OMNIDIRECTIONAL LOUDSPEAKER DRIVER WITH SECTORS MEMBRANE

Michele Pontillo

Acoustic System Designer, Doctor in Mathematics, michele.pontillon3yp@gmail.com

Ruben Pico

Institut d'Investigació per a la Gestió Integrada de les Zones Costaneres (IGIC), Universitat Politècnica de València (UPV), 46730 Gandia, Spain, rpico@upv.edu.es

Paco Castells

Instituto ITACA, Universitat Politècnica de València, Valencia 46022, Spain, fcastells@eln.upv.es

Abstract. An omnidirectional loudspeaker driver, whose membrane is shaped in different sector materials to optimize the frequency response, is here considered. The study starts analyzing the original "Walsh driver", designed by Lincoln Walsh at the end of the sixties. The driver is a tapered tall cone mounted face down on top of the enclosure, with the concave side volume seeing internal damping material and the external side radiating towards the listening area. In the first prototypes the membrane was of paper; in a second time it was partially covered by different metal foils on respective sector areas to optimize the frequency response band emitted by the related sector. Over the years titan and carbon fiber have been also used, sometimes in drivers with only one sector. Considering, however, the progress made in recent years in new materials, the purpose of this study is to investigate how a composed membrane can give the possibility to achieve a more balanced response, controlling some parameters such as density, stiffness, thickness, etc.

INTRODUCTION

The speaker studied in this work is a wide band, thought to reproduce the widest possible audio band, starting from the voice band and expanding it, if possible, over. The reason why its inventor [1] decided to develop it was the conviction that not only is the frequency response very important for a realistic listening experience, but also the phase response (besides, of course, many other characteristics, as harmonic distortion, intermodulation distortion, transient response, spectral decay, etc.) together with its special, omnidirectional, polar pattern [2]. Apparently, it can seem like a normal, elongated, cone driver, but the way it radiates is a bit different. In fact, after the band in which it behaves like a piston, radiating longitudinal waves, the principle here is to use the travelling bending waves on the surface of the cone itself to generate sound. As it is known from many studies [5], [6], [12], a traditional dynamic driver works as a piston only until a certain frequency (for a typical driver this happens until $Ka < 1$, with $k = 2\pi/\lambda$ wavenumber, λ wavelength and a radius of the membrane). After that frequency, many different modes can affect the behavior of the membrane, with some deformations and delays in different areas - respect the time of arrival of the signals to the voice coil - creating, as consequence, aberrations (peaks and dips) in the frequency response, besides other anomalies in the time domain capable of compromising the transient response. This obliges the use of different specialized drivers for different audio bands (woofers, midranges, tweeters, etc.), whose singular response must be integrated with the other ones by crossovers [7]. The use of passive crossovers, including reactive components (inductors and capacitors), makes the control of the phase difficult, if not at the cost of sacrificing other aspects, as the already mentioned time response. Not negligible is also the fact that, generally, the various drivers do not have a coincident center - except the case of a coaxial one - generating different arrival times to the ears of the listener. By using active crossovers, today, with the addition of DSP elaboration, the integration is a bit simpler, even if the consequences of non-coincident centers in case of multi-way speakers remain. For all these reasons, having the possibility to use only one driver can be an advantage in some applications, because it also means the use of only one amplifier channel.

The use of a singular membrane with high stiffness suffers much less of the phase problems described for a piston driver.

In Fig. 1 a picture of a Walsh Driver is shown, built in the nineties, by Ohm Loudspeakers, using three sectors.

Fig. 1 – A sample of a Walsh Driver

Fig 2 – Two drivers with only one sector, made of Titan (left) or Carbon Fiber (right), both made by German Physics

The study is set up to consider two sectors, everyone divided into two adjacent layers. In general, it would be easy to extend it to more sectors: this option can be considered for future insights. The eventual cases of one singular material used for the entire membrane is a subset of it, in which the different sectors can be considered having the same identical properties.

In Fig. 1 it is easy to note three different sectors, internally all made by paper, and covered, respectively, the top layer by a titanium foil, dedicated to the high frequencies, and the mid layer with an aluminum foil, for the mid frequencies. The different stiffness and velocity of sound in those materials have been used to optimize the mechanical impedances for a better interface between the radiating sector and the air.

The drawing below shows a schematic structure of the driver, along a vertical section plane:

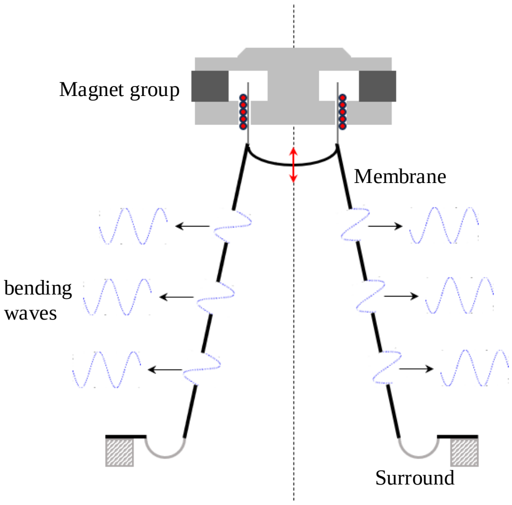


Figure 3 – schematic structure

A theoretical advantage of this structure is due to the fact that, meanwhile the wave travels down to the cone, a vertical cylindrical wavefront is generated, with virtually no phase errors.

This is in favor of the coherency of the re-created image of the sound stage.

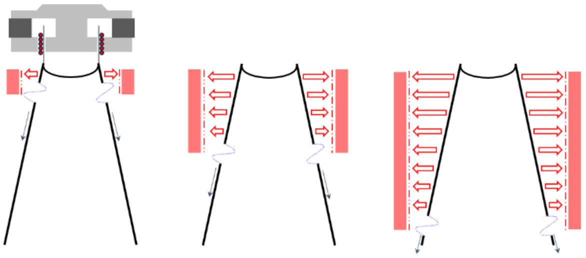


Figure 4 – A cylindrical wavefront is generated by the waves sides emissions

GEOMETRY

The geometry of the speaker – Fig.5 - is included in a circular axisymmetric (spherical in 3D) environment which, on the side circumference, sees a PML (Perfectly Matched Layer) as absorbing layer. This last one avoids any reflection, simulating the behavior of a free field that we can imagine equivalent to an anechoic chamber.

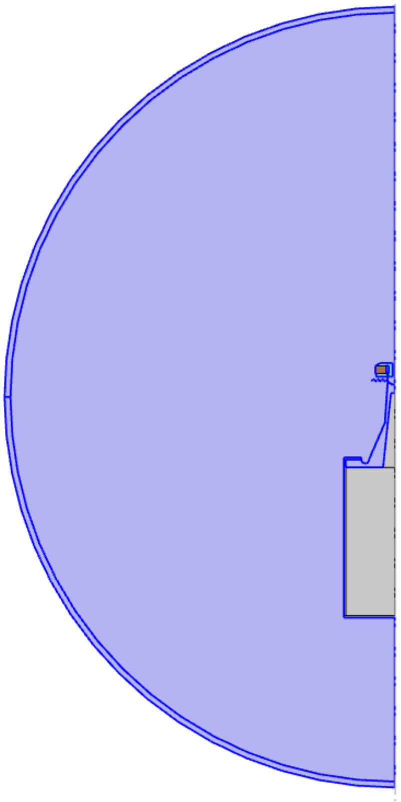


Figure 5 – Geometry of the speaker including a PML on the external circumference

The components included in the speaker are described in the following list.

A magnet group made by:

- a Bottom plate (1);
- a toroidal Neodymium Ring(2);
- a Top plate (3);
- a Voice Coil (4);
- a Former (5), where the VC is mounted;
- a Spider (6);
- a Copper cap (7);
- an Aluminum ring (8);

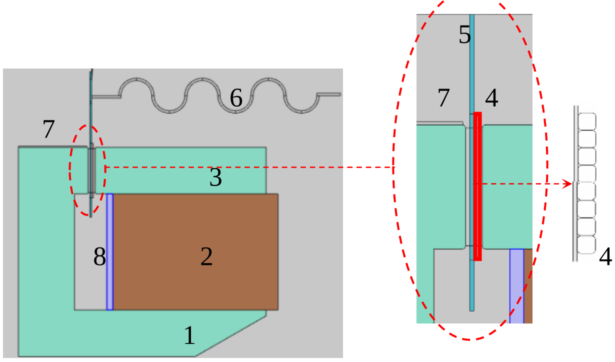


Figure 6 – Magnet group with details

A membrane (9) divided into sectors:

- (9a) First Sector (connected with the former);
- (9b) Second Sector (connected with the surround).

  Each, in turn, is divided into two layers (Front and Rear):

A semicircular surround (10).

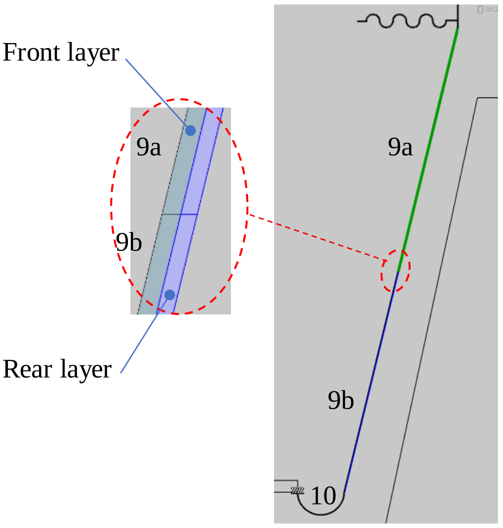


Fig. 7 – Membrane (9) and Surround (10)

The driver is mounted in a Box (11), containing Porous Absorbing Material (12).

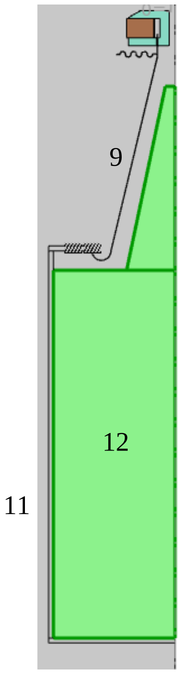


Fig. 8 – Box with damping material

The box is necessary to avoid an acoustic "short-circuit" between the waves emitted by the internal and the external sides of the membrane. The damping material is used to absorb the emission of the internal side of the membrane (above all at mid-high frequencies), whose radiations is not used in this case. For the same reason, a dust-cap is not included in the geometry. A second function performed by the damping material is to increase the apparent volume load "seen" by the driver, able to extend the bass frequency response at the same volume.

MATERIALS and their respective domains are the following:

- **Air** (PML, room, internal side of the magnet and air-gap);
- **Soft Iron** (top plate of the magnet, bottom plate including T-yoke);
- **Cloth** (all parts of the spider and the two rear layers 9a and 9b of the sectors of the membrane);
- **Coil** (V.C. - homogenized)
- **Glass fiber** (former)
- **Aluminum** (Box walls, second sector front layer, internal ring magnet);
- **Porous Material** (inside the box);
- **Paper-phenolic** (first sector front layer);
- **Rubber** (Surround);
- **Copper** (copper cap);
- **Neodymium N52** (magnet).

Different materials and their combinations have been tested specifically for the **sectors**. Among them:

- **Paper-phenolic**, a special paper used for light membrane loudspeakers with very low density (360 Kg/m^3), high Young modulus (1 Gpa) and average Poisson ratio (0.33).
- **Aluminum** (sheet), with high density (2630 Kg/m^3), very high Young modulus (69 Gpa) and average Poisson ratio (0.33).
- **Titanium**, with high density (4040 Kg/m^3), very high Young modulus (105 Gpa) and average Poisson ratio (0.33).
- **Plastic coated paper**, with medium density (940 Kg/m^3), low Young modulus (5 pa) and average Poisson ratio (0.35).
- **Composite**, with medium density (1200 Kg/m^3), high Young modulus (2 Gpa) and high Poisson ratio (0.42).
- **Glass Fiber**, with medium density (2000 Kg/m^3), high Young modulus (70 Gpa) and average Poisson ratio (0.33).

In the results section there is a description about which are their best combinations.

The Mesh uses the Free Triangular elements, high density (to respect the condition $\Delta x = c/5/f_{max} = 344/5/8000$).

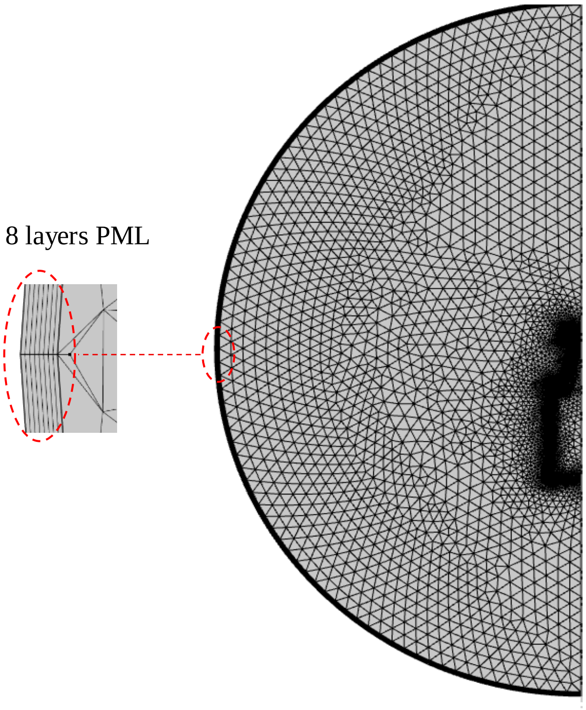


Fig. 9 – Mesh

BENDING WAVES THEORY

Bending waves - also called flexural waves - are complex waves, described by a system of 4 equations 4th order, that don´t have an analytical solution [4], [6], [11]. They are dispersive, which means that the propagation velocity through a material varies with frequency [3]. The frequency at which the velocity through the material is equal to that one of the sound is called coincident frequency f_c. After that frequency the radiation increases much more than in the previous band.

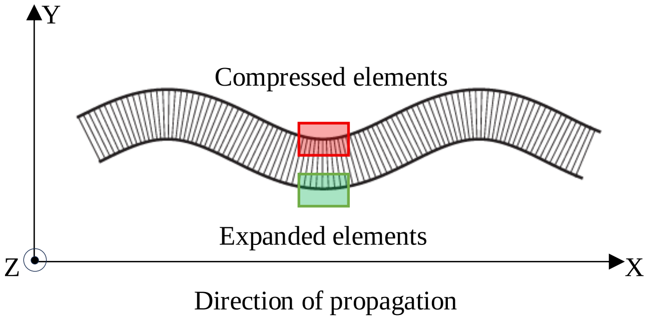


Fig 10 – Bendig wave schematization of a thin beam.

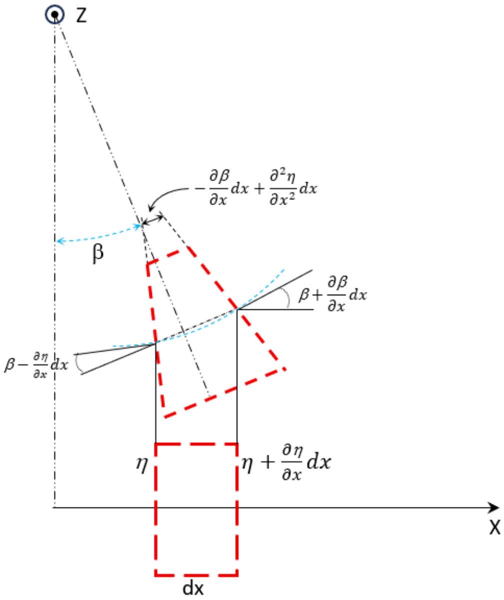


Fig 11 - Schematization of a compressed element (ref. Fig. 10) of a bending wave on a plate, with a rotation β around Z axis.

η = lateral movement along X

$\beta \sim \frac{\partial\eta}{dx}$ small rotation angle around Z

The variables involved are rotation (around Z axis in Fig. 10 and Fig. 11), transverse velocity, bending moment and share forces.

On a plane, the equation can be written as:

$$\frac{\partial^4 u_y}{\partial x^4} - \frac{\omega^2 m}{B} u_y = 0 \qquad [1]$$

where:

- B is the bending stiffness per unit length;
- m is the mass per unit area;
- u_y is the transverse velocity;
- ω is the angular frequency.

B can be defined as the property of an element to resist bending when subjected to an external force. In a general form, it can be written as

$$B = E \cdot I \qquad [2]$$

with E young modulus of the material and I inertia moment of the element. I depends on the geometry and mass and it can be considered as the resistance offered from the element to be rotated. If we consider the element divided into infinitesimal masses dm, we can write:

$$I = \int r^2 dm \qquad [kg * m^2] \qquad [3]$$

with r distance from the rotational axis.

Supposing to consider the membrane divided into many, very narrow, vertical sections, we can approximate every one of them as a singular subtle beam.

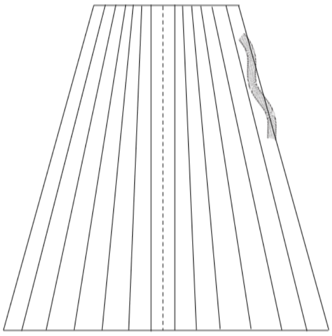


Fig. 12 - Cone surface divided into many thin plates

For a plate the bending stiffness is:

$$B = \frac{Eh^3}{12(1-\upsilon^2)} \qquad [N * m] \qquad [4]$$

with h thickens of the plate and ν Poisson Ratio (ratio of transverse strain over axial strain).

The critical frequency is:

$$f_c = \frac{c^2}{2\pi}\sqrt{\frac{m}{B}} \qquad [5]$$

with c speed of sound.

PHYSICS

The physics used are three:

a) **Magnetic Fields**,
b) **Pressure Acoustic**, Frequency Domain
c) **Solid Mechanics**.

They are coupled among them by the **MULTIPHYSICS**:

- **Acoustic Structure Boundary**, to couple pressure Acoustics and Solid Mechanics:
- **Magnetomechanics**, to couple Solid Mechanics and Magnetic Fields.

The equations involved are many. In Magnetic fields, we have (in the vacuum):

$\boldsymbol{B} = \boldsymbol{\mu_0 H}$ with B Magnetic Induction [T], H Magnetic Field [A/m] and μ_0 magnetic permeability [Tm/A].

$\boldsymbol{D} = \boldsymbol{\varepsilon_0 E}$ with D Electric Induction [C/m^2], E Electric Field [V/m] and ε_0 electric permittivity [C^2/(N*m^2)].

$\boldsymbol{J} = \boldsymbol{\sigma E}$ with J Electric Current Density [A/m^2], E Electric Field [V/m] and σ electrical conductivity [Siemens/m].

Derived by Maxwell´s equations we have:

$\boldsymbol{B} = \nabla \times \boldsymbol{A}$ with A Magnetic Potential and ∇ the Nabla operator vector (first derivatives).

$\boldsymbol{J} = \nabla \times \boldsymbol{H}$ Ampère's Law.

In Pressure Acoustic the most important equation is the **Wave Equation**.

Supposing the fluid (air) uncompressible, adiabatic and without viscous effects, it can be written:

$$-\frac{1}{\rho_0 c^2}\frac{\partial^2 p}{\partial t^2} + \nabla \cdot \left(-\frac{1}{\rho_0}\nabla \mathbf{p}\right) = 0 \qquad [6]$$

with ρ density of the air [kg/m^3], p acoustic pressure [Pa] and c speed of sound [m/s].

A solution in two dimensions (x and time t) is of type:

$$P(x,t) = p(x) sen(\omega t) = p(x) e^{i\omega t} \qquad [7]$$

By using the exponential formula, we can arrive to write the homogeneous Helmholtz equation:

$$\nabla \cdot \left(-\frac{1}{\rho}(\nabla \mathbf{p})\right) - \frac{\omega^2}{\rho c^2} p_t = 0 \qquad [8]$$

which has as solution a plane wave: $p = P_0 e^{i(\omega t - k \cdot x)}$.

In the case of the inhomogeneous version, adding the presence of sources distribution, with a monopolar source Q_m and a dipolar source q_d we obtain:

$$\boldsymbol{\nabla}\cdot\left(-\frac{1}{\rho}(\nabla \boldsymbol{p_t}-\boldsymbol{q_d})\right)-\frac{\omega^2}{\rho c^2}\boldsymbol{p_t}=\boldsymbol{Q_m} \qquad [9]$$

where p_t is the total acoustic pressure, ρ the density of the fluid, c the speed of sound and ω the angular frequency.

In Solid Mechanics the principal equation is related to the second Newton law ($F=ma$), that in the Lagrangian version has the shape:

$$\rho\frac{\partial^2 \boldsymbol{u}}{\partial t^2}=\boldsymbol{\nabla}\cdot(\boldsymbol{FS})^{\boldsymbol{T}}+\boldsymbol{F_V} \qquad [10]$$

with ρ the mass density, $\boldsymbol{u}$ displacement field, $\boldsymbol{F} = \mathbf{I} + \nabla\mathbf{u}$, deformation gradient, I identity tensor (equivalent to identity matrix), S stress tensor (stored energy variation depending on the deformation gradient), F_V external applied force.

In **Magnetomechanics** the most important coupling happens by the Lorentz Force, which general shape is:

$$\boldsymbol{F}=\boldsymbol{q}(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B}) \qquad [11]$$

with F force acting on a particle with elementary charge q, moving with velocity v, due to an external electric field $\boldsymbol{E}$ and a magnetic field $\boldsymbol{B}$.

In our case, considering that magnetic induction B is orthogonal to the direction of the current $\boldsymbol{i}$ flowing in the voice coil, we can write $\boldsymbol{F} = \boldsymbol{Bli}$ with l length of the voice coil immersed in $\boldsymbol{B}$.

If n is the number of turns of the voice coil inside $\boldsymbol{B}$, we can write:

$$nI = \int_A J\,dA \qquad [12]$$

With dA a cross-section of the coil, $\boldsymbol{I}$ current vector and $\boldsymbol{J}$ current density vector.

The force applied to the voice coil is:

$$\boldsymbol{F}=-\int_V \boldsymbol{JB_R}\,\boldsymbol{dV} \qquad [13]$$

With $\mathbf{B_r}$ the radial component of the magnetic flux density and V volume of the voice coil immersed in it.

Considering also the voltage V_0 applied to the voice coil, the total force applied to the voice coil becomes:

$$\boldsymbol{F}=\frac{\boldsymbol{Bl}V_{\boldsymbol{0}}}{\boldsymbol{Z}}-\frac{\boldsymbol{v}\,(\boldsymbol{BL})^{\boldsymbol{2}}}{\boldsymbol{Z}} \qquad [14]$$

with l length of the voice coil, $\boldsymbol{v}$ its velocity and Z its impedance.

RESULTS AND DISCUSSIONS

From the impedance graph we can see that the R_e (DC resistance) of the speaker is about 6 ohms:

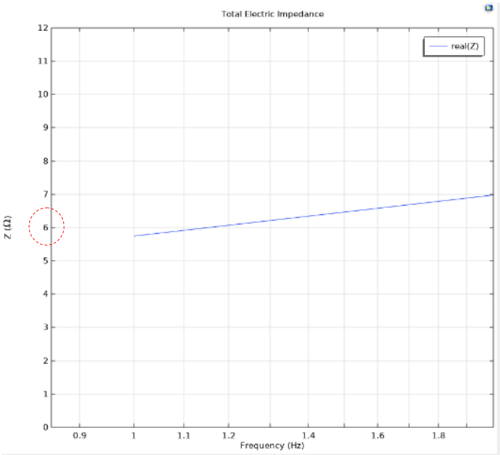
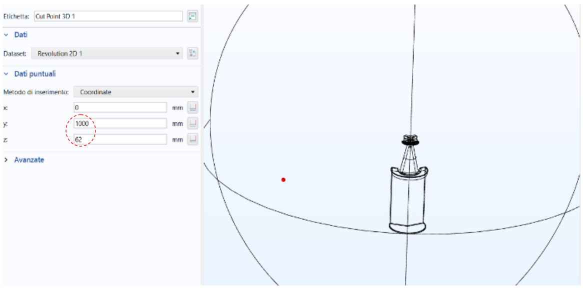


Fig. 13 – Electrical Impedance at low frequency

We can approximate the nominal impedance Z_{nom} at 8 ohm, so, to have 1 W, we can drive the speaker with 2.83V Rms (corresponding to $2.83 * \sqrt{2} = 4$V peak).

The measurements want to be made at 1 meter from the vertical axis of the speaker, at about half height of the cone. To choose a dedicated point, it is possible to use a "Cut Point 3D" to specify the coordinates:


Etichetta: Cut Point 3D 1

Dati

Dataset: Revolution 2D 1

Dati puntuali

Metodo di inserimento: Coordinate

x: 0 mm

y: 1000 mm

z: 62 mm

Fig. 14 – Cut Point 3D

In that point we can choose the variable to evaluate, which, in this case, is the acoustic pressure level (SPL).

Different materials and their combinations have been tested for the **sectors** (listed in the Material section). After many examinations, Paper-phenolic and Aluminum were the best to obtain a balanced (less peaks and dips) frequency response.

Note that also **Foam** and **Cloth** have been evaluated as internal layers of the membrane, to check their capacity of damping. Between them the Cloth results better. I used it for a while but, in the end, I decided don´t use it.

The first test, anyhow, was just to see the behavior of the entire membrane constituted by only one material (all sectors of the same material):

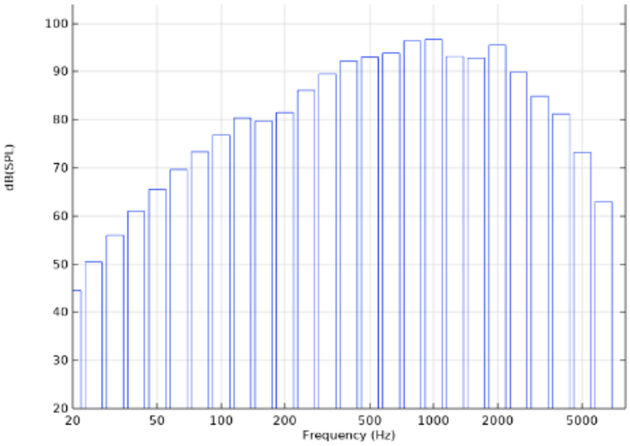


Fig 15 - All sectors in Paper-phenolic

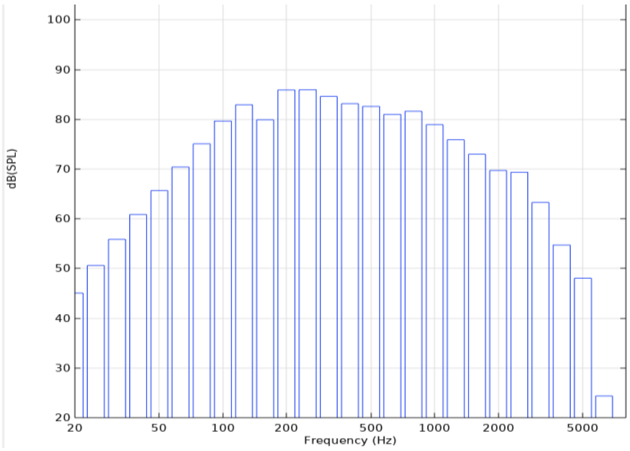


Fig 16 - All sectors in Aluminum

Leaving equal stiffness, it is clear the influence of the mass (too light for the paper to have enough bass frequencies and too heavy for the aluminum to have enough high frequencies).

Moving to the case in which the two sectors have different materials, we can see in Fig. 17 the result of the first sector (the one attached to the voice coil) in Paper-phenolic and the second sector in Aluminum:

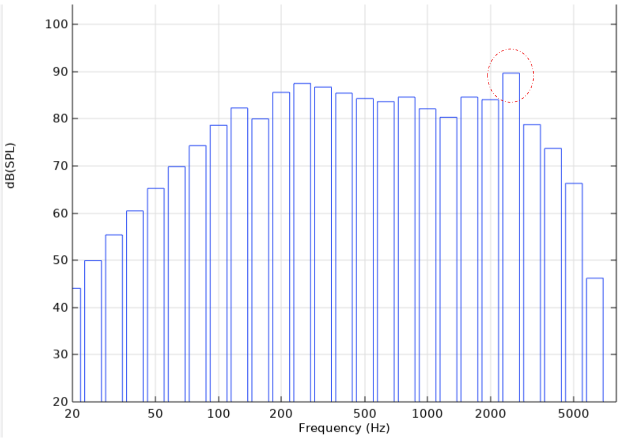


Fig 17 - First sector Paper-phenolic, second one Aluminum

It is possible to start to see the improvement in using the two materials, with an advantageous superposition of the benefits of both. However, the response is not yet sufficiently regular.

An anomaly to try to remove is the peak at 2500 Hz.

It derives from the connection between the end of the second sector of the membrane and the Surround. This last one was defined, at the beginning, by an angle of 180° (Fig. 18 - semi-circumference) and so its tangent and the one of the attached sector couldn´t be parallel (red circle):

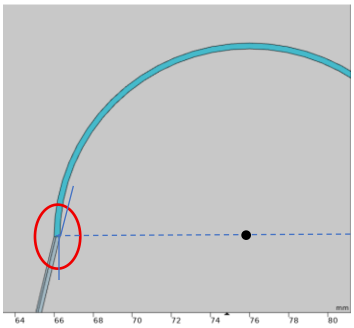


Fig 18 - Surround defined with angle 180°

Reducing the angle of the Surround at 173° and changing the attach point with the membrane helps to have closer parallel tangents:

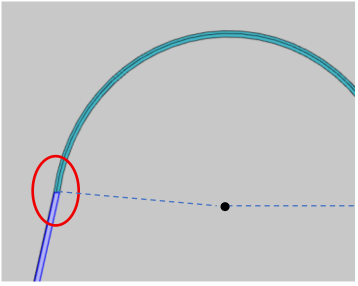


Fig 19 - Surround defined with angle 173°

The result is a reduction of the peak at 2500 Hz:

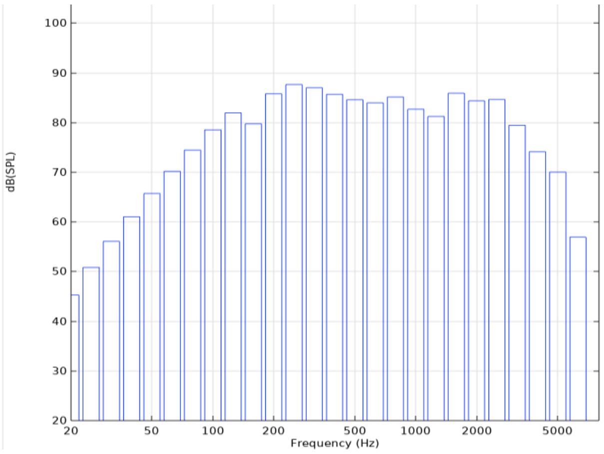


Fig 20 - New Surround geometry (173°). Both internal sectors in Cloth

Lastly, another adjustment has been made in the connection between the former and the membrane (first sector), enlarging it, in total, from 1.3mm to 1.7mm.

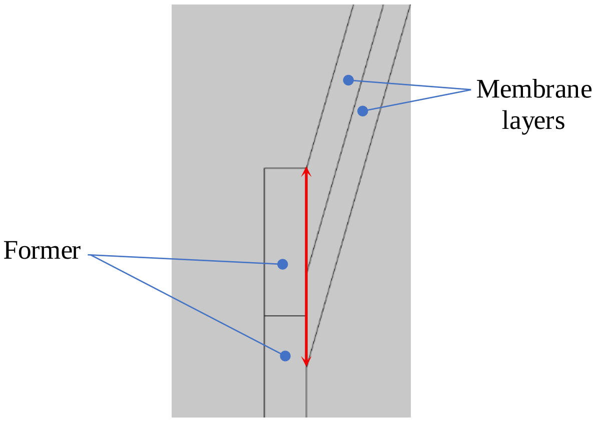


Fig 21. New Connection Former-Membrane

By this way there is a better transmission of the longitudinal force from the former to the membrane, without incrementing too much the mass.

Initially the two internal sides of the sectors were left in Cloth. However, testing to substitute it with the Paper-phenolic, the result was a very similar response, but with a higher final SPL level (about +1.5dB). This is very probably due to density, that in case of the Paper-phenolic is lower (360 Kg/m^3 against 950 Kg/m^3). For this reason, the final decision was don´t use the cloth more, but the Paper-phenolic instead of it (Fig. 22).

The result (Fig. 22) in comparison Fig. 20 is a more extended response and a higher SPL output (higher efficiency):

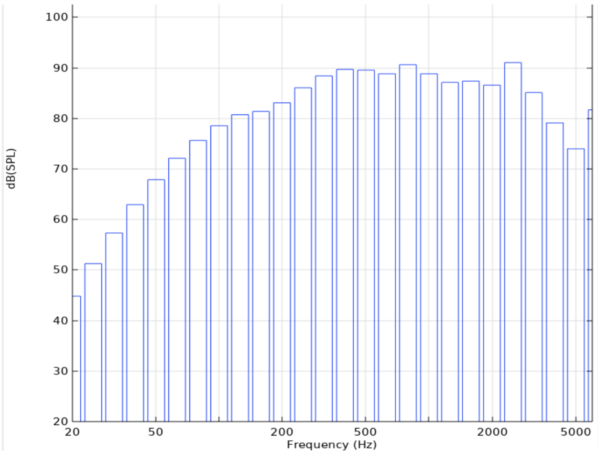


Fig. 22 – Substitution of the Cloth of the internal sides of the sectors with Paper-phenolic.

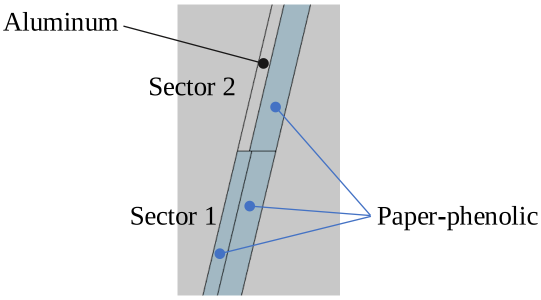


Fig 23 – Final membrane materials (ref. to Fig.21).

The response in Fig. 22 can be considered usable in the audio band [120Hz ÷ 4KHz], covering almost all the vocal band, that is the most important for our hearing, also being the one in which we have more sensitivity to the phase. It can be assumed as a good initial result for the purpose we had set.

Other interesting graphs are related to the total SPL distribution inside the volume:

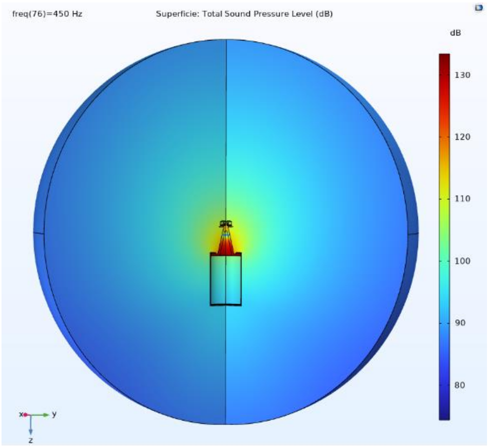


Fig 24 – SPL distribution at 450 Hz

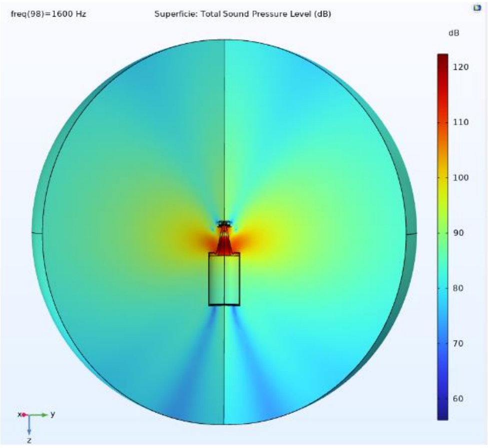


Fig. 25 - SPL distribution at 1600 Hz

By the Mode Shape it is also possible to see the behavior of the membrane at different frequencies:

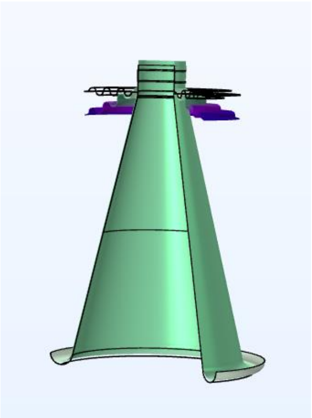


Fig. 26 – At 190 Hz the cone is still acting as a piston

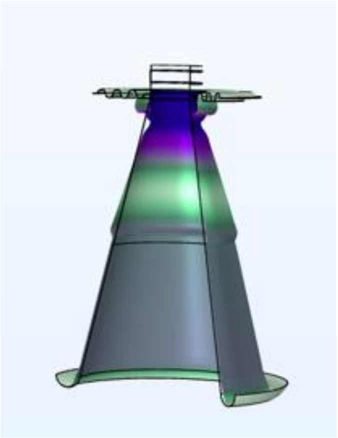


Fig. 27 – At 2189 Hz the sectors start to decouple

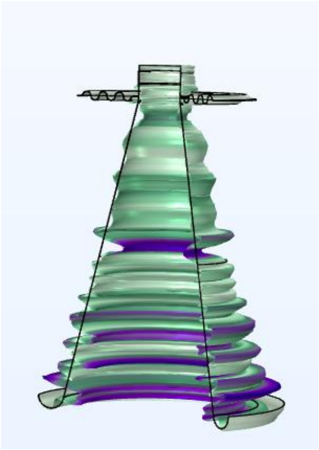


Fig. 28 – Increasing the frequency (5850 Hz) the travelling waves become evident

In the end, also the polar pattern diagram can be selected.

Obviously, being the geometry 2D axial-symmetric, the results will be circles; however, it is possible to verify the amplitude at different frequencies.

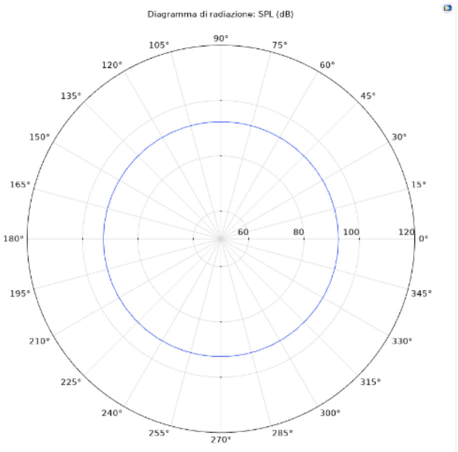


Fig. 29 – polar pattern at 1250 Hz

V. CONCLUSIONS

Different materials for the sectors of the membrane of a Walsh Driver have been investigated. As the two sectors are divided everyone into two sides, in total 4 different materials can be used. The combinations are many. In general, it would be difficult to say which can be the best one in absolute: it depends on the application. In some cases, a better extension is preferred, in other ones it can be the transient response (here not treated), or the efficiency, etc.

Our purpose, anyhow, was to find a satisficing extension of the frequency response, at a reasonable SPL sensitivity (we can consider it as an average of about 86-87dB), trying to cover the voice band, to avoid being obliged to use crossovers in that band - able to change the phase - which is the most sensitive for our hearing. A good result has been obtained by using Paper-phenolic and Aluminum layers.

For future studies it would be convenient to consider two different aspects of deepening:

a) The mechanical behavior.

By this point of view, it would be very useful to implement a 3D model, which will help to investigate not only the radial behavior of the diaphragm, but the circular ones too, adding their intervention to the frequency response. A time - transient - modal analysis of a truncated-conical surface would be also useful. Other changes in the geometry, of course, can be investigated, as, for example, the height of the cone, the minimum and maximum radius ratio, the height where the two sectors are connected, their relative angles of the tangents where they are connected, the voice coil diameter, etc.

Not negligible it would be a study of the different types of distortions introduced by the movement (harmonic, intermodulation, non-linearities, etc.) [14].

b) The acoustic analysis.

Omnidirectional speakers, with their radiation at 360° on parallel planes, are able to excite differently than a traditional direct radiator loudspeaker the room modes and reverberation of the environment where they are positioned. Direct sound and reverberated sound of the recording are superposed to the room response.

For these reasons, the complex sounds arriving at our eardrums in time would also need a study based on psychoacoustics principles [8], especially those on which our perception of direction is based: ITD (Interaural Time Difference), ILD (Interaural Level Difference), HRTF (Head Related Transfer Functions) [9] [10] and HAAS effect.

By these insides, it would be clearer to have indications about which aspects of the driver would be more important to optimize, together with more precise suggestions about the room positioning and treatment.

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