this an echo.

If the reflection of sound occurs in a room it may be a process of repetition from one wall to another and so on, until it finally dies away. The time interval between the direct sound and a reflection of the sound may then be so small that the ear does not distinguish it. The impression is had of being surrounded or wrapped up in a sound effect which should have come and gone quickly. This continuation of sound is called reverberation. A certain amount of it is desirable because it gives naturalness and a certain aliveness to the sound. Too much reverberation prevents separate sound effects from being distinguished from each other, bringing confusion and lack of intelligibility.

REFRACTION

In brief this applies to a change of direction of a sound as it passes from one medium to another, as when it enters and leaves a wall between two rooms. This may be compared to the bending of light waves as they pass through glass, water or other medium having a density different from that of air.

DISPERSION

The reflection of sound heretofore described applied to surfaces which were generally flat. If the reflecting surface is rough and irregular the reflection will be in many directions, and the sound is said to be scattered or dispersed.

ABSORPTION

We have so far discussed decreasing intensity of sound only as it was caused by the distance of travel of a pulsation. We find another cause for an intensity decrease, and it is based on a change of sound energy into heat energy. This happens when a sound is partly reflected from a surface material which is slightly porous to air particles. As the particles next to the surface move forward under increased pressure, they cause friction with the particles of the material against and into which they are trying to move. This reduces the amplitude of their movement, and the energy of pulsation is partly transferred into heating the material and the air particles themselves. This temperature increase is not a measurable quality; the thought is presented to you merely to make clear what happens to sound energy when rugs and curtains are placed on the floor and walls of a room.

A REMINDER

In a lesson that deals with fundamentals of such importance as those of SOUND, a particular effort must be made by the instructing staff to present the subject in a clear and easily understood manner. To that end we have consistently adhered to the use of the word "pulsation" throughout this lesson. You are again informed that common practice in the sound industries has established the use of the word "wave". Other lessons on the subject of sound will tend to use the latter word. In studying them you may have a cause to refer back to what you have learned in this lesson. In doing so, interpret the meaning of the popular word "wave" as being the same as that of "pulsation" as used here.

EXAMINATION QUESTIONS

1. Through what mediums may sound be propagated?

2. Explain how sound travels.

3. How does sound vary the current in a telephone circuit?

4. Explain how a beat is produced?

5. What is the meaning of the word "Amplitude" as used in sound?

6. What is meant by the "third harmonic"?

7. What is meant by "frequency"?

8. What is the frequency of a pulsation caused by reflection from a wall or other large flat surface?

9. What may cause a reflected pulsation to be much less in amplitude than the original pulsation, considering them at some point in space close to the reflecting surface?

10. What differentiates the tone of one musical instrument from that of another instrument, even when they have the same frequency?

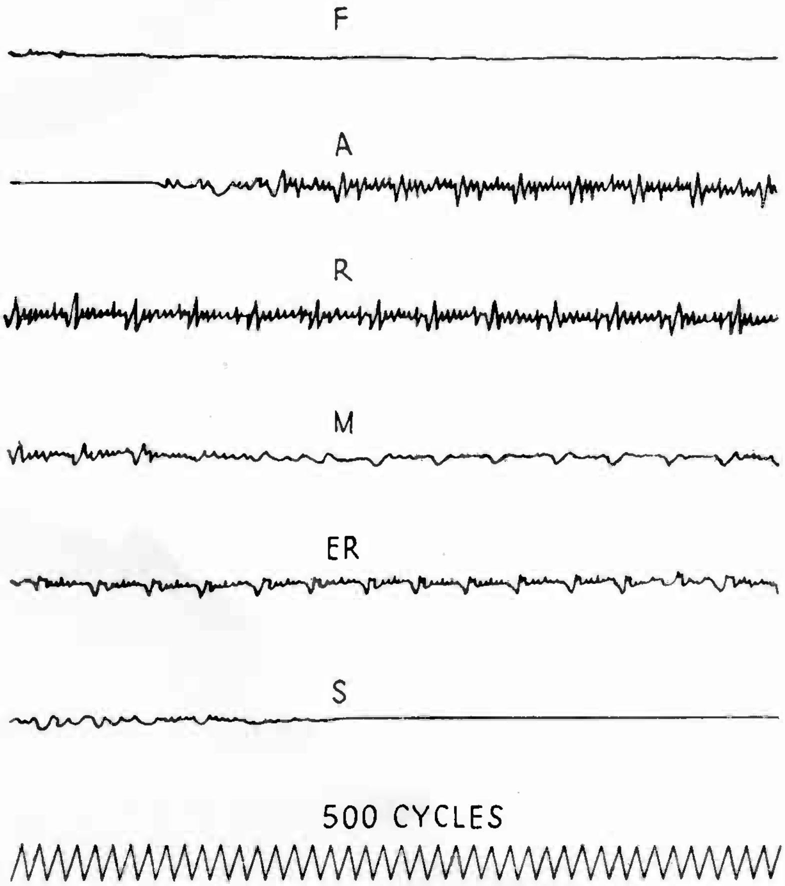

Chart showing frequency analysis of the spoken word, "farmers".

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