Loudspeaker Design

Converting the electronic "message" from the amplifier into sound requires the loudspeaker to undergo physical contortions which may, or may not, distort the message. Understanding the fundamentals of achieving "distortionless contortions" may help in selecting the loudspeaker best suited to your requirements.

NORMAN H. CROWHURST*

This is not an article on how to design a loudspeaker. For one thing, very few readers are likely to have the opportunity of designing their own loudspeaker. On the other hand, anyone pursuing audio as a hobby is interested in good reproduction and hence is concerned in getting a good loudspeaker. In this connection, many are wanting to know "what the score is" about the different ways of designing a loudspeaker system. This is because the fact still remains that the loudspeaker is the weakest link in the reproducing chain and because of the divergence of design approaches used in the products available in this field.

To clarify this matter we will explain some of the simple principles of loudspeaker design, so that those interested can better understand how different approaches to the problem attempt to achieve their objective. The aim of any system, of course, is to convert the electrical energy delivered by the amplifier into acoustical energy in the room, with the greatest degree of fidelity possible.

We would like to have sound waves whose pressure variations are directly proportional to the voltage variations at the output of the amplifier, regardless of the frequency and amplitude of the fluctuations. Unfortunately, however, to date there is no direct means that is commercially practical, of transferring electrical energy into acoustical energy without going through some mechanical medium. The nearest practical approach to this is an electrostatic loudspeaker. But this has to have a diaphragm to transform the electrical force between its plates into mechanical movement of the air.

Table 1

Mechanical system	Electrical system	Acoustical system
Force	Voltage	Pressure
Velocity	Current	Volume movement
Displacement	Charge	Volume displacement
Friction	Resistance	Viscous action
Mass	Inductance	Air mass
Compliance	Capacitance	Air compliance
Lever	Transformer	Change in area

The more conventional dynamic type loudspeaker uses a voice coil, the currents in which produce mechanical force, which in turn drives the diaphragm, and the diaphragm, by contact with the air, produces movement in the form of sound waves. So we have two transfers of energy to think about, electro-mechanical from the voice coil to the diaphragm, and mechanical-acoustical from the diaphragm to the atmosphere.

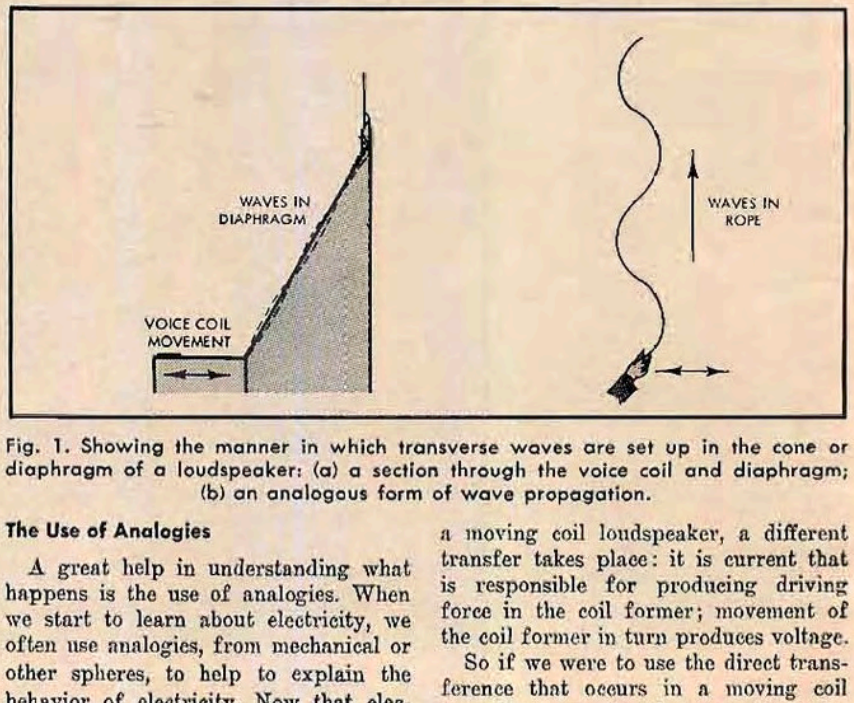

Fig. 1. Showing the manner in which transverse waves are set up in the cone or diaphragm of a loudspeaker: (a) a section through the voice coil and diaphragm; (b) an analogous form of wave propagation.

The Use of Analogies

A great help in understanding what happens is the use of analogies. When we start to learn about electricity, we often use analogies, from mechanical or other spheres, to help to explain the behavior of electricity. Now that electronic circuits have progressed so far, and the general understanding of them improved so well, it is often helpful to reverse the procedure and use electrical circuits as analogies for mechanical or acoustical behavior.

An important thing to realize is that an analogy is only a convenient parallel way of thinking. *It does not express identity,* nor does it relate quantities that can be transformed directly from one to another.

Table 1 lists the more conventional analogies used. The left hand column gives the mechanical quantity, the center column gives the equivalent electrical quantity in the analogy, while the right hand column gives the acoustical quantity that corresponds.

In this system of analogy we make force *equivalent* to voltage, but this does not say we can convert force into voltage in an electro-mechanical transducer. If we use an electrostatic device, it is true that the electrical voltage produces a deflection force on the diaphragm, but when we use a dynamic device, such as a moving coil loudspeaker, a different transfer takes place: it is current that is responsible for producing driving force in the coil former; movement of the coil former in turn produces voltage.

So if we were to use the direct transference that occurs in a moving coil transducer, we should reverse the order of the analogy and make current correspond with force and voltage with movement. On the other hand, in the electrostatic transducer, it is the voltage that produces force on the diaphragm; while movement of the diaphragm causes charge to flow in or out of the transducer in the form of current. To avoid confusing the issue, we will only use the one analogy.

Following the analogies down, they are fairly simple to follow: mechanical friction corresponds with resistance. This is evident because both are responsible for the dissipation of energy in their respective systems.

---

* *216-18 40th Ave., Bayside, N. Y.*

Mass corresponds with inductance: the mass or weight of a moving object, which is called its inertia, tends to continue its course of movement until a force is applied to change it. Force is needed to start the movement, and again to stop it. In electrical circuits, using the analogy, this is the characteristic of inductance where the current tends to be steady and has to have a voltage applied in order to change it.

A compliance corresponds with a capacitance: application of a force produces a deflection or displacement in the compliance that will remain until the force is removed, the same as application of a voltage produces a charge on the capacitance. When the pressure on a compliance is changed, the mechanical device moves. When a voltage on the capacitance is changed, current flows in or out of it.

In an electrical circuit a transformer changes a combination of high voltage with low current to a lower voltage with higher current, or vice versa. It changes the relationship between voltage and current at which energy is transmitted. In mechanics a lever enables a small force with a large movement to produce a large force with a small movement or vice versa, thus performing a function in mechanical circuitry similar to a transformer in electrical circuitry.

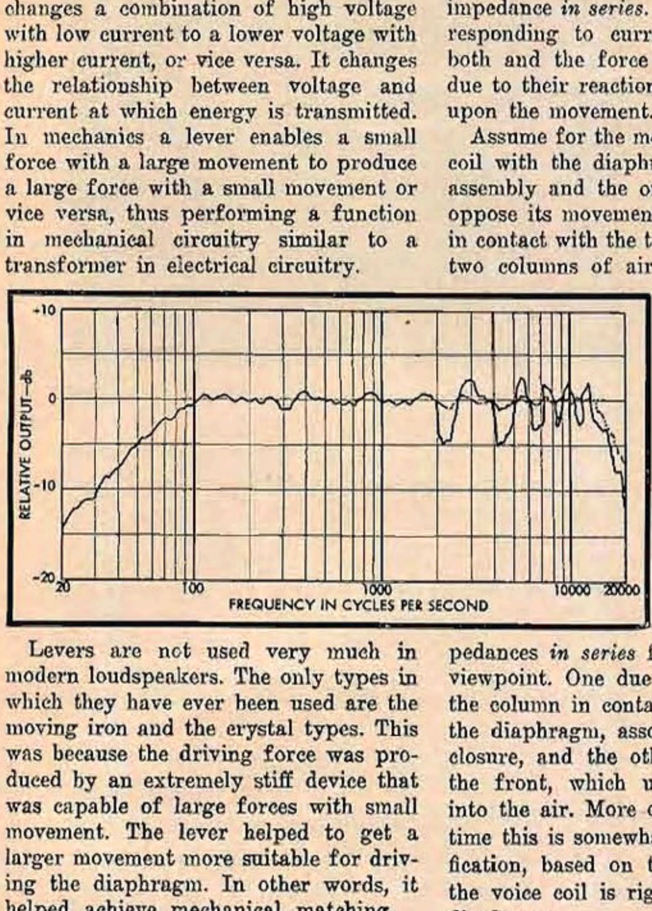

Fig. 2. The effect of the transverse waves in the diaphragm on the frequency response: the solid curve represents incorrect termination, while the dotted one shows what correct termination in the surround does.

Levers are not used very much in modern loudspeakers. The only types in which they have ever been used are the moving iron and the crystal types. This was because the driving force was produced by an extremely stiff device that was capable of large forces with small movement. The lever helped to get a larger movement more suitable for driving the diaphragm. In other words, it helped achieve mechanical matching.

The reason why levers are avoided in the mechanical design of loudspeakers is that they are not so easy to design with a wide frequency response as are electrical transformers. A lever to operate equally well at all frequencies from 20 to 20,000 cps is a very difficult requirement to meet.

Electromechanical Part

Now let's see how the electromechanical analogy helps us in understanding the behavior of a loudspeaker. We have a driving force from the voice coil, the object of which is to produce a movement of the diaphragm for the purpose of transmitting the energy to the air on a uniform voltage-pressure basis. To figure out an equivalent electrical circuit for the mechanical action, we have to think about what opposes the movement due to the force supplied by the voice coil.

This is equivalent to the impedance presented to an electrical source voltage. The current accepted by the impedance is analogous to movement: the lower the impedance, the greater the current; the lower the mechanical impedance, the greater the movement produced by a given force. So if forces due to two kinds of mechanical reaction are both combining to oppose movement of the voice coil, these two forces must be considered as equivalent to components of impedance *in series*. The movement, corresponding to current, is common to both and the force that they produce, due to their reaction, will be dependent upon the movement.

Assume for the moment that the voice coil with the diaphragm forms a rigid assembly and the only forces that will oppose its movement are due to the air in contact with the two sides of it. These two columns of air reflect as two impedances *in series* from the mechanical viewpoint. One due to the behavior of the column in contact with the back of the diaphragm, associated with the enclosure, and the other in contact with the front, which usually radiates out into the air. More of this anon; meantime this is somewhat of an oversimplification, based on the assumption that the voice coil is rigidly coupled to the diaphragm.

This is not quite true. It is coupled by material having certain mechanical properties and that is what we want to consider immediately. The diaphragm is not completely rigid, so the center part, attached to the voice coil, can move in a manner somewhat different from the outer periphery and the various other parts of the diaphragm.

The easiest way to think of the transmission of movement from the voice coil, applied at the inner periphery of a loudspeaker diaphragm, to the outer periphery is in terms of a mechanical transmission line. The force applied is approximately transverse. This is illustrated in *Fig.* 1. In our ideal conception the diaphragm should move back and forth as an entity with the voice coil, but due to its mechanical compliance or stiffness and its effective distributed mass, in conjunction with the effect of air in contact with its surfaces, it tends to behave like a length of string or rope when one end of it is waved to and fro sideways. The essential difference from this analogy is that the length of string is *relatively* flexible, while the diaphragm is *relatively* rigid. However, the same kind of effect occurs to a limited extent.

The transmission velocity or speed at which the wave travels outward from the voice coil is similar to—or not *very* different from—the speed of sound in air which, in *very* round figures, is 1000 feet per second. Using this figure, a wavelength at 1000 cps occupies one foot, which gives us a useful basis for considering when this transmission effect could set up interference patterns.

At high frequencies, where the wavelength is shorter, the distance from the voice coil to the periphery of the diaphragm becomes several wavelengths of transversely propagated wave, so the diaphragm can break up into patterns due to the reflected wave (if any reflection occurs). This is the cause of the irregularity in frequency response toward the top end of the frequency range of most single unit loudspeakers.

Much of this can be smoothed out by careful attention to the compliance of the diaphragm surround—the crinkled part that allows it to move back and forth freely at the periphery. Use of a suitable impregnating compound possessing an appropriate combination of compliance and viscosity, provides a terminating impedance in the mechanical material of the surround which prevents reflection and hence avoids the break-up effect. This method of treatment will do much toward flattening the upper end of the loudspeaker frequency response. *Figure* 2 shows this.

A difficulty arises in the fact that the properties of most of these impregnating compounds change with aging, and hence the upper frequency response deteriorates as the diaphragm gets older.

Attention to the compliance of the spider or centering device attached to the inner periphery of the diaphragm will also assist in controlling the movement, although this is strictly at the "sending end" of the transmission line and appears merely as a series element in the driving force.

If the loudspeaker is driven from an amplifier with a high damping factor,

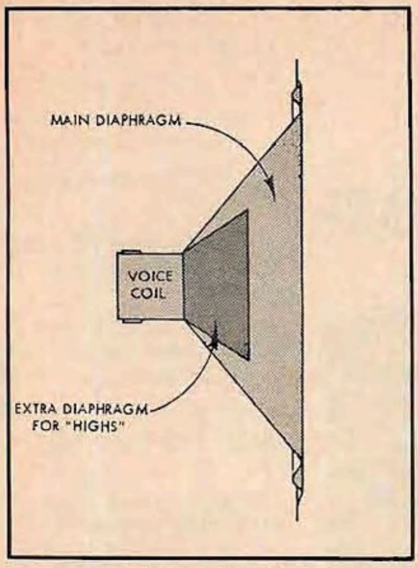

Fig. 3. One kind of modification to a loudspeaker diaphragm that is designed to augment the reproduction of higher frequencies.

the voice coil will offer fairly high mechanical resistance to being moved by the diaphragm, and hence the electrical effect can be considered as equivalent to a mechanical high impedance source. The effect of viscosity in the spider will merely add to the effective mechanical source resistance.

Nonlinear Distortion

A more important feature of the spider is that its compliance should have linear properties. The restoring force should always be proportional to the deflection, otherwise it will distort the movement of the diaphragm.

There are two possible causes of nonlinear distortion in a loudspeaker:

(1) due to nonlinearity of the driving force, because the magnetic flux in the air gap is nonuniform. This will mean that the same current in the voice coil will not produce the same force at all positions in the gap, and consequently the driving force from the voice coil will not be uniform with the electrical currents supplied to it.

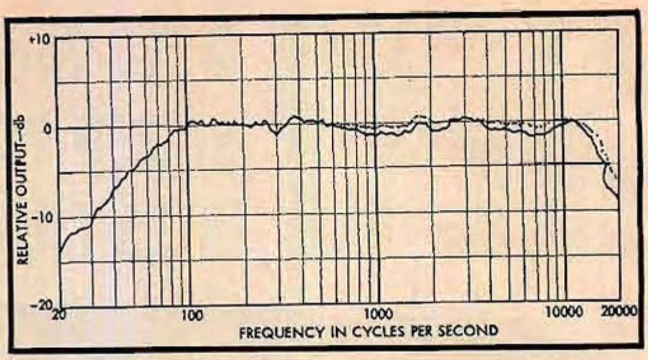

Fig. 5. The effect of the diaphragm arrangement of *Fig.* 4: the solid curve shows the fluctuation caused by the transition when successive rings become inactive; the dotted line shows what might be expected if the transition were continuous.

(2) due to nonlinearity of the opposition to movement, because the restoring force is not linearly proportional to the deflection of the diahragm. This means that the movement of the diaphragm will not be uniform with the force applied to it.

Special Diaphragms

What is the effect of a small diaphragm attached to the same voice coil inside the larger one, as at *Fig.* 3?. From the mechanical standpoint this additional diaphragm is not likely to produce any irregularities. It will vibrate as an entity at the upper frequencies, and so will not behave as a transmission line, like the large one. For this reason it will prove more effective for the radiation of the higher frequencies in the band. As regards its effect on uniformity of movement at different frequencies, it should have quite a linear performance because it exerts a uniform additional opposition force at the voice coil. Its principal effect will be that of increased effective mass at the voice coil.

If it were attached at some point between the center and periphery of the large diaphragm there would be a time delay which would cause reflection defects and irregularities in the frequency response of the movement against driving force. But being attached directly to the voice coil former it should not produce this kind of effect. However, it may produce irregularities due to acoustic effects in the air adjacent to the two diaphragms. This must be considered separately.

There is another way of dealing with this problem which consists of introducing corrugations into the cone at one or more points other than the periphery. This is then analogous to a lump-loaded transmission line, in which the inductance and capacitance comes in lumps instead of being continuously distributed. This is illustrated at *Fig.* 4.

There is a difference between this arrangement and a transmission line: in this arrangement, energy can be radiated by movement, represented by current, in any part of the diaphragm; this is shown by resistance elements; in a transmission line, we usually consider only the energy reaching the far end, which in this case is wasted in the surround.

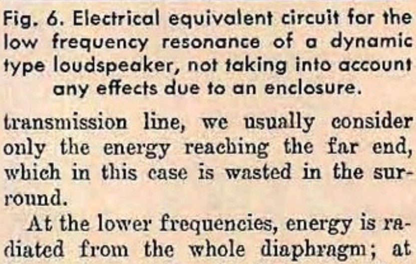

Fig. 6. Electrical equivalent circuit for the low frequency resonance of a dynamic type loudspeaker, not taking into account any effects due to an enclosure.

At the lower frequencies, energy is radiated from the whole diaphragm; at higher frequencies, the low-pass action of the line elements prevents transmission to the outer rings and all the energy is radiated from the inner section(s).

The effect of this system is to produce a very gradual fluctuation in efficiency, represented in the response at *Fig.* 5. Compared with *Fig.* 2, this is an improvement, but the uniform diaphragm correctly damped *can* be better.

To summarize then, the mechanical part of the loudspeaker has two principal properties that contribute to its frequency response. These are:

(1) A major resonance, due to the mass of the whole of the diaphragm and voice coil, together with a quantity of air that can be considered as moving with it, in conjunction with the compliance of the surround and spider (neglecting for the moment the compliance of the air in contact with the diaphragm).

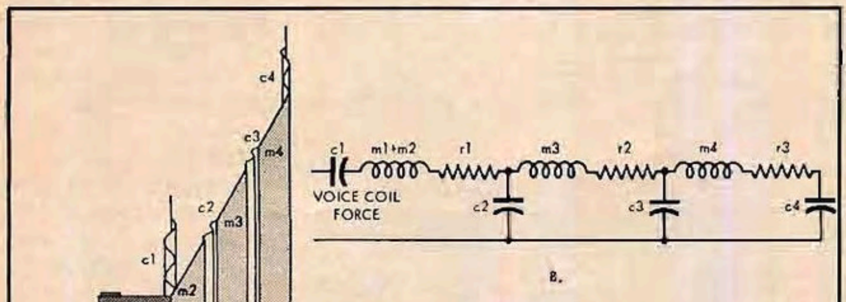

Fig. 4. Another method of improving the performance of a large diaphragm: (a) a physical cross-section through the voice coil and diaphragm assembly; (b) electrical equivalent circuit.

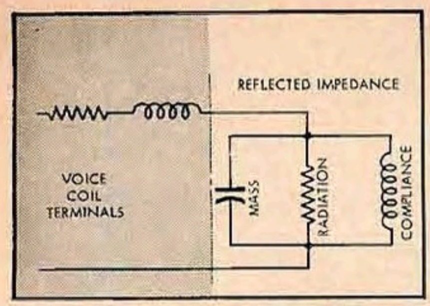

Fig. 7. The electrical impedance diagram, showing the components reflected into the electrical circuit due to the mechanical resonance represented in *Fig.* 6.

These two major lumped components produce a low frequency resonance, the equivalent circuit of which is shown at *Fig.* 6.

(2) At the high frequency end of the response the diaphragm tends to behave as a transmission line, causing some degree of breakup. The continuous type of transmission line cannot readily be shown as an equivalent circuit, because it consists of an infinitely distributed mass and compliance, the configuration of which is similar to that of a low-pass filter as at *Fig.* 4 but when the number of inductances and capacitances is infinitely large, and each is infinitely small, the arrangement does not produce a low-pass characteristic, but a progressive phase delay which can become several cycles by the time the terminating point, which is the periphery of the diaphragm, is reached.

Irregularities at this end of the response can be minimized either by ensuring that the equivalent continuous transmission line is correctly terminated, by attention to the properties of the surround material or by the alternative lumped arrangement of *Fig.* 4.

Electromechanical Coupling

The analogy circuit of *Fig.* 6 shows the resonant circuit as a series one because this is the way the mechanical behavior of the circuit works out, but the electrical characteristics as measured at the voice-coil terminals will also be influenced by the resonance. Because the diaphragm movement is greater at this resonant frequency there will be an increased back e.m.f. in the voice coil which will represent an increased dynamic impedance. From this it will be found that the electrical equivalent must take the form shown in *Fig.* 7.

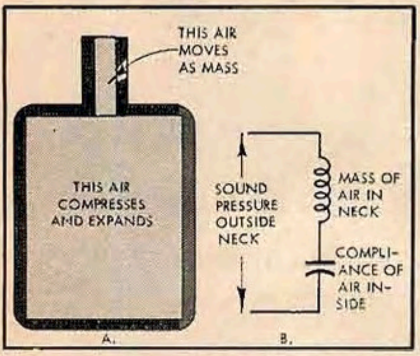

Fig. 8. A narrow necked bottle, or Helmholtz resonator, illustrates the basic acoustical analogy: (a) a cross-section through the bottle; (b) electrical equivalent circuit for same.

This shows that the mechanical analogy series circuit transfers through the electromechanical action to become an effective parallel resonant circuit. The magnitude of the reactance values in this electrical resonant circuit will depend on the efficiency of the electromechanical transfer.

Similarly, looking at the mechanical arrangement the effectiveness of the electrical damping, provided by the voice coil with a high damping factor amplifier, will also depend upon the electromechanical efficiency. This means the effectiveness of any attempt at damping by adjusting the amplifier damping factor is definitely limited.

Mechanical-Acoustical Coupling

We have discussed the factors controlling the relationship between the electrical driving force and the diaphragm vibration. The next thing is to transfer the diaphragm vibration to the air.

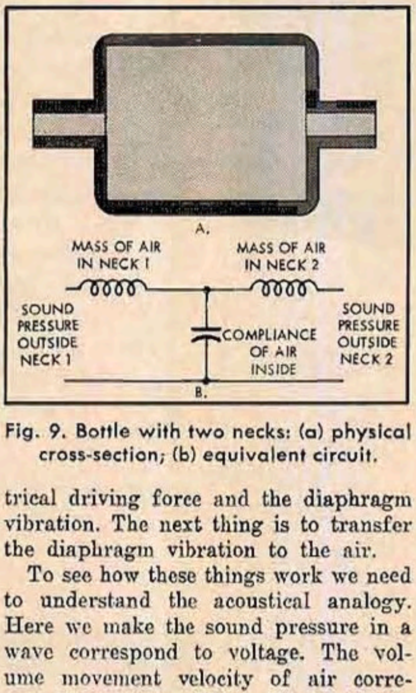

Fig. 9. Bottle with two necks: (a) physical cross-section; (b) equivalent circuit.

To see how these things work we need to understand the acoustical analogy. Here we make the sound pressure in a wave correspond to voltage. The volume movement velocity of air corresponds to current. The volume displacement will correspond to charge.

Acoustical resistance due to the viscosity of the air when particles have to move over some surface or one another, is equivalent to resistance. The mass, or inertia, of the air in movement is equivalent to inductance; while the compliance, or compressibility of the air, is equivalent to capacitance.

These last two are the most important ones to understand and particularly is it important to grasp how they fit together in an equivalent circuit. Consider a Helmholtz resonator—or just a bottle with a narrow neck—as at *Fig.* 8.

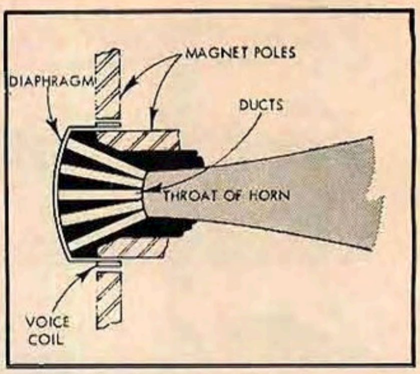

Fig. 10. Cross-section of simple acoustical transformer, applied to a horn type loudspeaker unit.

The air inside the bottle contributes to the resonant frequency excited at the mouth merely because of its compressibility. This air does not move appreciably—it just compresses and expands alternately. In the neck of the bottle, on the other hand, the air oscillates to and fro, and hence the important feature about this "piece" of air is its mass. So the resonant frequency is determined by considering the effective compliance of the volume of air inside the bottle, in conjunction with the effective mass of the air that goes to and fro in the neck.

As a very small sound pressure at resonant frequency will cause a big volume movement of air in the neck of the bottle, the equivalent circuit is that shown at *Fig.* 8b, it is a series resonant circuit.

Now suppose we have a container with an opening at both ends and a volume of air enclosed as at *Fig.* 9. A sound pressure at one opening will have immediately next to it the opposing force of the mass of air in the neck which looks like an inductance. At the other end of this neck is the volume of air the compliance of which looks like a capacitance. As the pressure of all the air in the bottle is approximately uniform throughout, the mass of air at the other end of the space has the same pressure at its input side as has the mass of air at the first neck on the inside of the bottle. This whole volume is at constant pressure at any instant in time.

So the inside of both necks must be

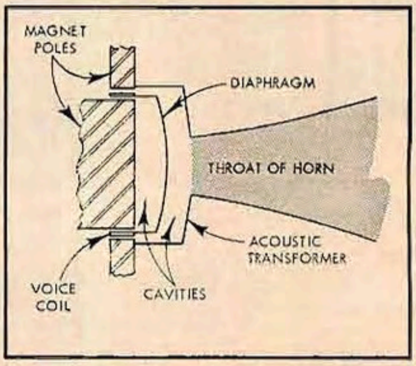

Fig. 11. An improved type of acoustical transformer.

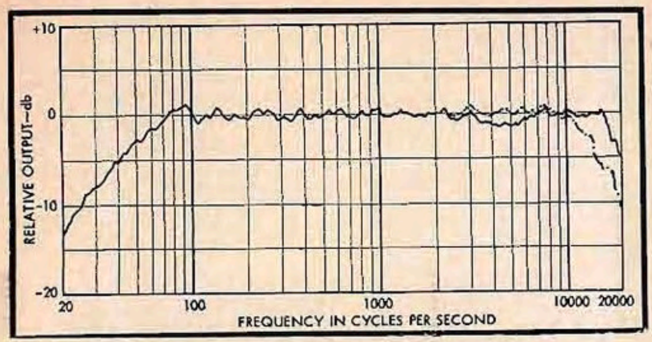

Fig. 12. The acoustical effect of the diaphragm shown in *Fig.* 3: the solid curve shows the response produced, the dotted one the theoretical effect of eliminating the acoustic absorption. The dot-dash section represents removing the small diaphragm.

represented, in an equivalent or analogy circuit, by the same electrical point in the network. This means that the analogy circuit of the whole arrangement looks like a low-pass "T" filter configuration as at B in *Fig.* 9.

From the acoustic response viewpoint it would not matter appreciably whether the two necks were located at opposite ends of the space, or next to one another, or in any other position, because the pressure inside will vary without appreciable volume movement of the air. In practice there will be some slight difference due to the fact that air does move to a small extent inside the space. There is not a sudden transition from air that moves to air that compresses. There is a small region where the air does both.

Propagation

A sound wave propagated through air in the form of a plane wave—that is, where the frontal area of the wave is not expanding—presents a transmission impedance that is characteristic, because the pressure and velocity get passed on unchanged, except for a slight attenuation due to the viscosity of the air.

A continuous exponential horn above its cut-off frequency looks like a resistance too. This is because the wave propagates down the expansion and produces a gradual transition, from high-pressure high-volume movement at the throat or neck, to a low-pressure low-volume movement at the flare end. If the rate of transition from one end to the other is correct, the ratio between the pressure and particle velocity at all points down the development will be uniform, which means that the horn development looks like a constant resistance.

A transition in area, from small to large, or large to small, through a relatively short distance, behaves as an acoustical transformer. In a narrow neck, for instance, a high pressure with a given volume displacement, on reaching a sudden expansion encounters a sudden freedom of movement which causes the pressure to drop. At the same time the volume movement is allowed to increase at this point. So the step in area exchanges one ratio of pressure to volume movement for another ratio, like a transformer changes the ratio of voltage and current from one impedance to another.

When sound is radiated outward freely, the air near the source moves more, for the pressure fluctuation involved, than the air further out. This means it has an inductive component to its impedance. In fact a large proportion of the inductance in *Fig.* 6 is due to radiation. This is why the resonance of this kind of speaker has to be at the low-frequency end. That way, a constant voltage, representing constant sound pressure, is delivered to the inductance-resistance combination. This principle is termed mass-controlling diaphragm movement, because the principal reactance opposing movement is mass, throughout the audio spectrum.

Application

All of these simple acoustic devices occur in loudspeaker design somewhere or other. The acoustic transformer is utilized in horn-type loudspeakers to match the diaphragm movement to the throat of the horn. Usually the diaphragm is larger than the throat of the horn as shown at *Fig.* 10. The air movement picked up from the diaphragm has to be compressed down to the size of the throat.

If any cavity is enclosed *between* the diaphragm and the throat, this will behave as a capacitance and cause a high-frequency roll-off by absorption. So, to minimize the volume of such cavity a good method adopted is the use of a number of channels to pick off the pressure uniformly from different parts of the diaphragm and conduct the column of air into a single throat, as shown in *Fig.* 11. This makes an efficient transformer up to quite high frequencies, whereas the abrupt change in size loses efficiency at the high frequencies due to the capacitance effect of the cavity which it produces.

Another example of cavity effect can occur with the diaphragm arrangement shown in *Fig.* 3. As it is not a deep cavity—nor does it have a narrow mouth—its effect will not be very pronounced, but it will result in a slight absorption over a fairly wide range of frequencies, as suggested in *Fig.* 12.

Enclosures

But the thing which is of greater interest in loudspeaker design is the construction used for the lower frequencies—enclosures of various types. The bass-reflex enclosure operates in a manner similar to the container with a neck at both ends, the diaphragm being placed in one neck as the driving point, while the other neck is the vent of the enclosure.

Figure 13 shows the simplified analogy diagram for a bass-reflex enclosure, assuming that the volume is pure capacitance and the port pure inductance. In practice these assumptions are not quite true, but they do not seriously invalidate the representation. This circuit shows how the enclosure can damp the basic resonance of the speaker by having the combined dynamic impedance consisting of the port, the volume of the enclosure, and the radiation resistance, as a shunt tuned circuit, damp the series tuned circuit, consisting of front radiation resistance with the effective mass and compliance of the diaphragm and its associated components. It is possible for these two to be exactly complementary so as to damp out the mechanical resonance of the diaphragm system.

If this was all that a bass-reflex enclosure did it would merely pull down

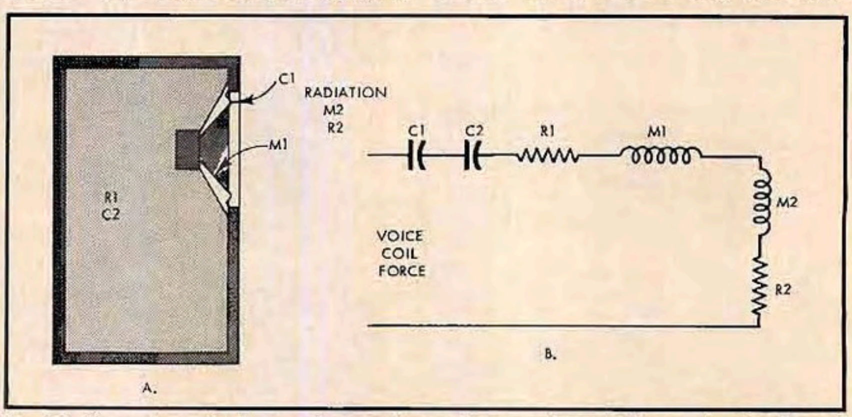

Fig. 13. The action of a bass reflex enclosure is somewhat similar to the bottle with two necks of *Fig.* 9: at (a) a cross-section through a bass reflex enclosure; (b) the equivalent circuit.

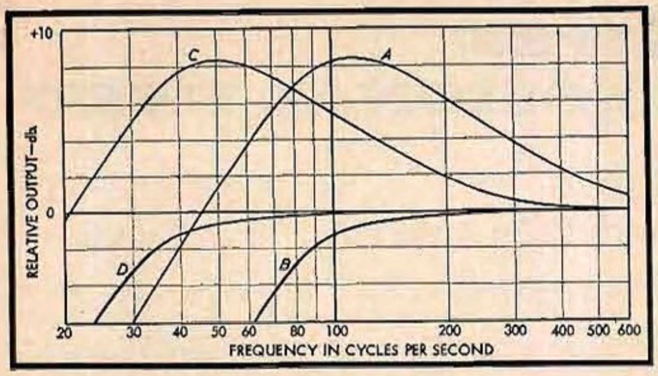

Fig. 14. Action of a bass-reflex enclosure. *A* is the curve of the unit without an enclosure; *B* represents the effect of the enclosure in pulling down the peak.

the peak at the low-frequency end of the loudspeaker's response curve without extending the frequency range any lower down, as in *Fig*. 14. But the additional mass (inductance) of the port, lowers the resonant frequency, without having to make the diaphragm mass too great for good operation at higher frequencies.

At the mutual resonance of the system the radiation from both the diaphragm and the port is in phase. This can be appreciated best by thinking of the resonance of the bottle with two necks. Although the energy is excited in one neck, due to the fact that the air inside the bottle compresses and expands as an entity, the air flow in the two necks will be almost exactly in phase, there being just a slight lead in the one providing the drive. This is in fact what happens with a vented enclosure.

In the case of the latest type of low-frequency reproducer the *mechanical* construction is made with a very large compliance, so that the natural resonance is extremely low (this is when no enclosure is used). Then the size of the enclosure, which is sealed and not vented, is adjusted so that the over-all compliance of the diaphragm and that of the enclosure produces a resonant frequency at the extreme bottom end of the audio spectrum—where it should be. The interior of the cabinet is treated to provide an acoustic resistance effect that damps the resonance. An analogy circuit is shown in *Fig*. 15. In this way an extremely smooth low-frequency response can be obtained.

This is just one approach to the problem and it involves the use of one of the newer special type loudspeaker units, with extremely high compliance, so that the diaphragm appears to be very floppy. These units can only be used in such enclosures, otherwise they would rapidly damage themselves.

Other approaches to the low-frequency problem use all kinds of enclosures with labyrinths and folded horns. In the case of a folded horn, the objective is to maintain a correct exponential rate of expansion during the folding of the expanding channel in different directions. This way effective transmission is achieved without the need for the excessive length necessary in a straight horn development.

Some units use a folded horn development from one side of the diaphragm, usually the rear, with a built-in acoustic low-pass filter, using a large cavity for the capacitance and a slot for the beginning part of the horn as an inductance. This makes the horn useful for only a comparatively narrow range of frequencies between its own natural cutoff, which is very low, and the acoustic low-pass filter cutoff. The entire arrangement provides loading for the rear of the diaphragm in this frequency range. Above the low-pass cutoff frequency the diaphragm loses its rear loading, allowing it to radiate from the front side. So the result is, that frequencies above the chosen crossover, which may be, say, 200 cps, are radiated directly from the front of the diaphragm, while frequencies from 20 to 200 cps are radiated via the acoustic horn. This is illustrated at *Fig*. 16. In this case, the length of the horn and the position of its mouth must be adjusted so that the radiation is in phase from back and front of the diaphragm at the chosen crossover frequency. This is just an example.

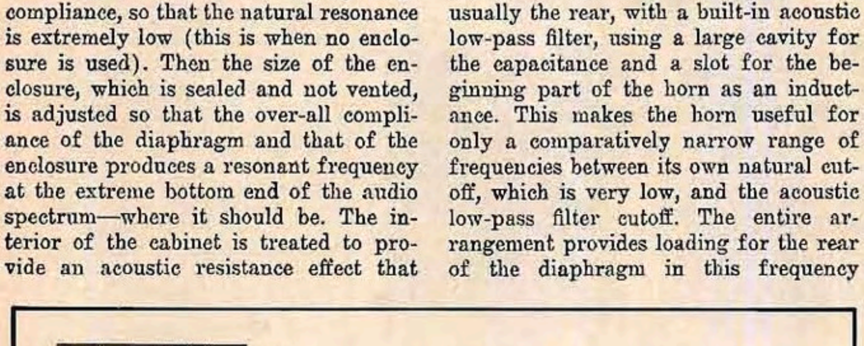

Fig. 15. A comparatively new method of handling low-frequency response: at (A) a cross-section; at (B) an analogy diagram. C_1 is several times as great as C_2, so that the latter becomes the controlling compliance.

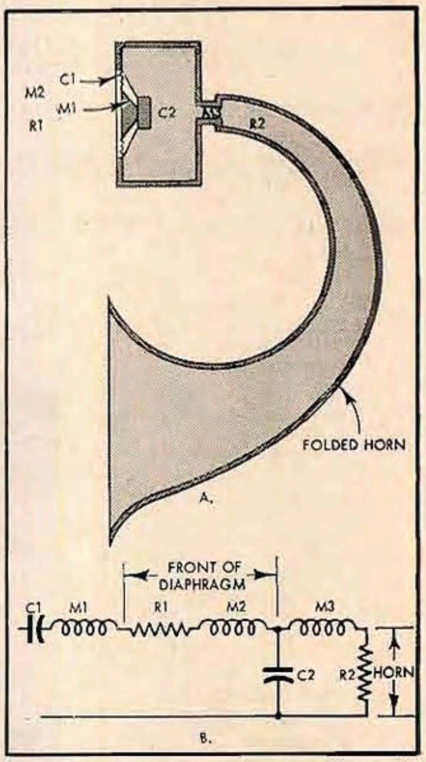

Fig. 16. Another kind of low-frequency system, using a folded horn and acoustic low-pass filter: (A) a simplified physical diagram (in practice the horn is folded, to save space); (B) analogy diagram. The value of r_2 is much greater than r_1, so that for frequencies below the acoustic low-pass filter (c_2, m_3) rolloff the major radiation is from the horn. Above this frequency r_2 ceases to be coupled, so the major radiation is from r_1, m_2. The physical disposition of the horn mouth and diaphragm must be such that, at the chosen crossover, the energy from both emerges in phase.

To give details of every enclosure system on the market would take a separate article to describe each and show how its design was developed. The foregoing provides a basis so that anyone interested can figure out how any particular loudspeaker system has been engineered to get the desired results. This knowledge will then prove helpful in judging to what extent the design is successful in achieving its objective. Æ