Titanium Cone Loudspeaker

EVOLUTION AND DESIGN

By E. J. JORDAN, Assoc.I.E.R.E.

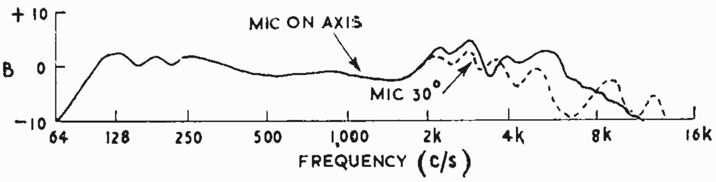
E. J. JORDAN, who recently joined Audio & Design Ltd., of Maidenhead, as a director, started his career in the service department of G.E.C. He then spent twelve years with Goodmans Industries and in 1964 became technical director of Jordan-Watts Ltd. of Hayes, Middx., where he produced the first "modular" loudspeaker.

SOME years ago a friend gave me a book which he had purchased for 6d from an old bookshop. It was McLachlan's "Elements of Loud Speaker Practice" published in 1935. It makes fascinating and, for the author, somewhat sobering reading, inasmuch as that in over 30 years there has been so little apparent progress in loudspeaker development. Among the many possible loudspeaker types described are the full range push-pull electrostatic loudspeaker and the Blatthaller loudspeaker, forerunner of the French Orthophase. The last chapter is headed "Recent Developments" and introduces firstly the concept of a large moving-coil loudspeaker used together with a horn loaded tweeter in conjunction with a crossover system, and secondly a moving-coil loudspeaker having a small auxiliary cone attached to the centre of the main cone to handle the high frequencies (Voigt, of course). The frequency response of the last-mentioned is comparable to that of many modern hi-fi loudspeakers and is reproduced in Fig. 1. For direct comparison the frequency response of a modern 12 in twin-cone loudspeaker is shown in Fig. 2.

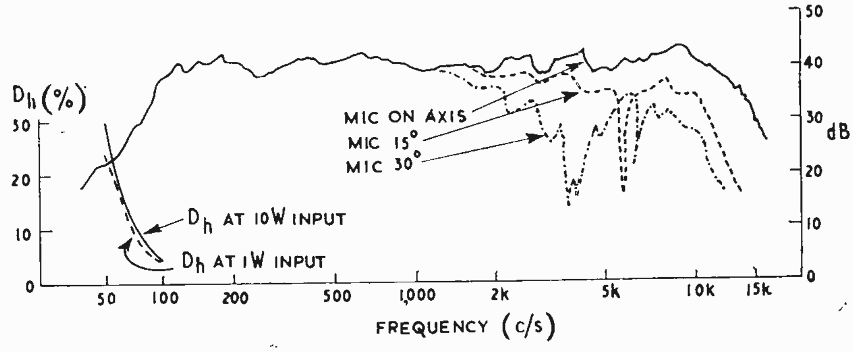
Undoubtedly one of the main reasons for the slow progress has been that at the time the book was written loudspeaker design thinking was well ahead of the availability of suitable materials and engineering techniques with which to implement the ideas. Modern technology has now provided us with a vast range of metals, ceramics and plastics that allow us to realize the principles established so long ago.

Once valve amplifiers had reached the stage where a few relatively low distortion watts were available, the single paper cone moving-coil loudspeaker emerged as by far the most satisfactory compromise between quality and economics, and continues so to be. With the progressive improvement of broadcasting and recording quality there came a demand for a wider frequency range than could then be obtained from the single paper cone and crossover systems, and double-cone systems were extensively developed. In addition to Voigt, Goodmans Industries were largely responsible for the sophistication of double-cone techniques. This is apparent in their famous "Axiom" range. Many companies developed excellent crossover systems and it is worth noting that, while widely varying techniques were used in tweeter design, the low frequencies were invariably handled by the ever faithful paper cone moving-coil loudspeaker.

The difficulty in obtaining a smooth extended high frequency response from a single cone was practical rather than theoretical. As we shall show later it is necessary to use a flared cone in order to obtain a good high frequency performance, but because of their poor strength/weight ratio paper flared cones were prone to non-linear flexing at low frequencies, resulting in harmonic and intermodulation distortion. Metal cones were tried on and off right from the start but the highly resonant nature of metal precluded these as a satisfactory material for many years. A significant breakthrough in this respect was made by Hugh Brittain of G.E.C. Research Laboratories by using a 6 in straight sided Duralumin cone having a plastics (p.v.c.) edge termination which, together with a controlled deformation in the cone body, largely overcame the resonance problems associated with metal. This resulted in a loudspeaker with a very acceptable frequency response and a harmonic distortion level which was so low that it has not yet been improved upon. Details of this were published in *Wireless World*, Nov-



Above:—Fig. 1. Response curve of twin diaphragm m.c. loudspeaker (Voigt) with tractrix horn about 4ft long and 4ft square at mouth (Reproduced from "Elements of Loud Speaker Practice"—McLachlan, 1935).



Right:—Fig. 2. Response, distribution and total harmonic distortion curves of 12 in twin cone m.c. loudspeaker in enclosure.

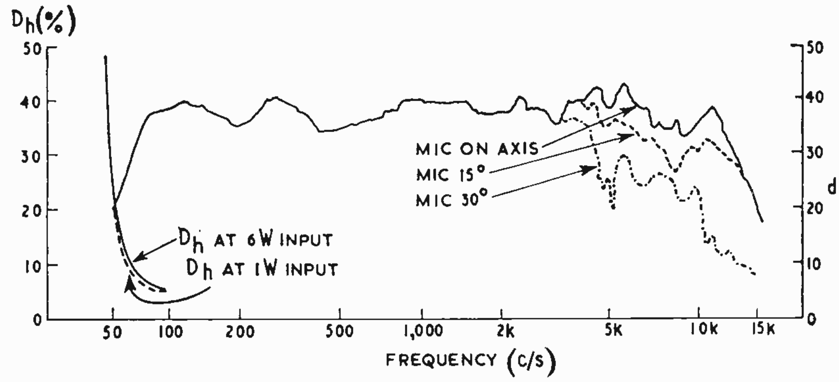


Fig. 3. Performance curves of 8 in hyperbolic paper cone m.c. loudspeaker.

ember-December 1952 and January 1953.

Shortly after this the author worked on the problems associated with flared cones and discovered that the distortion could be reduced to acceptable proportions by the use of (a) a very flexible surround, and (b) a flare following a hyperbolic law. The resulting loudspeaker, now known as the "Axiette," is still marketed by Goodmans. Its response curve is shown in Fig. 3.

Throughout these years the improvement in materials was most apparent in the realm of permanent magnets, which, for a given total flux were a fraction of the size of their pre-war counterparts. Plastics technology was forging ahead and most loudspeaker engineers were keeping a very close watch on this industry, hoping for a plastics panacea to the problems of cone design. This came —not, however, to the protagonists of cone loudspeakers but to the full-range electrostatic loudspeaker.

A direction in which remarkable advances have since been made has been the reduction in the overall size of loudspeaker systems. Theoretically efficiency may be traded for size for a given low frequency limit *reductio ad absurdum.* As usual, practical mechanical problems set a limit, but the vast majority of present-day hi-fi loudspeakers are very much smaller and less efficient than their earlier counterparts—an approach now made acceptable by the availability of domestic power amplifiers with outputs of up to 100 watts. This trend was started by Edgar Vilcher in the U.S.A. when he developed the "acoustic suspension system" which basically comprises a large massive bass cone loudspeaker fitted with a highly flexible suspension and housed in a small airtight enclosure. Implicit in this approach is the use of some form of crossover system and separate radiators in the high frequencies.

The birth of the now well-known full-range electrostatic loudspeaker was announced in a series of articles in *Wireless World* in 1956 and a completely new standard in sound reproduction was established.

The most significant advantage of the electrostatic loudspeaker over existing loudspeakers was in its transient performance. The importance of transient response has been stressed often enough over the years by the pundits but it has been played down to a large extent by many manufacturers and grossly underrated by the hi-fi public generally. The reason for this may be due to the difficulties associated with making measurements of transient performance compared with simple frequency response curves.

Some indication of transient performance can be obtained from response curves[1]. For example, the ability of the moving system to allow sufficient acceleration to adequately reproduce transient sounds is directly related to its high frequency performance. The worst aspect of transient performance, however, is the prolonged "ringing" that can follow a transient. Any transient is composed of a series of harmonically related overtones and any sharp resonances in the system which fall into this range of overtones are often not very apparent on the response curve except to the experienced observer, who can recognize them as tiny, near vertical changes of level. Even this is not entirely reliable because such effects can be produced by other causes. The situation is illustrated by reference to the two hypothetical response curves shown in Fig. 4. It is extremely likely that loudspeaker A would reproduce sounds with a far higher degree of accuracy than loudspeaker B. Even though B has the flatter curve, the transient ringing associated with the small sharp changes could result in extreme colouration and very poor definition. Curve B could well be described as "angry."

The electrostatic loudspeaker is a perfect example of the above argument. Its measured response curve is unusual and certainly not level (Fig. 5), but it has the one outstanding quality that renders its shortcomings relatively unimportant, and this is the complete lack of colouration (or, in the words of the advertisements, "this loudspeaker lacks character"). It is a salutary lesson to listen to white noise on a loudspeaker comparator while switching between various high quality systems including the electrostatic loudspeaker. All the conventional cabinet systems have pronounced "vowel" sounds which are entirely absent from the e.s.l. (Incidentally, for purposes of educating the ear a good "live" white noise is the sound of car tyres on a wet road.)

All of which brings us back to about the present time. We have inherited a veritable fund of basic principles, the advantage of over 30 years of further development and an almost unlimited range of materials and techniques. Whither now? Faced with this situation, the author adopted the approach now to be described.

Design objective.—The problem was to recreate sound as accurately as possible within the confines of the listening area—in this case the domestic living room or lounge. As a starting point we will assume a medium room of 2,000 cubic feet. The programme material likely to make the greatest demands on the available sound power and frequency range is that provided by a full concert orchestra. We will assume the listening level to be such as to provide a peak intensity at the ears similar to that experienced in a typical seat in a concert hall, and finally we will let the low frequency limit be 30 c/s. For domestic reproduction this frequency is quite low enough since very few recordings extend as low as this and the room dimensions limit bass reproduction to a frequency given by:

$$f = \frac{560}{\text{longest dimension in feet}}$$

From the above information can be calculated the total acoustic power required in the room and hence the volume velocity (diaphragm area × excursion × frequency) required from the loudspeaker (Appendix 1). It is necessary to choose a suitable ratio of diaphragm area to excursion. However, the choice of diaphragm dimensions must be determined in part by a number of other factors which we will now consider.

The loudspeaker diaphragm has to draw its energy from the electrical output of the amplifier and transfer it to the air in the form of sound waves. This transfer is profoundly affected by the impedance of the air load, which in turn is determined by the diaphragm dimensions and frequency. It is well known that the radiation resistance curve abruptly changes shape about the point where $kr=2$*. This corresponds to the frequency where, assuming a circular diaphragm, the circumference is equal to 2 wavelengths.

Although the entire radiation resistance curve may be exactly represented as a Bessel function, it is usually considered adequate to use the two approximate expressions given in Appendix 2 dealing with the parts of the curve above and below the "knee" respectively.

Consider first those frequencies below the "knee." It can be shown that for the radiated power to be independent of frequency the diaphragm must be rigid and either have a mechanical impedance that is very much lower than the air load or a mechanical impedance that is dominantly mass (known as the condition of mass control). Either of these conditions are realizable in practice but the condition of mass control offers a number of advantages:

1. It renders the low frequency performance less dependent on room acoustics.
2. Performance is less critically dependent on the position of the loudspeaker in the room.
3. It makes domestically acceptable enclosure systems which are necessary in order to secure an adequate low frequency performance.

Above the "knee" of the curve a mass-controlled diaphragm will cause the radiated power to fall as frequency rises at the rate of 6 dB per octave. The polar response becomes progressively more narrow as frequency rises. These two factors obviously render a mass-controlled rigid diaphragm unsuitable for high frequencies. There are two solutions to the problem. One is to provide a smaller diaphragm and use some form of mechanical or electrical crossover system. The other is to cause the existing diaphragm to reduce its effective diameter as frequency rises. The effect of this is also to reduce the mass of the diaphragm, and since at these frequencies the radiated power is proportional to the effective area and inversely proportional to the square of the mass it follows that the smaller the cone the higher will be the efficiency, the mass and the area being directly proportional to each other (see Appendix 3). Provided the correct ratio of diameter to frequency could be maintained both the radiated power response and the polar response could theoretically be independent of frequency.

Again it is seen that a choice has to be made and it is clearly seen in theory at least that the second arrangement is to be preferred, inasmuch as it does not introduce any abrupt discontinuities in the system. Any arrangement using multiple diaphragm crossover techniques is likely to suffer from three serious drawbacks. First, at the crossover frequency the radiated power is shared between two diaphragms of different size and hence different polar response. This means that there must be an abrupt change in the power response if the axial pressure response is to be maintained, or vice versa. Secondly, the electrical impedance looking into a loudspeaker system incorporating electrical crossover networks must inevitably exhibit considerable phase change about the crossover frequencies. Crossover frequency networks are designed to be matched by constant resistance at all of their terminations, a condition which is never fulfilled in practice. The effects of such a load applied to the output of an amplifier may in many cases considerably affect the phase of the negative feedback voltages, thereby degrading the performance of the amplifier. Thirdly, the inevitably resonant nature of the crossover system will introduce transient distortion of the type discussed above.

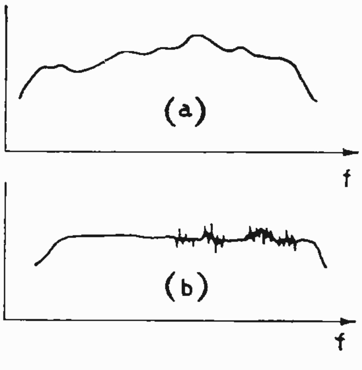


Fig. 4. Curve (b), although flatter, has the "angry" appearance associated with a poor transient response and is less acceptable than curve (a).

Accepting then the desirability of the "reducing diameter" approach we find that one of the simplest ways of achieving this in practice is to apply the driving force at the centre of the diaphragm only. It can readily be visualized that if the diaphragm were, for example, a stretched membrane of some low-loss material, at the higher frequencies ripples would spread out from the driving point and travel to the edge. If some damping media were applied to such a diaphragm the ripples would undergo severe attenuation as they moved outwards, so that the displacement at the point of application of the force was considerably greater than at any other point and most of the sound radiation would be from this central point. Clearly with such an arrangement as this the effective central working area would be a function of

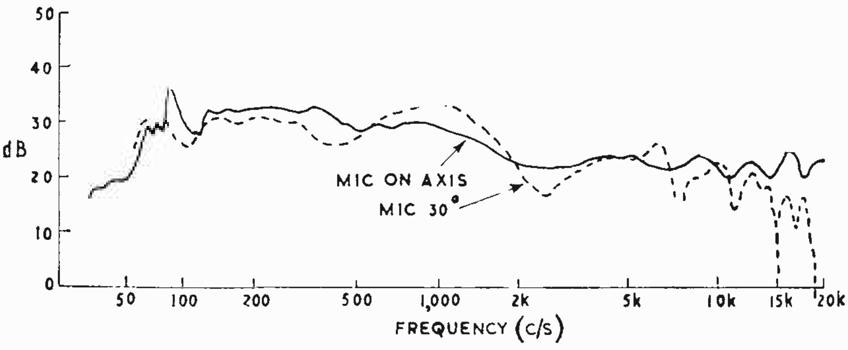


Fig. 5. Performance curves of full range electrostatic loudspeaker.

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*Radiation resistance is the real part of the acoustic impedance of the air load. It is plotted vertically in normalized form $R_{MA}/\pi r2\rho c$ against normalized frequency kr $(=2\pi r\lambda/)$ plotted horizontally (where R_{MA} = radiation resistance in newton-seconds/metre, r = diaphragm radius in metres; ρ = density of air in kg/m^3; c = velocity of sound in m/sec λ = sound wavelength in metres; and $k=2\pi/\lambda$).

wavelength and therefore frequency, thus giving us the type of operation we require.

It is fairly obvious at this point that we have talked ourselves willy-nilly into a fair description of the operation of a single-cone loudspeaker at high frequencies. The single-cone loudspeaker, by its very nature, has intrinsically the right sort of characteristics necessary for full range sound reproduction, and even the poorest examples of this type of loudspeaker provide very acceptable results. This was appreciated, in principle if not in detail, 40 years ago, and, as we have already indicated, this loudspeaker has by far the most satisfactory all round performance for general purpose applications. Its performance has been limited at low frequencies for the want of a good suspension system. The problem at high frequencies is that of producing a cone of such form, material and dimensions as will operate to the precise requirements.

In fact it is no less a problem to define the "precise requirements" in material terms. There has been no tractable mathematical approach for dealing with this other than the author's own very limited contribution which gives no more than an indication of the relationship between the various physical parameters of the cone. This is outlined in Appendix 3. Fig. 6 shows how the effective cone diameter reduces as frequency rises due to cone flexure. The expressions in Appendix 3 show that in order to secure a level response the first mode of flexure must start at the "knee" frequency and that a flared profile is necessary to provide the correct rate of area reduction with rising frequency. By the choice of suitable profiles the radiated power response may be made to rise or remain level or to fall. The high frequency limit of a loudspeaker is reached when the radiating area has been reduced to a point where its effective mass becomes equal to that of the voice coil. The last-mentioned provides a non-reducing factor in the total moving mass and above this frequency the efficiency falls. It may be mentioned at this stage that the further loss of efficiency at high frequencies is incurred by voice coil inductance, but from what has been said it will be seen that this can be compensated by means of the cone design. In practice, however, the more we make use of the facility of increasing efficiency as frequency rises the more restricted will be the ultimate high frequency limit. The overall high frequency efficiency over the frequency range above the "knee" is largely a function of the material from which the cone is made.

Apart from the considerations of the response curve a high overall high frequency efficiency is extremely desirable, inasmuch as it permits the use of damping techniques to avoid transient ringing. Any form of damping reduces overall efficiency and the greater the intrinsic efficiency of the cone the more freely can we apply damping media to improve the transient performance.

Generally speaking the higher the velocity of sound within the material the greater will be the efficiency and therefore the more extended may be the high frequency response. Further, high sound velocities are usually associated with materials having a high strength/weight ratio. This is also the property necessary to eliminate the distortion associated with flared cones. As we have previously said, the strength/weight ratio of paper is not particularly high and, in addition, paper is a relatively inexact and unstable material in mechanical terms. The reasons why the single-cone approach has not received greater attention are now becoming apparent.

We now see that we are faced with the problem of determining the cone material, shape and dimensions with very little mathematical assistance, yet in order to secure a smooth extended high frequency response devoid of colouration it is imperative to be able to determine these factors very accurately and further to retain this accuracy throughout manufacture. The approach has therefore to be entirely experimental. The tooling necessary to produce cones of almost any form is very complex, and such experimental work demands that cone tools be made and discarded until the correct parameters are obtained. Naturally one cannot afford to be haphazard in this approach, and each cone form tested must result from a logical assessment of the performance of the previous one. Nevertheless this work is very time-consuming and very expensive and it is easy to understand why this problem has not been previously tackled with any degree of thoroughness, especially when one considers that all there is to show at the end is a single-cone loudspeaker with little or no "gimmick value."

Some 12 years after developing the hyperbolic paper cone 8 in loudspeaker, the author experimented with small aluminium cones, which led to the development of the Jordan-Watts module. This cone had a hyperbolic flare which closely approached a pure radius. The frequency response of this unit is shown in Fig. 7. It will be noted that the axial frequency response is fairly smooth and level but the off-axis response is falling towards the high end. This indicates that the mean hemispherical power response (m.h.p.r.) is falling. The shape of the mean hemispherical power response is of far greater importance than that of the axial pressure response.

It was not until three years later that the author had the opportunity to experiment with a variety of alternative flares, and he discovered that

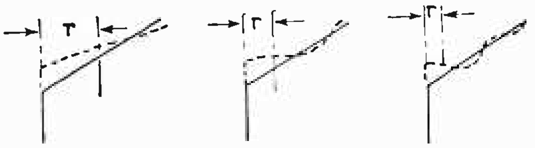


Fig. 6. Indicating how the effective cone radius (r) may decrease with rising frequency.

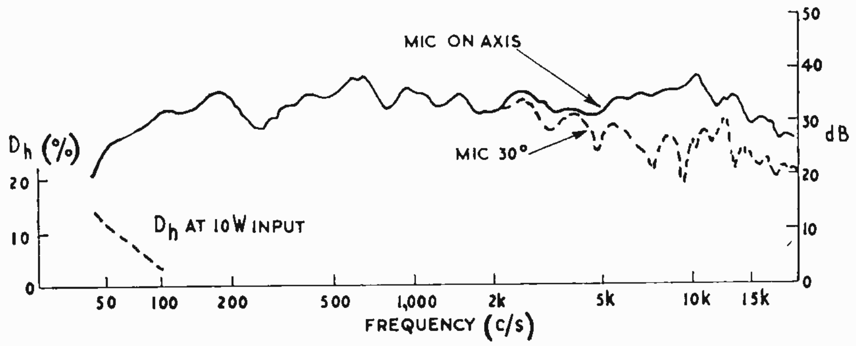
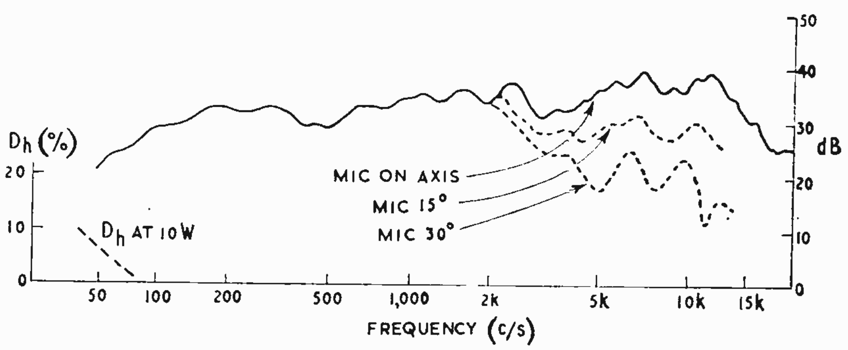
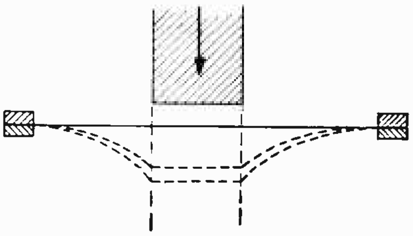


Fig. 7. Performance curves of 4 in dia. aluminium cone having a hyperbolic profile approaching a radius.



Above: Fig. 8. Performance curves of 4in dia. aluminium cone having a hyperbolic profile given by $y = 0.75/x$.



Right: Fig. 9. Showing the formation of a hyperbolic form by displacement at the centre of a stretched membrane.

although he could raise the m.h.p.r. it was at the expense of the high frequency limit. An acceptable compromise is shown in Fig. 8, which is the response of a unit similar to the previous one but employing an aluminium cone with a flare given by the law $y=0{\cdot}75/x$. Although this curve does not appear to be as good as the previous one there was, on listening tests, considerably less colouration, and the improved transient performance gave the impression of a more extended top response. This range of experiments virtually exhausted the possibilities of aluminium as a cone material which, although it gave results considerably superior to those of paper cones, still left something to be desired, and again the search was on for a new material.

The clue was given in an advertisement by Imperial Metal Industries Ltd. describing titanium as having "a greater strength weight ratio than any other structural metal." Samples were immediately ordered and duly received. As a starting point one of the sample pieces was placed in the tool used for the previous aluminium cone and when pressure was applied the material immediately shattered; and the author's company was then faced with the agonizing prospect of having to find out how to tool for titanium before knowing if the metal was going to be satisfactory in any case. This was done, however, and the advantages of titanium became immediately apparent, and experiments were once again undertaken to determine the correct cone law. Shortly after this another breakthrough was made whereby it became immediately possible to obtain the correct flare in any material without any further tests.

This came as the realization that a stretched membrane displaced at its centre would follow a hyperbolic curve (Fig. 9). If the displacing force is oscillating the lines of stress and strain will lie along the natural hyperbolic curve and there will be no tendency whatever for the material to be displaced from this curve at any point. This is exactly the situation required in a loudspeaker cone to avoid unwanted "break-up," and not only shows the advantage of the hyperbolic law in principle but also tells us exactly how to achieve it in practice—i.e. a sheet of the proposed material, in this case titanium, is subjected to considerable tension, placed in an annular clamp and the centre displaced by a cylindrical tool. This is the technique now used in the manufacture of titanium cone loudspeaker modules and systems marketed by Audio & Design Ltd.

The metal titanium.—Out of interest readers may like to know that titanium is the fourth most abundant metal found in the Earth's surface. It is an element and the material used in loudspeaker cones is 99·9% pure. In addition to its exceptionally high strength/weight ratio it does not corrode and will withstand extremely high temperatures. It is produced in this country by Imperial Metal Industries (Kynock) Ltd., Birmingham, a subsidiary of I.C.I. It has become commercially available only during the past 10 years and, because of its properties, its principal applications are in the aerospace industry. In spite of the abundance of the crude ore the metal is expensive, owing to the very elaborate refining and milling processes required. The material is extremely difficult to work with and the rate of tool wear is high. In our application the grain size is of very great importance.

The coil.—The voice coil of the loudspeaker has to be as light as possible consistent with reasonable efficiency. Considerations of high frequency performance have led us to an actual cone (piston) diameter of about 4in. From this we have calculated (see Appendix 1) a peak displacement of $\pm\frac{1}{8}$ inch in order to provide the required low frequency radiated power level, assuming reflex loading. Thus, in order to provide a constant driving force either the coil must be $\frac{1}{4}$in longer than the depth of the magnetic gap or vice versa. In the interests of lightness the short-coil, deep-gap approach is used, and this incidentally also provides a higher magnetic efficiency.

Considerations of total magnetic flux and flux density led to the adoption of a magnetic gap diameter, and therefore coil diameter, of approximately $1\frac{1}{2}$in. The coil itself comprises a $\frac{1}{4}$in aluminium winding on an aluminium former of thickness 0.0015in. The winding is immersed into the centre of a $\frac{1}{2}$in deep magnetic gap.

The mechanical attachment between the top of the coil former and the cone neck is of paramount importance and must be effected by means of a very thin layer of hard-setting adhesive. Any flexibility at this join will lead to three severe defects: (a) premature mechanical failure (the forces developed across the glue line are very considerable); (b) attenuation of the high frequency response and colouration due to the resonance resulting from the mass of the cone and the compliance of the adhesive; and (c) harmonic and intermodulation distortion at high frequencies due to the inevitable non-linearity of the compliance.

The flexible surround.—Since the cone is moving and the supporting framework is not, the cone must be supported at its edge by means of a flexible coupling which has to perform the following quite separate functions:

1. To permit complete freedom of the cone to move axially and to

restrict any sideways movement.

2. To provide an airtight seal between the edge of the cone and the enclosure. Further in this respect it must appear acoustically opaque to back-pressures emanating within the enclosure.

3. To provide a satisfactory termination to the cone at high frequencies in order to effect as much as possible the complete absorption of the incident flexure waves arriving at the cone edge. Failure to do this will result in reflected waves, leading to interference effects and colouration.

4. The rim must be intrinsically non-resonant.

5. The rim must be made of a material that does not age and is mechanically stable under all conditions of climate.

One technique employed by the author was to use a composite plastics rim, attached to which was an annular metal spring. This spring had two natural positions, a normal and an inverted cone frustum, i.e., it would always attempt to spring either up or down away from the flat position. When attached to the plastic rim, it was held against its will in the flat position, and by carefully balancing the force of the spring against the rim stiffness a cone surround was obtained that offered almost zero stiffness to axial movement and complied perfectly with the first two of the above requirements. However, extreme difficulty was experienced in meeting requirement 4.

The problems were finally overcome by the use of an impregnated polyether foam. The method of impregnation, which is novel, is such as to produce the effect of a "tapered" transmission line between the edge of the cone and the chassis.

Restoring force.—In the interests of mechanical stability it is essential that the cone assembly be provided with a restoring force to ensure that the coil always moves relative to a fixed mean position in the centre of the magnetic field. It is important for this restoring force *not* to be applied at the cone edge since this would incur cone flexing at low frequencies. The ideal position for the restoring force is at the rear of the cone where it acts also as a means of centring to maintain the coil in its correct axial position within the magnetic gap. If the axis of the cone is arranged in the horizontal position the location of the suspension system should be such as to support the cone and coil system at its centre of gravity (acknowledgement to Percy Wilson).

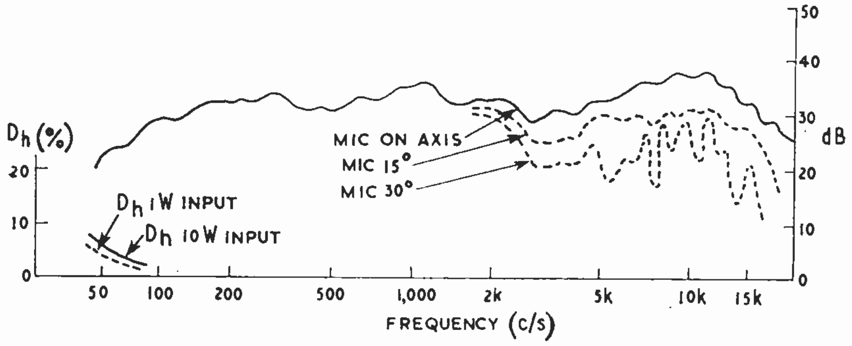
As a result of the restoring force the complete system will exhibit a resonance below which the condition of mass control will be no longer operative. The resonant frequency must therefore be near the lower limit of the required frequency range.

One very important requirement for the suspension system is that it must be completely linear over the full range of cone displacement. Failure to be so results in the very high harmonic distortion apparent in the extreme bass response of many loudspeakers. The suspension system itself must be mechanically stable, and this requirement led to the use of three tangentially disposed beryllium copper cantilevers (two of which are used to carry the voice coil current). The cantilevers are attached at their inner ends to a rigid insulating annulus surrounding the coil and attached to the coil via a "lossy" compliant medium the purpose of which is to ensure that the mass of the suspension system is decoupled from the coil at high frequencies.

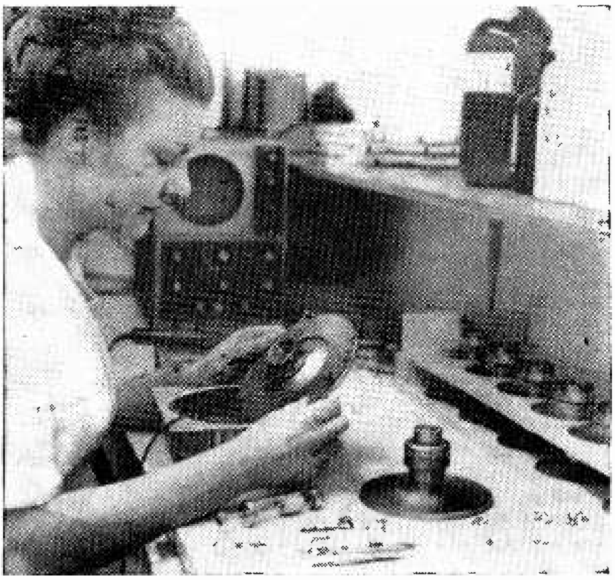
Chassis.—In the loudspeaker described the entire moving assembly is built up on a removable top plate which in turn is screwed to four supporting members attached to the magnet system. The entire assembly is suspended in a vented housing via an insulating medium to avoid transmission of energy to the housing and mechanical resonances. The detachable moving assembly is readily replaced in the event of misuse or damage, as shown in the photograph. The entire assembly is produced under laboratory conditions in a state of clinical cleanliness. .

Enclosure.—The titanium cone loudspeaker module was designed for reflex loading which, if correctly designed provides an extended low frequency performance having a very low distortion level within an enclosure of acceptable domestic dimensions.

It can be shown that for optimum performance the Q of the funda-



Above: Fig. 10. Performance curves of 4in diameter titanium cone loudspeaker.



Left: Assembling a titanium-cone loudspeaker. The entire moving assembly is mounted on a detachable ring. The outer housing is vented.

mental cone resonance in free air should be 0.62^2. If the internal volume of the enclosure is then such that the enclosed air stiffness is 1.62 of the suspension stiffness and the reflex vent is arranged to tune the enclosure to the free air resonance of the loudspeaker, the overall frequency response will be perfectly level down to that frequency. By an appropriate increase in enclosure size and retuning, the response can be extended to as much as an octave below this frequency with a response variation of not more than ±3dB.

A source of difficulty sometimes encountered with reflex loading is that at very low frequencies, i.e. below 20 c/s, the acoustic load applied to the cone falls very considerably and factors such as motor rumble can cause very considerable cone displacement. A solution to this problem has been found in the provision of a semi-flexible plastics diaphragm spanning the inside of the enclosure between the loudspeaker and vent. This has virtually no effect upon frequency down to the enclosure resonance, but below this it provides a progressively increasing stiffness controlled load.

Performance data.—The power response, axial pressure response, polar response and distortion are shown in the composite curve in Fig. 10. Unfortunately the author had insufficient time to secure facilities for transient testing but the performance in this respect can be demonstrated by white noise tests.

The question of Doppler distortion is often raised in reference to small full-range loudspeakers. There has recently been some dispute about the significance of this type of distortion, but accepting for the moment that its significance is proved, it is normally applied to small loudspeakers on the assumption that very large cone displacements are necessary to produce adequate radiated power at low frequencies. In our case this is not so since, owing to the efficiency of the type of reflex loading employed, the cone displacement of the loudspeaker described is no more than that encountered in the cone of a conventional 12in loudspeaker.

Final thoughts.—The most significant subjective advantages gained by the use of titanium as a cone material have been in the high frequency and transient responses. The author feels that at the moment there is no entirely adequate explanation for these subjective advantages in terms of the performance parameters normally discussed but that further light may be thrown upon the matter by an examination of the property of mechanical hysteresis within the cone. It is reasonably obvious that titanium will have a lower hysteresis loss when subjected to alternating flexure than any other diaphragm material hitherto used, and in the not too distant future it is hoped to make a complete examination of the relationship between mechanical hysteresis and subjective and objective transient performance.

My thanks are due to Imperial Metal Industries Ltd. for their very considerable help and advice on tooling and their extensive tests to determine the optimum material characteristics for our purpose; to John Martin of Martin Watch Laboratories, Bracknell, for his development of the cone tooling described; and to my assistant Margaret Collett for her work on the experimental and production prototypes.

REFERENCES

1. " Loudspeakers " by E. J. Jordan, Page 49. Focal Press, London (1963).
2. As above, p. 154, eqns. 10.19 to 10.23.

APPENDIX 1

Acoustic power P_r required to reproduce a full orchestra in a medium room (2,000 cu. ft.) at serious listening level (say 80dB) is 0.002 watts. Assume an l.f. limit of 40 c/s.

$$P_r = v^2 R_{MA} \,.\, 10^{-7} \text{ acoustic watts}$$

where v = r.m.s. velocity of cone

$$\therefore 0.002 = v^2\, 2.18 \times 10^{-6} \times r^4 \times 40^2 \times 10^{-7}$$

$$v^2 r^4 = \frac{0.002 \times 10^{-7}}{2.18 \times 10^{-6} \times 40^2}$$

$$\therefore vr^2 = 2.4 \times 10^3$$

From considerations of h.f. response discussed in text, r was found to be 6 cm.

$$\therefore v = \frac{2.4 \times 10^3}{36} \doteqdot 67 \text{ cm/sec}$$

$$\therefore v_{peak} = 1.11 \times 67 = 74.5 \text{ cm/sec}$$

From which the peak-to-peak displacement at 40 c/s

$$\frac{74.5}{2 \times 40} = 0.94 \text{ cm} = 0.366 \text{ inch.}$$

(Symbols defined in footnote on p. 555).

APPENDIX 2

Approximate expressions for radiation resistance (R_{MA}) above and below the curve " knee " are:

When $kr \ll 2$

$$R_{MA} \doteqdot 2.18 \times 10^{-6} f^2 r^4 \text{ mech. ohms.}$$

When $kr \gg 2$

$$R_{MA} \doteqdot 2.16 \times 10^5 r^2 \text{ mech. ohms.}$$

(Symbols defined in footnote on p. 555).

APPENDIX 3

Assume condition of mass control:—

$$P_r \propto \frac{F^2}{\omega^2 L_M{}^2} \,.\, R_{MA}$$

where L_M = cone mass.

When $kr \gg 2$ $R_{MA} \propto r^2 \propto A$

For a given cone thickness:—

$$L_M \propto r^2$$

$$\therefore \quad Pr \propto \frac{1}{f^2\, r^4} \,.\, r^2$$

If the effective cone radius were to remain independent of frequency, P_r would fall at 6 dB/octave. Including losses due to the voice coil inductance, this becomes 12 dB/octave. To compensate the above expression must vary as f^4.

$$\therefore \frac{1}{f^2\, r^4} \,.\, r^2 \propto f^4$$

$$\therefore \frac{1}{r^2} \propto f^6$$

$$\text{or } \frac{1}{r} \propto f^3$$

but r is a function of $\left(\frac{c_c}{f}\right)$

where c_c is the velocity of flexural wave motion in the cone.

Then $\frac{c_c}{f}$ must vary as $\frac{1}{f^3}$

$$\text{or } c_c \propto \frac{1}{f^2}$$

In a straight-sided cone, $c_c \propto 1/f$ approx. Thus the above indicates the need of a flared cone.

Consider now the frequency at which the reduction of radius should start. This is given by

$$f = \frac{c_c}{l_c}$$

where l_c is length of cone side.

The frequency corresponding to $kr = 2$ is

$$f = \frac{c}{\pi r}$$

where c is the velocity of sound in air. These two frequencies should be coincidental

$$\therefore \frac{c_c}{l_c} = \frac{c}{\pi r}$$

$$\therefore \frac{c_c \,.\, r}{l_c} = \frac{c}{\pi}$$

$$\therefore c_c \sin\theta = \frac{c}{\pi} = \text{const.}$$

where θ is the angle between the cone side and the axis.

While we are unable to calculate absolute values from the expressions, they do give a very good guide in experimental determination.

(Symbols defined in footnote on p. 555).