New Methodology for the Acoustic Design of Compression Driver Phase Plugs with Concentric Annular Channels*

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Compression drivers couple a radiating diaphragm to a horn throat of smaller area, resulting in high efficiency. When coupled to a suitable horn, this area reduction improves the match between the output mechanical impedance of the driver and the loading acoustic radiation impedance. Early workers had devised a phase plug to fill most of the cavity volume. Applying both an equal path-length and a modal approach to a phase plug with concentric annular channels coupled to a cavity shaped as a flat disk is explored. The assumption that the cavity may be represented as a flat disk is investigated by comparing its behavior with that of an axially vibrating rigid spherical cap radiating into a curved cavity. It is demonstrated that channel arrangements derived for a flat disk are not optimum for use in a typical compression driver with a curved cavity. A new methodology for calculating the channel positions and areas giving least modal excitation is described. The impact of the new approach is illustrated with a practical design.

0 INTRODUCTION

In compression drivers a large diaphragm is coupled to a small horn throat resulting in high efficiency. For this efficiency to be maintained to high frequencies the volume of the resulting cavity, between horn and diaphragm, must be kept small. Early workers devised a phase plug to fill most of the cavity volume and connect the diaphragm to the horn throat with concentric annular channels of equal length to avoid destructive interference [1]. Later work, representing the cavity as a flat disk, describes a method of calculating the positions and areas of these annular channels where they exit the cavity, giving least modal excitation, thus avoiding undesirable response irregularities [2].

Others [3] found that achieving this high compression ratio required the cavity between horn throat and diaphragm to be "plugged," reducing the air volume and high-frequency loss due to its compliance. Further improvement at high frequencies could be made by splitting the sound path between diaphragm and throat into a number of channels of equal length and of smoothly increasing areas. These devices soon became known as phase plugs since they were intended to correct the phase by providing paths of equal length from the diaphragm to the horn throat, thus avoiding destructive interference. Phase plugs allow large diaphragms and correspondingly large voice coils to be used with directional horns, yielding a massive increase in efficiency and maximum SPL when compared to an equivalent direct-radiating loudspeaker. Poorly designed phase plugs exhibit large response irregularities, which often limit driver performance.

In this paper we first explore equal-path-length and modal methods of phase-plug design on an idealized model with a cylindrical air cavity and planar rigid piston using the finite-element method (FEM). We will then compare this flat-disk-shaped cavity to a more realistic spherical-cap-shaped cavity. A new methodology for the positioning and sizing of annular phase-plug channels is then presented.

0.1 Compression Driver Description

Fig. 1 shows a schematic section through a typical compression driver with an annular channel phase plug. The ring magnet produces an intense magnetic field,

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which is concentrated in the magnetic gap by the highly permeable top plate and yoke. The voice coil is immersed in this strong radial field; current flowing in it results in an axial force. This force is transmitted to the diaphragm by a rigid former. A flexible suspension maintains the centralization of the coil, while allowing axial motion. Axial displacement of the diaphragm causes the cavity thickness to be reduced, resulting in an airflow down the channels, through the driver exit and into the horn. In the driver considered in this paper, the magnetic gap is filled with magnetic fluid. This simplifies the acoustic behavior by blocking the air cavity in the magnet.

0.2 FEM Methodology

The geometries being considered in this paper are all axisymmetric and orientated with the *x* axis being the axis of rotational symmetry. To take advantage of this symmetry in the analysis, second-order axisymmetric elements are used throughout.

The models of idealized compression-driver diaphragms are represented with shell elements, having repeated freedoms and restraints to replicate rigid-body motion. The air is represented by "solid" quadrilateral elements. The termination of the channels is achieved by applying the specific impedance of air as a boundary condition to the channel ends. This avoids reflections as the channels are narrow compared to a wavelength, and only plane waves can propagate within them. The effects of viscosity are neglected in these models.

The models of idealized compression drivers have a constant force applied to the diaphragm, whereas the models of the cavity only have an enforced constant diaphragm displacement.

The FEM examples of idealized drivers have a moving mass of 0.04 gram, with 1 N of driving force applied. All models have an 80-mm-diameter diaphragm with a cavity thickness of 0.3 mm and a compression ratio (the ratio of total channel area to diaphragm area) of 15.

The solutions are obtained with the PAFEC [4] steady-state solver running on an Intel Xeon 2.33-GHz processor. For the idealized compression drivers this allowed 500 frequencies to be solved in 20 seconds.

The idealized driver models are solved to obtain the frequency responses of the pressure at selected points near the channel end. For our purposes the aim is to have smooth responses with the same sound pressure frequency and phase responses in all channels.

The models of a cavity without channels have the frequency response extracted over a range of positions expressed as radii for the flat disk or cavity angle in the curved cases. Contour plots of the pressure in the cavity as a function of frequency and position are produced to illustrate the pressure behavior in the cavity.

1 CURRENT PHASE-PLUG DESIGN METHODS

1.1 Equal-Path-Length Approach

One of the earliest concepts applied to positioning the channels in a phase plug results from considering the effect of destructive interference. If we assume that the sound simply travels from a point on the diaphragm to the nearest channel, it would then seem reasonable to assume that when the furthest distance from a diaphragm to a channel is a half-wavelength, we could expect some destructive inference to occur. This leads to the conclusion that if we position the channels to keep the channel spacing to less than a half-wavelength of the highest frequency in the desired bandwidth, then we could expect a good response up to this frequency [5].

To explore this idea further we will consider the results of an FEM model of an idealized version of the compression driver shown in Fig. 1. Compression drivers with magnetic fluid in the gap fit the idealized model best since the fluid may be assumed to remain stationary. The resulting acoustical seal, shown in Fig. 2, prevents sound leakage out of the cavity between diaphragm and phase plug.

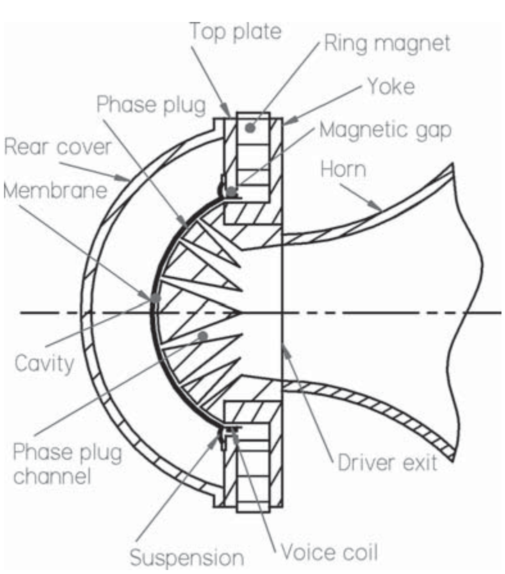


Fig. 1. Diagram of compression driver.

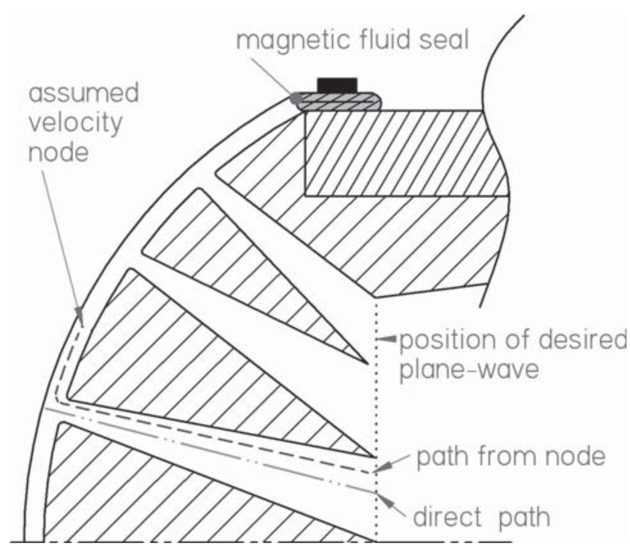


Fig. 2. Detail of compression driver showing path lengths from diaphragm to position of desired wavefront.

The idealized driver shown in Fig. 3 has three channels and a circular planar piston. The piston is constrained to move as a rigid body and forms one face of the cylindrical cavity. The other face has one central cylindrical channel and two equally spaced annular channels terminated with an appropriate impedance to avoid reflections. This geometry is described in Smith [2, p. 310, fig. 8].

The difference between the longest and shortest routes from the diaphragm to a channel is 16 mm, which is half a wavelength at 10.625 kHz. The results of the FEM analysis are shown in Fig. 4 with the pressures in the three channels plotted.

It may be observed that these pressures are not regular and do not all have dips at 10 kHz as one may expect. In addition some severe peaks are present in the response, which cannot be readily explained by path-length difference and interference.

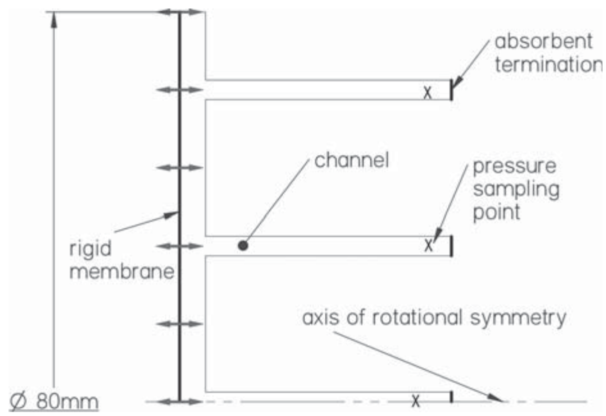


Fig. 3. Geometry used for FEM model with three evenly spaced channels.

1.2 Modal Control by Channel Balancing

When a phase plug is placed in front of the radiating diaphragm, a thin cavity is created. The response irregularities observed in Section 1.1 are due to the excitation of acoustic resonances in this cavity.

The nature of these resonances can be clearly demonstrated if the same cavity as analyzed before, with the channels removed, is driven by a source at its outside diameter. Fig. 5 shows a contour plot of the pressure variations across the cavity radius (vertical axis) with frequency (horizontal axis) calculated by an FEM model for this case.

1.2.1 Modal Excitation by Channels Alone

An interesting solution exists when the same cylindrical cavity with no channels is driven by a circular planar rigid diaphragm on one of its faces. The piston is constrained to move with a fixed displacement to avoid pressure variations with frequency. The pressure variation across the cavity radius is displayed in Fig. 6. There is a maximum of 0.002-dB variation across the entire cavity.

There is no modal excitation since axially the cavity is much smaller than a wavelength, even at the highest frequency considered, and the radial modes are not excited as they are driven orthogonally. From this result we may now conclude that, in the case of the evenly spaced channels discussed in Section 1.1, it is the presence of the channels that is responsible for the presence of the cavity modes.

1.2.2 Suppression of Modes by Channel Position and Size

Smith [2] shows that in this simplified cylindrical representation it is possible to choose the areas and radii of

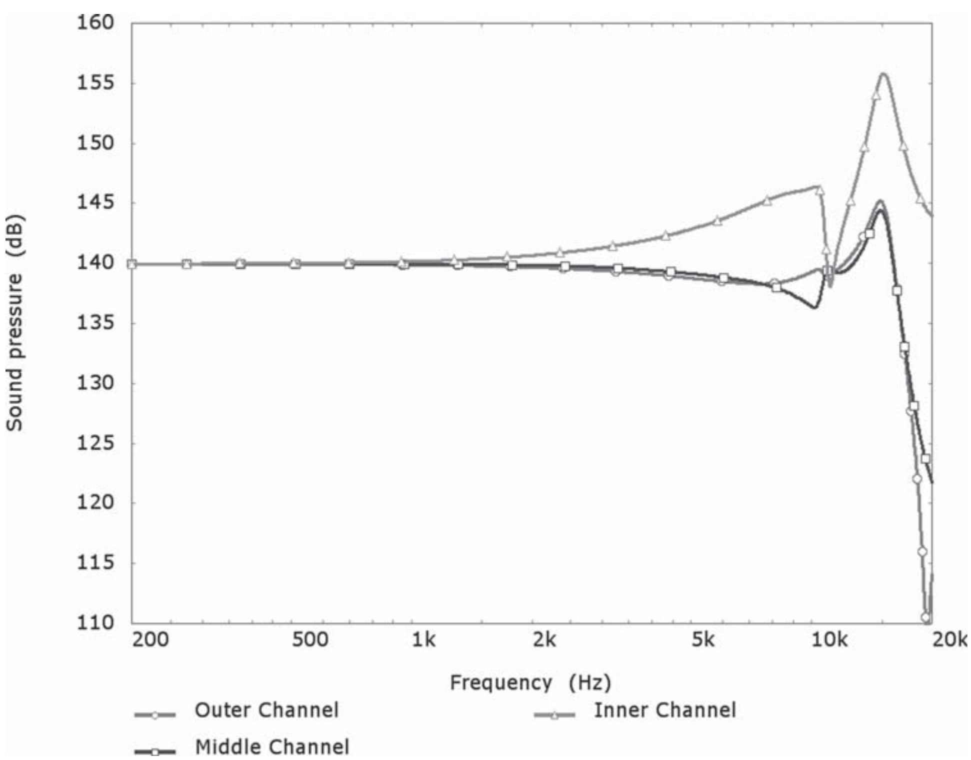


Fig. 4. Pressure response of cylindrical cavity with equal channel widths and equal path length.

the N channels so that the modal excitation from each cancels for modes up to the Nth mode. An example of such a design is illustrated in Murray [6].

Fig. 7(a) shows the excitation of the first radial cavity mode by each of three phase-plug channels positioned as described by Smith. The three modal excitations sum to zero because of the presence of each channel, and the mode is suppressed.

Fig. 7(b) displays the same information, this time for the second radial cavity mode. The degree to which each channel excites the mode is dependent upon the channel area and also the magnitude of the mode at the channel position. This is why the magnitude of excitation from each channel is not the same in the two cases plotted.

The third, radial mode is also suppressed, though this is not plotted as it is a trivial result—each channel is posi-

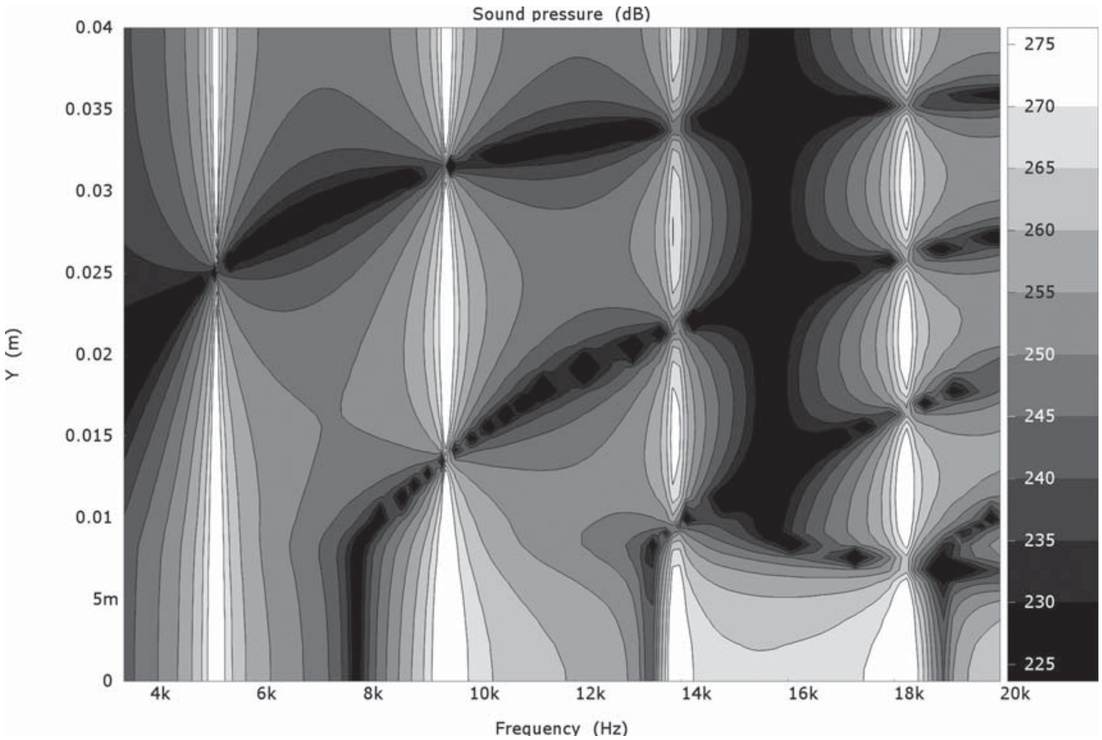


Fig. 5. Pressure variations in cavity with source at outside diameter.

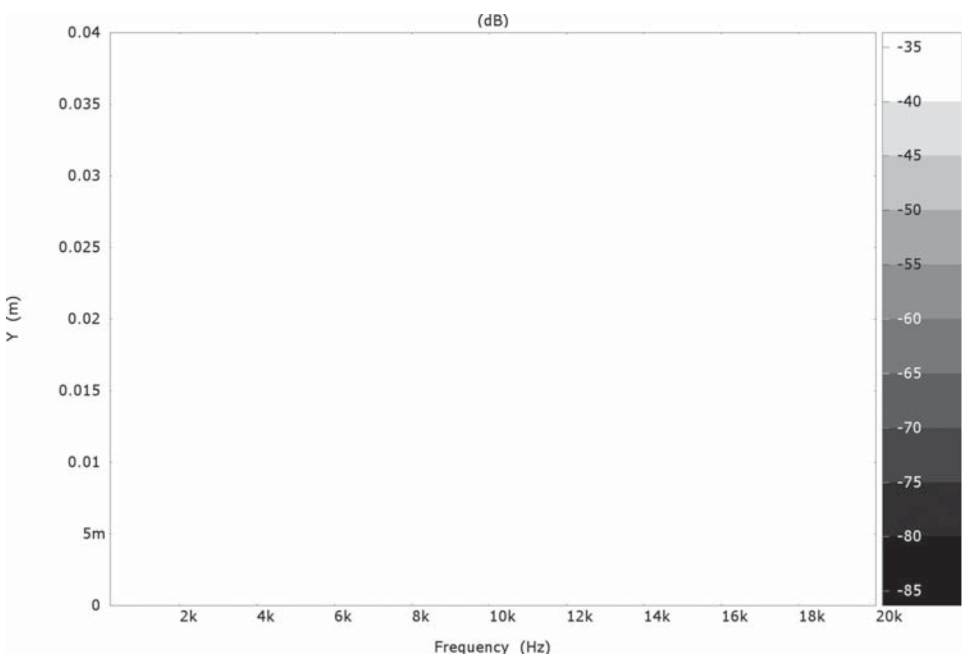


Fig. 6. Planar piston in cylindrical cavity. No contours since pressure variation is only 0.002 dB.

tioned at a nodal line and each provides no contribution to the modal excitation.

The vectors show the excitation of the modes at the channel positions. In all three cases, at any position in the cavity, the pressure cancels, resulting in zero modal excitation. The interested reader is directed to the Appendix.

Fig. 8 shows the pressure response of each channel calculated by an FEM model of a three-channel Smith phase plug. The channel pressures are almost identical, confirming the almost complete absence of cavity modes.

1.2.3 Effect of Practical Departure from a Cylindrical Geometry

In practice compression driver diaphragms need the curvature to be sufficiently rigid and are shaped as a spherical cap. The more curved the diaphragm, the higher

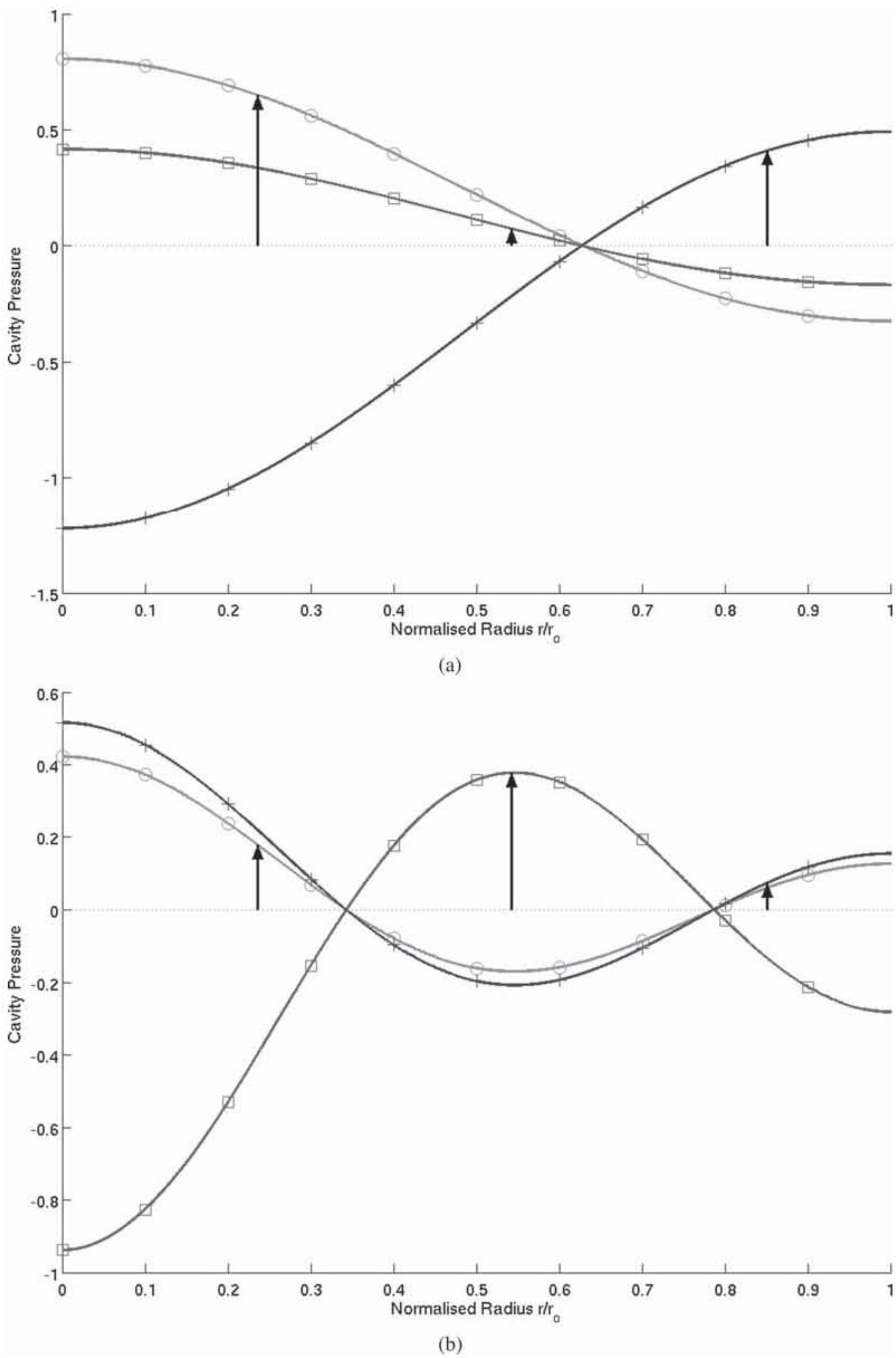


Fig. 7. Pressure excited by each channel plotted against normalized radius. (a) First mode. (b) Second mode.

the first parasitic structural mode. The effect of this departure from the simplified cylindrical geometry cannot be neglected. The motion of the diaphragm is no longer orthogonal to the cavity resonances.

Fig. 9 shows that an axially moving spherical cap will excite resonances in the, now curved, compression cavity. The positions and ratios calculated by Smith's analysis will not suppress this modal excitation.

1.3 Modal Excitation by Diaphragm

The important aspect of the behavior that is overlooked by an analysis in cylindrical coordinates is the excitation

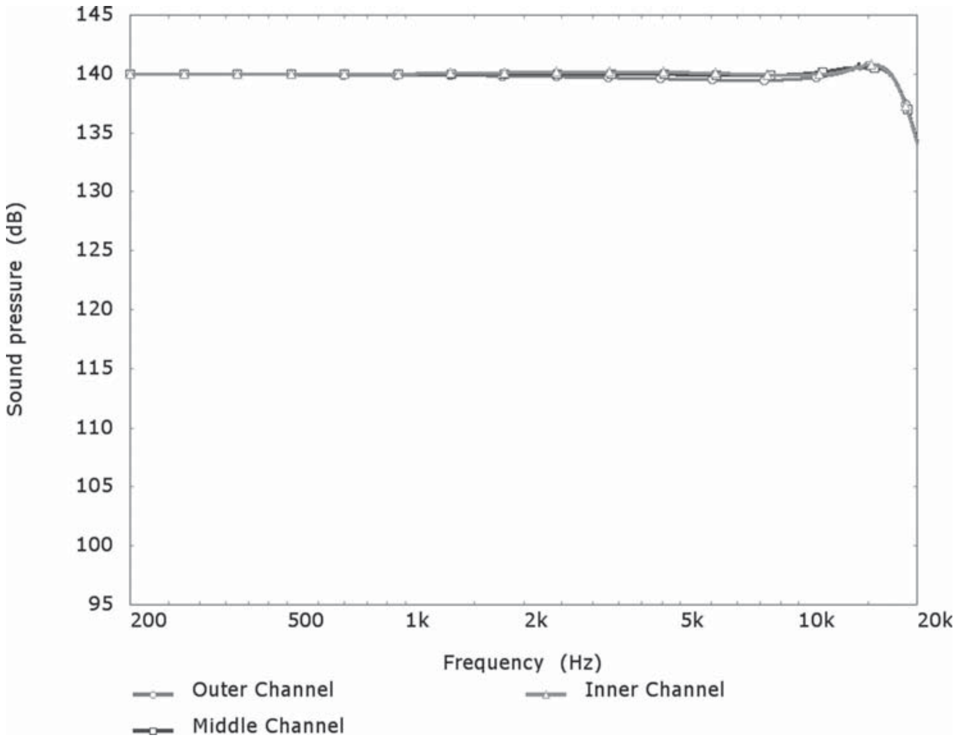


Fig. 8. Pressure response of planar piston with phase-plug design to suppress modes.

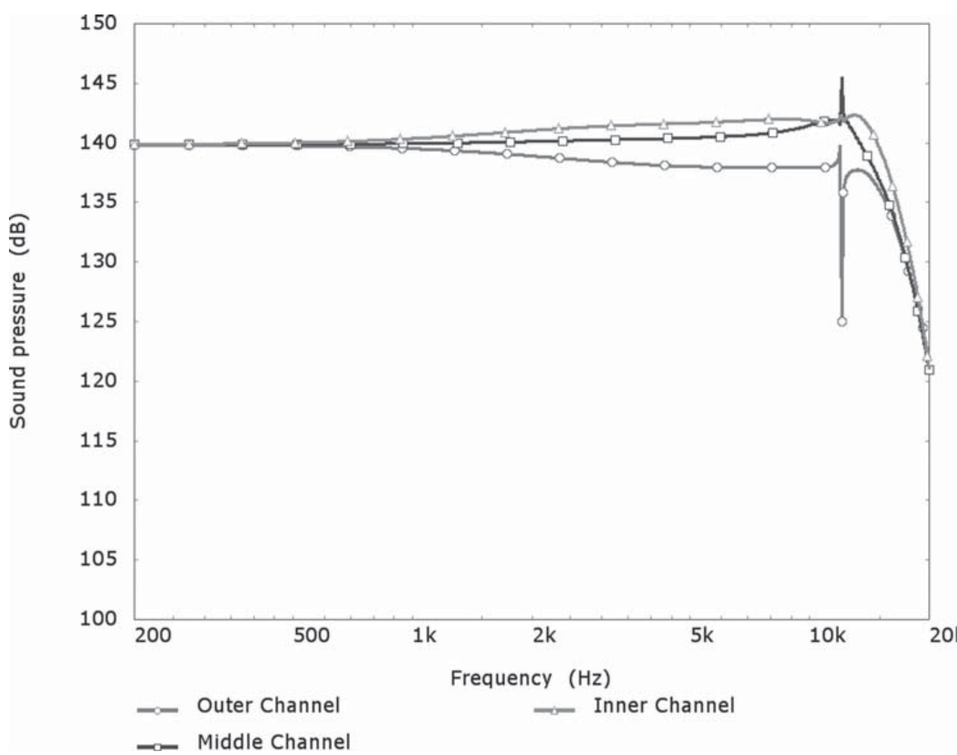


Fig. 9. Spherical-cap diaphragm with channels defined by applying result for cylindrical cavity.

of the cavity modes directly from the diaphragm motion. Fig. 10 shows the pressure in a curved cavity with no channels excited by an axially moving spherical cap. Unlike for the planar piston, the resulting volume velocity is not orthogonal to the modes and the cavity resonances are excited.

1.4 Suppression of Modes by Balancing Channel and Diaphragm Excitation

In order to improve upon Smith's method for setting the channel geometry, it is necessary to analyze the behavior of the diaphragm, cavity, and channels in a spherical coordinate system. This allows a representation closer to the practical reality since cavity and diaphragm are spherical caps just as in real compression drivers.

Conceptually the approach is similar to Smith's. All excitation of the cavity modes is synthesized such that the overall pressure variation in the cavity is zero. Whereas in Fig. 7(a) and 7(b) all contributions are due to the volume velocity at the channel entrances, we now have an additional contribution due to the velocity of the diaphragm itself.

Fig. 11 shows the modal excitations from the channels and diaphragms for a design with a curvature of 55° measured from the axis of rotation to the dome edge. The channel positions and areas are designed so that the modal excitations due to each channel and also due to the diaphragm sum to produce zero pressure variation in the cavity. The derivation of the positions and areas of channels required to achieve this modal suppression was carried out by two different methods.

1) The curved cavity was analyzed using a parameterized FEM model. Among the parameters of the model were the design variables in which we are interested—positions and areas of the channels. An optimization was used to minimize the difference between the three channel pressures.

2) The behavior of the cavity was analyzed analytically in a manner similar to that of Smith, albeit in spherical coordinates. The details of this analysis are given in the Appendix.

In both cases very similar results were obtained. Unlike the Smith design guidelines, the channel geometry is dependent upon the curvature of the dome diaphragm and compression chamber. The degree to which the dome itself excites the cavity modes is dependent upon the cavity angle. The new design method tends toward the Smith guidelines as the angle of the cavity curvature is decreased and the flat, cylindrical situation is approached.

It may be observed from Tables 1 and 2 that the change in the calculated widths of the channels is much larger than the change in the positions. In both cases we position our channels to be very close to the nodal lines of the *N*th cavity mode. The similarity in positioning highlights that in both cases the mode shape is very similar and these nodal lines occur in roughly the same position around the cavity.

Being a little more precise, with the new design method the target is, in fact, not to place the channels

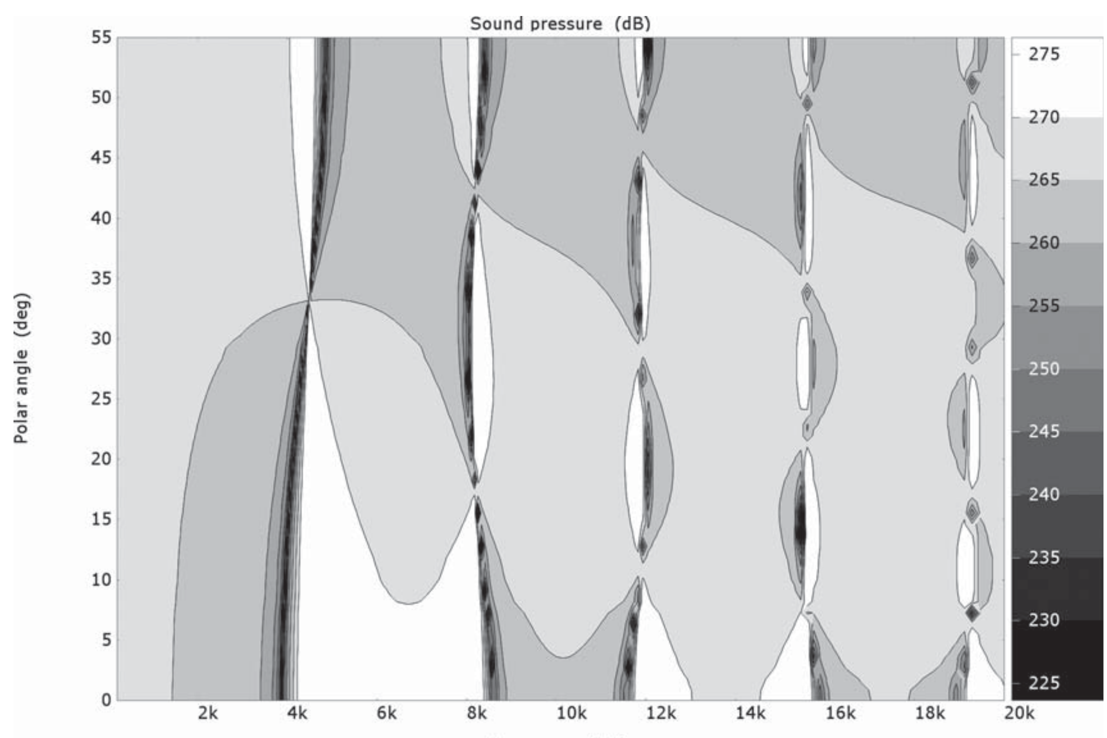


Fig. 10. FEM model of curved cavity, no channels, rigid axially moving diaphragm.

in exactly the nodal positions but, as with the lower modes, to compensate for the excitation by the dome diaphragm. The channels are placed slightly away from the nodal lines. However, this shift is very small as inevitably the channels excite the *N*th mode constructively. In addition the dome modal excitation reduces with higher modes. Only a minute shift is required to match the channel excitation to the dome excitation. In practice it is not clear whether the best solution is to attempt to suppress the *N*th mode or to simply decouple the channels from it and aim positionally directly for the nodal lines. This is largely academic with any

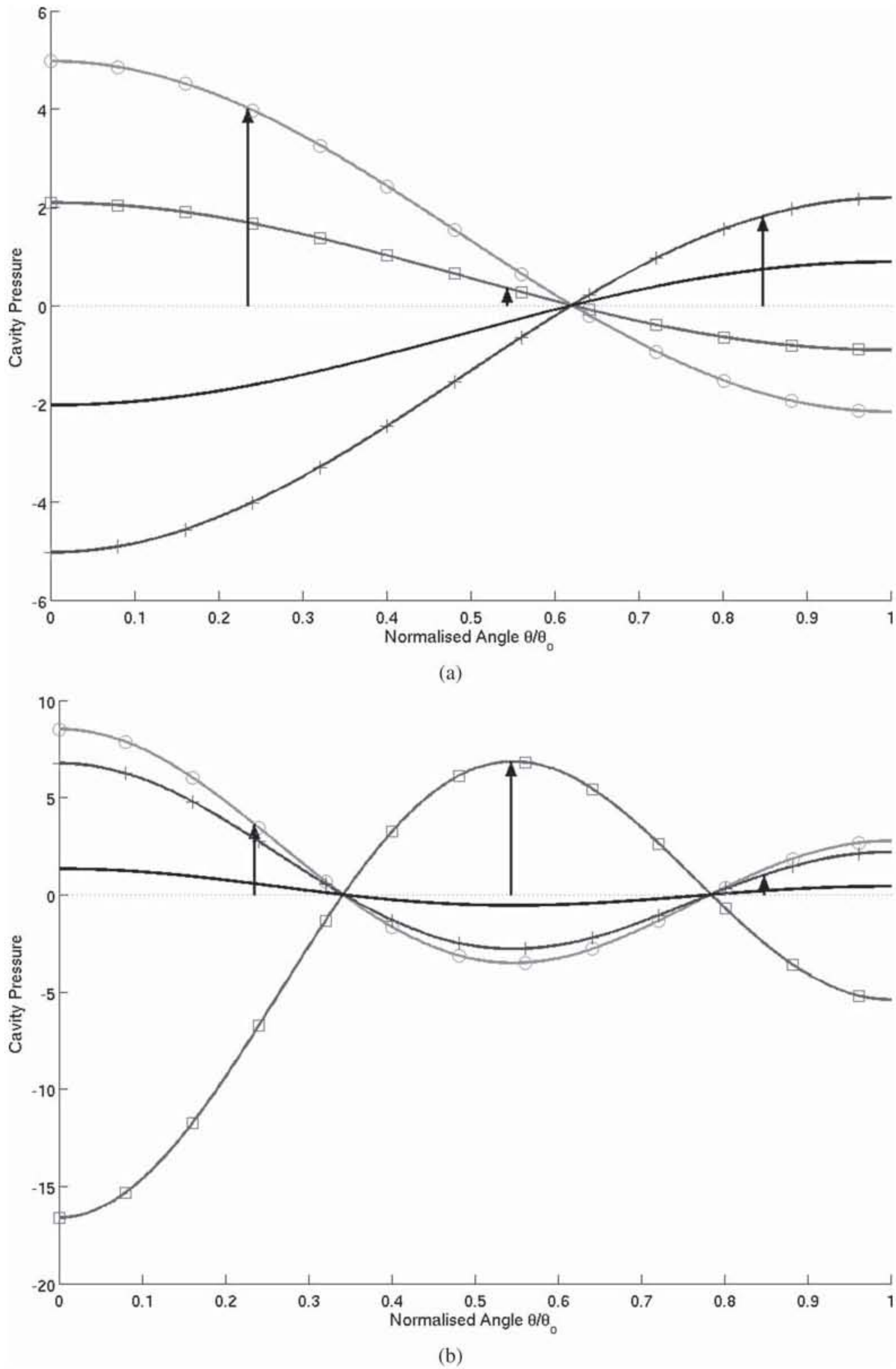


Fig. 11. Pressure excited by each channel (broken lines) and diaphragm (solid line) plotted against normalized cavity angle. (a) First mode. (b) Second mode. (c) Third mode.

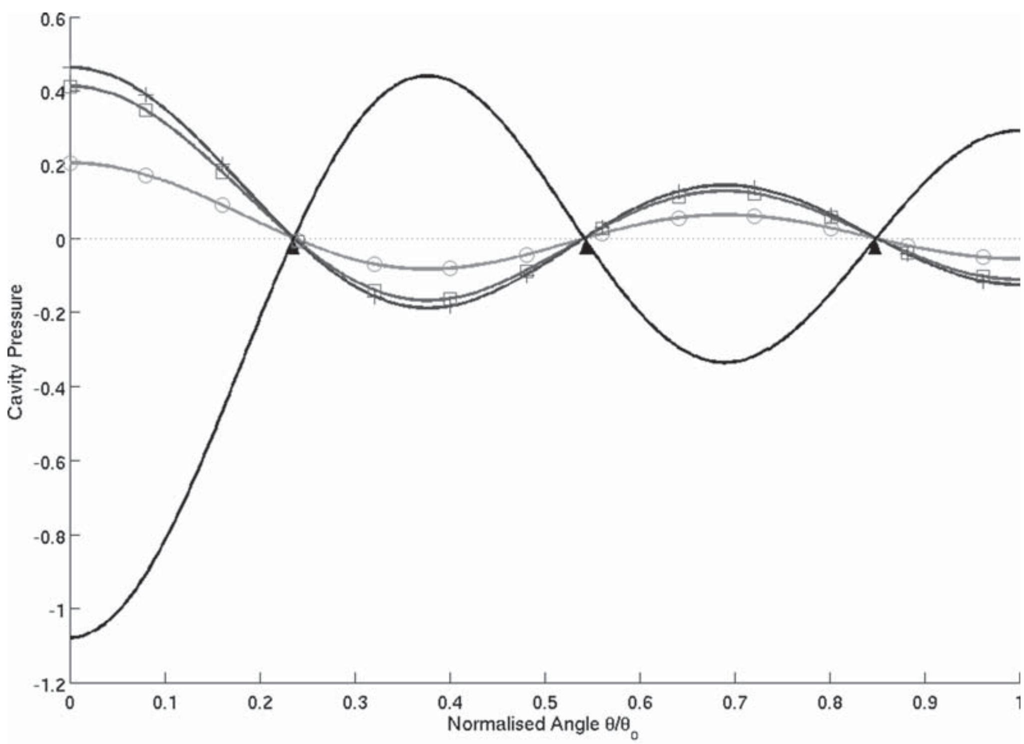
reasonable dome angle and the cases $N > 1$. In practical terms the positional difference is minute, as can be seen from Table 1. For the case $N = 1$, however, this question remains.

Fig. 12 shows the pressures in the three channels calculated by an FEM model of the same curved cavity as in Fig. 9, with the channels arranged using the new design method. A good improvement in the regularity of the pressure in each of the channels can be observed.

It is interesting to note that it is not possible to synthesize a design to work as well in the curved cavity as can be achieved in the flat-disk case (Fig. 8). With the flat-disk cavity it is not necessary to link the channel velocity to the diaphragm velocity as all the excitation of the modes is by the channels. With the curved case this added complication results in a small quadrature component between channel and diaphragm velocity that cannot be suppressed. In addition, it is very safe to assume that in the case of the flat disk, the acoustical impedance of each of the channels is the same. However, this is certainly a less accurate assumption in the curved case as the channels themselves are forced to have some curvature. Nevertheless it is clear that the assumptions made in the analytical analysis are quite reasonable because of the good agreement with the optimized FEM results.

2 APPLICATION TO PRACTICAL COMPRESSION DRIVER

The approach described in this paper was developed during the design of a 1.4-in (35.5-mm)-diameter exit compression driver. This driver has a 3-in (76-mm) voice coil wound with copper-clad aluminum wire onto a glass-filled polyimide former. The former is coupled to a titanium dome diaphragm, which is supported by a polyimide surround. The acoustic FEM model used in the driver development includes most physical detail. The mesh used was associatively linked to a parameterized solid model. This allowed most aspects of the design to be readily varied. For example, channel position, width, and length were all controlled by parameters in addition to many other aspects of the design. The mechanical parts



(c)

Fig. 11. *Continued*

Table 1. Comparison of channel positions for a three-channel design having a 55° curved cavity and a flat cavity [7].

55°	Flat Disk
0.235 θ_0	0.238 r_0
0.543 θ_0	0.543 r_0
0.848 θ_0	0.853 r_0

Table 2. Comparison of channel widths for a three-channel design having a 55° curved cavity and a flat cavity [7].

55°	Flat Disk
1	1
0.9056	1.025
0.6973	1.065

are all flexible and are coupled to the acoustical parts of the model.

Many FEM models of other domains were used, static magnetic for magnet design, magnetodynamic for copper sleeve design, and derivation of blocked impedance of voice coil. The use of these other FEM techniques to derive the frequency response of a driver are described in [8]. In addition large-displacement analysis was used to evaluate compliance variation with diaphragm displacement due to the surround, resulting in the choice of a small surround with a single roll.

One important aspect of the phase-plug design was the length and area of the channels themselves. While the application of path lengths to the positions of the channels was not found to give a useful result, the lengths of the channels themselves were found to be important. This is illustrated as an example in [8]. The final phase-plug design is illustrated in Fig. 13 mounted on a horn.

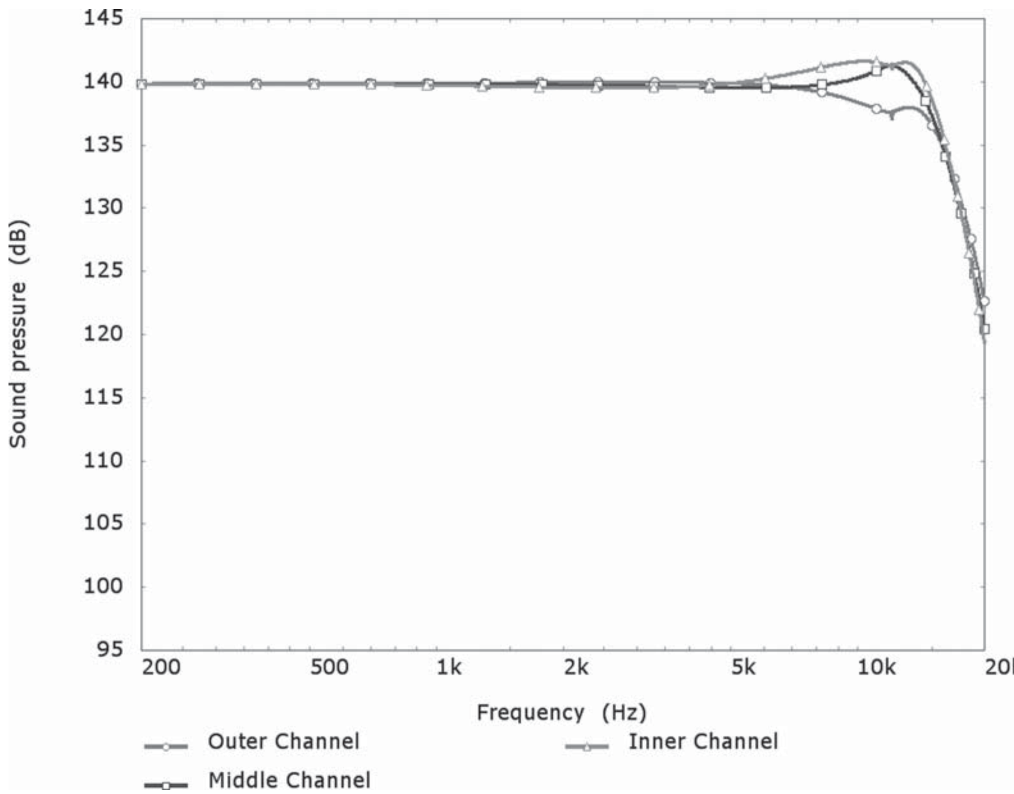


Fig. 12. Spherical cavity with channel position and width derived by new approach.

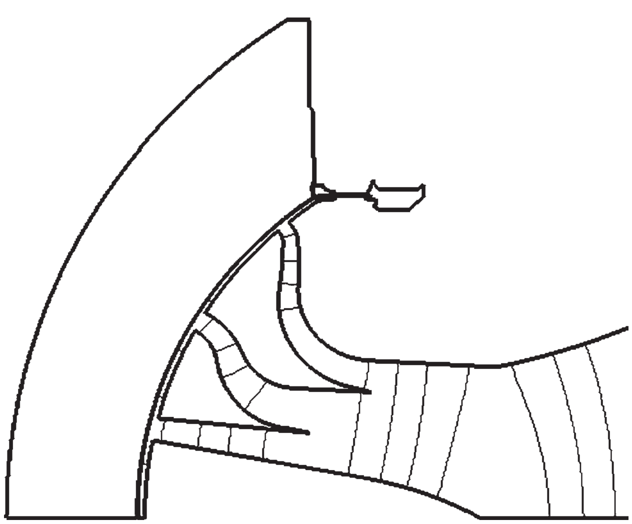


Fig. 13. FEM model of final design on horn showing iso pressure contours at 8.417 Hz.

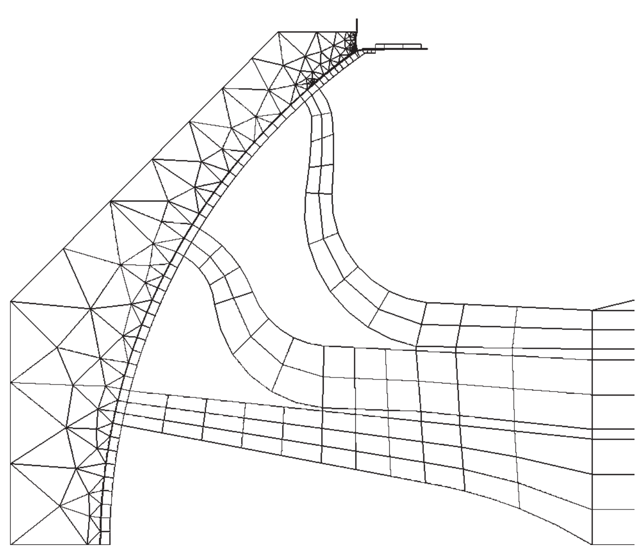


Fig. 14. Acoustical FEM mesh of full compression driver.

The FEM mesh used for this calculation is shown in Fig. 14.

3 DISCUSSION

This work, by necessity rather than intention, has resulted in an interesting counterpoint of analytical and computational analysis. FEM is used as a tool to get at the behavior by splitting the problem or design into abstract experiments. Analytical analysis helps to confirm the physics and that an optimum solution is reached. It also makes it possible to generalize (for example, for many angles). For some cases with too many degrees of freedom there is no alternative.

FEM can, of course, go further and attempt to find solutions for more complex cases such as optimum positions and widths of channels when the dome is not rigid or there are cavity and dome shapes that cannot be described by separable coordinate systems.

Computational analysis is not, however, required to understand that the cylindrical representation is not a sufficient description of the problem considered. Conversely, the analytical analysis of the spherical case is complicated by the presence of Legendre functions of noninteger order and integrals of these functions. Issues dealing with such expressions are neatly sidestepped as happily we are able to insert a little numerical analysis when other routes fail. The eigenfunctions used in the analysis are, in fact, calculated with FEM models.

The traditional analytical analysis approach of reducing a problem into easy-to-understand simply behaving parts is a truly powerful way of applying FEM modeling. The parts can be analyzed and conquered individually. Assumptions can be checked and the parts reassembled after they are understood.

The improved design guidelines for compression drivers outlined in this work are a result of increasing the realism of the analytic model. However, there are still a number of aspects in which a practical driver might differ from this improved model. For example, the compression driver under consideration in this paper uses a magnetic fluid to seal the voice coil gap at the outside edge of the compression cavity. It is assumed that compressibility of the fluid is not significant and the fluid does not move as a result of the acoustical pressure in the cavity. Hence the outside edge of the cavity is modeled as having a zero particle velocity boundary condition at the voice coil gap. However, if the gap is not filled with magnetic fluid this boundary condition would diverge from that assumed. There would be some complex radial particle velocity at the outside edge of the cavity. Depending upon the severity of this divergence of the boundary conditions, a degradation in the compression driver performance may be seen compared to the results shown here.

For individual designs modern numerical modeling tools are more than powerful enough for considering additional features on a case-by-case basis. Fig. 15 is a good indicator of how accurate these techniques can be. The modeled results shown include the nonrigidity of the compression driver diaphragm, and, of course, the measurement captures all effects, such as viscous behavior in the channels.

4 CONCLUSIONS

The equal-path-length approach does not take into account the modal behavior and cannot be expected to produce optimum results in every case. Smith's methodology is very successful with the flat-disk-shaped cavity giving almost total suppression of the modes. However,

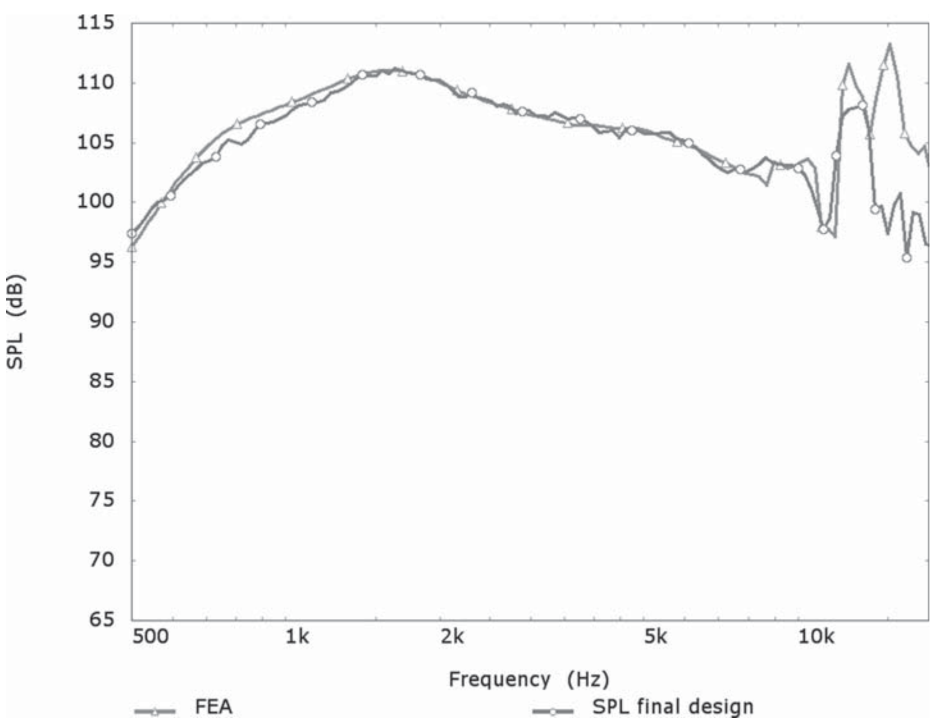


Fig. 15. FEM versus measured frequency response on axisymmetric horn.

when applied to a cavity shaped like a spherical cap Smith's technique does not produce such good results. While for the planar diaphragm the channels alone excite the modes, the spherical-cap diaphragm excites the modes even in the absence of channels. In this paper it is demonstrated that the correct choice of channel widths and positions can compensate for the normal volume velocity variations of the diaphragm and avoid exciting modes.

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APPENDIX
ANALYTICAL ANALYSIS OF CYLINDRICAL AND CURVED CAVITY

An analytical analysis of the compression cavity is presented in this appendix. In addition to the analysis in a spherical coordinate system, as described in the main body of the paper, Smith's analysis in a cylindrical cavity is repeated in the same terms as the new analysis so that the two methods may be compared directly.

The driven behavior an acoustical enclosure can be described as a summation in the following form:

$$p(\boldsymbol{x}) = \sum_{n=0}^{\infty} \frac{\omega\rho_0 c_0^2 \Psi_n(\boldsymbol{x})}{V\left[\omega c_0 D_{nn} + \mathrm{j}\left(\omega^2 - \omega_n^2\right)\right]} \times \int_S \Psi_n(\boldsymbol{y}) u(\boldsymbol{y}) \cdot \boldsymbol{n}\, \mathrm{d}S \quad (1)$$

where $\Psi_n(\boldsymbol{x})$ and ω_n are the eigenfunctions and eigenvalues of the enclosure.

This form of expression, sometimes referred to as a modal decomposition, was described by Morse and Bolt [16]. A clear explanation and modern derivation of the expression can be found in Nelson and Elliot [9].

A.1 Analysis with Cylindrical Geometry

The compression cavity is analyzed in a simplified cylindrical geometry, as illustrated in Fig. 16. This is a repetition of the analysis performed by Smith [2].

A.1.1 Eigenfunction and Eigenfrequency Calculation

Starting from the Helmholtz equation,

$$\nabla^2 p + \frac{\omega^2}{c_0^2} p = 0. \quad (2)$$

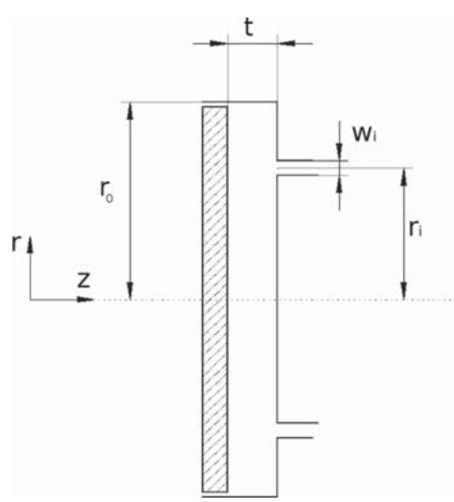

Fig. 16. Cylindrical representation of compression driver.

In cylindrical coordinates the Laplacian can be written as [10]

$$\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2}. \tag{3}$$

The compression chamber is a thin disk. In the operating range of the driver the pressure variation across the thickness of the disk is negligible. In addition, the cavity, diaphragm, and channel entrances are rotationally symmetric. We can remove some terms from the Laplacian to have

$$\nabla^2 p = \frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r}. \tag{4}$$

Substituting Eq. (4) into Eq. (2) and multiplying by r^2,

$$r^2\frac{\partial^2 p}{\partial r^2} + r\frac{\partial p}{\partial r} + r^2\frac{\omega^2}{c_0^2}p = 0. \tag{5}$$

Bowman [11] describes a transformed version of the Bessel differential equation [12], a simplified version of which is

$$x^2\frac{\mathrm{d}^2 y}{\mathrm{d}x^2} + x\frac{\mathrm{d}y}{\mathrm{d}x} + x^2\alpha^2 y = 0. \tag{6}$$

The similarity of Eqs. (5) and (6) is clear. Eq. (6) has the solutions

$$y = C_1 J_0(\alpha x) + C_2 Y_0(\alpha x) \tag{7}$$

where J_0 is a Bessel function of the first kind and Y_0 is a Bessel function of the second kind. Y_0 is singular at $Y_0(0)$. Constraining the pressure in the cavity to be finite, we shall assume that the pressure eigenfunction may be described as

$$\Psi_n(r) = C_1 J_0(\alpha r). \tag{8}$$

The pressure must obey the rigid-wall boundary condition at the diameter of the cylindrical cavity, as described by Eqn. (9).

$$\left[\frac{\mathrm{d}\Psi_n(r)}{\mathrm{d}r} = 0\right]_{r=r_0}. \tag{9}$$

This requirement can be met by the choice of α,

$$\alpha_n = \frac{j_n}{r_0}, \qquad J_1(j_n) = 0 \tag{10}$$

where j_n is the nth root of the Bessel function of the first kind J_1. The eigenfrequencies can be found by equating $\alpha^2 = \omega^2/c_0^2$.

A.1.2 Pressure Response of Cavity without Channels

Having calculated the rigid-wall eigenfunctions and frequencies we may now analyze the driven behavior of the compression cavity. It is interesting to first perform this analysis for a cavity having a rigid-disk diaphragm radiator occupying the entire entrance side and no channels on the exit side.

As discussed previously, the pressure in the cavity can be described as a summation of contributions from each of the calculated eigenfunctions. We neglect the damping term D_{nn} present in Eq. (1) since this is vanishingly small in the rigid-wall compression cavity,

$$p(\boldsymbol{x}) = \frac{\mathrm{j}\omega\rho_0 c_0^2}{V}\sum_{n=0}^{\infty}\frac{\Psi_n(\boldsymbol{x})}{\omega_n^2 - \omega^2}\int \Psi_n(\boldsymbol{y})u(\boldsymbol{y})\cdot\boldsymbol{n}\,\mathrm{d}S. \tag{11}$$

The cavity is only driven by the diaphragm on the entrance side of the compression cavity. The surface velocity is zero at all other locations on the enclosure walls. The integral on the right-hand side can be rewritten by a change of variables,

$$\int_S \Psi_n(\boldsymbol{y})u(\boldsymbol{y})\cdot\boldsymbol{n}\,\mathrm{d}S = \int_{r=0}^{r_0}\Psi_n(r)u_0 2\pi r\,\mathrm{d}r \tag{12}$$

where u_0 is the diaphragm velocity. Because of the orthogonality of the eigenfunctions, it is clear that this integral is only nonzero for $n = 0$,

$$\int_{r=0}^{r_0}\Psi_n(r)u_0 2\pi r\,\mathrm{d}r = \begin{cases} u_0\pi r_0^2, & n = 0 \\ 0, & n \neq 0 \end{cases}. \tag{13}$$

The summation in Eq. (11) disappears and the pressure in the cavity is simply

$$p = \frac{\rho_0 c_0^2}{\mathrm{j}\omega V}u_0\pi r_0^2. \tag{14}$$

The pressure field in the cavity does not have contributions from any mode other than the zeroth, the static 0-Hz mode. This is because the excitation is orthogonal to all other calculated eigenfunctions. The expression in Eq. (14) is that of a simple acoustical compliance C_a, with acoustical impedance $\rho_0 c_0^2/\mathrm{j}\omega V = 1/\mathrm{j}\omega C_\mathrm{a}$, driven by a volume velocity of strength $u_0\pi r_0^2$.

A.1.3 Pressure Response of Cavity with a Number of Annular Exit Channels

The arrangement of a compression driver is to have not only a radiating diaphragm on one face of the cylindrical compression cavity, but also a number of exit channels on the opposite face, which lead through the phase plug and to the horn, through which sound is radiated.

The exit side surface normal acoustic particle velocity is represented by the function $f(r)$, defined as

$$f(r) = \begin{cases} 0, & r \neq r_1, r \neq r_2, r \neq r_3, \cdots \\ u_1, & r = r_1 \\ u_2, & r = r_2. \\ \vdots & \end{cases} \tag{15}$$

We may extend Eq. (14) to include pressure variations in the cavity occurring due to the velocity $f(r)$,

$$p(r) = \frac{\mathrm{j}\omega\rho_0 c_0^2}{V}\left[\frac{u_0\pi r_0^2}{-\omega^2} + \sum_{n=0}^{\infty}\frac{\Psi_n(r)}{\omega_n^2 - \omega^2}\int_S \Psi_n(\hat{r})\,f(\hat{r})\,\mathrm{d}S\right]. \tag{16}$$

As the channels are narrow, we approximate that the integral may be evaluated with reasonable accuracy as

$$\int_S \Psi_n(\hat{r})f(\hat{r})\ \mathrm{d}S \approx \sum_{i=1}^{N}\Psi_n(r_i)A_i u_i \tag{17}$$

where A_i is the area of the ith channel entrance, r_i is the radial location of the channel, and u_i is the acoustic particle velocity at the channel entrance. Then

$$p(r) = \frac{\rho_0 c_0^2}{\mathrm{j}\omega V}u_0\pi r_0^2 + \frac{\mathrm{j}\omega\rho_0 c_0^2}{V} \times \sum_{n=0}^{\infty}\frac{\Psi_n(r)}{\omega_n^2-\omega^2}\sum_{i=1}^{N}\Psi_n(r_i)A_i u_i. \tag{18}$$

A.1.4 Suppression of Modal Excitation by Channel Arrangement

By separating the zeroth term from the first summation, as in Eq. (19), we can show the pressure in the cavity in terms of the lumped desired behavior plus undesirable terms caused by the excitation of the cavity modes due to the velocity in the compression channels,

$$p(r) = \frac{\rho_0 c_0^2}{\mathrm{j}\omega V}\left[u_0\pi r_0^2 + \sum_{i=1}^{N}A_i u_i\right] + \frac{\mathrm{j}\omega\rho_0 c_0^2}{V}\sum_{n=0}^{\infty}\frac{\Psi_n(r)}{\omega_n^2-\omega^2}\sum_{i=1}^{N}\Psi_n(r_i)A_i u_i. \tag{19}$$

From this expression it is clear that in order to suppress the excitation of a mode m, we require that

$$\sum_{i=1}^{N}\Psi_m(r_i)A_i u_i = 0. \tag{20}$$

It is assumed that we wish to suppress the first N modes, where N is the number of annular channels in the cavity, and thus enforce the lumped behavior to as high a frequency as possible. In this case we assume that if our geometry provides good modal suppression, the diaphragm velocity and the cavity pressure can be related simply by the lumped terms

$$p = \frac{\rho_0 c_0^2}{\mathrm{j}\omega V}\left[u_0\pi r_0^2 + \sum_{i=1}^{N}A_i u_i\right]. \tag{21}$$

The velocities at the channel entrances can be related to the cavity pressure at the channel entrance by the acoustic impedance of the channel,

$$u_i = \frac{p}{z_i}. \tag{22}$$

In the suppressed mode case the pressure in the cavity is constant. If we assume that the acoustic impedance of each channel is identical it must follow that the acoustic particle velocity in each channel entrance is identical and Eq. (20) simplifies to

$$\sum_{i=1}^{N}\Psi_m(r_i)A_i = 0. \tag{23}$$

This condition can be met by the choice of the channel entrance areas A_i and channel positions r_i. The easiest way to achieve this is to set r_i to the nodal positions of the highest mode that we wish to suppress. This then leaves $N - 1$ equations with $N - 1$ unknowns, which can be solved to find the ratios of the areas of the channels.

For example, in the case of a three-channel phase plug we choose

$$\begin{aligned} r_1 &= 0.238r_0 \\ r_2 &= 0.543r_0\,. \\ r_3 &= 0.853r_0 \end{aligned} \tag{24}$$

Solving the simultaneous equations as described gives the corresponding area ratios

$$\begin{aligned} \frac{A_3}{A_1} &= 3.817 \\ \frac{A_2}{A_1} &= 2.3386 \end{aligned} \tag{25}$$

which can be written equivalently as channel width ratios,

$$\begin{aligned} \frac{w_3}{w_1} &= 1.065 \\ \frac{w_2}{w_1} &= 1.025. \end{aligned} \tag{26}$$

This result is a repetition of that demonstrated by Smith [2].

A.2 Analysis with Spherical Geometry

The cavity analysis is repeated in a spherical coordinate system, approximating the geometry shown in Fig. 17.

A.2.1 Eigenfunction and Eigenfrequency Calculation

Starting from the Helmholtz equation,

$$\nabla^2 p + \frac{\omega^2}{c_0^2}p = 0. \tag{27}$$

In spherical coordinates the Laplacian can be written as [13]

$$\nabla^2 p = \frac{\partial^2 p}{\partial h^2} + \frac{2}{h}\frac{\partial p}{\partial h} + \frac{1}{h^2\sin^2\phi}\frac{\partial^2 p}{\partial\theta^2} + \frac{1}{h^2}\frac{\partial^2 p}{\partial\phi^2} + \frac{\cos\phi}{h^2\sin\phi}\frac{\partial p}{\partial\phi}. \tag{28}$$

The compression chamber is thin in h. In the operating range of the driver, the pressure variations across the thickness of

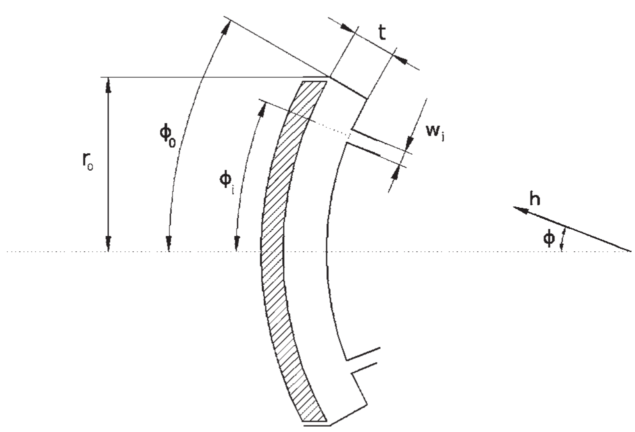

Fig. 17. Spherical representation of compression driver.

the cavity are negligible. In addition the cavity, diaphragm, and channel entrances are rotationally symmetric. We can remove some terms from the Laplacian to give

$$\nabla^2 p = \frac{1}{h^2}\frac{\partial^2 p}{\partial \phi^2} + \frac{\cos\phi}{h^2 \sin\phi}\frac{\partial p}{\partial \phi}. \tag{29}$$

Substituting Eq. (29) into Eq. (27) and multiplying by h^2,

$$\frac{\partial^2 p}{\partial \phi^2} + \frac{\cos\phi}{\sin\phi}\frac{\partial p}{\partial \phi} + \frac{h^2\omega^2}{c_0^2} p = 0. \tag{30}$$

A form of the associated Legendre differential equation written for $x = \cos\varphi$ is written as [14]

$$\frac{\partial^2 y}{\partial \varphi^2} + \frac{\cos\varphi}{\sin\varphi}\frac{\partial y}{\partial \varphi} + \iota(\iota+1)y = 0. \tag{31}$$

The similarity of Eqs. (30) and (31) is clear. Eq. (31) has two linearly independent solutions as follows:

$$y = C_1 P_\iota(\cos\varphi) + C_2 Q_\iota(\cos\varphi) \tag{32}$$

where $P_\iota(x)$ is a Legendre function of order ι, which is finite for all values of x. $Q_\iota(x)$ is a Legendre function of order ι, which is singular for $x = \pm 1$. Note that as we cannot guarantee that ι is an integer, we cannot assume that these functions are Legendre polynomials.

Constraining the pressure in the cavity to be finite, we shall assume that the pressure eigenfunction may be described by

$$\Psi_n(\phi) = C_1 P_\iota(\cos\phi). \tag{33}$$

The pressure must obey the rigid-wall boundary condition at the diameter of the cavity,

$$\left[\frac{\mathrm{d}\Psi_n(\phi)}{\mathrm{d}\phi} = 0\right]_{\phi=\phi_0}. \tag{34}$$

This requirement can be met by choice of ι. Hoersch demonstrates that a Legendre function of the first kind may be approximately described as a summation of Bessel functions [15]. Using this expression for the Legendre function in Eq. (33), it is possible to analytically derive values of ι_n that solve Eq. (34) in terms of a summation of Bessel function roots. The eigenfrequencies can then be found as

$$\iota_n(\iota_n+1) = \frac{h^2\omega_n^2}{c_0^2} = r_0^2\frac{\omega_n^2}{c_0^2\sin^2\phi_0}. \tag{35}$$

Hoerch's Bessel summation description of Legendre functions is approximate and only valid for a small range of x and ι. To improve the accuracy of the computation, FEM derived values of ω_n and $\Psi_n(\phi)$ are actually used to generate the final channel position and widths in Section A.2.4.

A.2.2 Pressure Response of Cavity without Channels

Having calculated the rigid-wall eigenfunctions and frequencies we may now analyze the driven behavior of the compression cavity. This is first considered for the situation where there are no exit channels present.

As discussed, the pressure in the cavity can be described as a summation of contributions from each of the calculated eigenfunctions. We neglect the damping term D_{nn} present in Eq. (1) as this is vanishingly small in the rigidly-wall compression cavity,

$$p(\boldsymbol{x}) = \frac{\mathrm{j}\omega\rho_0 c_0^2}{V}\sum_{n=0}^{\infty}\frac{\Psi_n(\boldsymbol{x})}{\omega_n^2-\omega^2}\int \Psi_n(\boldsymbol{y})u(\boldsymbol{y})\cdot\boldsymbol{n}\,\mathrm{d}S. \tag{36}$$

The cavity is only driven by the diaphragm on the entrance side of the compression cavity. The surface velocity is zero at all other locations on the enclosure walls. The integral on the right-hand side can be rewritten by a change of variables

$$\hat{S} = \frac{2\pi r_0^2}{\sin^2\phi_0}(1-\cos\phi) \rightarrow \frac{d\hat{S}}{d\phi} = \frac{2\pi r_0^2}{\sin^2\phi_0}\sin(\phi)$$

$$\times \int_S \Psi_n(\boldsymbol{y})u(\boldsymbol{y})\cdot\boldsymbol{n}\,\mathrm{d}S = \frac{\pi r_0^2}{\sin^2\phi_0}\int_{\phi=0}^{\phi_0}\Psi_n(\phi)u_0\sin(2\phi)\,\mathrm{d}\phi \tag{37}$$

where u_0 is the diaphragm velocity. For the case when $n = 0$ this integral is evaluated as

$$\frac{\pi r_0^2}{\sin^2\phi_0}\int_{\phi=0}^{\phi_0} u_0\sin(2\phi)\,\mathrm{d}\phi = u_0\pi r_0^2 \tag{38}$$

which is the same result as for an equivalent disk diaphragm of the same r_0.

Substituting Eq. (37) into Eq. (36) we can write the pressure in the cavity as

$$p(\phi) = \frac{\rho_0 c_0^2}{\mathrm{j}\omega V}u_0\pi r_0^2 + \frac{\mathrm{j}\omega\rho_0 c_0^2}{V}\sum_{n=0}^{\infty}\frac{\Psi_n(\phi)}{\omega_n^2-\omega^2}\frac{\pi r_0^2}{\sin^2\phi_0}$$

$$\times\int_{\hat{\phi}=0}^{\phi_0}\Psi_n(\hat{\phi})u_0\sin(2\hat{\phi})\,\mathrm{d}\hat{\phi}. \tag{39}$$

In this case we find that in addition to the static sound pressure terms, which we saw in the case of the cylindrical cavity, Eq. (14), we now also see some excitation of the cavity modes from the diaphragm motion itself.

A.2.3 Pressure Response of Cavity with a Number of Annular Exit Channels

The arrangement of a compression driver is to have not only a radiating diaphragm on one face of the compression cavity, but also a number of exit channels on the opposite face. The exit side surface normal acoustic particle velocity is represented by the function $f(\phi)$, defined as

$$f(\phi) = \begin{cases} 0, & \phi \neq \phi_1, \phi \neq \phi_2, \phi \neq \phi_3, \ \ldots \\ u_1, & \phi = \phi_1 \\ u_2, & \phi = \phi_2 \\ u_3, & \phi = \phi_3 \\ \vdots & \end{cases}. \tag{40}$$

We may extend Eq. (39) to include pressure variations in the cavity occurring due to the velocity $f(\phi)$,

$$p(\phi) = \frac{j\omega\rho_0 c_0^2}{V}\sum_{n=0}^{\infty}\frac{\Psi_n(\phi)}{\omega_n^2-\omega^2}\,\frac{\pi r_0^2}{\sin^2\phi_0} \times \int_{\hat{\phi}=0}^{\phi_0}\Psi_n(\hat{\phi})u_0\sin(2\hat{\phi})\,d\hat{\phi} + \frac{j\omega\rho_0 c_0^2}{V}\sum_{n=0}^{\infty}\frac{\Psi_n(\phi)}{\omega_n^2-\omega^2}\int_{\hat{S}}\Psi_n(\hat{\phi})f(\hat{\phi})\,dS. \quad (41)$$

As the channels are narrow, we approximate that the integral may be evaluated with reasonable accuracy as

$$\int_S \Psi_n(\hat{\phi})\,f(\hat{\phi})\,dS \approx \sum_{i=1}^{N}\Psi_n(\phi_i)A_i u_i. \quad (42)$$

Inserting this result into Eq. (41) we have

$$p(\phi) = \frac{j\omega\rho_0 c_0^2}{V}\sum_{n=0}^{\infty}\frac{\Psi_n(\phi)}{\omega_n^2-\omega^2} \times \left[\frac{\pi r_0^2}{\sin^2\phi_0}\int_{\hat{\phi}=0}^{\phi_0}\Psi_n(\hat{\phi})u_0\sin(2\hat{\phi})\,d\hat{\phi}. + \sum_{i=1}^{N}\Psi_n(\phi_i)A_i u_i\right]. \quad (43)$$

A.2.4 Suppression of Modal Excitation by Channel Arrangement

By separating the $n = 0$ terms from the summations we can again show the pressure in the cavity in terms of the lumped desired behavior plus undesirable terms caused by excitation of the cavity modes, due to the velocity in the compression channels and the diaphragm. We then have

$$p(\phi) = \frac{\rho_0 c_0^2}{j\omega V}\left[u_0\pi r_0^2 + \sum_{i=1}^{N}A_i u_i\right] + \frac{j\omega\rho_0 c_0^2}{V}\sum_{n=0}^{\infty}\frac{\Psi_n(\phi)}{\omega_n^2-\omega^2}\left[\frac{\pi r_0^2}{\sin^2\phi_0} \times \int_{\hat{\phi}=0}^{\phi_0}\Psi_n(\hat{\phi})u_0\sin(2\hat{\phi})\,d\hat{\phi} + \sum_{i=1}^{N}\Psi_n(\phi_i)A_i u_i\right]. \quad (44)$$

From Eq. (44) it is clear that in order to suppress the excitation of a mode m we require that

$$\sum_{i=1}^{N}\Psi_n(\phi_i)A_i u_i = \frac{-\pi r_0^2}{\sin^2\phi_0}\int_{\hat{\phi}=0}^{\phi_0}\Psi_n(\hat{\phi})u_0\sin(2\hat{\phi})\,d\hat{\phi}. \quad (45)$$

As before it is assumed that we wish to suppress the first N modes, where N is the number of annular channels in the cavity, and thus enforce the lumped behavior to as high a frequency as possible. In this case we assume that if our geometry provides good modal suppression the diaphragm velocity and the cavity pressure can be related simply by the lumped terms,

$$p = \frac{\rho_0 c_0^2}{j\omega V}\left[u_0\pi r_0^2 + \sum_{i=1}^{N}A_i u_i\right]. \quad (46)$$

The velocities at the channel entrances can be related to the cavity pressure at the channel entrance by the acoustic impedance of the channel. We again assume that the acoustic impedance of each channel entrance is identical, from which it follows that the entrance channel velocities must also be the same. We also make the further assumption that the channel-specific acoustic impedance is $\rho_0 c_0$. In addition we approximate that $V \approx dh\pi r_0^2$, where t is the cavity thickness. We can relate the diaphragm velocity to the channel entrance velocity by inserting these conditions into Eq. (46),

$$u_0 = u_i\left(j\frac{t}{\lambda} - \frac{A_T}{\pi r_0^2}\right) \quad (47)$$

where A_T is the total combined area of the channel entrances and λ is the acoustic wavelength at frequency ω. From Eq. (47) we can see that the real part of the channel velocities is related by the compression ratio. The quadrature component presents a difficulty. In order for us to balance the channel excitation of the modes to cancel with the diaphragm excitation of the modes the velocities associated with each must be in phase. There is nothing that can be done to suppress this quadrature component. Looking at the expression more closely we can see that this component is insignificant when the cavity thickness, compared to the acoustic wavelength, is smaller than the inverse of the compression ratio. In order to continue our analysis, we assume that we can neglect this component.

The variable ζ_n, defined as

$$\zeta_n = \frac{1}{\sin^2\phi_0}\int_{\hat{\phi}=0}^{\phi_0}\Psi_n(\hat{\phi})\sin(2\hat{\phi})\,d\hat{\phi} \quad (48)$$

represents the degree of the modal excitation by the diaphragm. This can be evaluated numerically, or by other means, for each cavity mode.

Substituting the real part of Eq. (47) into Eq. (45) along with ζ_n and the simple relationship between the area of the individual channels and the total channel area $\Sigma_{i=1}^{N}A_i = A_T$, we can write

$$\sum_{i=1}^{N}A_i(\Psi_n(\phi_i) - \zeta_n) = 0. \quad (49)$$

Modal suppression is then achieved by meeting the condition in Eq. (49). This can be most easily done by setting the channel positions ϕ_i such that

$$\Psi_N(\phi_i) = \zeta_N. \quad (50)$$

This leaves a system of $N - 1$ equations with $N - 1$ unknowns, which can be solved to find the ratios of the areas of the channels. For example, in the case of a three-channel phase plug with $\phi_0 = 55°$ we can calculate

$$\begin{aligned}\zeta_1 &= 0.0624392\\ \zeta_2 &= -0.012609\\ \zeta_3 &= 0.0048689.\end{aligned} \tag{51}$$

We then choose our channel positions to be

$$\begin{aligned}\phi_1 &= 0.2350\phi_0\\ \phi_2 &= 0.5431\phi_0\\ \phi_3 &= 0.8476\phi_0.\end{aligned} \tag{52}$$

The simultaneous equations can then be solved to find the channel areas,

$$\begin{aligned}\frac{A_2}{A_1} &= 2.0158\\ \frac{A_3}{A_1} &= 2.2649\end{aligned} \tag{53}$$

which can be written equivalently as channel width ratios,

$$\begin{aligned}\frac{w_2}{w_1} &= 0.9056\\ \frac{w_3}{w_1} &= 0.6973.\end{aligned} \tag{54}$$

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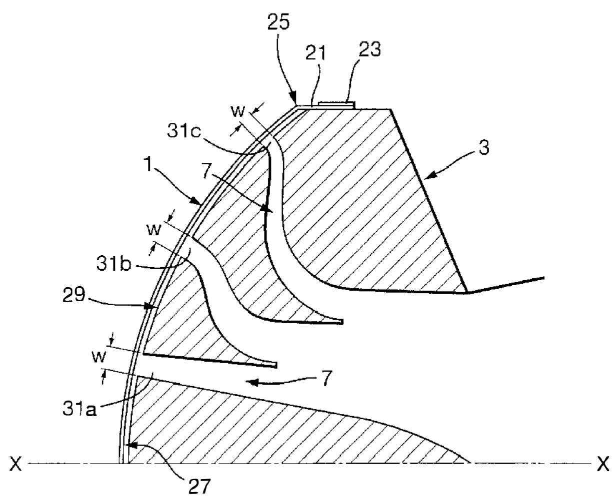
Other: **online EPODOC, WPI**

(54) Abstract Title**: Phase plug with openings of variable size**

(57) A phase plug 3 comprises a body having an input side for receiving acoustic waves from a diaphragm 1 and an output side for transmitting the acoustic waves, the body including a plurality of channels 7 extending from the input side to the output side. The input side comprises an input surface with a plurality of openings 31a-31c constituting entrances to the channels, the input surface being substantially part of a sphere or an ellipsoid in shape. The areas of the openings vary with radial position on the input surface, measured from a central axis X-X of the plug. The variation in areas may be a trigonometric function (cosine is suggested) of the angle subtended at the centre of the sphere or focus of the ellipsoid between the central axis and the radial position. The openings may be in the form of slots with varying widths W.

Fig.2.



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Phase Plug for Compression Driver

The present invention relates to loudspeakers, and particularly relates to compression drivers and to phase plugs for compression drivers.

A compression driver is a type of loudspeaker in which an acoustically radiating diaphragm radiates acoustic waves into a small cavity. The cavity is connected by a phase plug (also known as a phase adaptor, a phase transformer, an acoustic transformer, etc.) to an aperture, which normally opens into a horn waveguide. The small cavity and throat area present the diaphragm with a high acoustic load, and because of this, it tends to be highly efficient. However, the cavity in front of the diaphragm can cause acoustic problems at high frequencies. In particular, the cavity can exhibit strong resonances (known as cavity modes) at distinct frequencies that are commonly within the working band of the compression driver. These resonances can undesirably introduce large pressure response variations in the output of the compression driver. Additionally, the high pressure levels in the cavity that occur when the resonances are excited are undesirable for driver linearity. The severity of the resonance problem is determined primarily by the shape of the cavity, the design of the phase plug and, more specifically, the location and size of the pathways (channels) through the phase plug.

The Journal of the Acoustical Society of America, Volume 25, No. 2, March 1953 (Bob H Smith of the University of California), discloses an investigation of the air chamber of horn type loudspeakers, which includes a method of calculating the positions and sizes of the entrances to the channels (pathways) in a phase plug with annular channels (slots). The aim of the disclosed method is to avoid the excitation of resonances caused by the motion of the air entering and leaving the channels in the phase plug. According to the mathematical analysis presented in that technical paper, in an ideal phase plug with annular channels, the widths of the channels should be very nearly the same irrespective of their radial position in the phase plug, but with increasing radial position the channel width should normally increase very gradually.

Whereas the technical paper by Bob Smith considers only the effect of the motion of the air in the channels, in reality resonances are also excited by the motion of the diaphragm itself. The present inventors have performed a new analysis including the latter effect, and have accordingly devised the present invention.

Accordingly, a first aspect of the present invention provides a phase plug, comprising a body having an input side for receiving acoustic waves and an output side for transmitting acoustic waves, the body including a plurality of channels extending from the input side to the output side for propagating acoustic waves through the body, wherein the input side comprises an input surface which includes a plurality of openings constituting entrances for the channels, the input surface being substantially part of a sphere or an ellipsoid in shape, and wherein the areas of the openings vary with radial position on the input surface, the radial position being measured in a direction extending perpendicularly from a central axis extending through the input surface, the variation in the areas being a function of the cosine of an angle subtended at the centre of the sphere or a focus of the ellipsoid between the central axis and the radial position.

In some preferred embodiments of the invention, as well as the areas of the openings varying with radial position on the input surface, the variation in the areas of the openings may be described by a mathematical relationship which includes the radial position as a function of the relationship. Preferably, the mathematical variation in the areas of the openings is substantially proportional to a function in the range $r.\cos^{1/2}\Phi$ to $r.\cos^{2}\Phi$, where r is the radial position and Φ is the angle. Most preferably, the variation in the areas of the openings is substantially proportional to $r.\cos\Phi$, where r is the radial position and Φ is the angle.

In especially preferred embodiments of the invention, one or more of the openings has the form of one or more slots, each slot having a constant or varying width. (Preferably substantially all of the openings have the form of slots.) For example, in some embodiments, each slot has a substantially constant width, but the widths of the slots vary with radial position on the input surface of the phase plug. Such versions of the invention preferably have a plurality of slots arranged spaced apart from each other in an annular fashion around the central axis of the phase plug. (There will generally be connection parts extending across the annular slots, to join together the parts of the phase plug body that are separated from each other by the slots.) In other embodiments, each slot has a varying width. Such versions of the invention preferably have a plurality of slots arranged in a radial fashion around the central axis of the phase plug. Yet other embodiments of the invention are a combination of these two versions, in which the phase plug includes one or more slots arranged in an annular fashion around the central axis and also includes one or more slots arranged in a radial fashion around the central axis. The annular slot(s) may be situated closer to the central axis than the radial slot(s), or vice versa, and/or the annular slots and radial slots may alternate in a radial direction extending away from the central axis, for example. In all such main types of phase plug according to the invention, the widths of the slots preferably vary with radial position as a function of the cosine of the angle Φ.

A second aspect of the invention accordingly provides a phase plug, comprising a body having an input side for receiving acoustic waves and an output side for transmitting acoustic waves, the body including a plurality of channels extending from the input side to the output side for propagating acoustic waves through the body, wherein the input side comprises an input surface which includes a plurality of slots constituting entrances for the channels, the input surface being substantially part of a sphere or an ellipsoid in shape, and wherein the widths of the slots vary with radial position on the input surface, the radial position being measured in a direction extending perpendicularly from a central axis extending through the input surface, the variation in the slot widths being a function of the cosine of an angle subtended at the centre of the sphere or a focus of the ellipsoid between the central axis and the radial position.

In some embodiments of the invention, the variation in the widths of the slots (with radial position on the input surface) may be described by a mathematical relationship which includes the radial position as a function of the relationship. This is preferably the case for slots that are arranged in a substantially radial orientation on the input surface about the central axis, for example. Thus, for example, the width of each slot may vary substantially in proportion to a function in the range $r.\cos^{1/2}\Phi$ to $r.\cos^2\Phi$, where r is the radial position and Φ is the angle. More preferably, the width of each slot may vary substantially in proportion to $r.\cos\Phi$, where r is the radial position and Φ is the angle. For phase plugs in which one or more of the slots are arranged in a substantially radial orientation on the input surface about the central axis, they preferably are joined to each other via an opening at an axially central region of the input surface.

Additionally or allternatively, for some embodiments of phase plug according to the invention, the variation in the widths of the slots (with radial position on the input surface) may be described mathematically by means of a relationship that does not include the radial position as a function of the relationship. This is preferably the case for slots that are substantially annular or substantially part of an annulus, in shape, for example. Thus, for example, the widths of the slots may vary substantially in proportion to a function in the range $\cos^{1/2}\Phi$ to $\cos^2\Phi$, where Φ is the angle. Preferably, the widths of the slots vary substantially in proportion to $\cos\Phi$, where Φ is the angle. As mentioned above, for embodiments of the phase plug having one or more annular slots, each slot preferably is arranged such that the axis of its annulus is substantially coaxial with the central axis of the phase plug, and preferably each slot has a substantially constant width, but the widths of the slots vary with radial position on the input surface of the phase plug.

In some embodiments of the invention, the input surface is concave, e.g. for use with a diaphragm having a convex radiating surface. Alternatively, in other embodiments of the invention the input surface is convex, e.g. for use with a diaphragm having a concave radiating surface.

A third aspect of the invention provides a compression driver, comprising a phase plug according to the first or second aspect of the invention, and an acoustically radiating diaphragm situated adjacent to the input side of the phase plug.

The diaphragm of the compression driver preferably has either a convex or a concave acoustically radiating surface. Preferably, the acoustically radiating surface of the diaphragm is substantially part of a sphere or an ellipsoid in shape. Advantageously, the acoustically radiating surface of the diaphragm may be substantially rigid.

The compression driver preferably includes a horn waveguide situated adjacent to the output side of the phase plug. In at least some embodiments of the invention, the horn waveguide is non-circular in cross-section perpendicular to the central axis. For example, the horn may be oval in cross-section, or indeed substantially any shape. However, for many embodiments of the invention, the horn waveguide is substantially circular in cross-section perpendicular to the central axis.

The horn waveguide may be substantially frusto-conical (i.e. the horn waveguide may be substantially conical but truncated at the throat of the horn). However, the horn waveguide may be flared, e.g. flared such that it follows a substantially exponential curve, or a substantially parabolic curve, or another flared curve. Other horn waveguide shapes are also possible.

The horn waveguide may be a static waveguide, or it may itself be an acoustically radiating diaphragm, e.g a cone diaphragm. Consequently, in some embodiments of the invention, the horn waveguide may comprise a driven acoustically radiating diaphragm. The horn diaphragm may be driven substantially independently of the dome-shaped diaphragm, for example such that the horn diaphragm is arranged to radiate acoustic waves of generally lower frequency than is the dome-shaped diaphragm. Consequently, the loudspeaker may include a drive unit to drive the horn diaphragm. An example of a suitable arrangement (but without a phase plug according to the present invention) in which the horn waveguide itself comprises an acoustically radiating diaphragm, is disclosed in United States Patent No. 5,548,657.

A fourth aspect of the invention provides a combination loudspeaker comprising an acoustically radiating horn diaphragm, a driver for the horn diaphragm, and a compression driver according to the third aspect of the invention located in, or adjacent to, a throat of the horn diaphragm. Preferably the compression driver is arranged to radiate high frequency sounds, and the horn diaphragm preferably is arranged to radiate low or mid-range frequency sounds.

It is to be understood that any feature of any aspect of the invention may be a feature of any other aspect of the invention.

The phase plug preferably is formed from one or more of: a metal or metal alloy material; a composite material; a plastics material; a ceramic material.

The diaphragm of the compression driver preferably is formed from a substantially rigid low density material, for example one or more of: a metal or metal alloy material; a composite material; a plastics material; a ceramic material. Some preferred metals for forming a suitable metal or metal alloy material include: titanium; aluminium; and beryllium. The acoustically radiating surface of the diaphragm of the compression driver may be formed from a specialist material, for example diamond (especially chemically deposited diamond).

The horn waveguide may be formed from any suitable material, for example one or more of: a metal or metal alloy material; a composite material; a plastics material; a fabric material; a ceramic material. For those embodiments of the invention in which the horn waveguide is an acoustically radiating diaphragm, it preferably is formed from a plastics material or a fabric material, for example. Metal and/or paper may be preferable in some cases.

Some preferred embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings, of which:

Figure 1 is a cross-sectional schematic representation of one embodiment of a compression driver according to the invention;

Figure 2 is a partial cross-sectional schematic representation of a first embodiment of a phase plug according to the invention, together with an acoustically radiating diaphragm;

Figure 3 shows six views ((a) to (f)) of a second embodiment of a phase plug according to the invention;

Figure 4 is a schematic diagram indicating the radial position r and the angle Φ used to define features of the invention;

Figure 5 is a graphical representation indicating variations in channel entrance opening areas and slot widths of preferred embodiments of phase plugs according to the invention; and

Figure 6 is a schematic cross-sectional representation of a combination loudspeaker according to the invention, comprising a convex radiating diaphragm, a phase plug of the type illustrated in Figure 3, and a radiating horn diaphragm.

Figure 1 is a cross-sectional schematic representation of one embodiment of a compression driver according to the invention. The compression driver comprises an acoustically radiating diaphragm 1 having a concave acoustically radiating surface situated adjacent to an input side of a phase plug 3. On an opposite (output) side of the phase plug 3 is a horn waveguide 5. The diaphragm 1, phase plug 3, and horn waveguide 5 have a central axis X-X extending therethrough. The diaphragm 1, phase plug 3, and horn waveguide 5 are arranged such that acoustic waves generated by the diaphragm 1 are propagated through channels 7 extending through the phase plug 3 from the input side to the output side of the phase plug and are then received and propagated by the horn waveguide 5. The diaphragm 1 is driven by means of a driver assembly comprising a centre pole part 9, an outer pole part 11, and a magnet 13. Specifically, an annular skirt portion of the diaphragm 1, which projects from the circumference of the acoustically radiating surface, carries an electrically conductive coil, and the coil and skirt portion of the diaphragm are situated in a gap 15 between the centre pole part 9 and the outer pole part 11, which gap has a magnetic field extending across it. A clamp ring 17 and a rear enclosure part 19 are also shown.

Everything described above with reference to schematic Figure 1 is conventional and well known to the skilled person. The novelty of the present invention lies primarily in the details of the phase plug, which will now be described.

Figure 2 is a partial cross-sectional schematic representation of a first embodiment of a phase plug 3 according to the invention, together with an acoustically radiating diaphragm 1, of a compression driver as illustrated schematically in Figure 1. The annular skirt portion 21 of the diaphragm 1 which carries an electrically conductive coil 23, and which projects from the circumference 25 of the acoustically radiating surface, is shown schematically in Figure 2. The acoustically radiating surface 27 of the diaphragm is concave, and lies adjacent to a correspondingly convex input surface 29 of the phase plug 3. Both the concave acoustically radiating surface 27 and the convex input surface 29 comprise part of a sphere (or an ellipsoid, but preferably a sphere) in shape, and they are substantially concentric. The phase plug 3 includes a plurality of channels 7 extending from its input side (adjacent to the diaphragm 1) to its output side (closer to the horn waveguide 5) for propagating acoustic waves through the body of the phase plug. Consequently, the input surface 29 of the phase plug 3 includes a plurality of openings 31 constituting entrances for the channels 7. More particularly, the phase plug 3 includes three substantially coaxial annular channels 7, having respective coaxial annular slot entrance openings 31a, 31b and 31c. Annular slot 31a is the closest to the central axis X-X, annular slot 31c is the furthest from the central axis X-X, and annular slot 31b is situated between slots 31a and 31c. Each slot 31 has a substantially constant (fixed) width for substantially its entire extent, but the width of each slot is different to the width of each other slot, in a particular defined relationship (described below).

The inventors of the present invention have found that if the areas, and the widths, of the slots 31 vary as a function of the cosine of the angle subtended at the centre of the sphere (or a focus of the ellipsoid) defining the input surface 29 of the phase plug between the central axis X-X and the radial position of the slot on the input surface, then the phase plug can significantly reduce, or can even substantially eliminate, the excitation of acoustic resonances (cavity modes) in the region between the diaphragm 1 and the throat of the horn waveguide 5. The definitions of the angle (which is designated as Φ) and the radial position (which is designated as r) are illustrated in Figure 4. The radial position r is measured in a direction extending perpendicularly from the central axis X-X extending through the input surface 29 of the phase plug 3. (The particular value of the angle Φ and the particular value of the distance r shown in Figure 4 constitute just one such angle and one such radial distance; each of the slots 31 will have its own particular value of the angle Φ and the radial distance r, defined and measured from the central axis X-X as shown in Figure 4.)

The inventors have found, in particular, that acoustic resonances can be significantly reduced (or even substantially eliminated) if the variation in the areas of the openings 31 (e.g. slots) is substantially proportional to a function in the range $r.\cos^{1/2}\Phi$ to $r.\cos^{2}\Phi$. Thus, for example, for some embodiments of the invention, the variation may be substantially proportional to $r.\cos\Phi$.

The variation in the areas of the slots 31a, 31b and 31c of Figure 2 is shown graphically in Figure 5, in which the horizontal axis indicates the angle Φ of each slot (in degrees), and the vertical axis indicates the open area of each slot (in arbitrary units). Each of the slots 31a, 31b and 31c is indicated on the graph (as a small labelled oval), together with the functions $r.\cos^{1/2}\Phi$, $r.\cos\Phi$ and $r.\cos^{2}\Phi$. As can be seen, all of the slots fall within the range defined by the limits $r.\cos^{1/2}\Phi$ and $r.\cos^{2}\Phi$.

Additionally (as mentioned above) the widths W of the annular slots of the phase plug 3 illustrated in Figure 2 preferably vary substantially in proportion to a function in the range $\cos^{1/2}\Phi$ to $\cos^{2}\Phi$. More preferably, the widths W of the slots vary approximately in proportion to $\cos\Phi$. The widths W of the slots are indicated in Figure 2.

Figure 3 shows six views ((a) to (f)) of an alternative embodiment of a phase plug 3 according to the invention. The phase plug 3 of Figure 3 comprises a body having an input side 33 for receiving acoustic waves and an output side 35 for transmitting acoustic waves. A plurality of channels 7 extends from the input side 33 to the output side 35 for propagating acoustic waves through the body of the phase plug 3. The input side 33 comprises a concave input surface 29 which includes a plurality of openings 31 in the form of slots, which constitute entrances for the channels 7. The input surface is substantially part of a sphere (or an ellipsoid, but preferably a sphere) in shape. The slots 31 are arranged in a substantially radial orientation on the input surface 29 about the central axis X-X. In the embodiment illustrated in Figure 3, the phase plug 3 includes seven channels, and thus seven slots, but fewer, or a greater number, of slots could be used instead. Each channel 7 (and thus also each slot 31, which is an entrance of a channel) is partially defined, and separated from neighbouring channels 7, by a pair of spaced apart fins 37. Because there are seven channels there are also seven radially arranged spaced-apart fins 37. Each fin projects towards the central axis X-X from an outer circumferential part 39 of the phase plug 3. The circumferential part 39 has a generally frusto-conical shape, with its smallest radius adjacent to the input side 33 and its largest radius adjacent to the output side 35.

The area distributions of the slots 31, and thus also the widths of the slots, vary with radial position r on the input surface 29 of the phase plug 3 illustrated in Figure 3. More particularly, the area distributions and the widths of the slots 31 vary as a function of the radial position r and the cosine of the angle Φ (which are defined in the same way as illustrated in Figure 4). Specifically, the variation in both the area distributions of the slots 31, and the widths of the slots 31, is substantially proportional to a function in the range $r.\cos^{1/2}\Phi$ to $r.\cos^2\Phi$, for example approximately proportional to $r.\cos\Phi$. Because such a variation in slot width would mean that the width of each slot reduces to zero at the central axis X-X (where r=0), the phase plug could include an axially central part of the phase plug body where all of the fins 37 are joined together. However, in order to comply with the ideal mathematical variation in slot width, any such axially central part of the phase plug body would ideally need to be vanishingly small in radius (which is difficult or impossible to achieve). Thus, the physical embodiment of the phase plug at the central axis X-X will generally be an approximation to the ideal mathematical variation in slot width, e.g. either comprising a small axially central part of the phase plug body or comprising an axially central opening 38 which joins all of the slots to each other. The latter version is the one illustrated in Figure 3.

While the slot openings 31 on the input surface 29 of the phase plug 3 of Figure 3 comply with the above-mentioned mathematical relationships, the output sides of the channels 7 do not necessarily comply with those mathematical relationships. In Figure 3, each channel 7 widens in an approximately exponential manner in a direction parallel to the central axis X-X from the input side 33 to the output side 35. As shown in view (f) of Figure 3, the output edge 41 of each fin 37 has a thin substantially constant width. Additionally, the output edge 41 of each fin 37 curves substantially continuously from the circumferential part 39 at the output end 35 of the phase plug 3, to the radially innermost part of the fin at the input surface 29.

Figure 6 is a schematic cross-sectional representation of a combination loudspeaker 51 according to the invention, comprising a convex dome-shaped radiating diaphragm 53, a phase plug 3 of the type illustrated in Figure 3, and a radiating horn diaphragm 55. The convex radiating diaphragm 53 and the phase plug 3 are located in the throat of the horn diaphragm 55. The convex radiating diaphragm 53 is arranged to radiate high frequency sounds, and the horn diaphragm 55 is arranged to radiate low or mid-range frequency sounds. The combination loudspeaker 51 includes a "surround" 57 in the throat of the horn diaphragm 55 that supports the convex radiating diaphragm 53 via a flexible annular web 59, and attached to this surround 57 is a support 61 for the phase plug 3. An inner cylindrical part 65 of the horn diaphragm 55 carries a conductive coil of a driver for the horn diaphragm, which extends into a magnetic gap of the driver (not shown). The horn diaphragm 55 is supported by a second flexible annular web 67 at its outer periphery, and the outer periphery of the second flexible annular web 67 is attached to an outer support 69.

It will be understood that other embodiments of the invention, and modifications of the described and illustrated embodiments of the invention, are possible within the definitions of the invention provided in the appended claims.

Claims

1. A phase plug, comprising a body having an input side for receiving acoustic waves and an output side for transmitting acoustic waves, the body including a plurality of channels extending from the input side to the output side for propagating acoustic waves through the body, wherein the input side comprises an input surface which includes a plurality of openings constituting entrances for the channels, the input surface being substantially part of a sphere or an ellipsoid in shape, and wherein the areas of the openings vary with radial position on the input surface, the radial position being measured in a direction extending perpendicularly from a central axis extending through the input surface, the variation in the areas being a function of the cosine of an angle subtended at the centre of the sphere or a focus of the ellipsoid between the central axis and the radial position.

2. A phase plug according to claim 1, in which the variation in the areas of the openings is also a function of the radial position.

3. A phase plug according to claim 2, in which the variation in the areas of the openings is substantially proportional to a function in the range $r.\cos^{1/2}\Phi$ to $r.\cos^{2}\Phi$, where r is the radial position and Φ is the angle.

4. A phase plug according to claim 2 or claim 3, in which the variation in the areas of the openings is substantially proportional to $r.\cos\Phi$, where r is the radial position and Φ is the angle.

5. A phase plug according to any preceding claim, in which one or more of the openings has the form of one or more slots, each slot having a constant or varying width.

6. A phase plug according to claim 5, in which all of the openings have the form of slots.

7. A phase plug according to claim 5 or claim 6, in which the widths of the slots vary with radial position as a function of the cosine of the angle.

8. A phase plug, comprising a body having an input side for receiving acoustic waves and an output side for transmitting acoustic waves, the body including a plurality of channels extending from the input side to the output side for propagating acoustic waves through the body, wherein the input side comprises an input surface which includes a plurality of slots constituting entrances for the channels, the input surface being substantially part of a sphere or an ellipsoid in shape, and wherein the widths of the slots vary with radial position on the input surface, the radial position being measured in a direction extending perpendicularly from a central axis extending through the input surface, the variation in the slot widths being a function of the cosine of an angle subtended at the centre of the sphere or a focus of the ellipsoid between the central axis and the radial position.

9. A phase plug according to claim 8, in which the variation in the widths of the slots is also a function of the radial position.

10. A phase plug according to any one of claims 7 to 9, in which the width of each slot varies substantially in proportion to a function in the range $r.\cos^{1/2}\Phi$ to $r.\cos^2\Phi$, where r is the radial position and Φ is the angle.

11. A phase plug according to any one of claims 7 to 10, in which the width of each slot varies substantially in proportion to $r.\cos\Phi$, where r is the radial position and Φ is the angle.

12. A phase plug according to any one of claims 5 to 11, in which one or more of said slots are arranged in a substantially radial orientation on the input surface about the central axis.

13. A phase plug according to claim 12, in which the slots are joined to each other via an opening at an axially central region of the input surface.

14. A phase plug according to claim 7 or claim 8, in which the widths of the slots vary substantially in proportion to a function in the range $\cos^{1/2}\Phi$ to $\cos^2\Phi$, where Φ is the angle.

15. A phase plug according to claim 14, in which the widths of the slots vary substantially in proportion to $\cos\Phi$, where Φ is the angle.

16. A phase plug according to any one of claims 5 to 15, in which one or more of said slots are substantially annular or substantially part of an annulus, in shape.

17. A phase plug according to claim 16, in which each slot is arranged such that the axis of its annulus is substantially coaxial with the central axis.

18. A phase plug according to claim 16 when dependent upon claim 12, which includes one or more radial slots and one or more annular slots.

19. A phase plug according to any preceding claim, in which the input surface is concave.

20. A phase plug according to any one of claims 1 to 18, in which the input surface is convex.

21. A compression driver, comprising a phase plug according to any preceding claim, and an acoustically radiating diaphragm situated adjacent to the input side of the phase plug.

22. A compression driver according to claim 21, in which the diaphragm has a convex acoustically radiating surface.

23. A compression driver according to claim 21, in which the diaphragm has a concave acoustically radiating surface.

24. A compression driver according to claim 22 or claim 23, in which the acoustically radiating surface of the diaphragm is substantially part of a sphere or an ellipsoid in shape.

25. A compression driver according to any one of claims 21 to 24, in which the acoustically radiating surface of the diaphragm is substantially rigid.

26. A compression driver according to any one of claims 21 to 25, further comprising a horn waveguide situated adjacent to the output side of the phase plug.

27. A combination loudspeaker, comprising an acoustically radiating horn diaphragm, a driver for the horn diaphragm, and a compression driver according to any one of claims 21 to 26 located in, or adjacent to, a throat of the horn diaphragm.

28. A combination loudspeaker according to claim 27 when dependent upon claim 26, in which the acoustically radiating horn diaphragm comprises the horn waveguide of the compression driver.

The Patent Office

For Innovation

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Application No: GB0607452.0 **Examiner:** Mr Stuart Jarvis

Claims searched: 1 and 8 **Date of search:** 12 July 2006

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
X	1, 2, 5, 6, 8, 9, 12, 16-18, 20, 21, 23-26	US 2005/0105753 A1 Manzini - See the figures and the abstract
X	1, 2, 5, 6, 8, 9, 12, 16-18, 20, 21, 23-26	US 5117462 A JBL - See the figures and col 3 lines 25-44
X	1, 2, 5-9, 12, 16, 17, 20, 23-26	US 2004/0156519 A1 Geddes - See figures 2 and 3
X	1, 2, 5, 6, 8, 9, 12, 20, 21, 23-26	US 4050541 A Altec - See particularly figure 8
X	1, 2, 5, 6, 8, 9, 12, 19, 21, 22, 25, 26	US 4628155 A Robineau - See the figures and the abstract
A	-	US 2003/0215107 A1 Werner - See figure 2 and paragraphs 27 and 28

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art
Y	Document indicating lack of inventive step if combined with one or more other documents of same category	P	Document published on or after the declared priority date but before the filing date of this invention
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^{X} :

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G10K; H04R

The following online and other databases have been used in the preparation of this search report

EPODOC, WPI

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Fig.1.

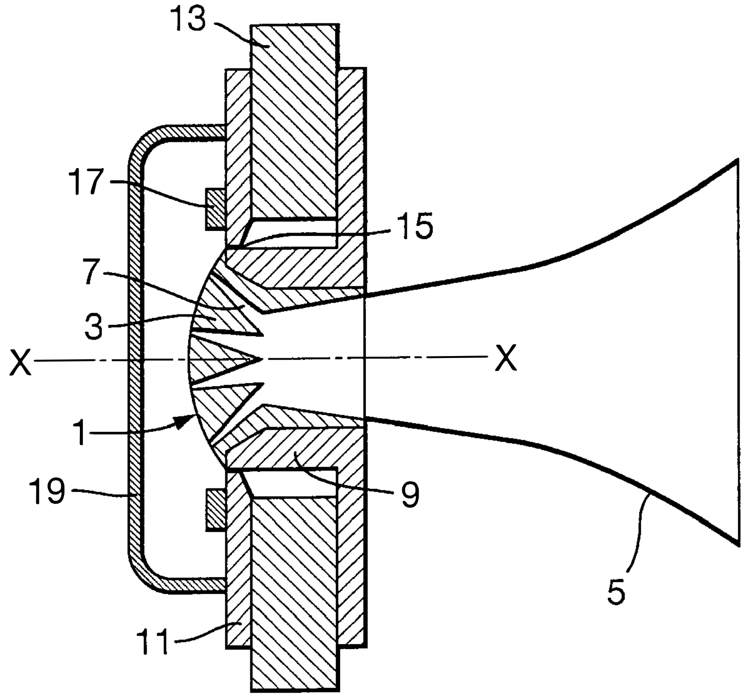


Fig.2.

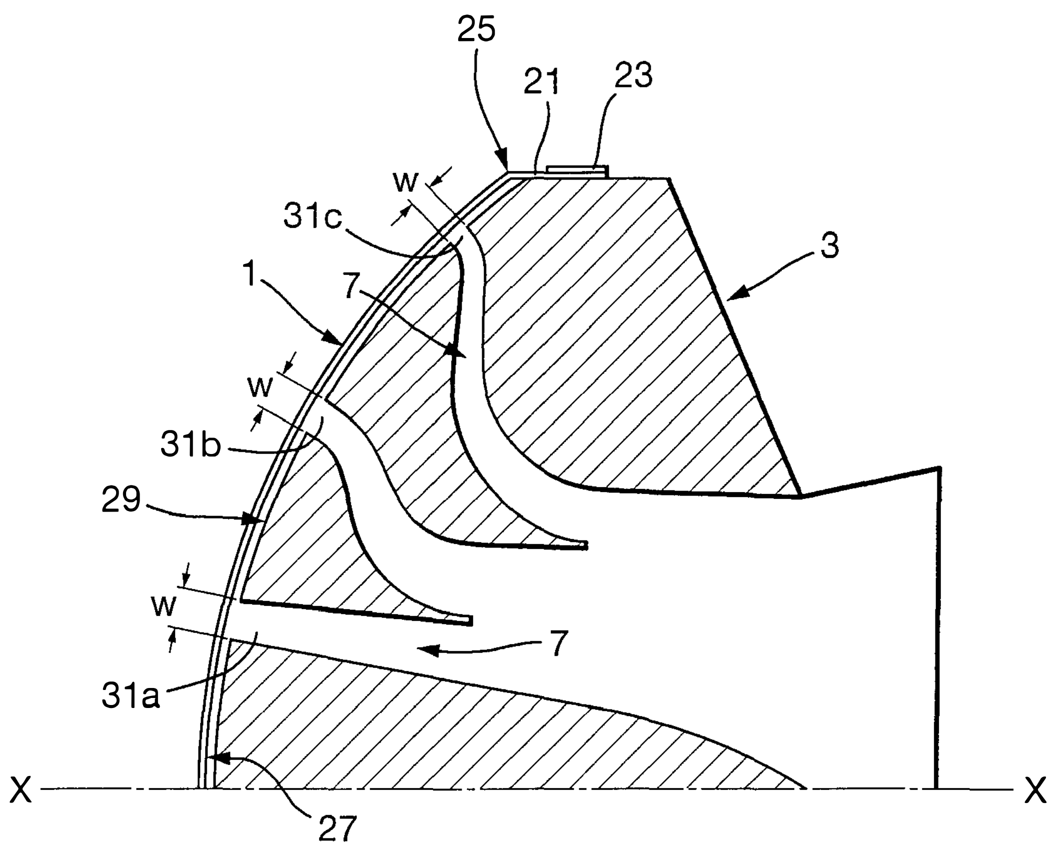


Fig.3(a)

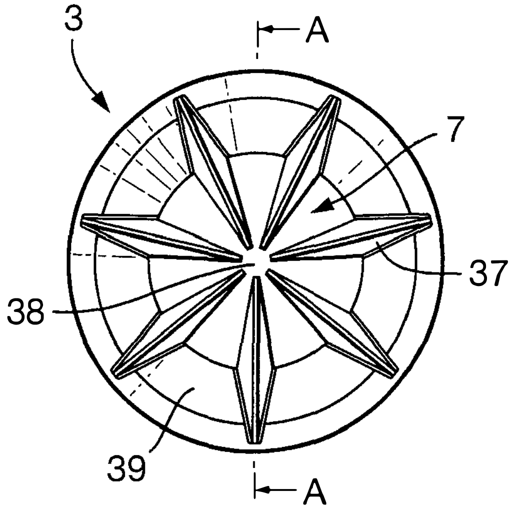


Fig.3(b)

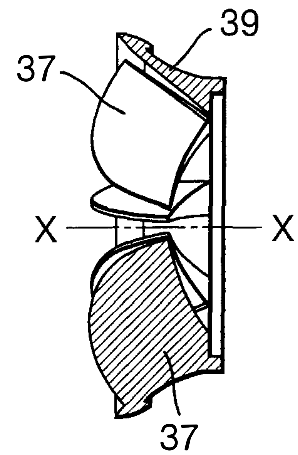


Fig.3(c)

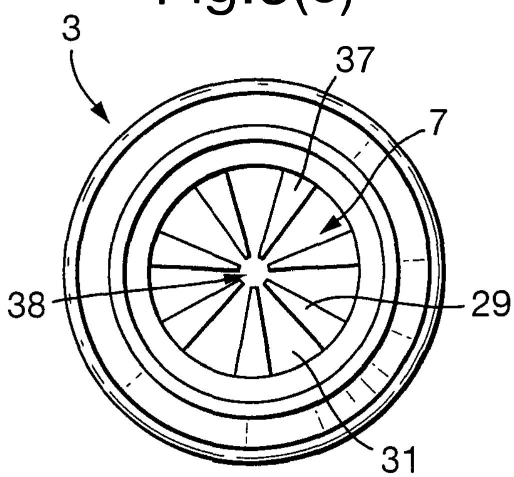


Fig.3(d)

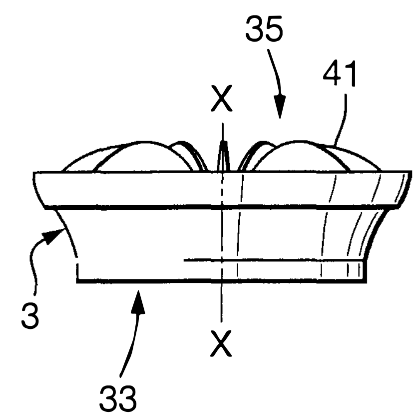


Fig.3(e)

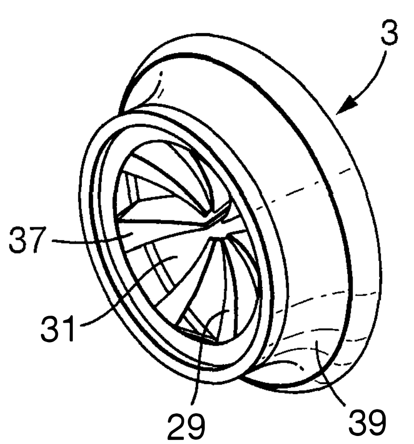


Fig.3(f)

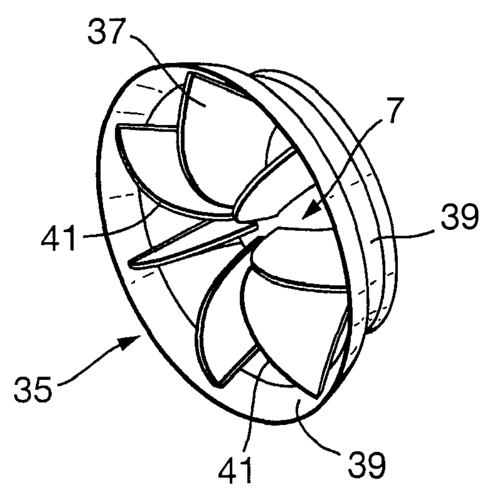


Fig.4.

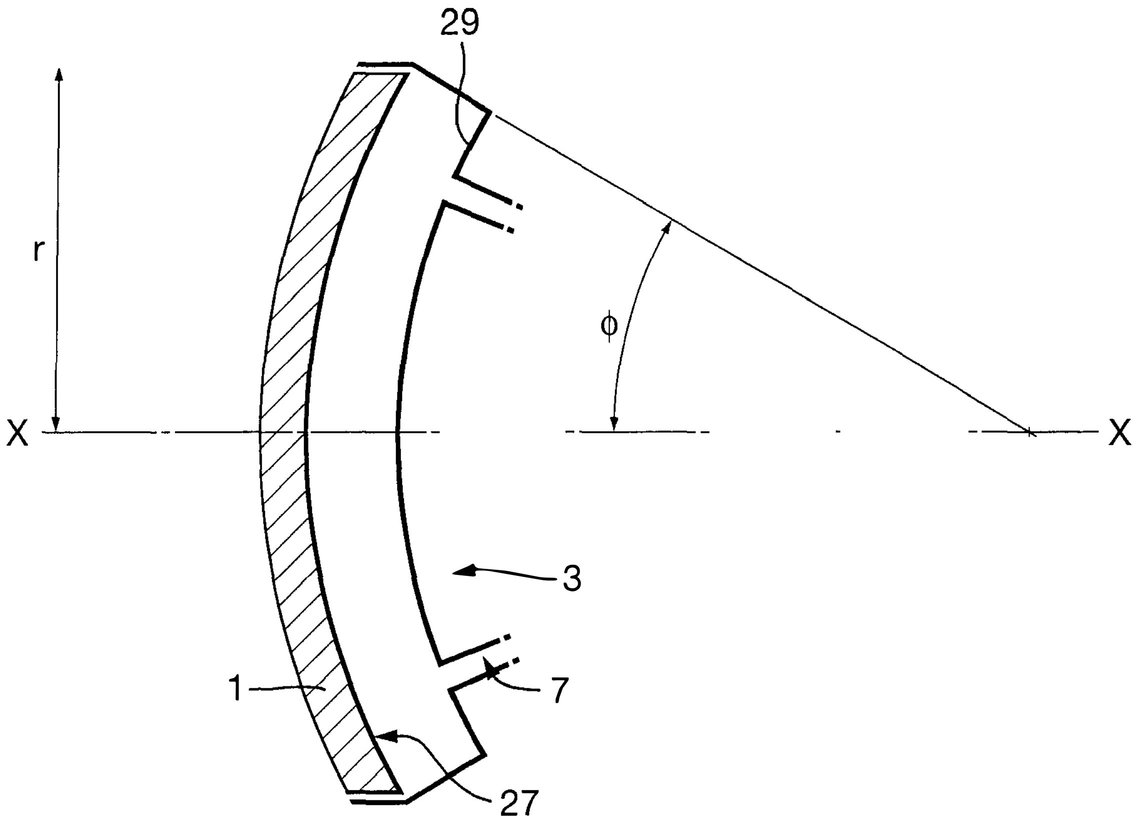
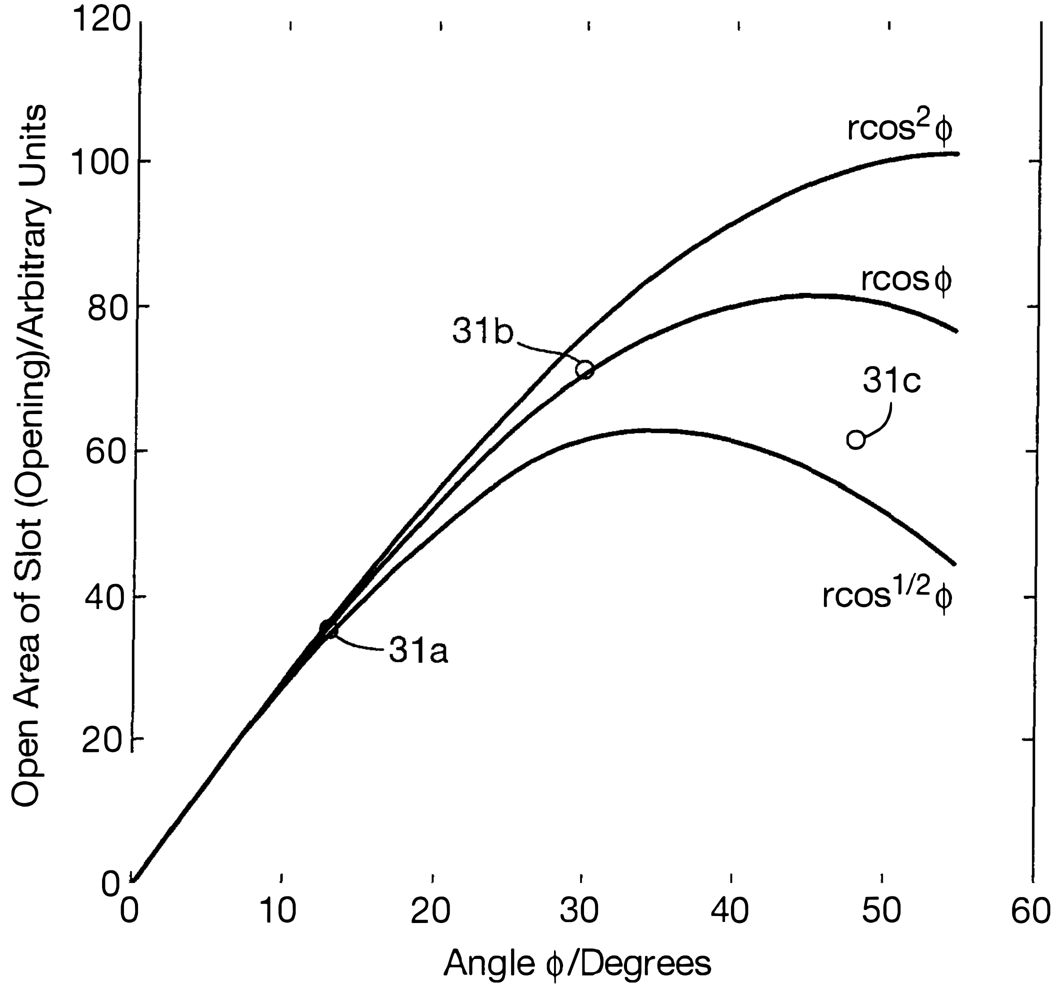


Fig.5.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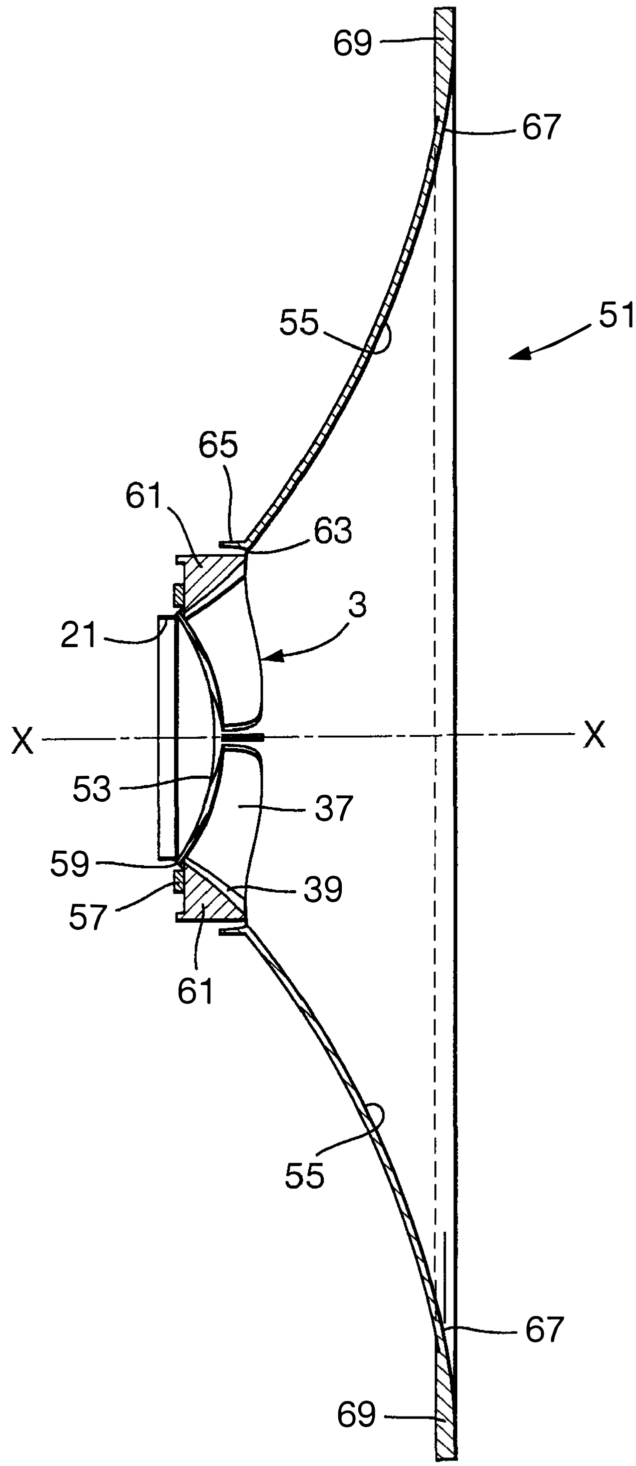

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United States Patent [19]

Fincham

[11] **Patent Number: 5,548,657**

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[54] **COMPOUND LOUDSPEAKER DRIVE UNIT**

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[63] Continuation of Ser. No. 970,542, Nov. 2, 1992, abandoned, which is a continuation of Ser. No. 870,231, Apr. 20, 1992, abandoned, which is a continuation of Ser. No. 603,679, Nov. 2, 1990, abandoned.

[30] **Foreign Application Priority Data**

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[51] **Int. Cl.**[6] **H04R 25/00**

[52] **U.S. Cl.** **381/182**; 381/205

[58] **Field of Search** 381/182, 99, 204, 381/195, 192, 194; 181/144, 199

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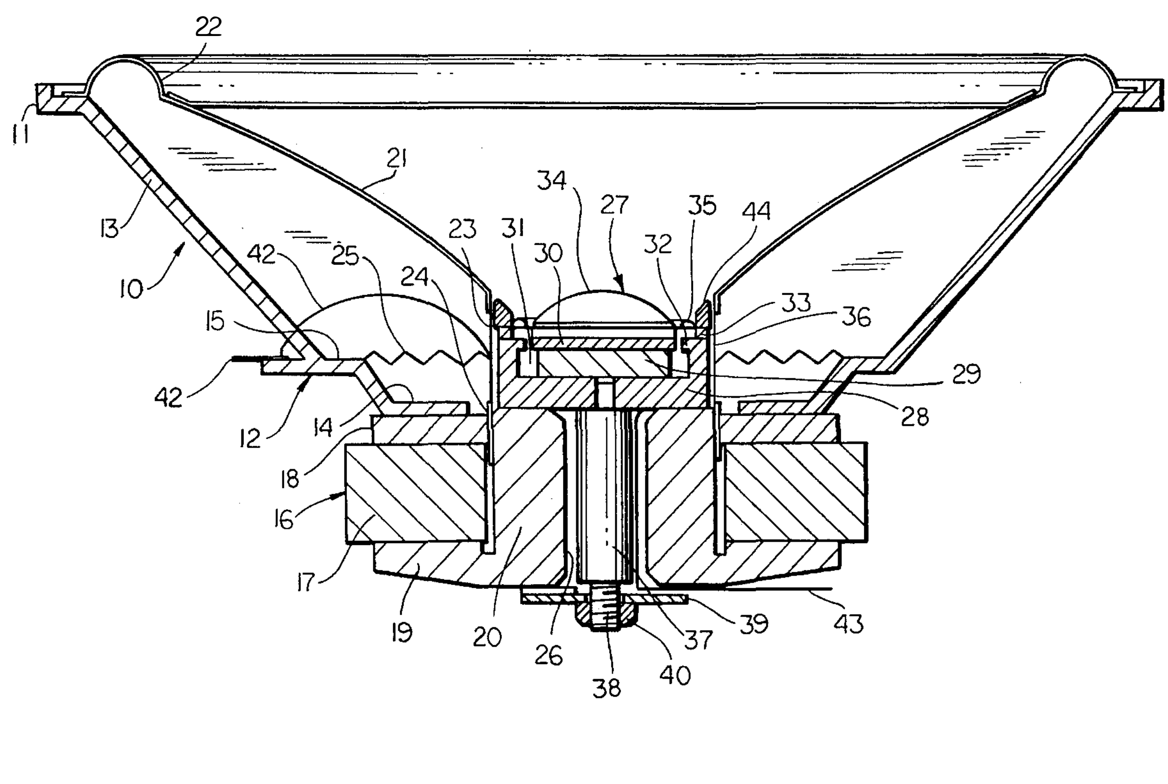
[57] **ABSTRACT**

A compound loudspeaker drive unit comprises a low frequency unit having an outwardly and forwardly flaring conical diaphragm and a high frequency drive unit located in or adjacent to the neck of the low frequency conical diaphragm such that the acoustic centers of the two units are substantially coincident and, for a cross-over frequency range in which both drive units contribute significant sound output, the directivity of sound radiation from the high frequency unit as acoustically loaded by the low frequency conical diaphragm is substantially the same as that of the low frequency unit. A magnet structure for the high frequency unit utilises a magnet formed of neodymium iron boron which enables the high frequency unit to be positioned within a drive coil for the low frequency diaphragm while providing a required high value of magnetic flux.

4 Claims, 1 Drawing Sheet



COMPOUND LOUDSPEAKER DRIVE UNIT

This application is a continuation of application Ser. No. 970,542 filed Nov. 2, 1992 now abandoned which is a continuation of application Ser. No. 870,231, filed Apr. 20, 1992, now abandoned, which is a continuation of application Ser. No. 07/603,679, filed Nov. 2, 1990, now abandoned.

This invention relates to loudspeakers and in particular to compound loudspeaker drive units in which separate diaphragms are provided for reproduction of the low and high audio frequencies.

In some known loudspeaker systems, separate loudspeaker drive units are provided for reproduction of bands of audio frequencies, for example a woofer unit for reproduction of sounds in a low frequency band and a tweeter unit for reproduction of sounds in a high frequency band. The voice coils of the loudspeaker drive units are connected to the output of a power amplifier, or other source, through a suitable cross-over filter network which ensures that only electrical signals representing sounds in the appropriate bands are applied to the individual loudspeaker voice coils. The characteristic of the cross-over filter is arranged so that in a mid frequency cross-over band intermediate the low and high frequency bands the outputs of the two loudspeaker drive units tail off; the output of the low frequency loudspeaker drive unit reduces with increase of frequency while the output of the high frequency loudspeaker drive unit reduces with decrease in frequency. At a so-called crossover frequency the low and high frequency loudspeaker drive units have outputs which are equal but reduced in comparison with their outputs within their respective frequency bands. The electrical energisations of the respective voice coils are adjusted so that the sound outputs of the loudspeaker drive units are relatively matched and together provide a substantially uniform output over the total frequency range of the combination of the two loudspeaker drive units. The sound radiated from each of the drive units may be said to emanate from the apparent sound source or acoustic center of that unit; the position of the acoustic center is a function of the design of the particular unit and may be determined by acoustic measurement.

When separate loudspeaker drive units are provided, the apparent sound sources are physically offset from one another. The loudspeaker drive units are usually mounted on a common baffle such that they lie in a common plane and are offset in a vertical direction in the plane of the baffle. For a listener positioned approximately in line with the axes of the loudspeaker drive units and approximately equidistant from the acoustic centers of both drive units, a desired balance of output from the two drive units can be obtained. However if the position of the listener is moved from the equidistant position, the distances between the listener and the acoustic centers of the two loudspeaker drive units will be different and hence sounds in the mid frequency band produced by both loudspeakers will be received by the listener from the two drive units with a difference in time. This time difference between sounds received from the two drive units results in a change in phase relationship of the sounds received at the listening position from the two drive units. The sounds from the two drive units no longer add together as intended in the cross-over band. Consequently the resultant received sound levels will vary with frequency and the overall sound output of the loudspeaker combination will appear to the listener to be non-uniform. The resulting raggedness in sound output colours the sound and, with stereo sound systems, there is a loss of clarity in the apparent location of instruments in the sound stage. This is particularly apparent in respect of sound frequencies in the upper mid-range, for example in the region of 3 kHz, at which the offset of the drive units relative to one another is comparable to the wavelength of the sound. At a frequency of 3 kHz the wavelength is approximately 4 inches or 100 cm.

In an attempt to overcome the undesirable effects on sounds received at positions which are not equidistant from the two loudspeaker drive units, it is known to combine the low and high frequency loudspeaker drive units in a single compound co-axial construction. The compound co-axial loudspeaker drive unit consists of a generally conical low frequency diaphragm driven by a voice coil interacting with a magnetic structure having a central pole extending through the voice coil. A high frequency diaphragm is positioned to the rear of the structure and sound output from this diaphragm is directed to the front of the loudspeaker drive unit by means of a horn structure extending co-axially through the center pole of the magnetic structure which interacts with the low frequency diaphragm. Thus both the low frequency and high frequency sounds are directed in a generally forward direction from the compound loudspeaker drive unit. In this co-axial form of loudspeaker construction there is no vertical or horizontal offset of the apparent sound sources for low and high frequencies. However the low frequency diaphragm is positioned at the front of the loudspeaker unit whereas the high frequency diaphragm is positioned at the rear of the loudspeaker unit and this results in relative displacement of the apparent sound sources in the direction of the axis of the drive unit and an undesirable time difference in the arrival, at the listener, of sounds from the high and low frequency diaphragms.

SUMMARY OF THE INVENTION

According to one aspect of the invention a compound loudspeaker drive unit comprises a first transducer operable to generate sounds in a low frequency range and a second transducer operable to generate sounds in a high frequency range, said low and high frequency ranges overlapping in a cross-over region; said first transducer having a conical diaphragm flaring outwardly and forwardly from a neck; said second transducer being located in or adjacent to the neck of the conical diaphragm of the first transducer in such a position that effective acoustic centers of the first and second transducers are coincident and that in the cross-over region the flaring of the conical diaphragm imposes a directivity upon the radiation of sound from the second transducer whereby the directivities of the first and second transducers are matched over frequencies in the cross-over region where both transducers make significant contributions to the sound output of the drive unit.

According to a second aspect of the invention a compound loudspeaker drive unit comprises a low frequency moving coil drive unit and a high frequency moving coil drive unit; said high frequency drive unit including magnetic means interacting with the moving coil thereof, said magnetic means including a permanent magnet formed of neodymium iron boron or of material having magnetic properties substantially similar or superior thereto.

Preferably the compound loudspeaker drive unit includes a low frequency drive unit comprising a substantially frusto-conical low frequency diaphragm flaring outwardly in a forward direction from a neck thereof, a low frequency voice coil connected to said neck of the diaphragm; and first magnetic means providing a magnetic flux interacting with the low frequency voice coil whereby electrical energisation of the voice coil is effective to impart movement to the diaphragm to produce sounds in a low frequency range; and

a high frequency loudspeaker drive unit positioned adjacent to said neck of the low frequency diaphragm and comprising a high frequency diaphragm carrying a high frequency voice coil; and second magnetic means including a permanent magnet formed of neodymium iron boron, or of a material having magnetic properties substantially similar or superior thereto, providing a magnetic flux interacting with the high frequency voice coil whereby electrical energisation of the high frequency voice coil is effective to impart movement to the high frequency diaphragm to produce sounds in a high frequency range overlapping the low frequency range in a cross-over band.

Preferably the high frequency drive unit is disposed relative to the low frequency drive unit such that the apparent sound sources of the two units are substantially coincident.

If desired an annular baffle member may be provided effective to provide a continuation of the surface of the low frequency diaphragm toward the high frequency diaphragm.

According to a third aspect of the invention in a loudspeaker comprising co-axially disposed low and high frequency drive units the high frequency drive unit is manufactured separately from said low frequency drive unit and is secured to a pole piece of magnetic means of the low frequency drive unit.

Preferably the pole piece of the low frequency drive unit has a central bore extending therethrough and the high frequency drive unit has a rod, preferably of non-magnetic material, projecting therefrom and engaging within said bore to locate the high frequency drive unit relative to the low frequency drive unit.

BRIEF DESCRIPTION OF THE DRAWING

An embodiment of the invention will now be described by way of example with reference to the drawing which shows a cross section through the axis of a moving coil compound loudspeaker drive unit.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to the drawing, a compound loudspeaker drive unit with low frequency and high frequency transducers having co-axial low and high frequency voice coils comprises a chassis **10** in the form of a conical basket having a front annular rim **11** connected to a rear annular member **12** by means of a number of ribs **13**. The rear annular member **12** has an annular flange **14** and an annular seat **15**. Secured to the flange **14** is a first magnetic structure **16** for the low frequency loudspeaker drive unit. The magnetic structure **16** comprises a magnet ring **17**, which may for example be formed of barium ferrite, a front annular plate **18** which forms an outer pole and a member **45** which forms a backplate **19** and an inner pole **20**. The plate **18**, magnet ring **17** and member **45** are held together to provide a magnetic path interrupted by a non-magnetic air gap between the **18** formed by plate and the inner pole **20**. The poles are circular and form therebetween an annular air gap. The low frequency transducer or loudspeaker drive unit comprises a diaphragm **21** of generally frusto-conical form supported along the front outer edge thereof by a flexible surround **22** secured to the front rim **11** of the chassis **10**. A tubular coil former **23** is secured to the rear edge of the diaphragm **21** and is arranged to extend co-axially of the air gap in the magnetic structure **16**. The coil former carries a voice coil **24** positioned on the former such that the coil extends through the air gap. The coil is of sufficient axial length as to ensure that for normal excursions of the voice coil, the poles always lie within the length of the voice coil. A suspension member **25**, in the form of a spider consisting of inner and outer rings interconnected by flexible legs or consisting of a corrugated sheet having annular corrugations, is secured between the coil former **23** and the annular seat **15** of the chassis **10** in order to ensure that the coil former, and voice coil carried thereby, are maintained concentric with the poles of the magnetic structure and out of physical contact with the poles during sound producing excursions of the diaphragm **21**. The member **45** forming the backplate **19** and inner pole has a bore **26** extending co-axially thereof for the purpose of mounting a high frequency drive unit **27**.

The high frequency transducer or drive unit **27** comprises a second magnetic structure consisting of a pot **28**, a disc shaped magnet **29** and a disc shaped inner pole **30**. The pot **28** has a cylindrical outer surface so dimensioned as to fit within the interior of the coil former **23** without making physical contact therewith. The pot is formed with a circular recess **31** to receive the magnet **29** and an annular lip **32** to form an outer pole. One circular pole face of the magnet **29** is held in engagement with the bottom wall of the recess **31** and the disc shaped inner pole **30** is held in engagement with the other circular pole face of the magnet such that the circular outer periphery of the inner pole **30** lies co-axially with and within the lip **22** forming the outer pole. A non-magnetic air gap extends between the inner and outer poles. A spacer ring **33** is secured to the front face of the pot **28**. Preferably the magnet **29** is formed of neodymium iron boron which allows a very substantially enhanced magnetic field strength as compared with other available magnetic materials to be attained in the air gap between the poles. As a result, the overall size of the high frequency magnetic structure, for a required flux in the air gap, can be smaller than hitherto thereby allowing the high frequency drive unit to be positioned within the coil former of the low frequency drive unit immediately adjacent to the apex of the low frequency diaphragm **21**. However it will be appreciated that the magnet **29** may be formed of other materials having magnetic properties substantially similar or superior to that of neodymium iron boron. A high frequency domed diaphragm **34** has an annular support **35** of annular corrugated form and this support is secured at its outer periphery to the spacer ring **33**. Secured to the domed diaphragm **34** is a cylindrical coil former carrying a high frequency voice coil **36** such that the voice coil extends through the air gap between the poles **30, 32** of the magnetic structure.

In order to centralise the high frequency unit relative to the low frequency unit, and in particular to ensure that the high frequency unit is coaxial with and does not interfere with motion of the low frequency voice coil a rod **37**, preferably of non-magnetic material, is secured centrally to the rear face of the pot **28** and extends through the bore **26** of the low frequency magnetic structure. The high frequency drive unit tends to be held in engagement with the pole **20** of the magnetic structure **16** by magnetic attraction therebetween but is secured to the structure **16** by a threaded end portion **38** of the rod **37** extending through an aperture in a plate **39** positioned at the rear of the backplate **19** and a nut **40** threaded onto the end portion **38**.

Connections to the low frequency voice coil **24** are provided by means of flexible leadout conductors **41** extending from the voice coil **24** to external connectors **42**. Connections to the high frequency voice coil **36** are provided by flexible conductors **43** which extend along a recess in the outer wall of the pot **28**, between the pot **28** and the inner pole **20** and thence through the bore **26** to external connectors (not shown). In order to allow the conductors to extend through the bore **26**, the rod **37** has a diameter smaller than that of the bore **26** so as to leave an annular space through which the conductors **43** extend. Means, not shown, are provided between the pole piece **20** and the pot **28** to ensure that the rod lies co-axially with the bore **26**. This means may be a disc secured to the pole piece **20** and having a central aperture of a diameter to receive the rod **37** in a sliding fit. The disc may be grooved to provide a passageway for the conductors **43** between the pole piece **20** and the pot **28**. The rod **37** may be of circular, hexagonal or other section and the disc would be provided with a central aperture of matching shape.

Instead of utilising a rod **37** of diameter smaller than that of the bore **26**, if the rod is of hexagonal section its diameter may be of a size such that the rod is a sliding fit in the bore **26** to locate the high frequency drive unit co-axially of the pole piece **20** of the low frequency drive unit. Spaces between the faces of the hexagonal section rod and the wall of the bore **26** provide passageways for the conductors **43**. Instead of using a plate **39** to secure the high frequency drive unit, a moulding may be used. The moulding would be located by means of a boss on the moulding entering the bore **26**. The moulding may be so formed as to provide a mounting for other components such as the electronic components of a cross-over filter and terminals for electrical drive signals for the compound loudspeaker drive unit. As an alternative to the end **38** of the rod **37** being externally threaded, the end of the rod may be bored and threaded internally to receive a screw.

The construction described hereinbefore is particularly convenient in manufacture of the compound loudspeaker drive unit in that the high frequency drive unit is centralised relative to the low frequency drive unit prior to the high frequency drive unit reaching its final rest position on the pole piece **20**. As a result the high frequency unit is prevented from engaging the low frequency voice coil during assembly of the compound loudspeaker drive unit. Furthermore this construction facilitates dis-assembly of the high frequency drive unit from the low frequency drive unit if and when any servicing of the units is necessitated without any need to demagnetise either of the magnetic assemblies.

If desired, an annular baffle **44** having a frusto-conical front surface is secured to the front of the high frequency drive unit to provide a continuation of the surface of the low frequency diaphragm **21** towards the domed high frequency diaphragm.

It will be appreciated that with the high frequency drive unit positioned at or adjacent to the neck of the diaphragm of the low frequency drive unit, as in the above described construction of compound loudspeaker drive unit, the apparent sound source or acoustic center of the high frequency drive unit is substantially co-incident with the apparent sound source or acoustic center of the low frequency drive unit. The radiation pattern or directivity of the low frequency drive unit is determined inter alia by the form of the low frequency diaphragm. With the high frequency drive unit positioned adjacent to the neck of the low frequency diaphragm, the form of the low frequency diaphragm imposes its directivity upon the radiation pattern or directivity of the high frequency unit. Consequently at frequencies at which both drive units contribute significant sound output, both drive units have substantially similar patterns of radiation or directivity. As a result the relative sound contributions from the two drive units as perceived by a listener are substantially unaffected by the listener being positioned at off axis positions.

The low frequency conical diaphragm is shown in the drawing as being of conical form having an angle of flare which increases from the neck of the diaphragm toward the outer periphery of the diaphragm. However it will be appreciated that the diaphragm may be of conical form having a uniform angle of flare. Also, the low frequency conical diaphragm may be of circular, elliptical or other section as desired.

The high frequency diaphragm is shown in the drawing as being of domed form. Such a diaphragm is suitable because its acoustic center may readily be located in close coincidence with that of the low frequency diaphragm, and because, in the frequency range where both drive units contribute significant sound output, its small size relative to wavelength gives it, by itself, essentially non-directional sound radiation, allowing the effective directivity to be determined by the low frequency diaphragm. It will be appreciated that the high frequency diaphragm may alternatively be of any other form that provides these characteristics.

I claim:

1. A compound loudspeaker drive unit including a low frequency conical diaphragm flaring outwardly and forwardly from a neck of said low frequency conical diaphragm to generate sound output in a low frequency range, said low frequency conical diaphragm having a first effective acoustic center and having a first directivity;

a high frequency diaphragm of domed form to generate sound output in a high frequency range, said high frequency diaphragm having a second effective acoustic center;

said low frequency range of sound and said high frequency range of sound overlapping in a cross-over region and both said low frequency conical diaphragm and said high frequency diaphragm being effective to make significant contributions to sound output in said cross over region;

said low frequency conical diaphragm and said high frequency diaphragm being located coaxially and said high frequency diaphragm being located adjacent said neck of said low frequency diaphragm so that said second effective acoustic center of said high frequency diaphragm is substantially coincident with said first effective acoustic center of said low frequency conical diaphragm and in said cross-over region where both said low frequency conical diaphragm and said high frequency diaphragm make significant contributions to the sound output the flaring of said low frequency conical diaphragm being effective to impose said first directivity upon said high frequency diaphragm so that said sound output from said high frequency diaphragm has a directivity matched to said first directivity of sound output from said low frequency conical diaphragm;

first magnetic means including a first magnetic flux path provided by a first central pole piece and a first outer pole piece extending around said first central pole piece with a first air gap between said first central pole piece and said first outer pole piece; and a first magnet to generate a first magnetic flux in said first flux path;

a cylindrical voice coil former secured to said neck of said low frequency conical diaphragm and extending rearwardly from said neck, said coil former including a first portion secured to the neck and a second portion extending rearwardly from said first portion in said first air gap and a first voice coil carried by said second portion of said cylindrical voice coil former, said first voice coil being located in said first air gap and electromagnetically coupled with said first magnetic flux;

second magnetic means including a second magnetic flux path provided by a second central pole piece and a second outer pole piece with a second air gap therebetween; said second outer pole piece being mounted on said first central pole piece and being located within said first portion of said coil former; said first magnetic flux path being separable from said second magnetic flux path; and a second magnet of neodymium iron boron compound to generate a second magnetic flux in said second flux path and said second air gap; and

a second voice coil secured to a peripheral edge of the domed high frequency diaphragm and extending in said second air gap and electromagnetically coupled with said second magnetic flux.

2. The compound loudspeaker drive unit as claimed in claim **1** wherein the low frequency diaphragm flares outwardly with a progressively increasing angle of flare from the neck to a front peripheral edge of said low frequency conical diaphragm.

3. A compound loudspeaker drive unit including a low frequency conical diaphragm flaring outwardly and forwardly from a neck of said low frequency conical diaphragm to generate sounds in a low frequency range, said low frequency conical diaphragm having an effective first acoustic center; a cylindrical voice coil former secured to said neck of said low frequency conical diaphragm and a first voice coil carried by said cylindrical voice coil former;

a high frequency diaphragm of domed form to generate sounds in a high frequency range, said high frequency diaphragm having an effective second acoustic center; a second voice coil secured to a peripheral edge of said high frequency diaphragm; and

magnetic means including first and second air gaps in which said first and second voice coils respectively extend, said magnetic means producing a first magnetic flux in said first air gap interacting with said first voice coil and a second magnetic flux in said second air gap interacting with said second voice coil;

said magnetic means comprising a first magnetic structure including a first permanent magnet producing said first magnetic flux in a first magnetic flux path in said first magnetic structure and in said first air gap; and a second magnetic structure including a second permanent magnet producing said second magnetic flux in a second magnetic flux path in said second magnetic structure and in said second air gap, said second magnetic flux path being separable from said first magnetic flux path;

and said second permanent magnet being formed of a neodymium iron boron compound so that for a required magnitude of magnetic flux in said second air gap said second magnetic structure is of sufficiently small size to be accommodated within said voice coil former, said high frequency diaphragm being located with said peripheral edge thereof aligned rearwardly of the neck of said low frequency diaphragm and with said effective first acoustic center coincident with said effective second acoustic center, respectively, and the flaring of said low frequency conical diaphragm establishing a directivity of said low frequency diaphragm which is imposed on said high frequency diaphragm to cause said low frequency diaphragm and said high frequency diaphragm to have directivities that are matched over frequencies in the cross-over region where both said low frequency conical diaphragm and said high frequency diaphragm make significant contributions to the sound output of the drive unit;

wherein the first magnetic structure and low frequency conical diaphragm comprises a first manufactured unit in which said first magnetic structure includes a central pole piece having a bore extending centrally therethrough; and the second magnet structure and the high frequency diaphragm comprises a second manufactured unit separate from said first manufactured unit and including a rod extending rearwardly from said second magnetic structure; said rod extending through said bore and being effective to locate said second manufactured unit relative to said first manufactured unit.

4. The compound loudspeaker drive unit as claimed in claim **3** wherein a wall of the bore in the central pole piece and the rod extending therethrough define a passage and including conductors providing electrical connections to the second voice coil and wherein said conductors extend through said passage.

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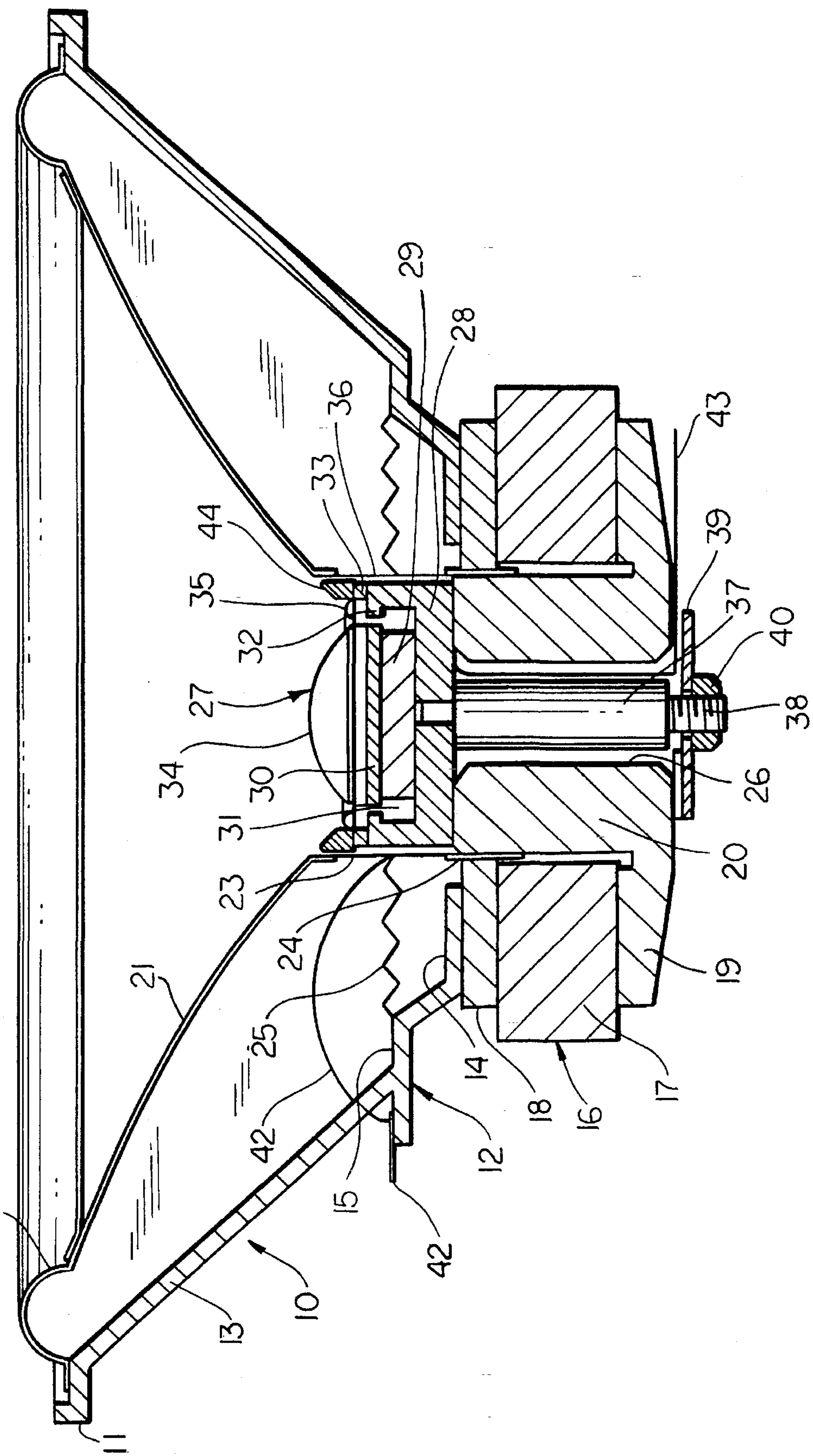
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