ACTIVE UNIMORPH CONTROLLED DIAPHRAGM – A NOVEL METHOD FOR MODAL CONTROL OF LOUDSPEAKER TRANSDUCER DIAPHRAGMS

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1 INTRODUCTION

The control of diaphragm resonance has been an ongoing challenge for loudspeaker transducer designers. Resonance is an expected feature of moving coil loudspeakers. The fundamental resonance of the transducer involves all the moving parts that sit within the suspension components. These components oscillate as a single degree of freedom system, largely determining the lower frequency performance of the loudspeaker. A wealth of knowledge, standards and a comprehensive toolbox exists to help the loudspeaker designer based on this relatively simple representation.
For round loudspeakers, considering only the axisymmetric case for the diaphragm component, the resonance behaviour above this fundamental resonance comprises an incremental sequence of structural bending modes from the outer diaphragm edge as frequency is increased. These modes are generally regarded to produce undesirable effects that produce narrow bandwidth frequency response undulations, directivity discontinuities and nonlinear distortions in the reproduced audio. Extending this to 3D geometry that may include elliptical and racetrack geometries, additional bending mode behaviour through the circumference (bell modes) that are superimposed on the axisymmetric modes become evident[1].
Design strategies have been developed to suppress these effects by careful selection of materials and shapes, often using numerical modelling tools such as the finite and boundary element methods, FEM/ BEM as a platform to trial, predict and define the necessary parameters to achieve best performance.
In this paper, a different method will be discussed based on the interaction of two distinct, active electroacoustic transducer types, a moving coil loudspeaker and a piezo unimorph. By working together, it was found that potentially valuable improvements in audio quality can be achieved throughout the frequency range where diaphragm resonance would otherwise be problematic. Furthermore, it is suggested that a broad sweep of limitations that would normally confront the designer might be re-evaluated. Geometry that would be understood as prone to mechanical breakup might now be considered viable, with the promise of performance improvements and packaging advantages.

2 PERFORMANCE TARGETS FOR TRANSDUCER

2.1 Frequency Response

Ideally the axial frequency response for a fixed voltage would be flat and smooth through the full driver use-band, producing a constant SPL with frequency. Diaphragm resonance however causes the frequency response to become irregular over narrow bands due to the mechanical breakup of the principal radiating components. There are limited options for addressing this problem. Diaphragm materials and shapes are generally optimised by engineers to either lessen the frequency response variation or shift the effect out of band where the driver's application is limited to the bandwidth where the response is pistonic.

2.2 Directivity Index and Sound Power Level

Moving coil loudspeakers incorporate a diaphragm of finite size that is primarily selected to maximise efficiency as this can reduce the cost of other components in the transducer and preceding audio chain. As the driver size increase, so too does its directivity and radiators of greater diameter beam sound into smaller angles at lower frequencies. For the idealised case of a flat oscillating piston in an infinite baffle, the pressure is multiplied by the following directivity factor D, to describe the angular dependence:

$$D(a, \theta) = \left| \frac{2J_1(ka\ Sin\ \theta)}{ka\ Sin\ \theta} \right|$$

Equation 1 – Directivity Factor for Flat Rigid Piston in Infinite Baffle

Engineering the diaphragm shape and material specifications using numerical modelling tools, and aligning it with the drive and suspension components can produce better controlled frequency responses. FEM/ BEM modelling is now routine in loudspeaker engineering and increasingly this is done using optimisation routines to which these tools are well suited[2]. Permutations of a generally conical shape are common and variations within that can control the distribution and magnitude of the break-up resonances. Being of finite depth however means that an inevitable disturbance to the sound radiation occurs not only on-axis, but also at angles off-axis.
By observing the effect of increasing the depth of a rigid diaphragm in an infinite baffle, it can be shown that the otherwise consistently overlapping off axis contributions of the flat piston, are affected by acoustic interferences introduced by the conical shape. These pure acoustic effects are also observed in the DI and PWL responses and can be most graphically identified as flaring effects in an otherwise progressively tapering directivity contour plot. These effects are illustrated below for the case where a flat rigid piston is compared with a cone radiator (30deg semi-apex angle) in an infinite baffle.

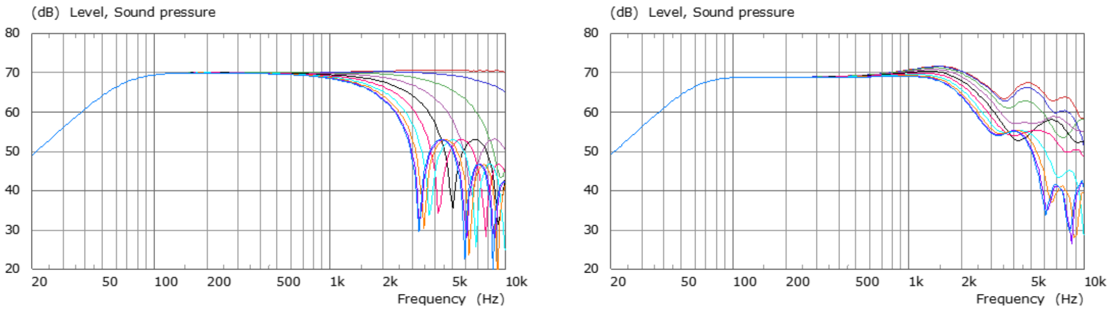

Figure 1 –Off Axis Frequency Responses (0 – 90deg) Comparing Baffled Rigid Flat Piston and Rigid Cone

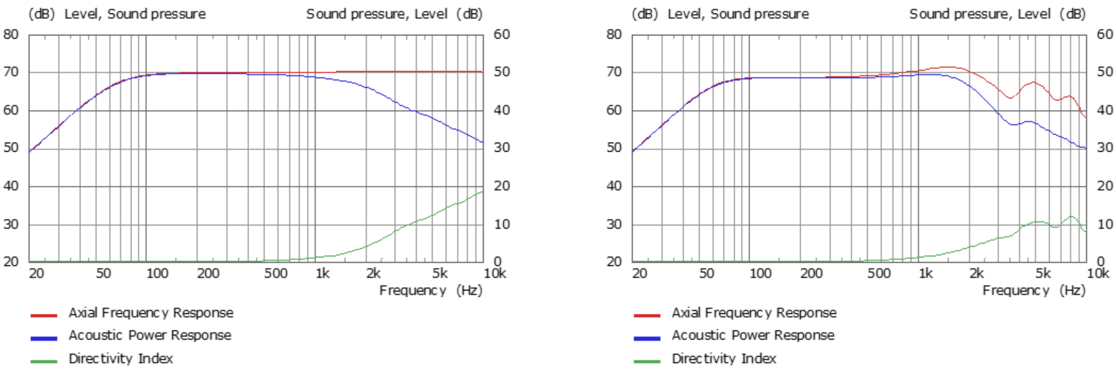

Figure 2 – Acoustic Power and Directivity Index for Baffled Rigid Flat Piston and Rigid Cone

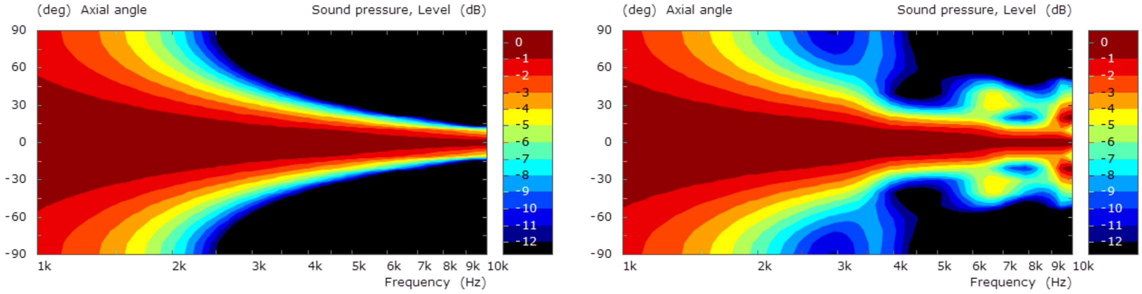

Figure 3: Normalised and Mirrored Directivity Contours for Baffled Rigid Flat Piston and Rigid Cone

Figure 1,Figure 2 and Figure 3 together illustrate that even as rigid bodies, the diaphragm shape has an influence on the radiated sound both in terms of the flatness of the responses and directivity. The cone shape does not achieve the same directivity as the flat diaphragm.

Diaphragm breakup modes result in abrupt changes in directivity as different parts of the radiating surface de-couple and the effective radiator size changes discontinuously with increasing frequency. In terms of how this might sound, in a reverberant environment where much of the received audio content is from reflected energy, the variations in sound committed to the environment and back to the listener may produce timbral colouration.
ANSI/CTA-2034A[3] outlines a measurement standard using orbits of sound pressure measurements as basis data that considers the radiation of the loudspeaker not only directly on its axis, but also over solid angles. Amongst other post-processing, estimates of sound power (PWL), directivity index (DI) and in-room response are presented to infer a level of performance within a room setting.

In the broader scope of audio design, there are also cases where high and low directivity is desirable from the transducer, provided these are controlled. These may include situations where sound is projected away from the listener towards a reflective surface, perhaps to broaden the perceived stage or conversely where the output is directed towards the listener and suppress the effect of room reflections. For the purposes of this paper, the target would be a controlled directivity taper to high frequencies with the overall directivity governed by the diameter of the transducer.

2.3 Distortion

Nonlinear distortion effects are well understood in loudspeaker design, particularly at low frequencies where the driver is forced into high excursion. In these cases, it is mechanics of the suspension components that contribute, along with electromagnetic effects from the motor rather than diaphragm flexure.

In the upper frequency range however, the onset of diaphragm breakup also brings elevated amounts of audible harmonic distortion that increases with input level as illustrated in the example below, which are measurements taken of an 80mm full-range driver with paper diaphragm.

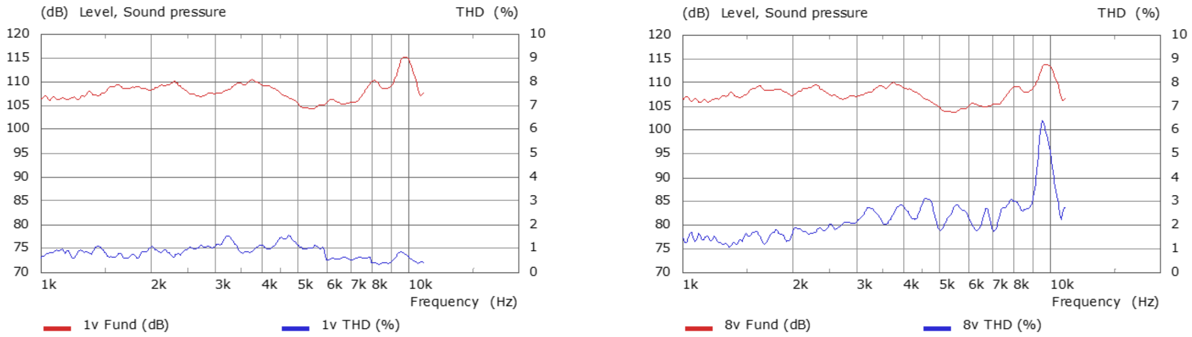

Figure 4 – Harmonic Distortion through Diaphragm Resonance Region with Stimulus at 1v and 8v

When the applied signal voltage, swept over a band of frequencies where diaphragm breakup occurs is increased to the driver, the reproduced audio has increased harmonic content.

As this type of distortion is largely related to dynamic bending behaviour of the diaphragm, it follows that if the diaphragm did not break up into flexural modes, then the resulting distortion would be lower.

3 TRANSDUCER DIAPHRAGM GEOMETRY

3.1 Flat Diaphragm

Based on previous discussion, a flat, rigid diaphragm would serve as an ideal radiating surface with predictable and controlled directivity. A flat diaphragm is mechanically weak and under oscillatory loading from the voice coil may produce a worst-case for bending/ breakup modes and their associated frequency response undulations, directivity problems and distortions. Light, stiff and sandwiched material layups offer some mitigation, however this is limited. If it were possible to maintain a flat diaphragm over an extended frequency range, an improvement of these important audio reproduction issues might be expected.

Additionally in terms of packaging, a flat diaphragm would also reduce the overall height of the transducer. This would be valuable in space critical applications such as in laptops and other mobile devices.

4 IMPLEMENTATION OF PIEZO UNIMORPH TRANSDUCER

4.1 What is a Piezo Unimorph transducer

This is a type of transducer that is often used in applications where good audio reproduction quality is not a primary concern, but where acoustic output, packaging and low cost are important. Examples of these applications are in safety alarms, pet scarers and wrist watches. High electroacoustic efficiency can be achieved, but generally over small bandwidths and these devices are therefore useful where simple tones/ beeps are required to be reproduced.

Piezo unimorph transducers are polarised and reciprocal devices used in both sensing applications as well as acoustic radiators. A ubiquitous embodiment is the piezo disk bender transducer which is illustrated below.

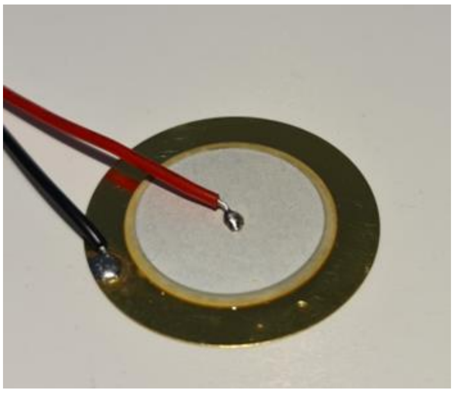

Figure 5 – Piezo Bender Transducer

The material polarisation is established during manufacture and the electrodes are realised as thin conductive plates that sandwich a piezoelectric ceramic material, most commonly lead zirconate titanate (PZT). In Figure 5, the electrodes are connected by soldering the positive plate directly, and the earthed electrode via a conductive plate, which is the diaphragm of the transducer. The assembly where a single piezo element is attached to the conductive plate is called a unimorph whereas an assembly comprising a brass disk with a piezo element on each side is called a bimorph.
The transduction is broadly the conversion of an applied electrical voltage to enforced bending behaviour in the diaphragm and from this, sound radiation.

Electrically, piezo drivers operate over a higher voltage range and draw lower currents than moving coil loudspeakers. The electrical impedance is mainly capacitive and power requirements are generally low, though as a capacitive device this is dependent upon the element size and frequency at which the device is operated. When driving around the resonance frequency, the device draws more current. Specific amplifier chips are available with output voltage ranges around +/-200Vpp although many PZT based elements similar to that shown in Figure 5 specify a limit of 30Vpp. The piezo transducer will operate using a conventional power amplifier, however given these general characteristics, a specialised amplifier will perform optimally.

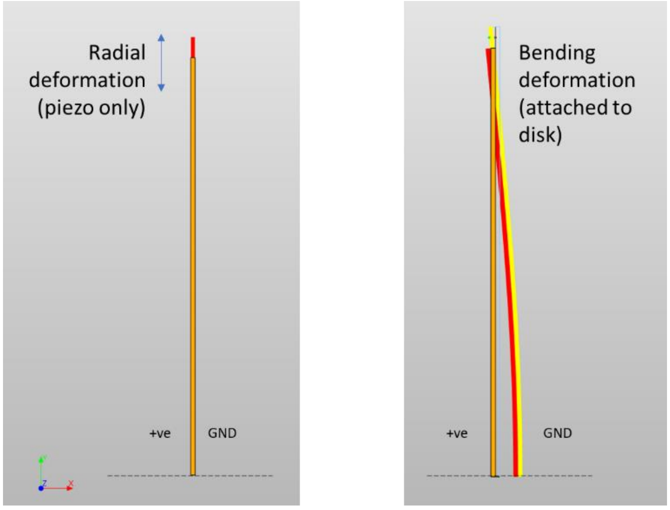

Figure 6 – Piezo UniMorph Deflection Under Applied Voltage (axisymmetric)

Figure 6 illustrates the piezo element in a finite element model both on its own and when attached to a brass disk. Under an applied AC voltage, the element alone swells and contracts radially, but does not produce a bending motion, however when attached to the brass plate, the mechanical unimorph assembly bends in response to the input signal. As a device that is specifically polarised and can be controlled with an AC signal, there is scope to implement this technology as a control system for diaphragm bending problems.

4.2 Application to a Moving Coil Loudspeaker in FEM/ BEM Simulation

As discussed, a piezo unimorph transducer is typically used as a sound reproduction device in its own right, however this technology could also have a valuable application as part of a control system for suppressing diaphragm modes in moving coil loudspeakers.
The foregoing has presented the case for moving coil loudspeakers with flat diaphragm geometry, but has also highlighted their susceptibility to mechanical breakup when excited over a broader frequency range. It is proposed that a piezo unimorph attached to a flat moving coil loudspeaker diaphragm could provide suitable mitigation, opening up new system design possibilities with improved audio quality in a shallower package. Figure 7 shows a simple loudspeaker embodiment in axisymmetric view.

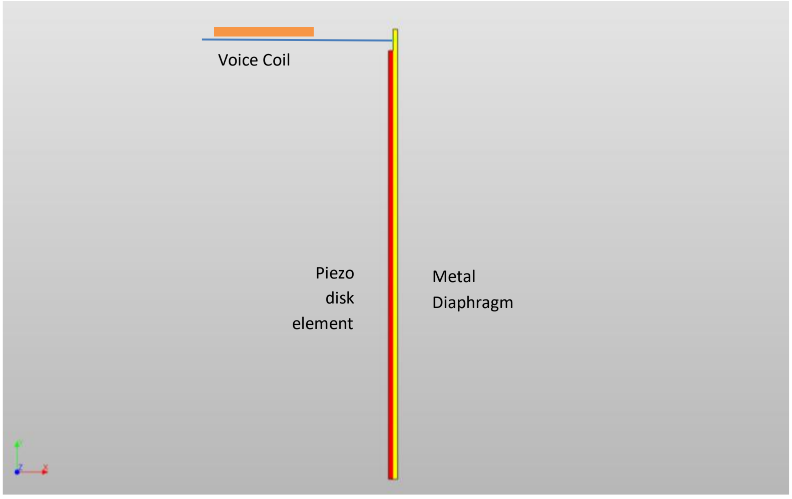

Figure 7 – Piezo Bender Transducer Applied to Loudspeaker (axisymmetric)

This assembly comprises a metal disk with a piezo element attached to the rear surface and a voice coil attached to the outer edge. A 40mm piezo disk was modelled using piezoelectric elements and material parameters for PZT-4, with the front and rear surfaces defined as electrodes to which a separate AC signal is applied. This corrective signal would be derived from the input signal to voice coil of the loudspeaker, but polarised and filtered such that the piezo acts to suppress modal flexure of the diaphragm assembly. The front surface was mechanically and electrically coupled to a 42mm conductive disk made from brass. The conductive disk, which is the diaphragm of the loudspeaker was excited using a voice coil attached close to the outer edge. This was the primary drive to the loudspeaker. Additional lumped elements were included to represent the voice coil's mass and electrical damping effect plus a spring element to provide the stiffness representing a peripheral suspension component.
This geometrical definition of the mechanical parts formed the basis of a multi-physics finite element model with exterior acoustics modelled in the forward half space with an acoustic boundary element terminating at an infinite baffle. Although simplified to highlight the effect of the piezo, the model should be sufficiently representative of a real transducer.
The scenarios modelled were when the loudspeaker is excited with 1v by the voice coil on its own, and then when a corrective signal was applied to the piezo element. The corrective signal in this exploratory case was successively approximated by manually updating a complex voltage spectrum to the piezo until the model indicated that the overall diaphragm bending reduced such that the assembly behaved as a piston.

5 RESULTS FROM FEM/ BEM SIMULATIONS

5.1 Mechanical Deformation and Acoustic Response (no corrective signal)

The diaphragm deformation as a result of modal behaviour is indicated in the axisymmetric and 3D views below.

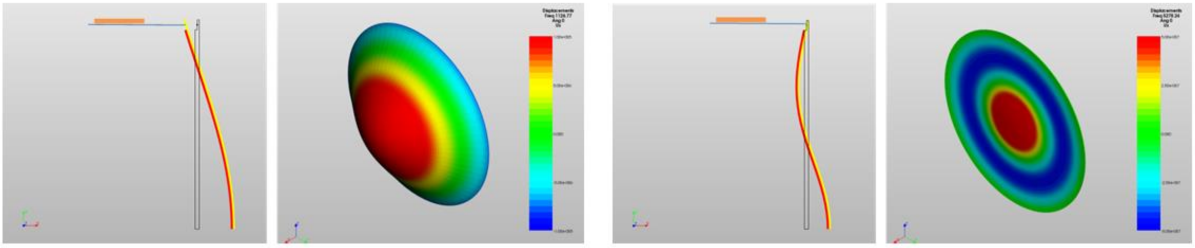

Figure 8 – Axisymmetric and 3D views of Mechanical Diaphragm Deformation with no Piezo Excitation

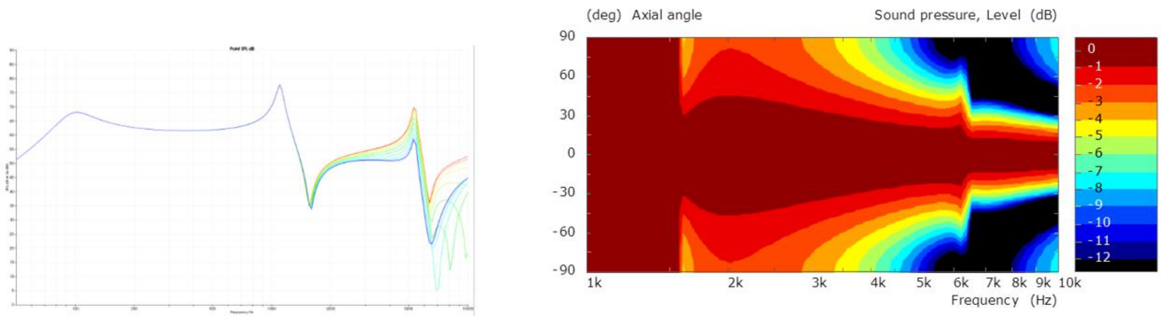

Figure 9 – Off-Axis Freq Resp @1m, 0 to 90deg and Normalised Directivity, no Piezo Excitation

5.2 Iteratively Derived Correction Signal

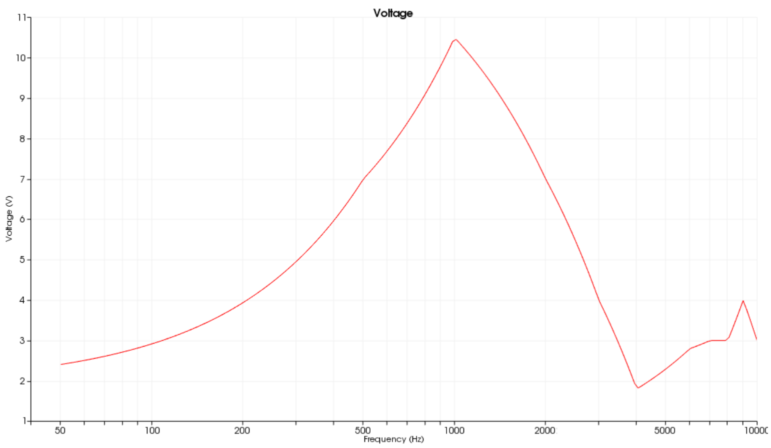

Figure 10 – Voltage Applied to Piezo Electrodes to Control Diaphragm Bending at Resonance

5.3 Mechanical Deformation and Acoustic Response (with corrective signal)

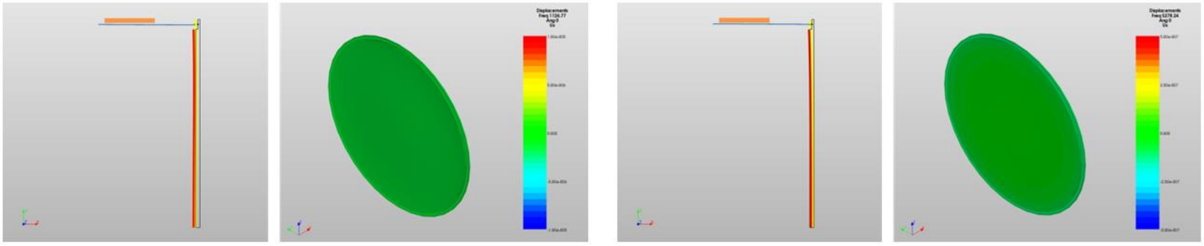

Figure 11 - Axisymmetric and 3D views of Mechanical Diaphragm Deformation with Corrective Piezo Excitation

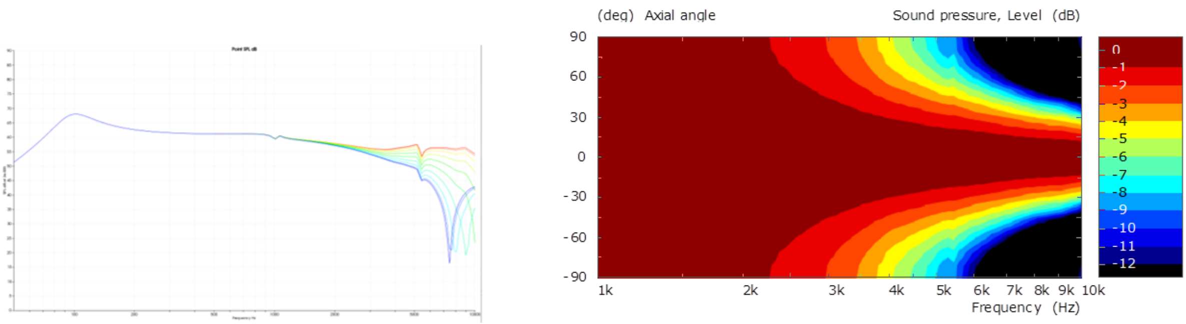

Figure 12 - Off-Axis Freq Resp @1m, 0 to 90deg and Normalised Directivity, Corrective Piezo Excitation

6 DISCUSSION AND POTENTIAL APPLICATIONS

The simulation results illustrate both the mechanical and acoustic changes when the audio signal was applied over a sweep of frequencies from 50Hz to 10kHz for the case where no signal is applied to the piezo and when a corrective signal was applied.
Figure 8 shows the mechanical deformation for the first 2 axisymmetric bending modes and Figure 9 the corresponding frequency responses on and off axis which are presented as individual curves as well as mirrored contour plots which were normalised to the axial response.
When no signal is applied to the piezo element, the frequency response includes the 2 diaphragm resonances as very distinct features in the acoustic response and a directivity contour that is discontinuous at the modal frequencies.
Applying the corrective signal shown in Figure 10, a substantial reduction in diaphragm deformation was evident as shown in Figure 11 causing it to behave in a more piston-like manner and providing a first indication that the modes had been suppressed. The acoustic results in Figure 12 reflect the change in mechanical behaviour and the undulations in the frequency responses between 0 and 90º are significantly reduced with only a weak witness to the modes. The acoustic contour plots additionally show a more ideally tapered directivity response, free of narrowband “flaring”.
The results also show that the frequency response where the piezo is activated is negatively sloping. Acoustic output is often compromised in systems that cancel modes, which are often exploited to increase efficiency, but at the cost of other performance attributes. The downwards slope is a relatively simple correction to make using electronic filtering on the input signal to invert the behaviour to give a flat response.

Overall, the combination of degenerating the diaphragm geometry to that of a flat disk and the suppression of modal behaviour results in a radiation characteristic that mimics that described by Equation 1. This potentially simplifies the acoustic design of an audio system utilising this concept.
Below are examples of where this technology could be deployed.

6.1 Loudspeaker with controlled upper range directivity

A useful application could be a mid-high frequency driver with uninterrupted flat geometry to interface with a baffle. This is illustrated below.

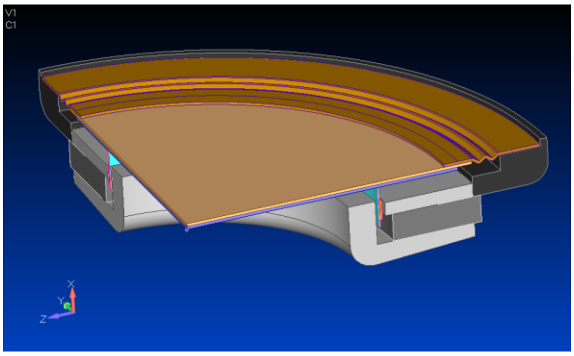

Figure 13 – Example of Driver Concept Incorporating the Piezo Element (underside of diaphragm)

Figure 13 illustrates the features of this driver including a ring motor system to facilitate electrical connections to the main driver and the piezo element whilst preserving the exterior aesthetics.

6.2 Laptop transducer

These devices are often recessed into the device and radiate through apertures to the exterior. Directivity under these circumstances is less of a concern because the loudspeaker does not radiate directly into the listening space, however other advantages such as shallow packaging and control over significant bending behaviour in the diaphragm would help to smooth the frequency response and control distortion.

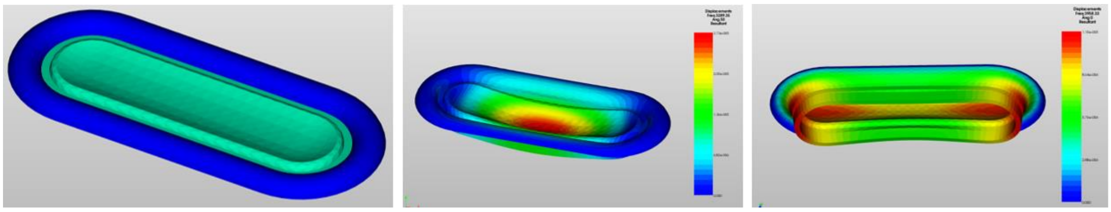

Figure 14 – 3214 Racetrack Driver Model, Bending Evident in Diaphragm and Voice Coil

Figure 14 shows the bending modes that commonly occur in high aspect ratio drivers. These modes are not only due to the diaphragm, but the assembly of the diaphragm and voice coil. Constraining the diaphragm to remain flat using an active piezo element may provide a solution to these issues.

7 CONCLUSIONS

In moving coil driver design, a common problem is successfully controlling diaphragm resonance. Break up modes that deteriorate the audio quality in the upper range of the drive unit's use band produce narrowband undulations, discontinuous directivity patterns and harmonic distortion. Mitigations are limited to curtailment of the driver bandwidth and electrically crossing over to another driver suited to cover a higher frequency range or by carefully designing the moving parts to balance and damp the dynamic mechanical system to suppress the acoustic effects. Because both diaphragm shape and resonance affect both frequency response and directivity, there are no effective remedies to solve these issues on the individual transducer using signal processing.
This paper has presented another potential "tool in the box" for transducer engineers. By implementing a second controllable transducer as an active layer to cancel bending in the diaphragm, issues associated with diaphragm modes can in turn be cancelled. Using the finite and boundary element methods, a model was created to investigate the muti-physics behaviour of two coupled transducers of distinct types with performance targets justified and inspired by common operational problems.
The results from the simulations indicate that the required cancellation was possible and the intended performance could be reached by dialling in the appropriate control signal. This promises to be a simpler design route than trialling numerous transducer components.
Clearly, in the domain of modelling, some aspects were idealised in the absence of the additional data to characterise them. These include the uniformity of the structures both in terms of geometry, material properties and boundary conditions and it remains to be seen how well the performance can be realised in a physical prototype.

It was proposed that in order to simultaneously achieve a flat frequency response and a smoothly tapering directivity response, a flat piston was needed. Mitigating the usual problem of breakup modes when implementing this geometry, a piezo transducer was employed to counteract the modes ensuring that the piston remained so through the full operating bandwidth. The input signal to the piezo to achieve the necessary cancellation was a modified form of the input signal to the voice coil. The modification would take the form of voltage amplification and a filtering process that effectively "tunes" the piezo element to apply the dynamic control, in this case to maintain a rigid body motion over the diaphragm surface. Once this filter is "baked in" to the audio system, it is expected that the mode cancellation and its benefit remain and main input to the loudspeaker (from which the piezo control signal is derived) can be filtered to accommodate more general adjustments such as low/ high pass, shelf and slopes.
An additional channel of audio to drive the piezo element may be justified against other costs if there is clearly differentiated audio performance. Additionally, many loudspeakers and audio reproducing devices currently in the marketplace are powered using onboard electronics and therefore a convenient platform for implementation may already exist.
Although maybe not a solution for all applications, it is envisaged that this approach could be a useful complementary technology providing additional options for audio hardware engineering.

8 FURTHER WORK

Further investigation is required to understand more about what opportunities are on offer with this concept as well as implementation challenges:

- Consideration of a different performance target such as controlling the modes in such a way that directivity is broadened over certain frequency ranges. This may involve modal enhancement in the structure as opposed to the suppression implemented in this paper.
- Although this paper has focussed on a PZT bender transducer as the mode-controlling element, there are numerous options available for this class of transducer. In addition to larger hard ceramics, there are also PVDF (polyvinylidene fluoride) films that may serve a similar purpose, particularly where the loudspeaker diaphragm membranes are light and flexible.

- Physical prototyping and experimentation will provide better insights into second order behaviour and would help create an understand of the feasibility and limitation of the technology.
- An improved method to efficiently evaluate the correction voltage for specific designs is required

9 REFERENCES

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