A New Methodology For The Acoustic Design Of Compression Driver Phase Plugs With Radial Channels

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1. INTRODUCTION

The efficiency of electromagnetic direct-radiating loudspeakers is fundamentally restricted: the input impedance is dominated by the electrical resistance of the coil and the majority of the input power is dissipated as heat. The portion of the input impedance occurring because of electroacoustical transduction is small by comparison and, typically, maximum efficiencies of only a few percent are possible.

Compression drivers couple a vibrating membrane to a wave guide with a cross-sectional area smaller than the membrane. When coupled to a suitable horn, this arrangement results in a large and wide-bandwidth increase in the radiation resistance experienced by the vibrating membrane. Far higher efficiencies can be achieved (up to 80%): the portion of the electrical input impedance occurring because of electroacoustical transduction becomes of comparable magnitude to the coil resistance.

Early workers [1] found that, by splitting the sound path between membrane and horn into a number of channels, the bandwidth of increased radiation resistance could be usefully extended and smoothed. Such devices became known as “phase plugs” since the design of the channels is intended to compensate for phase differences so that constructive summation occurs at the horn throat.

Commercial phase plug designs tend to be annular having one or more annular acoustical channels between the membrane and horn. The literature on this kind of phase plug is quite mature in spite of the relatively few publications on the topic. The most important of these is undoubtedly Bob Smith's work [2] in which he not only identifies modal excitation in the compression chamber as the cause of response irregularity, but also proposes a method of positioning the phase plug channels in order to avoid this excitation. Unfortunately, this work was, to a great extent, overlooked by his contemporaries and only later popularised by Murray [3]. Many commercial designs, either by design or inheritance, are based on the geometry proposed by Smith. Recent work by the authors has extended Smith's method to account for the curvature of the compression cavity common with modern domed membranes [4]. The authors work also employs numerical models to illustrate the importance of using phase plug design methods that take account of the compression chamber modes.

An alternative arrangement for the phase plug was described by Blackburn [5] in his 1939 patent. In this embodiment, the channels between compression cavity and horn throat are arranged radially, extending from the centre of the dome to the periphery. One of the early cited advantages for this arrangement is that the phase plug moulding may be achieved with a single cavity tool, whereas the more common annular plug design requires a number of annular parts to form the channels. The radial-channel phase plug is also subsequently the subject of other patents [6][7].

Surprisingly, the only published work on the acoustical behaviour is by Henricksen [8][9] in his two comparisons to annular phase plugs. However, the analysis presented in these papers uses an equivalent technique to the equal path-length approach, which was originally proposed by Wente [10], superseded by Smith [2], and shown to be inadequate by the authors [4].

In this paper we present a new methodology for the design of radial-channel compression driver phase plugs. It is demonstrated that the radial geometry is only suitable if strict conditions are met for the geometry of the dome and horn throat. These conditions are, in fact, similar to those required for the optimum performance of a direct-radiating loudspeaker placed directly in a horn [11]. It is demonstrated that modes in the compression cavity are excited by the radiating membrane and that the phase plug must be carefully constructed to compensate for this excitation. The geometry of the channel entrance is derived in order to minimise the excitation of these modes in an equivalent analysis to that presented by the authors for annular phase plug designs [4]. Numerically modelled examples of the new phase plug geometry are presented. Practical limitations of the design are discussed and the radial channel approach is compared to the more common annular phase plug arrangement.

1.1. Radial Phase Plug Arrangement

Figure 1 shows a plan view of an annular phase plug viewed from the membrane side. The channel entrances are marked in black.

Figure 2 shows the radial phase plug arrangement as described by Matsuoka [6]. Again, the black areas show the channel entrances. In this version the radial channels are of a constant width.

Figure 1: Annular channel arrangement.

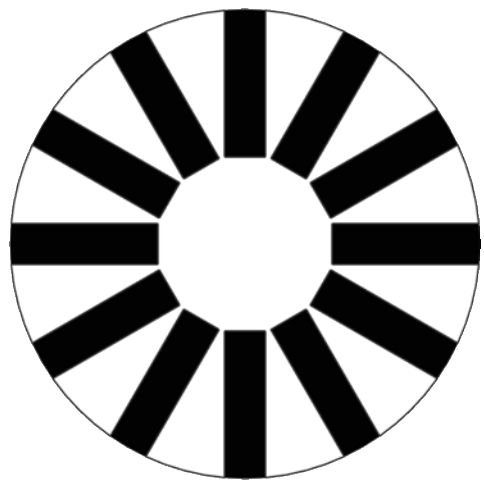

Figure 2: Radial channel arrangement, after Matsuoka.

A slightly different geometry is described by Henricksen [8], shown in Figure 3. The channels are this time at a constant angle and the walls, in addition to the centre of the channel, are radial.

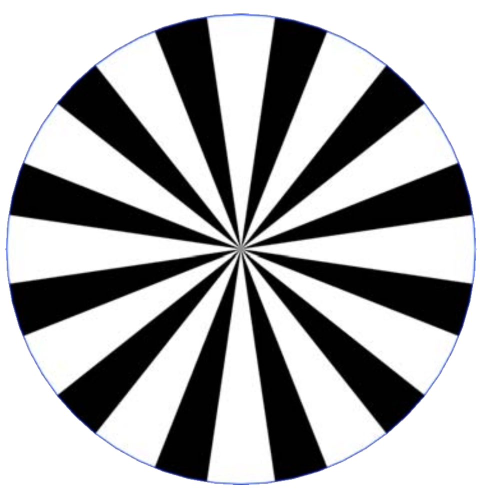

Figure 3: Radial channel arrangement, after Henricksen.

An important difference between the annular design and the radial designs is the symmetry. The annular phase plugs are rotationally symmetric about the axis of the driver (axisymmetry). This symmetry will also be reflected in the acoustical behaviour of the driver: the sound fields occurring will also be axisymmetric. The radial designs do not have this complete axisymmetry; however, they do have circumferential periodicity. If the order of this periodicity is sufficiently high, little circumferential pressure variation is seen. The phase plugs in this paper have a circumferential order of 12. This is high enough that no circumferential pressure variation occurs in the bandwidth in which we are interested.

Figure 4 shows a schematic layout of a radial channel compression drive.

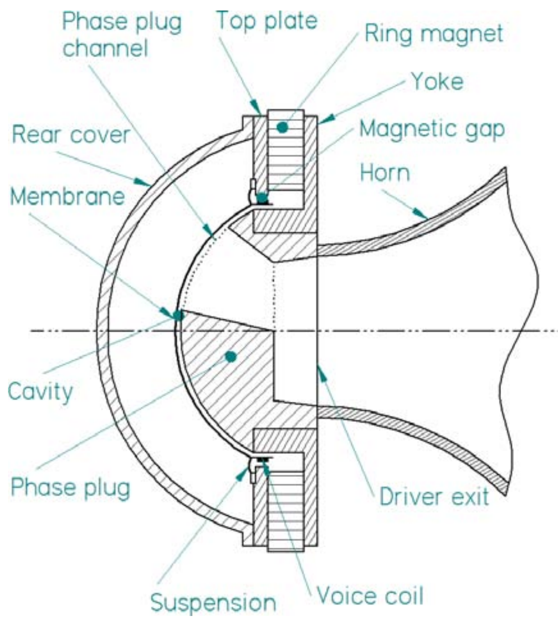

Figure 4: Schematic illustration of a radial channel compression driver.

1.2. Applied FEM Techniques

Radial-channel phase plugs do not have axisymmetric geometry and thus need three dimensional models. Such models require a large number of elements and correspondingly have a high number of freedoms. Solution of the full three dimensional models would have taken months. The number of elements may be reduced by exploiting the periodicity of the geometries. Only the geometry between axial planes of symmetry passing midway through the channel and the covered part of the membrane need be meshed. Swept mesh techniques allow the mesh to be formed from a reasonable number of second-order hexahedral and prism shaped elements.

Terminating the phase plug channels could not be achieved with a ρc_o termination as the wavefront shapes are not generally planar. Wave-envelope elements were an obvious choice for the conical horn as they allow the flare to be extended to infinity in a computationally efficient manner [12], achieving an infinite termination. The first 75mm of the horn is modelled with finite elements and the region beyond this is modelled with wave-envelope elements. However, the cylindrical geometry required to model the Matsuoka & Hendricksen arrangements was somewhat problematic because wave envelope elements will not work in this case.

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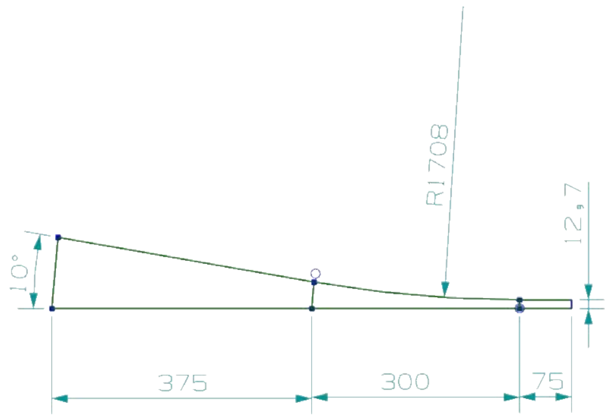

Figure 5: Geometry used to provide infinite tube termination. Tube extends to the right, 10 degree wave envelope area is positioned on the left.

After some thought a coupling waveguide was introduced to link the cylindrical geometry to a conical flare, the cylindrical and coupling waveguide are modelled with finite elements and the conical section with wave-envelope elements. Using the results shown in [13], this exponential coupling waveguide was designed to avoid reflections where the flare changes from exponential to conical. This geometry was further refined using FEM analysis to ensure that spurious reflections did not occur. The resulting geometry is shown in Figure 5.

The membrane is meshed using thin shell elements and constrained to move rigidly with unity velocity in all models. All phase plug models are of compression ratio 2.

As a consequence of this approach, the models in this paper with phase plugs took between one and two hours to solve over 200 frequencies. The models without phase plugs were meshed with second-order axisymmetric elements and solved in two to three minutes.

2. ANALYSIS

2.1. Impedance Tube FEM

Some initial FEM modelling was performed using the radial arrangements as described in section 1.1. These models were simplified so that the acoustical behaviour could be considered in isolation: the membrane behaves like a perfect axially moving rigid piston. The channels are straight and of constant cross section, terminated as described in section 1.1.

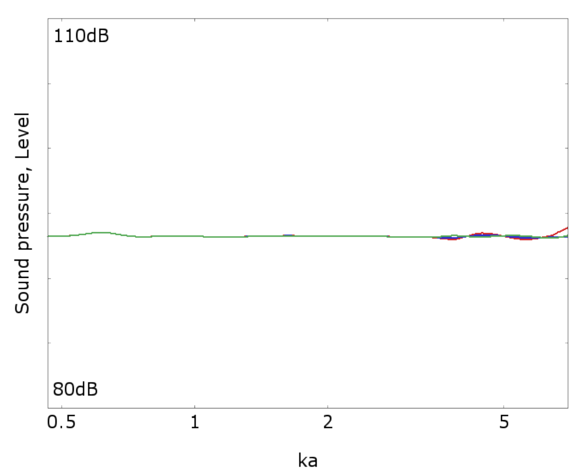

Figure 6: Model 1. FEM computed pressure response at r_0 for planar membrane radiating into impedance tube.

Model 1 is of a planar membrane of radius r_0 radiating into a tube of radius r_0. The pressure was sampled at three equally spaced positions across the tube $2r_0$ from the membrane. These results are plotted in Figure 6 against normalised wavenumber. As anticipated, the membrane perfectly excites plane-wave propagation in the tube and the pressure is equal at the sampling points at all frequencies. The +/- 0.1dB of ripple is a result of reflections due to the change of area in the coupling flare.

Model 2 and model 3 are of the same situation as model 1 but for the addition of radial phase plugs to the front of the membrane. Rather than a complete tube, it is only the channels that are extended to an infinite termination.

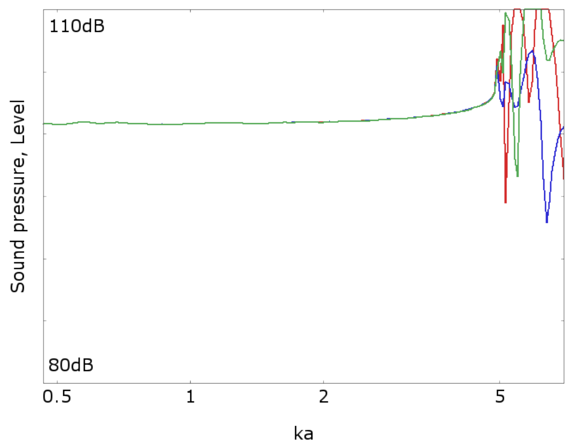

Figure 7: Model 2. FEM computed pressure response at ٢r_0 for planar membrane, Matsuoka-style radial phase plug and constant section channels with infinite termination.

Model 2 uses the Matsuoka phase plug design (see section 1.1), the pressure results at 2r. are plotted in Figure 7. Model 3 uses the Henricksen phase plug design (see section 1.1), the pressure results at ٢r_0 are plotted in Figure 8.

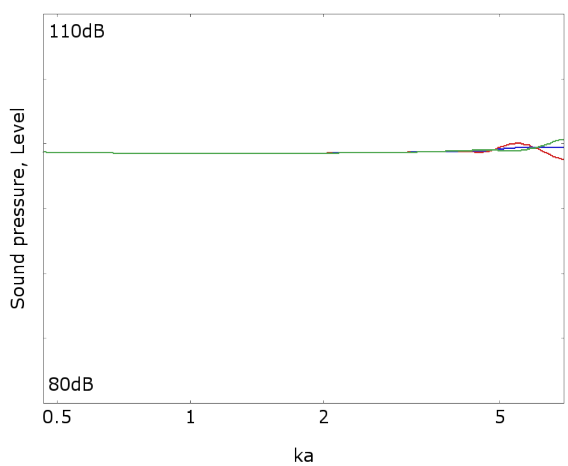

Figure 8: Model 3. FEM computed pressure response at ٢r_0 for planar membrane, Henricksen-style radial phase plug and constant section channels with infinite termination.

Both phase plugs have resulted in an increased pressure level in the channels of approximately 7dB.

The performance of the Henricksen design is significantly superior to the Matsuoka version, which displays some severe resonant behaviour above around a ka of 5. The Henricksen version, by comparison, is virtually just an elevated repeat of the simple planar membrane and tube result of model 1,

Figure 6. A slight separation of the three pressure responses is observed at the extreme top end of the results. This occurs due to the onset of circumferential pressure variation in the driver.

Real compression drivers do not use a flat planar membrane. The membrane must move rigidly over the whole frequency range of the drive unit. Available materials are not sufficiently stiff to achieve this with a thin planar membrane. The overwhelming majority of compression drivers use domed membranes shaped like a spherical cap formed from a thin film material. This construction massively improves the rigidity of the membrane and allows it to operate rigidly over a wide frequency range.

As it was the more successful of the two radial designs, the Henricksen-style radial plug model was adjusted so that the planar membrane was replaced with a domed membrane. All domed membranes in this work are of 40 degrees measured from axis to edge. The channels are again constant area and straight. Figure 9 shows the pressure results at the same three points in the channels.

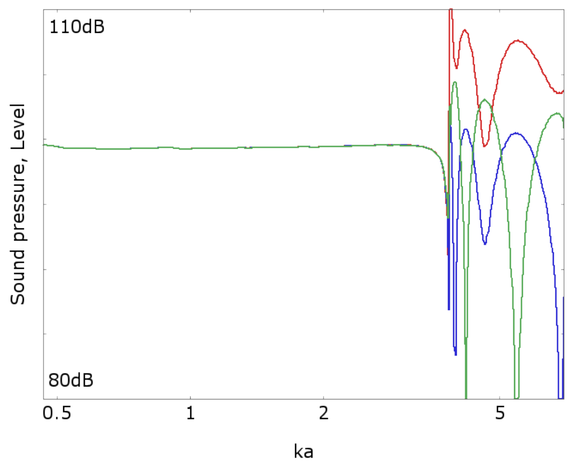

Figure 9: Model 4. FEM computed pressure response at ٢r_0 *for a 40 degree dome membrane, Henricksen-style radial phase plug and constant section channels with infinite termination.*

It can be seen that the change to a dome membrane has severely deteriorated the performance of the design.

2.2. Channel Propagation

Figure 10 shows a simple representation of a compression driver. During operation of a properly designed compression driver, the compression cavity behaves like a very small ideal compliance. This is achieved by firstly keeping the cavity volume to an absolute minimum and secondly by avoiding cavity pressure distributions other than the zeroth static mode. The surface normal velocity that the radiating membrane moves into the cavity and the normal acoustical velocity at the channel entrances is then simply linked: the volume velocity entering the cavity is equal to the volume velocity leaving the cavity.

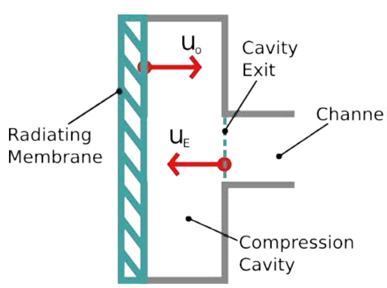

Figure 10: Schematic representation of a compression driver.

In order to maintain this ideal to high frequencies, the cavity must continue to behave like a small acoustical compliance. Resonance must be avoided in both the cavity and the phase plug.

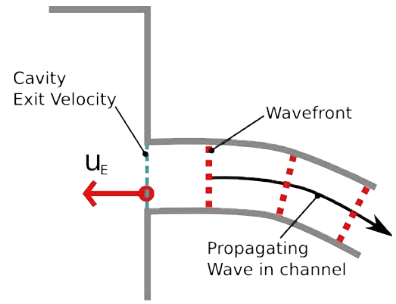

Figure 11: Channel wave propagation in the annular case.

We wish to couple the velocity of air leaving the cavity to the channels so that waves are cleanly propagated to the horn. If this cannot be achieved there is little chance of avoiding resonance.

In the annular case, the phase plug is composed of narrow channels. Within the channels a plane wave will propagate, as illustrated in Figure 11. The cavity exit velocity is nicely coupled to this propagating wave.

In the radial case, with planar membrane and cylindrical cavity, the cavity surface shape and cavity surface-normal direction are a good match for a propagating plane wave. As we observed in the previous section, a simple planar radial compression driver will work well when used with a plane wave-tube.

As discussed in section 2.1 most compression drivers use a domed membrane. With the domed annular arrangement, the entrance is much narrower than a wavelength. The curvature does not effect the coupling between cavity and channel, and little difference is seen compared to the planar design. However, with the radial arrangement the channels occupy the full angle of the compression cavity and the entrance is larger than a wavelength at the upper end of the driver bandwidth. Additionally, the cavity surface shape clearly does not match the wavefront of a plane wave.

In order to ensure that a single parameter wave is propagated in the radial channel, we must match the channel shape to the curvature of the cavity as outlined in [14].

The simplest case that meets this requirement is an infinite conical expansion of the cavity exit in a spherical coordinate system coincident with the focus of the domed membrane.

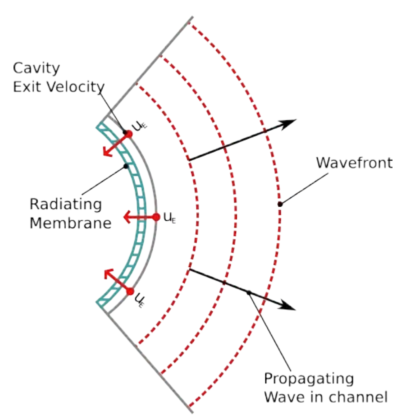

Figure 12: Conical channel geometry propagates a spherical wave to match exit velocity direction.

This requirement is somewhat restrictive compared to an annular design where the channels can be quite severely routed to suit the horn and assembly in question. These restrictions are very similar to the optimum geometry of dome radiating directly into a conical waveguide [11].

2.3. Conical Horn FEM

To confirm the validity of the conclusions of section 2.2 further FEM models were generated. These models all have 40 degree dome membranes and, rather than extruded constant area channels, have channels that are expanded to match the dome: the channel walls are perpendicular to the dome. The channels are terminated as described in section 1.1. The expansion of the channels can be thought of as an infinite conical expansion.

Model 4 is of a simple, axially moving dome membrane radiating directly into a conical horn. As before, the pressure was sampled at three evenly spaced positions $^{Y}r_0$ from the membrane. Figure 13 shows these results.

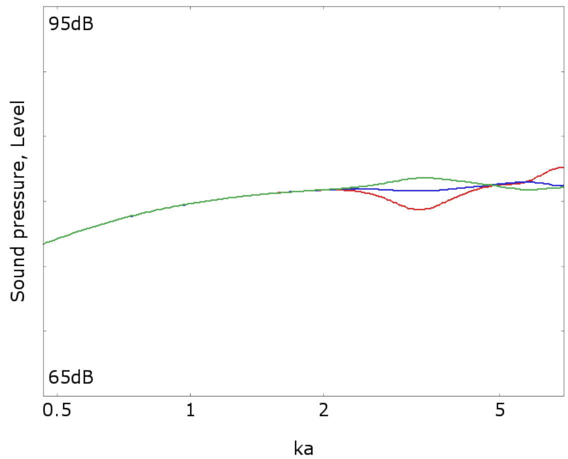

Figure 13: Model 4. FEM computed pressure response at $^{Y}r_0$ from dome membrane radiating directly into an infinite conical horn

This configuration results in a very smooth pressure response in the horn, as is described in [11]. There is approximately 2.5dB maximum variation in pressure between the three sampling locations, this occurs at ka 3.3.

Model 5 is very similar but for the addition of a radial channel phase plug. The channel entrances of the phase plug are of constant polar angle, in the same arrangement as discussed by Henricksen. However, in this case the phase plug is placed on the convex side of the dome membrane, and the wavefronts, and channels, expand away from the compression cavity.

The equivalent pressure results for model 5 are shown in Figure 14. It is remarkable that the pressure responses are so similar to those computed in model 4 (Figure 13). The effect of the compression can be seen in the 7dB increase in level. As with the direct radiating case, we see approximately 2.5dB maximum variation in pressure between the three sampling locations at ka 3.3.

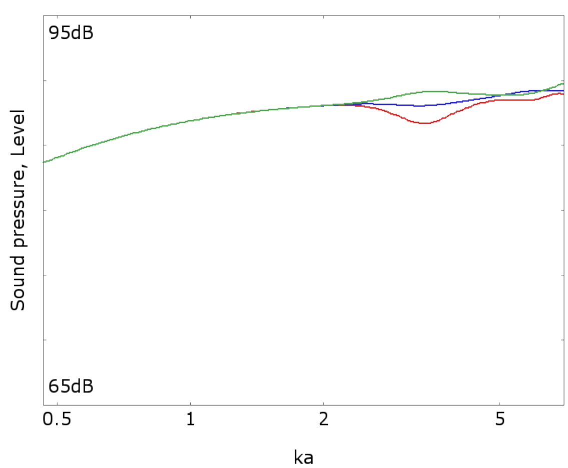

Figure 14: Model 5. FEM computed pressure response at $^{Y}r_0$ from dome membrane with Henricksen-based radial channel phase plug, radiating into infinite conical channels.

Thus far we have not considered the effect of modal excitation in the compression cavity. In the next section we shall refine the design to account for this in a similar way to [4].

2.4. Cavity Mode Minimisation

The large diameter compression cavity has acoustical modes that occur in the driver bandwidth. It is essential that these are not excited in order for the cavity to behave like a simple acoustical compliance. We wish to only see static pressure variation in the compression cavity.

Unfortunately, the curvature of the membrane is a disadvantage in this regard. With a planar membrane and a cylindrical compression cavity, the normal velocity applied to the cavity by the moving membrane is constant over the surface of the cavity. This excitation is ideal as it ensures that none of the higher acoustical modes is excited by the membrane motion [4]. However, with a rigid domed radiator, although the axial velocity of the dome surface is constant, the curvature of the surface means that the normal velocity varies as shown in Figure 15.

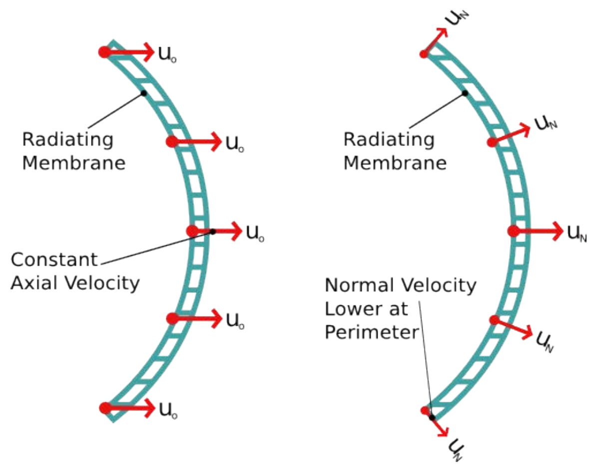

Figure 15: The normal velocity of a rigid, axially-moving, spherical cap surface is lower at the perimeter

If this variation in the normal velocity is ignored, the higher order acoustical modes of the cavity will be excited; it will not behave like a simple acoustical compliance; and resonance will be seen in the final compression driver.

This situation is exactly the same as that which was tackled in the authors' previous paper on annular compression driver design [4]. In the radial-channel compression driver, the solution is more straightforward. Assuming that the compression cavity in our final design will behave like a small acoustical compliance, the membrane velocity is related to the channel entrance acoustical velocity by the compression ratio.

$$-u_E \frac{A_T}{\pi r_o^2} \approx u_o \tag{1}$$

The normal velocity of the membrane reduces toward the periphery. Suppression is easily achieved by profiling the exit side to match this normal velocity, by reducing the channel width towards the periphery. This is possible as the velocity at the exit side will naturally act in the opposing polarity on the cavity, and the exit volume velocity is equal to the membrane volume velocity.

$$u_N(\phi) = u_o \cos\phi \tag{2}$$

It is trivial to calculate the normal velocity of the membrane, equation 2, and we require the area profile of the channel entrances to be.

$$A(\phi)=\frac{A_T}{\pi r_o^{2}}\cos(\phi) \tag{3}$$

2.5. Cos(ϕ) Weighting FEM

The proposed area weighting is shown applied to a 12-channel radial phase plug in Figure 16 alongside an equivalent constant angle version. It may be observed that the channels are narrower at the perimeter of the driver compared to the constant angle version.

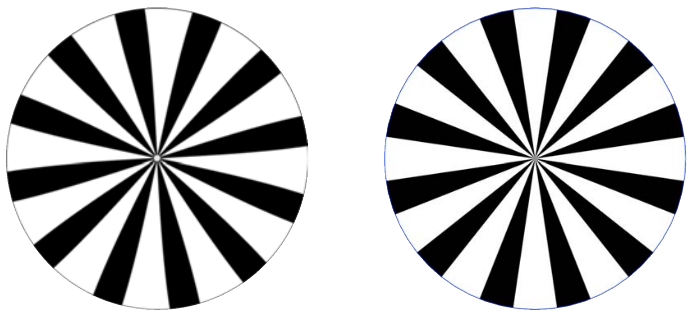

Figure 16: Comparison of Cos weighted radial channel arrangement (left) with Henricksen constant polar angle arrangement (right). Channel entrances are black.

Model 6 was generated to test the new phase plug design. The pressure was sampled at three evenly spaced positions in the channels $2r_0$ from the radiating membrane. These responses are plotted in Figure 17. The separation in the responses at ka=3.3 completely suppressed.

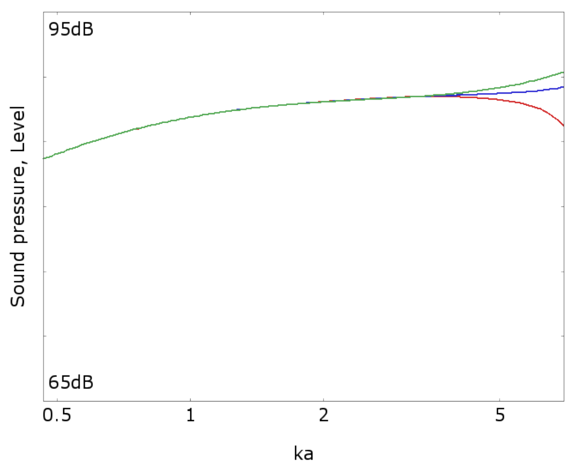

Figure 17: Model 6. FEM computed pressure response at $2r_0$ from dome membrane with Cos weighted radial-channel phase plug, radiating into infinite conical channels.

The separation at ka=5 is believed to be due to circumferential excitation.

3. APPLICATION TO A PRACTICAL DRIVER

The cos weighted radial phase plug was first applied to a real production drive unit for a 19mm diameter high frequency driver. The technology is known commercially as the “Tangerine Waveguide”. The practical embodiment of the phase plug, with finite termination of the channels and non-vanishing edges, is shown in Figure 18.

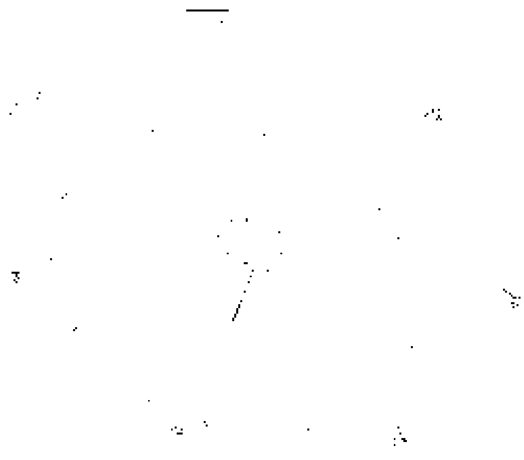

Figure 18: The "Tangerine Waveguide"

For this particular application, the original goal of the phase plug was to protect the dome without introducing unwanted acoustic artefacts. This was achieved by using a small compression ratio and short channel length. However, even in this parochial role, a useful increase of efficiency is achieved.

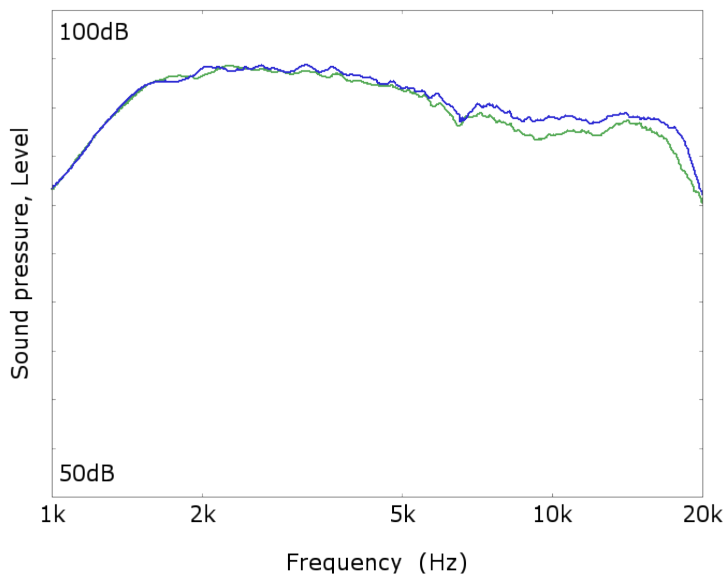

Figure 19: Axial pressure response at 1m of 19mm diameter tweeter radiating into 2π steradians, input voltage 2.83V.

Green (lower) line: uncovered dome.

Blue (upper) line: dome covered with "Tangerine Waveguide"

Figure 19 shows the measured 2π axial pressure response of the driver at 1m with and without the "Tangerine Waveguide". Despite the modest size and compression ratio, the addition of the phase plug increases the efficiency of the driver by 2dB above 6kHz. An improvement is also observed in the dispersion of the driver.

A more recent and more demanding application was for a 25mm diameter high frequency driver where an extra 5dB of sensitivity was required in addition to extending the bandwidth to well beyond 20kHz. The extra sensitivity was achieved by covering more of the diaphragm. The larger size of the dome and increased high frequency bandwidth meant that radial modes had to be considered. With only seven segments radial modes cause a dip in the pass-band and the number of segments had to be increased to 12. However, to ease manufacturing of the "tangerine waveguide" the number of segments must be reduced near the central axis. The resulting geometry is shown in Figure 20. The response with and without the "Tangerine Waveguide" is shown in Figure 21. It can be seen that not only is the level increased but the response is also smoother. It is worth noting that this result could only be achieved after much work to ensure the high frequency driver was behaving in an almost ideal manner.

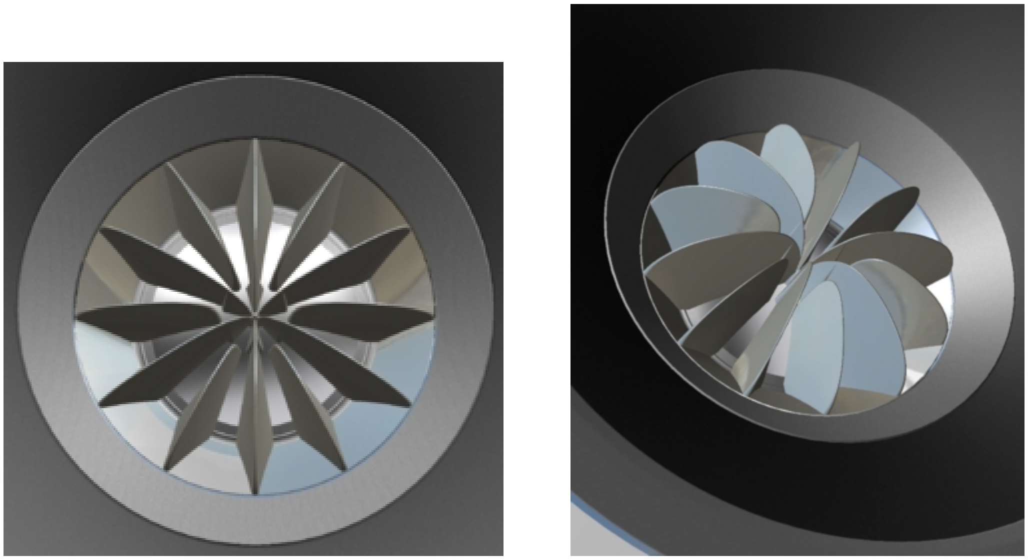

Figure 20: Plan and isometric views of the new high compression ratio phase-plug for the 25mm diameter diaphragm

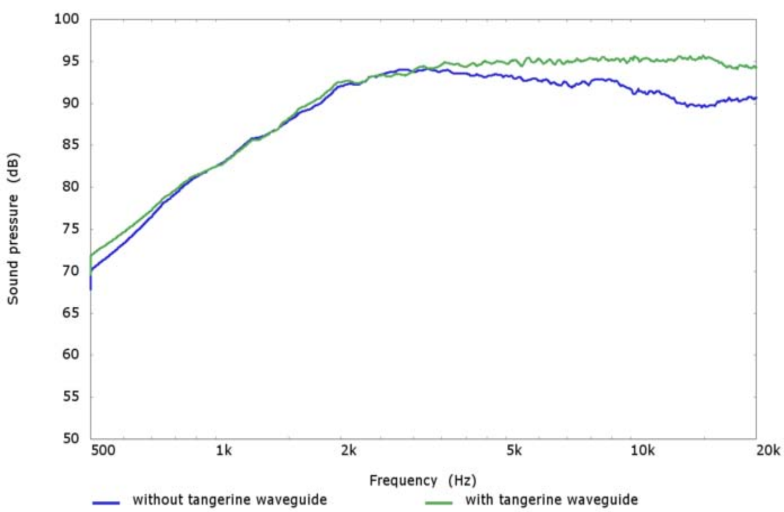

Figure 21: Axial pressure response at 1m of the new high compression ratio phase-plug for the 25mm diameter diaphragm

4. DISCUSSION

The generic concept of a compression driver is relatively simple: the area difference between the membrane and phase plug channels is used to increase the radiation impedance experienced by the membrane. The behaviour is like a simple lever, a small motion at the membrane is translated to a large motion in the phase plug channels.

The design challenge is to make the real device behave like this simple ideal over a wide bandwidth:

- maintaining rigid membrane motion.
- ensuring the compression cavity is mode free and simply behaving.
- ensuring that the radiated sound is cleanly propagated from channels into the horn without reflection, resonance or diffraction.

The common annular ring phase plug has evolved as the most popular realisation with good reason: it allows almost complete separation of the three design goals, specifically the last two acoustical challenges. The compression cavity modes are managed with careful control of the channel entrance geometry and by ensuring that they present a constant acoustical impedance to the chamber [2][4]. The annular channels may be arranged as required to ensure that the phase and amplitude of the propagating sound is consistent at the horn throat and that the wave cleanly propagates [15].

With a radial channel arrangement it is not possible to be so “orthogonal” in design. There are some clear difficulties with the geometry which make it harder to deal with.

Firstly, the annular ring compression driver is axisymmetric and there is no need to consider circumferential pressure variation in the driver. This is not the case for the radial version.

Secondly, with the annular design the channel entrances are narrow in the radial direction. The acoustical pressure is always very nearly constant across the whole entrance to each channel. The radial version, on the other hand, is narrow in the circumferential direction but wide in the radial direction. The acoustical pressure is not necessarily constant across each channel entrance.

This second distinction is particularly important. In the annular version the coupling between each channel and the compression chamber is approximately one-dimensional. Cavity excitation due to each channel can be balanced by adjustment of the channel entrance size and position alone. Provided that the channels sum correctly at the horn throat, the paths of the channels and the geometry of the horn and wave-guide do not affect the chamber modal behaviour. The channels can be routed as required to work with the horn in question. In practice, a single, annular design can be made to work acceptably on a range of different horns. However, with the radial design, the acoustical behaviour of the compression cavity, phase plug channels and horn is highly interdependent because of this continuous coupling in the radial direction.

Even a carefully designed and fabricated annular phase plug compression driver exhibits a few very narrow band resonances. The smallest mismatch in the pressure and acoustical velocity where the channels are joined at the throat will cause reflected waves. These waves excite longitudinal modes in the channels, resulting in narrow band “glitches” in the acoustic impedance at the channel entrances and thus in the acoustic output. With a radial phase plug compression driver it is possible to completely avoid these resonances since the channels behave identically due to the symmetry.

The idealised geometries investigated in the paper extend to infinity and do not take into account a number of practical details. Firstly the dome must be supported with a flexible seal known as a surround. The surround will radiate additional sound and require an extension of the cavity, which must be taken into account in the acoustic design. Furthermore, the phase plug must be truncated to a finite length requiring a circumferential flare of the channels. Where the phase plug is fabricated as an injection moulding, minimum wall thickness and tool steel thickness must also be taken into account. These factors necessitate additional design and modelling iterations to achieve a satisfactory result.

5. CONCLUSION

A radial-channel geometry allows the phase plug to be manufactured from a single moulding. However, the increased geometric complexity requires greater sophistication and effort both in FEM and analytical modelling.

While it is easy to achieve good theoretical performance with a planar membrane and simple radial phase plug, when more realistic membrane shapes are introduced the performance is seriously degraded.

With an annular phase plug, the wavefront shape may be altered by adjusting the channel lengths to suit the horn geometry in question. A radial-channel phase plug, on the other hand, can only perform ideally if the shape of membrane and horn conform to similar constraints as a direct-radiating membrane and waveguide [11].

Additionally, further performance increases can be made by considering the modal behaviour of the compression cavity, as previously considered for annular phase plug design [2][4].

The resulting designs can perform exceptionally well and practical implementation gives useful acoustical and practical benefits.

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