Design rules to develop grommets with high acoustic performances using finite element analysis

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Abstract: In the automotive industry, acoustic insulation of the engine compartment is one of the key points for the NVH comfort of vehicles. Grommets of the firewall are an important path of noise from engine to passengers' cabin. Acoustic requirements defined by automotive manufacturers for firewall insulating materials and for grommets are more and more constraining. One of the main indicators used by OEMs to determine the acoustic performance of grommets is the Insertion Loss (IL). It is the difference of the sound pressures between two configurations: a reference and the configuration with the part to be assessed. One way to measure the IL of a part is the use of a small cabin. It consists in a dedicated bench having one emitting room, one receiving room and the tested part at the interface. Suppliers may need to test several prototypes to meet the OEMs' specifications. In this context, the numerical simulation of the small cabin can provide a helpful support in the design phase of the grommets. A parametric model is developed in order to easily modify the geometry, the mesh or the input data. The objective is to compare IL computed with different models. Correlation between experiments in small cabin and simulations is achieved up to 10 kHz. It demonstrates equivalent trends of the IL spectra and levels. Many parameters are studied to define design rules for acoustic performances. Approximatively one hundred different grommets configurations are computed to cover the design space. Perspectives of the work are to validate these design rules on other grommet geometries and to improve the acoustic simulation methodology.

Keywords: Simulation, Acoustic, Correlation

1. Introduction

Acoustic insulation of the engine compartment is an important factor of the NVH comfort of vehicles. With the use of efficient soundproofing materials to improve the insulation of vehicles, the grommets of the firewall have begun an important path of noise from the engine to the passenger's cabin. For this particular reason, acoustic specifications of OEMs for firewall are more and more constraining, especially for the wiring grommets. The Insertion Loss (IL) is one of the main indicator to determine their acoustic performance. The IL is the difference of Sound Pressure Level (SPL) between two configurations: a reference configuration and a configuration with the tested sample. The IL can be measured with the use of the small cabin. It is a specific test bench with an emission room and a reception room. The tested parts being at the interface of these two rooms. Suppliers need to test several prototypes and combinations of different geometrical configurations and/or different materials. It can lead to prohibitive and long-term development to fit the OEM's specifications. One way of improvement of the design development is the simulation of the small cabin. A finite element model of small cabin has been realized with the finite element software Code_Aster. Code_Aster is an open source software developed by EDF (French Electricity Company). It is used worldwide in various industrial sectors. The pre-processing and the post-processing have been performed with the open source software Salome. The main purpose of this study is to provide a computational method of the small cabin to determine the IL of wiring grommets from a finite element model.

First, the description of different methods and models used to compute the small cabin is presented. A brief description of the small cabin bench is given. In order to validate the numerical method, an understanding of the measurement of IL in the small cabin is necessary. Hypotheses of the computational method are then given. Loading, boundary conditions and mechanical properties have been defined to match with the real conditions of the measurement of IL in the small cabin. Two numerical models of the small cabin are set up: a 3D model and a 2D axisymmetric model.

Second, a validation of the methods and the models is fulfilled with the correlation between the measurement and the computation. It is achieved with the measurement of high reference, i.e. a simple measurement in the small cabin of the steel sheet and the soundproofing materials.

After this validation, a parametric model is built from the axisymmetric model. The configuration of geometrical dimensions of the small cabin and the wiring grommet, as well as mesh or computational parameters are provided in a simple file written in Python language.

A comparative acoustic indicator is then developed. With geometric parameter variation, each grommet configuration is compared to a reference and an indicator is computed. An optimal configuration can be obtained with indicator evolution.

A geometric parameter is studied to understand simulation tool and show an optimal configuration. Geometric parameter is studied by experiment, and simulation allows to understand testing results. Then, an optimal configuration is chosen from the analysis of bench test results and mechanical behavior of the grommet.

Finally, conclusion and perspectives are presented. Several proposals are given to improve the model. Design rules need to be completed with another grommets to develop rules for grommet categories.

2. Methods and model

2.1 Description of the small cabin

The small cabin (see Figure 1) is mainly composed by two parts: an emission room and a reception room. The determination of the Insertion Loss (IL) in the small cabin consists in measuring the Sound Pressure Level (SPL) of the two configurations [1].

$$IL(dB) = 20*\log_{10}\left(\frac{p_{cfg2}}{p_0}\right) - 20*\log_{10}\left(\frac{p_{cfg1}}{p_0}\right) \quad [1]$$

p_{cfg1} and p_{cfg2} are respectively the transmitted pressure measured in the reception room of the first configuration and the second configuration. p_0 is the reference pressure and it equals to 20 µPa. The IL is always expressed in dB.

In the first configuration, a 1mm thickness steel sheet is set at the interface between the two rooms of the small cabin. In the second configuration, the part is tied up in the steel sheet and soundproofing materials (felt layer and a heavy mass layer). Four microphones are used in the reception room to measure the transmitted SPL. The IL is determined as the difference of the transmitted SPL for the two configurations. The higher the IL, the better the acoustic performance of the tested sample is.

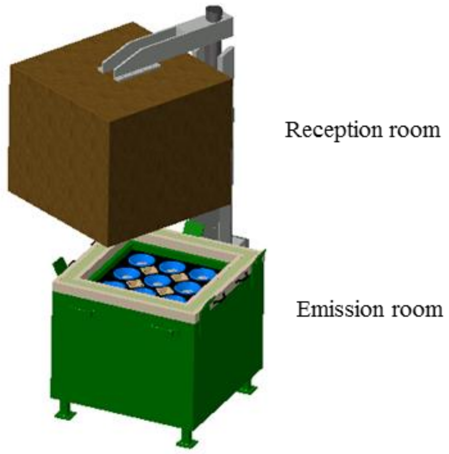

Figure 1: CAD model of a small cabin.

One can observe the emission room and the reception room of the small cabin on Figure 1.

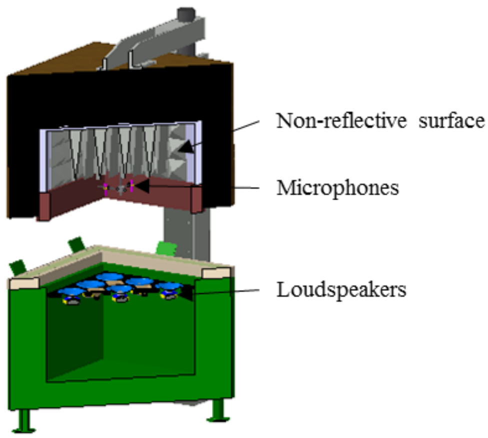

Figure 2: Cross-section of the CAD model of a small cabin.

One can observe on Figure 2 a cross-section of the CAD model of a small cabin. Loudspeakers are placed in the emission room and the microphones are placed in the reception room. One may remark the use of porous material in the reception room to avoid acoustic waves reflection.

Wiring grommets are a noise path from engine to passengers' cabin through the firewall. The tested parts in small cabin are composed by the wiring grommet, a strand and an insert to tie it to the steel sheet.

2.2 Computational method

The first step of this study is to compute the entire small cabin via Finite Element Analysis (FEA).

The air in the rooms and inside the grommet is computed with fluid elements and the structural parts as 3D or 2D elements ([1] and [2]). A fluid/structure coupled model is needed. The use of a fluid/structure coupling in Code_Aster involves several constraints on the model and the computational method, as the definition of the damping. In this particular case of the computation of a wiring grommet in small cabin, the damping factor has to be defined as a global value that covers the entire model (fluid and solid elements). So, this value of damping is an important fitting parameter between measurements and computed results of IL.

In order to prevent reflection of acoustic waves in the cabin, an impedance condition is applied on the internal sides and roof of the reception part of the cabin. This impedance condition is defined to ρc (approximately 408 Pa.s/m) with ρ air density and c sound velocity.

CAE model of a grommet in a small cabin consists in modelling several components:

- A cabin filled by air
- A grommet in EPDM
- An insert in PA66
- A harness
- A steel metal sheet
- A soundproofing material

Mechanical properties of each material are given below.

Material	Young's Modulus (Pa)	Poisson factor	Density (kg/m^3)
Steel	2,1E+11	0,30	7,8E+3
PA66	1,3E+6	0,49	1,1E+3
EPDM	2,0E+6	0,49	1,0E+3
Harness	1,0E+6	0,40	3,0E+3

Table 1: Mechanical properties of material used in the computation.

The harness is normally composed by several wires passing through the grommet. During small cabin measurements, the harness is covered by mastic in the emission and the reception room. The mastic has the particularity to avoid the acoustic waves to pass through the strand. Moreover, harness is beribboned with plastic tap. Thus, only the acoustic performance of the wiring grommet is measured. After a computational validation, the harness is computed as a material with a low Young's modulus.

As explained in the previous section, the soundproofing material is composed of a felt layer and a heavy mass layer. The felt is commonly defined as a porous material in finite element method. However, Code_Aster software does not allow to carry out studies with porous material for now. The felt can be defined either as solid elements or fluid elements. A comparison of IL computed with felt as air (fluid elements) or solid elements (low Young's modulus and low density) has been realized. Despite few differences on IL results, the computation of the felt as air has been chosen. This material could better represent the breath of the soundproofing materials that occurs during measurements. The heavy mass layer is in EPDM.

For the calculation, edges of the metal sheet are clamped. The emission of acoustic waves by loudspeakers in small cabin is closed to a diffuse field. As the Code_Aster software doesn't allow to realize calculation with a diffuse field loading, planar waves loading is applied on several non-collinear surfaces of the cabin. This type of loading permits to get close to a diffuse field condition. In experimental or simulation, conditions are close to a diffuse field but it's not perfectly it.

SPL in the reception room of the cabin is measured by four microphones set as a cross at 0.055 m of the grommet. Acoustic pressure is computed at the same location as in measurements. Experience in small cabin measurements show that the position of microphones in the reception room is an important parameter. Indeed, two measurements of the same samples with microphones placed at others locations can lead to significant differences between the two measured IL.

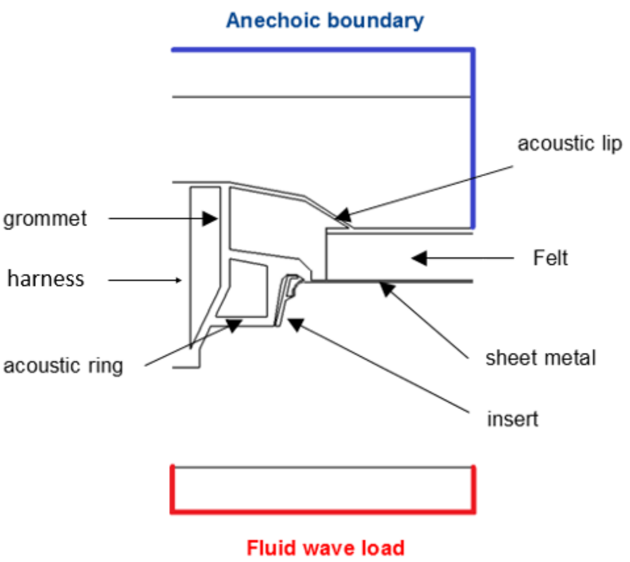

Figure 3: Materials, loading and boundary conditions of a dash grommet (cross-section).

Measurements in small cabin are performed from the third octave centre frequency of 100 Hz to the third octave centre frequency of 10 kHz. The size of the elements in the mesh of the model highly depends of the frequency. In order to obtain acceptable results, it is strongly recommended to have an element size equal to the sixth of the wavelength. The upper frequency for a calculation to the center frequency of

10 kHz is 11.225 kHz. At this frequency, air wavelength equals to 0.03 m. Thus, the maximal size of elements for the mesh is about 0.005 m.

Mesh of structure element is sized with a convergence test and not depends of this condition.

2.3 3D Model

A 3D model is built from the CAD model of the wiring grommet. The main drawback of a 3D model is the number of degrees of freedom (dof) of the model.

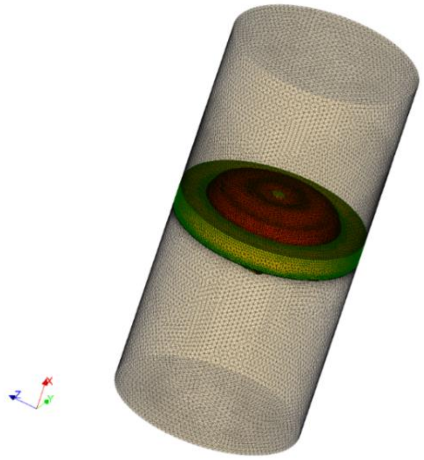

Figure 4: Mesh of the 3D model of the small cabin with the dash grommet.

The representation of the entire small cabin with the suitable size of elements would provide a prohibitive time of calculation with more than one-million-and-a-half degrees of freedom.

2.4 Axisymmetric model

As the wiring grommets computed are mainly symmetrical, a solution to avoid a too important number of degrees of freedom is to compute the small cabin via an axisymmetric model. This model is an axisymmetric model where only the half section of the small cabin and the wiring grommet are computed. Keeping in mind that the main aim of this study was to easily compare different configurations of grommets, the axisymmetric model could be more convenient (faster computation and easier to set up).

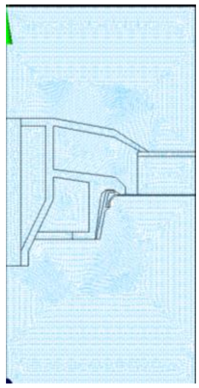

Figure 5: Mesh of the axisymmetric model of the small cabin with the wiring grommet (zoom).

The advantage of this model is the low number of degrees of freedom required to perform the calculation. This value can easily be divided by ten in comparison with a 3D model. Moreover, this axisymmetric model allows to refine the mesh in order to check the accuracy of the model with a convergence test.

3. Validation with high reference

As first result, a correlation of the 3D model and axisymmetric model is realized from measurements of high reference in small cabin. The aim of this comparison is not to perfectly fit the measurements but to check that the two computed models follow the same trends than the measurement.

Before any analysis, one may consider the prominent impact of acoustic leaks that occur during small cabin measurements.

The upper reference of the small cabin consists in a measurement of the transmitted SPL of the set of a full steel sheet and soundproofing materials on one hand and a measurement of the transmitted pressure of the steel sheet only on the other hand.

The computation of the high reference allows to validate the calculation methodology with a simpler model than the one with the wiring grommet. Loading, boundary conditions and fluid/structure interface as explained in the previous chapter have been validated. Moreover, this correlation also validated the use of axisymmetric model instead of a 3D model.

A first calculation of the 3D model has been realized. The meshing of the entire small cabin in the frequency range of the measurements (i.e. a maximal size of elements of 0.005m) leads to a model with a too important number of degrees of freedom to complete the calculation. The aim of this validation was to fit computation with measurements for all the frequency ranges. Choice of reducing the dimensions of the small cabin has been made to decrease the number of dof in the model. Thus, the 3D model has been reduced to a small cabin of 0.5m width (instead of

0.9m). The height has also been reduced. The final 3D model has approximatively 100 000 dof.

In order to validate the use of the axisymmetric model to compare different grommets, this model is reduced to the same dimensions of the small cabin than the 3D model. The axisymmetric model has less than 10 000 degrees of freedom. Results are presented in Figure 6.

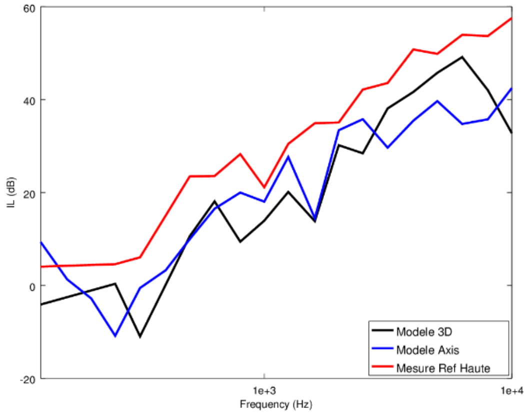

Figure 6: Measured IL (red curve) and computed IL for different models (3D model in black and axisymmetric model in blue) of the high reference.

One may observe that the two computed IL are lower than the measured IL for most of the frequency range. Also, the three curves of IL follow the same slope. For a parametric study and design rules, axisymmetric model is used. Same slope is obtained and simulation cost is less important.

4. Parametric model

After the validation of the computational method and model with the high reference, axisymmetric model is used to create the parametric model. This 2D model allows an easier geometrical set up and a faster calculation in order to increase comparison of several grommet models. Each step of the calculation (pre-processing, calculation parameters and post-processing) can be adjusted and automated so a non-user of FEM software can perform calculation. The configuration file is written in Python language and the open source software Salome is used to create the parametric model.

First, the user has to enter a set of dimensions of the grommet (grommet thickness, strand diameter, etc.) and the small cabin (width, length, etc.).

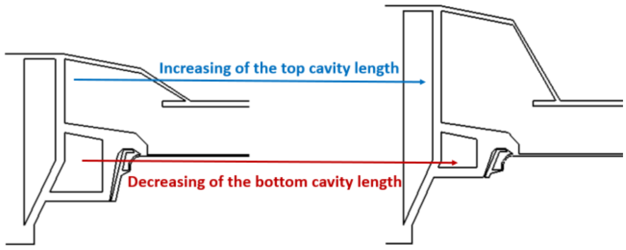

Figure 7: Example of geometrical configuration of a grommet.

As for the geometric model, mesh is entirely configured by the user (size of finite elements, type of elements, etc.).

Finally, user can also configure the command file used to launch the calculation. Mechanical properties of materials, material affectation to the model or frequency range of the study are chosen in the command file.

During this project, approximatively one hundred different grommets configurations are computed to cover the design space. All of this study was done in a short time thanks to the parametric model.

5. Development of acoustic comparative indicator for virtual products

Several kinds of grommet are studied, and several IL evolution are computed. To compare each configuration to the others, and develop design rules, an acoustic comparative indicator is needed. It can be possible to compare each grommet IL evolution with parameter variation, but it is really difficult. Evolution of an indicator is easier to understand and gives more information.

As acoustic Renault requirement, a target is defined. This requirement takes in account experimental bench characteristic with references which can be simulated. Two references are needed: high reference as perfect insulation and low reference as bad insulation. It means:

- High reference: Sheet metal + insulation
- Low reference: Sheet metal + insulation with hole of dash grommet diameter

These two references are simulated and an IL evolution is obtained for each. Then, the requirement is computed for each frequency [2].

$$Requirement = [(\mathrm{Re}\, f_{high}(f) - \mathrm{Re}\, f_{low}(f)) * 0{,}75] + \mathrm{Re}\, f_{low}(f) [2]$$

To validate simulation of high reference and low reference, and calculation of requirement, a correlation is done with experimental tests. Results are presented on Figure 8. References and requirement show the same behaviour with a constant offset. This offset will be study with perspectives of this project.

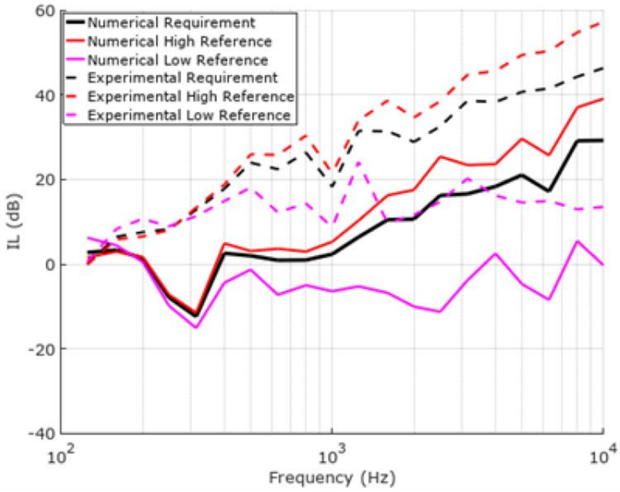

Figure 8: Correlation between experimental and numerical requirement.

For a geometric parameter variation, each IL evolution is compared to numerical requirement. A "demerit" is computed [3].

$$Demerit = \sum_{f_{\max}}^{f_{\min}} [IL_{requirement}(f) - IL_{simulated}(f)] \qquad [3]$$

Demerit is a comparative indicator of grommet acoustic performances. It can be plotted with geometric parameter variation. Demerit minimum is optimal configuration for best acoustic performances.

6. Study case of geometric parameter

Parametric model allows to study quickly a lot of parameters. An important acoustic parameter to be optimized is the cavity length. A patent was filed by Leoni for the dissociation of the acoustic lip with the grommet body (cavity 2) and utilisation of a cavity below (cavity 1). The presence of two air chambers is the content of Leoni's patent.

Different lengths of the cavity 2 were computed as observed on Figure 9. Some configuration are not really possible to be produced but in simulation, it is possible to study all possibilities and understand the behaviour of the system.

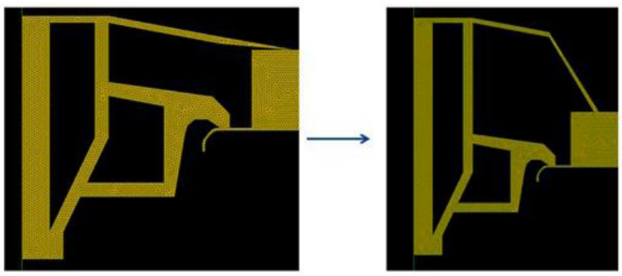

Figure 9: Evolution of the second cavity length.

During product development, experimental tests were done with a cavity length divided by two to understand its influence. Grommets with a cavity length of 10mm and 20mm were tested. Conclusion of experimental results were cavity length is not important.

Parametric model is limited at 17mm minimum for second cavity length. Simulations were computed for a length of 17mm and 32mm to study influence of divide the length by two.

It is possible to confront experimental and numerical results as observed on Figure 10. When the cavity length is divided by two, same phenomenon was obtained in test and simulation between 400Hz and 6300Hz (frequency range important for automobile study). Acoustic performance doesn't change much and a better insertion loss is obtained between 1000Hz and 2000Hz.

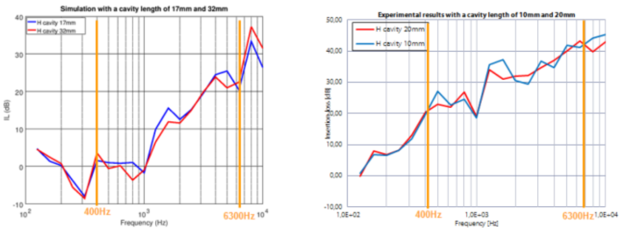

Figure 10: Comparison of IL evolution between experimental results (right) and simulation (left).

Then, insertion loss is computed for nine cavity configurations and a demerit evolution with the cavity length is obtained (cf. Figure 11). Demerit curve admits an evolution with two constant levels and a quick decrease around a length of 40mm. The red curve is a fitting of this evolution.

Previously, cavity length was divided by two on the first constant level (10mm to 20mm and 17mm to 32mm). Demerit is the same for each configuration, so acoustic performances are similar. With experimental tests, same conclusion was obtained.

The optimal length is around 45mm. It's not necessary to have a length higher because a second constant level was obtained. So acoustic performance would not change for a product cost and a volume more important.

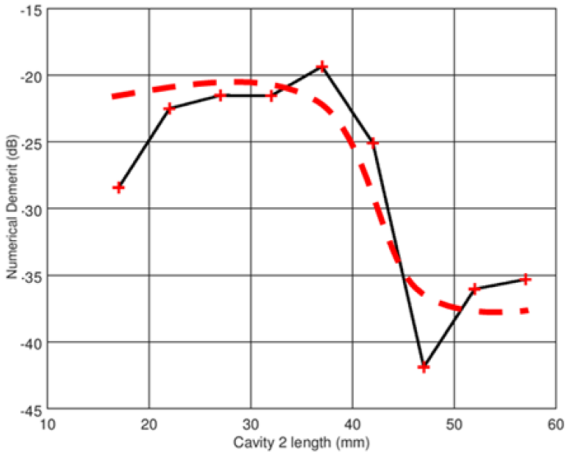

Figure 11: Demerit evolution for a variation on cavity length.

With simulation tool, it is possible to observe acoustic pressure fields. A length of 37mm and 47 was studied at 4000Hz on Figure 11. The two acoustic fields admit the same scale.

It is difficult to see level difference in the reception between configurations. Even so an acoustic pressure slightly lower is observed for 47mm configuration.

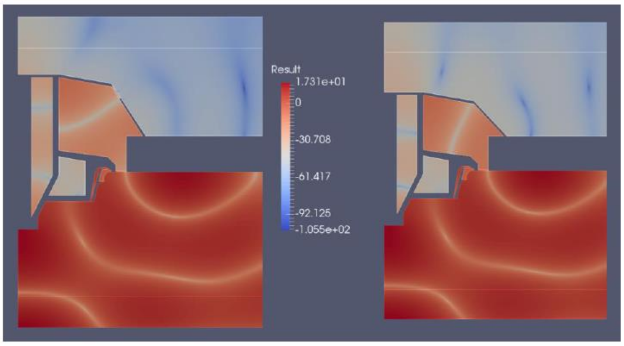

Figure 12: Acoustic pressure at 4000Hz for cavity length of 47mm (left) and 37mm (right).

To understand results obtained, displacements along Y-axis of the lip at 4000Hz are plotted on Figure 13. The two grommets are superposed and a same scale is used. Less displacements of the acoustic lip are observed for the highest cavity.

A lip is like a membrane: with a dynamic solicitation, it will generate some acoustic waves like a loudspeaker. With a cavity length higher, acoustic lip is less excited and shows less displacement. So less acoustic waves are produced and acoustic pressure in reception room is reduced.

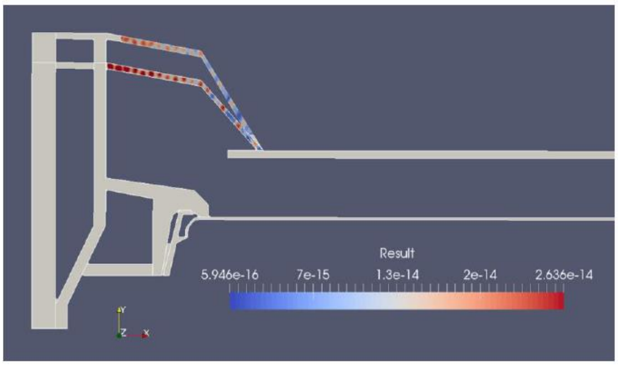

Figure 13: Y displacement distribution at 4000Hz for a cavity length of 37mm and 47mm.

5. Conclusion and perspectives

A finite element model of the small cabin has been developed with the open source finite element software Code_Aster. In order to validate the computational method, two different models have been tested, a 3D model and an axisymmetric model. The limitation of 3D model appears due to the important dimensions of the small cabin and the large frequency band of the measurement for the determination of the IL. As long as the wiring grommet is symmetric, the axisymmetric model provides same trends of results than the 3D model, with ten times less degrees of freedom. This parameter is quite important and allows the user to launch a set of several configurations of wiring grommets in order to highlight indicators (geometrical configuration, material properties, etc.) that could improve the acoustic performance of the wiring grommets.

An entire parametric model has also been realized. The geometry, the mesh and the calculation configuration can easily be modified in a Python file. This type of model allows the user to realize several calculations of wiring grommets. For this study, parametric model allows to compute approximatively one hundred different grommet configurations.

To compare geometric parameters, an acoustic comparative indicator was developed: Demerit to compare each grommet configuration with a reference as Renault requirement. Evolution of demerit with geometric parameters variation allows to choose an optimal configuration for acoustic performances.

An example of complete case study allows to see optimal configuration of second cavity length, and validate results with experimental testing. Simulation allows to understand results based on the analysis of acoustic pressure fields and mechanical behavior of the grommet.

Design rules were obtained for axisymmetric grommet and shared to Leoni design team. This document allows to know which configuration is better for seven principal parameters as observed in Figure 14 :

1. Thickness of the global structure
2. Acoustic lip thickness
3. Second cavity length
4. First cavity length
5. Acoustic ring thickness
6. Thickness of vertical partition
7. Thickness of horizontal partition

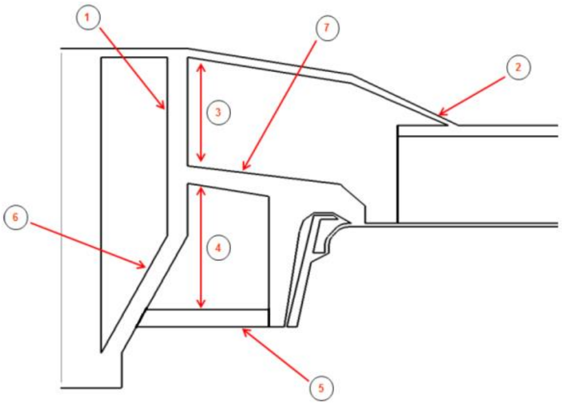

Figure 14 : Geometric parameters studied.

Design rules shared to Leoni design team allows to know a rough size of each parameter for this kind of grommet. More than a rough size, document includes details of grommet behavior with parameter variations.

Enhancements could still improve the finite element model. The application of a global damping factor to the entire model is a limitation for a good correlation between measurements and computation. This problem seems to occur when the fluid/structure interface has several different surfaces, as in the simulation of the small cabin test. Thus, other ways of computation of damping factor are possible in Code_Aster and have to be explored.

Another way of improvement is the computation of the felt as a porous material. As the Code_Aster software is open-source, one can add a tailor-made development of the porous material computation as existing in commercial finite element software.

Design rules obtained need to be validated on axisymmetric grommets close to HJD product. Then, different geometries can be study to develop design rules for grommet categories. Vehicle environment doesn't allow the same grommet geometry and design rules are necessary to avoid several prototypes.

6. Acknowledgement

Leoni for their confidence on CEVAA expertise in simulation and experimental tests.

7. References

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8. Glossary

IL: *Insertion Loss*
SPL: *Sound Pressure Level*
DOF: *Degrees of Freedom*
CAD: *Computer Aided-Design*
FEM: *Finite Element Method*