

FE Simulation of the Transmission Loss Performance of Vehicle Acoustic Components at Low and Medium Frequencies

Rainer Stelzer and Theophane Courtois
Autoneum AG

Ki-Sang Chae, Daewon SEO, and Seok-Gil Hong
Hyundai Motor Company

ABSTRACT

The assessment of the Transmission Loss (TL) of vehicle components at Low-Mid Frequencies generally raises difficulties associated to the physical mechanisms of the noise transmission through the automotive panel. As far as testing is concerned, it is common in the automotive industry to perform double room TL measurements of component baffled cut-outs, while numerical methods are rather applied when prototype or hardware variants are not available. Indeed, in the context of recent efforts for reduction of vehicle prototypes, the use of simulation is constantly challenged to deliver reliable means of decision during virtual design phase.

While the Transfer matrix method is commonly and conveniently used at Mid-High frequencies for the calculation of a trimmed panel, the simulation of energy transfer at low frequencies must take into account modal interactions between the vehicle component and the acoustic environment. After providing a brief review of the established approaches for TL simulation at LF, the article will present a new FE methodology for TL simulation and introduce the advantages of "in-situ" TL simulations by means of fluid-structure FE calculation. In a first step, results are given on bare flat plate as well as bare vehicle structures, in comparison to the results of mass law representations. In a second step, it is shown how the simulation of insulation trims by means of poro-elastic FE can be used to assess the TL of in-situ trimmed vehicle components. On one hand, the FE simulation of the in-situ TLs highlights the limitations of the Transfer matrix method at low frequencies. On the other hand, it is shown that, as far as only the Insertion Loss (IL) of the insulation treatment is concerned, the transfer matrix method can be used in a broader range toward lower frequencies.

CITATION: Stelzer, R., Courtois, T., Chae, K., SEO, D. et al., "FE Simulation of the Transmission Loss Performance of Vehicle Acoustic Components at Low and Medium Frequencies," *SAE Int. J. Passeng. Cars - Mech. Syst.* 7(3):2014, doi:10.4271/2014-01-2081.

INTRODUCTION

The assessment of transmission loss (TL) in the automotive industry is required for the quantification of transfer of acoustical energy through the body or treated body of vehicles. Most of the time, the knowledge of the transmission loss is necessary at component level, because it is directly related to the acoustical performance of the corresponding acoustic part, which is covering this part of the body, and for which it is necessary to set the individual acoustic TL targets. The main examples of such so-called "acoustical components" are the dash insulator covering the firewall, or the floor insulator including the carpet covering the floor structure. This component approach makes sense from the point of view of industrial automotive parts, but is also adapted to the practical methods for assessment of the transmission loss. For obvious reasons, it is more practical to measure the transmission loss of a component isolated from its vehicle environment and

inserted into a framed setup between two coupled rooms, because it fits in such a way the theory of TL through a baffled partition. In practice, such measurements require the knowledge of the incident as well as the transmitted sound power measured in two coupled rooms. Such rooms are either reverberant to create a diffuse sound field, in which the sound power can be easily measured by means of microphones, or anechoic or semi-anechoic, in which the free field incident/ radiated power can be measured by means of intensimetry technics. Those measurements are performed according to international standards ([1] and [2]) either on flat sample setups, or on cut-outs of components like the dash of a car.

When measurements are not possible due to time constraints, or physical components simply not available, the simulation is used for TL evaluation, allowing comparing different design variations or material modifications against

quantified objectives in terms of NVH but also weight and cost. The most practical way to simulate the TL of a partition is the mass law, or transfer matrix method, that allows to take into account the noise reduction not only through the base structural panel, but also through the covering acoustic treatment present under the form of sandwiched material layers. However, the use of the mass law limits the simulation to situations where the partition can be assumed flat and infinite, or at least the combination of few flat partitions, which contribution to the overall TL is linked to their area proportion. At low frequencies for example, and when partitions have 3 dimensional shapes, this is not possible. A typical situation, where such limitation is experienced, is during the definition of air-borne coupling factors necessary to couple SEA acoustic cavities separated by a partition.

It is important to stress out here, that most of the calculation methods applied for the simulation of TL at low frequencies are based on the usage of Finite Element (FEM), Infinite Elements (IFEM) or Boundary Elements (BEM) methods, and tend to emulate the measurement approach, and its associated measured acoustical quantities as introduced previously (incident and transmitted power). This, among other, requires sometimes the simulation of the corresponding measurement environments, such as huge reverberant cavities or free fields, which have a high cost in terms of model size and associated simulation time.

In this paper we propose an approach based on the usage of FEM for the simulation of the TL of a component, when the component remains in its environment. Instead of "cutting" the component at its boundary by applying framed boundary conditions, it remains coupled to the rest of the body structure and is interfering with the surrounding air only through a defined coupling area. The incident power is defined by means of free-field parietal pressure at one side, but the transmitted power is simply derived from the pressure response calculated in the passenger compartment. This approach has the advantage of exploiting the digital data basically available during the vehicle development without modifications, and this article highlights the validity of such a simulation, while stressing out its limitations and possible further improvements.

After being succinctly defined in a first part, the calculation method for the TL is applied in configurations, where the partitions of consideration are of kind of untreated panels, such as bare plate or bare body. In a second part, the partitions of consideration are treated panels, such as trimmed plate or trimmed body. In the case of acoustically relevant vehicle components, such as dash and floor, the trim is designed so that the noise transmission is minimized. Finally, the benefits of the presented method will be discussed on the basis of its correlation with the mass law or transfer matrix method.

TRANSMISSION LOSS OF BARE PANELS

Definition and Calculation Methods

One very important physical process in the area of acoustics is the transmission through a partition because questions, like how to reduce the sound energy inside a room like a passenger compartment and so to make it less noisy, are raised very often in the everyday life of the industry. To characterize this physical process of the transmission the well-known quantity of the transmission loss TL is used. The TL is defined as follows [3]:

$$TL = 10 \log_{10} \frac{P_{in}}{P_{trans}} \quad (1)$$

where P_{in} is the incident power and P_{trans} is the transmitted power. The transmission loss can be determined by measurements but there is also a great interest to predict it by calculations and to reduce in this way the number of measurements, which are in general more time consuming and cost intensive. Thus, the calculation of the transmission loss is an important topic of the acoustic research since a long time. First models to describe the transmission, like the very often used and well-known mass law and the formula of Cremer, are based on the analytical mathematical description of the reflection and the transmission of plane waves in semi-infinite spaces when they come in the contact with a flat infinite plate. In this way, the formula of Cremer, an extension of the mass law, can be finally written as [3]:

$$TL = 10 \log_{10} \left[1 + \left(\omega m - B \omega^3 \frac{\{\sin \vartheta\}^4}{c^4} \right)^2 \left(\frac{\cos \vartheta}{2\rho c} \right)^2 \right] \quad (2)$$

where ω is the angular frequency, ϑ is the angle of incidence, c is the speed of sound in the fluid, ρ is the density of the fluid, B is the bending stiffness of the plate and m is the mass per area of the plate. Such a wave approach can be also used for partitions that have more than one layer like for double-layered steel constructions of a car. Here, the reflection and the transmission of the waves are described just on all the boundaries of the different layers. The relation between the variables, displacements and or pressures, at one side and the other side of a layer can be expressed then by so called transfer matrices. Through combination of such transfer matrices, a global transfer matrix can be built so that there is a direct relation between the pressures and the displacements of two fluids which are located on both sides of the multi-layered partition. This method is called in the literature - because of the used matrices - the transfer matrix method or shortly said TMM [4]. The wave based approaches give good accurate results for high frequencies but due to their associated assumptions - plane waves, infinite partitions and semi-infinite fluid spaces

- they fail in general for low frequencies. To get also accurate results for the low frequency range and for complex geometries, like in the case of a car component, the finite element method (FEM) is more appropriate. Quite often the FEM approach is also combined with the boundary element method (BEM) like in [5], in which only boundaries are described with a mesh of finite elements, or with the statistical energy analysis (SEA), for example in [6], which is an energy based method more for higher frequencies. That is done to reduce the computational cost, which is necessary to make FEM based calculations up to higher frequencies, or to simulate radiations in a free acoustic sound field.

Used FEM based Calculation Procedure

The aim of the article is to predict the transmission loss under the real condition of a closed cavity as a receiving space like a passenger compartment and not under the condition of a free space as it is assumed for example for the mass law and in the case of intensity measurements on the receiving side. The advantage of this procedure is that also the influence of the cavity on the TL can be taken into account. Such a so called "in-situ" TL is discussed in the literature for example in [7] and [8]. In this article pure FEM is used for such calculations and FEM systems are built up as shown in Figure 1. Here, a closed cavity is coupled only through a part of its boundaries, for example a flat steel plate, to a hemispherical cavity. The flat circular surface of the hemispherical cavity is assumed to be rigid except on the coupling area. This is similar to the assumption of a partition in a rigid baffle used in other transmission loss calculations like in [9]. The other surface of the hemispherical cavity has a boundary impedance Z defined as follows:

$$Z = \rho c \quad (3)$$

where ρ is the density and c the speed of the sound of the fluid. In this way, this cavity is assumed to be open to a free space [10]. The whole system is excited by monopole sources distributed in the hemispherical cavity as shown in Figure 2, so that a lot of different angles of incidence occur on the partition of concern. For each of these single source loads the averaged quadratic pressure in the closed rectangular cavity is first calculated. Through averaging the results obtained for each excitation, an averaged quadratic pressure is calculated, which is more or less equal to a response under a diffuse field excitation. To calculate then the transmission loss, the transmitted power can be predicted by using the conservation principle for the energy. Thus, the power P_{trans} transmitted to the receiving cavity is equal to the power P_{dis} which is dissipated in the same cavity:

$$P_{trans} = P_{dis} = \eta \omega E = \eta \omega V \frac{p^2}{\rho c^2} \quad (4)$$

where η is the damping factor of the fluid, V is the volume of the cavity and p^2 is the averaged quadratic pressure in the cavity. The energy E corresponds here to the space averaged energy of a closed diffuse sound field [11] and can be predicted by averaging the pressure over a representative high enough number of positions. The same procedure with the conservation principle is also used for measurements where the TL of a partition is predicted by putting it in-between two closed rooms [12]. Using this principle for both closed rooms it results for the TL:

$$TL_{in situ} = 10 \log_{10} \left(\frac{p_e^2}{p_r^2} \right) - 10 \log_{10} \left(\frac{A_r}{S} \right) \quad (5)$$

Where A_r is the equivalent absorption area, S is the area of the partition between the two rooms and p_e^2 and p_r^2 are the averaged quadratic pressures in the emitting and receiving room. But in the case presented here the sending room is an open semi-infinite space. Thus, to get the second necessary value for the transmission loss (see equation (1)), the incident power, the pressures p_s radiated from each source to the surface of the partition are calculated analytically at the positions of the structural nodes of the FEM-mesh of the panel using the following equation [13]:

$$p_s = -\frac{i\rho\dot{Q}}{4\pi R} e^{ikR} \quad (6)$$

where $\dot{Q}$ is the acoustic volume acceleration of the source, R is the radial distance from the center of the source and k is the wavenumber. The diffuse incident power is predicted in a second step by calculating the incident power P_{in} for each load case and by averaging these results:

$$P_{in} = \int \frac{p_s^2}{2\rho c} dA \quad (7)$$

This described procedure can be used not only for the small plate-box system shown in Figure 1 but also for more complex partitions and cavities. In this article it is also used to determine the transmission losses of vehicle components, such as the dash and the floor (see Figure 3). In this case, the closed rectangular cavity (like in Figure 1) is substituted by the vehicle passenger compartment and the flat plate partition by the dash or the floor of the vehicle itself. In order to represent correctly the dynamic behavior of the component in its structural environment, the whole structural body of the vehicle is present in the calculation, but only the part of interest for the TL calculation is acoustically excited and coupled with the two cavities.