Development of Gel-based Panel Loudspeakers

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Declaration

I hereby declare that the work presented in this thesis was solely carried out by myself at Edinburgh Napier University, except where due acknowledgement is made, and that it has not been submitted for any other degree.

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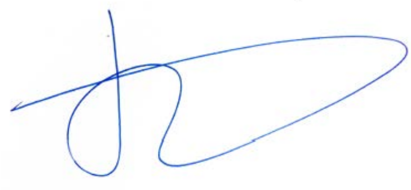

Date

25/05/2012

Abstract

Loudspeaker research has been carried out for many years and some of the latest developments involve a panel to produce the sound. Using panels to produce sound offers many possible advantages – for example, it is possible to create sound using a window or a house wall. However, to make these new sound devices feasible, it is necessary to investigate further the exact frequency response of these drivers, how they compare with traditional technologies and how efficient they are.

This research has been focussed on the optimisation of gel-type panel drivers and their performance under different conditions. Gel-based drivers have their structure based on soft rubber type materials (gel), and that same gel transfers the vibrations from the driver to the panel. In addition, this thesis covers the development of design tools necessary to predict and improve the gel-based drivers performance. Consequently, a Finite Element Analysis package was employed to enable the simulation of the gel-based drivers. Laser Doppler vibrometer measurements to validate the process were also carried out.

Other factors investigated included gel hardness, driver position on the panel, panel material and overall frequency response compared to conventional loudspeaker technology.

Acknowledgements

This dissertation has been written with the support of a long list of people giving me support. I want to start by thanking Mr Gareth Smith of Edinburgh Napier University who drove me on the first steps of the development of the gel-based technology - without him I would have never started this research.

I owe my warmest gratitude to my supervisor Mr. Alan Davidson for all the times he has encouraged me to continue and manage the project on the right path.

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Chapter 1 Aims and Objectives

The main aim of the research is to investigate the performance of gel-based loudspeaker drivers and involved researching the following specific areas:

(i) The transfer of vibrations from several types of gel-based drivers to different types of surfaces to produce sound.

(ii) The design of gel-based drivers that incorporate flexible materials to create transverse waves into a panel using transducers with pistonic movement.

(iii) Testing of materials with different properties and geometries as a medium of wave transmission and wave da1mping.

(iv) Comparing simulated and actual performance of gel-based drivers.

(v) Determining a design which exhibits a wide frequency spectrum of sound reproduction, within the accepted standards of efficiency and using a broad range of materials.

Chapter 2 discusses some theoretical considerations of sound production and propagation including the constituent parts of traditional and modern speakers, magnetic issues, power handling and heat dissipation. It also discusses some of the literature underpinning its principles.

Chapter 3 describes the experimental work involving sound pressure tests in an anechoic chamber. The sound performance over appropriate frequency ranges is investigated against a number of variables including gel-based driver size, gel type, speaker position and panel material.

Chapter 4 examines the structure and mechanical behaviour of gel-based drivers using finite element analysis simulations. It compares simulation results from the COMSOL software package with results obtained experimentally in Chapter 3.

Chapter 5 includes some accurate measurements made using the Laser Doppler Vibrometer (LDV) technique to validate the finite element process and addresses the mechanical dynamic performance of the gel-based driver and panel system.

Chapter 6 contains a general discussion of the results of the research work, conclusions from the work as well as contribution to knowledge .

Chapter 7 makes recommendations for future work.

Chapter 2 Theoretical Considerations

2.1 Introduction

This chapter will give a brief overview of the basics of sound propagation and reception as well as an in-depth treatment of loudspeaker design and performance.

2.1.1 Sound Waves

What we perceive as sound is a longitudinal wave that propagates through gases, liquids and solids. It is a periodic sinusoidal change of pressure and human ears perceive sound when the periodic change of pressure occurs between 20 and 20,000 times per second (Hz). The time between the differences of the pressure is perceived as the tone, while the difference between the maximum and the minimum pressure is responsible for the volume level.

2.1.2 Acoustic Wave Propagation

There are different ways to describe the mechanism involved in the propagation of acoustic waves. Conventional loudspeakers use the movement of the cone or diaphragm[1] (Figure 2.3) as the source of sound.

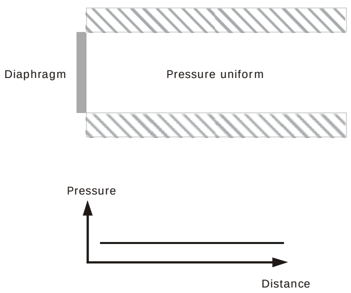


Figure 2.1

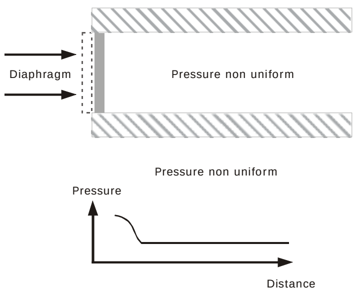


Figure 2.2

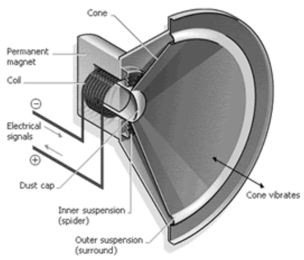


Figure 2.3[1]

Figures 2.1 and 2.2 show the process of sound propagation. Before the diaphragm mounted at the end of a uniform pipe moves (Figure 2.1), the pressure in the pipe is the same everywhere and equal to the atmospheric pressure. The movement of the diaphragm (Figure 2.2) compresses the air adjacent to it and locally increases the air pressure. The difference between the two pressures into the pipe gives rise to a force, which causes the air to move from the high pressure region to the atmospheric one. This process continues through the pipe at the speed of sound (343.8 m/s at 20 °C and 30% humidity).

2.1.3 Sound Pressure Level

As explained in the previous section, the sound phenomenon is a periodic change in pressure. In air, the quietest audible sounds are around 20μPa, whereas those that are due to sounds on the threshold of ear-pain are of the order of 20 Pa (one million times more powerful). Therefore the measurement of sound pressure level using linear numbers is inefficient. The most common way to measure the sound pressure level is using a logarithm of the ratio of two powers[2] called the Bel, and the decibel i.e. one tenth of a Bel. The acoustic pressure is measured in Pascals (N/m^2). The measurement of the acoustic pressure in dB is made as follows:

$$\text{Decibels} = 10 \times \log_{10}\left\{\frac{P^2}{P_o^2}\right\} = 20 \times \log_{10}\left\{\frac{P}{P_o}\right\}$$

Equation 2.4

P – Actual acoustic pressure (taken during measurements)

P_o – The reference static pressure of 20μ Pa (0dB)

20 – factor used because dB originates from power ratios where acoustic power is proportional to the square of the pressure and a factor of 2 has therefore been taken outside the logarithm

2.1.4 Harmonics

Harmonics are a series of subsidiary vibrations that accompany a primary or fundamental wave-motion vibration. Harmonics result when the vibrating body vibrates simultaneously as a whole and in equal parts (halves, thirds, fourths, and so on), producing wave frequencies that are in simple ratios with the fundamental frequency.

The fundamental frequency, (f), and higher harmonics (2f, 3f, 4f,...) are integer multiples of (f) and the resultant pressure fluctuation, (PR), is the sum of the fundamental, (P1), and the following harmonics, (P2, P3, P4).

2.2 Coil Drive Transducer Mechanisms

The first patent related to a transducer goes as far back as 1876 [3] with Alexander Graham Bell's telephone receiver. Bell produced a magnetic field by applying an input signal to a solenoid located around a field coil. The field attracted a thin soft iron diaphragm and the changes in the magnetic field produced vibrations to the diaphragm, which generated the analogue sound waves. Further developments of the described transducer were the basis for the moving-coil loudspeaker. In the 1920s, Rice and Kellog[4] described the essential principles of the direct radiating moving coil loudspeaker as is known today. Further developments in magnet technology[5] in the 1930s replaced the field coil by a permanent magnet. Since then very little changes had been made, and most of the loudspeakers used nowadays have the same structure as the ones in the 1930s.

2.2.1 Moving Coil Loudspeaker

Loudspeakers[6,7] are electro acoustic transducers that generate sound in response to an electrical input signal. Most of these transducers generate sound waves by vibrating a cone or diaphragm converting the electronic signal in to a mechanical movement through a voice coil between the two poles of a magnet. As a result, the mechanical movement generates a change in pressure, which creates sound waves.

There are several transducer types that create sound waves. Electrostatic, piezoelectric[8] and moving coil loudspeakers are examples of it. This research has been made using moving coil loudspeakers drives.

The moving coil loudspeakers consist of a diaphragm attached to a cylindrical coil of wire called the voice coil VC (Figure 2.5). The VC is suspended into a constant magnetic field B. When alternating current[9] I is supplied to the coil, the interaction of the current and the magnetic field induces a force on the coil. The diaphragm has a pistonic movement, which creates sound waves of the same frequency as the alternating current. This transduction is not equally efficient at all the frequencies. The electric and acoustic impedance constrain the efficiency of the transduction differently through the frequencies. Thus a different drive design is needed for each frequency. Most of the systems designed to produce waves to cover the full human audio range consist of three drives:

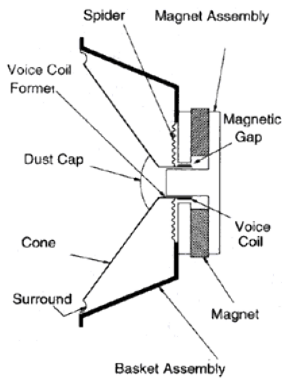


Figure 2.5[1] Section of Moving coil Loudspeaker

Subwoofer[10]: To produce frequencies from 20 to 400 Hz

Mid-range driver: To produce frequencies from 300 to 1000 Hz

Tweeter: To produce frequencies from 800 to 20.000 Hz or above.

A cross-over network is used to split the original signal from an amplifier to the three drives. Figure 2.5 shows a ferrite permanent magnet that produces a magnetic field where the coil is located (the magnetic gap). The voice coil is attached to the diaphragm or cone and subjected by the spider, which allows axial movement, and constrains the radial one.

2.2.1.1 Moving Coil Loudspeakers Performance Characteristics

Efficiency and sensitivity

Loudspeakers efficiency is defined as the ratio of the acoustic power coming out to the electrical power going in. On direct radiator moving coil loudspeakers, the received electric power is used in three ways: the heating of the coil, the mechanical damping of the system (enclosure and drive), and finally the acoustic energy transferred which is less than 1%.

Moving coil loudspeakers are usually rated according their SPL performance given a defined input. This is defined as the loudspeaker sensitivity. In most cases the input is 1 watt of power which will be the result of the voltage applied versus the loudspeaker impedance. 8 Ohms loudspeaker drivers will be required to be driven by 2.83Vrms to match the 1 watt input. Furthermore the measurement from the microphone is typically carried out at 1m. Typical home loudspeakers have a sensitivity of 85 to 90 dB for 1W at 1m.

Directivity

The directivity of loudspeaker studies how effective its sound radiation is around all axes and distances.

Moving coil loudspeaker sound radiation is calculated using the multiple combination of the simplest source of sound, the point source. A point source theoretically consists of an infinitesimal sphere that increase and decrease its diameter, which consequently produces a wave. If this wave is produced at the right frequency it will make sound. Moving coil loudspeakers radiation pattern can normally be simplified to two point sources commonly named dipole. However this will vary on the loudspeaker size, the distance and the frequency that the directivity is being measured.

2.2.2. The Voice Coil

The coil develops the driving force of the transducer. The movement of the voice coil occurs when there is a magnetic flux perpendicular to the current that is going through it. For example, if the coil is on the X axis and the magnetic flux is in the Y axis, the movement of the coil will be on the Z axis. The way that the coil will move will depend on the orientation of the north and south of the magnet and the positive and negative side of the coil. In general terms, the driving force is desired to be linear. Although it is simple to keep the current of a coil linear, the magnetic field reduces proportionally to the distance between the two poles. Therefore when the VC moves, the magnetic flux fluctuates and as a result, the strength of the transducer varies, even when the current received from the amplifier is constant. This effect will be different depending on the frequency that the transducer is subjected to. The lower the frequency, the longer will be the time in which the current will be constant. For this reason, the amplitude of the VC movement will then be higher.

Voice Coil Parts

The Coil

The function of the coil is to transfer electric current through a determinate path. Consequently, heat dissipation, weight, resistance, and reliability need to be taken into account. Coils are usually made of copper or aluminum wire. Copper has a higher density but lower resistivity. Therefore, to achieve a specific resistance the copper will have to be longer and heavier than the aluminum coil. On the other hand, aluminum will melt sooner and as a result will not be suitable for high power applications.

Coil Form

The coil is usually wound around a tube or bobbin and both parts are kept together to give structure to the set-up. The form used for the bobbin needs to be light, heat resistant and strong. The most common materials used are: Kraft (wood pulp), bond (cloth) paper tubes, paper based materials, aluminium and Kapton (DuPont trademark).

In some applications, the coil is wound on a cylindrical metal tool using copper wire surrounded by an adhesive. The process is carried out at a relatively high temperature and when the adhesive dries, the coil is ejected from the tool and a coil without a centre is achieved. This coil - now called an air coil - can be bonded to a bobbin.

2.2.3 The Diaphragm or Cone

The diaphragm shape is commonly a cone (Figure 4) and is responsible for the sound radiation. It approximates to the pistonic movement of a surface with the aim of creating changes in pressure in its surrounding area and which will be perceived as sound. To achieve control of these waves of air, the cone has to be as rigid as possible. As a cone operates, a complete pistonic movement is never achieved and the movement of the coil is transmitted to the extremes of the cone a few milliseconds later. Because of this, a completely flat surface will produce a wave different at the centre of the drive compared with their extremes. The angle will place the cone surround in a further-away position therefore the centre of the drive will move on phase with the extremes. Unfortunately that will only happen at frequencies where the time that the wave takes to travel from the coil to the cone surrounding is less than the frequency that the coil is reproducing, otherwise the cone will bend[11] and the following effect will occur.

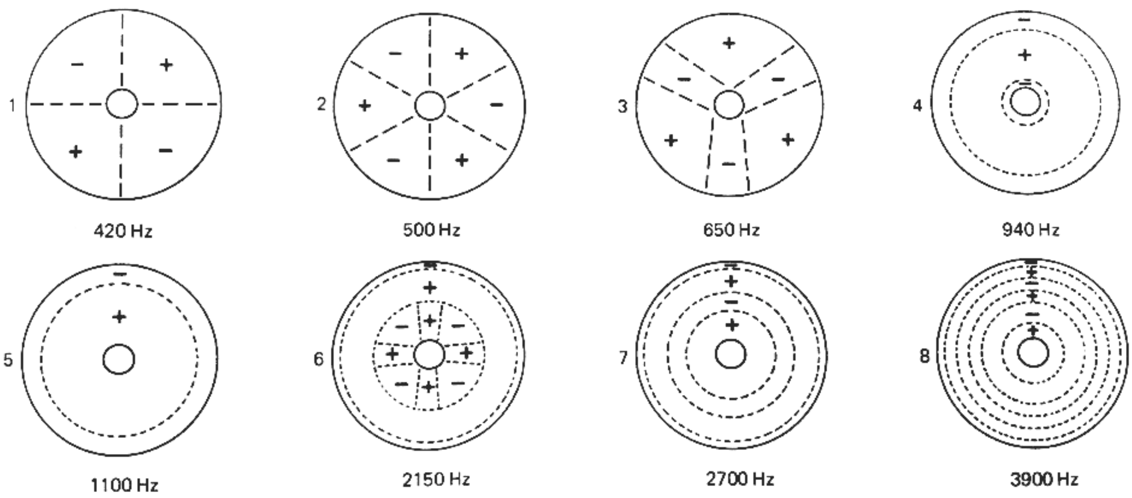


Figure 2.6[1] Bell modes of a loudspeakers cone

Figure 2.6 shows the “bell modes” which are exhibited at high frequencies. Bell Modes occur when the circumference, or the distance from the coils to the surround and back, is an integral number of wavelengths.

The negative and positive signs show the direction of the movement in each section of the cone. This behaviour will result in the cancellation and superposition of waves; therefore the final sound pressure level will be artificially increased or decreased from the original source. To avoid this distortion happening, loudspeaker manufactures usually use different cone designs for different frequencies.

2.2.4 Magnetic Issues

In early loudspeakers, a magnetic field[12] was created by passing a current through a coil of wire, so when the current finished the magnetic field disappeared. To simplify the structure of the drives, nowadays permanent magnets are used instead. Until a few years ago most of the driver’s manufacturers used Ferrite magnets but recently, developments have brought Neodymium Iron Boron and Samarium Cobalt magnets at an affordable cost, being up to 10 times more powerful than the original ferrite ones. Neodymium Iron Boron and Samarium Cobalt magnets are now the preferred choices for driver designers.

The magnetic power is measured in Tesla[13] (1 Tesla = 10,000 Gauss) and the magnitude of magnetic strength will be proportionally increased to the final strength of the transducer. The objective of the magnet is to produce a magnetic field in the gap in which the coil will move.

To concentrate the magnetic field, it is required to minimize the gap and the area where the field is located. The most common way to provide a circuit able to transfer the magnetic field from the magnet to the required points is by using steel plates. If the area or gap is increased, a bigger or more powerful magnet will be required to maintain the same final field. Therefore a circuit capable of transferring more magnetic field will be required and consequently, the cost, weight and volume of the drive will have been increased. As a result one of the cheapest and more practical ways of having an efficient drive design is to reduce the gap and the area where the coil will be moving.

2.2.5 The Suspension

The drive suspension usually consists of two parts: the spider and the surround.

The Spider

The spider is attached to the coil and its objective is to allow axial movement of the coil and constrain the lateral one. The spider stiffness will determine part of the total mechanical damping factor of the drive. The spider mass is usually very low so for the calculation of the final mass of the driver's moving parts, it is frequently ignored.

The Surround

The surround is typically an extension of the cone attached to the drive structure. PVC, Neoprene, textile or fibrous materials are commonly used for the manufacture of the surround. Its function is similar of the one described for the spider, but the surround has the added purpose to end the vibrations that come from the cone. As described in section 2.2 the total cancelling of the wave never happens, but a damping factor occurs instead and consequently the surround will damp the vibrations. However, the damping factor will vary according to the frequency.

2.2.6 The Chassis

As a main function, the chassis will provide the structure to keep all parts together and also support the enclosure of the system. A deeper look into the driver normal behaviour shows that the movement of the cone will create a reaction of the opposite direction to the rest of the drive components. This force has to be absorbed by the chassis, otherwise the system will start to vibrate and/or break. It has to be taken into account that the magnetic assemblies could be quite heavy and the design also has to consider the magnet compatibility of materials as the magnetic field could damage them.

2.2.7 Power Handling and Heat Dissipation

The mechanical damping of the system is particularly low above the system resonance. Therefore, the heating of the coil is where most of the energy is used. The coil resistance will increase with temperature and this will have a negative effect on the driver performance; hence the driver design will have to dissipate as much of this energy as possible. A common way to help conduction of the heat from the coil to the magnetic circuit is the use of Ferrofluid. This magnetic fluid fills the gap where the coil is and has a higher heat conductivity than air.

2.3 Horn Loudspeakers

Horn Loudspeakers[14] are very efficient, using 10% of the energy of a Standard Loudspeaker to get the same sound pressure level. Therefore they are used when high sound power is required. As shown in Figure 2.7, the moving-coil principle is used to drive a Horn loudspeaker but is optimised to work in a narrow throat of a low mass. This results in high efficiency around its resonance frequency. Some Horn drives use piezoelectric drives based on materials that have dimensional changes when an electric potential is applied across them. Examples of piezoelectric materials are: Rochelle salt, barium titanate, and some high-polymers[15]. Those drives are even more efficient, but their excursion is smaller than moving-coil ones, making them suitable for high frequencies only.

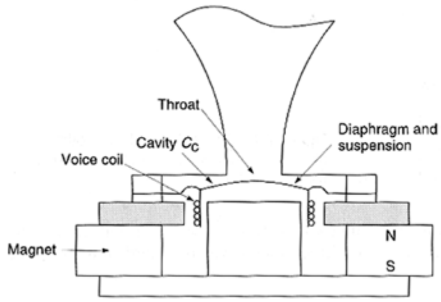


Figure 2.7[1]

2.4 Electrostatic Loudspeakers

The electrostatic loudspeaker can be modelled as a pair of capacitors plates as illustrated at Figure 2.8. One is stationary, while the other moves in response to an electrical current going through. The moving one, the diaphragm (B in Figure 2.8), needs to be very light and flexible so most of the electric forces developed between the two plates act effectively to create sound waves. Complex vibrational modes in the diaphragm are almost eliminated[16] making the performance very predictable. High voltages are involved in the process and to radiate enough sound pressure level, large diaphragms are needed.

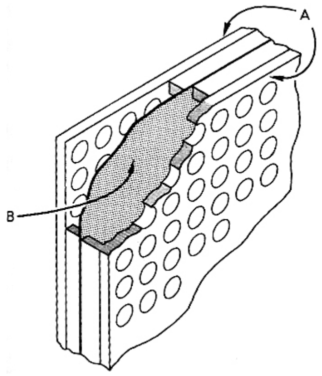


Figure 2.8[1]

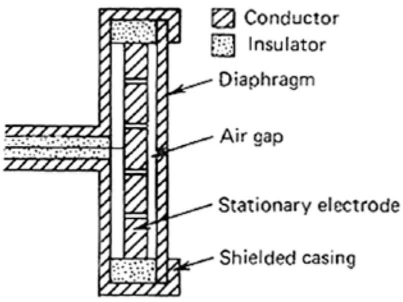


Figure 2.9[1]

2.5. The Distributed Mode Loudspeakers (DML)

2.5.1 Introduction[16, 17]

In 1994 Dr. Ken Heron from Defence Evaluation and Research Agency (DERA) applied for a patent for a DML. This invention essentially was a high stiffness aluminium honeycomb panel that was possible to use as a loudspeaker. It had a limited range of frequency range. The concept occurred because at the time, heavy panels of aircraft structures where substituted by lighter panel materials based on composite materials. The research discovered an unexpected increase in sound radiation from the new panels; therefore it was studied to use the technology as substitute loudspeakers. After this research, DERA sold the license to Verity Laboratories to develop the technology and bring it to commercialisation.

2.5.2 Theory

The DML can be represented as a flat plate with boundary conditions defined by the frame that supports it. The panel mode shapes and frequencies can be calculated as follows (Crighton 1992, p589):

$$\phi_{nm}(x,y) = \sin\left[n\pi x / L_x\right] \sin\left[m\pi y / L_y\right]$$

$$\omega^2_{nm} = \left[D/\rho h\right] \times \left[\left(n\pi / L_x\right) + \left(m\pi / L_y\right)\right]^2$$

The planar dimensions of the plate are defined by L_x and L_y. The thickness is h, ρ is the density of the plate material, and D the bending stiffness.

2.5.3 DML Coupling to the air

Using the Rayleigh integral it is possible to calculate the power radiated and describe the pressure created on the air as a result of a vibrating plate.

$$p(\mathbf{x}) = -\left(\frac{\rho_a \omega^2}{2\pi}\right)\int_A \left(\frac{e^{-ik_a r}}{r}\right) w(\mathbf{x}')d\mathbf{x}', \quad r = |\mathbf{x} - \mathbf{x}'|$$

X expresses the location of the pressure, W(x) its complex displacement, ρ_a is the air density, K_a is the acoustic wave number and w is the vibration frequency.

2.5.4 Sound Radiation from a DML[17,18,19]

The best way to understand the radiation from a DML is using a mathematical model; this can be achieved using a finite element analysis package such as Ansys. The variety of materials, shapes and transducers that relate to the DML performance is almost endless. In

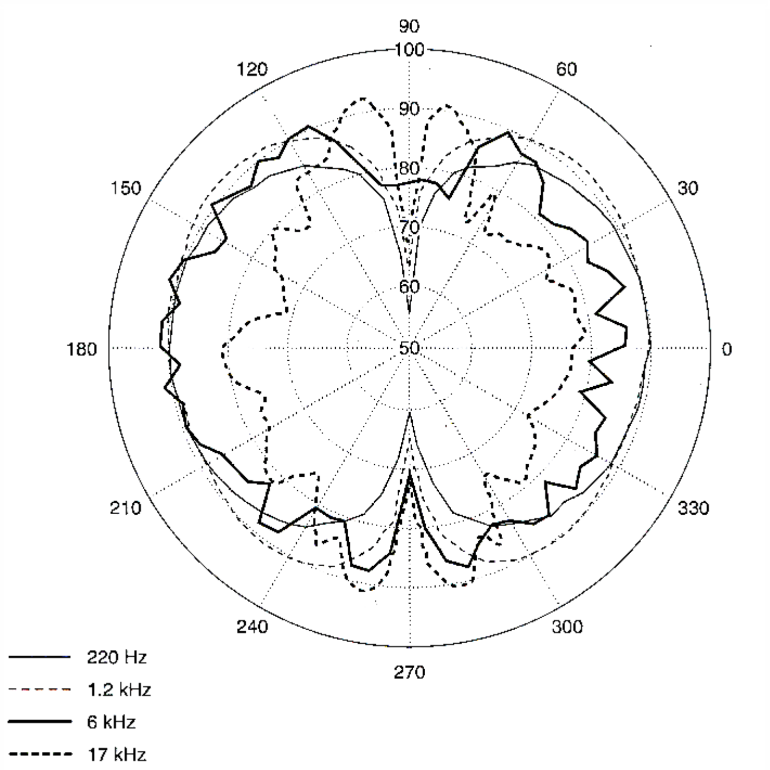


Figure 2.10

1998 Panzer and Harris[20] defined a modelling method to measure and describe the DML, but such a method is designed for specific transducers and technology. There is not a single study that records all the possibilities around DML, although most of the parts have been studied separately. E. Kinsler[21] investigated forced vibrations of membranes and the correspondent normal modes. In an infinite or finite panel with a single frequency, it is possible to mathematically define the nodes, and consequently the movement of each point of the panel. Although the interface between the transducer and the panel and how it affects the sound radiation has not been fully defined, it is clear that the behaviour of the panel is completely different to the behaviour of a diaphragm. In DML, the different areas of the panel oscillate in a diverse phase, and the movement of the transducer (coil, plate, membrane…) could be completely different from the movement of the panel within the contact area. Azima and Harris[22] define the DML as uniformly distributed bending modes to produce sound but applied only on light and stiff panels. Their study defines the mechanical impedance of the DML as being independent of the frequency and only being related to the panel stiffness and density.

2.5.5 Measurement of DML

In order to evaluate different DML performances, it is necessary define the test procedures that will be used to test them. The first consideration is the fact that there is a panel and a driver. The panel will radiate sound on both sides but the radiation may be different on each side - in particular in the high frequency range. In this thesis, all tests have been carried out with the microphone located on the driver side of the panel.

As described by Sheila Flanagan and Neil Harris[23] DMLs are perceived louder than standard cone loudspeakers. However, when measured with a microphone, they may register less dB sound pressure level. This may have to be taken in to account once the drivers are compared with standard cone loudspeakers.

2.5.6 DML Polar Pattern

In 1999 Angus et al[24], looked at the polar pattern of DML and discovered that it varies for every frequency, as traditional loudspeakers will do, although DMLs have a clear point where their pattern changes. At low frequencies and under the fundamental frequency of the system, the DML pattern will have a decrease in its dB sound pressure level linked with an increase of the angle. However above its fundamental frequency, the panel will radiate the sound from several points, making the polar pattern move up and down with the angle. Even though this may seem that some areas will not radiate any sound, the reality is that the system gets evenly balanced with the distance and boundary reflexions.

2.6. Multi-channel Electromechanical Film Panel Loudspeaker

2.6.1 Introduction

Electromechanical film panel loudspeakers[25] (EMFi) are based on the electrostatic principle (described in section 2.5). One of the advantages of these loudspeakers is the possibility of having the same panel as the source of sound and a surface to project video.

2.6.2 Description

A polypropylene film is used in between two panels on which the charge is held. On the Antila[19] et al study, 9 panels were used in a 500 by 600 mm array structure making an overall 1500 x 1800 mm panel. Since each of the small panels is connected independently, different signals can be applied to different sections. High frequency signals were produced simultaneously on each panel with the target to make the polar pattern less directional. On their subjective test, it was noted that the high frequencies were produced evenly when compared with standard loudspeakers. On the low frequency range, the system produced very small vibrations and so a subwoofer had to be used.

2.7 Multi-actuator Panels

2.7.1 Introduction

Standard electrodynamics loudspeakers are commonly used within an array to achieve full range reproduction, and wider polar pattern. Based on that, an array of actuators attached within two panels has been studied by Kuster et al[26].

2.7.2 Description

On the Multi Actuator Panels (MAP) several actuators are vibrating the same panel simultaneously. According to the Kuster study, the overall performance is related to the actuator itself and does not get affected by the panel boundaries. The sound energy comes mainly from the area of the panel nearby the actuator. The damping is usually very high making the rest of the area of the panel as not effective in reproducing sound. This enables the possibility of having different signals reproduced on the same panel. This feature may be used for a Stereo signal, for instance. This approach differs from the DML studied in section 3.1 in that with MAP, the panel boundaries in relation to the actuator do not seem to be so critical therefore the actuators position can be changed without much effect.

2.8 Finite Element Analysis (FEA) for Audio Devices

2.8.1 Introduction

Several Finite Element Analysis packages have been used to predict the performance of audio devices. The following section looks at a specific use of Comsol[27] and Ansys[28] packages for the prediction of the performance of horn loudspeakers. The Horn loudspeaker principle has been described previously in Section 2.4.

2.8.2 Description

The work by Murphy[29] et al studies the coupling of the vibrations from the horn to the air. It is considered critical to use a mesh of the right size and this is partially why the use of the FEA package is so important. Initial models with Ansys illustrated the sound pressure level around the horn, and the effects of modifying the horn shape.

With the use of Ansys, some programming was required, in particular to relate the vibrations to the power driven by the horn. It was noted that the version used of Ansys was from 1999 and therefore not as user-friendly as newer versions. The Ansys drawing aid package was just good enough for simple 2D structures but a different package of Ansys would have been needed for the study of more complex shapes.

The Comsol package - linked with a Solid Works[30] drawing aid package - allowed the drawing and definition part of the simulation to be simple and powerful. The Comsol version used was able to link the vibrations to the power driven by the horn. Comsol simulations allowed rapid calculations to be made and to be capable for complex structure analyses. Both packages were contrasted with real measurements and shown to be very accurate.

2.9 Traditional Loudspeakers Radiation

2.9.1 Point Monopole

The simplest acoustic source to analyze is a sphere whose radius varies sinusoidally with time and is referred to as the point monopole. The sound radiated by a point monopole is omni-directional and under ideal free-field acoustic conditions consists of spherical waves propagating away from the source. As it propagates, the acoustic pressure is spread over the area and decreases following the inverse square law:

The sound intensity is proportional to the square of pressure and reduces as the square of the distance from the source.

2.9.2 Sound Radiation from a Loudspeaker Diaphragm

The point monopole source of sound is a useful approximation to a real sound source such as a standard loudspeaker, due the source of sound being physically small compared to the sound wavelength radiated, and all the parts radiating usually operate in the same phase.

2.10 The Gel-based Driver [31,32,33,34]

2.10.1 Introduction

DML systems have the voice coil attached to a panel instead of a diaphragm as in traditional loudspeakers. The mechanical energy is then transferred to the panel where bending waves are distributed homogeneously and create standing waves in the air. This results in spatial diffusivity, broad frequency range and wide directivity.

However, to achieve high fidelity sound from a panel, it is important to create bending waves without constraining the panel itself. In other words, the driver has to produce vibrations through the panel, but at the same time has to minimize the damping of the previously transferred vibrations. This could partially be achieved by placing the driver in between modes of movement on the positions where less movement will occur and avoiding low frequencies were the movement of the panel is greater.

The gel driver technology differs from essentially previous DML technology in the way that the transducer is attached to the panel. Silicone or similar developed materials are added between the voice coil and the panel.

2.10.2 Structure

The coil is mounted on a rigid drive-plate, which in turn floats on the panel above a layer of gel. This allows the driver and coil to transfer the vibrations in the panel. The unit is also self-damping. The gel surround, at the same time, keeps the coil centred against the magnetic assembly.

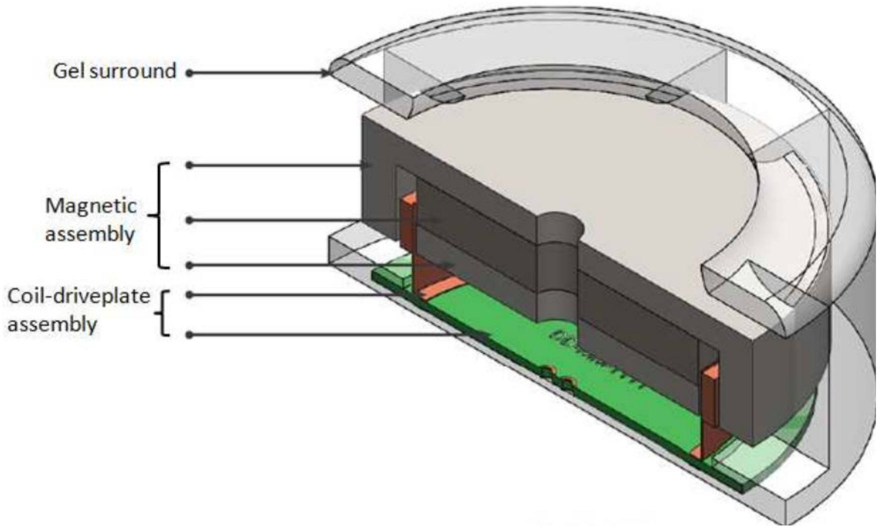


Figure 2.11 Gel-based driver structure

Figure 2.11 shows how the gel-based material surrounds the magnet, coil and drive plate replacing the spider/suspension of traditional cone and DML drivers. Note that the dimensions are just to give an idea of the proportions in this particular example. The magnet assembly will include steel plates and magnets. The surrounding gel may be covered by an external structure or external structure.

2.10.3 Mechanical considerations

The interaction of the magnetic field with the voice coil under an electrical force generates Fe. Equation 2.12 expresses the Fe as a result of the magnetic flux and current going through the coil of a gel-based driver.

$$f e (t) = F_e \ e^{iwt}$$

Equation 2.12

Figure 2.13 represents the mechanical interaction of the gel base driver components and the force generated by the coil and magnet interaction.

The driver mass is represented by the magnet assembly (M_m, M_{cdp}) and coil drive plate Z_p. X_m, X_{cdp} and X_p represent the displacement of the magnet, coil drive plate and panel, respectively. The resistance and stiffness between the magnetic assembly, the coil drive plate and panel is represented by r_1, r_2, r_3, k_1, k_2 and k_3.

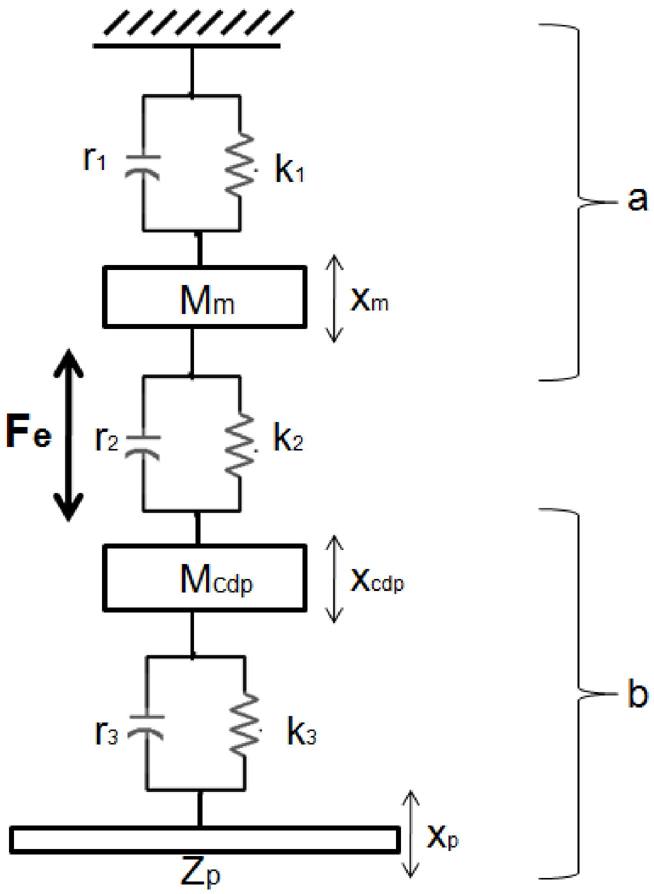


Figure 2.13 Mechanical element of the based gel driver

The Fe operates between 2 masses, the magnet Mm and the mass of the drive plate and coil Mcdp. On the Mm side, the mass will be constant, however on the Mcdp side, the type of panel used and its corresponding resistance will influence the overall mechanical behaviour, in particular the movement of the coil (excursion). The design of the gel-based driver will have to take into account the excursion of the coil, which will ultimately relate to the panel type used.

In terms of the overall displacement of the coil, it is important to note that the gel compression behaviour is only linear up to a certain point, where the gel won't compress any more, even if the force applied is increased. The following graph illustrates the behaviour of the gel once it is subjected to compression.

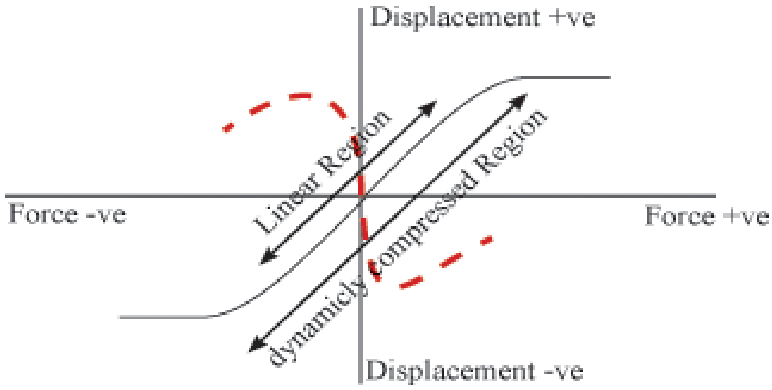


Figure 2.14, Gel-based driver displacement versus force

Once the gel-based driver is placed on to a panel, it will mostly have the same behaviour. Indeed the compliance of the material lowers with compression or expansion and there is a maximum reached where the material starts to behave in a non-linear way as represented in Figure 2.14. Therefore it is possible to design the gel of the driver so as to optimise the movement of the driver with the movement of the panel and consequently maximise efficiency and reduce distortion.

Figure 2.15 represents the impedance analogue of the gel-based driver - force and velocity have been substituted by voltage and current. Consequently the mass, resistance and compliance become inductance, electrical resistance and capacitance.

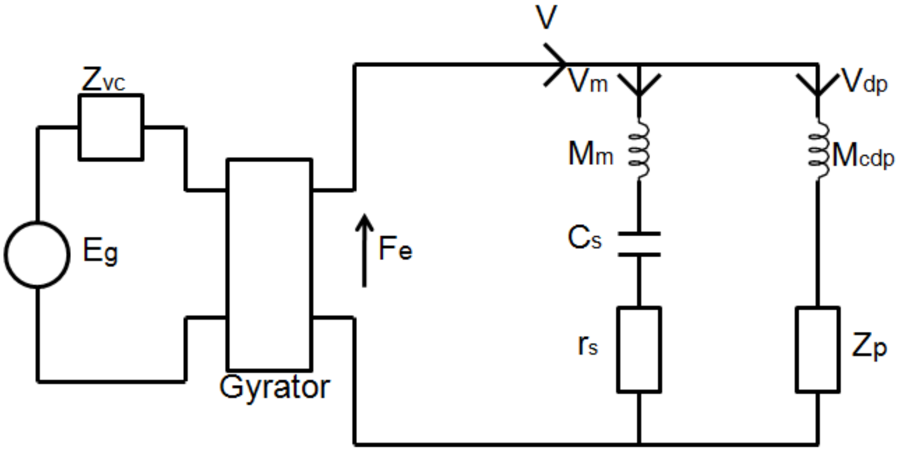


Figure 2.15 Illustrates the impedance analogue for a gel-based driver

2.10.4 Magnet and Drive Plate Movement

Figure 2.16 shows the behaviour of the magnet and coil once the driver is vibrating. Note that there are 3 main bodies moving - the panel, the drive plate and the magnet. These 3 parts do not move simultaneously - there are differences in the phase of each of them.

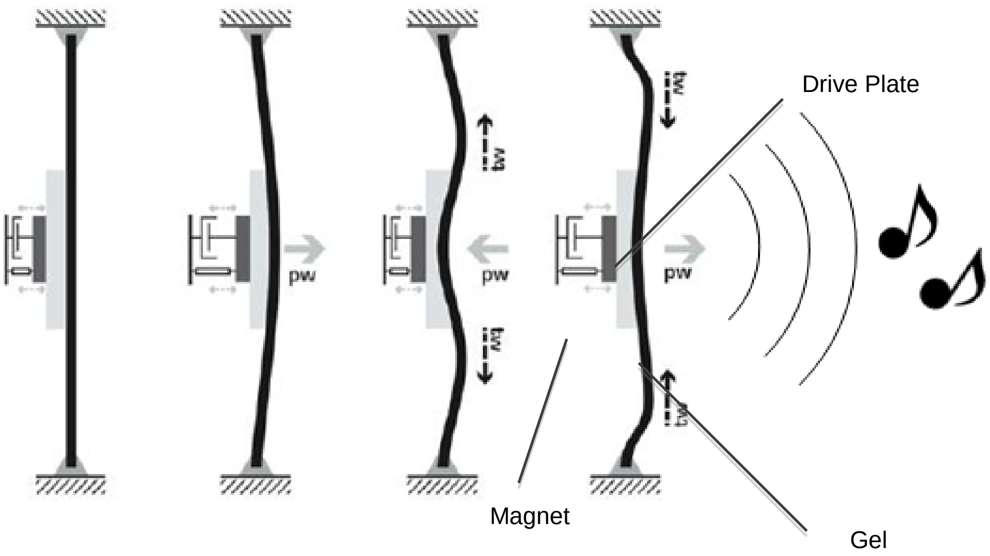


Figure. 2.16, Magnet and drive plate movement

Initially the magnet moves away from panel with an acceleration depending on amplitude. Shortly after, the magnet is then caught or held by the silicone gel at limits of compression/stretch. The driver inertia is then transferred to the panel, through the gel, by stretching until the coil pulls back and then the magnet reverses direction, with a following movement of the panel occurring through compression of the gel.

Chapter 3 Gel-based Driver Measurements

The following chapter describes work that measured and studied the frequency response of several gel-based drivers using an anechoic chamber.

3.1 Measurements Set-up

The equipment required for the experimental work and its general set up is shown as follows:

- CLIO[35] Interface (2 channels audio output, 1 Channel input)
- Digital Signal Processed by a PC
- Measurement Microphone (omnidirectional – flat response)
- Aluminium frame for panels (to fix panel boundaries)
- ABS, Wood (MDF) and aluminium panel 420 x 320 x 2 mm

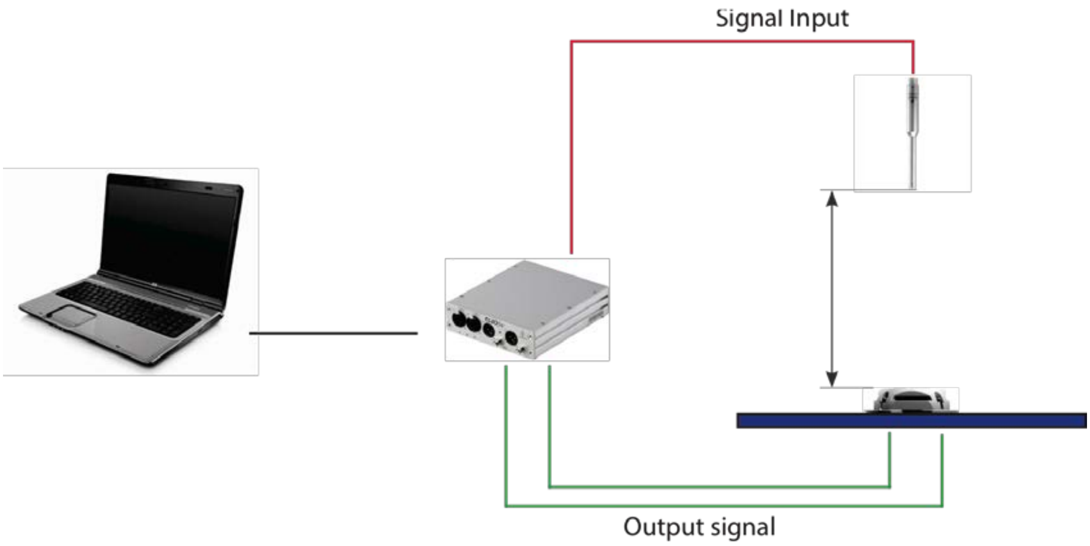


Figure 3.1 Measurement set up

A frame with the capacity to fix the panel boundaries was used. The background noise in dBA was less than 35dB inside the anechoic room. The panel in question was placed in the centre of the room, as close as possible to the floor (which was considered totally absorptive), in order to avoid immediate cancellation due to destructive interference of the generated wave in the surrounding air.

The RMS power driven to the drivers was either 1W or 10W at 25cm or 1m. These details are shown in each graph.

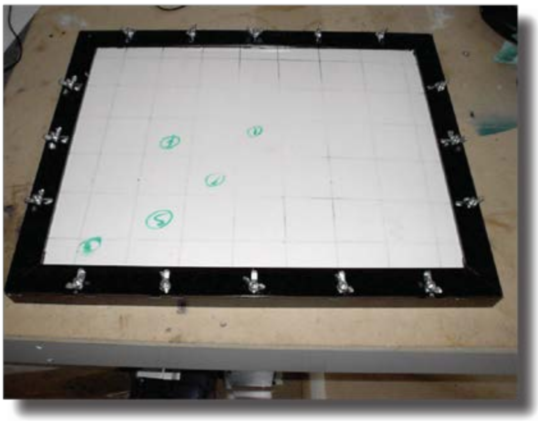


Figure 3.2 Panel set-up

Figure 3.3 Anechoic chamber

ABS Panel:

- Dimension: 420 x 320 x 2mm

- Density: 1040 kg/m^3

- Young's Modulus: 6.67E+08 Pa

- Poisson ratio: 0.42

- Damping factor: 0.015

3.2 Background Noise Level

Figure 3.4 shows the background noise levels of the anechoic chamber. The test was carried out with the drivers disconnected but with the microphone on. Some of the spectrum is under 30dB with the exception of the low end, which is 48dB. In any case it is well below what is expected from the driver's average performance above 70 dB.

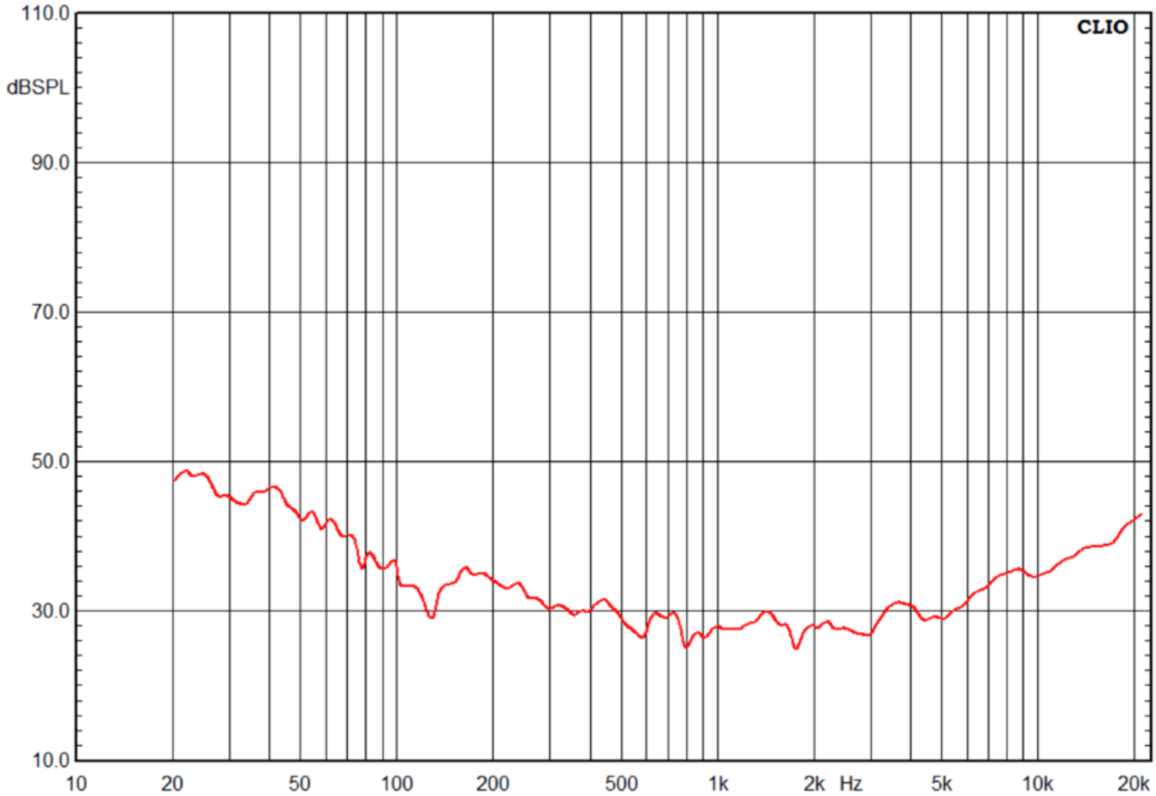


Figure 3.4 Background noise

3.3 Gel-based Driver A Measurements

3.3.1 Gel-based Driver A specification

Electrical and acoustical characteristics

Sound Pressure Level	98 +- 3 dB at 1W/10cm, 100 to 1000 Hz
Impedance	8 Ohms
Frequency Range	100-10000 Hz (related to surface being driven)
Power Handling	10 W (R.M.S.)
Magnet	N48
Overall Dimensions	See Figure 3.5

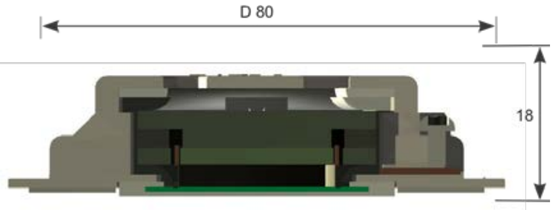


Figure 3.5 Gel-based driver A general dimensions

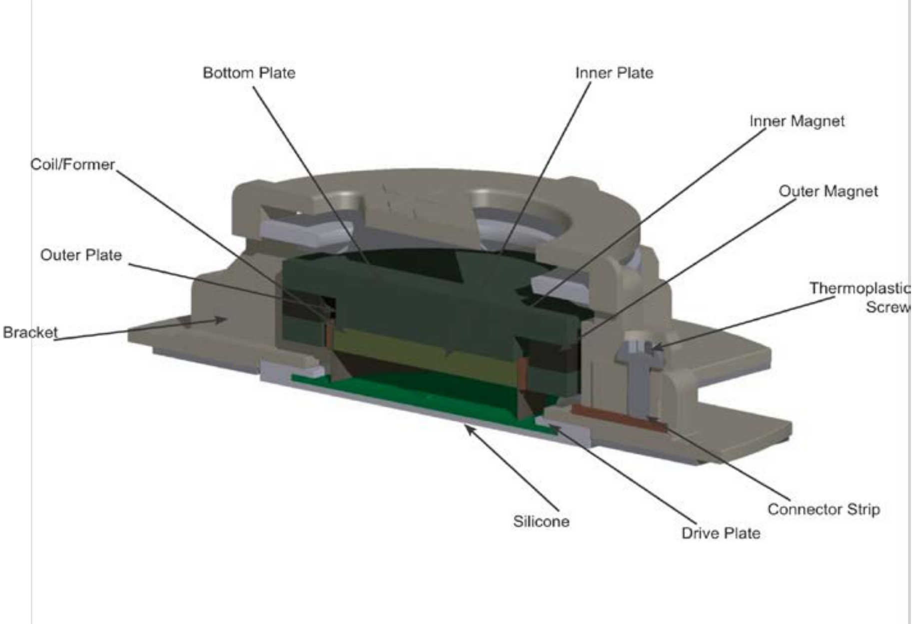


Figure 3.6 Gel-based driver A cross section

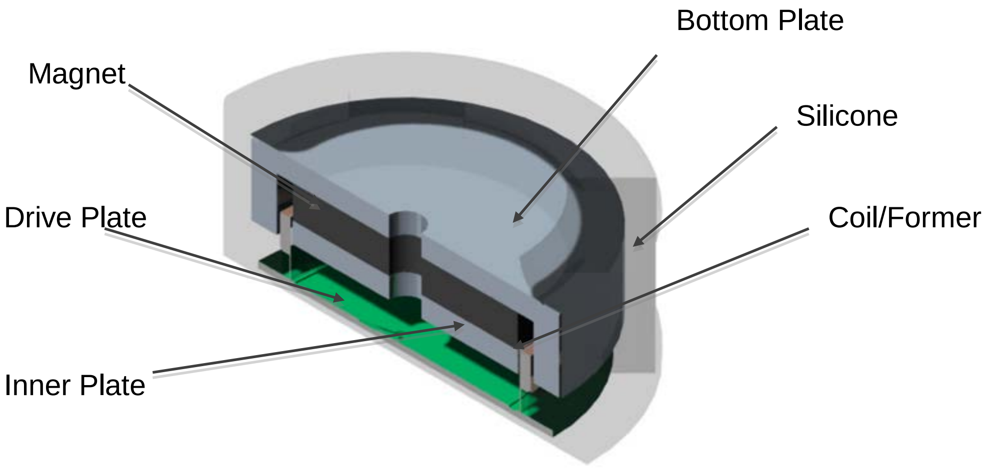


Figure 3.7 Gel-based driver A without structure

Materials Properties

Part	Material	Young's Modulus (Pa)	Poisson Ratio (NA)	Density (kg/m3)	Damping factor (NA)
Magnet	Neodymium 48 grade,	2.00E+11	0.33	7100	0.001
Plate	Steel	2.00E+11	0.27	7700	0.001
PCB (Drive Plate)	FR4	9.00E+08	0.42	1010	0.015
Coil	Copper	1.10E+11	0.35	8700	-
Former	Polymide	7.00E+10	0.33	2300	-
Bracket (holder)	ABS	6.67E+08	0.42	1040	0.015
Silicone Gel	Silicone (Elastosil 625 Wacker)	5.00E+05	0.45	920	0.3

Additional Silicone properties

Shore hardness:	A 8
Densityy:	1.2 g/cm3
Shrinkage (Flow direction):	3.5%
Compression Set at 23 °C:	21%
Elongation at break:	30kN/m
Tear strength:	30k
Tensile strength:	6500kPa
Working temperature:	250°C
Manufacturer/Product name:	ELASTOSIL® RT 625[32] (WACKER)

3.3.2 Sound Power Test

This first section is related to the driver structure and its performance at low and high power as well as at different distances - 100 cm and 25 cm. All drivers were tested with and without the external structure to quantify its effects on the overall system performance.

This reference test was carried out using the ABS Panel as described in Figure 3.2.

3.3.2.1 Gel-based Driver A with External Structure 1 W 1 m ABS Panel

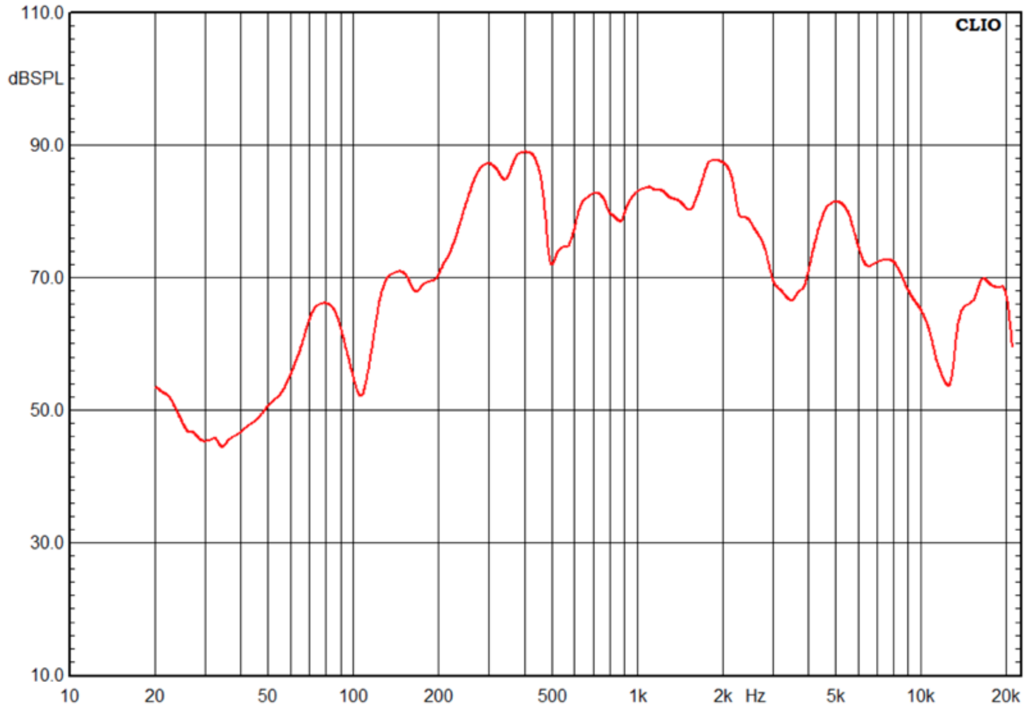


Figure 3.8 Gel-based driver A with external structure 1W 1m ABS panel

In Figure 3.8, the average performance is 82 dB sound pressure level between 300 Hz and 7 kHz; however, there are two drops of sound pressure level: 500 Hz, and 3.5 kHz.

3.3.2.2 Gel-based Driver A with External Structure 10 W 1 m ABS Panel

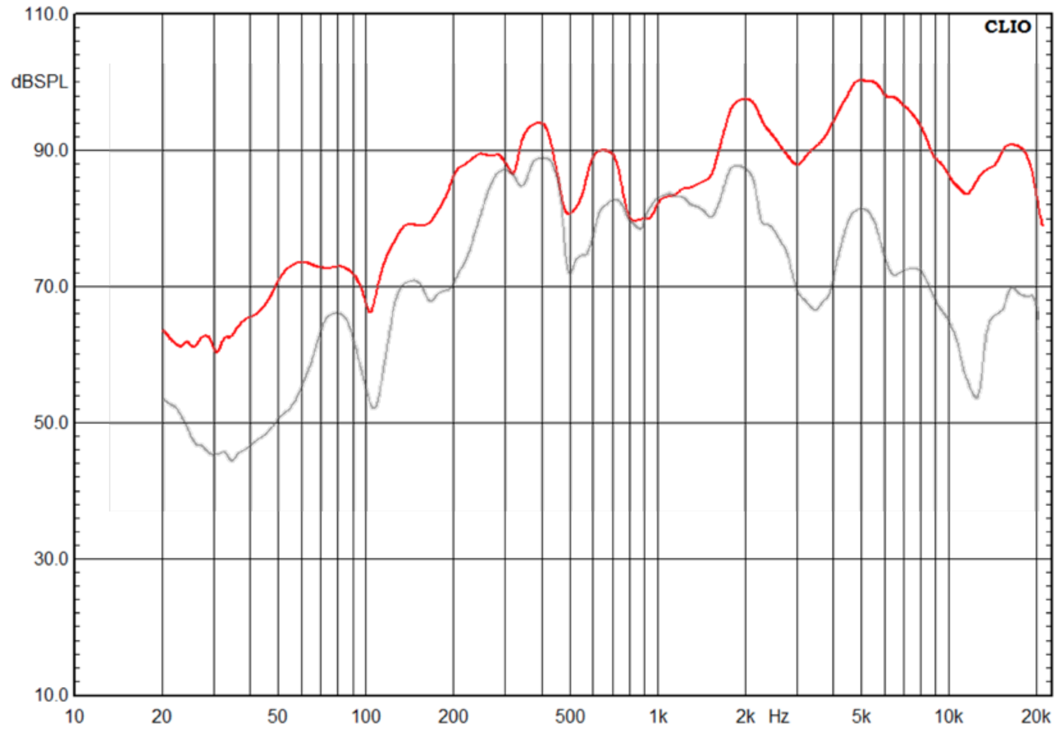


Figure 3.9 Red: Gel-based driver A with external structure 10W 1m ABS panel.
Black: Gel-based driver A with external structure 1W 1m ABS panel

On most loudspeaker systems, it is expected that when the power from the amplifier is doubled, an extra 3 dB sound pressure level should be received. Consequently the difference in power from the test on Figure 3.8 (black) and Figure 3.9 (red) should add an extra 10 dB on the 10W test. This is not the case at the low frequency range up to around 1 kHz, where the sound pressure level difference is around 7 dB. Above 2 kHz, the difference in sound pressure level increases from 10dB up to 20dB which makes the driver more efficient on the high end once powered at 10W. Therefore, in these two-compared tests, the difference in dB against the power is not linear across the frequency range and differs from standard loudspeaker systems.

3.3.2.3 Gel-based Driver A with External Structure 1 W 25 cm ABS Panel

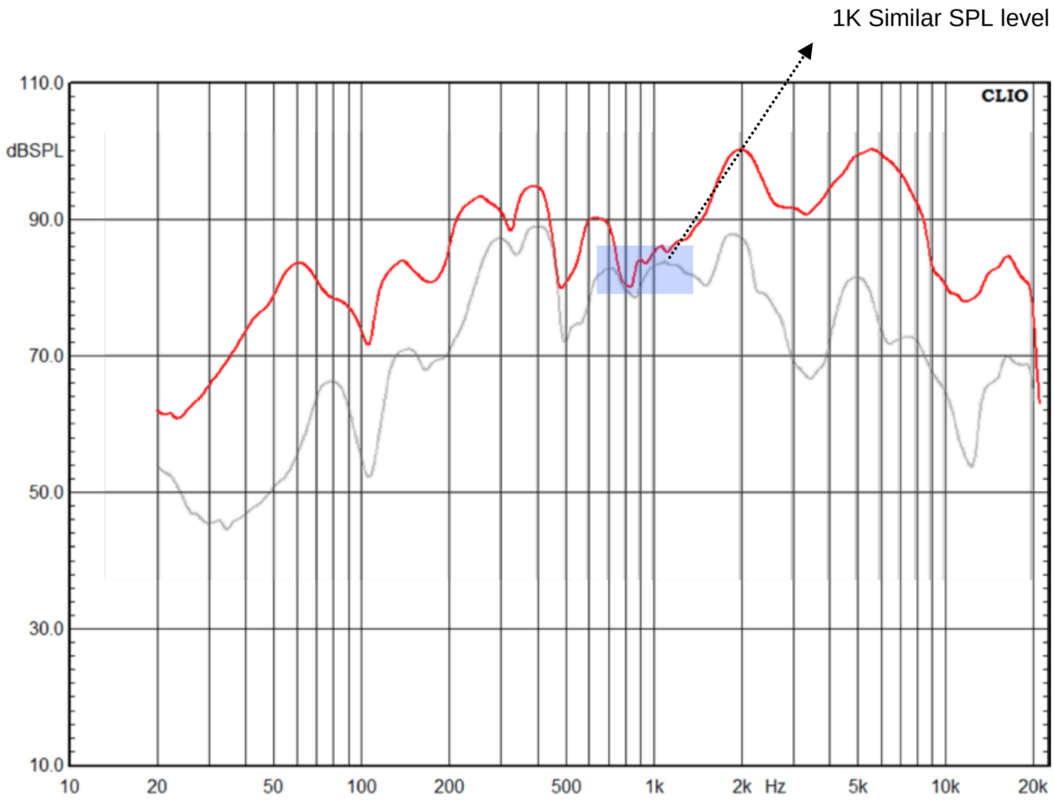


Figure 3.10 Red: Gel-based driver A with external structure 1W 25cm ABS panel.
Black: Gel-based driver A with external structure 1W 1m ABS panel

Figure 3.10 (red) illustrates test results with the microphone positioned at 25 cm from the panel and when compared with the test at 1 m (black), shows an overall higher sound pressure level. This is expected since the average loss of dB per distance is 6 dB for every time the distance is doubled; therefore, the test at 25 cm should be an average of 12 dB louder. It is important to point out that around 1 kHz, the sound pressure level on both tests show the same level. This result is unexpected and may be related to Figure 3.9 at 1m 10W where the extra power was not making the system as loud as expected between 1 kHz and 2 kHz.

3.3.2.4 Gel-based Driver A without External Structure 1 W 1 m ABS Panel

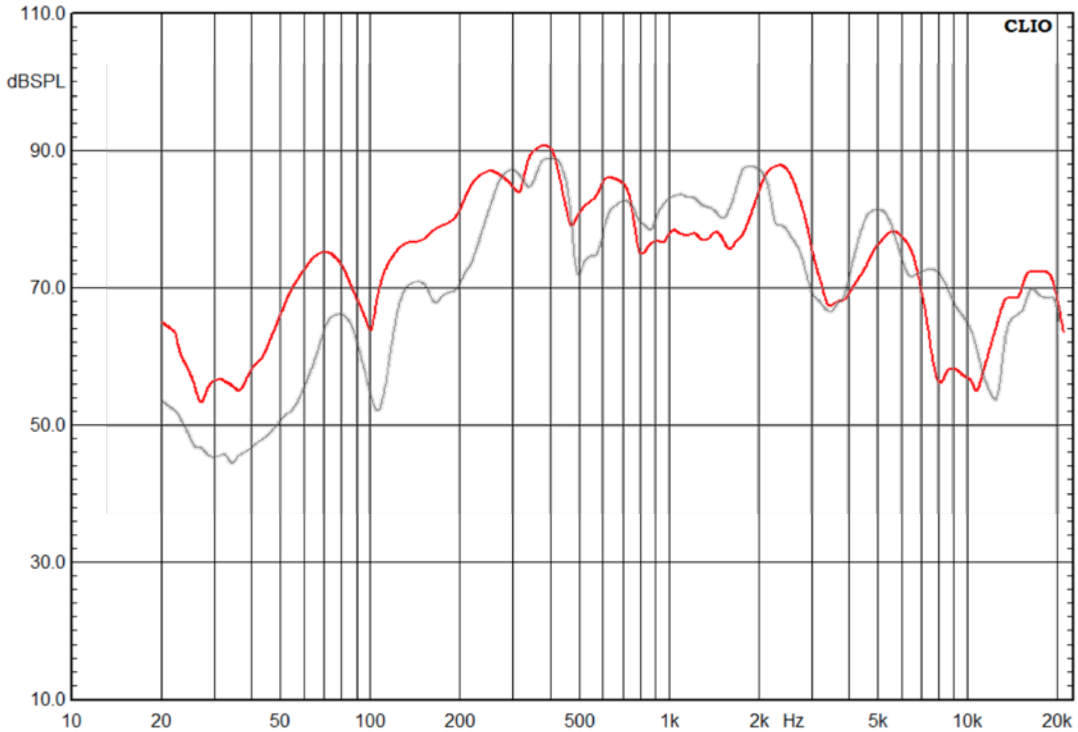


Figure 3.11 Red: Gel-based driver A without external structure 1W 1m ABS Panel
Black: Gel-based driver A with external structure 1W 1m ABS panel

The purpose of this test was to measure the effects that any external structure holding the gel-based driver had on performance (described in Figure 3.11). When the gel-based driver A without external structure (red) is compared with a test with the added external structure (black) it becomes clear that this external structure has a clear damping effect on the low frequency range, while the driver without the external structure is an average 8 dB louder from 20Hz to 150 Hz. On the other hand, the driver with the external structure becomes more efficient in the middle frequency range - being 7-8 dB louder between 500 Hz and 2 kHz.

3.3.2.5 Gel-based Driver A without External Structure 10 W 1 m ABS Panel

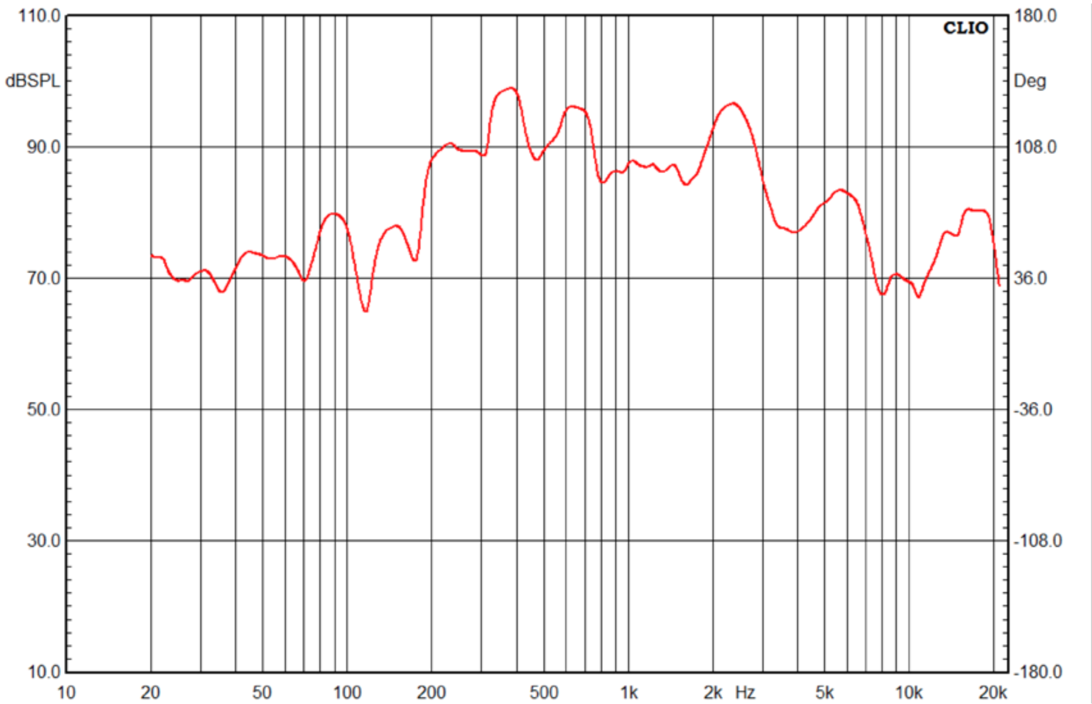


Figure 3.12 Gel-based driver A without external structure 10W 1m ABS panel

When the effects of the external structure were analysed at 10W, the results differed from those tested at 1 W. As seen in Figure 3.12, the test at 10W without the external structure - when compared with Figure 3.10 with the external structure – resulted in a gain in dB only at the low end frequency range, less than 70 Hz. Therefore at higher power, the external structure does not affect the range from 70 Hz to 150 Hz. Looking at the high frequency range, the structure makes the system more efficient only above 3 kHz. Once again, this differs from the test at 1 Watt, where the gain in dB as a result of adding the structure was only between 500 and 2 kHz.

3.3.2.6 Gel-based Driver A without External Structure 1 W 25 cm ABS Panel

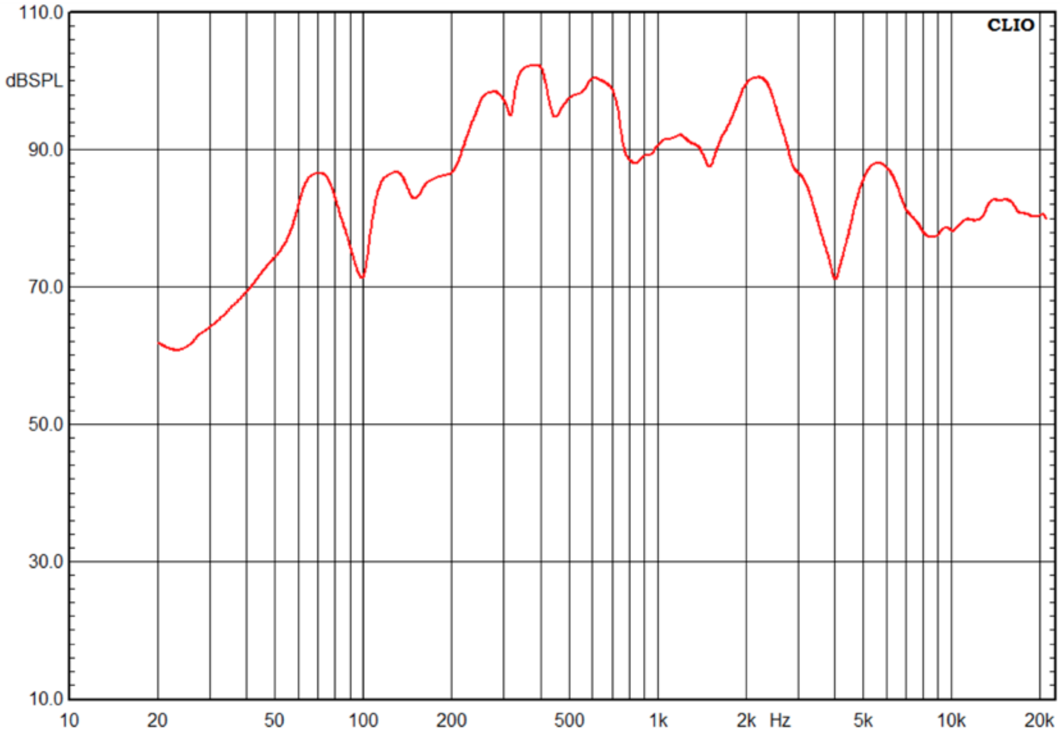


Figure 3.13 Gel-based driver without external structure 1W 25cm ABS panel

Figure 3.13 shows the effects of the external structure effects at 25 cm. It becomes clear that using the structure improves the efficiency at the high frequency range. In this case, only in the range above 3 kHz is the response louder. There is no major sound pressure level performance difference at the low frequency range.

3.4 Gel-based Driver B Measurements

3.4.1 Gel-based Driver B Specification – Softer Elastomer

The previous section showed the effects of the external structure on the overall gel based driver performance. The following section will show the effects of changing the gel hardness used on the driver itself. The driver is named gel-based driver B. This has the same structure as gel-based driver A with the exception of the thermoplastic elastomer part, where a new compound of a softer hardness has been used on the gel based driver B structure. The thermoplastic elastomer material properties are listed below.

Gel-based Driver B Components Material Properties

Part	Material	Young's Modulus (Pa)	Poisson Ratio	Density (kg/m3)	Damping Factor
Magnet	Neodymium 48 grade,	2.00E+11	0.33	7100	0.001
Plate	Steel	2.00E+11	0.27	7700	0.001
PCB (Drive Plate)	FR4	9.00E+08	0.42	1010	0.015
Coil	Copper	1.10E+11	0.35	8700	-
Former	Polymide	7.00E+10	0.33	2300	-
Bracket (holder)	ABS	6.67E+08	0.42	1040	0.015
Thermoplastic elastomer	Thermoplastic elastomer	1.30E+05	0.45	850	0.7

Additional thermoplastic elastomer properties

Shore hardness:	30 shore 00 (0 or under 0 shore A)
Density:	0.86 g/cm3
Shrinkage (Flow direction):	0.049 - 0.053 mm/mm
Compression Set at 23 °C:	21%
Elongation at break:	1290%
Tear strength:	40PLI /7kN/m
Tensile strength:	280psi/ 1931kPa
Working temperature:	70°C
Manufacturer/Product name:	Versaflex® CL2003X[33] (GLS)

3.4.2.1 Gel-based Driver B with External Structure 1 W 1 m ABS Panel

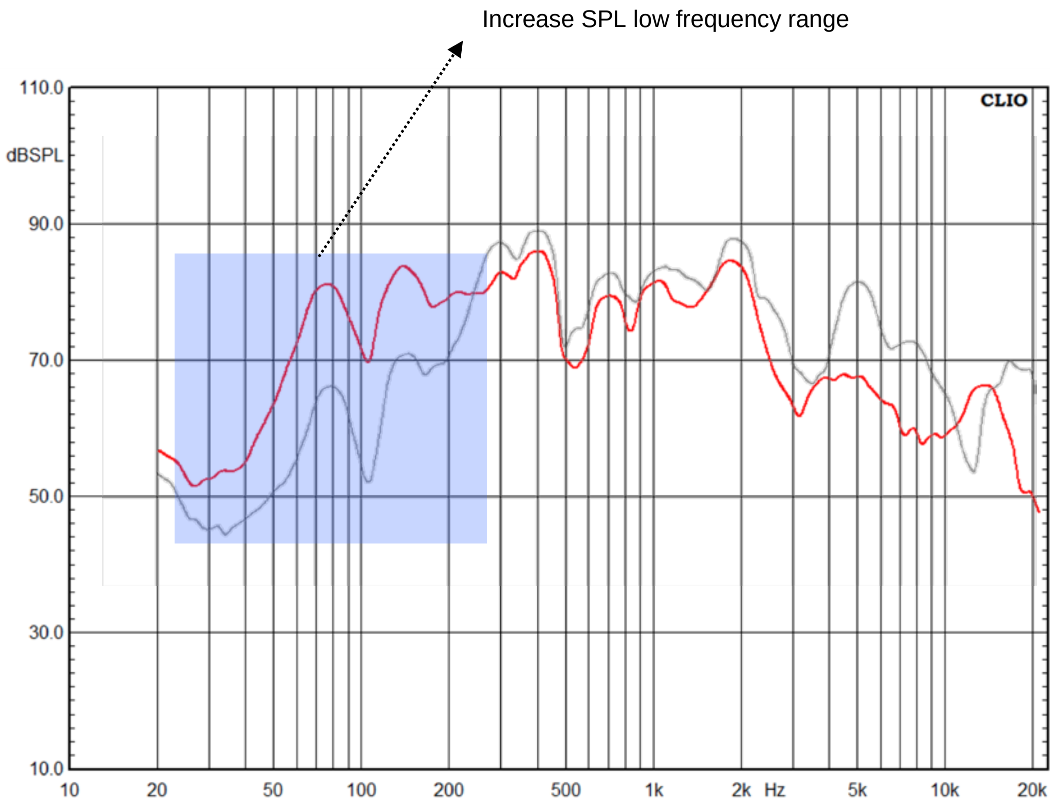


Figure 3.14 Red: Gel-based driver B with external structure 1W 1m ABS panel
Black: Gel-based driver A with external structure 1W 1m ABS panel

The results (Figure 3.14) of Gel-based driver B (red) in contrast with Gel-based driver A (black) indicate that changing the gel hardness to a softer one has a significant effect on the frequency range. In the first instance, it seems that the actual bandwidth is flatter, in particular at the low end, between 50 and 200 Hz. If the graph is compared with Figure 3.9 at 10W, it becomes clear that the softer material has an effect on the system efficiency. Overall this driver is 2-4 dB sound pressure level louder between 300 Hz and 2 kHz and 10 dB louder under 200 Hz. In the previous section, Figure 2.14 shows the relationship between the displacement and the force. If subjected to the same force, the gel-based driver B will have a higher acceleration, and consequently displacement, at low frequencies when compared with gel-based driver A. It is expected that the linear region versus force of gel-based driver B will be longer than that of gel-based driver A.

3.4.2.2 Gel-based Driver B with External Structure 10 W 1 m Panel

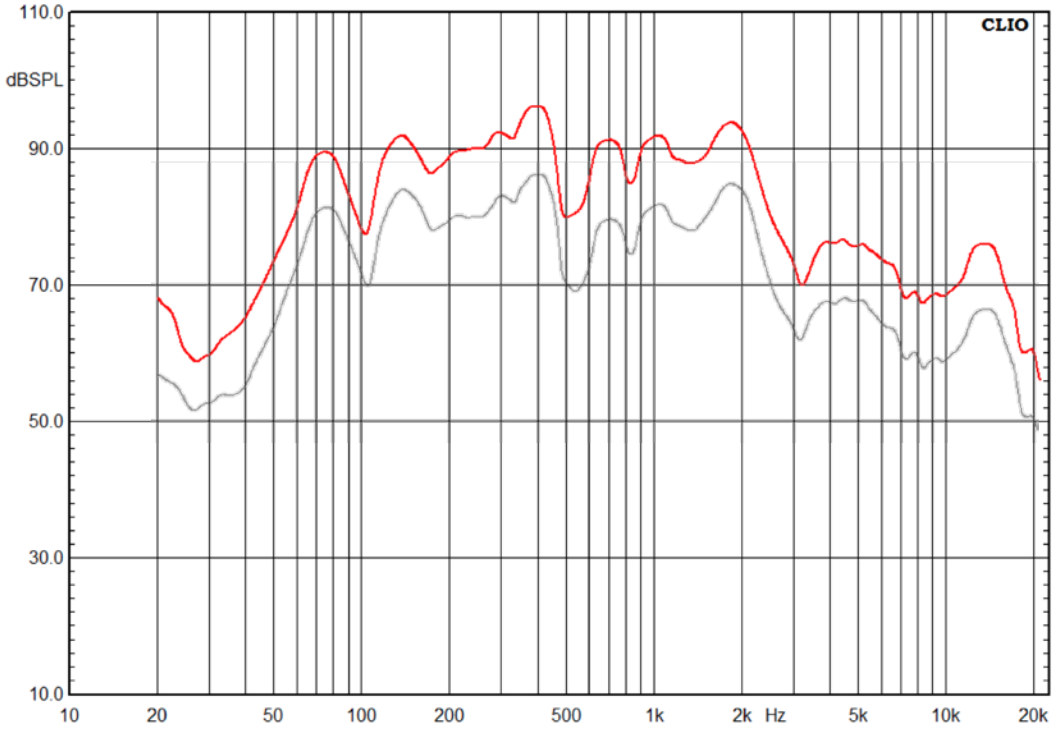


Figure 3.15 Red: Gel-based driver B with external structure 10W 1m panel
Black: Gel-based driver B with external structure 1W 1m panel

The gel-based driver played at 10W (red) should be 10 dB louder if compared to one played at 1W (Black). The average difference between both measured tests is 8-10 dB sound pressure level, so it is largely as expected. In this case the increase in dB is linear across the frequency range. This differs from the previous tests (Figures 3.8 and 3.9) where a harder silicone gel was being used. In those cases the increase in dB was more evident at the high frequency range. This may mean that the hard gel absorbs some of the energy at high frequencies.

3.4.2.3 Gel-based Driver B with External Structure 1 W 25 cm ABS Panel

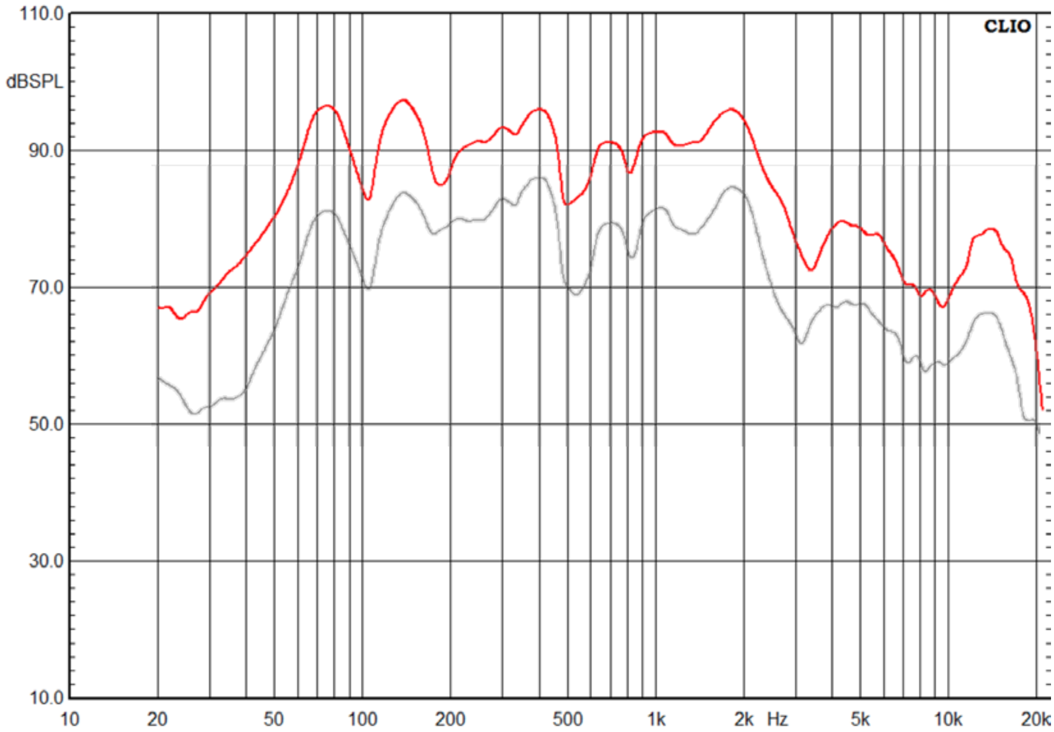


Figure 3.16 Red : Gel-based driver B with external structure 1W 25 CM ABS panel
Black: Gel-based driver B with external structure 1W 1m panel

Figure 3.16 shows the based driver 7 tested at 25 cm (red) and compared to one tested at 1 m (black) - the difference in the distance should give around 12 dB sound pressure level extra to the closer test and it can be seen that the test results are as expected. Note that not only the average is the same on both tests, but the peaks and troughs related to cancellations and couplings of the signals are almost identical. This is a sign that this has been tested in a proper anechoic environment; otherwise the reflections from walls could interfere differently at different distances.

3.4.2.4 Gel-based Driver B without External Structure 1 W 1 m ABS Panel

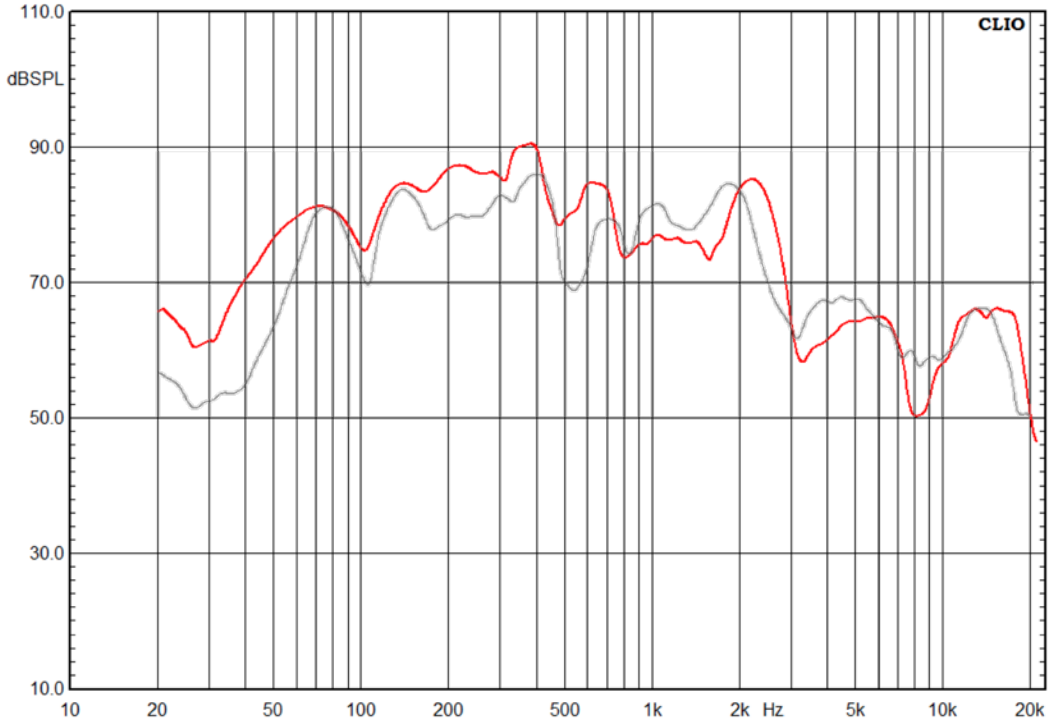


Figure 3.17 Red: Gel-based driver B without external structure 1W 1m ABS panel
Black: Gel-based driver B with external structure 1W 1m ABS panel

Figure 3.17 shows that the gel-based driver B is more efficient if used without the external structure - particularly at the low frequency range, under 600Hz. Note that in this region, it is flatter too. The presence of the structure not only has an effect on the system efficiency, it changes the patterns of cancellations and couplings. From 600 Hz to 20 kHz, both tests, with external structure (Figure 3.14) and without external structure (Figure 3.17), have a similar performance. This effect is quite similar to the test using the harder gel (Figures 3.8 and 3.9) - although the system with the external structure was slightly more efficient at high frequencies.

3.4.2.5 Gel-based Driver B without External Structure 10 W 1 m ABS Panel

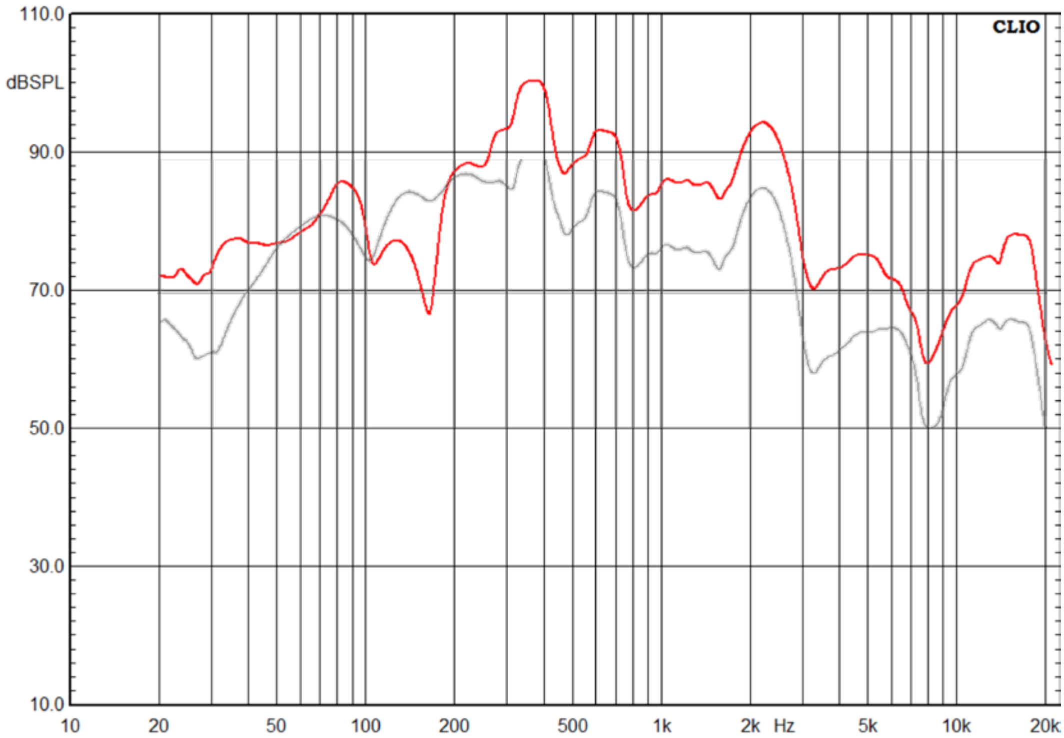


Figure 3.18 Red: Gel-based driver B without external structure 10W 1m ABS panel
Black: Gel-based driver B without external structure 1W 1m ABS panel

Figure 3.18 shows that the gel-based driver B played at 10W (red) did not show the expected extra 10 dB sound pressure level on the whole frequency range compared with the 1W test (black). The extra power is not reflected in particular at the low frequency range - under 500Hz.

Above 500 Hz there is a significant increase of around 6-8 dB sound pressure level. It seems that the extra energy applied to this system is not transformed into acoustic energy in the low frequency range. This could be because the excursion of the driver has reached its limit and the extra power does not add any more movement.

3.4.2.6 Gel-based Driver B without External Structure 1 W 25 cm ABS Panel

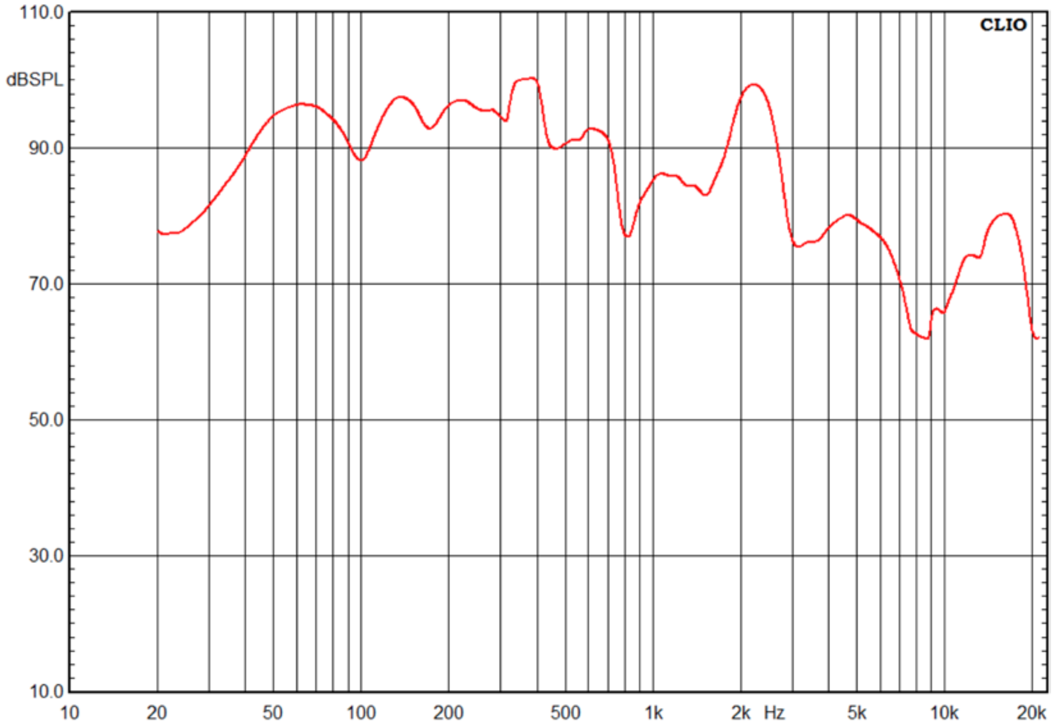


Figure 3.19 Gel-based driver B without external structure 1W 25cm ABS panel

Figure 3.19 shows the gel-based B driver without an external structure and tested at 25 cm. In this case the lack of the structure added to the soft gel and the proximity of the measurement, makes the response louder in the low frequency range. Looking at the graph alone, this could be quite similar to a response expected from a traditional moving coil loudspeaker subwoofer. On a subwoofer the cone of the driver is proportionally large (if compared with standard moving coil loudspeakers) in order to move enough air to produce low frequencies. With this gel B driver, the ABS panel manages to displace a large volume of air and achieves a similar effect, but the gel-based B driver is considerably smaller than an average subwoofer.

3.5 Gel-based Driver C Measurements

3.5.1 Gel-based Driver C Specification – Corner Only Attachment

Electrical and Acoustical Characteristics

Sound Pressure Level	90 +- 3 dB at 1W/25cm, 100 to 1000 Hz
Impedance	6 Ohms
Frequency Range	80-8000 Hz (Related to surface being driven)
Power Handling	5 W (R.M.S)
Magnet	N48

Overall Dimensions with external structure

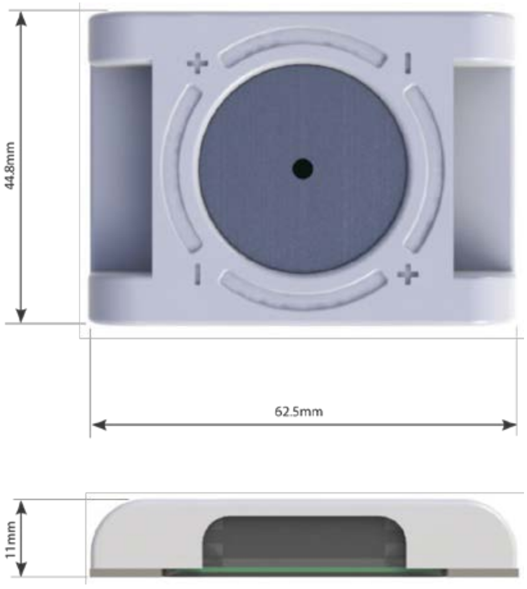


Figure 3.20 Gel-based driver C overall dimensions

Overall Dimensions without external structure

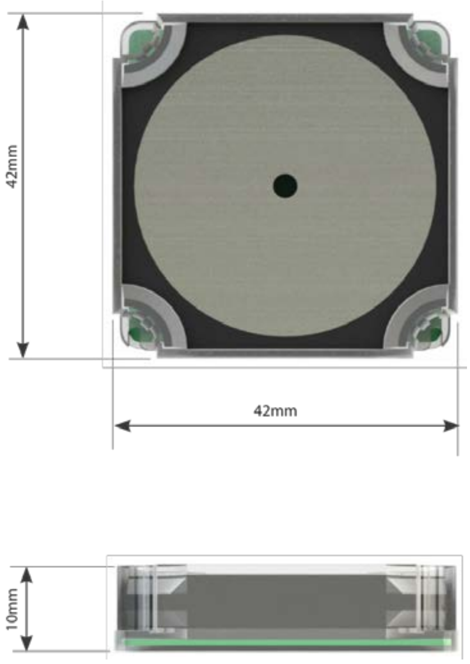


Figure 3.21 Gel-based driver C overall dimensions without external structure

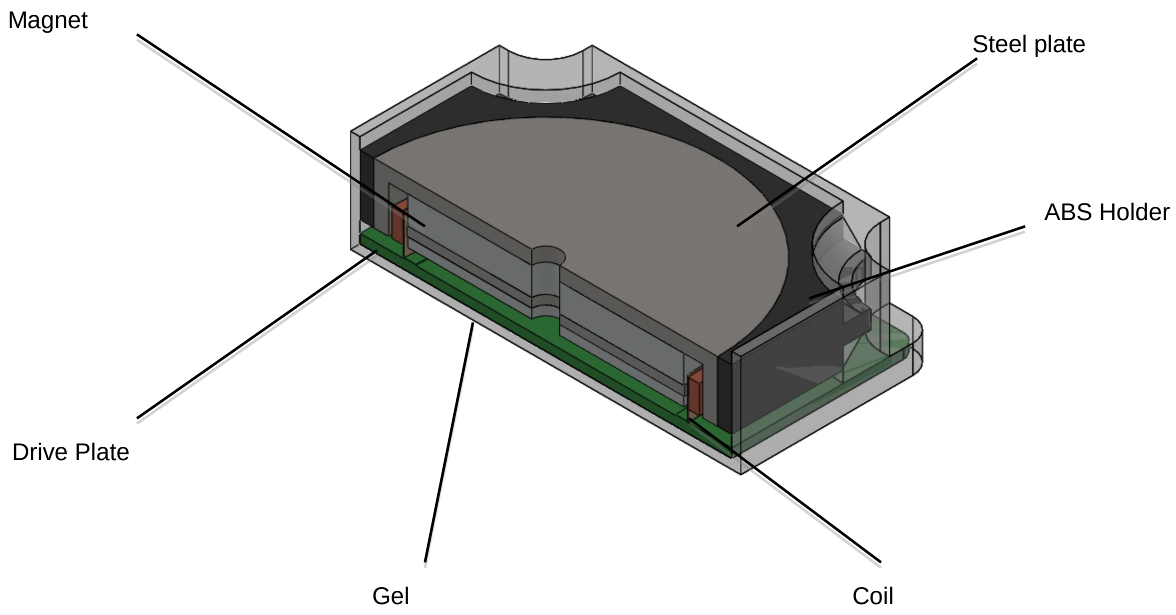


Figure 3.22

Gel-based Driver C Components Material Properties

Part	Material	Young's Modulus (Pa)	Poisson Ratio	Density (kg/m3)	Damping Factor
Magnet	Neodymium 48 grade,	2.00E+11	0.33	7100	0.001
Plate	Steel	2.00E+11	0.27	7700	0.001
PCB (Drive Plate)	FR4	9.00E+08	0.42	1010	0.015
Coil	Copper	1.10E+11	0.35	8700	-
Former	Polymide	7.00E+10	0.33	2300	-
Bracket (holder)	ABS	6.67E+08	0.42	1040	0.015
Thermoplastic elastomer	Thermoplastic elastomer	1.30E+05	0.45	850	0.7

Additional thermoplastic elastomer properties

Shore hardness:	30 shore 00 (0 or under 0 shore A)
Density:	0.86 g/cm3
Shrinkage (Flow direction):	0.049 - 0.053 mm/mm
Compression Set at 23 °C:	21%
Elongation at break:	1290%
Tear strength:	40PLI /7kN/m
Tensile strength:	280psi/ 1931kPa
Working temperature:	70°C
Manufacturer/Product name:	Versaflex® CL2003X[33] (GLS)

Note that in previous tests, the importance of the structure of the driver on frequency performance has been observed – particularly at low frequencies. This gel-based driver C has been designed so the corners only hold the magnetic assembly and this will reduce the stiffness between the magnetic assembly and the drive plate. It is believed that this will have an effect on the low frequency range and enable a more efficient way of transferring the waves from the driver to the panel.

3.5.2 Gel-based Driver C Results

3.5.2.2 Gel-based Driver C with External Structure 1 W 1 m ABS Panel

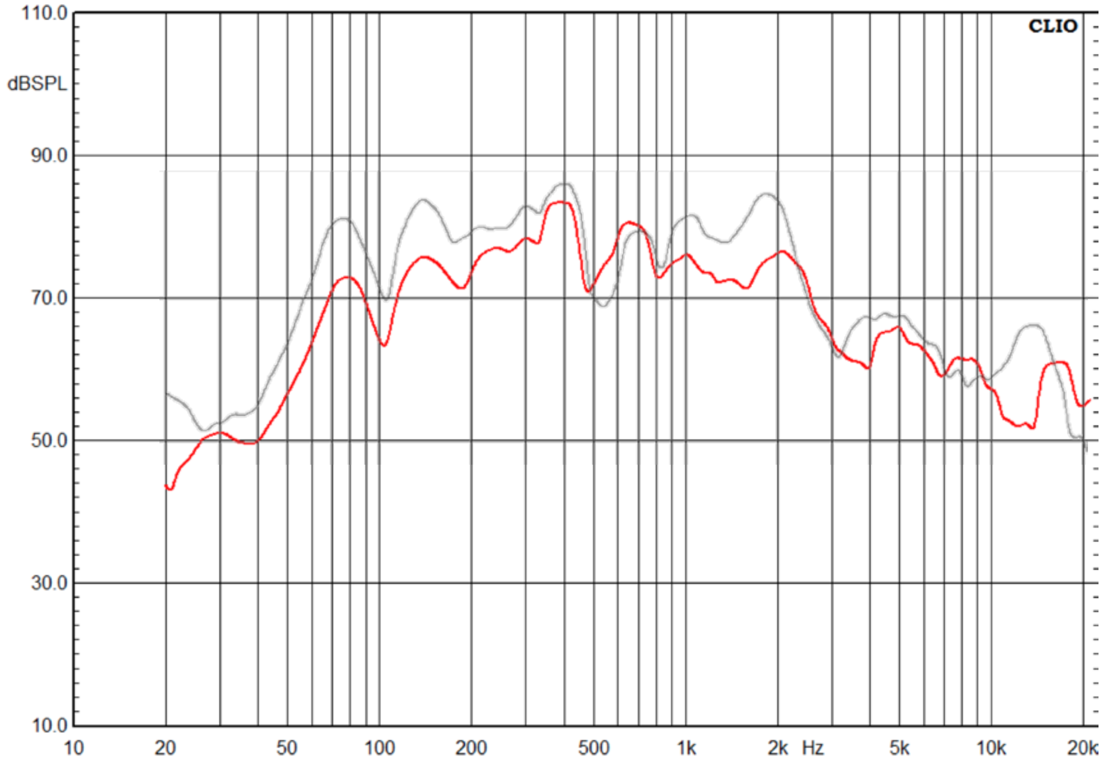


Figure 3.23 Red: Gel-based driver C with external structure 1W 1m ABS panel
Black: Gel-based driver B with external structure 1W 1m ABS panel

The gel-based driver C uses the same type of thermoplastic elastomer as the gel-based driver B but with a smaller magnet and this has an effect on its efficiency. Figure 3.23 shows that the dB level below 200 Hz is around 5 dB less while above this frequency, the performance of both drivers is quite similar. Taking into account that the gel-based B driver is twice the size of the gel-based C one, this latest structure is overall more efficient and its performance more balanced. The only area where it is not performing well is above 3 kHz. This is probably due the size of the coil - its inductance having an effect on the impedance at high frequencies.

3.5.2.3 Gel-based Driver C with External Structure 5 W 1 m ABS Panel

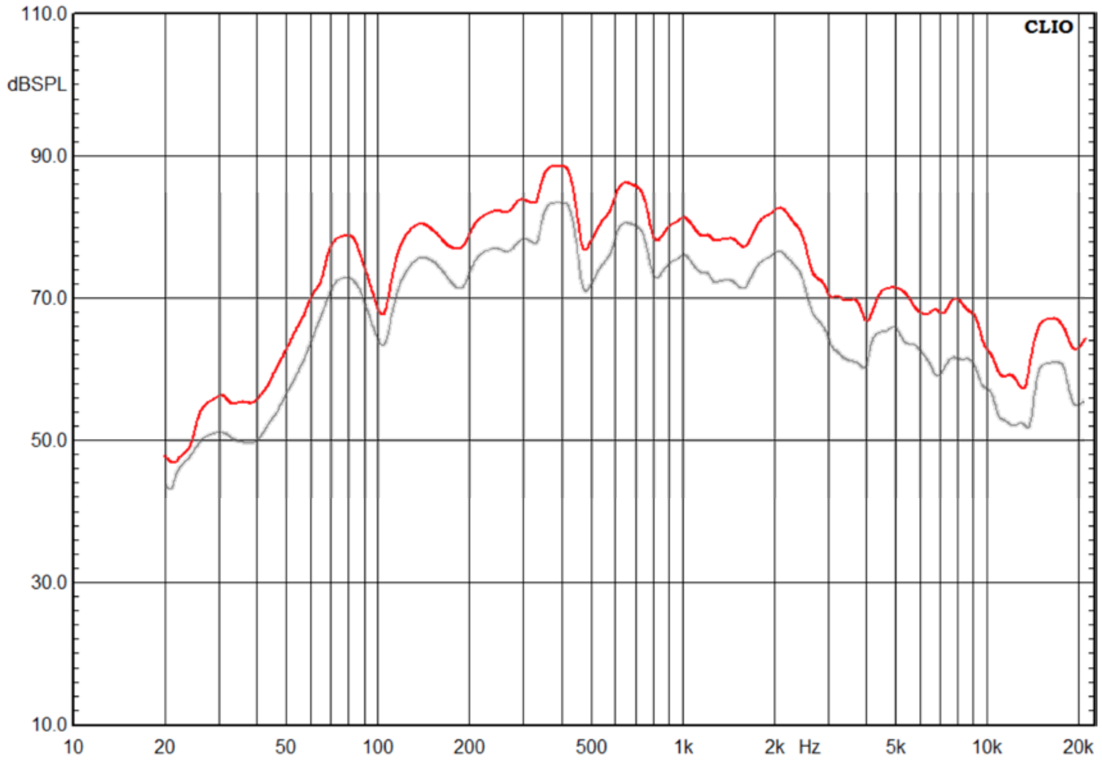


Figure 3.24 Red: Gel-based driver C with external structure 5W 1m ABS panel
Black: Gel-based driver C with external structure 1W 1m ABS panel

This gel-based C is rated at 5 W instead of the previous sections power test carried out at 1 W. The extra power should give 6 dB extra sound pressure level and as can be seen from Figures 3.24 and 3.23, both have the same shape and there is a 6 dB difference. For this reason, we assume that the driver performs linearly against the power.

3.5.2.4 Gel-based Driver C with External Structure 1 W 25 cm ABS Panel

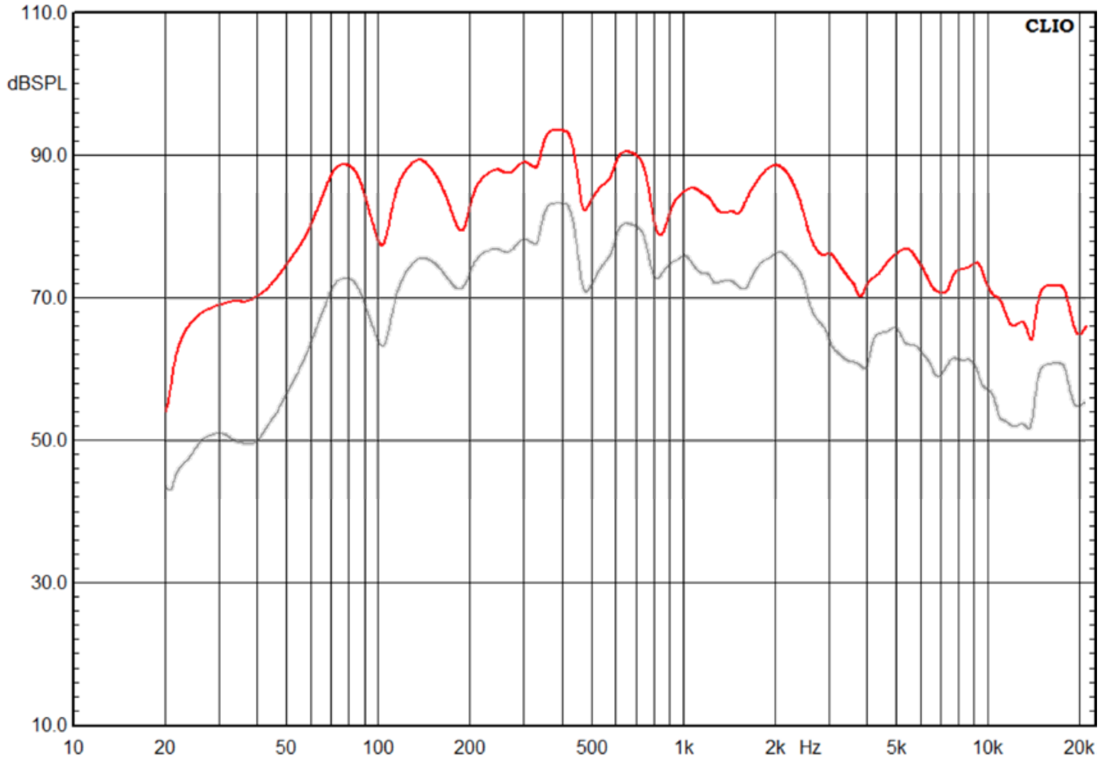


Figure 3.25 Red: Gel-based driver C with external structure 1W 25cm ABS panel
Black: Gel-based driver C with external structure 1W 1m ABS panel

Figure 3.25 shows the Gel-based driver C tested at 25 cm. The overall frequency response is very similar to the test made at 1 m and shown in Figure 3.23. The two main differences are the 12 dB sound pressure level increase because of the proximity at 25 cm and the low frequency range being relatively louder at high frequencies. Note that the sound pressure level descents seen at 100, 200 and 500 Hz are present at both 1 m and 25 cm positions and even when the gel-based driver B is being used. It is clear that these descents are related to the panel size and material and will always be present regardless of which driver is being used.

3.5.2.5 Gel-based Driver C without External Structure 1 W 1 m ABS Panel

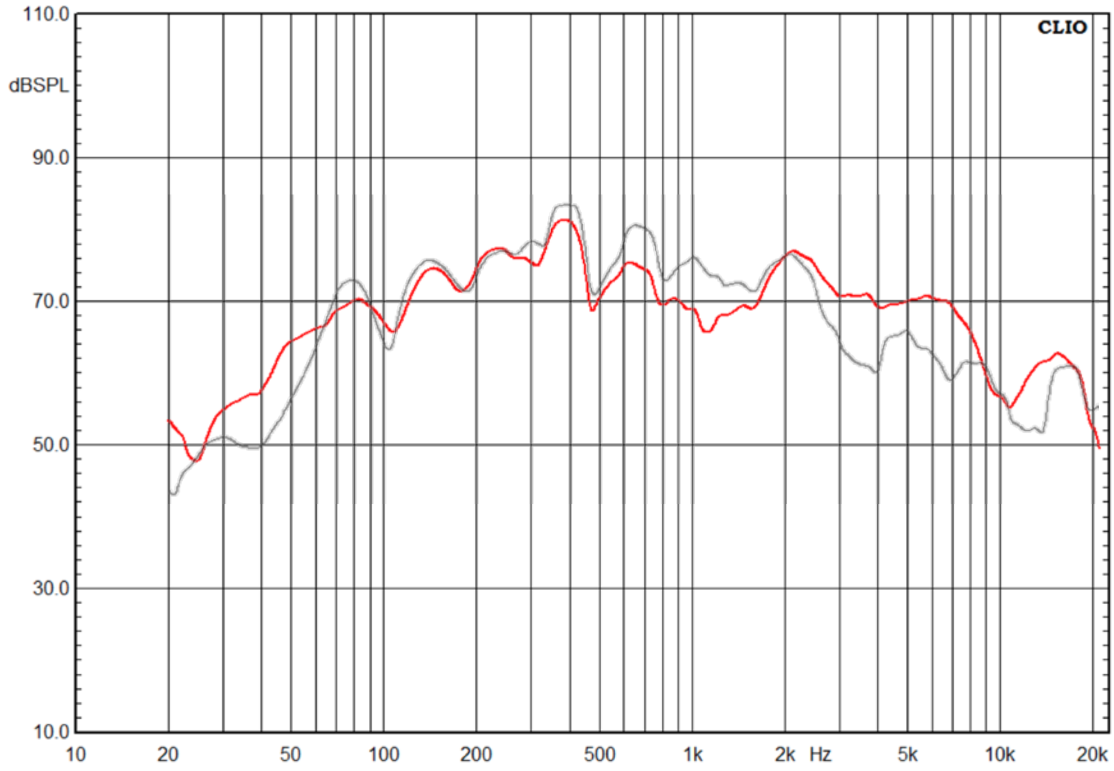


Figure 3.26 Red: Gel-based driver C without external structure 1W 1m ABS panel
Black: Gel-based driver C with external structure 1W 1m ABS panel

The gel-based driver C does not seem to be as affected by the structure compared to gel-based driver B; Figure 3.26 shows a very similar response to Figure 3.23 - in particular below 700 Hz. This may be due the design of the gel-based driver C structure where the gel is held only at the corners. Once the external structure is applied, this does not compress the corners, hence the gel structure is unmodified. This differs from gel-based drivers A and B where the structure had a clear impact on the driver performance in all frequency ranges and in particular below 600 Hz. Therefore the structure used on gel-based driver C will be more suitable for low frequency range applications since it does not restrain the driver movement and adversely affect performance. However, the gel-based driver C structure still has an effect at the mid- and high-frequency range. It will be interesting to look at the adhesive pads used to see if these have an impact on the high frequency performance.

3.5.2.6 Gel-based Driver C without External Structure 5 W 1 m ABS Panel

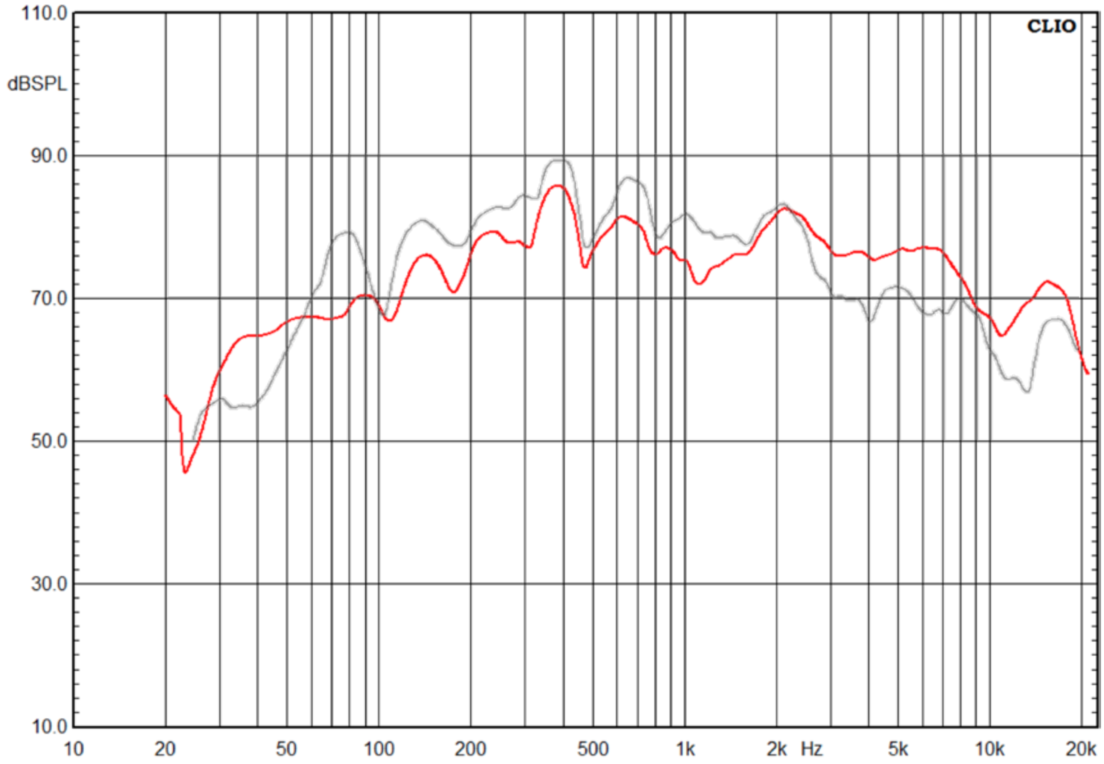


Figure 3.27 Red: Gel-based driver C without external structure 5W 1m ABS panel
Black: Gel-based driver C without external structure 1W 1m ABS panel

Figure 3.27 shows the gel-based driver C without the external structure and powered at 5W. The average increase of loudness is only around 3 dB sound pressure – less than that expected with such an increase in power. Around 6 dB extra is expected - compared to the 1W test – but this only happens above 3000 Hz. Below this frequency, the extra energy is not fully transformed into acoustic energy.

3.5.2.6 Gel-based Driver C without External structure 1 W 25 cm ABS Panel

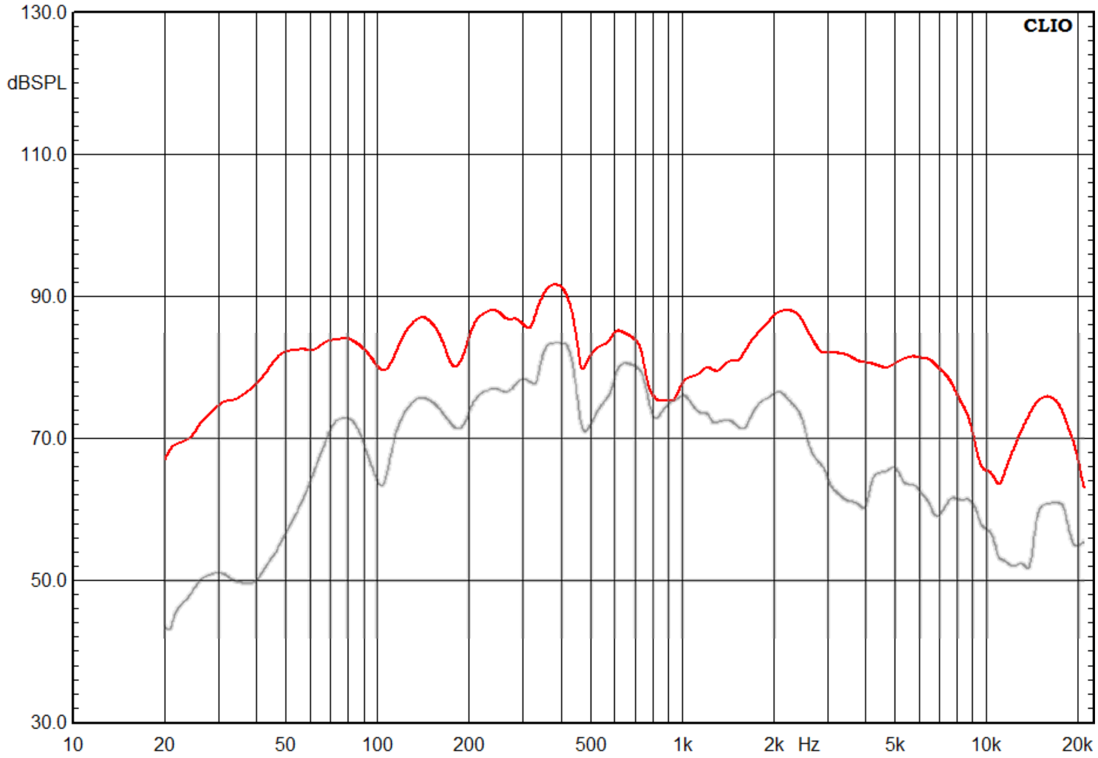


Figure 3.28 Red: Gel-based driver C with no external structure 1W 25cm ABS pane

Black: Gel-based driver C with no external structure 1W 1m ABS panel

Figure 3.28 shows the test result from the microphone being at 25 cm and using the gel-based driver C without the external structure. It performs around 12 dB sound pressure level higher on most of the frequency range when compared with the same test at 1 m (Figure 3.23). This is as expected in accordance with a 6 dB sound pressure level decrease as the distance from the source to the microphone is doubled. However, it seems that between 600 and 1000 Hz the difference in dB is less and at 900 Hz there is little or no difference.

3.6 Gel-based Driver D Measurements

3.6.1 Gel-based Driver D Specification – ¼ Size

Electrical and Acoustical Characteristics

Sound Pressure Level	90 +- 3 dB at 1W/10cm
Impedance	4 Ohms
Frequency Range	300-10000 Hz (Related to surface being driven)
Power Handling	4 W (R.M.S)
Magnet	N48

Overall Dimensions with External Structure

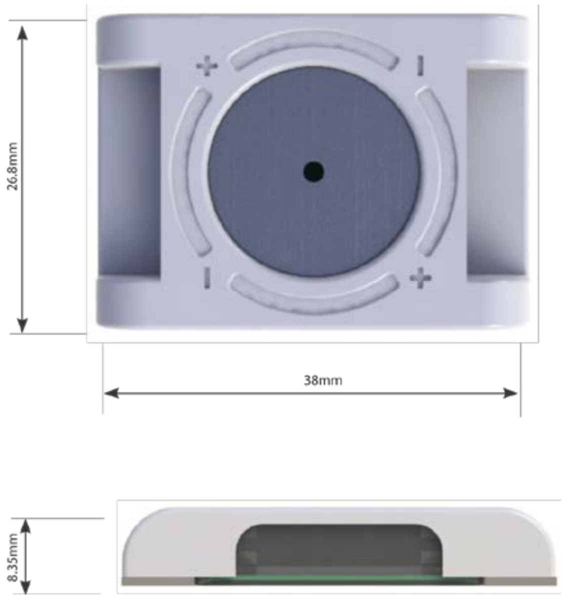


Figure 3.29 Gel-based driver D overall dimensions

Overall Dimensions without External Structure

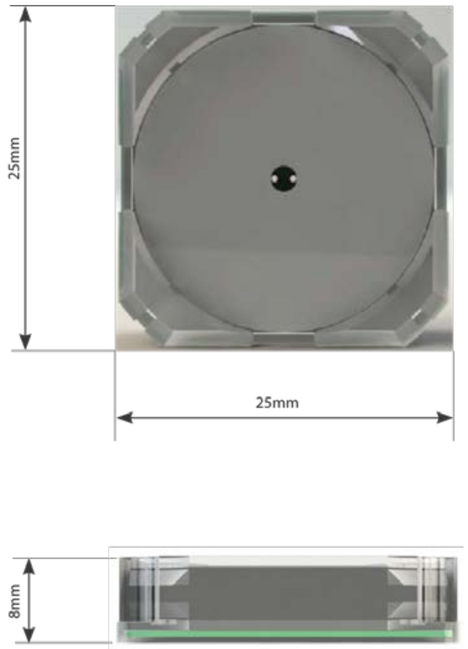


Figure 3.30 Gel-based driver D overall dimensions without external structure

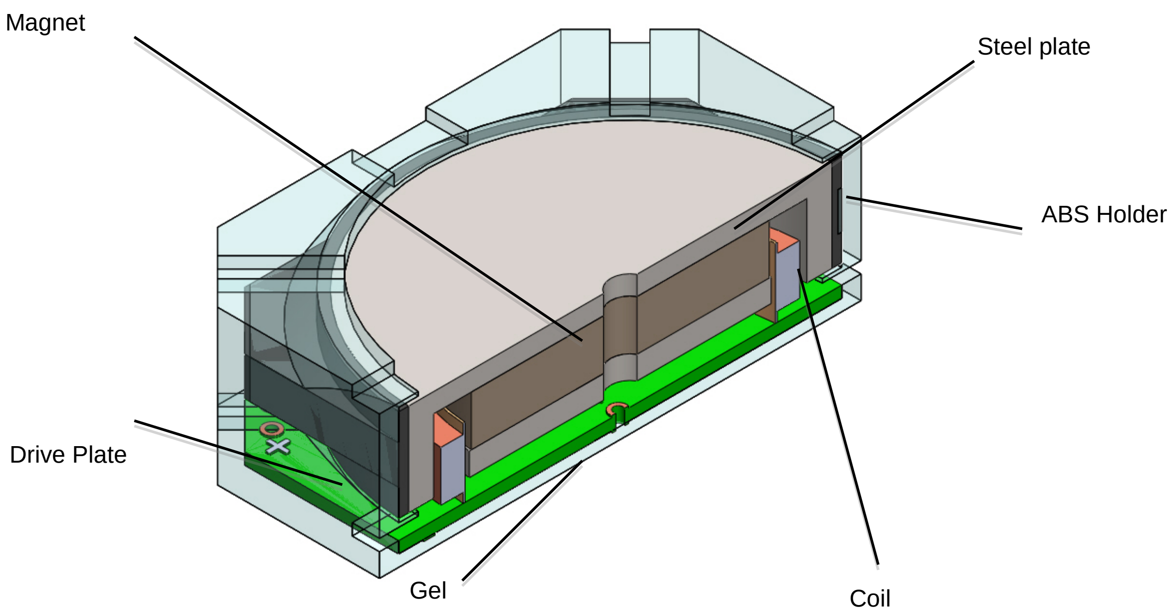


Figure 3.31 Gel-based driver D components

Gel based Driver D description

This section looks at the relationship between the size of the driver and its frequency response. Previously, it has been possible to achieve a reasonably efficient low frequency response with a relatively small driver. This gel-based driver D is ¼ of the size when compared to gel-based driver C and it is important to analyse whether with smaller drivers the bass will still be present. Note that in the following section, a 10 W power test has not been carried out since this gel-based driver is only rated up to 4W. Note also that gel-based drivers C and D share the same structure so in most cases, the two will be compared.

Gel-based Driver D Component Material Properties

Part	Material	Young's Modulus (Pa)	Poisson Ratio	Density (kg/m3)	Damping Factor
Magnet	Neodymium 48 grade,	2.00E+11	0.33	7100	0.001
Plate	Steel	2.00E+11	0.27	7700	0.001
PCB (Drive Plate)	FR4	9.00E+08	0.42	1010	0.015
Coil	Copper	1.10E+11	0.35	8700	-
Former	Polymide	7.00E+10	0.33	2300	-
Bracket (holder)	ABS	6.67E+08	0.42	1040	0.015
Thermoplastic elastomer	Thermoplastic elastomer	1.30E+05	0.45	850	0.7

Additional thermoplastic elastomer properties

Shore hardness:	30 shore 00 (0 or under 0 shore A)
Density :	0.86 g/cm3
Shrinkage (Flow direction):	0.049 - 0.053 mm/mm
Compression Set at 23 °C:	21%
Elongation at break:	1290%
Tear strength:	40PLI /7kN/m
Tensile strength:	280psi/ 1931kPa
Working temperature:	70°C
Manufacturer/Product name:	Versaflex® CL2003X[33] (GLS)

3.6.2 Gel-based Driver D Test Results

This section looks at the relationship between the size of the driver and its frequency response. It is clear that by using gel-based drivers, it is possible to have a good low frequency response with a relatively small driver. The gel-based driver D is ¼ of the size when compared to the Gel-based driver C and it is interesting to analyse whether with smaller drivers the bass is still present. Note that in the following section, a 10 W power test has not been carried out since the gel-based driver is only rated up to 4W. Note also that the gel-based drivers D and C share the same structure so in most cases, gel-based driver D will be compared with gel-based driver C.

3.6.2.1 Gel-based Driver D with External Structure 1 W 1 m ABS Panel

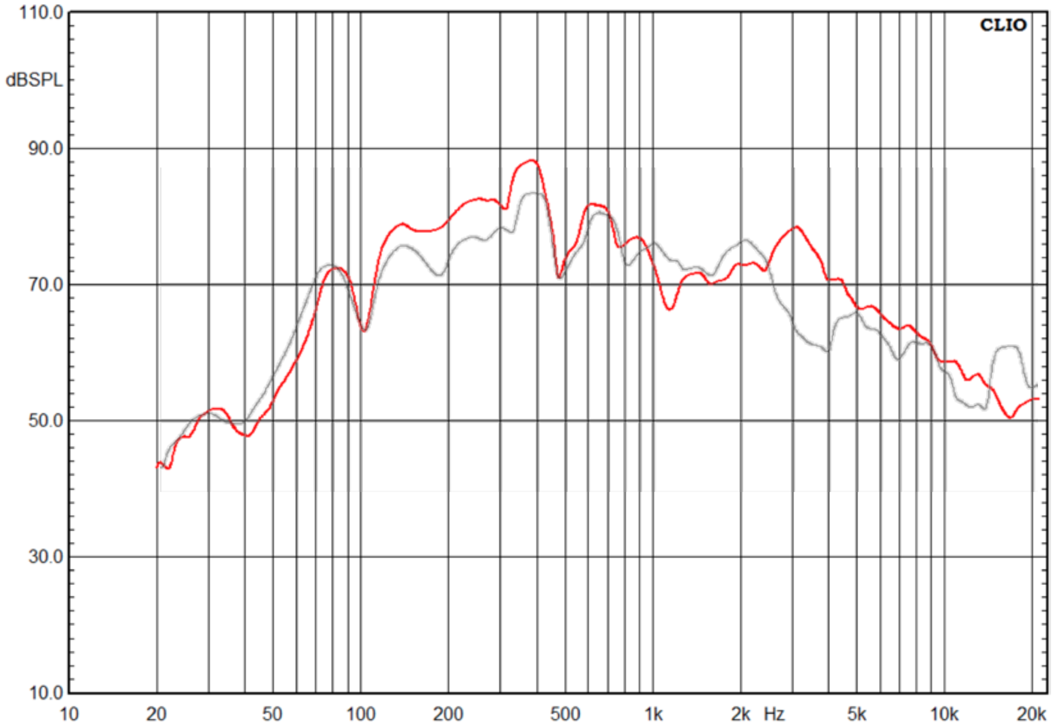


Figure 3.32 Red: Gel-based driver D with external structure 1W 1m ABS panel
Black: Gel-based driver C with external structure 1W 1m ABS panel

The reference test of the gel-based D (red) shows a similar frequency response to the reference test of the gel-based C (grey). Taking into account that the size of the gel-based driver D is ¼ of the gel bas driver C, the ratio of performance against size is very interesting. It needs to be taken in to account that gel-based D has a smaller bi than gel-based C due its magnet and coil size and this has a direct effect on the driver force. Yet looking at the graph, this difference in force seems only to be present between 100 Hz and 400 Hz, which is under the system resonance frequency.

3.6.2.2 Gel-based Driver D with External Structure 1 W 25 cm ABS Panel

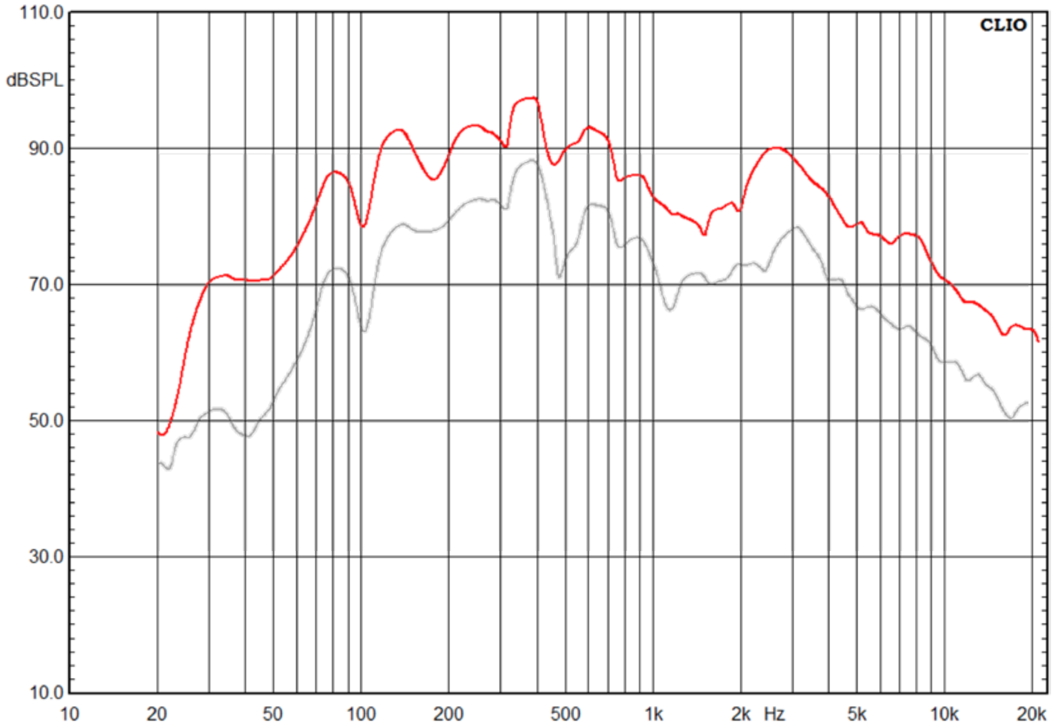


Figure 3.33 Red: Gel-based driver D with external structure 1W 25cm ABS panel
Black: Gel-based driver D with external structure 1W 1m ABS panel

The test (Figure 3.33) of gel-based driver D at 25 cm shows – over a wide frequency range - 12 dB sound pressure level higher than the same test (Figure 3.32) at 1 m. This differs from gel-based driver C where the test at 25 cm was not linearly 12 dB sound pressure level louder as expected. Taking into account that the above test and the gel-based driver C test were both carried out with the same panel, it seems that the differences may be due the resonance of the gel-based driver itself.

3.6.2.3 Gel-based Driver D without External Structure 1W 1m ABS Panel

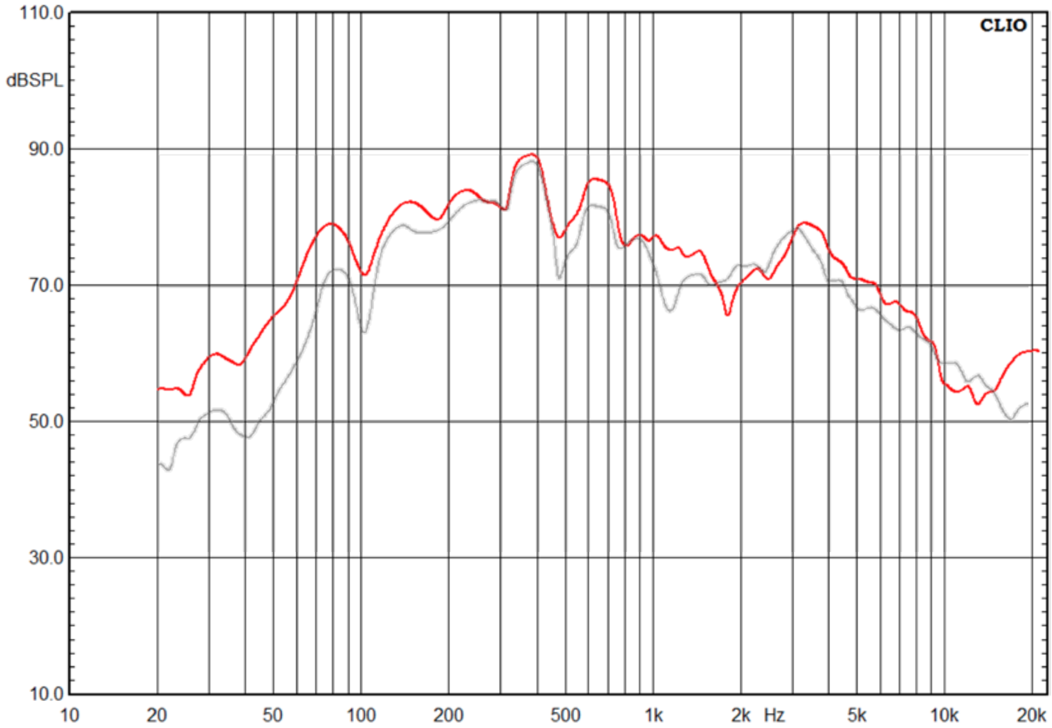


Figure 3.34 Red: Gel-based driver D without external structure 1W 1m ABS panel
Black: Gel-based driver D with external structure 1W 1m ABS panel

Gel-based driver D (without external structure) shows an overall performance increase in contrast (Figure 3.34) with the measurements with the external structure (grey). This is particularly clear at the low end - around 80 Hz. Consequently, the external structure must be constraining the movement of the driver and this becomes more evident at the low end of the frequency range when the driver reaches its maximum excursion.

3.6.2.4 Gel-based Driver D without External Structure 1 W 25 cm ABS Panel

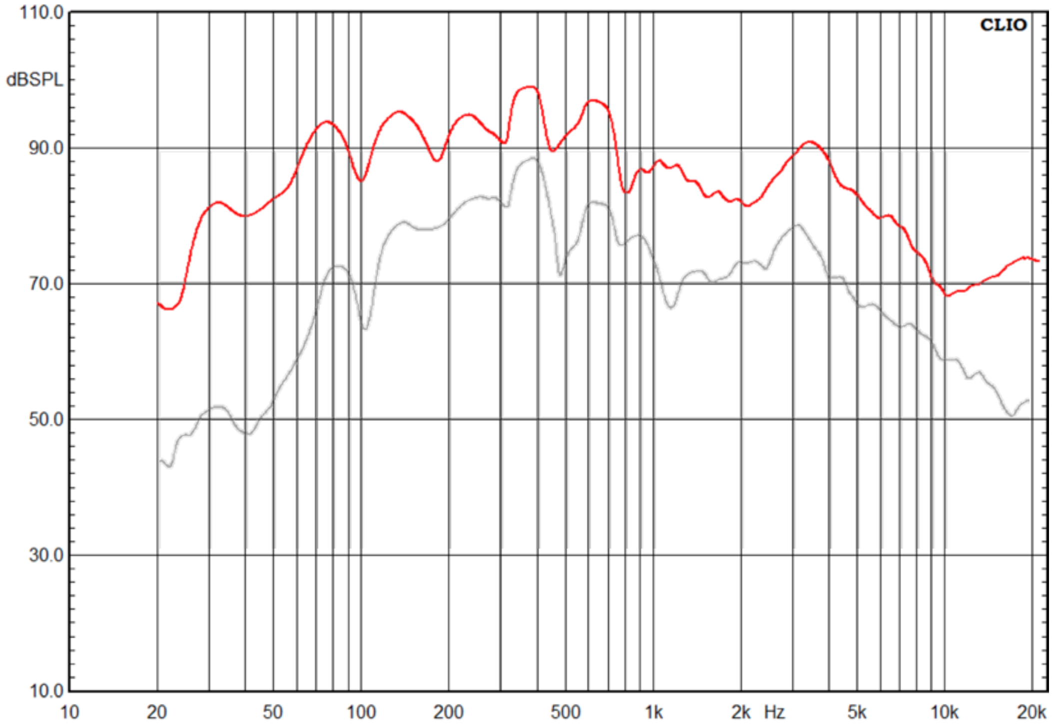


Figure 3.35 Red: Gel-based driver D without external structure 1W 25cm ABS panel
Black: Gel-based driver D without external structure 1W 1m ABS panel

The test of gel-based driver D at 25 cm and without the external structure shows the increase in dB at 30 Hz evident in Figure 3.34 but more apparent in Figure 3.35. This reflects the effect that the structure has in particular at the low frequencies. The gel-based driver should be designed to allow a greater degree of flexibility and it will then be able to reproduce lower frequencies.

3.7 Materials Performance Research

3.7.1 Materials Specifications

Aluminium Panel:

-Dimension: 420x320x2mm

- Density: 2700 kg/m3

- Young’s Modulus: 70e9 Pa

- Poisson ratio: 0.33

- Critical Coincidence Frequency: 6261Hz

Wood Panel:

- Dimension: 420x320x2mm

- Density: 770 kg/m3

- Young’s Modulus: 11.2e9 Pa

- Position ratio: 0.15

- Critical Coincidence Frequency: 8359Hz

3.7.1 Gel-based Driver A with External Structure 1 W 1 m Aluminum Panel

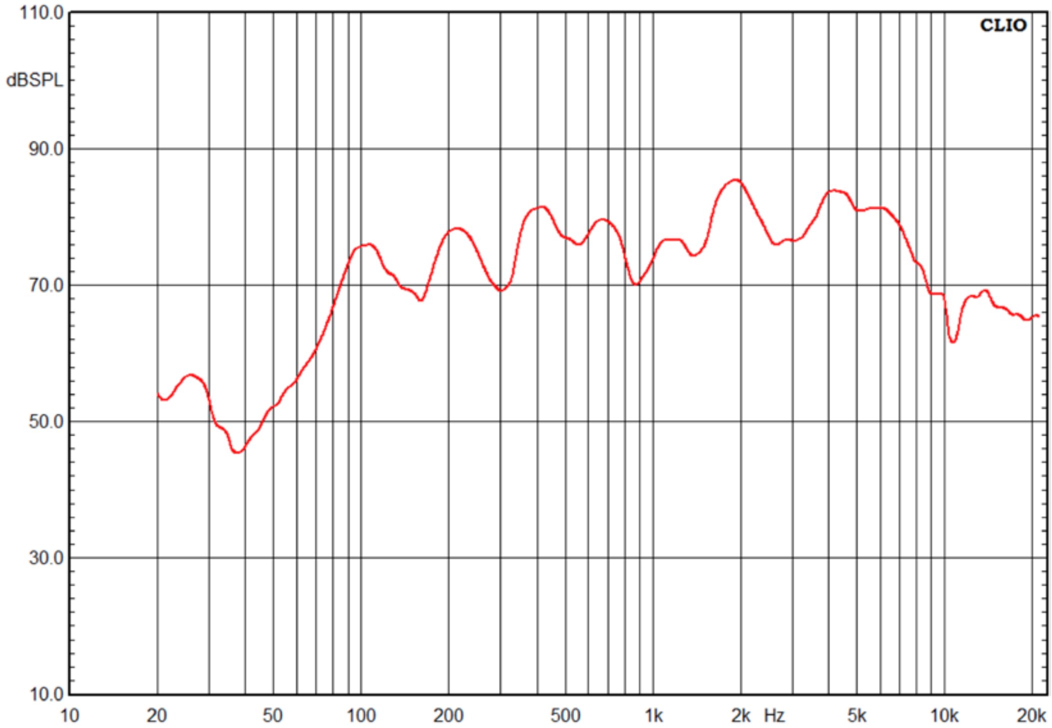


Figure 3.36 Gel-based driver A with external structure 1W 1m Aluminum panel

The test of gel-based driver A in Figure 3.36 using an aluminium panel shows a very flat response between 100 Hz and 10 kHz. This is the flattest response of the entire test programme. Therefore aluminium could be one of the preferred materials with which to use gel-based drivers. Once this test is compared with the reference test on an ABS panel in Figure 3.8, it can be appreciated that the resonance of aluminium is slightly higher and as a consequence, there is no response under 100 Hz. This is the only range where ABS outperforms aluminium.

3.7.2 Gel-based Driver A with External Structure 1 W 25 cm Aluminium Panel

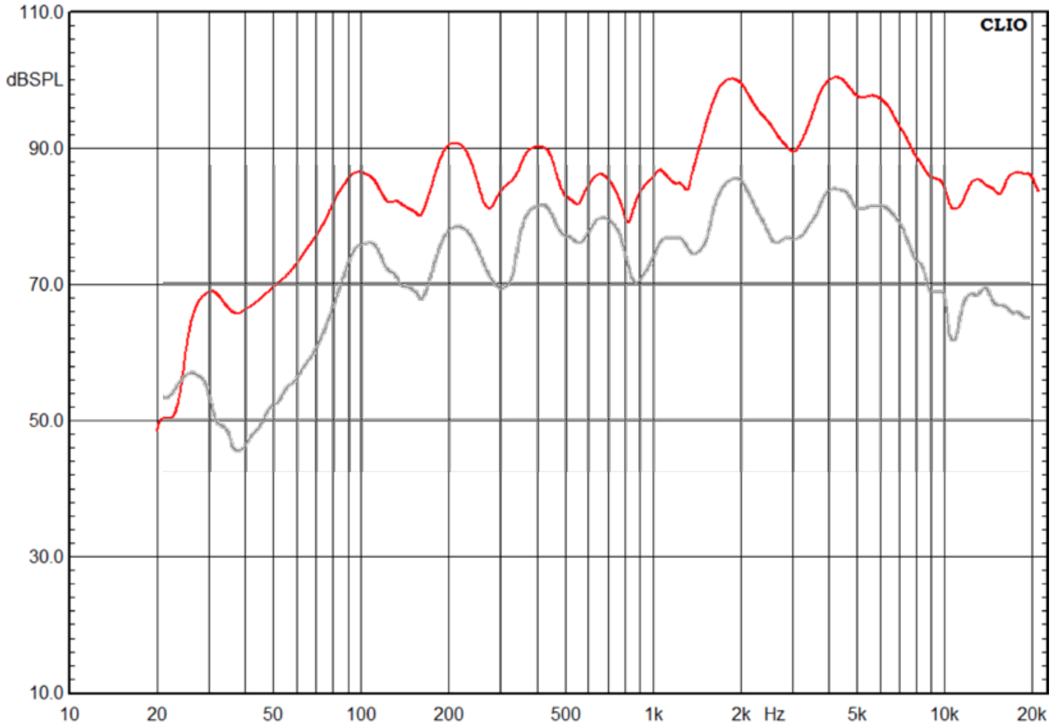


Figure 3.37 Red: Gel-based driver A with external structure 1W 25 cm aluminium panel
Black: Gel-based driver A with external structure 1W 1m aluminium panel

The test of the gel-based driver at 25 cm (Figure 3.37) with aluminium compared with the results at 1m has an expected 12 dB increase in the low frequency range but an unexpected increase in dB sound pressure level above 1.5 kHz - being around 16 dB louder. This frequency range is where the human ear sensibility is higher and will make the perception very loud. The shape of the graph in Figure 3.38 follows the same path as in Figure 3.36 so the distance does not affect the descents.

3.7.3 Gel-based Driver B with External Structure 1 W 1 m Aluminium Panel

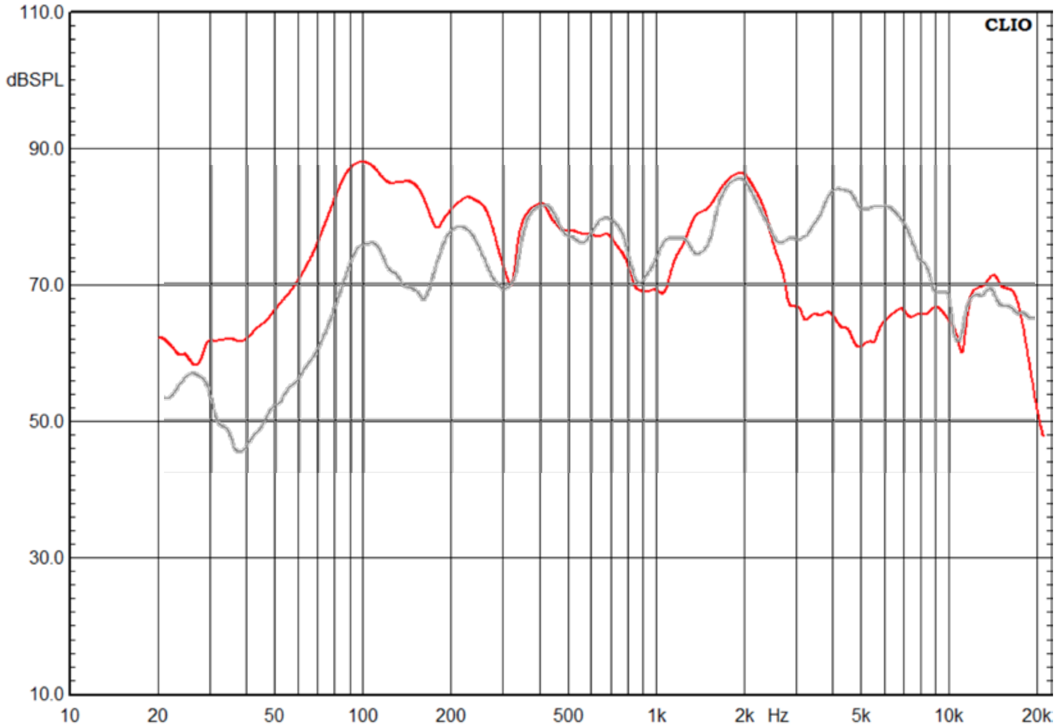


Figure 3.38 Red:Gel-based B with external structure 1W 1m aluminium panel
Black: Gel-based driver A with external structure 1W 1m aluminium panel

Gel-based driver B response has been particularly efficient at the low frequency range. There is a difference of 10 dB sound pressure level below 200 Hz between gel-based drivers A and B. The peak at 90 Hz is the resonance frequency of the system. Once more, this test with aluminium has more bass response than the equivalent one carried out with ABS. Due the nature of the gel-based driver B, the performance above 2 kHz falls significantly.

3.7.4 Gel-based Driver C with External Structure 1 W 1 m Aluminium Panel

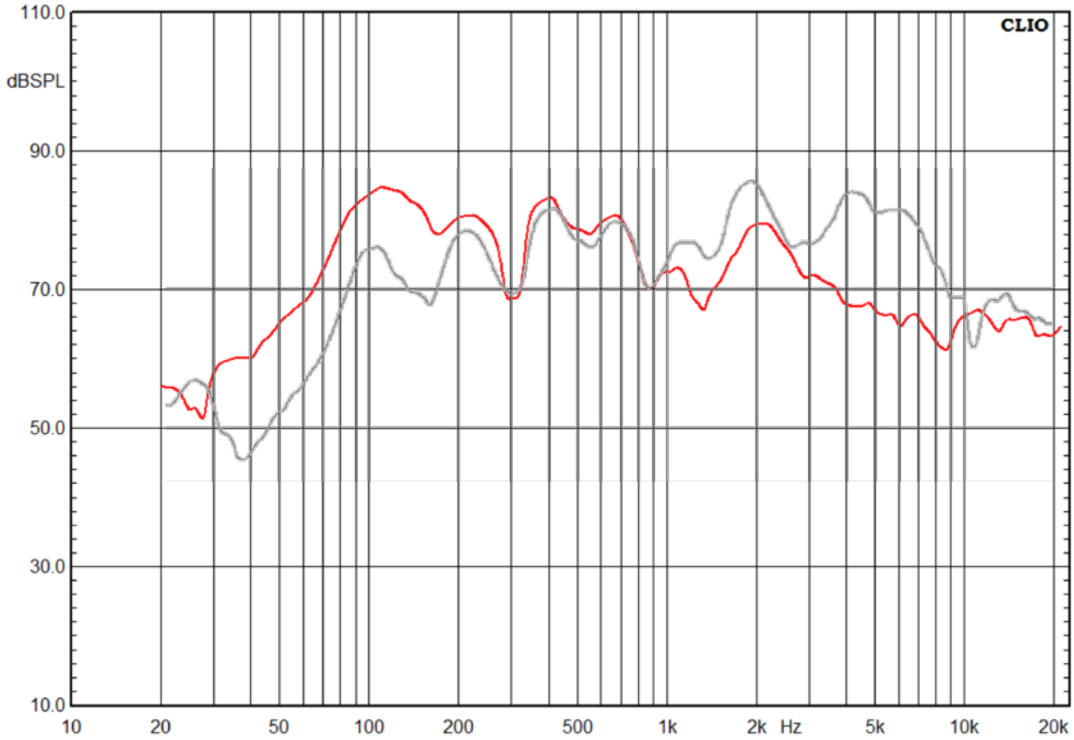


Figure 3.39 Red:Gel-based driver C with external structure 1W 1m aluminium panel
Black: Gel-based driver A with external structure 1W 1m aluminium panel

The test of the gel-based driver C with aluminium is 6 dB louder than the equivalent test using an ABS panel as shown in Figure 3.8. Like the other previous tests on aluminium, the system has its resonance at 100 Hz, where it becomes more efficient. The average performance response is around 84 dB sound pressure level from 100 Hz up to 2 kHz.

3.7.5 Gel-based Driver D with External Structure 1 W 1 m Aluminium Panel

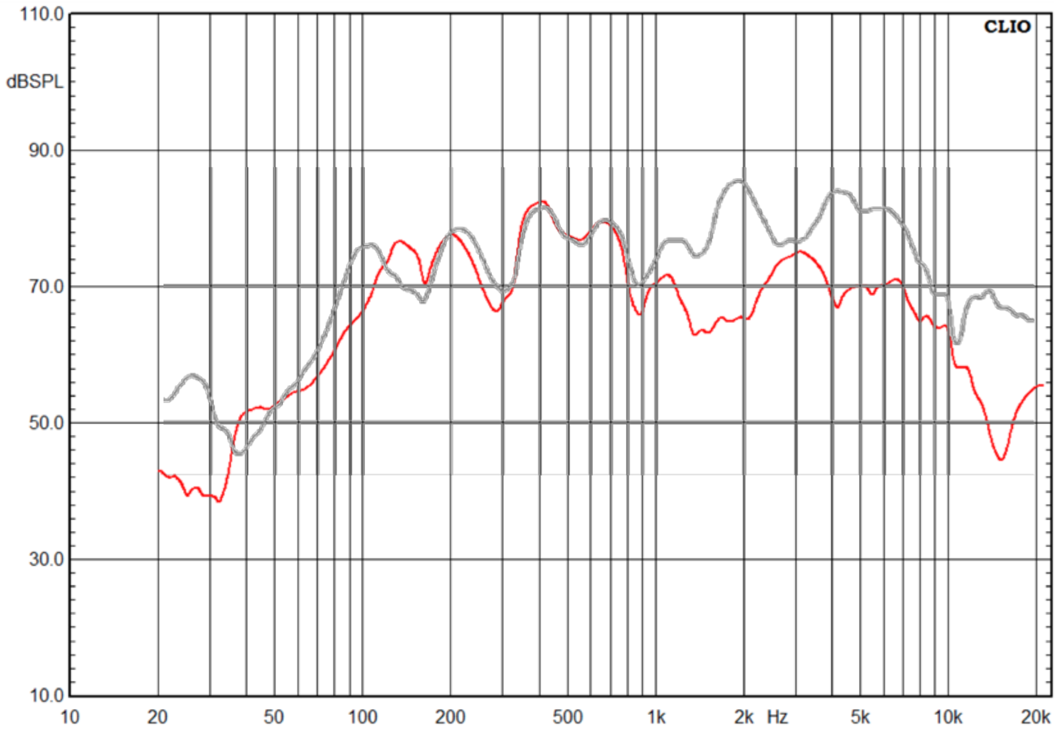


Figure 3.40 Red: Gel-based driver D with external structure 1W 1m aluminium panel
Black: Gel-based driver A with external structure 1W 1m aluminium panel

The gel-based driver D, as with the gel-based driver A, has two resonances - one at 150 - 200 Hz and a greater one at 400 Hz. In this case, the overall performance is quite flat up to 10 kHz, although slightly less efficient than the tests with gel-based drivers C and B. In this test it becomes clear that the driver has not only an effect on the efficiency of the system, but also on its frequency shape. This probably is related to the stiffness of the gel and the weight of the magnet.

3.7.6 Gel-based Driver A with External Structure 1 W 1 m Wood Panel

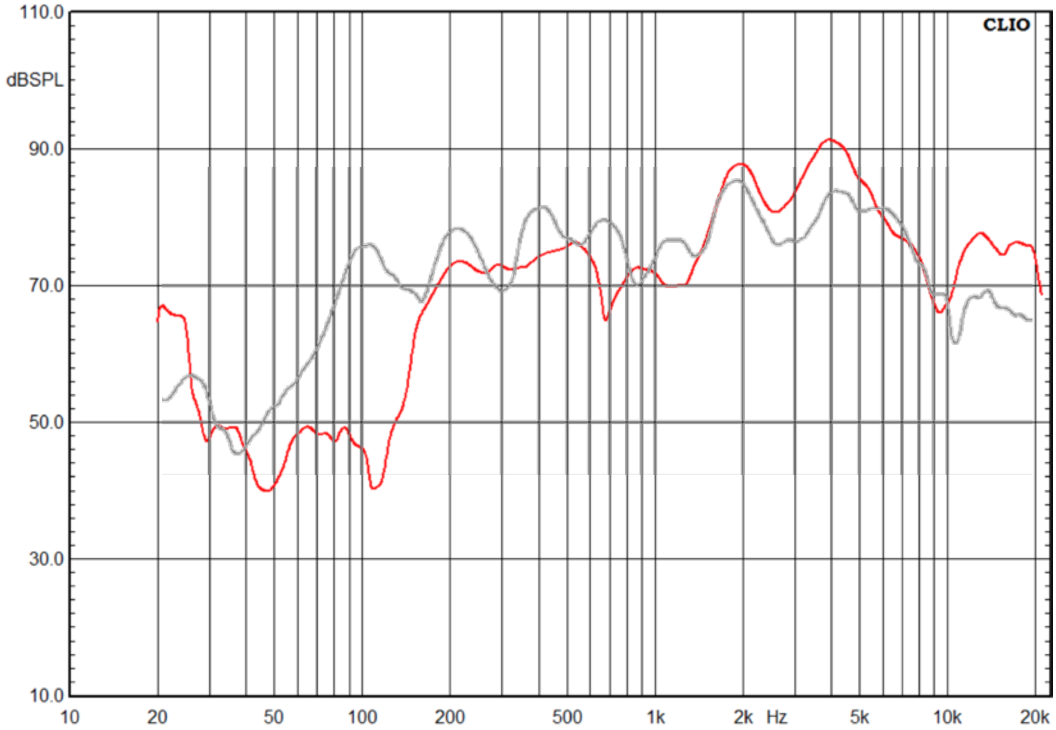


Figure 3.41 Red: Gel-based driver A with external structure 1W 1m wood panel
Black: Gel-based driver A with external structure 1W 1m aluminium panel

The wood reference test with the gel-based driver A, has a resonance at 200Hz but the system starts to perform more efficiently at 2 kHz and up to 5 kHz. This differs from the previous test using aluminium. In this case, the change from aluminium to wood of the panel material has a strong impact on the frequency response of the system in terms of dB sound pressure level and shape of the graph.

3.7.7 Gel-based Driver B with External Structure 1 W 1 m Wood Panel

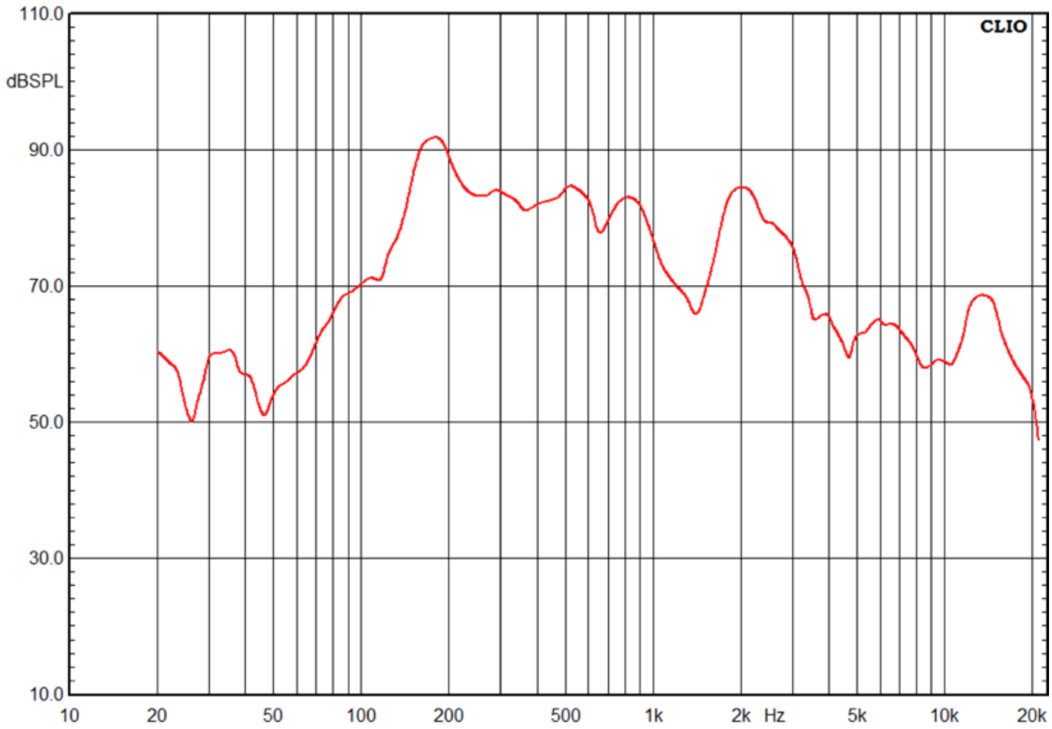


Figure 3.42 Gel-based driver B with external structure 1W 1m wood panel

Previous tests using an ABS panel have illustrated the difference in performance between the softer gel of driver B and the harder gel of driver A with an increase of around 6 – 9 dB on the low frequency range being measured. A similar dB sound pressure level increase effect happens on the wood panel but in this case with a greater magnitude. The results in Figure 3.42 show an increase of around 20 dB compared to Figure 3.41. It needs to be taken into account that that this wood panel resonance is at a higher frequency and this may explain such an extra increase of dB sound pressure level.

3.7.8 Gel-based Driver C with External Structure 1 W 1 m Wood Panel

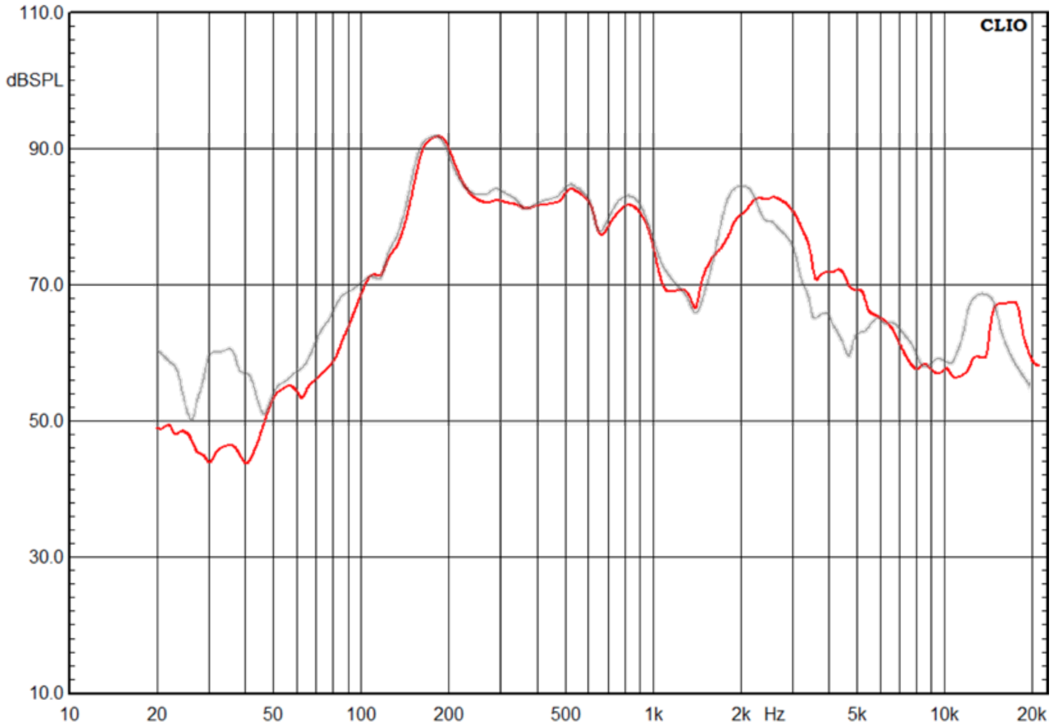


Figure 3.43 Red: Gel-based driver C with external structure 1W 1m wood panel
Black: Gel-based driver B with external structure 1W 1m wood panel

The test of gel-based driver C (Figure 3.43) performed in wood revealed results almost identical to those in Figure 3.42 for gel-based driver B. Both drivers have one important factor in common - the softness of the gel. The drivers have a different structure, different weight, size, etc. Once gel-based drivers C or B are compared with gel-based driver A (Figure 3.41), the differences in performance are substantial at low and high frequencies. Although the gel-based drivers A and B are almost identical in terms of their structure, the significant difference is the softness of the gel used.

3.7.9 Gel-based Driver D with External Structure 1 W 1 m Wood Panel

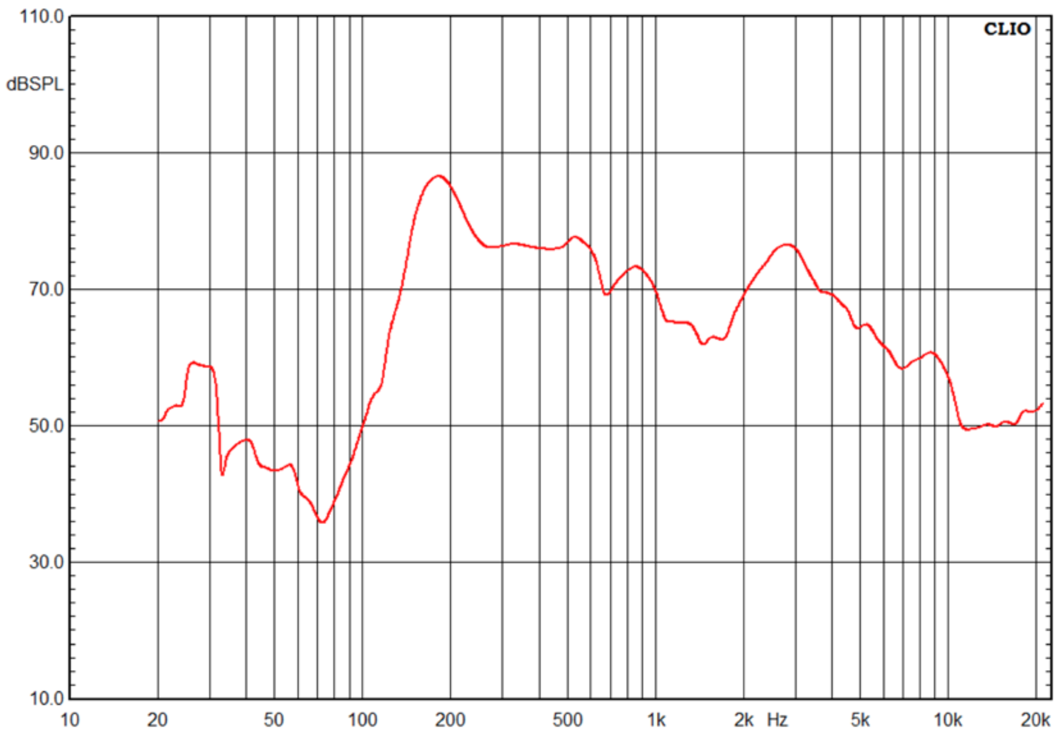


Figure 3.44 Gel-based driver D with external structure 1W 1m wood panel

Gel-based driver D is considerably smaller than gel-based drivers A, B and C. Consequently, its magnetic flux is also smaller and this will explain the 3-5 dB sound pressure level decrease. In terms of performance, there is little difference observed with the wood panel. In particular, the shape and the first resonant frequency of the system is not affected by the gel-based driver type. Once again, the only exception on the frequency for the first resonance is the gel-based driver A - using a harder gel.

3.8 Gel-based Driver C on an ABS Panel using Several Positions

The following section looks at the effects of placing the gel-based driver on different locations on the panel. As in the previous chapter, the tests were carried out in an anechoic chamber – in particular, with an ABS panel at 1 W and 1m. These results will be contrasted in C hapter 7 with laser measurements of the actual movements. Figure 3.45 shows five test positions – note that position 1 has already been tested and the results shown in Figure 3.23.

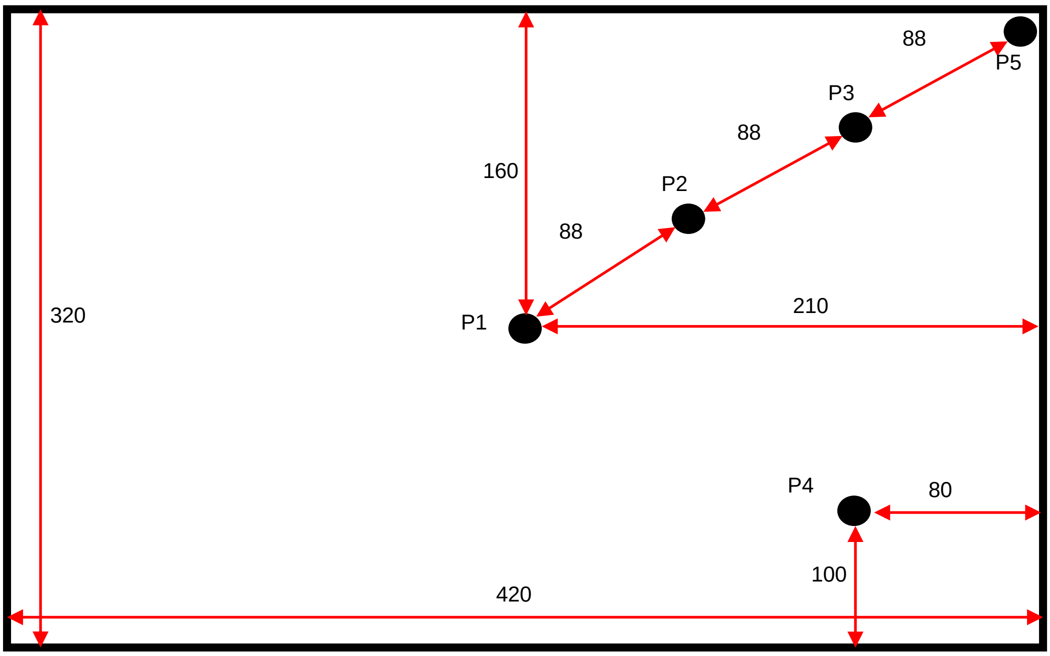


Figure 3.45 Gel driver positions

3.8.1 Gel-based Driver C - Position 2

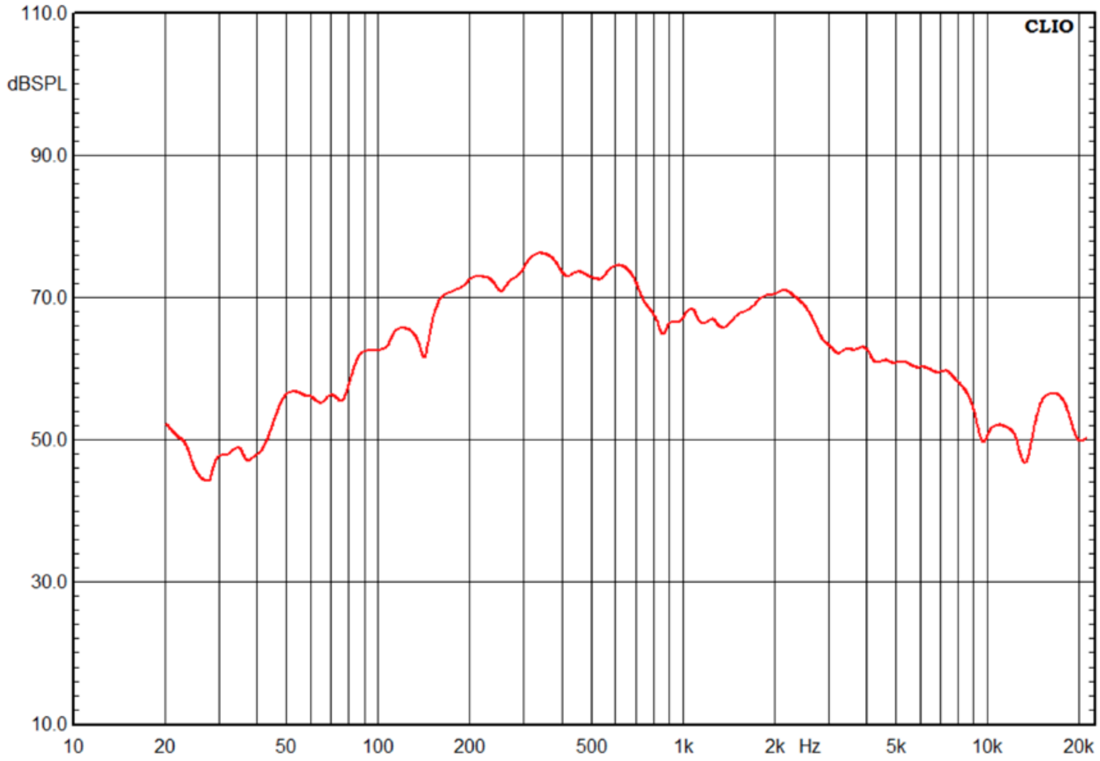


Figure 3.45 Gel driver C Position 2

Position 2 shows a very similar response to position 1 (Figure 3.23) in terms of the shape of the graph, although the position 2 performance average is slightly less efficient - around 3 dB sound pressure level lower. The graph in position 2 is as smooth as position 1 and there are no clear descents of dB within the spectrum. The slight off-centre position of this test does not seem to affect the overall performance.

3.8.2 Gel-based Driver C - Position 3

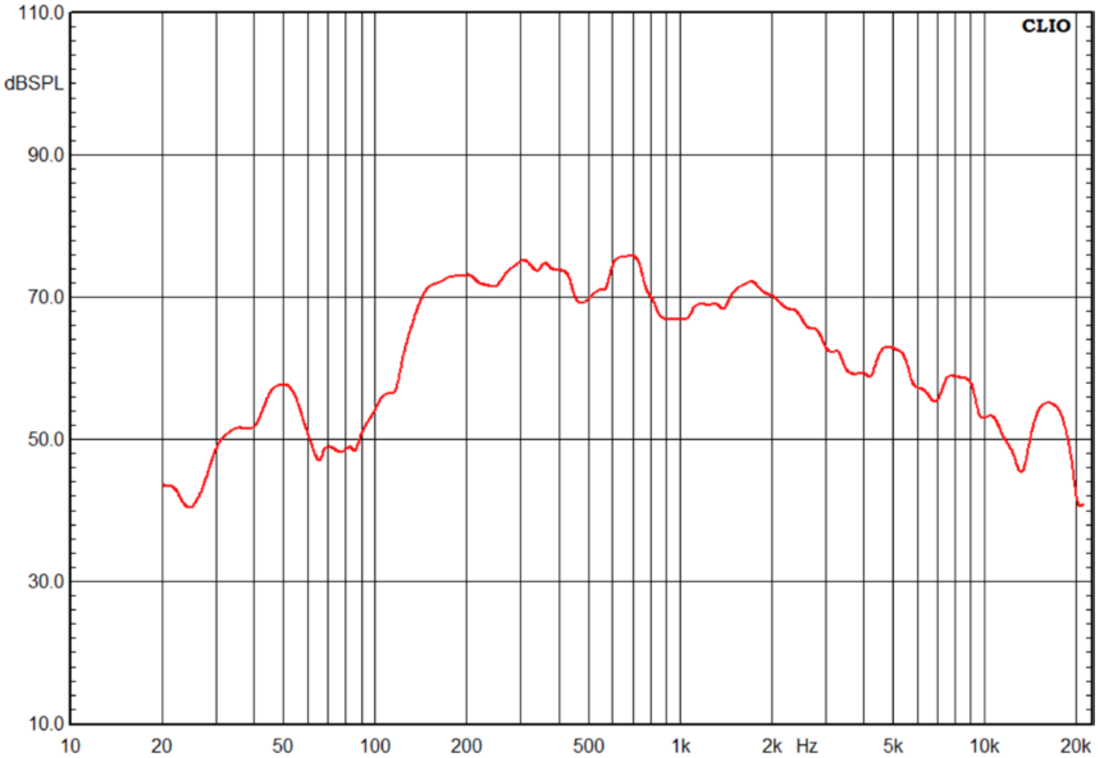


Figure 3.46 Gel driver C Position 3

Position 3 also reveals a similar performance when compared to positions 1 (Figure 3.23) and 2 (Figure 3.45) in the mid and high frequency response. However, below 200 Hz, position 3 is less efficient - it seems that getting the driver closer to the edge of the panel has a bad effect on the low frequency response. This may be due to the position being closer to the boundary of the panel and consequently it will be more difficult to bend - particularly at low frequencies where the greater movement occurs.

3.8.3 Gel-based Driver C - Position 4

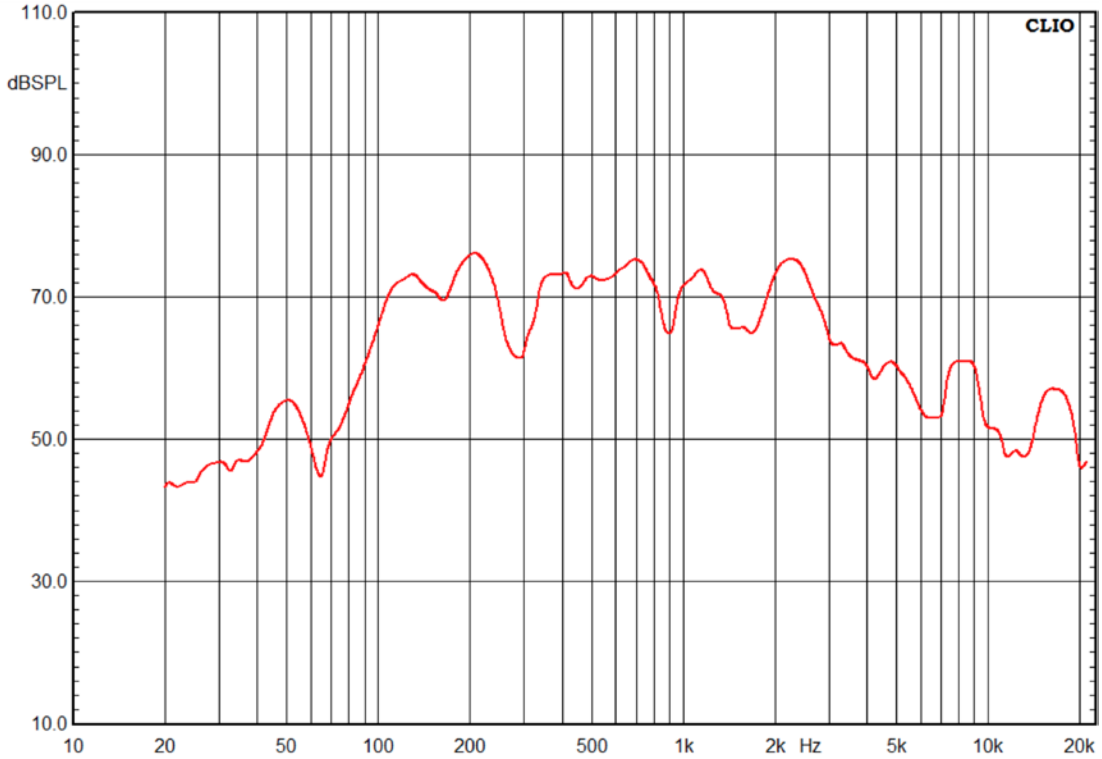


Figure 3.47 Gel driver C Position 4

Position 4 performance is again similar to that of position 1 (Figure 3.23) and 2 (Figure 3.45) - being close to the centre of the panel is probably the reason why its system resonance frequency is almost identical to position 1. In this case the overall performance is slightly more efficient at the high frequency response above 2 kHz.

3.8.4 Gel-based Driver C - Position 5

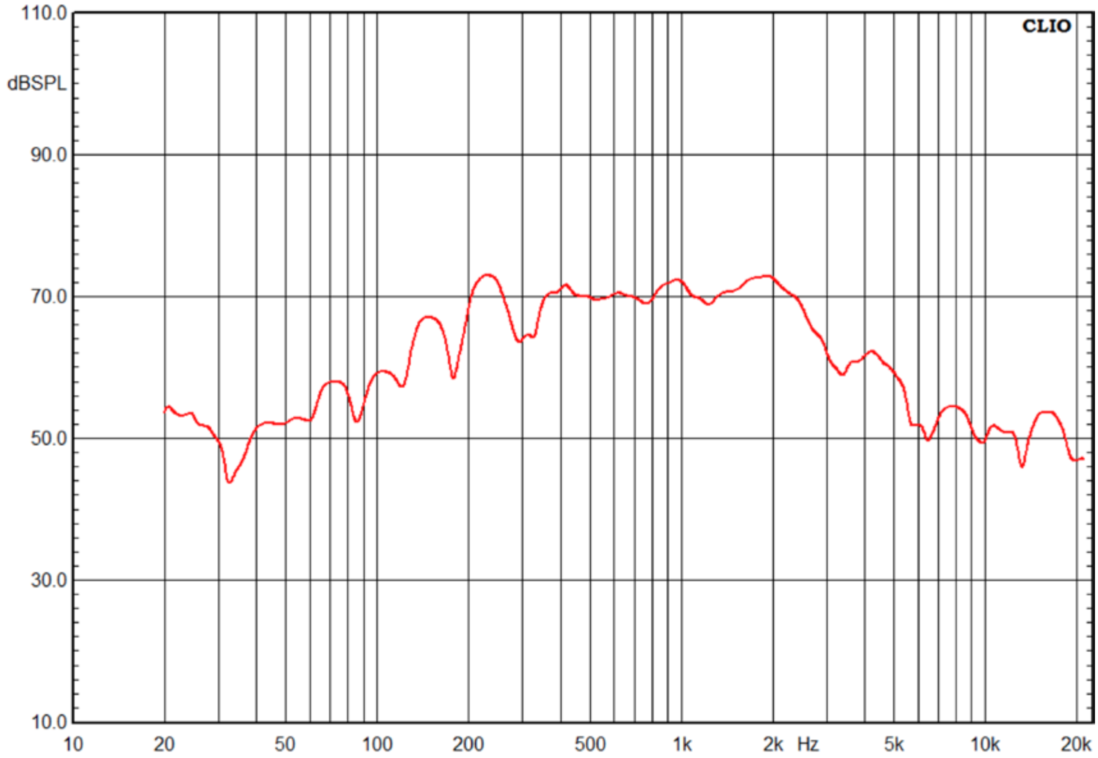


Figure 3.48 Gel driver C Position 5

Position 5 (Figure 3.48) is clearly the least efficient one compared to any of the other positions. The first resonance is at a higher frequency - around 250Hz – and this must be due the driver being at the corner of the panel, very close to the clamping points, and therefore to vibrate the panel, more energy is required - particularly at the low frequencies. In terms of efficiency and wide frequency response, placing the drivers close to the boundaries should be avoided.

3.9 Gel-based Driver Measurements - Conclusions

3.9.1 Power

All drivers have been tested at 1 W and at their rated power, 10 W or 5 W. The conclusion is that overall, the gel-based drivers' performance varies with the power at a similar rate to a traditional driver - an increase of 3dB sound pressure level each time the power is doubled. However, there are some frequencies were the dB increase is higher, in particular at the high frequency range. This suggests that the frequency response shape is related to the power. Therefore this is another factor that needs to be taken into consideration at the driver design stage.

These differences in performance can be due, in some cases, to the gel deformation absorbing most of the energy before it gets to the panel. This effect will be particularly accentuated at high frequencies. Once the power is increased, the driver excursion is higher and the gel gets to a point where it has already been compressed a lot and cannot absorb the vibrations from the driver at the same level. Therefore more vibrations are transferred to the panel. If this is the case the following driver design rule will apply:

To improve high frequency response, the thickness of the gel between the driver and the panel needs to be reduced.

3.9.2 Driver Type

3.9.2.1 Introduction

In Chapter 3, four types of drivers were tested and they were different in terms of size, weight, structure and gel hardness. Therefore, the following section looks at the consequences of those differences.

3.9.2.1 Gel-based Driver Size/Weight

Gel-based drivers A and B are the same size; gel-based driver C is half their size; gel-based driver D is ¼ the size of gel-based driver C. In terms of force (BL), it can be said that, in general, the larger the driver, the larger the magnet and the more metres of wire on its coil. Therefore, it is expected that larger drivers will be more efficient. However, with the gel-based drivers this is not always the case, and the following has been observed:

- The smaller the driver, the higher the first frequency resonance. This rule has some exceptions like the wood panel test and the gel-based driver A.
- The size of the driver does not have much influence on its performance in terms of the panel resonance frequency point.
- There is a relationship between the driver size and the average dB sound pressure level - this is louder if the driver gets bigger.
- Regardless of the driver size, the low frequency responses of all tests have clear dB sound pressure level descents at very similar frequencies.

3.9.2.2 Gel-based Driver Structure

Two types of structure have been tested. The gel-based drivers A and B are cylindrical while drivers C and D are square, and are the second type. Gel-based driver C is half the size of the gel-based driver B however gel-based driver C is more efficient over almost the entire frequency range. Once the structure is analysed, it can be observed than the gel-based driver C has only gel in the corners between the magnet and the drive plate. Gel-based driver B has gel all around between the magnet and the drive plate. Both drivers have gel surrounding them. Having gel on the corners eases the driver movement while still maintaining a good enough level of stiffness and structure to the driver. Therefore the square structure has the following advantages:

- More efficient
- Flatter response
- Square geometry is easy to be implemented into products, such as laptops, TVs, etc. although in terms of manufacturing, the square shape is slightly more expensive.

3.9.2.3 Gel-based Driver Gel Type

This research is based on having gel as the main body of a driver and it is expected that the softness of this gel will have an impact on its frequency response. Still the results show even more substantial changes. Gel-based A and B share the same structure, with the difference that the gel driver B is made of a softer gel. The bass response of the gel-based driver B outperforms - by 15-20 dB – the sound pressure level of gel-based driver A. This of particular interest for consumer electronics applications since these drivers are quite small and having such a high level of bass response is currently not possible with traditional loudspeakers. Gel driver B uses the softest gel available in the market for injection moulders and it would be very interesting to test even softer gels. Gel-based driver A is more efficient at the high frequency response; therefore the following conclusions have been made:

- The hardness of the gel has an impact on the driver frequency response.
- It is expected that the softer gel will be more suitable for large excursion scenarios as per low frequencies, however the softer gel the may not be good enough to keep the alignment of the coil. The results have shown that low hardness gels are more efficient at the low frequency range and still manage to maintain the coil alignment.
- The harder (Shore A 8) gels are more efficient at the high frequency range.

3.9.2.4 Gel Driver Location

The gel-based drivers have been designed to be used within consumer electronic products (Laptops, radios...). Consequently, it will not always be possible to locate these drivers at the centre of the device. Section 3.6 looked at the driver performance when located (i) at the centre, (ii) near the centre and (iii) at the corners. Note that the corner of the panel is where the clamping points were located. The following conclusions were made:

- The performance of the driver is not affected if the driver is located at the centre or near the centre of the panel.
- If the driver is located at a corner, the bass frequency response decreases.

3.9.3 Panel Material

The following section analyses the difference on the system performance due to the panel material with aluminium, ABS and wood having been tested.

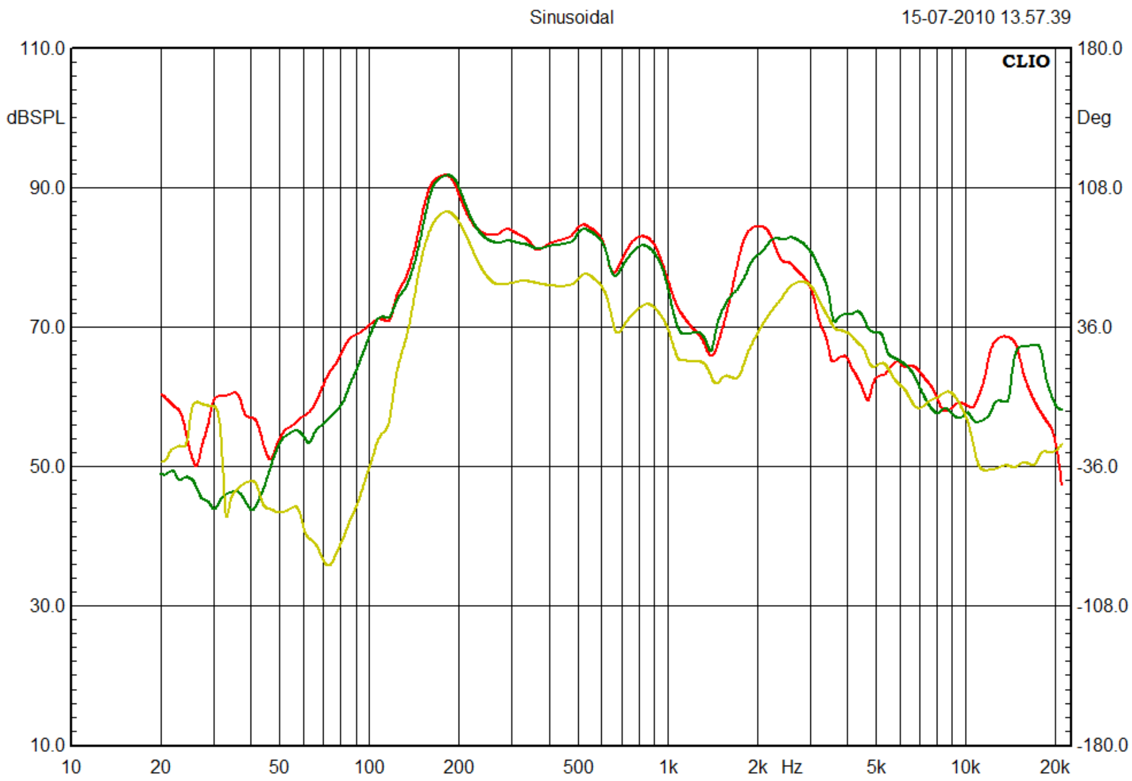


Figure 3.49 Gel-based driver B (red), C (green) and D (yellow) on wood panel

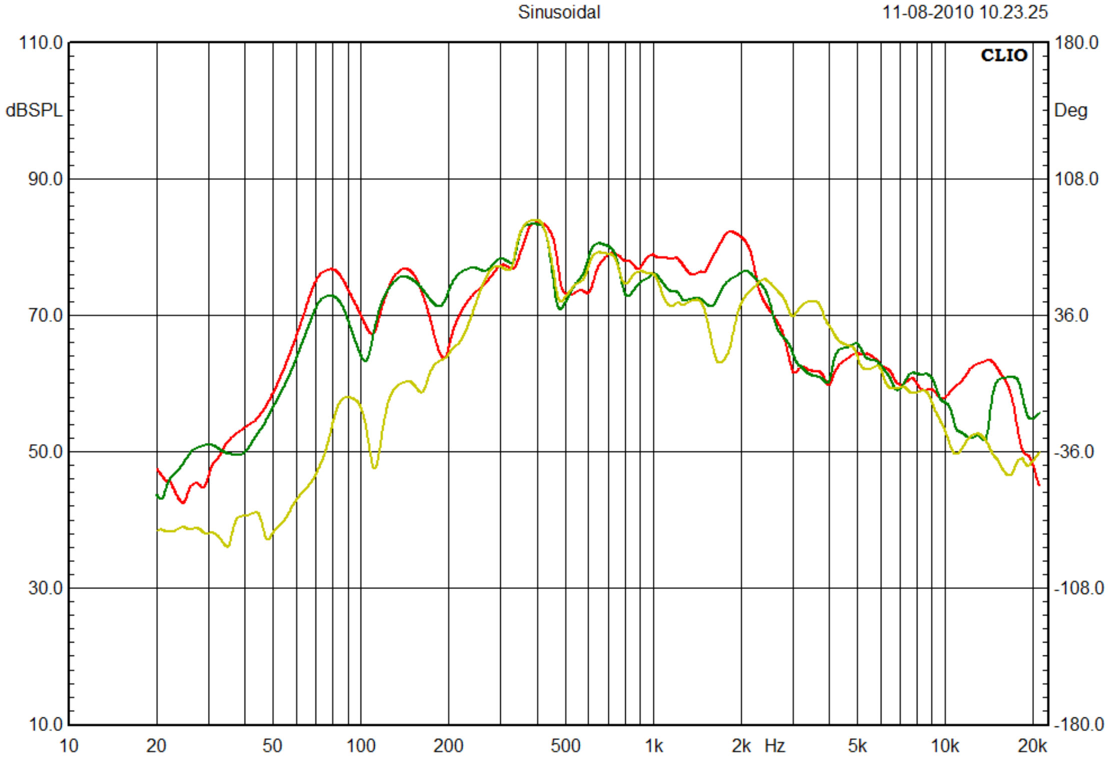


Figure 3.50 Gel-based driver B (red), C (green) and D (yellow) on ABS panel

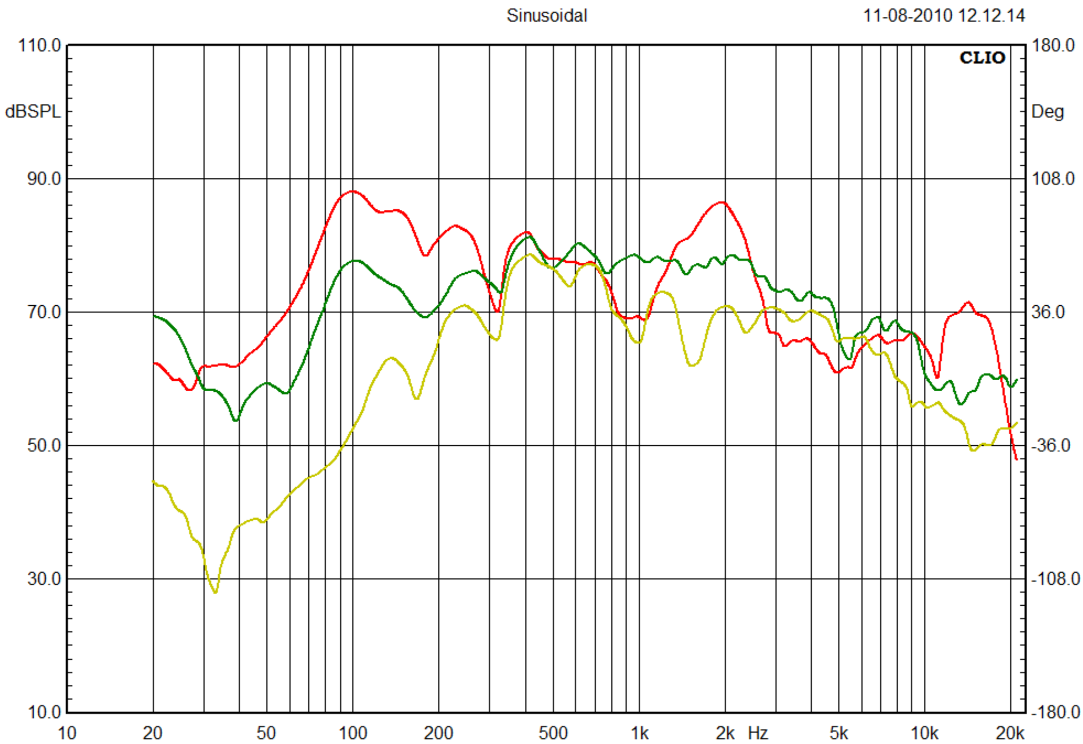


Figure 3.51 Gel-based driver B (red), C (green) and D (yellow) on aluminium panel

The first conclusion is that each panel material will have a direct effect on the system performance.

Figure 3.49 shows that the performance of the driver is very similar regardless of its size with the panel material being the main reason for the peaks and descents of dB sound pressure level. The main difference between the drivers is only on the average dB. In this case it looks that the material is then responsible for the shape of the graph. This contrasts with Figure 3.50 and Figure 3.51 where the performance of each driver was different even with the same panel. This difference in performance between drivers is particularly acute in the low frequency range. Looking at Figures 3.50 and 3.51, it is possible to see that above 400 Hz the three tested drivers have similar performances.

Therefore it is possible to summarize some guidelines to follow for designing a driver to perform in a particular way for a particular panel.

- The performance of the system will be affected by the panel material.
- The driver choice will not affect the performance of the panel at its resonance, and above this resonance the variations will be relatively small.
- The driver choice will affect the system response below the panel resonance frequency at the low frequency range.

Chapter 3 results have given an indication of some parameters that will affect the performance of the system. The panel material has a clear effect on frequencies response above the system resonance. The many drivers tested have shown a greater impact on the frequency response below resonance frequencies. Therefore the panel behaviour should change below and above frequency response. To explore this further the following chapter will look at finite element analysis simulations of the panel and driver.

Chapter 4 Finite Element (FE) Work

The influence of the gel-based driver structure on its performance has been tested and described in Chapter 3. The following chapter looks at the structure, design and optimisation of the gel-based driver using Finite Element Analysis. The main aim of this chapter is to predict the gel-based driver performance and enable changing of the driver design to accommodate particular requirements. This research has been carried out using two software packages: Comsol[21] and Ansys[22].

4.1 Gel-based Driver Simulation

The first stage of the driver design is the modelling of the magnetic circuit and coil characteristics. The magnet coil interaction will give the initial force which will then be transferred to the panel surface through the gel structure.

4.1.1 Electromagnetic Model

All studied gel-based drivers have an asymmetric design; consequently it is possible to use the 2D section of the driver only - 2D sections are quicker for the software to process. The initial step is to extract the force factor BL, the blocked coil impedance and the blocked coil inductance, in order to define the total electrical force as a function of frequency.

Figure 4.1 is the software representation of the time harmonic voltage applied to the voice coil.

$$V = V_0 exp(i\omega t)$$

Figure 4.1

$$F = B\,L\,I$$

Figure 4.2

In the calculation, the F = force, the L = wire length, B = magnetic flux and I = current. Since the coil consists on a number of turns (N) of a cross sectional area (A) the total force will then be represented as:

$$F_{\mathrm{e}} = -I\frac{2\pi N}{A}\int rB_r \mathrm{dA}$$

Figure 4.3

The voice coil current will depend on the applied voltage as per Figure 4.4.

$$I = (V_0 + V_{\mathrm{be}})/Z_{\mathrm{b}},$$

Figure 4.4

Zb is the electric impedance of the voice coil measured while the speaker's moving parts are stationary (blocked electric impedance) and the voltage induced in the coil sue its motion in though the magnetic gap is $-V_{be}$

To calculate the EMF the following parameters are used (Figure 4.5)

$$-V_{\mathrm{be}} = -v\frac{2\pi N}{A}\int rB_r \mathrm{dA}$$

Figure 4.5

$$BL = -\frac{2\pi N}{A}\int rB_r \mathrm{dA}$$

Figure 4.6

The blocked coil current travels through the driver when all of its parts are blocked (or stationary). This value should not significantly change along the frequency response, since there is ideally no motion. The only considerable change should be at high frequencies, when the current decreases - less energy is used for small waves lengths. COMSOL simulation showed results as expected:

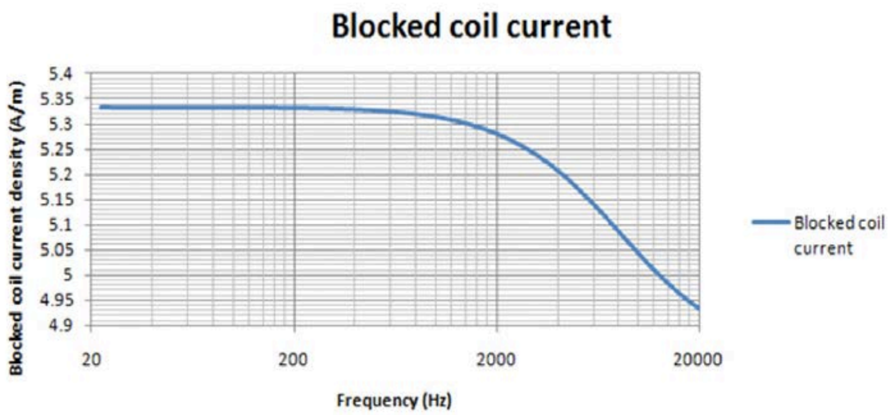
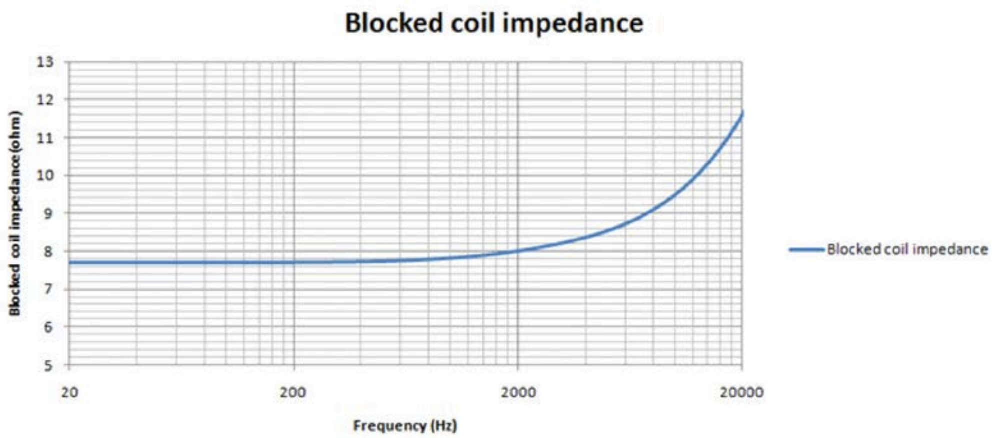
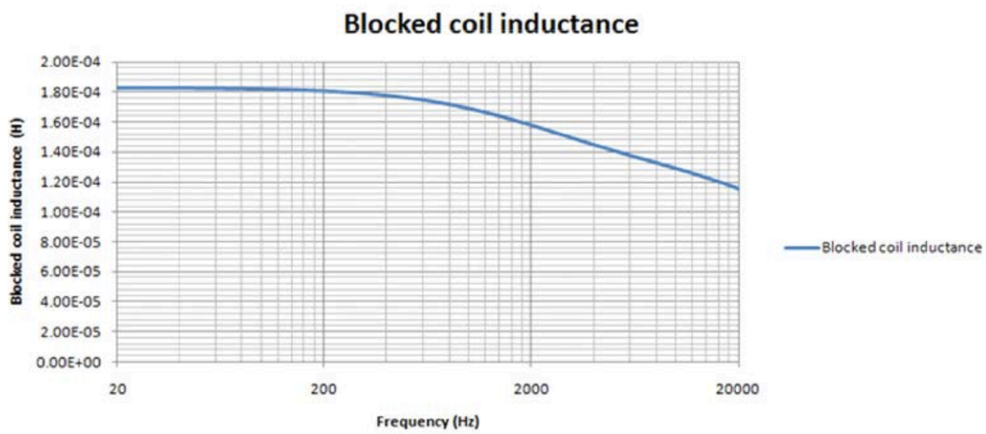


Figure 4.7 Real blocked coil density as function of frequency

Knowing the blocked current and voltage applied (4V peak equivalent to 2.82V RMS), the blocked coil impedance is easily defined as a complex number using Ohms law, and the blocked inductance can be obtained as an imaginary function.





Figures 4.8 and 4.9 Blocked coil impedance and inductance

The blocked coil inductance is the most important value, since it is through the force that is applied to the drive plate through the coil that sound is created. This force is defined as the product of the factor BL (that was already found) and the total current (Fe=BL*I), which is defined as function of the blocked impedance and the velocity of the coil.

The total current can be defined by Ohms law (I=V/Z) but the total voltage is the difference between the initial voltage (4V) and the voltage induced in the coil due to its motion through the magnetic field in the gap. The total current should behave like a harmonic function and changes along the frequency domain as a result of the possible resonances of the driver.

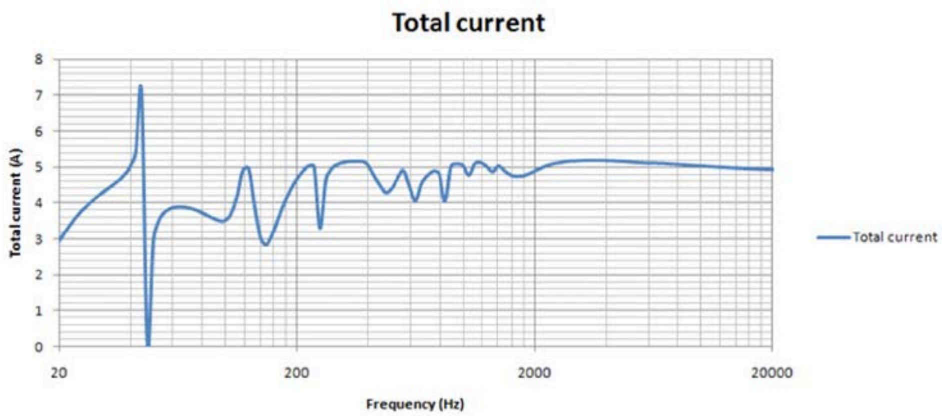


Figure 4.10 Variation of total current with frequency

It is seen that the level of current going through the coil changes considerably across the frequency range. There is a considerable peak at 47Hz, where the driver moves with little current. Above 47 Hz, the current going through the coil oscillates several times, however the variance decreases as the frequency goes up and from 2 KHz and becomes stable at 5 Amps. Having found the current, it is then possible to plot the BL factor and the total force is then obtained:

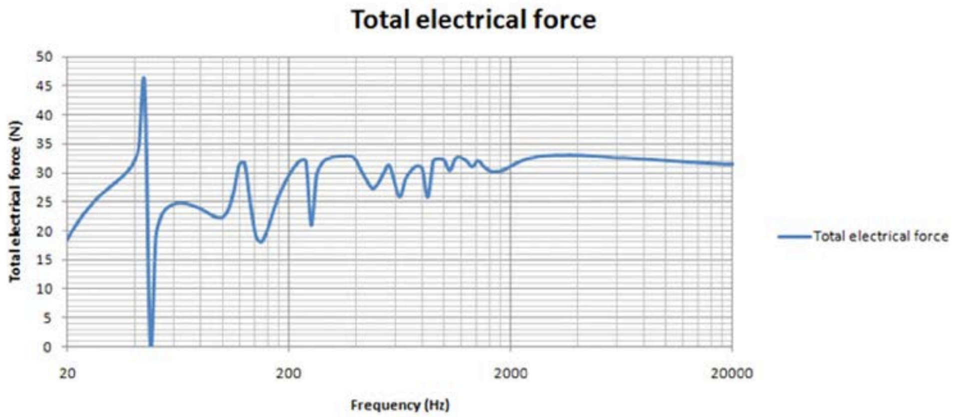


Figure 4.11 Total electrical force aginst frequency

It is clear that different forces are obtained at different frequencies, but as per the previous current graph, the system becomes stable above 2 kHz - the blocked coil impedance behaves as a linear function of frequency – perhaps because small wavelengths are produced.

Simulation Results Introduction

The following Figures (4.12 and 4.13) represent the magnetic flux across the section of the gel bass driver. It is necessary to first introduce the type of material as well as the permeability of each component, the magnet strength and the N and S polar location. Once all the parameters and drawings of the driver have been introduced to Comsol, the simulation is processed and represented. The legend on the right side of the graph symbolizes the Tesla level by colour range. This gives a clear overview of the areas of the gel-based driver where the magnetic flux is stronger. The arrows indicate the direction of the flux given by the N and S location of the poles. If this is reversed, the arrows will rotate 180 degrees.

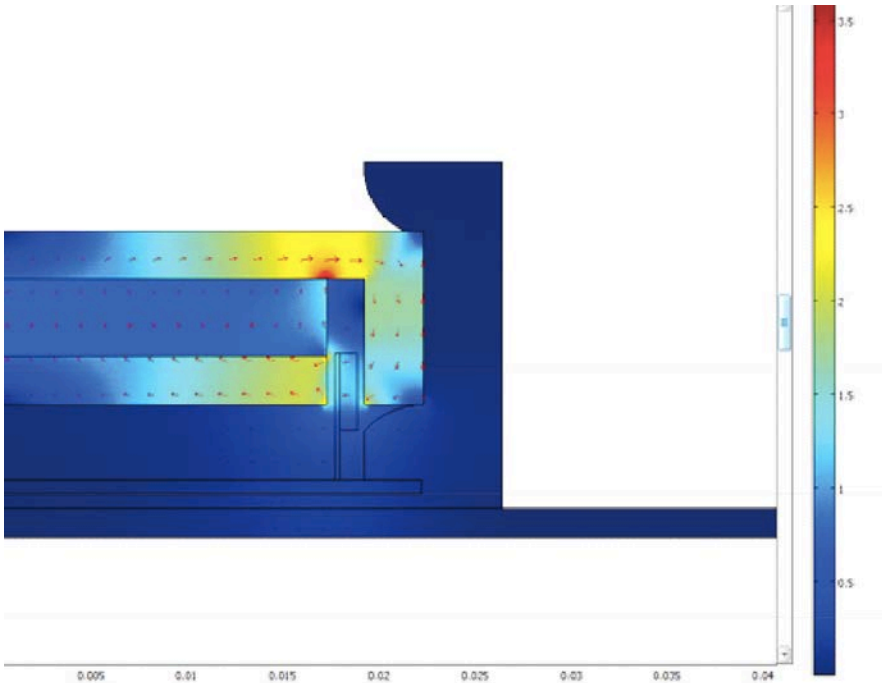


Figure 4.12 Gel-based B Magnetic circuit Comsol simulation

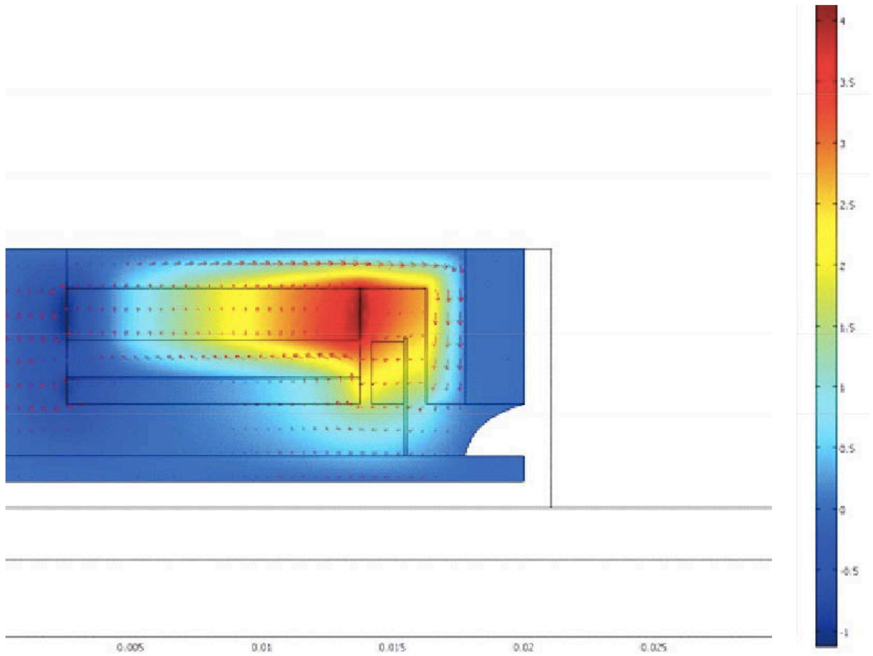


Figure 4.13 Gel-based C Magnetic circuit Comsol simulation

Figure 4.12 shows that the gel-based driver B magnetic circuit has a lower magnetic field value than the gel-based driver C shown in Figure 4.13. Even though gel-based driver B has a larger magnet, gel-based driver C is more efficiently designed. This is due to the optimisation of the magnetic structure design. The gel-based driver C average magnetic field around the coil is 1.7T while the gel-based driver B average magnetic field around the coil is 1.4T. The magnetic flux is perpendicular to the coil, so when a current is running through the coil, the resulting electromagnetic force is applied directly to the drive plate through the former. Notice also, that the maximum magnetic density is in the air gap (red colour) and this makes the circuit effective.

Once the force factor and the magnetic flux is known, the blocked coil impedance and the blocked coil inductance can be found. This is achieved by applying a voltage to the coil, and then obtaining the blocked coil current as a function of frequency. The total force factor, Fe, is just the BL multiplied by the current (at each frequency).

4.1.2 Mechanical Model

When the total electrical force (as a function of frequency) applied to the driver is known, the next step is to find the mechanical consequences on the panel, taking into account material properties such as Young's modulus, Poisson ratio, loss damping factor and density. The reaction force of the magnet is also an important value to take into account.

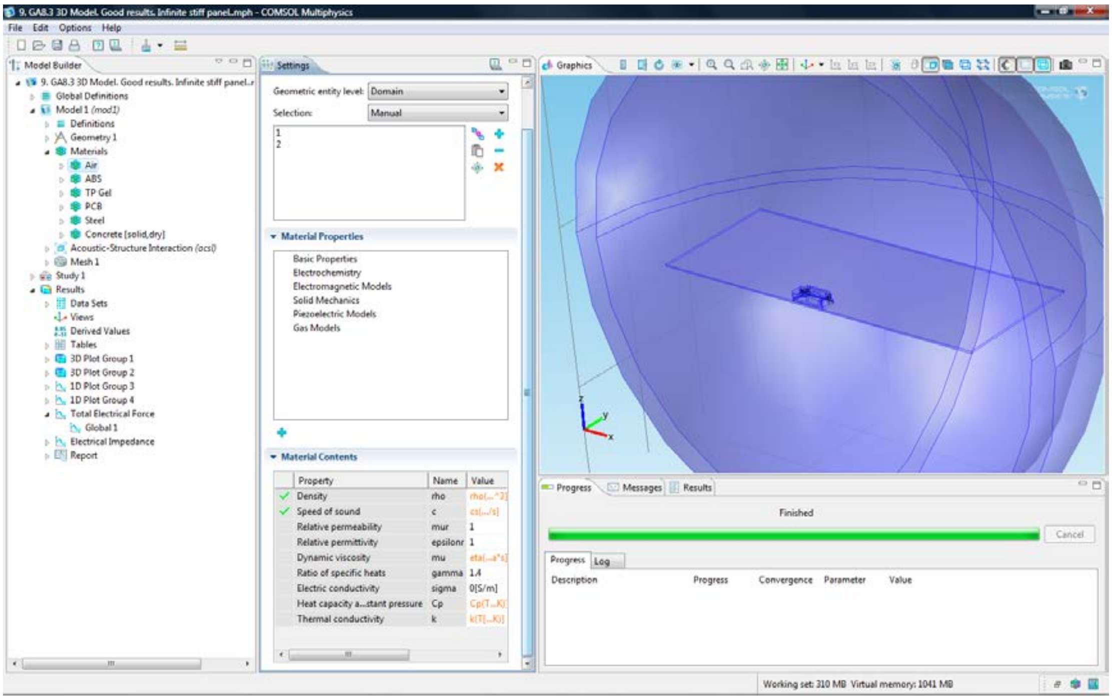


Figure 4.14 Materials parameters screen on Comsol Package

4.1.3 Acoustic Model

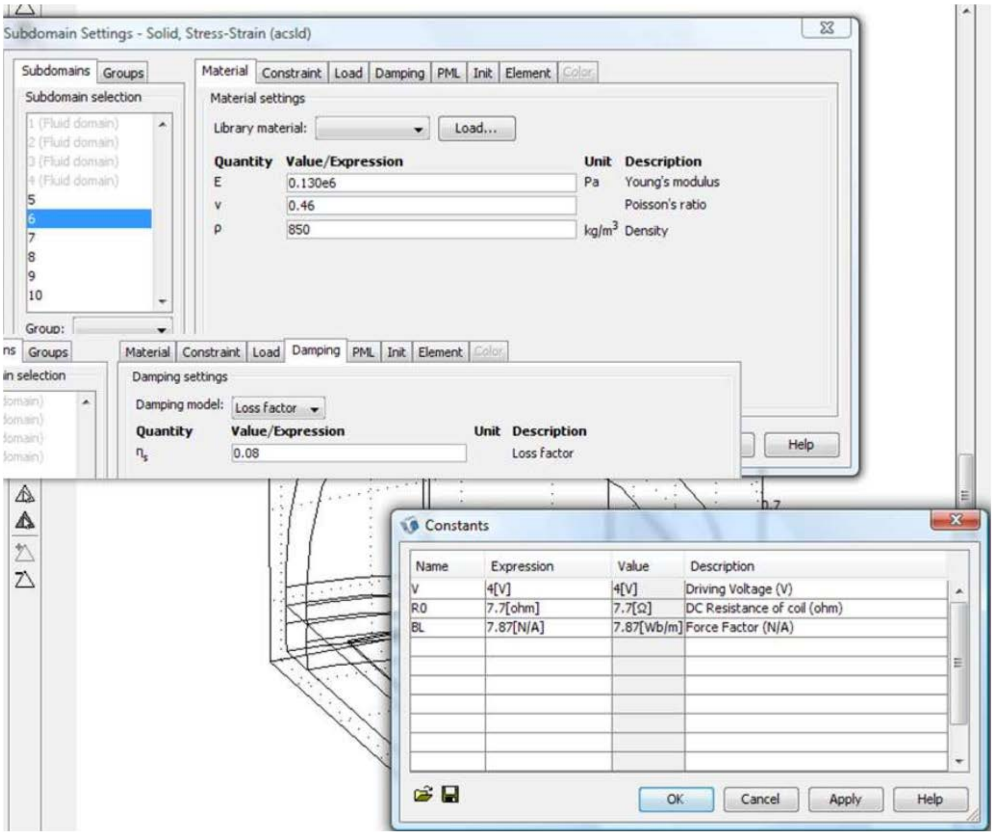


Figure 4.15 Input variables

In addition of the previously defined parameters it has been required to define the density of the air, temperature and boundary conditions. The gel-based driver was positioned on the centre of the panel,

The AC/DC module and Structure - Stress simulation module in Comsol Multiphysics were used to calculate the electrical force as a function of frequency and simulate the dynamic response of the panel. The Acoustic - Structure interaction module was used to simulate the sound pressure level and directivity of the sound radiation at 25 cm from the panel. Frequencies in the range 20 to 20,000 Hz were investigated and the driving voltage was an RMS level of 2.83V which equals 1 W of power on an 8 Ohms driver. The boundary condition along the edge of the panel was fixed.

The final step was to analyse the structural acceleration set-up of the perfect matched layers and obtain the total sound pressure level. The driver was modelled in a circular panel to minimise the processing need and therefore the simulation time.

An initial simulation was carried out to validate the system. A few frequencies were modelled with the intention of having an initial view of the results. The frequencies were chosen to follow octave bands.

COMSOL sound radiation revealed results to be expected. At low frequencies, the directivity factor was omnidirectional, as expected, on rectangular and circular modes of vibration, and as the frequency went up, the directivity became higher, and so the sound pressure level was sharper in the higher frequencies range.

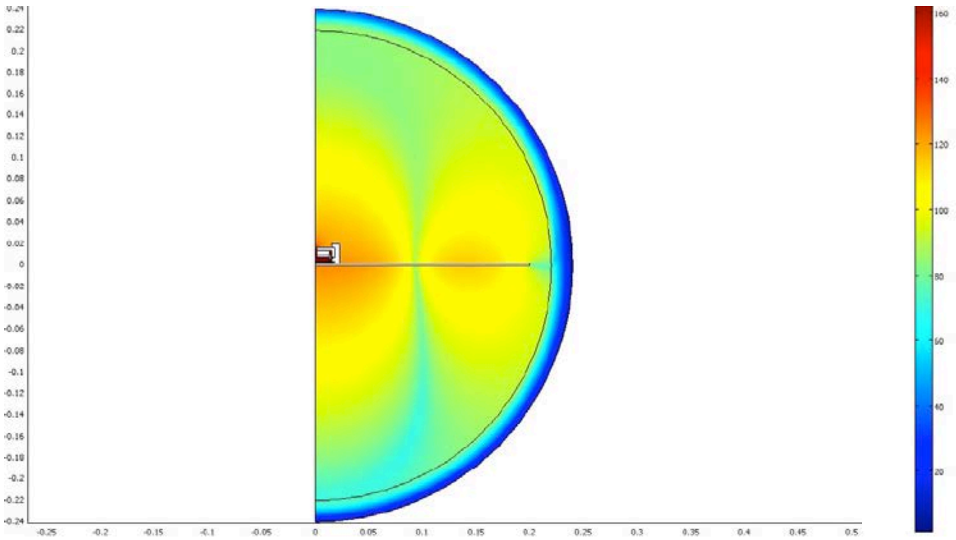


Figure 4.16 2D 25cm Gel-based driver B 100Hz, units dB SPL

Figure 4.16 shows the simulation of the performance in 2D around the gel-based driver at 100 Hz. The distance from the driver to the boundary of the simulation was 25 cm. It is possible to observe that the frequency response is spread evenly and decreased quite linearly with the perpendicular panel distance of the driver. There is one cancellation point between the driver and the edge of the panel, which indicates that a resonance of the system is lower than 100 Hz.

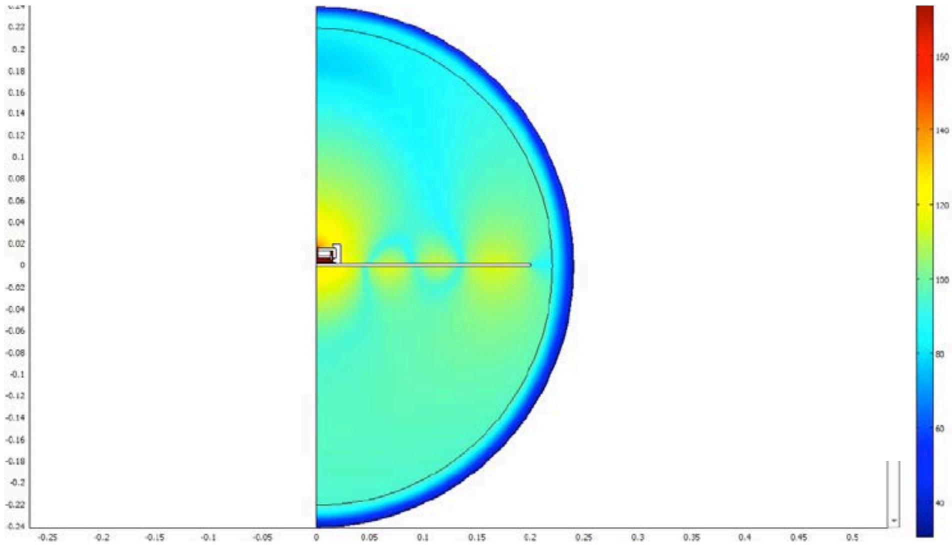


Figure 4.17 2D 25cm Gel-based driver B 334Hz, units dB sound pressure level

Figure 4.17 illustrates behaviour at 334Hz. The yellow areas are where the sound pressure level is higher. There are 4 areas between the driver and the panel edge, which equals three nodes of movement (half panel). Note that the areas with more energy are at the centre where the driver is located and at the panel edge. Both sides of the panel show a similar frequency response.

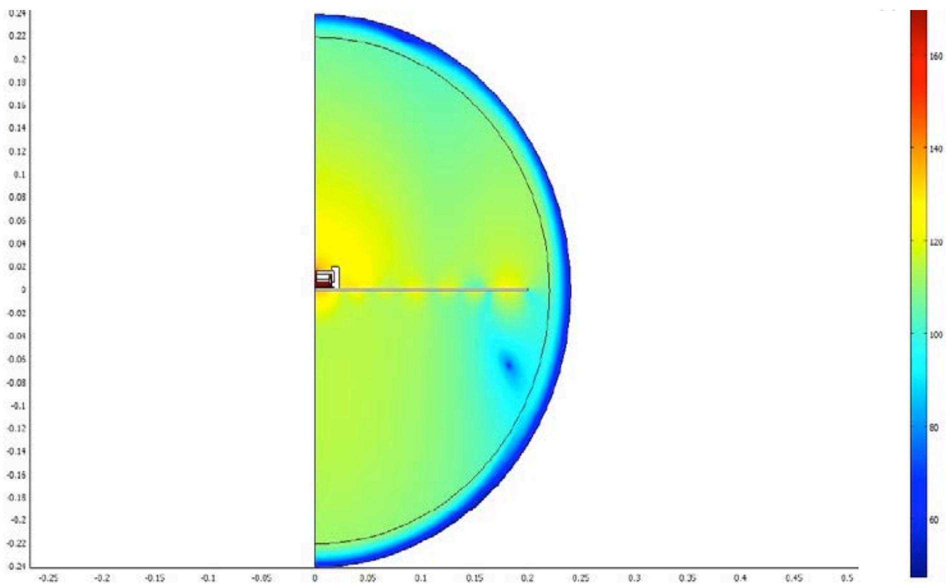


Figure 4.18 2D 25cm Gel-based driver B 1000Hz.units dB SPL

In Figure 4.18 (at 1000 Hz), the nodes are only clear near the panel, but the sound pressure level becomes evenly distributed the further it gets from the panel. Another interesting observation is that the sound pressure level is higher on the side where the driver is positioned. At lower frequencies, the sound pressure level was similar at both sides of the panel.

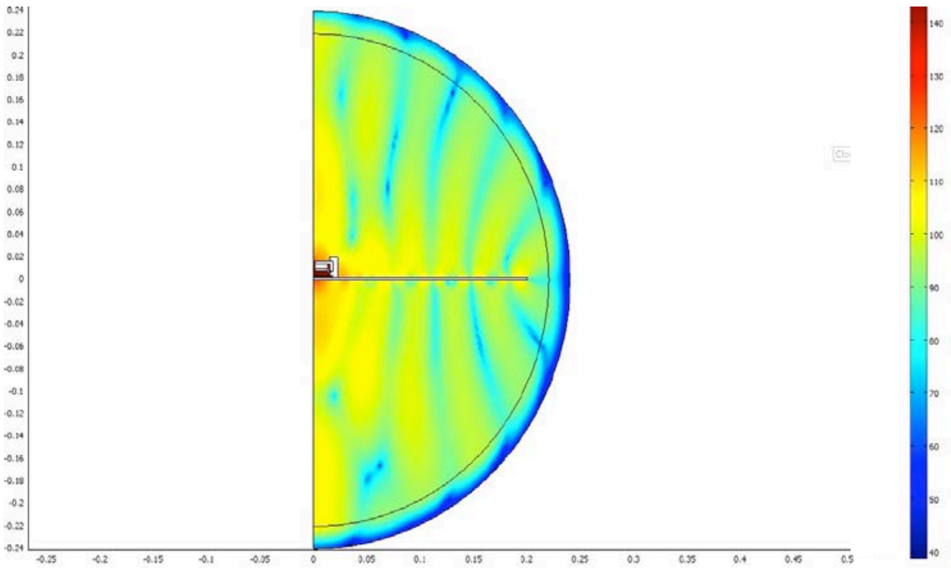


Figure 4.19 2D 25cm Gel-based driver B 5011Hz, units dB SPL

In Figure 4.19 (tested at 5011 Hz), the sound cancellations become much clearer - there is a drop of 25 dB sound pressure level in between the SPL peaks. At 25 cm, it is difficult to identify if the sound becomes evenly distributed as it gets further from the panel, but in any case the difference in dB is certainly less at the boundary of the test dropping to around 10 dB sound pressure level.

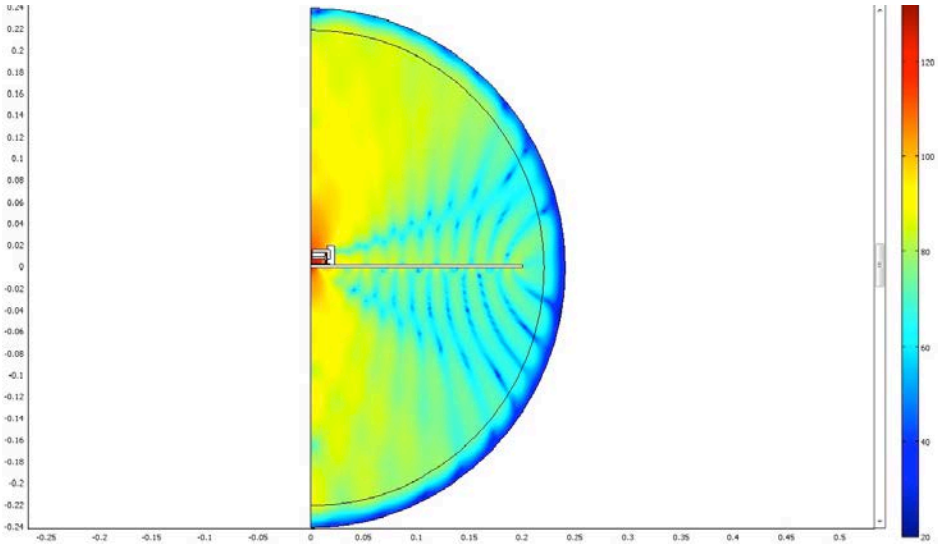


Figure 4.20 2D 25cm Gel-based driver B 10592Hz, units dB SPL

Figure 4.20 illustrates the result at a high frequency (10592 Hz). Here, the sound pressure level cancellations are very close to one another and eventually these cancellations dissipate. At the same time, it is possible to see that there is a clear difference of sound pressure level from the centre to the boundary of the panel. This is greater than 20 dB sound pressure level and is due to another angular cancellation that starts at the driver and moves at around 30 degrees towards the edge of the panel.

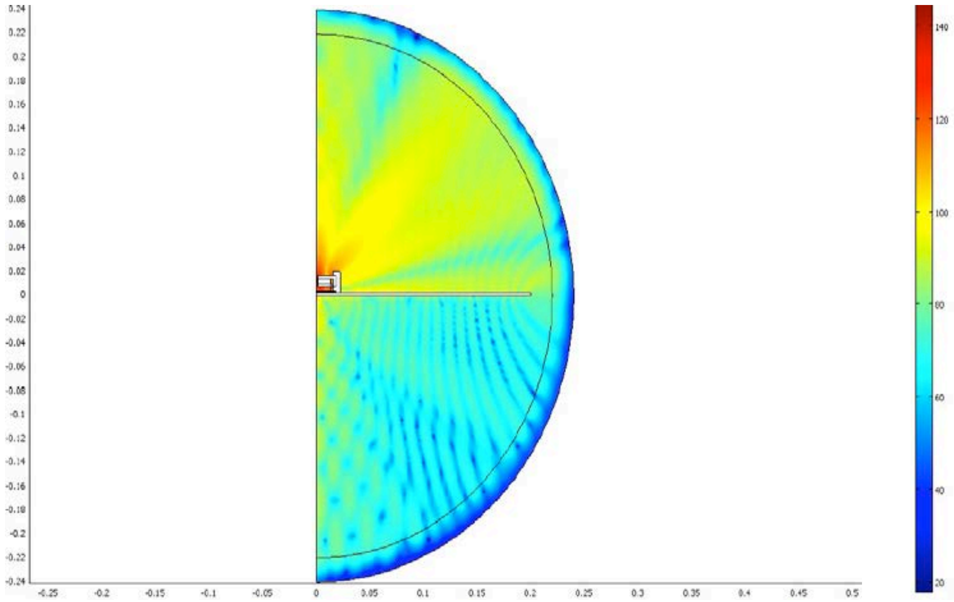


Figure 4.21 2D 25cm Gel-based driver B 16787Hz, units dB SPL

The simulation at 16787 Hz (Figure 4.21) shows, very clearly, the effects of the cancellations. In this case, the centre sound pressure level is clearly greater than that at the boundaries of the panel. This system will be very directional, which is a common feature of loudspeakers at high frequencies. It becomes very clear that most of the sound energy is going through the back of the driver.

4.2 Comparing Simulation Results with Frequency Response Tests

Here, the geometry used for real and simulated tests was kept as similar as possible. The only difference was that the simulated panel had a different shape (circular) so the resonances and modes may be slightly different. The COMSOL simulation results were similar to the reality test at almost all frequencies.

The following results show the real data and the COMSOL simulation when using the thermoplastic elastomer gel properties for gel-based driver B and gel-based driver C:

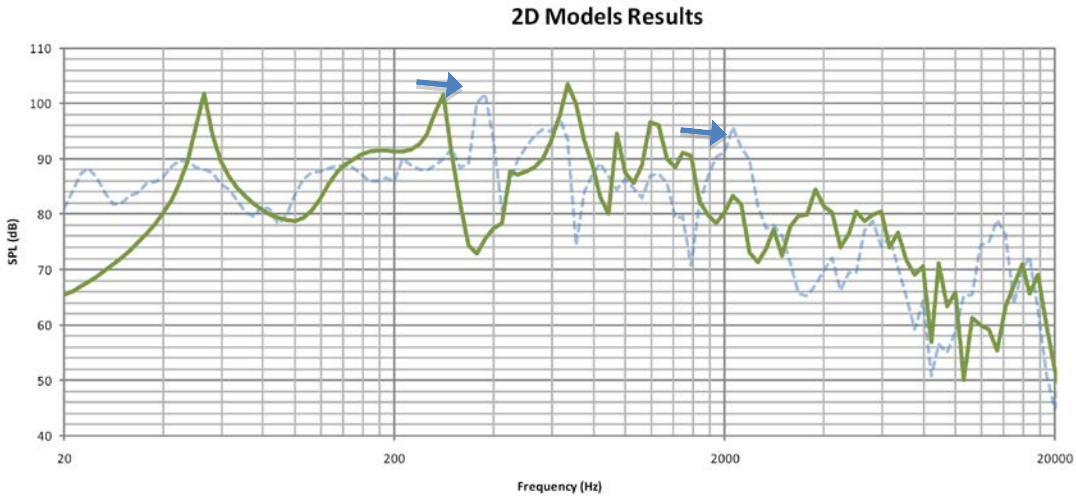


Figure 4.22 Gel-based driver B total sound presure level simulation (green).
Real data measurements at 25cm (blue)

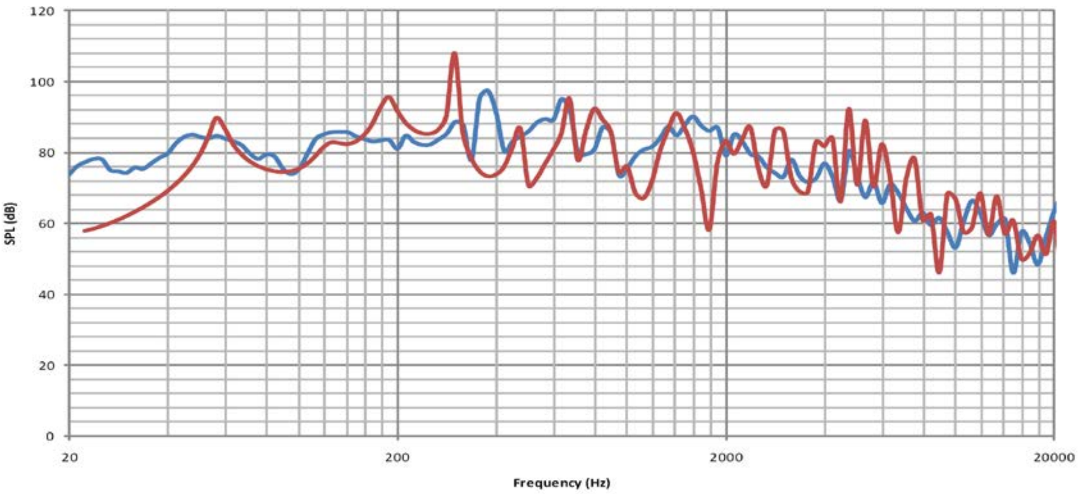


Figure 4.23 Gel-based driver C total sound presure level simulation (Red).
Real data measurements at 25cm (blue)

At low frequencies (below 100 Hz), a considerable difference can be seen - the simulation has an oscillating curve while the real data is almost constant (+/- 5 dB). In this case, the COMSOL results are closer to the measured data since the 80 dB of sound pressure level of the gel-based driver C at those low frequencies is distortion of the system.

An interesting result was obtained when investigating the material properties of the silicone. In reality, the thermoplastic elastomer gel has a better low frequency response than the silicone, because of its softness. The COMSOL simulation showed results as expected:

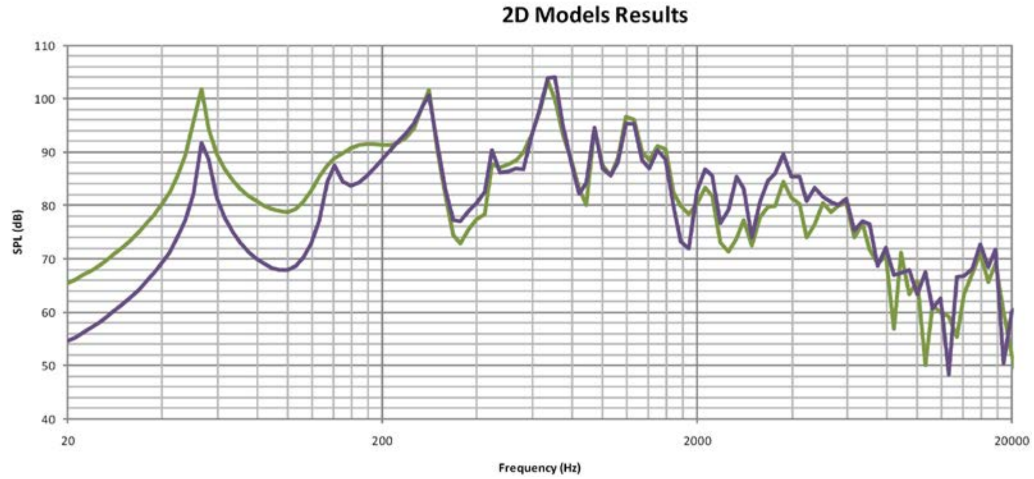


Figure 4.24 Gel-based driver A (purple) with silicone and gel-based driver B (green)

It's clear that the gel-based driver B with the thermoplastic elastomer gel has a more efficient frequency response than the gel-based driver B with silicone. In reality, the average difference between the gels is about 12 dB sound pressure level; in the COMSOL simulation, that difference is about 9 dB.

Another interesting result was obtained when 40V RMS (i.e. 100W @ 8 ohms) was applied to the driver. The results are logical in terms of peaks and general sound pressure level through the frequency range if compared with the early simulations at 2.8V. Note that at 40V RMS, heat will have an impact on performance and this simulation set-up does not take it into account. It is a limitation of the simulation software that is not a problem in previous tests where heat at 2.83V (1W) is low.

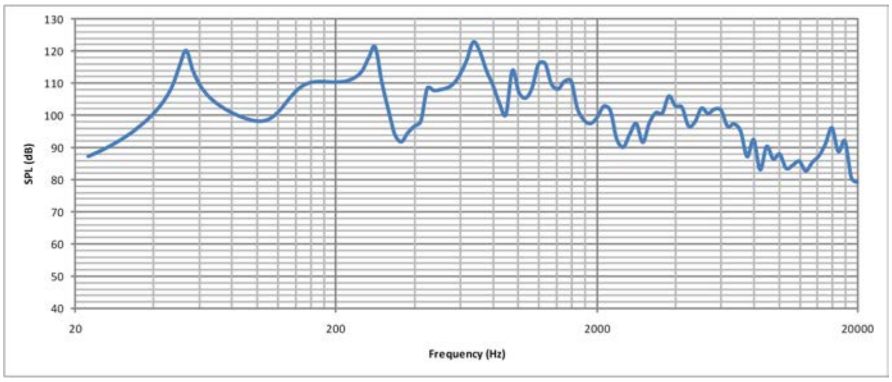


Figure 4.25 Gel-based driver B at 100W

4.3 Finite Element Analysis Conclusions

4.3.1 Introduction

Two different packages have been used to simulate the mechanical behaviour of the gel-based drivers. Although the Ansys package is well known as the standard for FEA, for this research it has only been used to visualize some of the internal movement of the driver. The Ansys package has proven to be quite complex to define and limited in terms of acoustics. The alternative package used, COMSOL, has been extremely useful, and in the author's opinion better suited for this type of research. Future work on gel-based drivers is likely to be carried out using the COMSOL package.

4.3.2 Acoustic Model

Using the COMSOL package, it has been possible to visualize how the sound waves are distributed around the panel. The following has been observed:

- The simulation package has proved to be quite accurate when contrasted with real measurement - in particular the overall shapes and levels of the graphs.
- At low frequencies, the system performance is the same on both sides of the panel.
- At high frequencies, there is much more dB sound pressure level on the driver side of the panel.
- The nodes of the panel vibrations can be visualized clearly at high frequencies and their consequent cancellations. These nodes correspond to descents of dB sound pressure level.
- The acoustic model is particularly useful to see how the sound propagates around the panel and enables a much more precise visualisation of its polar distribution in both sides of the panel. Section 3 measurements had the limitation of all

measurements being made in front of the panel, with no angle, and only at 25 and 100 cm.

- The good correlation of the acoustic model provides the opportunity to visualise the gel-based driver's performance without the need for building prototypes. This will reduce considerably the timescales and cost of the future development of gel-based drivers.

Chapter 5 Laser Doppler Vibrometer Measurements

5.1 Introduction

A laser Doppler vibrometer (LDV) is used to make non-contact vibration measurements of a surface. The laser beam from the LDV is directed at the surface of interest, and the vibration amplitude and frequency are extracted from the Doppler shift of the laser beam frequency due to the motion of the surface. The output of an LDV is a continuous analogue voltage that is directly proportional to the target velocity component along the direction of the laser beam.

Some advantages of an LDV over similar measurement devices - such as an accelerometer - are that the LDV can be directed at targets that are difficult to access, or that may be too small or too hot to attach a physical transducer. Also, the LDV makes the vibration measurement without mass-loading the target, which is especially important to ensure that the measurements did not affect the panel performance. The beam from the laser, which has a frequency fo, is divided into a reference beam and a test beam with a beam splitter. The test beam then passes through the Bragg cell, which adds a frequency shift fb. This frequency shifted beam then is directed to the target. The motion of the target adds a Doppler shift to the beam given by fd = 2*v(t)*cos(α)/λ, where v(t) is the velocity of the target as a function of time, α is the angle between the laser beam and the velocity vector, and λ is the wavelength of the light.

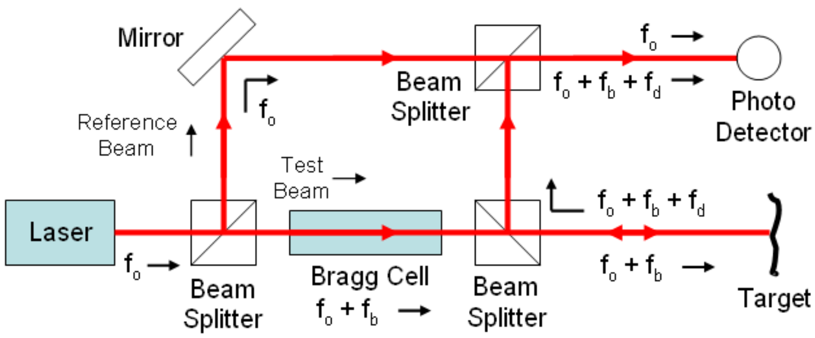


Figure 5.1 Laser Vibrometer

5.2 Equipment Used

Polytec PSV-400 Scanning Vibrometer[34]

The PSV-400 Scanning Vibrometer comprises both hardware and software. It includes a compact sensor head with an integrated scanning unit, a vibrometer controller and a data acquisition and management system. These components are complimented by software that controls the scanners, data processing, and visualization of the measurement results.

Carrying Out a Measurement from Start to Finish

To setup the system, the panel geometry is first defined. It is then scanned by several points that follow a virtual grid across the surface of the panel and distance is measured. The vibrometer automatically moves to each point on the scan grid, measures the response and validates the measurement by checking the signal-to-noise. When the scan is complete, several frequencies are chosen and then displayed and animated the deflection shape in 2-D and 3-D. presentation modes. These on-screen displays are extremely effective tools for understanding the details of the panel vibration.

The measurements have been carried out with a gel-based driver C on a 420x320x2 mm ABS and a 420x320x2mm wood panel using 1 W of power. The distance of the measurement is not relevant, since this is being chosen just to accommodate the optics presents at the moment of the measurement. For comparison purposes, the laser measurements will be contrasted with the sound pressure level measurements at 1 m.

5.3.1 ABS Panel Movement Measurements

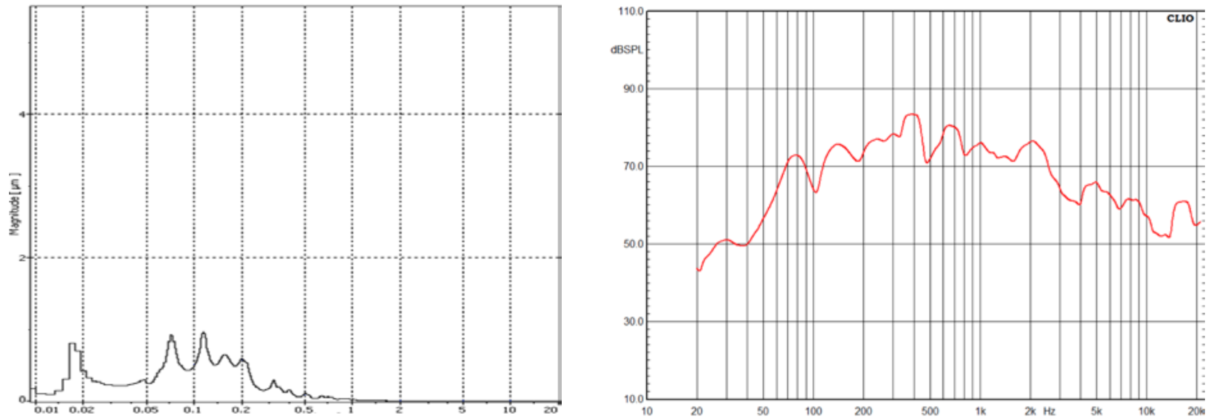


Figure 5.2. Left Displacement vs. Frequency (KHz) of Gel-based driver C Micro millimeters, Right Gel driver C test at 1W 1 m

Figure 5.2 shows the real values of panel movement - in this case, the maximum movement of the panel. It becomes clear that there is not a direct relationship between the panel movement and the sound pressure level measured on the right.

The higher movements occur in the low frequency range. This is expected, since the lower the frequency, the higher the movement, although because of the resonance of the system, this does not happen linearly, and the maximum movement appears at 120 Hz. Note that above 1 kHz, the movement of the panel reduces notably. To illustrate the high frequencies, the following graphs show them on a higher scale and enable the visualization of the panel behaviour.

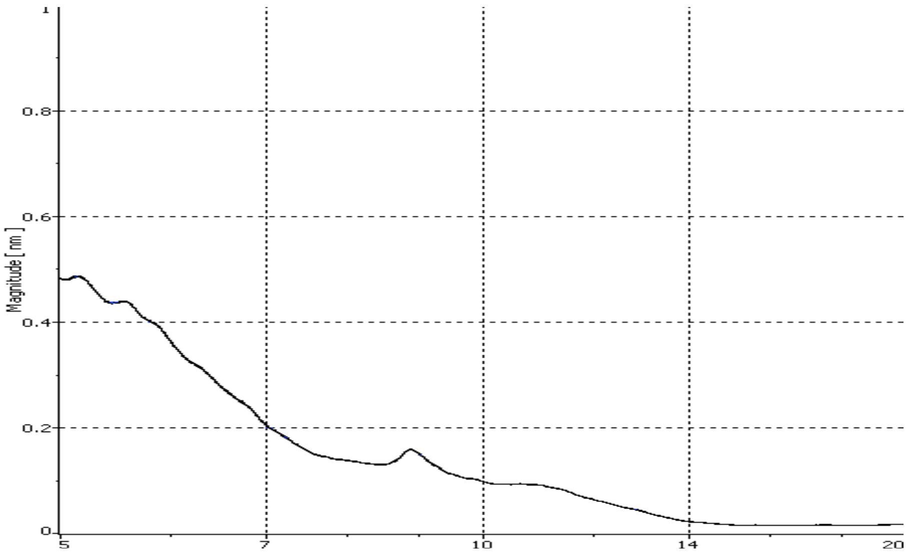


Figure 5.3 High frequency displacement of Gel-based driver C

Note the Figure 5.3 graph scale is in nm. The graph shows, as expected, a decrease of panel movement at higher frequencies.

5.4 ABS Panel Acceleration

According to Rayleigh Integral and the general wave equation, the velocity is proportional to the sound pressure level, so the acceleration vs. frequency graph should be taken into account:

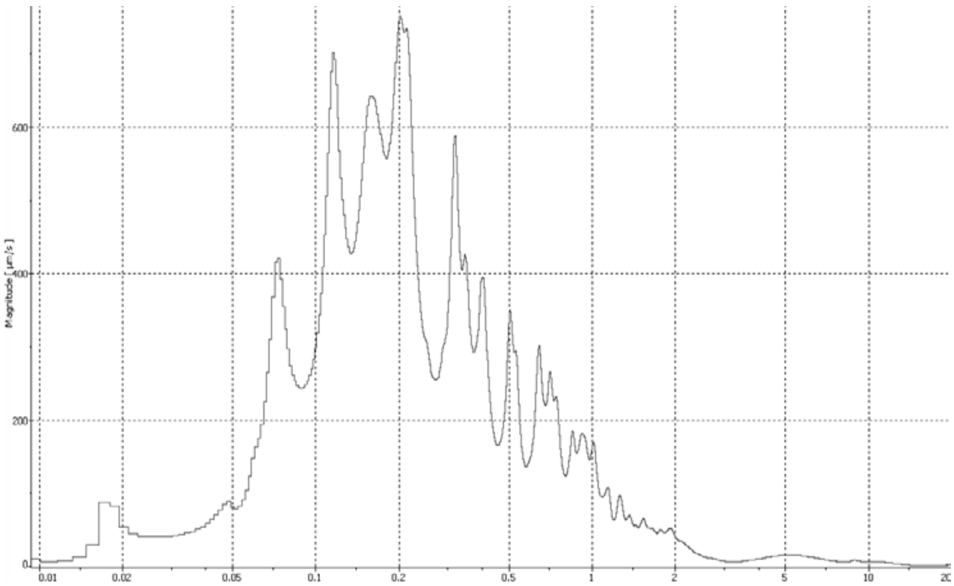


Figure 5.4. Velocity vs. Frequency of Gel-based driver C

Figure 5.4 illustrates the panel acceleration versus frequency. When compared with sound pressure level measurements as per Figure 3.24, the results are similar. At 100 Hz there is the fundamental frequency, and this is equally visible at the measured sound pressure level test. Between 200 and 2 kHz, both tests show high levels, in this case of acceleration, and on the other of sound pressure level. Above 2 kHz there is a clear drop in the acceleration - the same drop can be seen on the sound pressure level test, although this is at a slightly higher frequency. This may be due to some phase or cancellation measured by the microphone.

5.5 Behaviour of Gel-based Driver C in Several Positions

This section looks at the effects, in terms of movement and velocity, on the positioning of the gel-based driver at several points on the panel. The positions of the drivers have already been defined and illustrated (Figure 3.46) and in Section 3.6, it was clear that the position of the driver did not have a great effect on the overall system performance, the exception being if the driver was placed near the corners, where the clamping points were located.

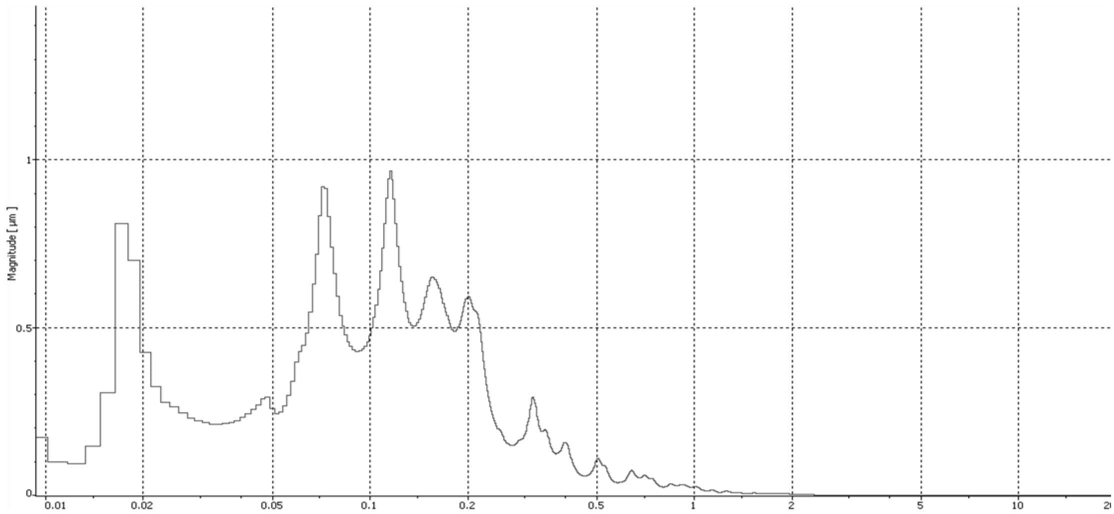


Figure 5.7 Gel-based driver position 1

Position 1 represents the centre of the panel and in this case, five resonance points can be seen. Although the magnitude of the movement changes substantially at these resonance points, they were not as clear in terms of dB sound pressure level (Figure 3.24) when the same panel and position was measured using a microphone.

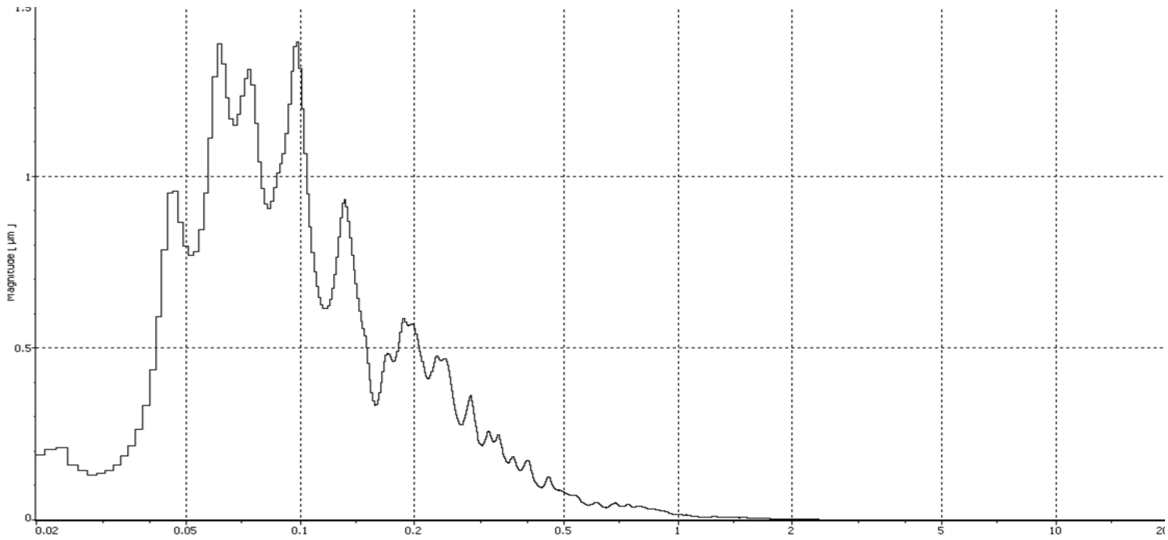


Figure 5.8 Gel-based driver position 2

Figure 5.8 shows measurements when the gel-based driver C was positioned off-centre. This has an effect on the resonance points when compared with Figure 5.7. However, as described in section 5.6, this does not change the frequency response significantly.

Moving the Gel-based driver C further to the corner of the panel has the effect of reducing the maximum movement of the panel; at the same time, it seems that the resonances move left on the graph, to lower frequencies.

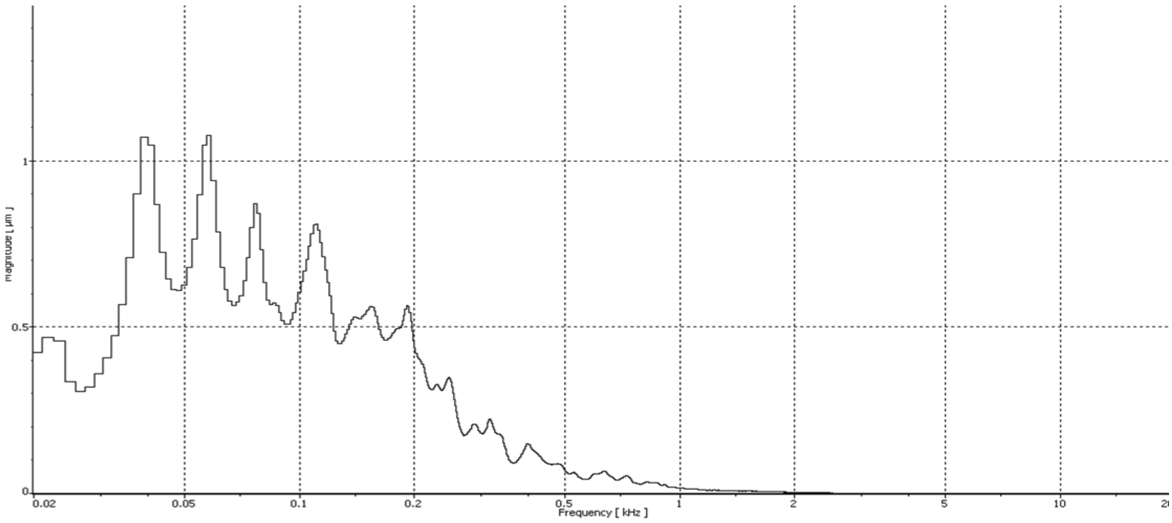


Figure 5.9 Gel-based driver position 3

It is possible to see that at position 4 (Figure 5.10), the panel behaviour is similar to positions 1, 2 and 3 (Figures 5.7, 5.8 and 5.9). As a result, locating the driver close to the centre of the panel brings the maximum movements.

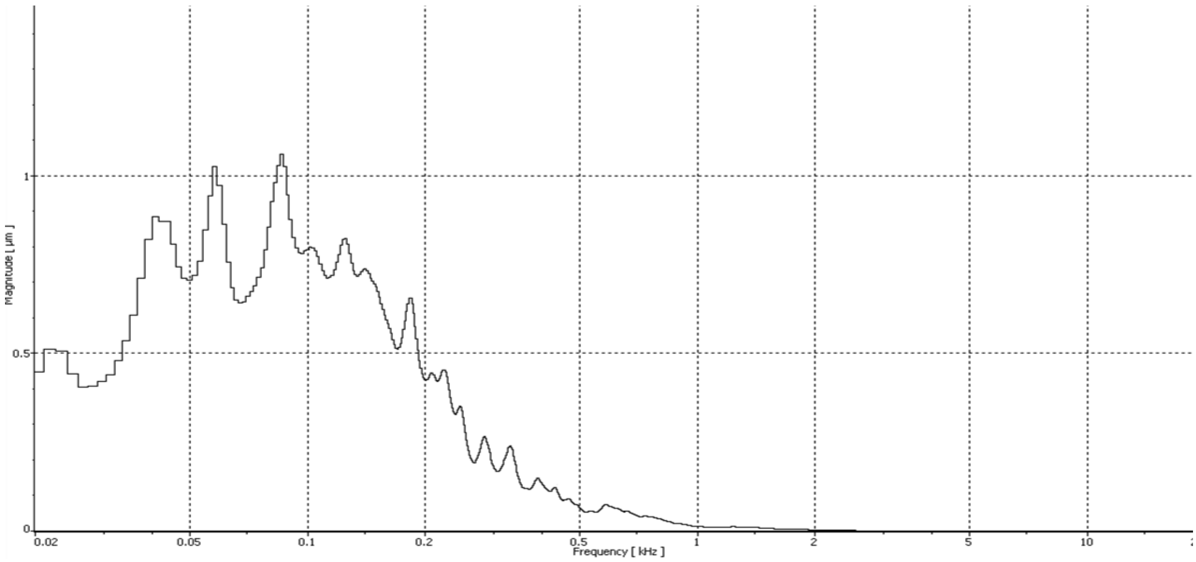


Figure 5.10 Gel-based driver position 4

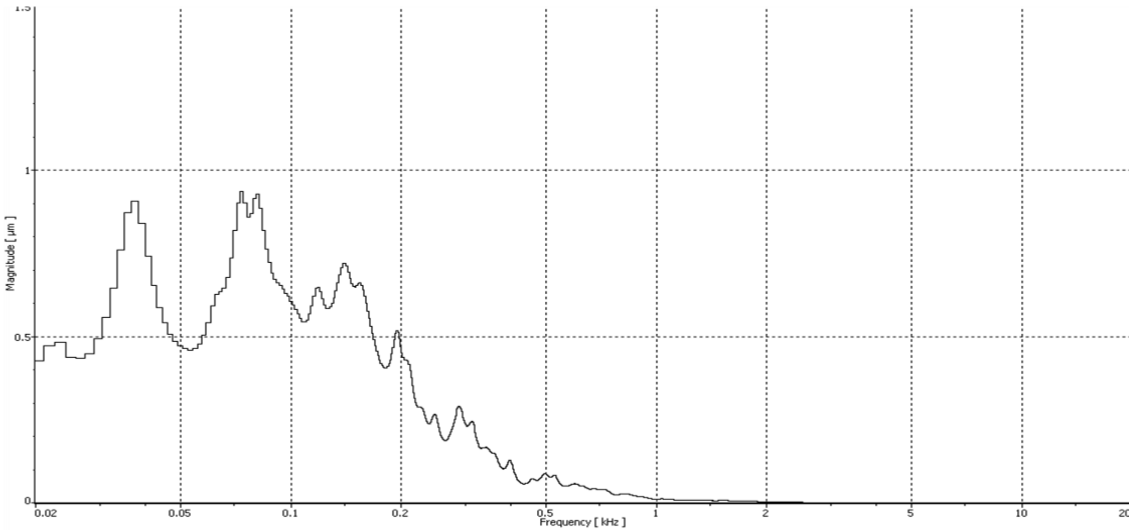


Figure 5.11 Gel-based driver position 5

The driver tested at position 5 (Figure 5.11) was located right at the corner of the panel where the clamping points were located. Even though there are quite high levels of panel movement displayed, the same measurements with a microphone seen in section 3.5 showed a significant reduction on the dB sound pressure level.

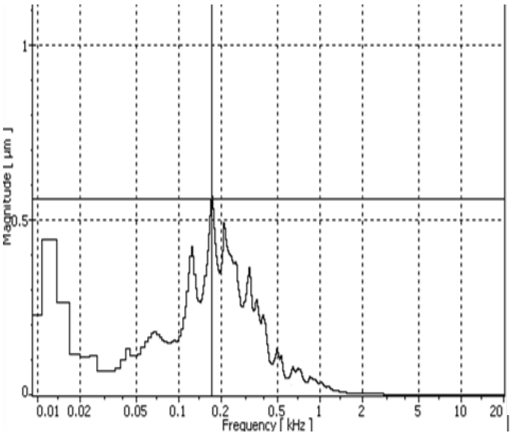
5.6 Gel-based Drivers A and B - Measurements and Comparison

Previous research has shown the relationship between the gel hardness and the frequency response on sound pressure level test and on simulations. The next section shows if vibration measurements can be used to identify some divergences.

The first test consisted of a gel-based driver B with Silicone HF30 (30 Shore A) being compared with a thermoplastic elastomer 2003X (0 Shore A). The drivers were tested in the centre of a 420x320x2mm ABS panel, and the goal was to find the effect of gel hardness.

HF30 Gel is harder than the TEP 2003X Gel (almost 20 times more). For the testing, 1 W of power has been used.

The following graphs show the result of displacement vs. frequency of both devices:



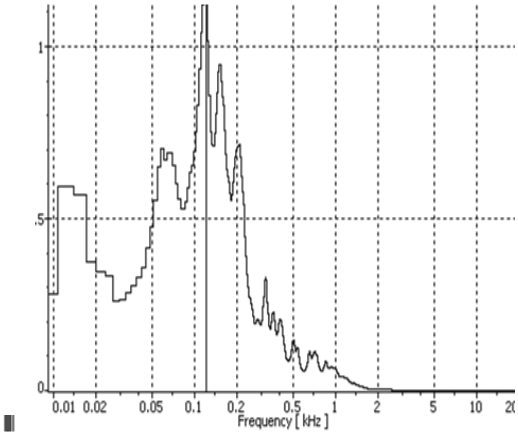
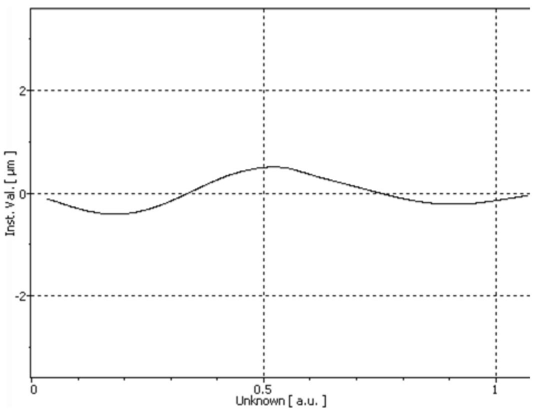


Figure 5.12 Displacement vs. Frequency of gel-based A with HF30 (left) and gel-based B with thermo plastic elastomer 2003X (right

Clearly, when using the thermoplastic elastomer 2003X gel, the displacement is much higher especially at frequencies below 1 kHz. The density of peaks in both testing is similar, so their response should be equally flat and smooth. When taking a look at the shape of the panel from the profile it becomes clear the increased movement occurs once the softer elastomer 2003X is used.



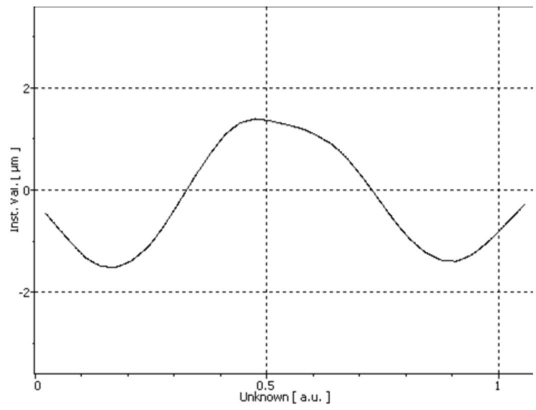


Figure 5.13 Profile of gel-based A with HF30 Gel (left) and gel-based B with thermoplastic elastomer 2003X (right)

The following pictures show the displacement of both devices in the Polytec Scan View software:

Figure 5.14 Displacement in 3D view at 125 Hz. thermoplastic elastomer 2003X (left) and HF30 (right)

In Figure 5.14, both pictures are in the same scale in the same view in the same instant time. It is clear to see that the gel-based driver B with thermoplastic elastomer 2003X has a greater displacement than the HF30. The same picture in bottom view is as follows:

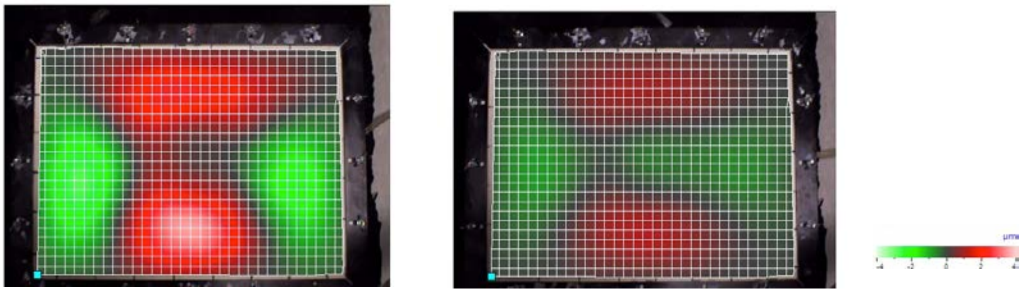


Figure 5.15 Displacement in bottom view at 125Hz. 2003X Gel (left) and HF30 (right)

The acoustic pressure is proportional to the acceleration of particle according to Rayleigh Integral (which is based on the wave equation). So, in order to find out if the displacement of the gel-based driver B with thermoplastic elastomer 2003X when producing sound pressure level, the acceleration vs. frequency graph should be taking into account:

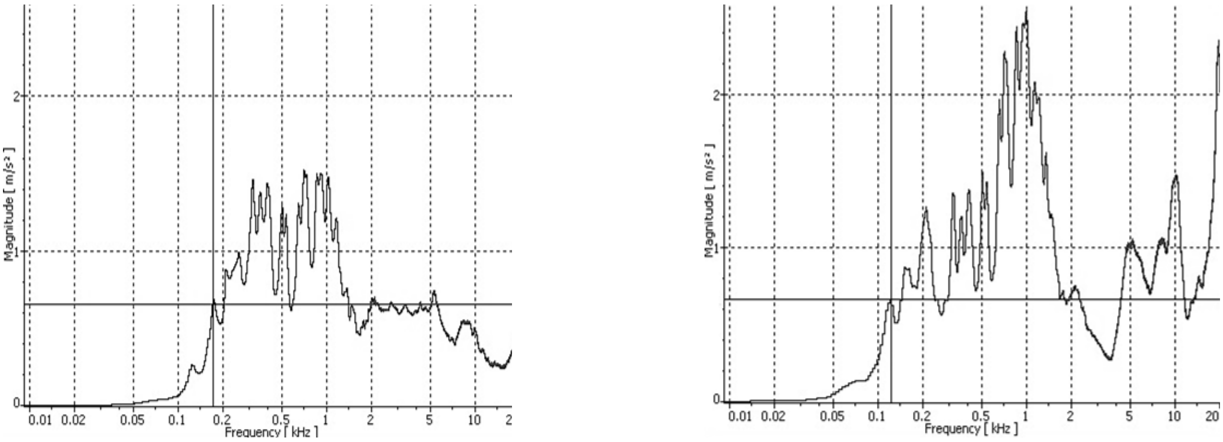


Figure 5.16 Acceleration vs. Frequency of Gel-based driver A with HF30 (left) and Gel-based driver B thermoplastic elastomer 2003X (right).

As expected, the gel-based driver B with thermoplastic elastomer 2003X has a greater acceleration at almost all frequencies when compared with the gel-based driver A (except around 5 kHz, where they show similar behaviour).

Previous testing in Chapter 3 (Figure 3.15) have proved that the softer gel is almost 20 dB higher at the low frequency range when compared with gel-based A. The vibration measurement test corroborates this and although the panel deformation pattern is similar with both elastomers, the magnitude of the movement is higher when the elastomer 2003X is being used.

5.7 Panel Behaviour Visualisation

The following graphs show real panel movements - a gel-based driver B on an ABS panel as described in section 5 was used. Please refer to the figure legend for the real scale of the movements. These graphs are not to scale - they have been maximised substantially to help the visualisation of the effects.

5.7.1 100 Hz Measurement Graph

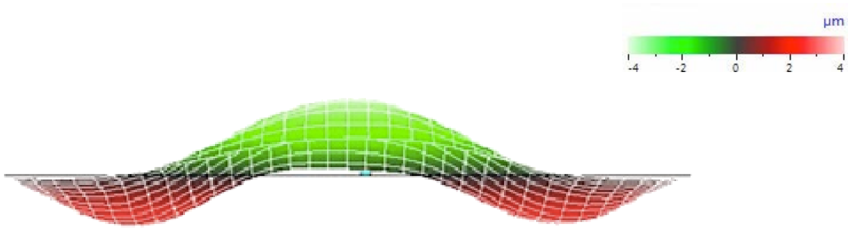


Figure 5.17 ½ panel/driver section (bottom) and panel side measurement at 100Hz

Figure 5.17 shows the panel movement at 100 Hz. This simulation frequency is very close to the resonance of the system therefore close to the maximum movement. The shape is sinusoidal, and almost identical at both sides of the panel. The centre of the panel where the driver is located is where the greater displacement occurs. Figure 5.17 demonstrate the 3-dimensional shape of the movement, hence the need for a driver with a gel that can be deformed to the shape of the panel

5.7.2 500 Hz Measurement Graph

Figure 5.18 Section (top) and side measurement at 500 Hz

The vibrometer result at 500 Hz shows the whole panel resonating and producing acoustic waves. The waves are sinusoidal, and although the corners are clamped, most of the panel is moving. The maximum movement occurs on the area where the driver is in connection with the panel.

The illustrated section of Figure 5.18 shows the waves of a similar size all over the panel. It is clear that the acoustic energy will be spread across the panel concentrated at nodes. Note that the waves are the same on both sides of the panel, which is the same that was seen on simulations at the frequency in Figure 5.17.

5.7.3 2 kHz Measurement Graph

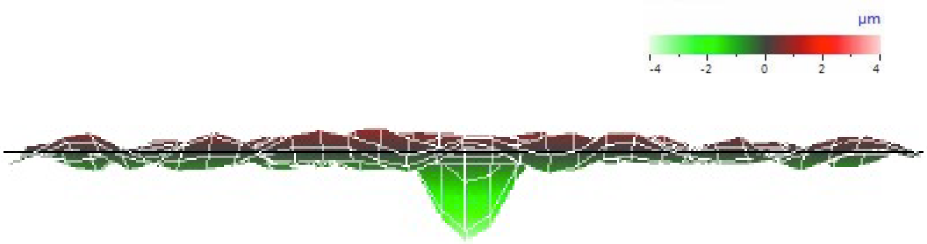


Figure 5.19 Section (top) and side measurement at 2 kHz

Figure 5.19 (2 kHz) shows that most of the movement occurs around the area where the driver is located. The rest of the panel is almost flat. This gives evidence that it may be possible to have two drivers on the same panel playing different signals simultaneously. This will be particular effective at high frequencies where it may be interesting if a stereo effect is required.

5.8 LDV Measurements Conclusions

5.8.1 ABS Panel Measurements

Section 5.3 provides the physical movement and acceleration of gel-based driver C on a 420x420x2mm ABS panel. It becomes clear that in terms of resonances and frequency response the acceleration shows a similar pattern than the measured testing in Chapter 3**.**

5.8.2 Driver Positions on Panel

In section 5.5, several panel positions of the gel-based driver C have been tested. Section 4 did not show major changes on sound pressure level levels if the drivers were located near the centre of the panel. The LDV measurements do not show a clear difference between the values of the peaks (maximum and minimum displacement or velocity), but there is a difference between the densities of the peaks. The test on position 1 has a flatter and smoother displacement curve; this was expected since previous acoustic testing showed a flatter frequency response. Tests on position 3 and 4 have lots of sharp peaks, which mean possible destructive interference of the sound field and non-effective movement of the panel. The ideal displacement-frequency curve should be exponential and smooth. Even the measured performance of the drivers is similar on most positions; further tests should be carried out to measure the polar pattern. The LDV difference on the movement of the panel indicates that some areas of the panel may behave differently once the driver position is changed. In terms of driver design this research has indicated the following rules:

- The best frequency response is when the driver is located at the centre of the panel, because in that position it can move the whole panel and is not limited to the stiffness of the frame.

- For high frequencies, the panel displacement at the centre is the same as the displacement at the corner.

- At high frequencies the driver is only vibrating a small area of the panel so sound does not depend on the stiffness caused by the frame.

- The panel should have different modes throughout the frequency domain. The Polytec vibrometer results illustrated that at low frequencies, the modes are clear and the displacement is higher than at high frequencies.

Chapter 6 General Discussion and Conclusions

6.1 Introduction

The following chapter discusses the findings from the anechoic chamber testing (Chapter 3), finite element analysis simulations (Chapter 4) and laser vibrometer measurements (Chapter 5). It also addresses the contribution to knowledge as well as recommending areas of future work.

6.2 Effect of Gel Type Elastomer Hardness

Chapter 3 investigated the results of several panel types and driver types as well as the effect of the gel type used. Figure 6.1 shows the results from gel-based drivers A and B - both had the same structure and test conditions with the exception of the hardness of the elastomer used for making the gel. It is clear that the choice of the gel hardness affects the frequency response of the system. The harder elastomer used on the gel-based diver A transferred the mid- and high-frequencies more efficiently, while the softer elastomer used on gel-based driver B made the system more efficient at the low frequency range. This effect is due the nature of the softer gel and the lower Young's Modulus of gel-based driver B allowing a greater degree of movement on both the magnetic circuit parts, and on the coil and the drive plate, when subjected to the same force.

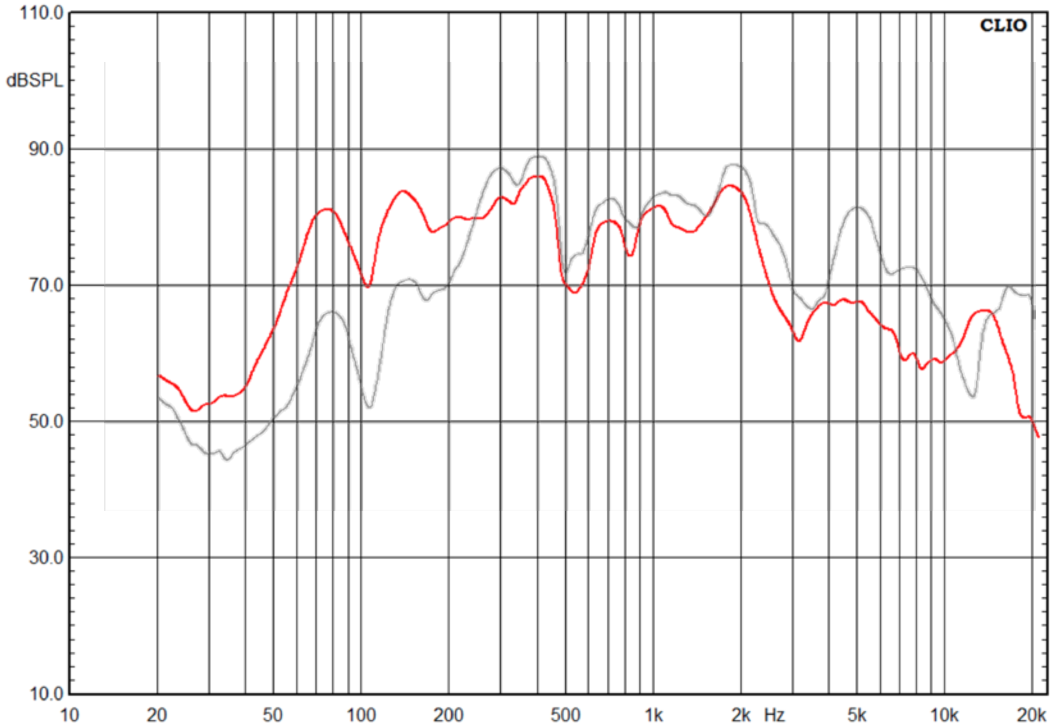


Figure 6.1 Gel-based drivers A (grey) and B (red)

The same combination of gel-based drivesr A and B with two elastomer hardness levels were simulated using the Comsol package and described in Chapter 4. The results are shown in Figure 6.2 and the pattern of both drivers is similar to the measurements shown in Figure 6.1. This is especially the case at the low frequency end of the spectrum -over the high frequency range, the differences between both drivers are difficult to appreciate. This may be because of the directivity of the high frequencies where the simulated test does not take into account accurately enough all the effects due cancellation and reflection of the sound waves.

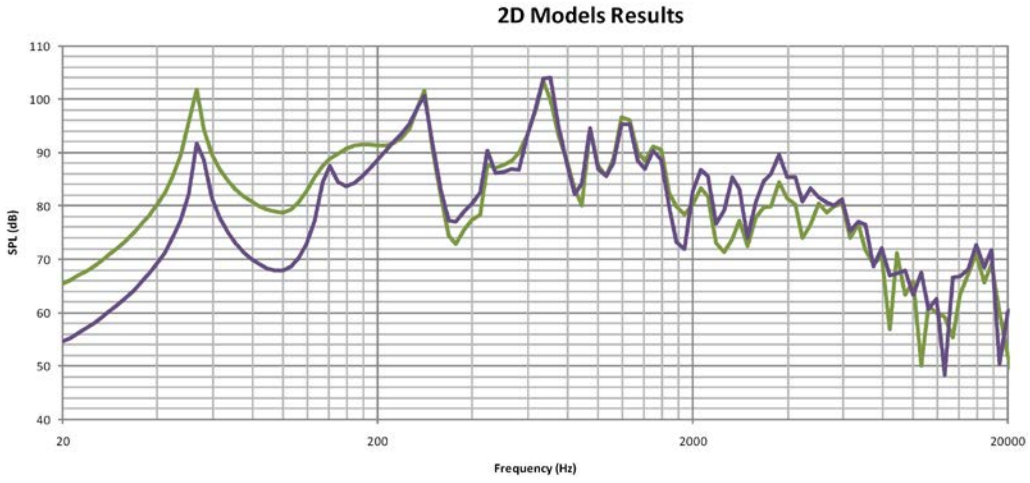


Figure 6.2 Simulation results from gel-based drivers A (purple) and B (green)

Fig 6.3 shows the laser Doppler physical measurements differences between gel-based drivers A and B. This confirms the observations from Chapters 3 and 4 – namely that the softer elastomer used on gel based driver B is more efficient at the low frequency range. The magnitude of the movement at high frequencies is of the order of nm. The package used for this test was not precise enough to be able to contrast both gel type drivers at high frequencies.

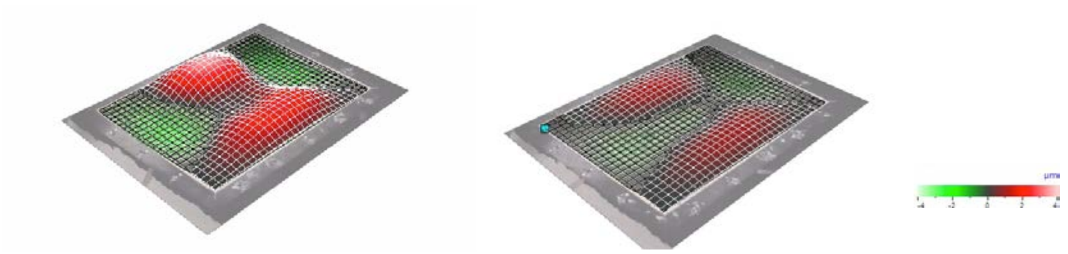


Figure 6.3 Displacement in 3D view at 125Hz for gel-based driver B (left) and A (right)

To better contrast the measurements described in Chapter 3 against the ones made in Chapter 5, it is important that the drivers compared were placed at exactly the same position on the panel. This is the case – as described in section 5.6 and section 3.3.3.1 where gel-based driver A and B are contrasted.

As already seen in Figure 6.1, gel-based driver B is more efficient than gel-based driver A under 200Hz. In Figure 6.7, laser Doppler measurements confirm this observation showing an increased movement of gel-based driver B below 200Hz; above this frequency, the panel movement of both set-ups is very similar. It is at the low frequency range - where the greater movement of the panel takes place – that laser Doppler measurements are particular useful.

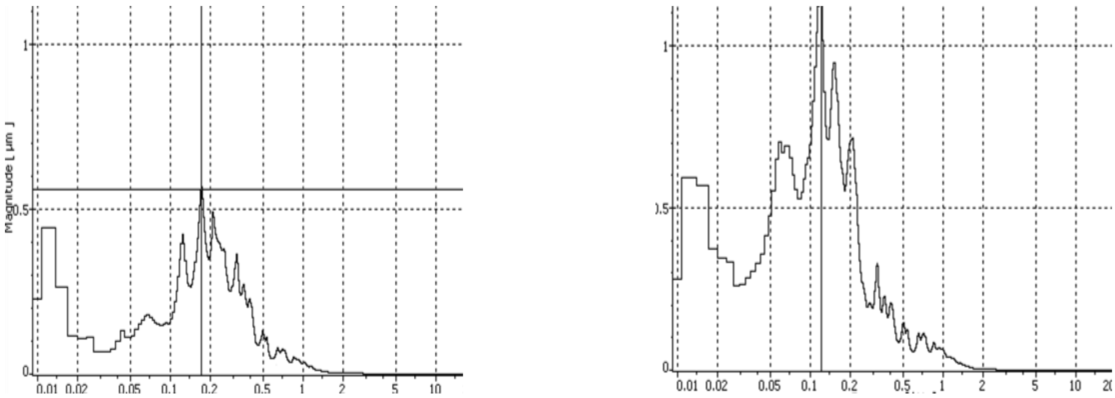


Figure 6.7 Laser Doppler measurements from gel-based drivers A (left) and B (right)

6.3 Effect of Driver Position on Panel

Chapter 6.3 studied the differences in frequency response of gel-based driver C on an ABS panel in relation the driver position on the panel. On the measurements made at 1W and 1m no major differences in the panel position were appreciated. The only area where it seemed to have an effect was at the low frequency range where position 4, which is off-centre, had a slightly lower initial resonance frequency. The laser Doppler measurements of the positions discussed above showed different results - in particular under 100Hz where position 2 was the one that moved the most. However at this low frequency range, the tests in Figure 6.4 were not accurate enough because of the anechoic chamber dimensions.

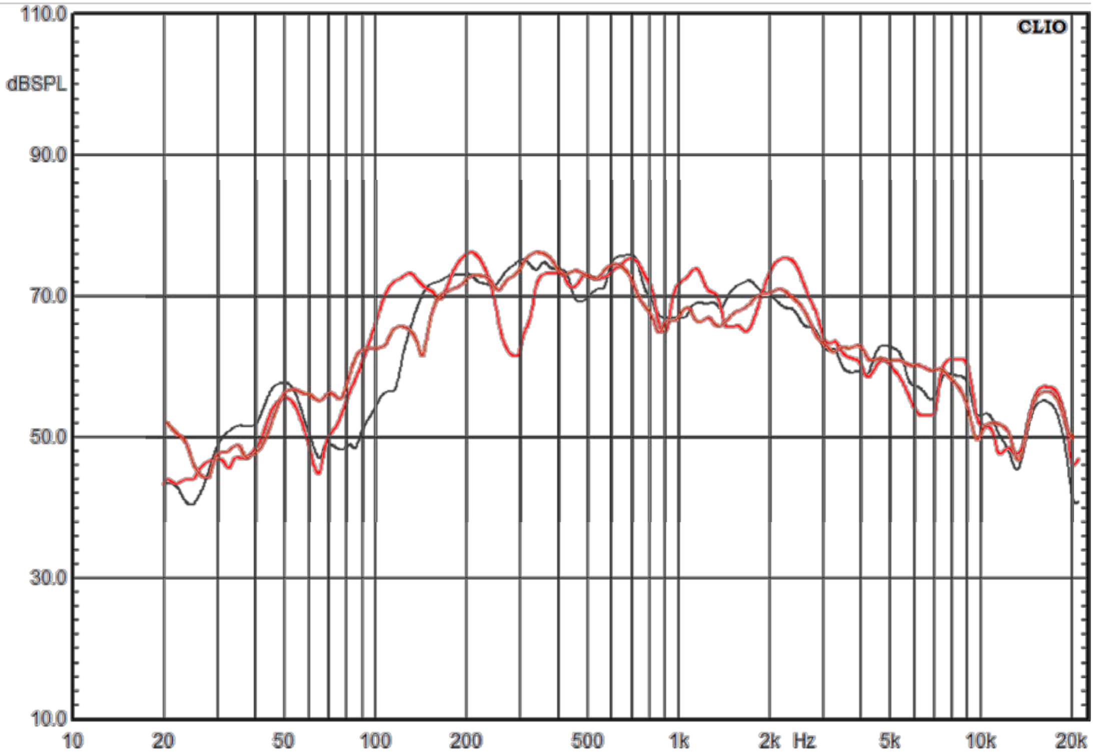


Figure 6.4 Results from positions 2 (blue), 3 (grey) and 4 (red)

Figure shows the equivalent positions tested using the laser Doppler technique. The resulting measurements were very useful in observing the panel behaviour and understanding better the movement that is going through the system; however it is difficult to predict the system performance from these measurements. This is due to the fact that on the laser Doppler measurements, only the movement of the panel surface points were taken into account, while in Chapter 3 the microphone measured the response at 1 m. Once the waves get to the microphone, constructive and destructive interference has taken place and this will change the frequency response graph considerably. However it is possible to observe that the magnitude of the panel movement was similar on all the positions tested.

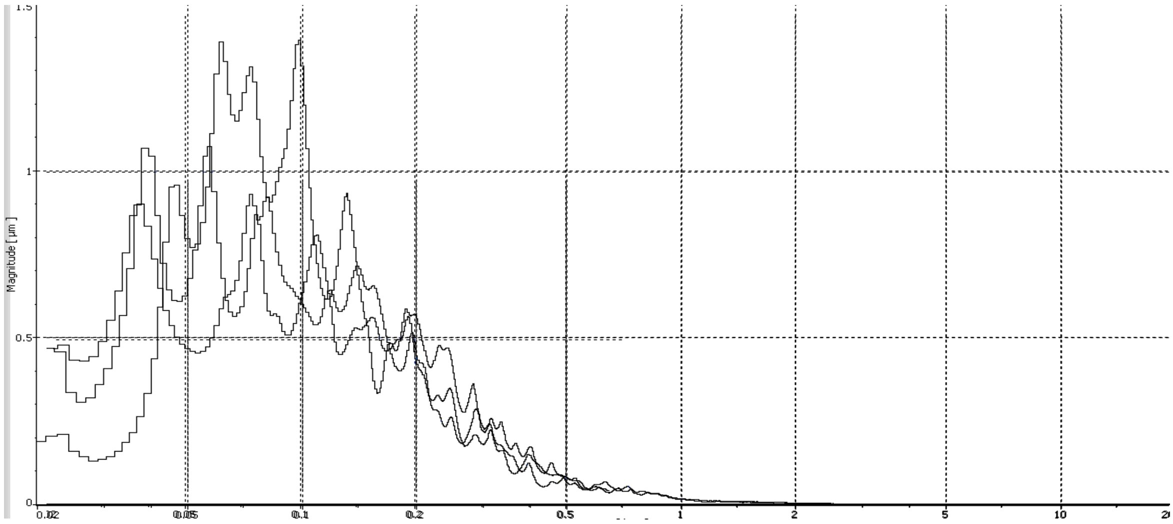


Figure 6.5 Laser Doppler measurements for positions 2 (black), 3 (red) and 4 (blue)

6.4 Gel-base Driver - Effects of Panel Materials

Chapter 3.9.3 has revealed the results of gel-based drivers, using several types of panel materials. It has been observed that the panel material affects the overall system performance in a similar way to the gel-based driver properties. The resonance of the gel based driver/panel system will be dependent on the properties of the panel. Below the system resonance frequency range, the panel will move pistonically; it will not have any nodes of movement and the efficiency of the system will mainly depend on the driver characteristics. Above the resonance frequency, some nodes of movement will be present. The panel nodal map will be a consequence of the frequency that the driver is being subjected to and the physical properties of the panel.

In terms of panel material, the wood panel has a clear resonance around 200Hz - this gives a good overall bass sound. On the other hand the wood is not very efficient in the high frequency range, above 3 kHz. ABS as a panel material is more efficient at the mid frequency range, while aluminum has the flattest frequency response of all the three panel materials tested. This makes aluminum the best material if we measure it by fidelity, however due the extra bass performance of the wood panel, this latter one may be considered to sound better.

6.5 Contribution to Knowledge

i. It has been shown that gel-based drivers are very effective in driving several types of panel materials and achieving (a) a wide frequency response and (b) efficient levels of dB sound pressure level.

ii. It has been possible to drive a panel from several positions while maintaining considerable similar frequency response.

iii. The gel hardness used has an impact on performance with the use of a low hardness gel improving the overall system at the low frequency range.

iv. Gel-based drivers handled relatively higher levels of power and transferred it to a panel efficiently at the low frequency range. Taking into account the size of these gel base drivers, similar sized drivers of an alternative technology capable of delivering a similar level of efficiency at the low frequency range, have not been found.

v. Gel-based drivers are scalable in size, and their behaviour is proportionally maintained.

vi. Using the Comsol package, it is possible to fully design gel-based drivers and simulate their performance very accurately.

Chapter 7 Future Work

The development of the gel-based audio drivers described in this thesis forms a foundation for future work in this area. The nature of the gel structure is mechanically completely different to any other loudspeaker device manufactured or investigated before. Consequently it has only been possible to define the main elements of the technology. This research describes only the early stage of the gel-based driver technology - there are many other areas that can be studied further, such as a wider range of panel materials, driver structure, gel-based microphone, gel piezoelectric drivers, the miniaturization of the drivers and gel audio driver arrays.

In addition it is suggested that further research is carried out on (i) downscaling the gel-based drivers to fit ultra-portable devices such as mobile phones, (ii) developing flatter structures, (iii) improving the efficiency of these drivers at the high frequency range and (iv) developing gel-based driver arrays to fit on flat electronic devices such as LCD TVs

In addition to those areas, it will be necessary to study further the effects of the vibrations created on the panels by gel audio drivers. This is to ensure that these vibrations do not create any problems to the other components fitted around those drivers. Any such unwanted effects would then need to be addressed by closer control of the vibrations.

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Appendix A List of Publications and Patents

Publications

1) Habeshaw, Rod; McMahon, Anthony; Munoz, Jordi; Pfann, Eugen; Stirling, Iain, "Design and Implementation of a DSP Enhanced Portable Speaker System" 32nd International Conference: DSP For Loudspeakers, "September 2007

2) Minsung, Cho; Prokofieva, Elena; Munoz, Jordi; Barker, Mike. "Improvement of sound quality by means of ultra-soft elastomer for the gel-type inertia driven DML-type transducer", J. AES Convention, May 2010

3) Minsung, Cho; Prokofieva, Elena; Munoz, Jordi; Barker, Mike. "A novel design for a gel-type DML transducer incorporating a solid panel projecting multiple independent sound sources" 40th International Conference: Spatial Audio: Sense the Sound of Space, October 2010

Patents

1) IMPROVEMENTS TO LOUDSPEAKER DRIVER ASSEMBLIES. Inventor: HYND IAN [GB] MUNOZ FRIGOLA JORDI [GB] SFX TECHNOLOGIES LTD [GB] EC:H04R1/02C

2) IMPROVEMENTS TO AUDIO DEVICES. Inventor: MUNOZ FRIGOLA JORDI [ES] WINTER RENE MEINHARD [IE] (+1) SFX TECHNOLOGIES LTD [GB] EC:H04R7/04D

3) HYDROGEL ACOUSTIC COUPLING FOR LOUDSPEAKER. Inventor: HYND IAN [GB]; HARRIS NORMAN [GB]; FRIGOLA JORDI MUNOZ [GB] G10K11/02

Appendix B Published Papers

Improvement of sound quality by means of Ultra-soft elastomer for the gel type inertia driven DML type transducer

Minsung Cho[1,2], Dr Elena Prokofieva[1], Dr Mike Barker[1], Jordi Munoz[2]
[1] Edinburgh Napier University, [2] SFX Technologies

ABSTRACT

Unlike standard DML transducers, the gel type inertia driven transducer (or simply called the gel transducer in this paper) designed as a mini woofer DML type transducer transfers its pistonic movement to the transverse wave of the panel through the gel surround. This mechanism allows an inertia of magnet assembly to the maximum during the pistonic movement. This maximum inertia boosts the force of moving voice coil so that sound pressure level increases as the acceleration of the panel increases proportionally to sound pressure level at low and medium frequency range from 50Hz to 1000 Hz. In addition it is found that the gel surround prevents reflected transverse wave of the panel from interfering the pistonic waves coming from the transducer. Results from mechanical testing for stiffness of the gel surround and the measurement of the laser scanning vibrometer for the displacement and acceleration of the panel with the gel transducer attached are presented, and these are compared to acoustical outputs.

1. INTRODUCTION

A distributed mode loudspeaker (DML) is an emerging alternative to standard conventional cone speaker designs. It is a flat, rigid and light panel that radiates acoustic energy by sustaining bending waves, rather than by pistonic motion. This class of loudspeaker produces radiation that is temporally and spatially diffuse with a wide directivity that is substantially independent of frequency [1].

A DML-type drive unit used for the present research is a gel-type inertia driven transducer, comprising a magnetic assembly, coil and drive plate (Fig.1). An important difference in mechanical construction is the incorporation of the gel surround in-between the drive plate and the panel, which gives two separate analogues for the standard DML and the gel type inertia driven transducer (Fig.2).

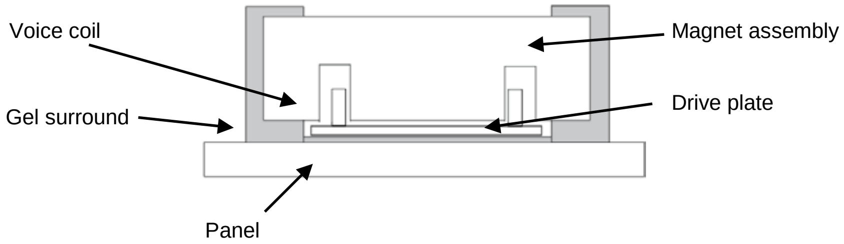
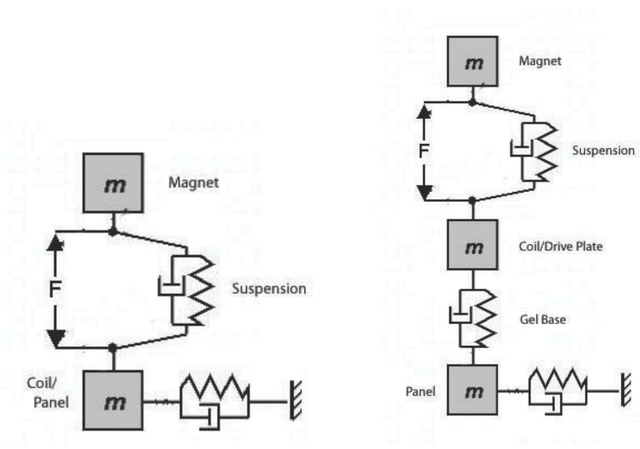


Fig.1 Gel type inertia driven transducer

This transducer is in permanent contact with the panel, without being bonded to it. The waves are transferred from the pistonic movement of the transducer, to the transverse wave of the panel through the gel surround. This gel surround acts as a suspension and does not constrain the panel.

The gel surround also enables to localize the force of the moving coil over the drive plate area. In addition the gel surround allows the magnet assembly to move at the greatest displacement. Hence the gel type inertia driven transducer is capable of radiating sound over the wide frequency range from 50 Hz to 15000 Hz.



(a) (b)

Fig. 2 Impedance analogue model of a standard DML (a) and the gel type inertia driven transducer (b)

The mechanical properties of the gel surround (i.e. hardness) are directly related to its ability to radiate the sound at low and medium frequency range from 50 Hz to 1000 Hz. The results of the theoretical investigation and experimental testing of the gel type inertia driven transducer with the different hardness of silicone elastomers are presented in this article.

2. TEST METHODOLOGY

2.1 Sample preparation

Poly addition silicones - Platsil® 71-20 (20 shore A) and Platsil® Gel 10 (10 shore A) - were used to make dumbbell shaped samples according to ASTM D412 and gel surrounds for mechanical and acoustical testing respectively. These silicone rubbers are two-component (organic material and catalyst) mixed in the ratio of 1 to 1 by volume and cures at room temperature. The softener was used to modify the hardness of original silicones to achieve the various range of the hardness from 0 shore A to 20 shore A.

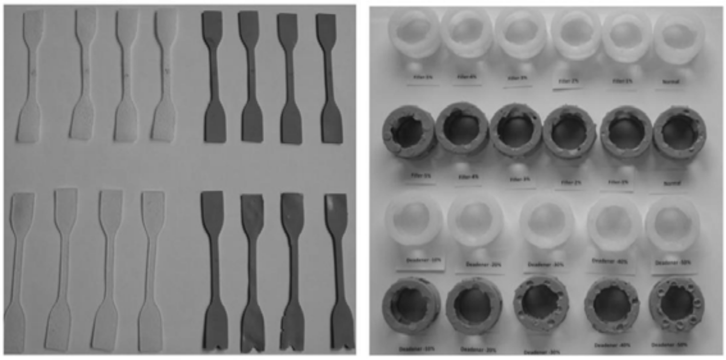


Fig.3 Dumbbell specimen and gel surrounds of silicone elastomer

Dumbbell specimen (Fig.3) is required for tensile testing that measure the force required to break a specimen and the extent to which the specimen stretches or elongates to that breaking point. For acoustic measurement, the gel surrounds (Fig.3) which is compatible with the existing magnet assembly of GA6 (one of Gel Audio® transducer designed by SFX Technologies Ltd) is also moulded.

2.2 Mechanical testing

JJ Lloyd single column tensile tester (100N load cell) was used for testing the samples to obtain stiffness in tension - stiffness in compression is also an important parameter in designing the gel surround. However it is not directly related to this paper. Hence stiffness in compression is not presented here. Rubber dumbbell specimens (ASTMD412) prepared were tested at test speed of 8.33mm/s. Unlike the materials that obey Hooke's law, elastomer such as silicones is regarded as a non-Hooken materials beyond 100% elongation (stress is proportional to strain up to 100% elongation that elasticity is stress dependent and sensitive to temperature and loading rate), tensile E modulus was measured at 100% elongation.

2.3 Acoustic testing

The magnet assembly and the voice coil (8Ω) used for this testing was used the same as a magnet assembly of GA6 (Gel Audio® designed by SFX Technologies Ltd). The gel transducer was positioned on the clamped ABS panel (420mm x 320mm x 2mm) and a sinusoidal pink noise was fed into it at 1w (r.m.s) at a range of 20Hz to 20kHz. A microphone was set up at 10 cm away from the sound source in the semi-anechoic chamber (2m x 1m x 0.5m).

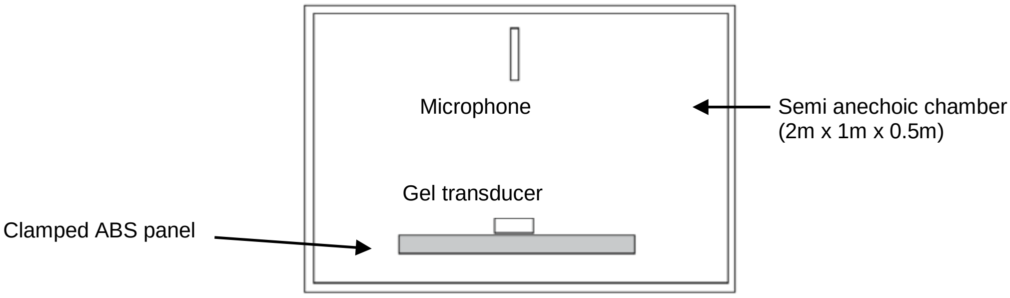


Fig. 4 Gel type inertia driven transducer positioned in the centre of the panel for the acoustic testing

2.4 Laser scanning vibrometer

Polytec laser scanning vibrometer (PSV_400_B) was used to measure the mechanical vibration of the ABS panel with the gel transducer attached in the centre. This vibrometer operates on the Doppler principle, measuring the frequency shift of backscattered laser light from a vibrating structure to determine its instantaneous velocity, displacement and acceleration. A periodic chirp signal (20Hz to 20kHz) at 1w(r.m.s) with a resolution of 5 Hz was fed into the transducer attached on the ABS panel. 200 points on the panel for laser scanning were set up. Following equations were used to calculate panel's displacement, velocity and acceleration.

Displacement: $D = \ (V_f + V_i) t = V_0 t + \ At^2$

Velocity: $V = V_0 + At$

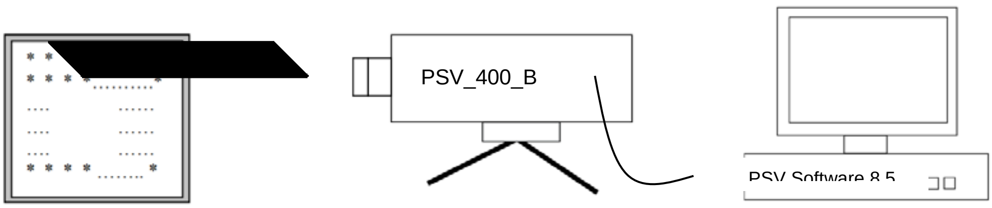


Fig. 5 Laser scanning vibrometer measurement

3. RESULTS and DISCUSSION

3.1 Stiffness of silicone elastomers in tension

The graph below shows stiffness silicone elastomers with the hardness of 0 shore A to 20 shore A.

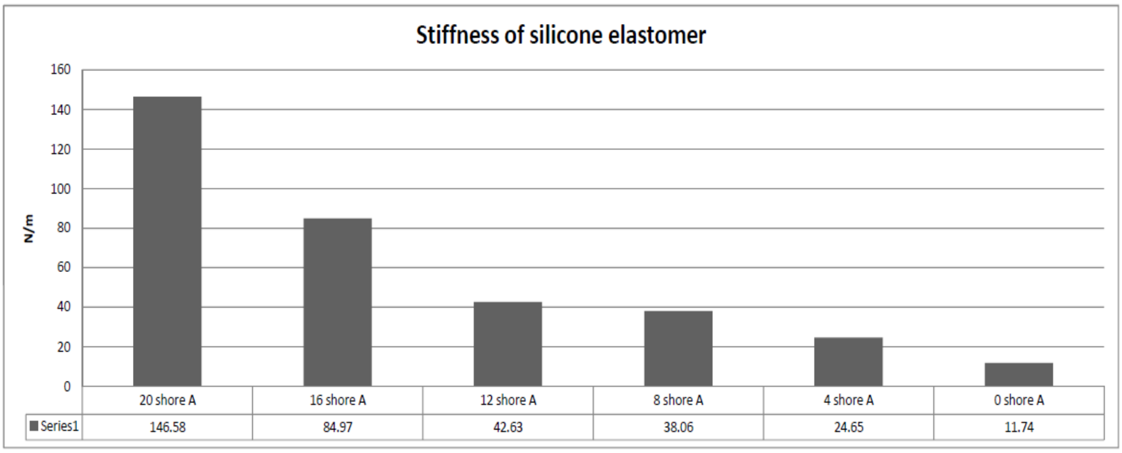


Fig.6 Stiffness of silicone elastomer in tension

Stiffness of gel surround is an important parameter since the gel surround acts as a cushion between a magnet assembly, a drive-plate and a panel. It serves to lower the resonant frequency of the gel transducer that enables to extend low frequency range which can be generated by the gel transducer.

$F_s =$ [2]

where C_g = 1/stiffness of the gel surround, M_g = mass of the magnet assembly

According to Helmholtz Resonance [2], the higher C_g of the gel surround - the lower stiffness leads to the lower F_s. As a result, the gel surround that has the low stiffness can deliver the lower bass sound when compared to the harder gel surround.

3.2 Analysis of vibrating panel's characterisation

Throughout the measurement of the laser scanning vibrometer, the displacement and the acceleration of the panel with the transducer attached to on the centre were measured.

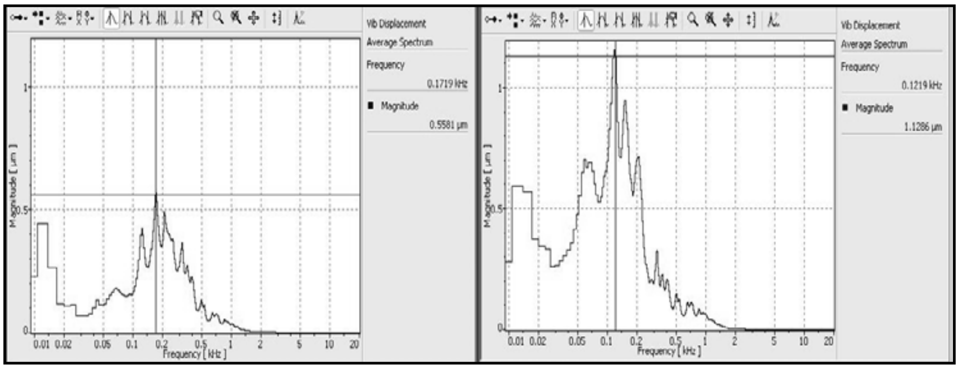


Fig.7 Average displacement of the panel (20 shore A (left) and 0 shore A (right))- 20Hz to 20kHz

Fig.7 shows that the transducer with 0 shore A gel surround creates higher average displacement than the one with 20 shore A.

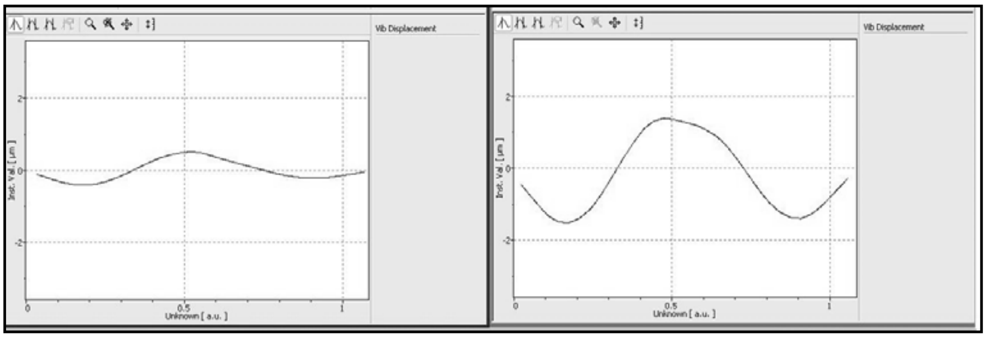


Fig.8 Displacement of the panel(20 shore A (left), 0 shore A (right)) at 100 Hz

According to Fig.8, it is more obvious that a magnitude of displacement of 0 shore A transducer is 2 times higher than 20 shore A transducer at 100Hz. It is because firstly, as the displacement of a magnet assembly is proportional to the force of the voice coil sit on the drive-plate, softer gel surround enables a magnet assembly to make greater inertia that leads to bigger displacement and also softer gel cushion contributes sinusoidal pistonic movement of a magnet assembly. Secondly, unlike standard DML transducers, the gel surround in contact with the panel allows the transducer to transfer the pistonic movement to the transverse wave of the panel with minor wave cancellations (Fig.9).

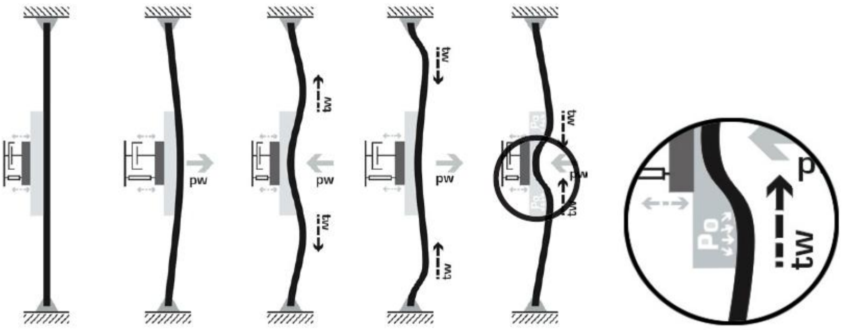


Fig. 9 The function of the gel surround on the panel

Sound pressure level can be predicted with a simple monopole approximation in the Rayleigh equation with respect to the mechanical vibration [3]. Hence sound pressure is proportional to the acceleration at low-mid frequency band.

Fig.10 shows that 0 shore A transducer exhibits higher acceleration than 20 shore A transducer over low-mid frequency band.

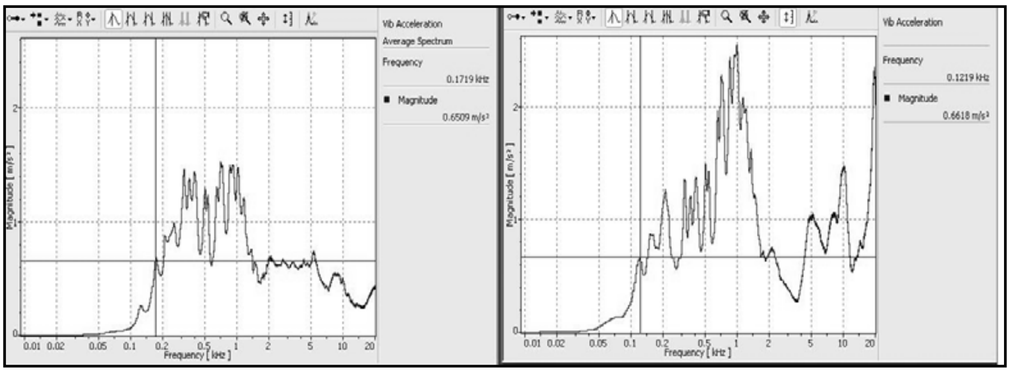


Fig. 10 Average acceleration of the panel (20 shore A (left), 0 shore A (right)) - 20Hz to 20kHz

3.3 Acoustic measurement

Acoustic efficiency of transducers with different hardness was measured and calculated according to equations as follows.

Average SPL = 10× log× [ ]

THD% = 100×[ ]

Efficiency (SPL + THD%) = 20×log×[([4].

Fig.11 indicates that efficiency increases as the hardness of gel surrounding decreases.

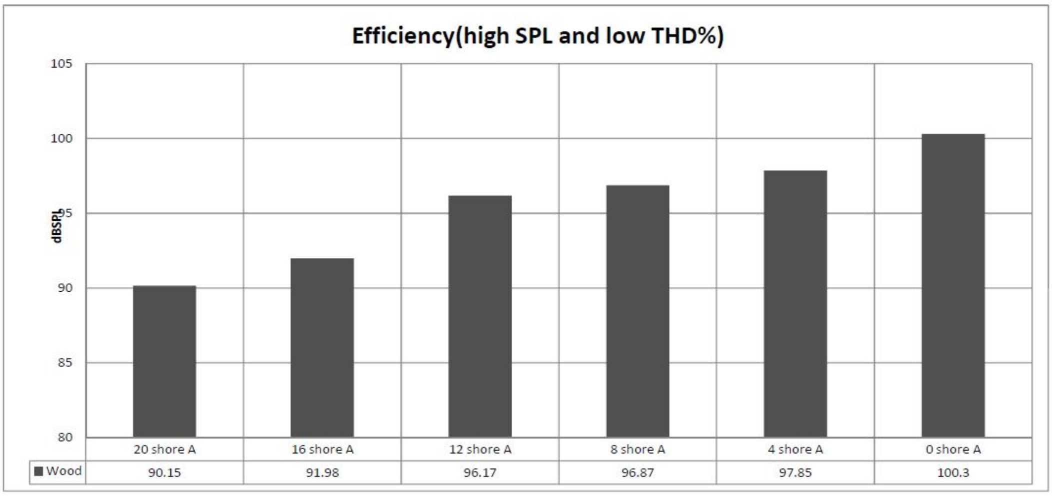
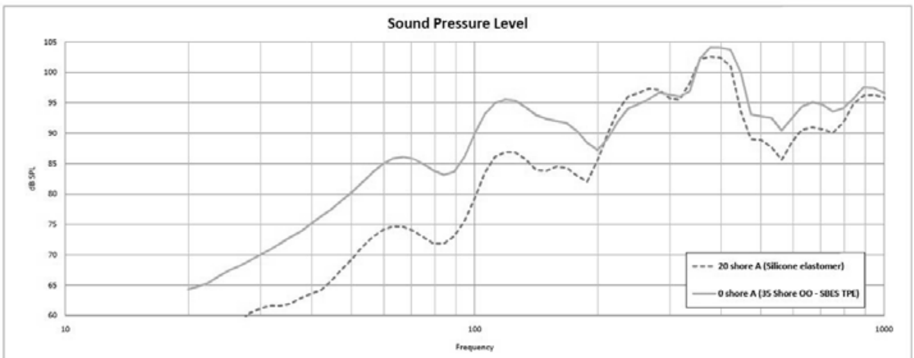


Fig. 11 Acoustic efficiency (high SPL and low THD%) of different hardness of gel surrounds

Sound pressure level and THD of 20 shore A transducer against 0 shore A transducer is compared with each other in Fig.12. (frequency band only up to 1000 Hz is displayed as gel type inertia driven transducer was initially developed to enhance bass sound)



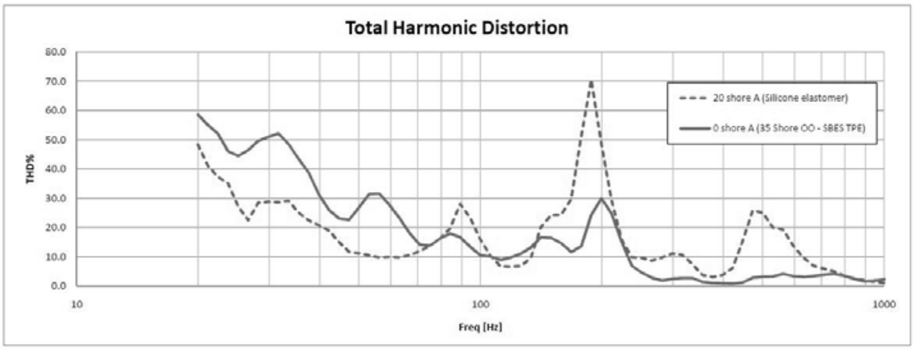


Fig. 12 Sound pressure level and THD of 20 shore A against 0 shore A on ABS panel (420mm x 320mm x 2mm)

It is obvious that 0 shore A transducer that brings up the higher displacement and acceleration than 20 shore A transducer, creates higher SPL especially between 50 Hz and 200 Hz in which greater inertia of movement of a magnet assembly is required. THD graph shows that 0 shore A transducer which has higher damping factor than 20 shore A prevents the transducer from being damaged and interfered by reflected transverse waves propagating toward the transducer.

It was found that the hardness of gel surround affects acoustic output of the transducer. The softer gel surround is more efficiency than the harder gel surround in terms of sound pressure level and THD at low-mid frequency range. However as Tan δ (damping factor) of the gel surround goes up, its E' (storage modulus - stiffness) will drop down proportionally [5]. It means that if hardness of the gel surround becomes too soft below 0 shore A (35 shore 00), the gel surround would end up having the negligible value of E'. And it may result in dampening the most of the pistonic force of the moving voice coil that is transferred to the panel. Thus those issues need to be dealt with as the future work.

4. CONCLUSION

In this paper it has been shown that the gel type inertia driven transducer transfers the pistonic wave to the transverse wave of the panel through the gel surround and the hardness of the gel surround is directly related to the movement of the panel greatly with respect to the displacement and the acceleration.

The softer gel surround in terms of its hardness enhances acoustic efficiency (high SPL and low THD) at low and mid frequency range from 50Hz to 1000 Hz since the higher displacement and acceleration of the panel are driven by softer gel surround. It is also proved that the soft gel surround not only dampens unnecessary transverse waves propagating toward the transducer but also contributes constructive interference instead of destructive interference causing physical distortions.

This paper results in the question that damping factor of the gel surround may not contribute proportionally to acoustic efficiency in the system of the gel type inertia driven transducer when the hardness of the gel surround goes too low. This issue needs to be answered.

ACKNOWLEDGEMENT

The authors wish to thank SFX Technologies and Edinburgh Napier university for the support of this work

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A novel design for a gel-type DML transducer incorporating a solid panel projecting multiple independent sound sources

Minsung Cho[1,2], Elena Prokofieva[1], Mike Barker[1], Jordi Munoz[2],

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[2]SFX Technologies Ltd, Edinburgh, UK

ABSTRACT

The gel-type DML transducer (referred to as the gel transducer in this paper) excites a panel to radiate sound waves through the gel surround. The panel breaks into different characteristic modes of vibration as frequency increases. At high frequencies above 1,600Hz, the extent of the moving area of the panel begins to reduce and becomes localised on the position of the gel transducer. This results in both the sound radiating area and volume velocity being reduced so that the directivity of the sound field narrows. As a result, a single panel with the two gel transducers attached can radiate independent sound sources with minimal acoustic cancellations at high frequencies. The current paper reports on this effect using theoretical and practical approaches.

1. INTRODUCTION

A distributed mode loudspeaker (DML) is an acoustic transducer who's electrical, mechanical and acoustical properties differ from traditional moving coil types. The sound is produced by generating uniformly distributed, free vibration in a stiff panel created by an exciter. The DML is identified with temporal and spatial diffusivity, radiation over a broad frequency range and a wide directivity spectrum [1].

Unlike standard DML transducers, the gel-type DML transducer radiates sound by transferring pistonic movement of a driver to a panel through a gel surround. The gel surround between the transducer and the panel allows more transverse waves propagating through the panel with minimal interference. This effect contributes to a higher sound pressure response radiated from the panel at low and medium frequencies in the range 50Hz to 1.5 kHz. Among various parameters of the speaker system, the location of the gel transducer on the panel has least influence on the quality of its acoustic performance, which allows more freedom in the design of the loudspeaker.

The longitudinal and transverse waves occur in the panel excited by the gel transducer and form the vibrating mode. The vibrating modes vary from frequency to frequency.
For low and mid frequencies, the peaks related to the vibrating modes are distributed along the surface of the panel. For high frequencies, the highest peaks are localised around the position of the transducer, whilst the rest of the panel is less affected. As a result, it is possible to "project" multiple independent sound sources from a solid panel excited by several gel transducers. The effect from the usage multiple transducers is most noticeable at higher frequencies.

2. THEORY

2.1 Gel transducer

The drive unit used for the current investigation is shown in Figure 1. The transducer consists of a magnet assembly, voice coil and drive plate. A thin layer of soft gel elastomer is placed between the drive plate and the radiating panel to create additional damping between the moving parts of the speaker construction.

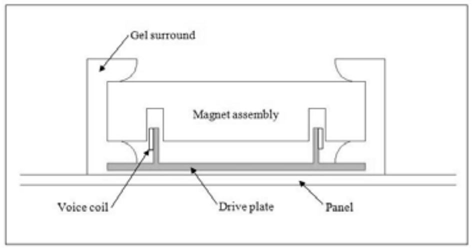
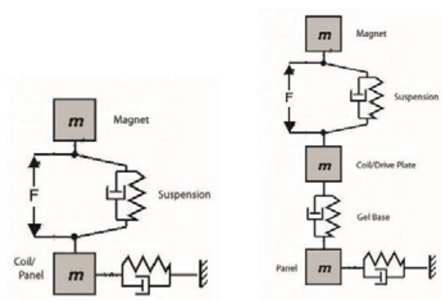


Figure 1: The gel transducer assembly

Figure 2 shows the impedance analogue models of a standard DML driver and the gel transducer to demonstrate the difference between the two systems [2].



(a) standard DML (b) gel transducer

Figure 2: Impedance analogue models of drivers

Unlike a standard DML, the gel transducer is connected to the panel via the gel layer so there is no physical bond between the transducer and the panel. The wave generated by the pistonic movement of the transducer is transferred to the panel through the gel layer. The gel layer also prevents the transverse wave travelling along the panel from causing cancellations, especially for low frequency wave when the displacement of panel is relatively high. In standard DML driver, the magnet assembly has rigid connection to the voice coil, which reduces its freedom of movement. In the proposed driver, the gel surround allows the magnet assembly to move with higher magnitude and create more energy transmitted to the panel.

It was investigated experimentally [2] that the stiffness of the gel surround greatly affects the acoustic performance of the gel transducer system.

2.2 Assumptions

The panel used for the problem is 2mm thick ABS (Acrylonitrile-Butadiene-Styrene) plastic. It was observed during the experiments that many conventional panels (including those manufactured from glass, wood and metal) also exhibit similar dynamic behaviour.

It is assumed that the drive plate of gel transducer behaves like a rigid piston at low frequencies, but as the frequency is increased to the mid-range, the movement of the panel becomes more complex, involving a combination of direct pistonic movement and circumferential deformation. These complex series of the vibrations are subsequently transferred to the panel which deforms in a random and unpredictable manner.

It is also assumed that all energy supplied to the panel is converted to acoustic radiation.

At high frequencies, the panel does not move as a rigid piston, and the system's behaviour becomes unpredictable, so it is difficult to establish how much energy goes to acoustic radiation.

2.3 Sound-pressure-related vibration modes

At the low frequencies, the panel moves as a rigid body. In first vibrating mode, the entire surface of the panel vibrates in phase due to high bending stiffness across the panel and long period of input signal. At higher frequencies, the panel changes the nature of its vibration modes. Following the rigid body mode, the bending mode breaks up over the panel proportionally. As frequency increases further, bending and longitudinal modes occur at the same time and the real moving area of the panel reduces [3].

These modes can be divided into three groups: in-phase region, anti-phase region and quadrature region which are the related to the phase as shown in Figure 3. In the quadrature region, the total volume velocity is always zero as in-phase and anti-phase regions occur at the same time. This effect is described in greater detail in [4].

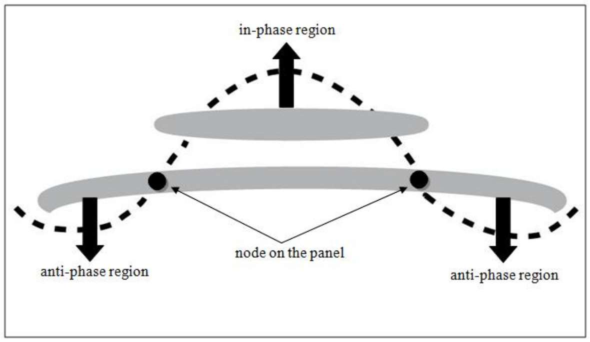


Figure 3: In-phase and anti-phase region on the panel

The in-phase region generates the sound and the anti-phase region offsets overall sound pressure by generating out-of-phase sound. The quadrature region generates no sound. As a result, if the in-phase region is dominant with a minimal anti-phase region, the sound pressure level will be the highest. If the in-phase region is equivalent to the anti-phase region, there will be a dip in the total sound pressure level response of the panel [5][6].

$P(j\omega, r_a) =$ (1)

$SPL(\omega, r_a) = []$ (2)

where P is the sound pressure at the point r_a in air and SPL is the sound pressure level at point r_a. P_0 (equals to 2 x 10^{-5} Pa) is the atmospheric pressure, ρ_0 is density of the air. The integration is taken at each point on the panel, r_p, over the sound radiating area S_p.

In equation (3) below, the accumulated acceleration, a_a shows that the displacement of the panel is converted into the acceleration by a frequency dependent factor, . Equation (4) shows the accumulated acceleration level (AAL).

$a_a(j\omega, r_a) =$ (3)

$AAL(\omega, r_a) = []$ (4)

where a_a is the accumulated acceleration at point r_a.

It can be demonstrated that equation (3) is identical to equation (1) for sound pressure, P except for the phase information, . At the same time, the sound pressure level (SPL) calculated by equation (2) is comparable to the AAL shown in equation (4), as long as the panel moves in phase like a rigid piston. Although the accuracy of the AAL decreases at high frequencies where the panel no longer moves as a rigid body, it shows correlation between the displacement of the panel and the SPL.

At high frequencies, the effective moving mass of the panel decreases, and the effective mass load on the assembly of the drive plate and voice coil also reduces. The ratio of the mass of the assembly of the drive plate and voice coil to the effective moving mass of the panel increases when the frequency rises. This phenomenon reduces the moving area of the panel. Since the sound pressure level is proportional to the in-phase region of the total deformation, the effective sound radiating area decreases at high frequencies [7].

2.4 Effective sound radiating area

Since the shape of the drive plate is circular, equations (5)(6)(7) below demonstrate that the radius of the effective sound radiating area (r_{ra}) decreases by the reciprocal of the frequency, whilst the sound radiating area (S_{ra}) and moving mass (m) of the panel both decrease by $1/f^2$.

$$r_{ra} = \qquad (5)$$

$$S_{ra} = \pi r_{ra}^2 \qquad (6)$$

$$m = S_{ra}^2 \rho_p d \qquad (7)$$

where the E is the Young's modulus and ρ_p is density of the panel [7].

2.5 Directivity pattern

The directivity pattern of sound radiated from the panel depends on its modes [8].

$$R = \; = \qquad (8)$$

where R is the real part of the acoustic radiation impedance and ρ_0 is the density of air. According to equation (8), the real part of the acoustic radiation impedance increases as frequency goes up and the effective radiating decreases. The impedance enhancement compensates the effect of the volume velocity reduction. As the result, the directivity remains narrow due to the reduced effective sound radiating area and volume velocity [9][10][11].

Like conventional loudspeakers, two sound fields radiated from the panel excited by two gel transducers interfere and a standing wave pattern is established. Depending on the phase of the path lengths from each sound source to any point, the intensity of two sound fields tends to add to or subtract from each other.

3. TEST METHODOLOGY

3.1 Finite element analysis

The performance of the complete speaker system was investigated using finite element analysis software. Comsol Multiphysics was used to simulate structural performance and acoustic behaviour of the panel radiating the sound.

The dimensions of the ABS panel used for the simulation are 420mm x 320mm x 2mm and the size of the gel transducer is 44mmØ and 18mm thick. The 8Ω gel transducer is positioned on the centre of the panel as shown in Figure 4.

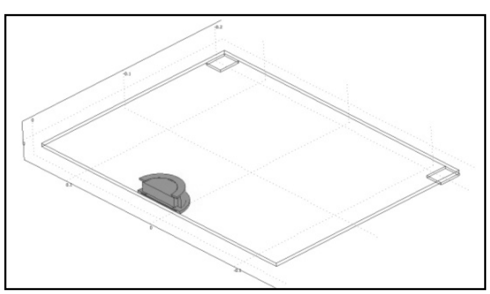


Figure 4: The quarter of the geometry of the panel

The AC/DC module and Structure - Stress simulation module in Comsol Multiphysics were used to calculate the electrical force as a function of frequency and simulate the dynamic response of the panel. The Acoustic - Structure interaction module was used to simulate the sound pressure level and directivity of the sound radiation at 25cm from the panel. Frequencies in the range 20Hz to 20,000Hz were investigated and the peak driving voltage is an RMS level of 2.83V. The boundary condition along the edge of the panel is fixed. In order to reduce the time required for analysis, the simulation was limited to only one quarter of the model.

3.2 Laser scanning

The shape of vibration pattern was observed by a Polytec laser scanning vibrometer (PSV_400_B). The two gel transducers were positioned on the panel with the distance of 200 mm as shown in Figure 5.

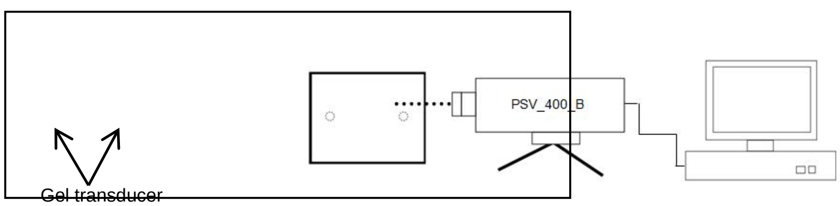


Figure 5: Laser scanning vibrometer measurement set up

This vibrometer operates on the Doppler principle, measuring the frequency shift of backscattered laser light from a vibrating structure to determine its instantaneous displacement [2]. A periodic chirp signal (20Hz to 20,000Hz) at 0.5W (r.m.s) with a resolution of 5 Hz was fed into the two gel transducers attached to the ABS panel respectively at the same time so that the total input power is 1W. The measurement was conducted for 200 points spread over the panel.

3.3 Acoustic testing

The two gel transducers were positioned on the both end of the panel. The ABS panel (size: 420mm x 320mm x 2mm) was clamped and placed 3cm high from the floor in the semi anechoic chamber. A microphone was set up at 25cm above the centre of the panel on axis as shown in Figure 6. An identical sinusoidal pink noise was fed into the two gel transducers at 0.5W (RMS) each at the same time at frequencies in the range 20Hz to 20,000Hz.
The one gel transducer was also tested at 1W (RMS) on the same panel as a comparison with the same testing set-up including the testing signal except for the input power.

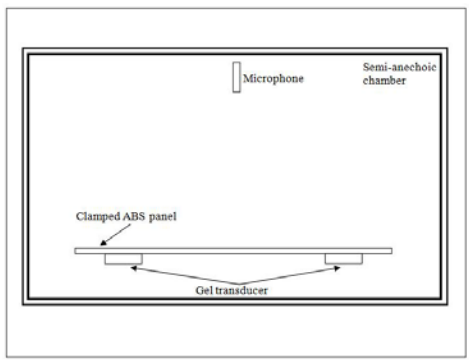
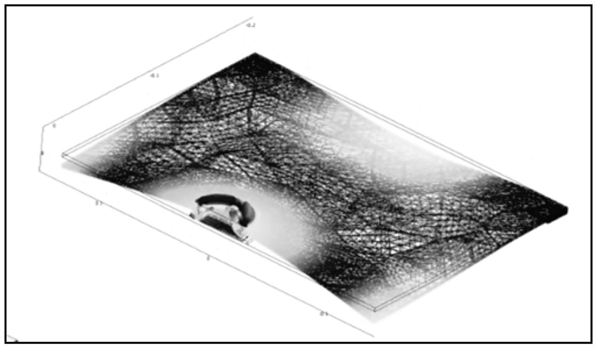


Figure 6: Acoustic testing set up

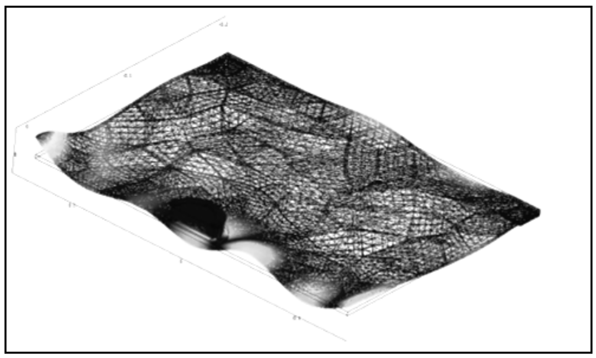
4. RESULTS

4.1 Finite element analysis

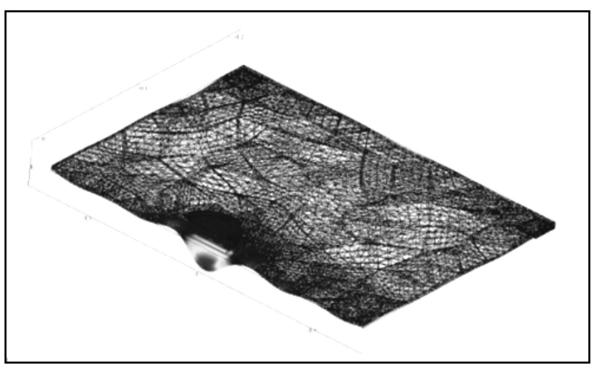
Figure 7 shows the total displacement of the panel computed in finite element analysis at 100Hz, 2,000Hz and 5,000Hz.



(a) 100Hz



(b) 2,000Hz

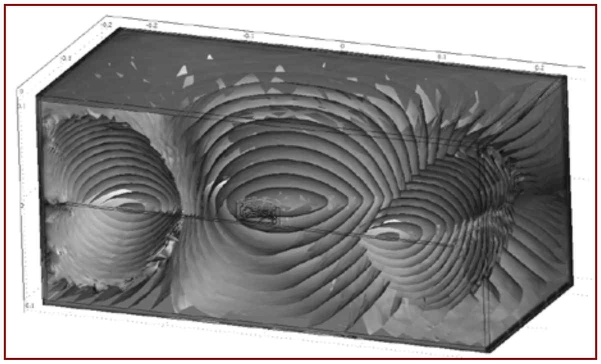


(c) 5,000Hz

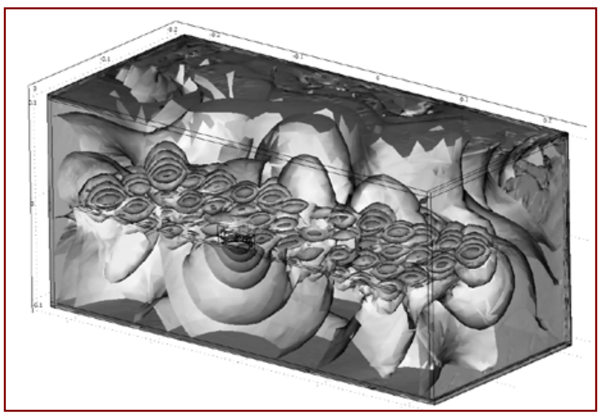
Figure 7: Structural simulation results

The panel at 100Hz behaves like a rigid piston as shown in Figure 7(a). It is because the period of the signal at low frequency is long compared to the speed of propagation. So the entire panel moves in essentially the same phase as if it were a rigid piston. As frequency rises, the period of signal becomes shorter than the speed of propagation. It results in phase shifts so that the panel breaks up into several modes. As frequency increases further, the moving area is limited to the region immediately surrounding the gel transducer as shown in Figure 7(b). This phenomenon is even more clearly shown at 5,000Hz as indicated at Figure 7(c).

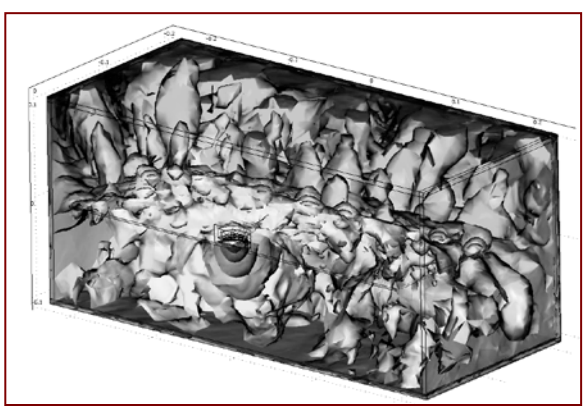
Figure 8 shows the directivity of the sound radiation at 100Hz, 2,000Hz and 5,000Hz.



(a) 100Hz



(b) 2,000Hz



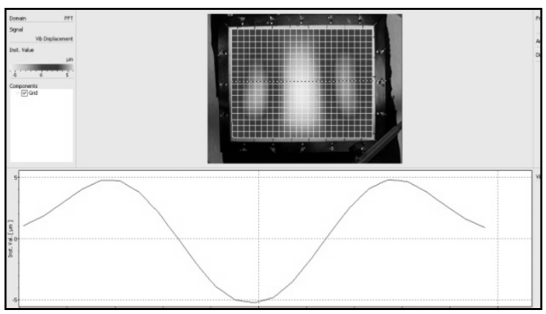
(c) 5,000Hz

Figure 8: Acoustic simulation results - the directivity pattern of the sound projected from the panel

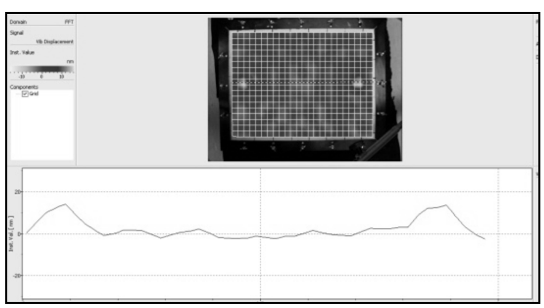
Figure 8(a) indicates that at 100Hz the whole panel moves as a rigid piston that results in sound radiation from the entire panel. As frequency increases higher, the moving area on the panel becomes localised shown in Figure 8(b) and (c). Therefore the directivity of the sound radiation is sharp and narrow over the moving area of the panel.

4.2 Laser scanning analysis

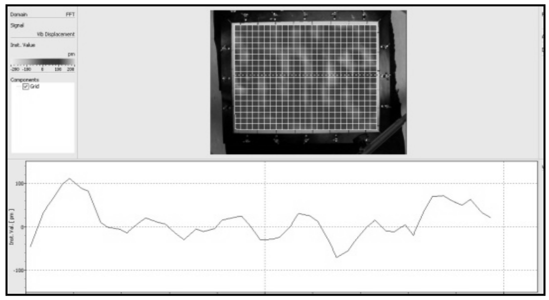
The displacement of the profile of the panel at different frequencies is shown in Figure 9. Y-axes is µm and x-axes is the profile of the panel.



(a) 100Hz



(b) 2,000Hz



(c) 10,000Hz

Figure 9: Maximum displacement of the profile of the panel excited by the two gel transducers

Figure 9(a) and (b) demonstrate that the moving area of the panel reduces and becomes localised on the position of the gel transducer as frequency increases. This effect became apparent at around 1,600Hz.

The amplitude of displacement of the panel from 100Hz to 2,000Hz also reduces from 5µm to 15nm. This is due to a decreasing electrical force generated by the gel transducer with increasing frequency, as well as the damping effect of the gel surround.

Figure 9(c) demonstrates that the positions of the in-phase and anti-phase regions occur randomly above 10,000Hz due to intermodulation distortions. The possible reason for this effect is random variations in the dynamic behaviour of the panel and gel surround.

4.3 Acoustic testing results

Figure 10 shows the SPL radiated by one gel transducer compared with two gel transducers.

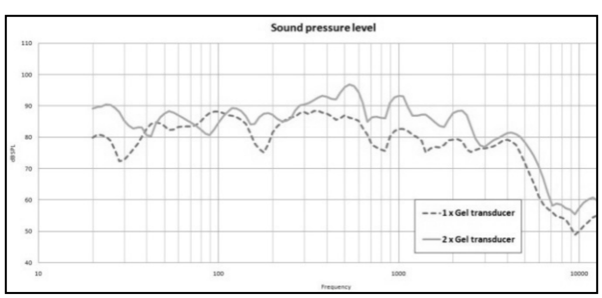


Figure 10: Sound pressure level of one gel transducer versus two gel transducers

The dotted and solid lines are the SPL of the one and two gel transducers measured at 1W and 0.5W of input power respectively. It was observed that the panel excited by the two gel transducers radiates higher SPL in comparison with the one gel transducer system proportionally at high frequency. It was also found that the panel excited by the two gel transducer projects higher SPL at low frequencies below 1,000Hz, although destructive wave cancellations expected at this frequency band. It is because the gel surround allows bending waves to travel through the panel with minimal wave cancellations.

It was also discovered that amplitude of displacement of the panel excited by the gel transducer at 0.5W and 1W above 1,000Hz is almost identical. This may explain that the overall acoustic intensity of the panel excited by the two gel transducer at 0.5W each is higher than the acoustic intensity of the panel excited by the one gel transducer at 1W.

5. DISCUSSION

It was predicted by the finite element analysis that the vibration mode of the panel, excited by the gel transducer, changes at different frequencies. Figure 7 shows that the moving area of the panel decreases as frequency increases as shown in Figure 7(b). In particular, this is clearly demonstrated at 5,000Hz (Figure 7(c)), where the sound radiating area has become localised within the immediate vicinity of the gel transducer. These simulation results were proved by the laser scanning vibrometer as shown in Figure 9. Furthermore the localisation of the moving area around the gel transducer was observed at 2,000Hz in the simulation analysis and above about 1,600Hz in laser scanning tests, whereas the bending mode occurs along the entire panel at low frequencies.

As a result, the effective sound radiating area on the panel decreases at high frequencies and causes a decrease in volume velocity so the directivity of the sound field becomes narrow as indicated in Figure 8. Additionally, as the frequency of the pistonic force that is applied to the panel from the drive unit increases at higher frequencies, the stiffness of the panel also increases. Therefore the anti-phase region of the panel is consequently minimised so the displacement of the panel at high frequencies, comprises mainly of the in-phase regions as shown in Figure 9(b). This contributes to minimal acoustic cancellations.

Therefore the panel with two gel transducers starts to radiate with two independent sound sources above about 1,600Hz. According to the previous paper [2], it was demonstrated that the acoustic performance of the single gel transducer covers the low and medium frequencies in the range 50Hz to 1,500Hz with good sound pressure level response. As a result, it is possible to set up a sound system with 2.1 channel configuration by utilizing a combination of multiple gel transducers. For example, the front screen of a TV with two gel transducers can radiate a stereo sound while a single gel transducer attached to the back panel of the TV covers low and medium frequencies in the range 50Hz to 1,600Hz.

However, Figure 9(c) indicates that due to the harmonics and intermodulation distortions resulting from random variations of the dynamic behaviour of the panel and gel surround at high frequencies, anti-phase regions occur above 10,000Hz.

As Figure 9(a) shows, at low frequencies, the single panel vibrates as a rigid body, so that it causes the phase interference between the two gel transducers. The acoustical cancellations occur within a lower frequency band (see Figure 10), and the constructive acoustical interference occurs within higher frequency bands.

In the present study, identical sinusoidal pink noise was fed into the two gel transducers at the same time. This may have provided more opportunities for mechanical and acoustical cancellations on the test panel. Therefore it is predicted that less destructive interference may be possible if a different signal is fed into the gel transducers separately at high frequencies.

6. CONCLUSION

The finite element analysis, the laser scanning and acoustic testing have been used to demonstrate that the effective sound radiating area of the panel reduces and becomes localised on the position of the gel transducer as frequency increases. Furthermore, due to this localisation, the volume velocity also decreases. It causes the directivity of the sound field to remain narrow. As a result, it is possible to radiate multiple independent sound sources from the single panel excited by an equal number of gel transducers. In this paper, only the two gel transducers were used to demonstrate two independent sound sources with minimal acoustic cancellations. However, random variations in the dynamic behaviour of the coupled panel and gel surround, resulted in intermodulation distortions above 10,000Hz.

Therefore it has been shown that a single panel, excited by two gel transducers, radiates two independent sound sources at high frequencies.

7. FUTURE WORK

It has been shown that the vibration modes of the panel change according to the frequency band. Those modes are also affected by the thickness and shape of the panel due to changes in stiffness. This implies that the size of the effective sound radiating region can be controlled. Therefore it might be possible for a single panel to radiate across the full audible frequency range from 50Hz to 15,000Hz.

The mechanical properties such as damping and stiffness of the gel surround also changes as a function of the temperature. It means that as the temperature changes, the dynamic behaviour of the gel transducer also changes. It will result in different acoustic behaviour. The research on this will be suitable for future work.

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DESIGN AND IMPLEMENTATION OF A DSP ENHANCED PORTABLE SPEAKER SYSTEM

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This paper describes the design and implementation of a low cost portable speaker system with digital signal processing (DSP) enhanced performance. The cost of incorporating DSP into a low cost consumer audio product is typically prohibitive. Latest transducer developments in conjunction with recent advances in low cost audio digital signal processors have made it possible to consider a commercial board level implementation of a small portable speaker system with significant audio quality enhancement.

INTRODUCTION

Miniature speaker systems are in abundant use in consumer devices. These may include mobile phones, personal digital assistants, portable music players, notebook PCs and display devices. They may also be found as dedicated accessories, for instance portable speaker units for use with portable music players that only have a limited loud speaker output or headphone output only.

Present portable speaker systems used as an accessory to a music playing device are typically low-cost lightweight units with an external power supply or internal batteries, analogue audio input, and possible rudimentary controls (for instance: on/off, volume).

These systems are now demanding a higher level of perceived audio quality. This can be achieved by improving component quality and performance or compensating for non-ideal performance using signal processing.

The following chapters describe design issues associated with low cost portable speaker systems relating to audio quality and cost, followed by digital signal processing techniques that can be used to enhance the audio quality, and finally an example of a commercial, cost sensitive implementation.

DESIGN ISSUES

Small Speakers

By their nature small speakers tend to have limited response at the low end of the audio frequency range, and have limited output power over the full audio spectrum resulting in non-linear distortions when driven to their limits. Different speaker technologies and designs may have more significant distortions at different frequencies.

In this case ‘Gel Audio’ (GA) [7] transducers from SFX Technologies Ltd [2] were used. These are inertia driven DML type drivers, with a magnetic assembly, coil and drive plate suspended within a hydro gel. The hydro gel also serves to couple the vibration of the assembly and drive plate to the panel.

When a signal is present, the coil/drive-plate moves with respect to the magnetic assembly, the inertial force is transmitted through the hydro gel to set up vibrations in the coupled panel. A low frequency limit is imposed for small mass Gel Audio drivers where the force on the panel can be no greater than the reactive force from the mass of the free floating magnetic assembly.

In this way, the transducers can be used to drive surfaces that can be external to the system enclosure. Therefore the overall system performance depends on the system itself as well as the surface it is in contact with. This feature is described in more detail in [6]

One beneficial aspect of using DML drivers over traditional cone drivers is the ability of the DML to act more omni-directionally over higher frequencies. In the unit discussed here, which is intended to be used as a table top device, the omni-directivity is a desirable trait.

Low cost enclosures

Low cost plastic enclosures typical of mass produced consumer devices can introduce resonances at particular frequencies. Multiple speakers within a single enclosure may also produce an interference effect creating resonances and regions of poor frequency reproduction.

In the discussed portable speaker system, both drivers are attached to opposite faces of the same rigid unit; in addition to the cancellation of inertia from two moving magnets in anti-phase, vibrations will also travel around the sides of the box and affect the opposite driver through interference. This interference is unavoidable in such a small stereo distributed mode loudspeaker (DML) system.

DSP Hardware

Like most consumer devices, mass-produced portable speaker systems have very aggressive cost expectations. Typical electronic hardware target production costs for a stereo unit without DSP and only rudimentary control are below $20/unit and sometimes below $10/unit.

Simple analogue filtering could be considered to make limited improvements to the audio response with marginal cost increase but also marginal increase in performance.

Traditionally the inclusion of digital audio processing would have a dramatic effect on the unit cost. The system would have required an often bulky and power-hungry DSP device, memory, accurate power regulation, analogue-to-digital conversion (ADC), digital to analogue conversion (DAC), and other ancillary devices like quartz crystals. All of these had a prohibitive impact on the cost of the electronic assembly.

More recent integrations (for instance [8], [9]) have resulted in smaller, lower power, lower cost devices that incorporate ADC, DSP and DAC into a single device, often with limited or fixed-function DSP facilities, but sometimes with highly programmable DSP functionality. With the reduction of ancillary components required, this has resulted in board level solutions that are of small enough size, power and cost to be commercially competitive.

TARGET SYSTEM

The following study and implementation is based on a unit comprising two Gel Audio transducers from SFX Technologies Ltd [2] with the electronic hardware and DSP software designed by Steepest Ascent Ltd [5]. The two transducers were mounted in a simple plastic enclosure (Box size: 100 x 50 x 20mm, 2mm ABS, Transducers: 25 x 9mm) one facing upwards, and one facing downwards.

Each transducer creates an individual distributed mode loudspeaker area, the upper facing driver exciting the top panel of the unit, the lower driver using the Gel-audio effect whereby the table or panel beneath the box unit is excited to perform as a larger area DML. Both drivers act to move the panel through inertia of their respective magnetic assemblies.

These two areas of panel movement are suited to different frequency bands, the small top panel of the box having a better response over the higher frequencies and the table top achieving greater bass response due to the larger surface area and lower resonance of the table top. This is shown in Figure 1.

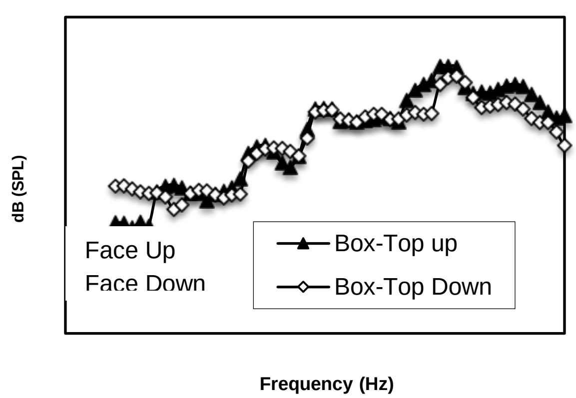


Figure 1 Transducer Orientation Performance

There is an inherent non-linear effect present in the mechanics of the driven panel loudspeakers which detracts from obtaining a flat frequency response. A driven panel has multiple resonances associated with it, due to the material and dimensions, the air coupling with the panel and the mechanical reaction between the moving mass and the panel. The frequency response is related to this accordingly with the standard response for an inertial driven panel being a series of peaks and troughs; it is the lower frequency range that suffers the greatest non-linearity from this effect. An extended and mostly flat frequency response is created only over areas where the modal/resonance density is high.

Figure 2 shows a close up view of the response of a driven panel from 700Hz to 1000Hz. The graph illustrates the large variations that can occur in dB level with frequency. It also illustrates an unexpected behaviour of the driven panel; that voltage input (dBu) is directly related to dB SPL for all frequencies, even if the output is not linear with frequency.

On Figure 2, it can be seen that the difference between the lines is a constant 3dB and occurs throughout the troughs and peaks. This shows that it is possible to raise the SPL even over areas of low response, such as the large trough shown below, due to the difficulty of exciting the driven panel at a position incompatible with the mode shape assumed at that frequency.

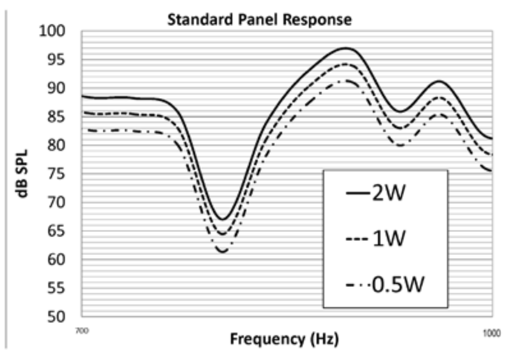


Figure 2: SPL Response of DML

There are no limitations imposed for reducing the peak levels in the frequency response, as a proportional cut in digital signal level over these areas will be achievable with any size of amplifier. However, the increase in signal level required to bring a large trough up to the average level of output will be greater than the range of a small amplifier.

For instance, for the 1W output plot on Figure 2, a band pass filter centered on the trough would need to supply a gain of around 20dB to bring the level up to the average of 85dB. As the output from the amplifier is already at 1W, the amplifier would then need to have extra headroom of 100W to raise the trough up to the average.

This will create problems with distortion in any small amplifier. Even if the filtered signal exists has sufficient headroom in the 1 bit digital domain, it can still be output at a level no greater than the maximum output set by the amplifier. It will always prove more efficient to reduce the gain of the peaks of the response, rather than to greatly over specify the gain of the amplifier in order to bring up the very low areas of frequency response.

CHARACTERISATION

The speaker system was characterised in terms of its frequency response by exciting the speaker system with a test tone and recording the power of the tone as measured by a microphone in a position considered to be a typical listening position relative to the speaker.

In order to provide a comparison, a good-quality set of desktop computer speakers and a competitive portable speaker unit (utilising conventional speakers) were also measured in this way.

In addition to the limited low frequency efficiency of a small, low mass inertia based driver acting on a thick panel such as a table top, are the effects of the cancellation of the sound between two drivers mounted back to back in a small box, (briefly covered in section 1.2) and the general response of a driven panel. (Covered in section 2)

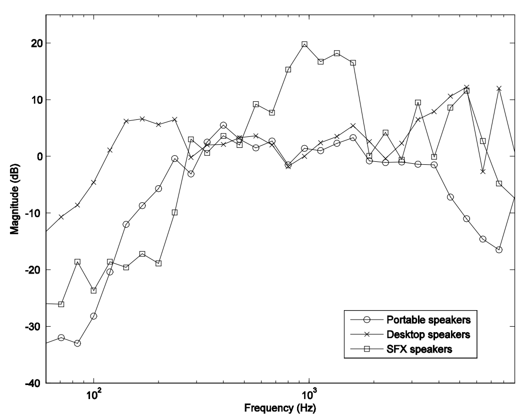


Figure 3: Response of various speakers to tones

Notable features of Figure 3 are the very weak response of the speaker system in the 100-200Hz range and the strong broad peak at around 1 kHz. The resulting sound of this response is very "tinny" and unpleasant to listen to. One positive feature of the speaker system in comparison to the comparison portable speakers is the good response beyond 5 kHz.

DSP SYSTEM PROPOSAL

As part of the investigation into improving the audio response via DSP, connecting the two transducers in anti-phase made a noticeable difference, but in subjective-listening the bass response was improved further by simply disconnecting one transducer entirely. This lead to the idea of applying a cross-over at a few hundred Hz, sending the low frequencies to one transducer and the high frequencies to the other. Of course, this means that stereo audio would not have been possible, should it have been desired, but due to the very small physical separation between speakers and with the typical orientation being one transducer "face down", one transducer "face up", good stereo reproduction cannot be expected anyway. The most beneficial arrangement was to send the low frequencies to the "face down" transducer and the high frequencies to the "face up" transducer. With such a crossover in place, the response was as shown in Figure 4, with the response without the crossover shown for reference.

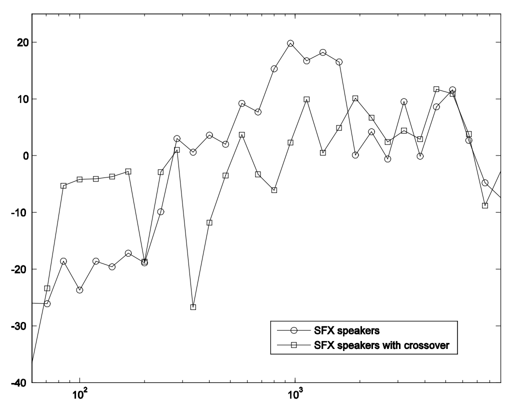


Figure 4: Response of SFX speakers with cross-over

The resulting response has a greatly improved level of bass frequency response, and the resonance around 1kHz has been greatly reduced.

Based on these findings and a perceived need for equalization in the mid to high frequencies, the overall DSP processing was designed as shown in Figure 5.

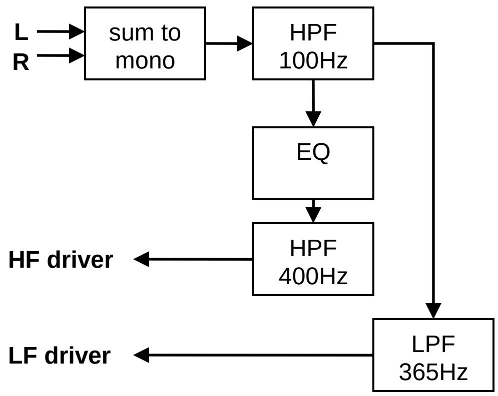


Figure 5: DSP system design

The 100Hz high pass filter was introduced to remove any very low frequencies where the speaker's response was poor, in order to prevent wasted energy and hence help extend battery life. The equalizer component has been introduced with the goal of flattening the frequency response in frequencies beyond 400Hz. The 400Hz high pass filter and 365Hz low pass filter are both 8-pole Butterworth IIR filters, selected to give as close to a flat overall magnitude response as possible.

EQUALISATION

As stated in the previous section, an equalizer was proposed to flatten the overall response of the speaker system at mid to high frequencies.

In order to design the equalization filter, white noise was driven through the speaker system and recorded using a microphone. The frequency response of the signal received by the microphone was then computed via an FFT and an FIR filter was designed that matched this frequency response. This FIR filter was then adaptively equalized using the architecture shown in Figure 6.

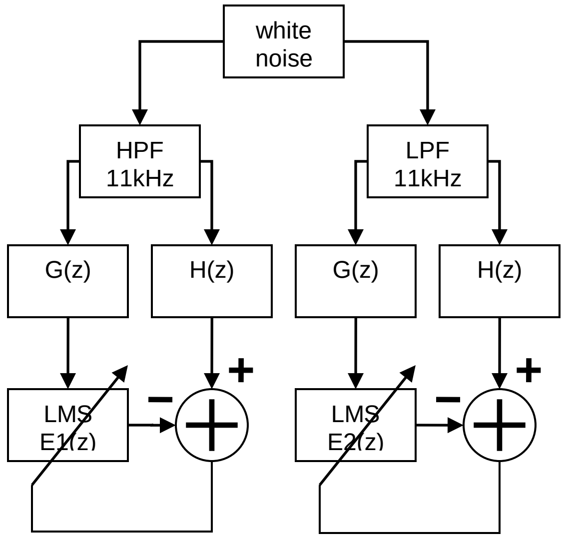


Figure 6: Equalization architecture

In Figure 7, H(z) is the measured frequency response of the microphone, obtained by playing white noise through a very good quality set of reference speakers and assuming all non-whiteness in the response was due to the microphone. Placing such a response in this adaptive architecture avoids the equalizer trying to compensate for any non-whiteness caused by the microphone's response. G(z) is the measured response of the un-equalized system, obtained by playing a pair white noise sources into the L and R inputs of Figure , with the equalization component omitted, and recording the output from the speakers with a microphone.

A second point of note is the use of high pass and low pass filters to split the band to equalize into two sub-bands, 0 to 11 kHz and 11 kHz to 24 kHz and equalizing each sub-band independently. Although this is not a true sub-band approach, the lack of stimulus in one half of the band for each equalizer means each equalizer will only adapt in that half of the band. This makes it easier for each equalizer to adapt, as the frequency response it is attempting to adapt to is less complicated. The adaptive algorithm used in each case is the Least Mean Squares (LMS) algorithm [4]. The final adapted responses of the equalizer are E1(z) and E2(z).

The overall FIR equalization filter indicated in Figure was obtained by the process illustrated in Figure . The final filter weights were obtained by taking the impulse response of this structure.

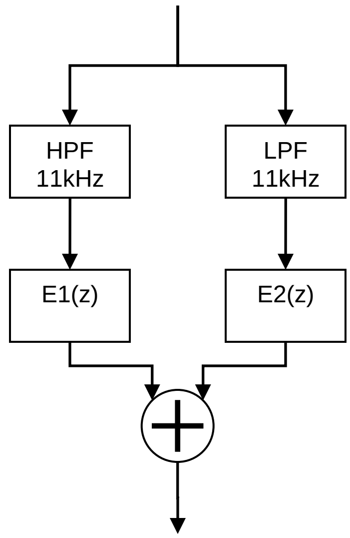


Figure 7: Final equalization filter construction

The final impulse response and magnitude response of the equalizer is shown in Figure .

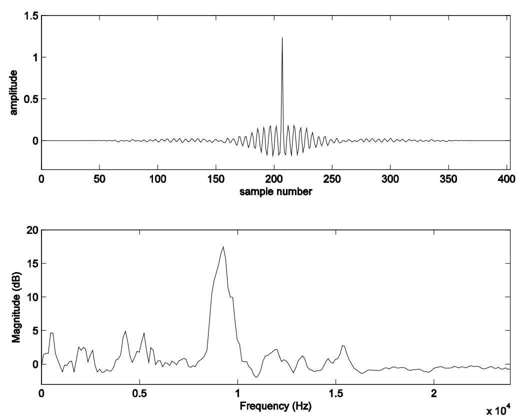


Figure 8: Equalization filter impulse and magnitude responses

FIR FILTER AS A SET OF BIQUADS

When considering the hardware implementation options for this DSP processing, it initially appeared that such a large FIR equalization filter as presented in the previous section may be prohibitively expensive to implement. Therefore a strategy of fitting a relatively small set of second order IIR filters (biquads) in parallel to match the approximate frequency response of the FIR filter was used. The set of biquads was of size 20, and the optimization was via a "brute-force" approach, choosing the best-fit parameters (coefficients) of each biquad in turn whilst assuming thus-far unoptimised biquads had a transfer function of simply 1/20. The resulting fit is shown in Figure . Note that this fitting was done solely on magnitude response and therefore the phase response of the set of biquads differs considerably from that for the FIR filter. In any case, the group delay deviation from the optimum never exceeded 4ms and in subjective listening tests this approach sounded not as good as the FIR in terms of equalization, but considerably better than the speakers without equalization, and therefore was considered an acceptable alternative should the large FIR equalizer prove overly expensive to implement.

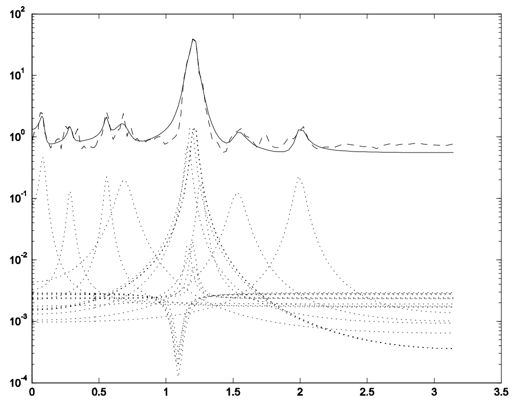
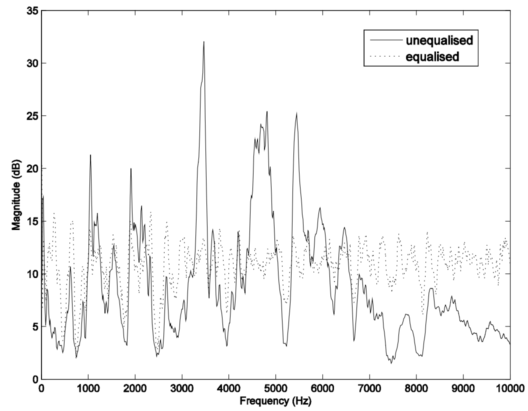


Figure 9: Biquad fitting

In Figure , the dashed line is the original FIR equalizer magnitude response, the solid line is the overall response of the 20 biquads, and the dotted lines represent the individual responses of each of the 20 biquads.

RESULTS

Figure 10 shows the overall frequency response before and after the equalization, with the upper subplot showing frequencies from 0 to 10 kHz and the lower subplot showing frequencies from 0 to 500Hz. This Figure was produced by driving a pair of white noises into the L and R inputs in Figure and recording the output from the speakers with a microphone. It can be seen that the equalization results in a much flatter overall response compared to the original series of high peaks and troughs associated with the original modal behaviour of the unit, and subjective listening confirms that the sound of the equalized system is greatly improved.



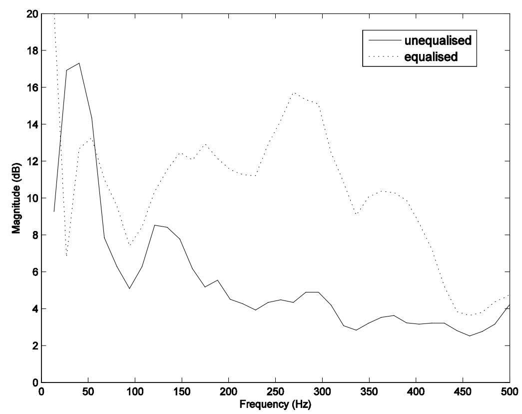


Figure 10: Response before and after equalization

HARDWARE IMPLEMENTATION

Digital Signal Processor

The selected processor is the ADAU1701 [3] processor from Analog Devices. The device consists of a programmable DSP core running at 50 MHz with options to run at 28bit or 56 bit precision, two sigma-delta ADCs and four sigma delta DACs. The development environment, SigmaStudio, is through a graphical interface where the signal flow is built from functional blocks.

The ADAV1701 has the ability to self-boot from an inexpensive serial eeprom. It has very few ancillary components and is physically small (48 Lead LQFP package) and inexpensive in volume. It runs off a 3.3V power supply, and with the aid of an external transistor, self regulates a 1.8V supply for its core.

System Architecture

The system architecture is shown in Figure 2. The goals of low cost and low component count are achieved through the use of the highly integrated DSP, passive filters, and highly integrated miniaturised amplifier.

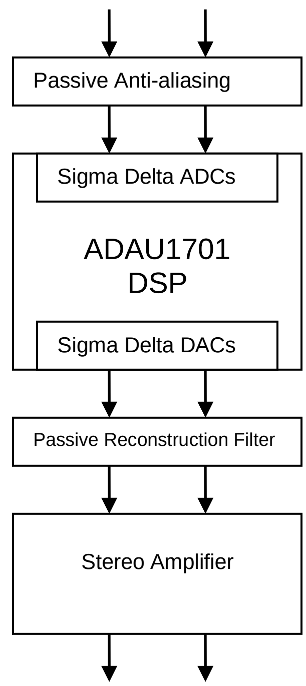


Figure 2 System Architecture

Simple Anti-aliasing and Reconstruction Filters

Simple passive filters afford a good enough performance for audio systems at this level of fidelity. The following simulations show the filters used for input anti-aliasing and output reconstruction.

The anti-aliasing filter circuit and response are shown in Figure 3 and Figure 4 respectively.

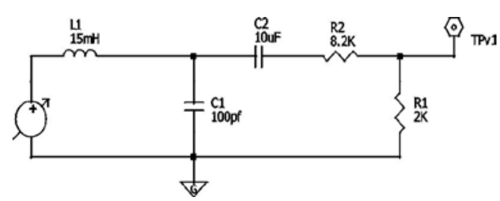


Figure 3 Anti-aliasing filter (spice)

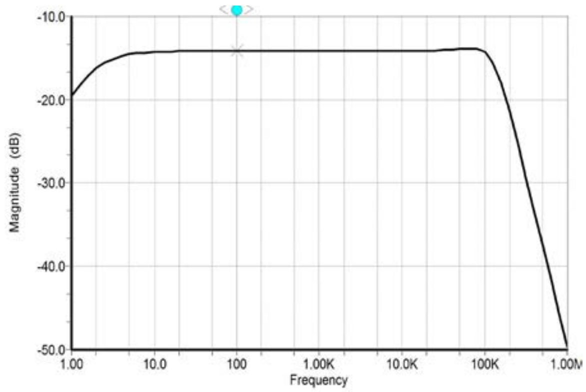


Figure 4 Anti-aliasing filter response

The reconstruction filter circuit and response are shown in Figure 5 and Figure 6.

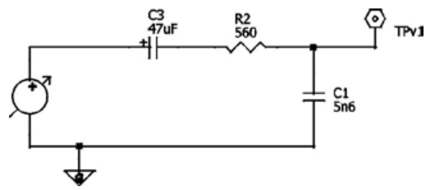


Figure 5 Reconstruction filter spice simulation

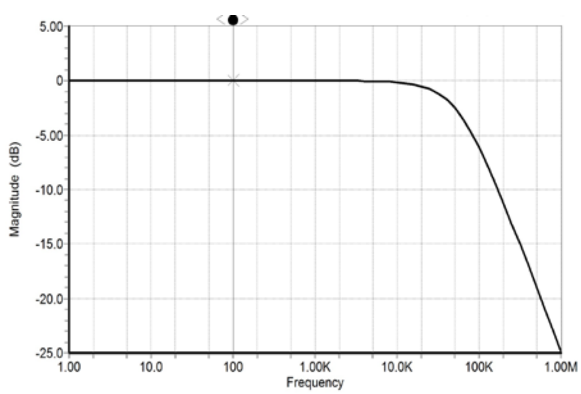


Figure 6 Reconstruction filter response

No system input gain required

An extra active gain stage to match the expected input audio level to the digital system dynamic range would be an unwanted addition to board area and component cost. The ADAU1701 ADC has a current mode input, so a single voltage-to-current resistor per channel allows the desired full scale output to be matched to a chosen max input level.

Amplifier Considerations

Standard implementations of Class AB and Class D amplifiers were implemented during product development. The desired output is approximately 1 Watt per channel, and there are a number of devices available to achieve this in a single package with very few addition components. Class AB amplifiers are less efficient and dissipate more heat, needing particular care with cooling. The surface mount packages typically have a cooling pad under the body of the device, which is designed to dissipate the heat through a matching contact on the board.

Class D amplifiers produced a louder output and, due to much improved efficiency, consumed less power. As the amplifier is the main power consuming device in the system, this has a significant impact on battery life.

Note that the presently available devices dictate that the link between the DSP and a Class D amplifier is still analogue. It is expected that a future improvement would be to have direct digital transfer to the amplifier, and possibly the amplifier integrated into the DSP device.

Layout Considerations

To support the addition of advanced digital processing to simple small amplifier designs, a more considered approach to PCB design for power and ground is required [1]. The PCB comprises 4 layers as shown in Figure 7. This enabled adequate signal routing and power plane positioning to achieve high quality audio reproduction.

Layer	Function
1	Components and routing
2	Ground
3	Split power plane
4	Routing and ground flooding

Figure 7 PCB Layers

In order to avoid interference between analogue audio signals, digital processor switching and ADC references, the power plane was split into the 3 regions, 5V-analogue, 3.3V-digital and 3.3V-ADC, as indicated in Figure 8. The components were positioned such that return current paths could be as short and straight as possible.

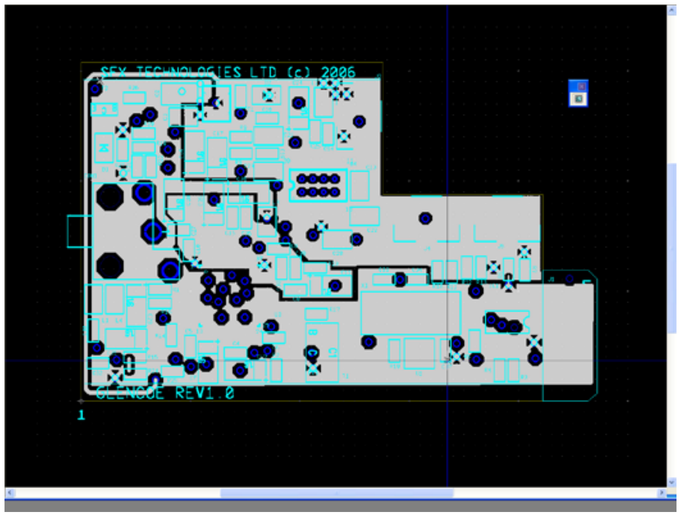


Figure 8 Split Power Plane

The assembled system is shown in Figure 9 measuring approximately 53mm x 40mm.

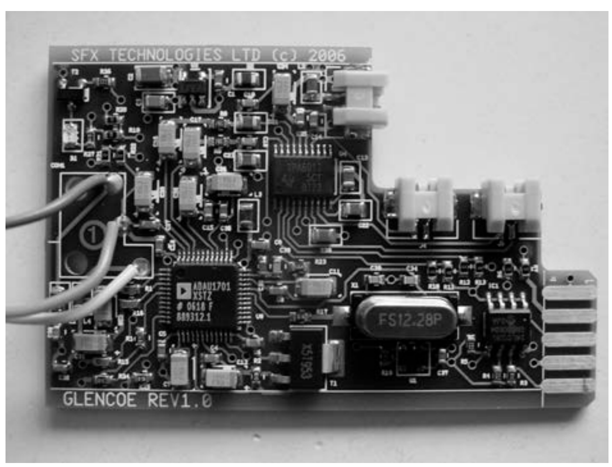


Figure 9 Assembled PCB

CONCLUSIONS

Digital signal processing devices and audio amplification devices are now available with sufficient integration and low enough volume pricing to allow a board level solution for a portable speaker system with advanced DSP correction algorithms.

Advanced adaptive techniques and careful filter design can provide significant improvement to perceived audio quality in a system where the speaker response and surrounding mechanical effects are not desirable.

In the respect of a DML system, DSP processing can be used to significantly even out the inherent non-linear response of a driven panel. However, the ability to raise low troughs in the frequency response will be limited by the maximum gain of the amplifier used.

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Appendix C   Gel-based Drivers Patents

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
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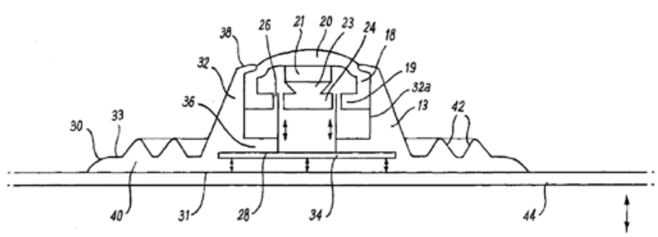
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

(88) Date of publication of the international search report: 24 February 2005

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: IMPROVEMENTS TO LOUDSPEAKER DRIVER ASSEMBLIES



(57) Abstract: An improved driver assembly for a panel loudspeaker includes a retaining element for locating the voice coil with respect to the magnet assembly and forming a surface for removable attachment of the driving assembly to a radiating member. In a preferred embodiment, the retaining element is injection moulded from a hydrogel material with Shore A hardness in the range 0 to 20.

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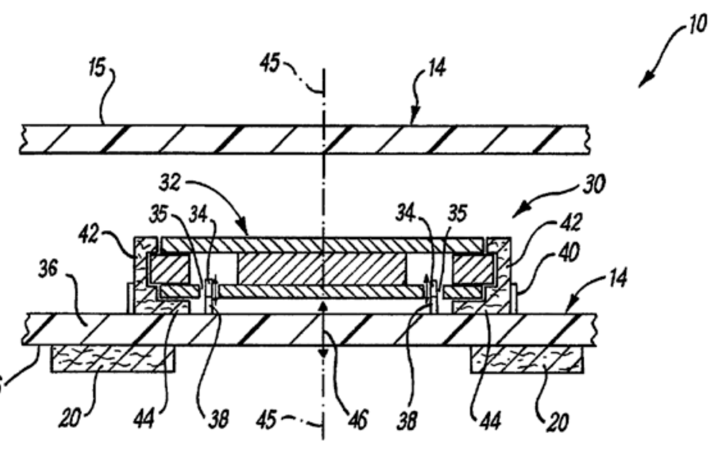
(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

[Continued on next page]

(54) **Title:** IMPROVEMENTS TO AUDIO DEVICES



(57) **Abstract:** An electronic device having an audio function and its loudspeaker arrangement are described. The electronic device comprises an exterior housing, an acoustic transducer and an acoustic radiator forming a part of the exterior housing of the electronic device. In one embodiment, the exterior housing undergoes pis tonic movement and is provided with hydrogel pads to couple an acoustic signal to an auxiliary surface, which then vibrates in a distributed mode. The voice coil may be directly bonded to the exterior housing. A formation may be provided to promote pistonic movement of a part of the exterior housing. Methods of operation and formation are also described.

WO 2007/045908 A1