Wireless World

JULY 1951 VOL. LVII. No. 7.

Sound Reproduction

THIS issue of *Wireless World* is devoted largely to the subject of sound reproduction-an expression which we use to cover all artificial methods of reproducing, reinforcing or recording natural sounds. Extra pages have been devoted to articles on various aspects of the subject; unfortunately, it is impossible to deal with all of them. Of all the offshoots of radio, sound reproduction is probably the largest and most diverse. In some directions it has broken away almost entirely from the radio (and, going back farther, wire telephony) techniques on which it is so largely based,. but in many respects the relationship is still close.

Among the many branches of electricity, electro-acoustics is unique in that it has attracted a large band of fervent devotees. The reasons for this are not far to seek: as a contributor points out elsewhere in this issue, the quest for perfect reproduction amounts to chasing the unattainable, and so offers a constant stimulus to human instincts. Again, art enters into it quite as much as science; that, perhaps, is why professionals in other branches become amateurs in the "audio" field, in which they find pleasurable relaxation. Here amateurism is seen at its best. Interest in the subject was never at a higher pitch than at the present time; according to correspondents in the U.S.A., the same applies in that country, where "hi-fi" tends almost to displace television.

Though there are no spectacular developments to record in sound reproduction progress is steady, but room for improvement still remains. The amplifier has perhaps approached nearest to perfection, and is now produced commercially in forms giving a degree of fidelity that would have been thought unattainable (or even unnecessary) a few years ago. This is a subject in which *Wireless World* has long concerned itself, and for many years we have regularly published designs of high-quality units. The "Williamson" amplifier, since the design was first printed, has achieved world-wide popularity. There is hardly a country in which a version adapted to local needs is not in use.

If the amplifier may at present be regarded as the strongest link in the chain of faithful reproduction, the loudspeaker is the weakest. Obviously the problems to be solved are most difficult, but there has been progress during the past twenty years or so-progress that would be regarded as phenomenal in a less rapidly developing art than our own. The loudspeaker is to some extent a war casualty; it has no special application to warfare, and so comparatively little work was done on it between 1939 and 1945. Since then, much effort has been devoted to its improvement, but the field is one in which there is still much scope for new ideas.

As many of our contributors have pointed out, the general public (as opposed to the growing band of enthusiasts) is not highly critical of reproduction quality. We find it hard to believe, however, that large sections of the public are really satisfied, and it should be easy enough to show them the pleasures they are missing. Unfortunately, however, under present conditions of broadcast distribution, it is only the favoured few who receive a signal capable of being well reproduced. This, as we have said, can only be put right by e.h.f. broadcasting, but, when that comes, the links between studios and transmitters must also be overhauled.

High fidelity, as it is called, is only part of the story. There is also high intelligibility, of greater importance for "public address" purposes and the like. A good deal of data on this subject is already available, but much remains to be done. For public address in places with a high prevailing noise level a more refined approach than mere brute force is needed. It would be fantastic to suggest a "synthetic sound" technique, akin to that demonstrated by Rudolf Pfenniger in 1933, but it is certain that highly artificial characteristics in speech reproduction can effect an improvement. And, apart from public address, we think investigation of synthetic sound production might well continue. In fact, that technique is actually employed with some effect in the Telekinema at the South Bank Exhibition. Though it may be amusing rather than epoch-making, as we said in 1933, the technique may yet provide a useful tool in the world of entertainment.

Loudspeaker Diaphragm Control

The Importance of Radiation Resistance Damping at High Frequencies

By J. MOIR*, M.I.E.E.

IN the May 1950 issue of *Wireless World* the writer reported the results of an experimental examination of the effect of the output impedance of an amplifier upon the transient oscillations of the loudspeaker cone and voice coil. A great deal of further work has been done and it is probable that some of the results may be of interest to the domestic high-quality enthusiast as well as to others with a more professional interest. First of all a brief recapitulation of the earlier results to avoid searching through your file of back numbers. It was shown that :-

1. Critical damping of the speaker voice coil is generally achieved by an amplifier having an output impedance greater than 10-20 per cent of the d.c. resistance of the speaker voice coil. For our purpose critical damping is obtained when the voice coil makes a unidirectional return (no overshoot) from an excursion to one side of its mean position.

2. Amplifier output impedance lower than 20 per cent of the speaker resistance, i.e. damping factors greater than five, produce little further increase in damping because the amplifier output impedance is in series with the d.c. resistance of the voice coil.

3. Other factors remaining constant, further reduction in the amplitude of the transient oscillation can be secured by an increase in flux density in the gap.

It is a characteristic weakness of an experimental approach, that it may do no more than show that the results obtained apply to the particular unit tested, so several units of radically different design were checked, the results being shown in Table 1.

In general a speaker having a low value of gap density will require a lower amplifier output impedance for critical damping than a unit having a high gap density. The majority of speakers with any pretension to high-fidelity performance are high flux density models used in conjunction with negative-feedback amplifiers of low output impedance; consequently it is in just that application where low output impedance is least necessary that it is more often obtained.

In view of the results shown in Table 1. it is thought that the critical damping resistance (amplifier output impedance) for the majority of speakers at present available is greater than about 10-20 per cent of the d.c. resistance of the voice coil.

It is pertinent to enquire about the further improvement that might be secured by applying greater-than-critical damping, as this could no doubt be secured if it proved to be of considerable value in the search for the ultimate in high fidelity. If perfect damping were obtained the motion of the voice coil would at all times be exactly in phase with the current in the voice coil, apparently an ideal state of affairs.

However, before deciding to concentrate on the problem of increasing the voice-coil damping let us take a glance at the performance of one of the other links in the high-quality chain, the listening room in which the high-fidelity enthusiast enjoys the results of his efforts. Reference to an earlier article (" The Acoustics of Small Rooms" *W. W.* May 1944) will show that any enclosure behaves as a resonant structure having an infinity of resonant frequencies given by the Rayleigh equation.

$$f = \frac{c}{2}\sqrt{\left(\frac{A^2}{L^2}+\frac{B^2}{W^2}+\frac{D^2}{H^2}\right)}$$

where c = velocity of sound in air, L = length, W = width, H = height, and A, B, D are the integers 1, 2, 3, 4, etc., substituted in turn. In a typical instance (the writer's lounge) this equation predicts the presence of eight resonant frequencies below about 100 c/s, as shown in Table 2, the presence of most of these having been confirmed by experiment. These are all in the same region of the audio spectrum as the fundamental voice-coil resonance of the majority of good loudspeakers, and there does not appear to be any good reason for believing that their effect upon the quality of reproduction will not be exactly the same as the effect of a speaker resonance when the Q factor (ωL/R) of the room is the same as the Q of the speaker voice-coil system. In both cases an exponentially decaying oscillation at the resonant frequency is added to the tail of every transient signal. An accurate calculation of the acoustic Q of the room is not possible, but a direct measurement of the 51-c/s

* British Thomson Houston Company.

TABLE I

Type of Speaker	D.C. Resistance of Voice Coil	Critical Damping Resistance
High-quality 17in unit	9.0 ohms	2.5 ohms
High-quality 12in unit	9.0 "	2.0 "
Cheap 7in (Make A)	8.2 "	1.2 "
Cheap 7in (Make B)	1.5 "	0.6 "
Cheap 7in (Make C)	11.5 "	4.7 "

TABLE 11

A	B	D	Resonant frequency (c/s)
1	0	0	36.8
0	1	0	51.1
0	0	1	68.6
1	1	0	62.9
0	1	1	85.5
1	0	1	77.6
2	0	0	73.6
0	2	0	102.3

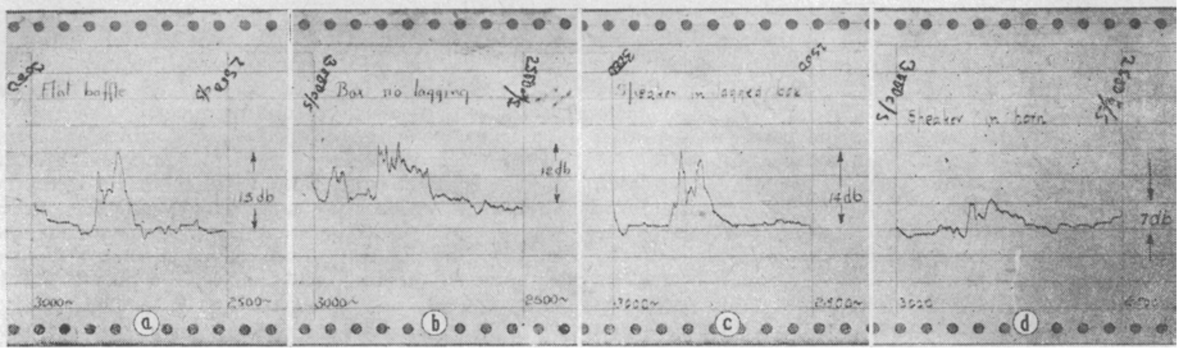

Fig. 1. Residual transient response of a 12-in. loudspeaker over the frequency range 2,500-3,000 c/s, (a) on a flat baffle, (b) in an unlagged box baffle, (c) in box baffle with hair felt lagging, (d) loaded by a short horn.

resonant mode, indicates that it has a Q between 13 and 15, whereas the Q of the damped speaker voice coil is between 0.5 and 1. Table II indicates that there are eight resonant modes below 100 c/s, and as all are known to have Q factors greater than 8, further efforts to obtain greater-than-critical damping of the speaker voice coil would appear to be a mis-directed effort, though the purist may derive some pleasure from "straining at the gnat."

Residual Transients

All the proceeding discussion has been concerned with the low-frequency resonance of the mass of the coil and cone with the compliance of the cone support, but though this is perhaps the most prominent mode, there is a very large number of resonant combinations spread throughout the whole audio frequency range. D. E. L. Shorter *(B.B.C. Quarterly,* Oct. 1946 and *W.W.* Dec 1946) has developed a technique for checking their presence, his preferred method of expressing the result being to plot the steady-state frequency characteristic together with the frequency characteristic of the residual sound at intervals of 10, 20, 30, 40 milliseconds after the electrical input to the speaker is removed. His results indicate the presence of many high-Q modes of vibration, but in general these "resonant sub-assemblies" are not tightly coupled to the voice coil, the results being that damping applied to the voice coil movement has little effect upon the amplitude of their transient oscillations following an exciting pulse. The looseness of the coupling between voice coil and the resonant elements is shown by the absence of any indication of change in voice-coil impedance at the frequency of resonance. As these mechanical resonances are distributed throughout the whole audio range their aural effect is likely to be of greater importance than the single resonance of the cone and surround. On the other hand, the number of room resonances per octave predicted by the Rayleigh equation increases, and their amplitude decreases, as the frequency rises, and consequently they tend to be relatively less important than the higher-frequency speaker resonances, which Shorter's work has shown to be of high Q with long transient hangovers.

A solution to the problem of damping these high-frequency resonant modes in the speaker may therefore be expected to produce a greater improvement in quality of reproduction than a solution to the problem of obtaining greater-than-critical damping of the basic voice-coil resonance.

On account of the relatively loose mechanical coupling between voice coil and the resonant regions of the cone, electrical damping of the h.f. resonances is extremely difficult (probably impossible), and it is therefore necessary to consider some alternative method. A solution having all the advantages would be to increase the resistive component of the air load upon the cone by modification to the speaker mounting. At the present time there are three main classes of speaker mounting, the flat baffle, vented cabinet including the labyrinth, and the exponential horn, each with its own particular advantages. The flat baffle makes little difference to the resistive component of the air loading on the cone over any large portion of the spectrum, whereas the vented cabinet may be designed or may just happen to increase the resistive loading over the bottom end of the range in the vicinity of the cone resonance, without making any significant contribution elsewhere. The same comment is true of the labyrinth, but the third method, the use of an exponential horn has real advantage in loading the speaker diaphragm, an advantage that is particularly marked in the region between 100 and 1,000 c/s.

Horn Loading

The acoustic resistance at the throat end of an exponential horn rises much more rapidly with increase in frequency than for a cone in an infinite baffle and at low frequency may be 50-100 times the value obtained without the horn. The increase can be calculated without serious difficulty, but the calculation involves a knowledge of the change in effective diaphragm area with frequency, information that can only be obtained experimentally with greater difficulty than there is in directly checking the reduction in transient oscillation due to the addition of the horn.

An experimental check on the correctness of the reasoning always inspires confidence and fortunately some earlier results on a typical 12in cone unit can be quoted. This was tested in a 3ft. sq. baffle, a felt-lined box, and a short exponential horn, the Shorter method of transient measurement being used. Transient oscillations in open cone speakers appear to be greatly affected by time, temperature and many other factors, so it was necessary to find a relatively narrow region of the complete response curve where a transient oscillation occurred in a stable manner, i.e., the results on a flat baffle could be repeated with consistency over periods of several hours. The amplitude of the transient oscillations 20 milliseconds after the electrical input had been cut off, was then checked with the speaker unit in the flat baffle, the box and the horn, particular care being taken to make certain that the test results for any method of mounting could be repeated.

Fig. 1 illustrates the results and it will be seen that there is little difference in the amplitude of the transient oscillation whether the speaker is mounted on a flat baffle, in an unlagged cabinet or in the same cabinet with thick hair felt lagging. Mounting the unit in a short horn reduces the amplitude of the oscillations by about 12-15 db. Though it may be a coincidence it is worth noting that in this particular case the addition of lagging to the cabinet appears to reduce the frequency band over which prominent oscillation occurs, though increasing the amplitude of the oscillation within that band. This sort of result is generally due to one of the box dimensions being a whole number of quarter wavelengths, and in this case the addition of one inch felt made the back to front dimension a whole number of quarter waves near the frequency of the transients. This point was not followed up, so this should be considered as a tentative explanation only.

Horn loudspeakers are characterized by a solidity and firmness of reproduction which within the writer's experience is not possessed by any other form of

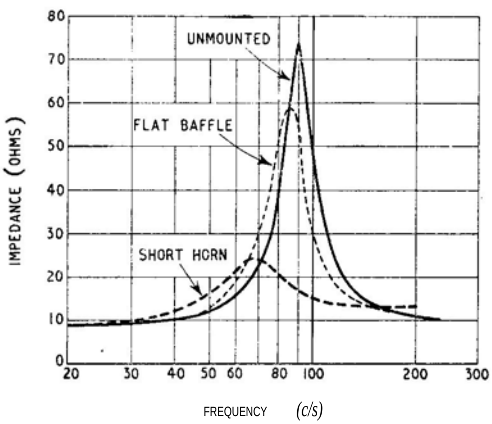

Fig. 2. Effect of loudspeake mounting on impedance of voice coil.

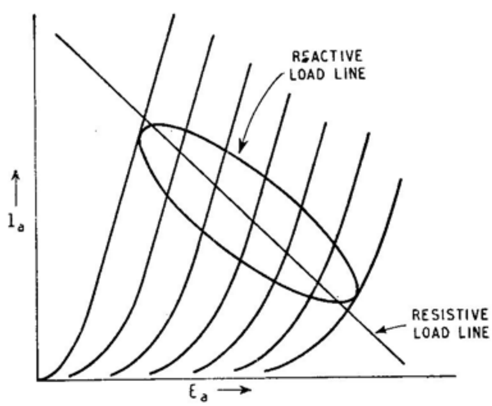

Fig. 3. Indicating the curve path followed by the operating point with a reactive load.

mounting, a characteristic that is believed to be due to effective damping of the cone motion. In this particular case the damping obtained appears to be about twice that expected on the basis of the usual estimations of effective cone diameter.

Earlier, we expressed the view that critical damping of the voice coil is not of particular importance when the loudspeaker is used in a small room but as all the equipment was set up, a particular 12-inch speaker was checked in three mountings to determine the amplifier output impedance required to give critical damping of the basic resonance. The results are as follows :-

TABLE III

Speaker Mounting	Source Impedance for Critical Damping
1. Open on bench	8 ohms
2. In 2,500 cubic inch box	2
3. In short horn.	12

This indicates that the Q of an enclosure may be greater than that of the speaker voice coil (i.e., a lower source resistance is required for critical damping) confirming that it may be necessary to use some artifice similar to D. E. L. Shorter's felt partition (W. W., Dec. 1950) if critical damping of an enclosure is really required.

There is one advantage of using a loudspeaker mounting that provides resistive loading of the cone, to which we have not so far referred. A lightly damped mechanically resonant voice coil system will have an impedance/frequency curve with a pronounced peak at the frequency of mechanical resonance, a typical sort of curve being shown in Fig. 2. Over this part of the frequency range the output stage of the amplifier is presented with a load that changes rapidly both in modulus (absolute value) and in phase angle, the change being particularly violent over the few cycles near resonance. A thermionic amplifier cannot provide power for this type of load without introducing serious distortion, a result that will be understood by referring to Fig. 3 showing the anode-voltage/anode-current curves for an output valve with load lines for a purely resistive and for a reactive load added to the diagram. For a resistive load the working path is the straight line shown but for a reactive load the " line" broadens to an ellipse which may take the operating point into regions where the anode current at peak negative grid signals is dangerously near or into cut off, thus increasing the working distortion far above the values taken from the curves for a matched resistive load.

Fig. 4 indicates the results obtained using an amplifier with low-impedance triodes in push pull in the output stage, curve A being the third-harmonic distortion when the amplifier was driving a pure resistance load, and curve B the third harmonic produced when a two-unit speaker combination was substituted. Although this particular speaker assembly has an impedance characteristic which is relatively flat in comparison with the majority of high-fidelity speakers at present on the market, it will be seen to increase the distortion by a factor of two to three times below 200 c/s.

There is therefore considerable merit in adopting a speaker mounting that will reduce the inherent impedance variations of the speaker unit itself, but it is almost impossible to make any specific statement about the relative advantages of the many types of speaker mountings in this respect. In general the flat baffle has little effect upon the impedance curve of the speaker unit and is therefore worst of all in respect of impedance variation. The vented cabinet may be designed to reduce the natural impedance variation of the basic unit, though there does not seem to be any unanimity of opinion among designers as to what should be done. In the case of the horn-loaded unit considerable reduction in the impedance variation of the basic unit can be secured by appropriate design. Fig. 2 indicates the impedance variation of a particular 12-in speaker unit, in free air, mounted on a 4ft square baffle and finally in an exponential horn designed to be contained in a 10,000 cubic inch box.

As shown in the earlier article these variations in impedance are directly related to the amplitude of the transient oscillations of the speaker, a flat curve such as that for the horn indicating highly damped motion of the coil and cone. In this particular instance the horn shows up to considerable advantage in reducing the amplifier distortion due to load impedance variation and in a large room should show a marked improvement due to the damping of the coil motion.

For completeness we may summarize the conclusions as follows ;—

1. Further evidence is produced to indicate that current designs of loudspeaker units are critically damped by an amplifier having an output impedance about 10-20 per cent of the d.c. resistance of the voice coil.

2. Truly aperiodic motion, i.e., greater-than-critical damping is not believed to have any advantage when the speaker is used in a small room, because the transient oscillations of the room are of the same nature and are of much greater amplitude.

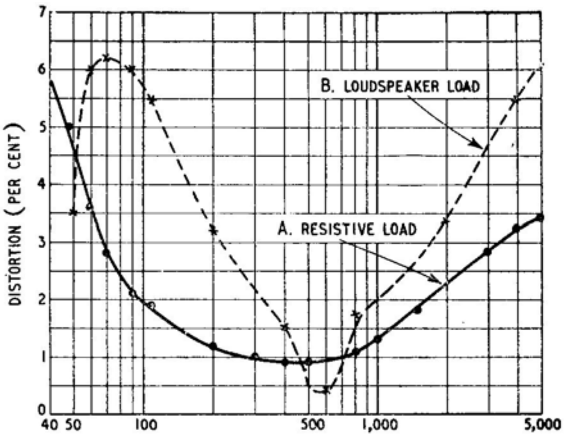

Fig. 4. Third-harmonic distortion produced by resistive and reactive loads.

3. Effort should rather be directed towards increasing the damping of the cone oscillation at the higher frequencies.

4. Further effort should be directed towards the production of speakers and mountings which give a flat overall voice-coil impedance curve.

5. One solution of both these problems is the use of an exponential horn.