

Compression Driver Simulation incl. Vibroacoustic, Viscothermal & Porous Acoustics

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Abstract: A compression driver is a moving coil type of electrodynamic loudspeaker driver with a phase plug in front of the diaphragm. The narrow slits in the phase plug call for a simulation model which incorporates viscous and thermal behaviour in air. The viscosity in the air and the high thermal conductivity at the boundary cause damping, affecting the vibroacoustic behaviour of the system. The model also includes porous acoustics since the driver has a foam plug in the rear chamber. In this paper a 4" compression driver is simulated using a fully coupled finite element approach, including the viscothermal behaviour. Measured and simulated responses for the sound pressure level and the impedance are compared. The model does not contain any approximations regarding the geometry of the driver and no tampering of the results has been done in order to improve the agreement between measured and simulated results.

Keywords: Compression driver, vibroacoustics, porous acoustics, viscothermal wave propagation.

1. Introduction

Compression drivers are a specific family of dynamic moving coil loudspeakers where the diaphragm doesn't radiate directly into free space. Instead a phase plug is fitted very close in front of the diaphragm. The back of the diaphragm radiates into a rear chamber with a foam plug. The phase plug has annular slits in it, so that the generated pressure wave has to pass through these slit where by it experiences an abrupt area change at the vicinity of the diaphragm. The slits end up in the drivers throat with a cross-sectional area which increases slightly towards its exit - the mouth. From the mouth of the throat the sound is radiated into a horn during the application of the compression driver.

The compression driver in question is the JBL2446J fitted with a replacement diaphragm made of beryllium manufactured by Materion. Figure 1 shows the different parts in the driver. The beryllium diaphragm is connected to the non-moving parts of the driver via a

suspension. Beryllium is characterized by being both very light and very stiff. The diaphragm is driven by a voice coil which is located in a static magnetic field generated by a permanent magnet. The diaphragm radiates sound into the rear chamber which has a foam plug in order to dampen acoustic modal behaviour in the chamber. On the front side of the diaphragm a thin air layer separates it from the phase plug, and the forward radiated sound is channelled through four concentric slits. The slits lead into the throat as shown in Figure 1. For testing purposes this type of driver is not loaded with a horn, but with a plane wave tube as indicated. Both measurements and the simulation model used the plane wave tube setup.

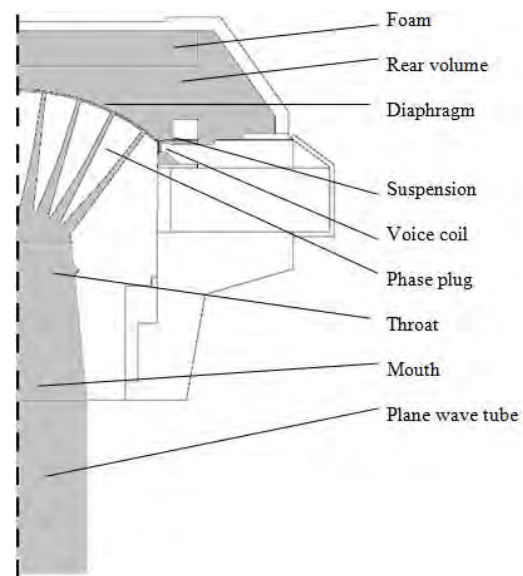


Figure 1. Overview of the moving parts, the foam plug and the air in the compression driver. The parts pertaining to the magnetic field are displayed white and without names for clarity. The plane wave tube used in the measurement setup and the simulation is also shown at the bottom.

The phase plug is shown in Figure 2. Several machined parts are assembled to form one part that makes up the slits whereas the other part gives the throat its geometry.



Figure 2. The phase plug is made of several parts making up the throat and the slits.

The combination of an added acoustic mass in the phase plug slits and the acoustic impedance transformation going from the area of the diaphragm to the area of the throat of the driver results in a better power conversion from mechanical energy in the moving diaphragm into acoustical energy. In other words, the driver is more efficient than a conventional driver, freely radiating in to air.

The compression driver has been tested in a plane wave tube in which it is assumed that plane waves are absorbed. In the experimental setup the tube is fitted with absorbing material compressed more and more towards the end of the tube. A microphone is fitted in the plane wave tube near the interface to the throat, with an option to rotate the microphone around the circumference of the plane wave tube. This way an average of measurements for different angles can be found in order to minimize the influence of asymmetry in the sound field. The process involved in making the diaphragm or any of the other materials in the driver are not perfect, and also the fitting of the individual parts can never be totally symmetric.

Simulating the vibroacoustic behaviour of compression drivers has been addressed in the literature using analytical lumped parameters [1], numerical finite element analysis (FEA) [2,3], and a combination of transmission matrices and FEA [4]. A dominant challenge comes from getting an accurate description of the acoustics in the slits, the space between the diaphragm and the phase plug, and the coupling between the diaphragm and the adjacent air. The goal in the present work has been to establish a model which efficiently and accurately simulates the vibroacoustic behaviour in the compression driver using solely a finite element approach.

The physics involved in the compression driver in question incorporates standard

acoustics, porous acoustics, structural mechanics, viscothermal acoustics and the proper multiphysic couplings between these fields. Most of these fields can be handled by commercially available simulation software packages, but the viscothermal acoustics is usually either not available, or approximations have been used making the software insufficient for general geometries, such as e.g. a compression driver. COMSOL Multiphysics, however, has viscothermal acoustics available in its most general form, and was therefore used for the simulations.

In the following sections the different simulation challenges are described.

2. Vibroacoustics

The compression driver with the plane wave tube is simulated as being 2D-axisymmetric. The selected physics in COMSOL Multiphysics are “Acoustic-Solid Interaction” for the standard acoustics domain, the porous domain and the mechanical domain, and “Thermoacoustics” for the viscothermal domain. Since harmonic variation is assumed, the study type used is “Frequency Domain”. An analysis is carried out in 1/12-octave steps from 20 to 20.000 Hz.

The objective is to find both the sound pressure level at the entrance of the plane wave tube as well as the electrical impedance of the driver. In the simulation a constant force is applied to the voice coil. By knowing the T/S-small parameters for the driver, the electromagnetic behaviour of the driver was included as a simple straight forward post-processing procedure to obtain the correct sound pressure level and impedance.

The plane wave tube is approximately 0.4m long and it is terminated at its end by the “Plane Wave Radiation” boundary condition available in the “Acoustics-Structure” module. The moving parts (voice coil, suspension, diaphragm) are simulated as linear elastic materials, each with a density, a Young’s modulus and a Poisson’s ratio. The material properties were found by an identification methods developed and used for moving coil drivers. The air in the plane wave tube is simulated as a standard acoustics domain, and so is the adjacent air in the phase plug. The foam insert in the rear volume is simulated using the Delany-Bazley model with standard

coefficients and a flow resistivity. A region encompassing the phase plug slits and the air between the membrane and the phase plug is simulated as a viscothermal domain using the “Thermoacoustics” module. The porous and viscothermal acoustics is described more in details below.

3. Porous acoustics

A foam plug is inserted in the rear chamber to dampen the acoustic resonances. This type of damping comes from the fibrous nature of the foam having a rigid skeleton filled with air. To simulate this behaviour a Delany-Bazley acoustic model was used. The pressure wave experiences loss in the rigid skeleton due to viscosity, but since the actual geometry of the foam is not known, a model is used where only the flow resistivity needs to be known. The Delany-Bazley model uses a complex and frequency dependent sound speed c_{DB} as well as a complex, frequency dependent density ρ_{DB} so that the wave equation reads

$$\frac{1}{\rho_{DB}} \nabla^2 p_a + \frac{1}{\rho_{DB}} \left(\frac{\omega}{c_{DB}} \right)^2 p_a = 0$$

where ω is the angular frequency and p_a is the dependent variable pressure. The complex valued parameters are functions of the flow resistivity which can be estimated from measurements.

4. Viscothermal acoustics

The necessity for including viscothermal effects comes from the driver geometry having narrow air layers in the phase plug and between the phase plug and the diaphragm. When sound moves in a viscous fluid the tangential velocity at boundaries is zero since the particles tend to stick to the boundary. This is prominent in a boundary layer extending from the boundary and into the bulk of the domain where the viscosity effects do not influence the propagating wave, since the particles can move freely here. Also, the temperature variation at the boundary is assumed zero since the heat conductivity of the boundary material is typically much higher than that of the fluid. So in a boundary layer there is energy transfer between the acoustic wave and the boundary. Near the boundary an isothermal process is assumed, whereas in the bulk the process is adiabatic, so that the temperature and the pressure are directly related.

In the boundary layer shear waves are present and the temperature variations associated with the pressure differences in the propagating wave are equalized, both taking out energy of the propagating wave. In standard acoustics viscosity and thermal conductivity are ignored in order to end up with the well-known wave equation. But when considering small geometries where the boundary layer takes up a considerable amount of the entire volume, dissipation must also be included in the model. The boundary layer thickness d_v is usually given as

$$d_v = \sqrt{\frac{2\mu}{\rho_0\omega}}$$

where μ viscosity of the fluid, ρ_0 is the fluid density and ω is the angular frequency. The boundary layer is large for low frequencies, and is about 0.5 mm at 20 Hz. The viscothermal effects are most important for small or narrow geometries, and around resonances where the dissipation affects the peaks/dips in the responses.

For certain simple geometries, such as e.g. a circular tube, this dissipation can actually be included accurately analytically, but for general geometries this is not possible. The procedure taken in this paper is to treat the entire mathematical description of a fluid with viscosity and thermal conductivity, i.e. the compressible flow equations. The equations are put in a weak form so that they can be solved using the finite element method. In the most current version of COMSOL Multiphysics v4.2 the equations are readily available, but the model was first established in an earlier version v4.1, where the equations and boundary conditions were set up manually. Compared to the existing models in the literature, the present model includes the viscothermal fluid characteristics in its most basic form, without assumption about the actual geometry or boundary layer thickness. Also, the couplings between the different fluid and structure domains are handled in the formulation.

The set of equations governing the viscothermal wave propagation is given here. It is assumed that the material parameters are constant, so that the fluid density ρ_0 , the specific heat C_p , the heat conductivity κ , the

shear viscosity μ and the bulk viscosity η are all independent of time and space within the viscothermal domain. Also, no sources are considered. Assuming that a variable is written as a sum of a small harmonic variation with angular frequency of ω and a steady state solution (subscript 0), and also that the mean velocity is zero, the dependent variables for the viscothermal domain are written as

$$\begin{aligned}\bar{\mathbf{v}} &= \mathbf{v}e^{i\omega t} \\ \bar{\rho} &= \rho_0 + \rho e^{i\omega t} \\ \bar{p} &= p_0 + p e^{i\omega t} \\ \bar{T} &= T_0 + T e^{i\omega t}\end{aligned}$$

for the velocity, density, pressure and temperature, respectively. Besides being constant in time the static variables are also constant in space.

With the above assumptions the viscothermal domain can be described by the linearised Navier-Stokes equation

$$\begin{aligned}i\omega\rho_0\mathbf{v} &= -\nabla p + \left(\frac{4}{3}\mu + \eta\right)\nabla(\nabla\cdot\mathbf{v}) \\ &\quad -\mu\nabla\times(\nabla\times\mathbf{v})\end{aligned}$$

the continuity equation

$$i\omega\rho + \rho_0\nabla\cdot\mathbf{v} = 0$$

the state equation for an ideal gas

$$\rho = \rho_0\left(\frac{p}{p_0} - \frac{T}{T_0}\right)$$

and the energy equation

$$\rho_0 C_p i\omega T = \kappa\nabla^2 T + i\omega p.$$

The equations are combined so that the density variation is eliminated and need not be considered in the calculations.

5. Coupling of physics

For the model to be fully coupled several different boundary and interface conditions were considered. For the viscothermal model a

boundary condition has to be set for both the velocity and the temperature. For the non-moving boundaries this means an isothermal condition ($T=0$) and a velocity of zero, whereas at the interfaces to the structure or the standard acoustics domain other continuity conditions have to be specified. The interfaces between standard acoustics and structural domains are handled automatically by COMSOL Multiphysics.

6. Results

Two fully coupled models were examined with the only difference between the two being that one had the viscothermal losses included whereas in the other model viscothermal losses were omitted. The measured and simulated responses for the sound pressure level and the total electrical impedance are illustrated in Figure 3 for the viscothermal case and in Figure 4 for the case without viscothermal dissipation. The measurements are taken as an average over four locations of the microphone in the plane wave tube (0° , 90° , 180° and 270°) to smoothen out non axi-symmetric behaviour due to production tolerances.

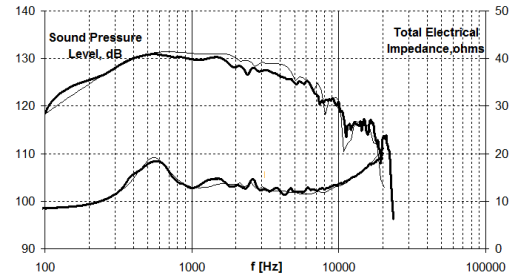


Figure 3. Model including viscothermal behaviour. The measured (thicker lines) and simulated (thinner lines) sound pressure levels (upper curves) and impedances (lower curves) for the case with viscothermal dissipation included.

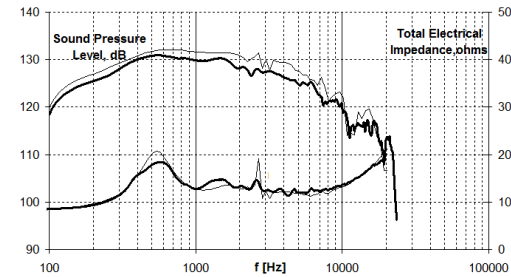


Figure 4. Model excluding viscothermal behaviour. The measured (thicker lines) and simulated (thinner lines) sound pressure levels (upper curves) and

impedances (lower curves) for the case with viscothermal dissipation omitted.

It is noted that the sound pressure level in the case with no viscothermal damping is generally higher than the measured level. This indicates that damping is actually present in the compression driver and so should also be included in the model. Furthermore, a few resonances are present in the model that are not present in the model with viscothermal damping included. E.g. at approximately 2.7 kHz there is a peak in both the sound pressure level and the impedance which is associated with a resonance in the two inner rings of the phase plug, as illustrated in Figure 5. With viscothermal losses included in the model this resonance is dampened and does not show in the simulated responses.

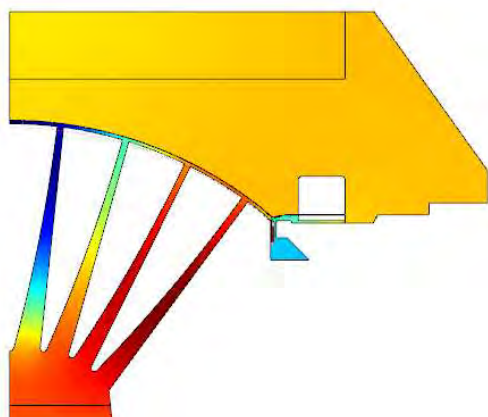


Figure 5. When the viscothermal dissipation is not included in the model a resonance in the two inner phase plug rings is present at approximately 2.7 kHz.

At approximately 12 kHz another resonance is present when viscothermal losses are not included in the model. Here, there is a standing wave in the air layer between the diaphragm and the phase plug, in the direction perpendicular to the normal of the diaphragm. This is illustrated in Figure 6.

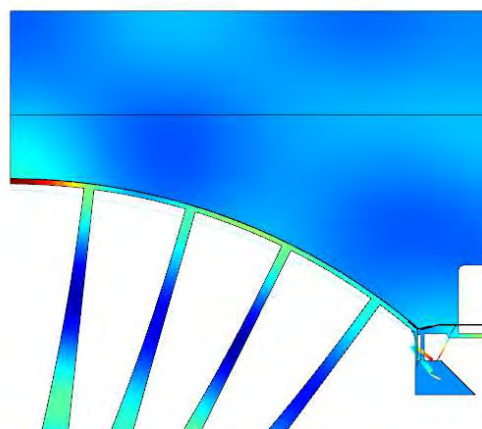


Figure 6. When the viscothermal dissipation is not included in the model a resonance at approximately 12kHz is present in the air layer between the diaphragm and the phase plug.

A great advantage of having a model of the compression driver is that one can examine the physics to a degree that a measurement cannot compare with. This is done by extracting variables at desired points and making illustrations/plots and animations to visualise the behaviour. E.g. in Figure 7 the sound pressure is visualised in the compression driver and plane wave tube at 12 kHz. Animations are ideal to help establish the viscothermal, porous acoustic and/or vibroacoustic behavior for a given frequency.

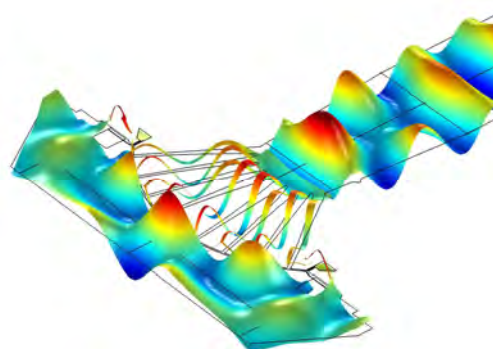


Figure 7. A visualisation of the pressure in the compression driver and plane wave tube at 12 kHz

Since the temperature is explicitly calculated in the viscothermal domain it is of course also possible to visualise this variable as shown in Figure 8 for a section of the phase plug. Near the boundaries the temperature (variation) is zero, i.e. an isothermal boundary condition, whereas in the bulk the temperature varies with the pressure.

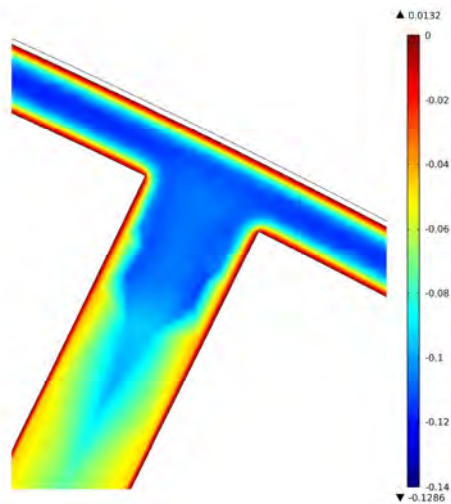


Figure 8. A visualisation of the temperature variation in a part of a slit as well as a section of the gap between the diaphragm and the phase plug.

With the model established the characteristics of the compression driver can be assessed for configurations that differ from the physical sample. For example, the sound pressure level and impedance responses have been calculated for the case of a titanium diaphragm and an aluminium diaphragm, respectively. The results are shown in Figure 9 where it can be seen that the response is highly affected by the choice of diaphragm material.

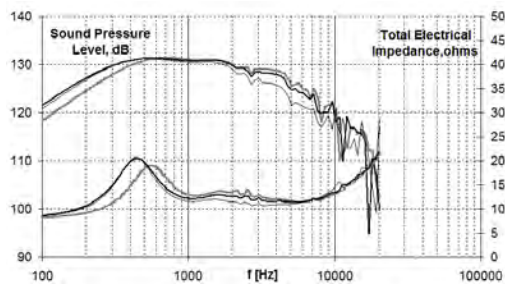


Figure 9. Using a model with viscothermal dissipation the sound pressure level and impedance has been calculated for an aluminium diaphragm (thinner line), a titanium diaphragm (thicker line) and the original beryllium diaphragm (checkered line).

7. Discussion

The model is 2D-axisymmetric whereas the physical driver used for the measurement is 3D. This means that any imperfections in the manufacturing of the physical driver mismatches with the 2D-simulation and any

3D features such as non axi-symmetric holes, cannot be captured in the simulation model. For example the diaphragm thickness is not constant while in the simulation model a nominal value is inserted. For these reasons a perfect match cannot be expected between simulated and measured results. There are observed disagreements between the results, e.g. the simulated impedance seems more dampened than the measured impedance. However, the model is accurate enough that the influence of changing parameters such as the distance between the diaphragm and the phase plug, the materials or the phase plug design, can be captured to a degree where decisions can be made to accurately guide the design process of the driver's parts.

The responses for the standard acoustic and the viscothermal acoustics models do differ, but perhaps the importance of including viscothermal dissipation does not seem to be worth the effort, based on the current case. However, for other configurations where the distance between the diaphragm and the phase plug is smaller, the coupling between the vibrations of the diaphragm and the viscothermal fluid affects the overall response more. Also, when different diaphragm materials are considered it is important to have a fully coupled model encompassing all relevant physics.

A further development of the model would be to include a horn. The horn could be optimized to meet certain demands to the efficiency, radiation pattern and so on in the simulation environment. Also, a 3D model could be considered to better capture the physics of the actual driver. A final and important step could be to set up a transient analysis including the viscothermal dissipation, so that e.g. multitone distortion could be assessed using the model.

8. Conclusions

A compression driver has been simulated using a finite element formulation. The model includes viscothermal effects in a general formulation, porous acoustics and vibroacoustics. These effects have a substantial impact on the response of this typical of compression driver. A compression driver has been examined both via the finite element model and measurements. The simulated sound pressure level and impedance agree well

and the importance of including the viscothermal dissipation has been illustrated.

9. References

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