

Principles and problems in loudspeaker design

If you ever wanted to know, in a practical fashion, what is involved in the design of a loudspeaker system, then here's a down-to-earth insight — ending in a real design.

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MORE MONEY can be saved by the construction of a pair of loudspeakers than any other single component of the hi-fi system. Unfortunately, they are also the most important hi-fi component! Unless the turntable or amplifier is particularly poor, the loudspeaker will undoubtedly determine the overall sound of the system. For this reason it is disappointing there are so few really good kit loudspeakers.

The fact that a "correct" loudspeaker doesn't exist is to be expected, since the principles of loudspeaker operation are enormously complex. Every loudspeaker model makes certain assumptions to simplify the mathematics and to make the model manageable. If these assumptions are overdone the model rapidly loses relevance, becoming incapable of making worthwhile predictions about the *real* loudspeaker. While it is true that a detailed understanding of

loudspeaker operation is not necessary to enable a kit loudspeaker to be built, some understanding will enable the optimum to be obtained from the loudspeaker and is essential for those brave experimenters who would like to get involved in modifying the loudspeaker drivers. When designing a loudspeaker it is necessary to understand the mechanism of operation of the drivers. Only then can the best choice of driver, enclosure type and crossover be established. Although loudspeaker design is as much an art as it is a science, the loudspeaker that has been created with a motley assortment of drivers placed in a box with some "general purpose crossover" is more likely to sound like a dropped saucepan than a good loudspeaker!

The most common loudspeaker consists of several moving-coil direct-radiating drivers mounted in an enclosure. These cover different frequency bands within the audio

spectrum. A crossover is used to separate these frequency bands and feed them to the appropriate driver.

If the drivers used had perfectly flat frequency responses, were constant eight ohm loads with infinite power handling, and the crossovers represented lossless transfer characteristics with no untoward interactions with the drivers, and if nature did not object to the reproduction of low frequencies in confined volumes (i.e. if the speed of sound was one tenth the speed it is) loudspeaker design would be a simple matter.

Most of these problems can be summarised with one word . . . inertia. This is that property of nature whereby things resist change. We can't really complain too strongly about inertia since it is responsible for much of the order that exists in the universe. Nevertheless, in loudspeaker design it causes real problems. The signal voltage from the power amp, the magnetic field

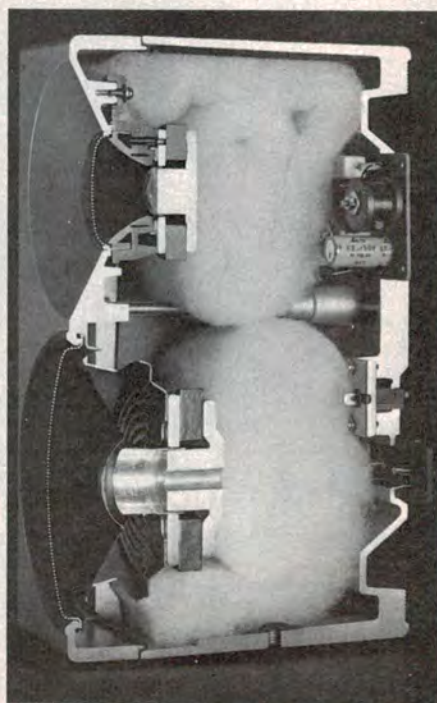
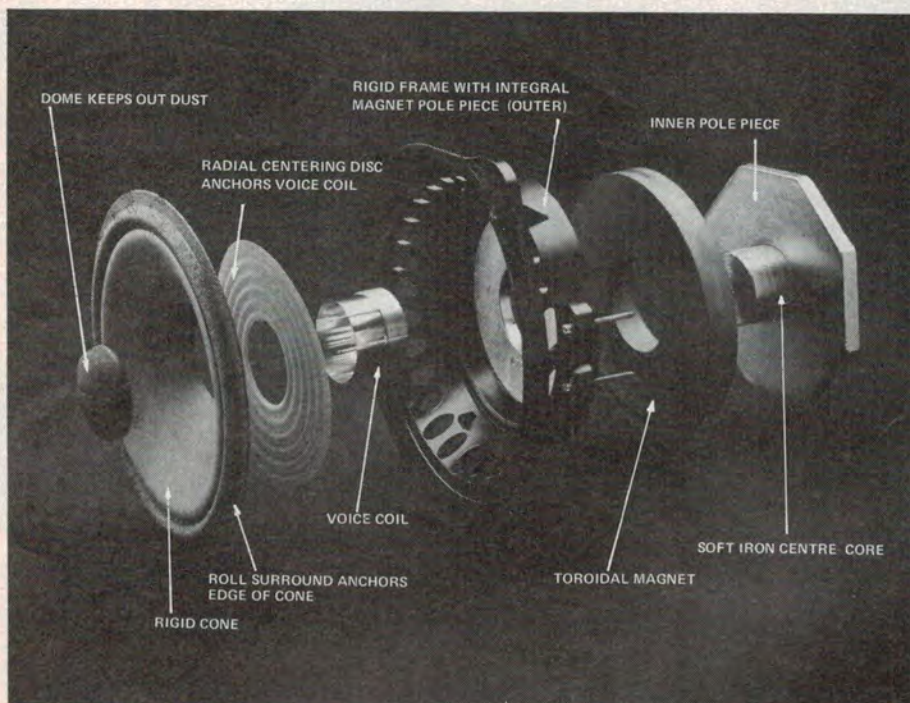


Figure 1. An exploded view of a moving-coil loudspeaker showing the various components in its construction. Compare this with the cutaway view of a speaker at right (Pic: courtesy Bose).

Cutaway view of a speaker unit showing internal construction (Pic: National).

around the voice coil, the movement of the coil and loudspeaker cone, all resist change. Since the objective of loudspeaker design is to convert an electrical signal into its exact acoustic counterpart, these sources of inertia cause errors resulting in distortion. The effects of inertia don't stop at just slowing down the system. The resistance to change of motion by the cone for example results in some parts of the cone moving before others. Sound waves start to travel along the cone itself, travelling radially out from the voice coil. Depending on the nature of the flexible surround between the cone and the chassis this sound wave will be partially reflected back down the cone. This causes constructive and destructive interference with the original sound wave propagating up the cone resulting in colouration. Clearly, this is not something the home constructor can do much about, since it depends on the manufacture of the particular driver concerned, but it indicates the sorts of problems that will be encountered.

The moving-coil direct-radiating speaker

The vast majority of drivers used in loudspeakers are of the moving coil type and as such all operate in a very similar way. Figure 1 shows a typical moving coil loudspeaker. Signal voltages from the power amp give rise to signal currents that flow through the voice coil. This is simply a coil of wire wound on a hollow circular former. In normal 8 ohm drivers the dc resistance of the voice coil is around 8 ohms, but the driver will only represent this resistance to the power amp at one specific frequency, the actual impedance of the driver varying widely as the frequency is varied (see Figure 2). A given signal voltage level will therefore produce different signal currents for different frequencies. The signal current causes a varying magnetic field to be produced around the voice coil. This field interacts with an intense magnetic field from the drivers' pole piece and magnet assembly causing a force to be exerted on the voice coil and loudspeaker cone.

As the cone moves it will compress or rarify the air immediately in front of it, creating an area of either increased or decreased pressure. These pressure variations comprise a sound wave that travels from the driver to our ears.

The electrical impedance of the driver is caused by several phenomena each one dominating in a specific frequency band. One of the most significant mechanisms is the back EMF (EMF stands for electromotive force, i.e.: voltage) of the driver. The move-

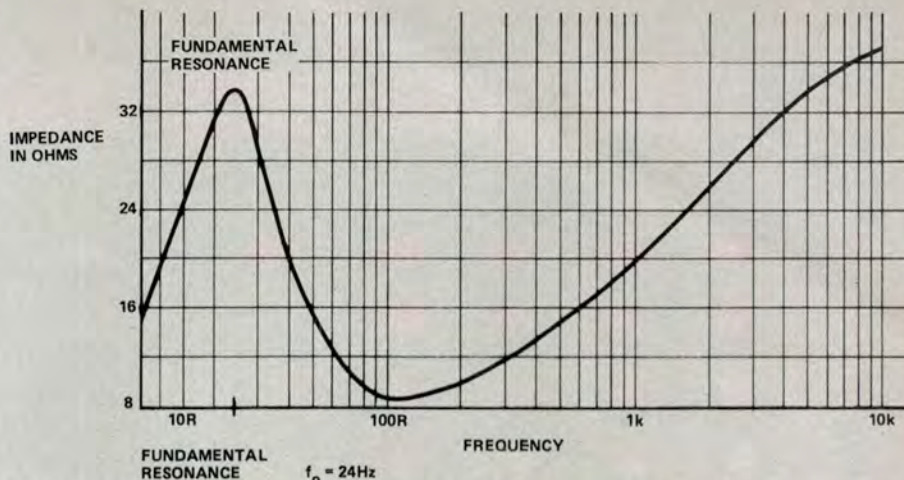


Figure 2. Typical impedance versus frequency characteristics of a moving-coil loudspeaker

ment of the voice coil in the magnetic field acts as a generator causing a current to flow in the voice coil. This current is of opposite polarity to the applied signal current (another natural application of the principle of inertia) causing decreased current flow in the voice coil for a given signal voltage. This is seen by the amplifier as an increase in the drivers' impedance.

EMF is given by the simple equation:

EQUATION 1

$e = B1v$ where 'e' is the back EMF in volts
'B' is the magnetic flux
'1' is the length of wire in the magnetic field
and 'v' is the velocity of the cone

Since the magnetic flux and the length of wire in the magnetic field can be considered as constants, the equation shows that the amount of EMF generated is directly proportional to the velocity of the cone.

So the electrical impedance is a secondary phenomenon, is certainly not constant, and does not relate directly to the radiated acoustic power. The amount of back EMF will be determined by the velocity of the cone, and this is a function of nearly every major parameter of the loudspeaker box.

The force exerted by the voice coil on the loudspeaker cone is given by the equation:

EQUATION 2

$F = Bil$ where 'F' = force on the voice coil
'B' = Magnetic field intensity
'i' = current in the voice coil
and 'l' = length of wire in the field

Again, regarding 'B' and 'l' as constants, the equation shows that it

is current and not voltage that determines the force on the voice coil. Since the voltage contains the signal information from the power amp, it would be necessary for a perfectly linear relationship to exist between applied voltage and resulting signal current flow if a distortionless signal is to be produced. The impedance would have to be a constant and this is not the case. Fortunately the movement of the cone is not directly related to the current in the voice coil in the simple way shown above or the frequency response of a loudspeaker would simply be the inverse of its rather lumpy impedance curve.

In order to understand the parameters that determine the acoustic power actually radiated, it is necessary to look at the sources of mechanical rather than electrical impedance.

Converting energy

In the operation of a moving-coil direct-radiating driver there are really two energy conversions going on simultaneously. First the electrical energy is converted into mechanical energy of the voice coil and cone. Secondly this mechanical energy is converted into acoustic energy by the interaction of the cone with the neighbouring air molecules. Both these conversions must be accurate if the final result is to be a low distortion replica of the input voltage waveform.

The laws that apply to mechanical and acoustic forces are directly analogous to those of electrical forces and for this reason we can represent what happens in any acoustic or mechanical problem by a circuit diagram. In mechanics and acoustics there are direct and simple relationships like Ohm's law in electronics. It is only the complex arrangement of mechanical or acoustic circuit elements that makes the picture look complicated.

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FIGURE 3A

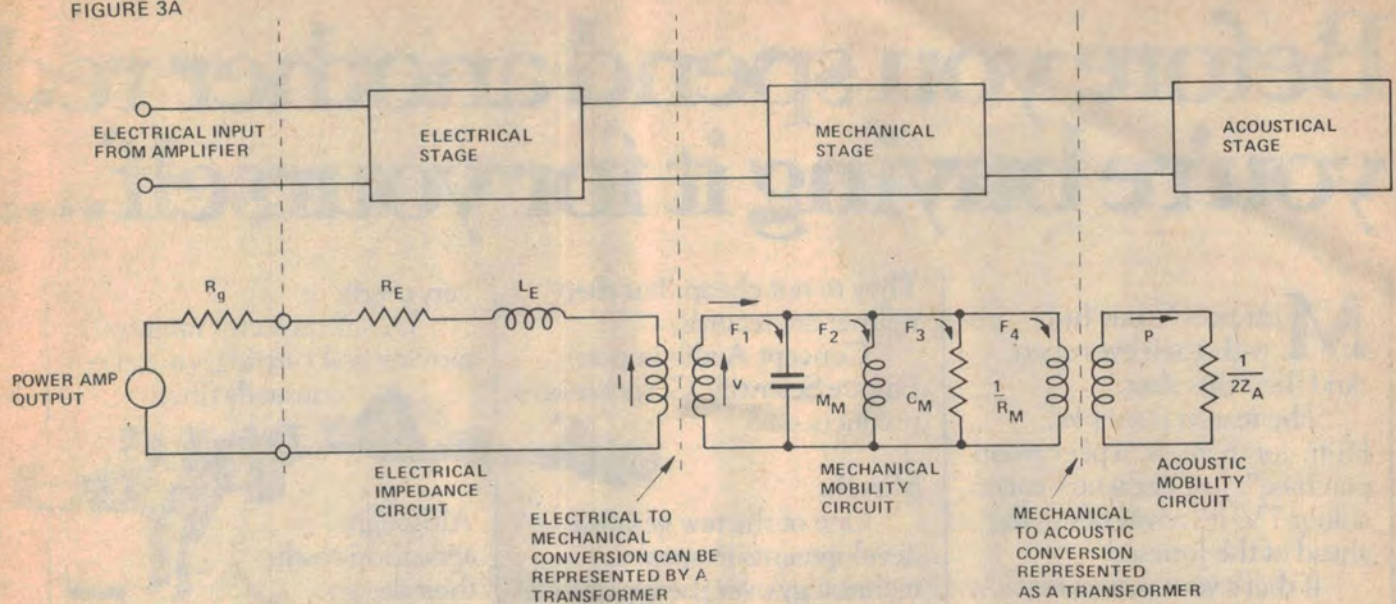


FIGURE 3B

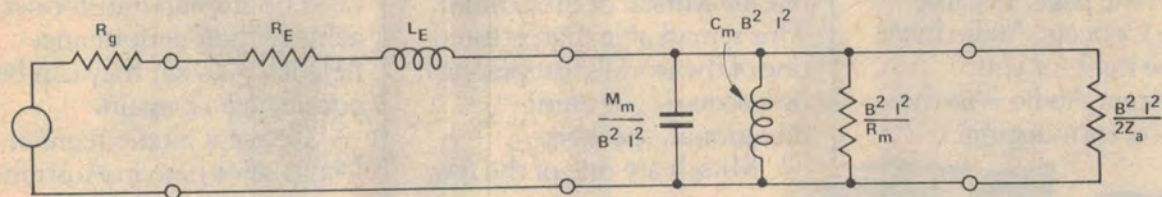


Figure 3. Equivalent circuit for a typical moving-coil direct-radiating driver mounted in an infinite baffle.

Just as an electronic circuit can look complex, but can be broken down into smaller and simpler circuits, so too can any acoustic or mechanical problem.

We can represent a complete picture of a dynamic loudspeaker by a circuit diagram showing electrical/mechanical and mechanical/acoustic conversions (see Figure 3a).

The power amplifier is connected via a net series resistance R_g , to the terminals of the loudspeakers. This resistance is the result of the internal resistance of the power amplifier and connecting cables. Since the voice coil is a coil of wire it possesses both inductance and resistance. The applied electrical signal sees these two in series and we represent this by the resistance R_E and the inductance L_E . The "E" simply implies that these are electrical quantities. Current flowing in the voice coil gives rise to the magnetic field that causes mechanical movement of the voice coil and cone assembly. This conversion of electrical to mechanical energy is represented in the circuit diagram as a transformer. Voltage across the primary is represented by the letter "e" and gives rise to velocity 'v', of the voice coil and cone assembly at the secondary of the transformer.

The total force applied by the voice coil ("F") is shown in the mechanical stage as "flowing" through the "wires" just as current would flow through the wires of an electrical circuit. This force sees three mechanical components in parallel, a mechanical capacitance M_M , a mechanical inductance C_M and a mechanical resistance, $1/R_M$. The mechanical capacitance M_M is caused by the mass of the cone. As frequency rises inertia comes into play and it becomes increasingly difficult for the cone to follow the input voltage waveform. The mass of the cone causes a frequency response roll-off at higher frequencies. This could be represented either by an inductance in series or a capacitance in parallel with the load. In Figure 3 this has been shown as the parallel capacitance, M_M .

A loudspeaker cone has a certain springiness, due to the nature of the cone's suspension and the overall construction of the particular driver. We specify this springiness by a spring constant, which is simply a number, represented by the letter 'k'. In loudspeaker technology we more often use the term compliance rather than spring constant. Compliance C_M , is defined as:

$$C_M = \frac{1}{k} \quad \text{where 'k' is the spring constant.}$$

The compliance impedes large movement of the cone. Since bass frequencies require longer cone excursions the compliance of the driver causes a frequency response that falls as frequency decreases. This can be represented as a capacitance in series or an inductance in parallel with the load. In Figure 3 the compliance C_M is represented as an inductor in parallel with the load.

The remaining term in the mechanical part of the loudspeaker circuit diagram is the mechanical resistance. Just as all circuit elements in an electronic circuit have resistance, so to does the mechanical circuit. The resistance is seen in series with the whole mechanical circuit and could be represented as a series resistor or a parallel inverse resistance. If R_M is the mechanical resistance of the circuit, an inverse resistance is defined as:

$$\frac{1}{R_M}$$

In Figure 3a force is shown as 'flowing' in the mechanical 'wires'. The total available force is shared into four major

parts; the forces needed for the mass M_M , the compliance C_M , the mechanical resistance R_M and the load. If we define these four forces as F_1 , F_2 , F_3 and F_4 respectively, we can say that

F (the total force available) = $F_1 + F_2 + F_3 + F_4$, and this has been shown in the mechanical circuit diagram. We have to represent the series resistance as an inverse resistance, $\frac{1}{R_M}$ and place it in parallel

with the load, to illustrate the way it obtains its part of the total available force (F).

In this case the load is the primary of the mechanical/acoustical transformer. Of course this transformer doesn't actually exist. It is merely a way of representing the conversion of mechanical energy to acoustic energy by the interaction of air molecules with the surface of the loudspeaker cone. Mechanical force in the primary of the transformer is converted into sound pressure 'p', in the acoustic circuit.

In Figure 3a it is assumed that the loudspeaker is mounted in an infinite baffle. This is a partition that extends to infinity in all directions, cutting the universe into two halves, with a hole in which the loudspeaker is mounted. This is just a little impractical, but the only important thing is that no sound produced by the back of the speaker cone can interact with the sound from the front.

In order to move air molecules, the cone must do work so the air impedes movement of the cone. This impedance is called the acoustic impedance and is represented in the circuit diagram by Z_A . Since the loudspeaker is mounted in an infinite baffle the acoustic impedance is the same on both sides of the cone and becomes $2Z_A$.

We are now in a position to understand the causes of variations in the electrical impedance and acoustic radiated power. As was shown earlier, the back EMF is one of the dominant forces acting to increase the driver's impedance. It is related to the velocity of the loudspeaker cone as was indicated by Equation 2. If the motion of the cone is impeded, i.e. if the cone is held, the velocity must decrease, causing a decrease in the amount of back EMF. The decreased back EMF will cause a drop in loudspeaker impedance. So an increase in mechanical impedance causes a decrease in electrical impedance. With this in mind the electrical/mechanical/acoustic circuit diagram of Figure 3a can be converted into the all electrical circuit diagram of Figure 3b.

This circuit predicts the impedance

characteristics of the driver. A generally increasing impedance with frequency is caused by L_E , while M_M , C_M , and R_M form a damped parallel resonant circuit. We would expect a sharp increase in impedance at one frequency, dropping to the dc resistance of R_E and R_G and then slowly rising as frequency increases. This is exactly the response as shown in Figure 2 which is the measured impedance response of a typical 12 inch (300 mm) woofer. This resonance point is called the fundamental resonance of the driver, and being a function of the compliance of the driver, can be expected to decrease in frequency a little as the driver wears in. This is the reason some loudspeaker experimenters "run in" the driver before measuring resonant frequency.

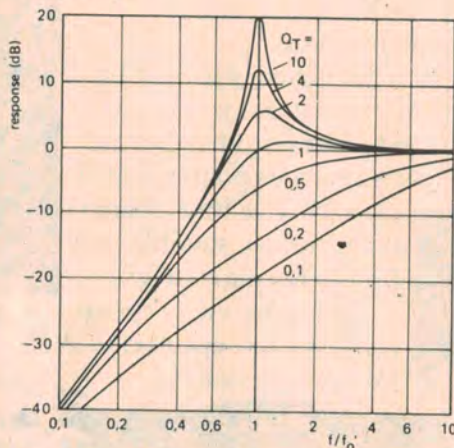


Figure 4. Normalized frequency response of a typical low frequency loudspeaker for different values of Q_T (after Hermans & Hull, Electronic Applications Bulletin, Vol. 35, No.2., Feb. 1978, Philips).

A more accurate model

The model of the loudspeaker developed so far has assumed that the shape of the loudspeaker cone remains unchanged and moves as a "rigid piston", following the input signal. This rigid piston theory works well at predicting the characteristics of drivers at low frequencies. At higher frequencies inertia again comes into play and the cone can no longer be considered as a rigid piston. If the driver remained a rigid piston throughout the audio spectrum its frequency response would fall off at a rate of 12 dB/octave at higher frequencies, limiting its useful frequency range.

The equation showing the relationship between the frequency of a sound and its associated wavelength is

$$\lambda \nu = V_A \quad \text{where } V_A \text{ is the velocity of sound in air}$$

$$\lambda \text{ is the wavelength in meters}$$

$$\text{and } \nu \text{ is the frequency in Hertz.}$$

The equation shows that the wavelength of sound decreases as frequency is increased. It should be noted that the velocity of sound depends on the medium in which the wave is propagating. The velocity of sound in the loudspeaker cone will be substantially different to that in air. Using this equation we can calculate the frequency at which the wavelength of sound approaches the radius of the loudspeaker cone. For a 300 mm (12 inch) loudspeaker this frequency is around 400 Hz and it is at this frequency that the rigid piston theory starts to come unstuck. Above this frequency the sound wave propagates up the cone, hopefully to be damped in the rubber surround. The sound wave is attenuated as it moves through the cone, and this attenuation effect increases with increasing frequency, causing a decrease in the effective cone diameter. This is the effect that enables a single cone loudspeaker to operate over a wide frequency range, since the decreasing effective cone diameter decreases the inertia presented to the coil assembly at higher frequencies. It should be noted that, in this range of the frequency spectrum, the rim and the cone will be radiating in anti-phase with the coil assembly. The way the cone material and suspension react to this multiple wave propagation is one of the biggest differences between a good driver and a poor one. It is for this reason that metal cones for instance are so often unsuccessful. Their ability to damp multiple resonances is generally poor in comparison to materials like paper or plastics.

Damping and Q-factor

In midranges and tweeters the drivers can be operated in frequency ranges that exclude their fundamental resonances. The crossover points are usually chosen so that at least one full octave exists between the crossover point and the fundamental resonance. In the case of bass drivers however it is necessary to operate the driver at and below the resonance of the woofer.

This is the main reason so many different bass loading principles have been developed. The fundamental resonance of the bass driver must be damped so that an acceptably flat frequency response can be established. If the resonance is not damped adequately, the all too common 'one note bass' sound results. This is a particularly noticeable and fatiguing loudspeaker fault and considerable effort must be spent on obtaining a smooth bass end response.

Since the loudspeaker is a resonant circuit the amount of damping can be specified by quoting the Q or quality factor. Q is defined by:

$$Q = \frac{f_0}{f_1 - f_2}$$

where f_0 is the frequency of the fundamental resonance, and f_1, f_2 are the 3 dB points.

Figure 4 shows a graph of bass-end frequency responses at a variety of Qs. Although the flattest response appears to be given by the case when the $Q=1$, this is not the optimally damped case and some boomy bass often occurs in bass systems with Qs around unity. The best Q is probably about 0.5. The bass is not boomy but is also not over-restricted which can happen if the Q drops to around 0.2 or 0.3. The best damping for any specific case needs to be established by experiment and ultimately, as always, the ear must be the final test.

Loudspeaker compliance, the total mass of the cone and the net series resistance with the voice coil, all determine the response of any loudspeaker system and any or all of these can be adjusted in order to achieve the optimum damping and frequency response. In practice, adjustments to the Q of the system are done by modifying the compliance and acoustic mass and resistances caused by the loudspeaker enclosure rather than modification of the driver itself.

The enclosure

The circuit in Figure 3 has been developed assuming that the driver is mounted in an infinite baffle. The air load on the cone of the loudspeaker is represented by an impedance of value:

$$\frac{1}{2Z_A}$$

When the driver is mounted in a practical loudspeaker enclosure, this acoustic impedance becomes a little more complicated and the circuit in Figure 5 replaces the simple resistor of Figure 3. This new impedance is made up of two major components. The radiation impedance from the front of the box (M_{AR}, R_{AR}) is related to the size of the baffle and is independent of the volume of the box.

The volume of air that the driver has access to is related to the effective radiating area of the cone and to the size of the baffle. Since bass frequencies have a greater dispersion than higher frequencies the volume of air accepting the radiated sound increases at lower frequencies. So the impedance on the front of the cone will be greatest at

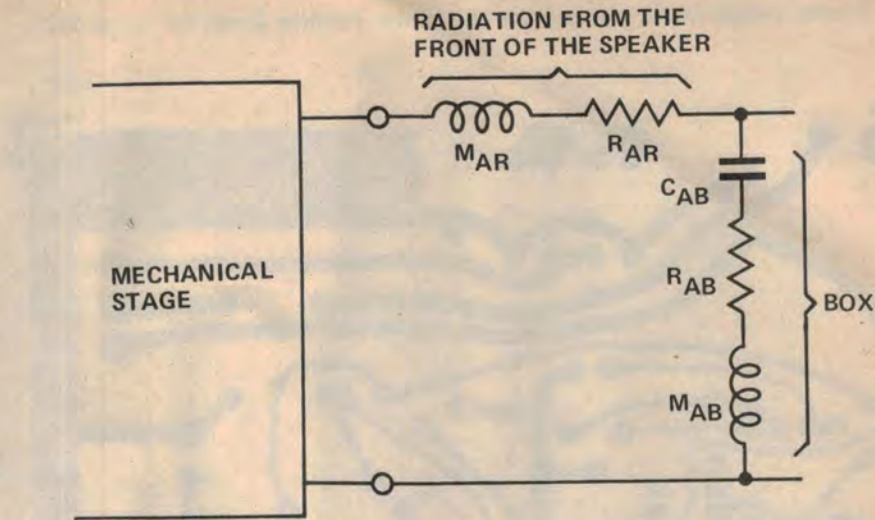


Figure 5. Equivalent circuit diagram for the acoustic stage of a direct-radiating moving-coil driver mounted in a sealed enclosure.

higher frequencies. If the size of the baffle is large in comparison to the radiating size of the driver the box approximates an infinite baffle down to a lower frequency than it would otherwise, and the frequency at which the driver has access to a 360° radiation pattern is decreased. This is represented by the series combination of the inductance M_{AR} and R_{AR} , which gives an impedance characteristic that increases with frequency like the front radiation.

The second component of the radiation impedance is caused by the enclosed volume of air within the box. If we consider a sealed enclosure the volume of air within the box will be compressed by the driver. So the enclosure volume will affect the overall compliance of the loudspeaker system. This acoustic compliance is represented in Figure 5 by the capacitance C_{AB} . The effect of this is to increase the stiffness of the loudspeaker cone resulting in an increase in the fundamental resonance of the enclosure.

The volume of air in the box will also have an equivalent mass represented by the inductance M_{AB} . This mass will also affect the resonance of the system by increasing the overall mass of the cone. The acoustic resistance with the enclosure is shown in Figure 5 as R_{AB} .

The final resonant frequency of the driver in the box is a function of the total effect of all the compliances and masses in the system. If the total mass is represented by M_a and the total effect of the compliances is C_a then the resonant frequency of the system will be given by the equation

$$f_0 = \frac{1}{2\pi\sqrt{M_a C_a}}$$

The equation shows that a decrease in either the total mass or compliance will cause an increase in the resonant frequency of the loudspeaker system.

Resonances

The acoustic circuit in Figure 5 represents the reactances caused by the enclosure around the resonant frequency, but as usual in loudspeaker science things get more complicated as frequency increases. As the wavelength of the sound wave produced inside the enclosure becomes shorter the box no longer acts as a simple spring. The produced wave travels from the back of the driver towards the rear and sides of the cabinet, where it is reflected back towards the driver. This sound wave will interact with the cone, either reinforcing or impeding the motion of the cone depending on the particular frequency. This results in successive rises and dips in the frequency response and for this reason it is important that this reflected wave is damped as much as possible. In order to absorb this unwanted energy the enclosure is usually lined with an absorptive material such as bonded mineral wool, acetate fibre or bonded hair felt.

The most important parameter of any of these materials is that they are reasonably open. If the material is too dense it will not only have little absorption but it will decrease the total available volume within the box. ▶

Generally a layer of 25 mm speaker innerbond on the back, sides, top and bottom is about right.

Lining the box also has the effect of altering the acoustic resistance on the back of the cone. This effect is often used to increase the damping and thereby decrease the Q of the system resonance. Usually the necessary damping can be only partially achieved and it is necessary to partially fill the box with an absorptive material as well. If the enclosure is completely filled sound waves within the enclosure are converted into heat in the filler material. Normally this overdamps the box resulting in a Q sometimes as low as 0.1.

Filling the box has one other major effect. Owing to the heating of the material inside the box and its different density to that of air, the velocity of sound within the enclosure is reduced dramatically. The speed of sound in air is around 344 m/s and this could drop to as low as 292 m/s. This has the effect of increasing the compliance of the enclosure and thereby decreasing resonant frequency in the same way as increasing the box volume would. An optimally filled box could appear some 30% to 40% bigger than it really is.

Throughout this article we have discussed the sealed enclosure, leaving explanations of other bass loading techniques to a later time. One of the most common enclosures is the bass reflex, which uses a port cut in the baffle to augment the bass radiation of the driver. The acoustic circuit diagram must show the effects of the mass, compliance and resistance of the port in addition to those shown for the rest of the box, making the loudspeaker equivalent circuit even more complicated. Both the bass reflex and the sealed enclosure are capable of very good results and it is not possible to state simply which is better. We have omitted a detailed discussion of the principles of the bass reflex loudspeaker simply for the sake of simplicity.

Next month we will deal with the problems of mating a collection of drivers to form a completed loudspeaker — another project in our 'Series 4000' line-up of hi-fi components.

Don't miss it! ●

References

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