# Advanced FEM Acoustic Simulations of Intake and Exhaust Components

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**Total vehicle noise is significantly impacted by the contribution of intake and exhaust lines. This article uses a finite element method (FEM), integrating advanced visco-thermal dissipative models, to analyze specific intake and exhaust line components. In particular, the acoustic performance of a catalytic converter and an air filter are simulated. Their models include the dissipative effects of small ducts and anisotropic porous materials respectively.**

In automotive NVH, total vehicle noise is significantly impacted by the contribution of intake and exhaust line components. Today's technologies can control intake and exhaust noise to the same degree as engine noise. Both automotive OEMs and suppliers are increasing their attention on intake and exhaust noise and solutions to mitigate them. Among these, the simulation of virtual prototypes allows a considerable reduction of time and cost in the development cycle compared to physical prototype testing. Acoustic simulation software provides accurate modeling capabilities for simulating any component involved in such systems.

This article focuses on the acoustical performance of intake and exhaust lines which are composed of ducts and volumes as shown in Figure 1. In particular, it presents the acoustic perspective of two specific components – an exhaust catalytic converter and an intake air filter. A finite element method integrated with advanced visco-thermal dissipative models is used. This article extends the capabilities previously presented by one of the authors.[1]

## Finite Element Method (FEM)

To study both the intake and exhaust lines, numerical simulation methods play an increasingly important role in the NVH department of OEMs and auto-suppliers. Among the numerous numerical acoustic methods, the finite element method (FEM) offers an advantageous combination of modeling flexibility, computational efficiency and results accuracy. Acoustical FEM can be easily coupled with structural FEM, which is already well-known to most structural analysts. The acoustical and structural coupling in the FEM environment is called vibro-acoustic FEM. Advanced direct FEM solvers, such as MUMPS[2] and PARDISO[3], are very efficient. With ever progressing computation resources, a vibro-acoustic FEM model can reach millions of degrees of freedom (DOF), while computation time continues to decrease.

Compared to the boundary element method (BEM), FEM allows the modeling of more complex physics such as visco-thermal dissipation. The historical obstacle of volume meshing of FEM does no longer exist. An increasing number of acoustical engineers are embracing FEM and relying on it for their daily product design work.

The FEM based acoustic simulation software Actran, developed by Free Field Technologies (FFT), an MSC Software Company, has been successfully applied to numerous intake and exhaust noise projects.[1,4-6] In this article, we demonstrate the capabilities of Actran in predicting intake and exhaust component performance where complex visco-thermal dissipation occurs and can correctly be taken into account.

## Visco-Thermal Dissipation

In the vibro-acoustic field, dissipative phenomena can occur in both the fluids and solids. Typically, viscous dissipation is not included in the FEM formulation as this is known to have negligible effects as long as the considered fluid domain is sufficiently large. On the contrary, in some specific cases viscous dissipation correctly models the physics. For example, in automotive intake or exhaust applications, visco-thermal dissipation occurs in the tiny ducts of a catalytic converter, in porous materials of air filters or in the perforations of muffler plates. Specifically, two dissipative

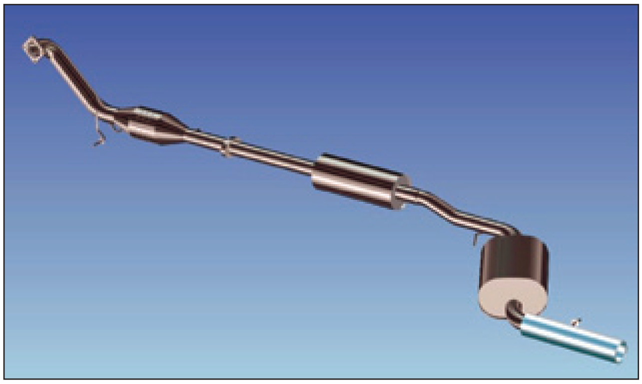

*Figure 1. Exhaust line.*

effects in fluids can be distinguished:

- Losses due to the fluid's viscosity, resulting from the presence of shear forces close to the rigid boundaries
- Losses due to the fluid's thermal conductivity, resulting from heat conduction effects between the fluid phase and the solid phase.

Both of those phenomena are localized within thin regions close to the walls, hence the term viscous and thermal boundary layers. Moreover, vibrations dissipate due to solid elastic hysteresis.

On the one hand, in FEM modeling the dissipation in solids is easily taken into account by introducing a complex number in the material's Young modulus. On the other hand, taking into account visco-thermal dissipation in fluids within a FEM model shall be done accordingly to the type of component to model.

In this article different advanced formulations are proposed to correctly model a catalytic converter and an intake air filter. Moreover, the reader is referred to a previous publication of the authors where an example of a perforated plate model is presented.[1]

## Sound Transmission Loss (STL or TL)

Transmission loss is the key indicator of acoustic performance related to pipe noise. One can numerically calculate the TL of a single component or the TL of an entire exhaust line. The TL is defined as the logarithmic ratio between the incident and transmitted power (Equation 1). All the components considered in this article will be analyzed by comparing the transmission loss of different analysis setups. To compute the transmission loss, a plane wave excitation is provided at the inlet and a non-reflective boundary condition is applied at both inlet and outlet of the components to ensure anechoic conditions for both propagating and reflected waves (see Figure 2).

$$TL = 10.\log_{10}(W_{Incident} / W_{Transmitted}) \quad (1)$$

## Catalytic Converter

A catalytic converter is a vehicle emission control device that converts harmful pollutants into carbon dioxide, water and nitrogen. It typically consists of one or more honeycomb bricks (the term honeycomb describes a structure of tiny channels). Engine noise propagates through the exhaust line and the catalytic converter. Since the viscous and thermal boundary layers occurring in the catalytic converter channels have thicknesses comparable to the hydraulic diameter of capillaries, dissipation of the acoustic wave cannot be neglected. In this case the challenge consists of modeling the acoustic propagation within tiny ducts in the presence of a mean flow. This challenge is addressed by the eXtended Low Reduced Frequency model (XLRF) developed by one of the authors.[7] This model assumes plane wave propagation within

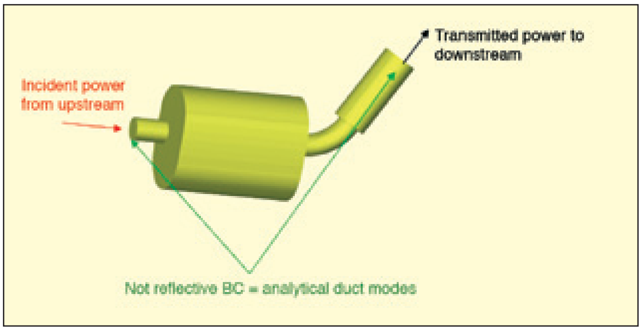


*Figure 2. Transmission loss of muffler.*

the channels and assumes a constant Mach number in the cross-section of the channels. These assumptions lead to an equivalent 1D scalar dissipative wave equation. In this article we show the acoustic transmission through the component depicted in Figure 3. It is constituted by an inlet duct, a capillary net representing the catalytic converter and an outlet duct.

The overall analysis is a two-step procedure:
- The mean flow is first computed by means of a compressible flow solver.
- The component's acoustic performance is then determined taking into account the output of the previous steps.

Both these steps have been computed by means of Actran's dedicated solvers.

Figure 4 compares the TL of the catalytic converter with and without flow, with and without taking into account the visco-thermal dissipation. As can be seen, the visco-thermal dissipation has a strong impact on the acoustic performance of the catalytic converter. The flow as well shall be considered in order to correctly model the acoustic performance of these types of components.

## Intake Air Filter

Particulate air filters are devices composed of a fibrous material which prevents abrasive particulates from entering the engine cylinders. The fibrous material is usually a plated porous medium as shown in Figure 5 and therefore it has anisotropic characteristics. The engine noise propagates upstream though the intake and is damped by the filter due to visco-thermal dissipation effects. In this case all the three dissipative effects described earlier occur. Typically, porous materials are modeled by means of the Biot model which can be extended to include the anisotropic nature of an air filter.[8] This model considers a heterogeneous medium as an equivalent homogeneous medium where the solid phase occupies a fraction 1–Ω of the volume while the fluid phase (air) occupies a fraction Ω of the volume. The model states that the interaction forces between the skeleton and the fluid are due to two factors – the inertia coupling and the viscous coupling. The former is linked to the tortuosity, and the latter is linked to the flow resistivity. These two quantities are scalars when dealing with isotropic materials, and diagonal 2nd order tensors when dealing with anisotropic media. In the case of the air filter, which is composed of a folded porous sheet, we consider the following characteristic referred to the local reference frame (see Figure 6):
- Along the transverse direction *z* the resistivity is linked to the porous material bulk resistivity $R_0$ by the following relation:

$$R_z = R_0 \frac{S}{S_0}\frac{h_0}{h} \qquad (2)$$

where $S$ is the filter cross-section, $h$ is the filter global thickness, $S_0$ is the area and $h_0$ is the thickness of the unfolded porous sheet.
- Along the folding direction *y* the resistivity is linked to the trasfer resistivity by the following relation:

$$R_y = R_z \left(\frac{S_0}{S}\right)^2 \qquad (3)$$

- A very small resistance along the remaining direction *x*.

The geometry displayed in Figure 7 is considered and three configurations are compared – a filtering unit modeled through an isotropic material and filtering unit modeled by an anisotropic porous sheet with two different orientations of the folding direction. An example of an acoustic map of the solution is depicted in Figure 8. As can be seen in Figure 9, the isotropic formulation leads to an overestimation of the TL compared to an anisotropic model. Moreover, with this approach, the optimal folding direction can be chosen from an acoustic perspective.

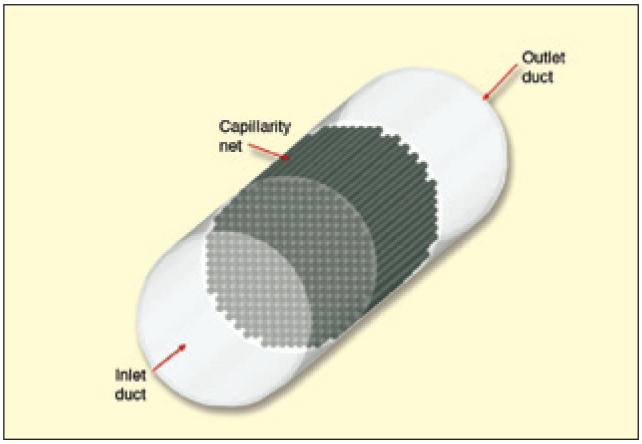


*Figure 3. Catalytic converter geometry.*

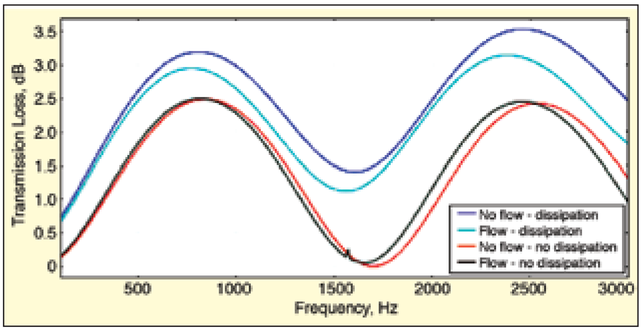


*Figure 4. Catalytic converter transmission loss.*

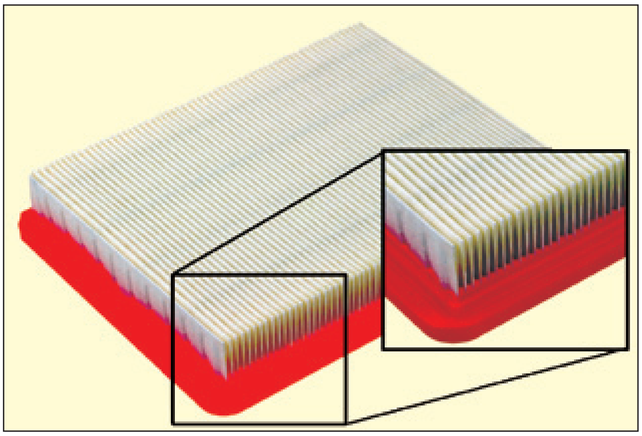

*Figure 5. Intake air filter.*

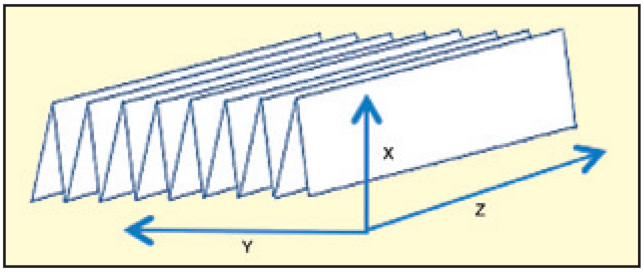


*Figure 6. Filter local reference frame.*

## Conclusions

In this article the modeling of visco-thermal dissipative effects were discussed aiming at highlighting the importance of including

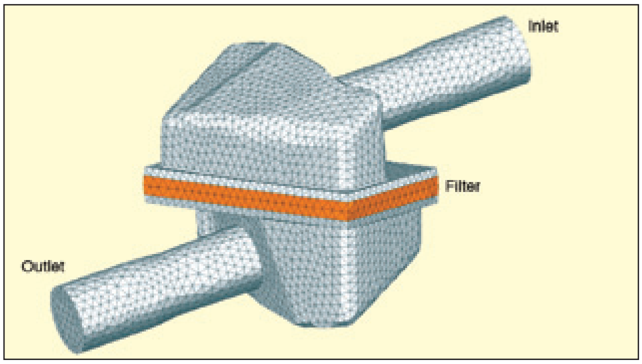


*Figure 7. Intake filtering component.*

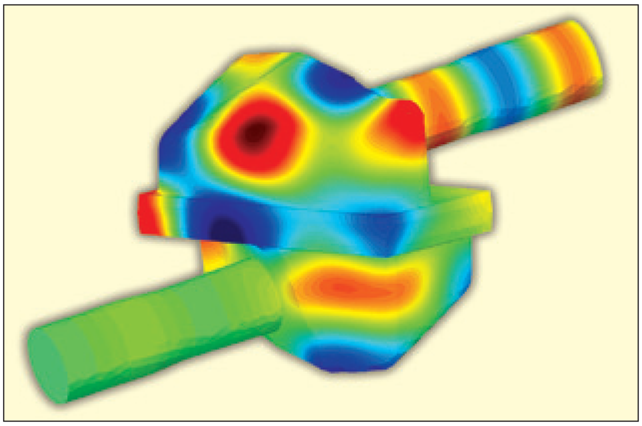

*Figure 8. Acoustic map at 2500 Hz.*

these effects in the numerical analysis of automotive intake and exhaust systems. The two different examples analyzed had unique features and therefore two different models where considered to

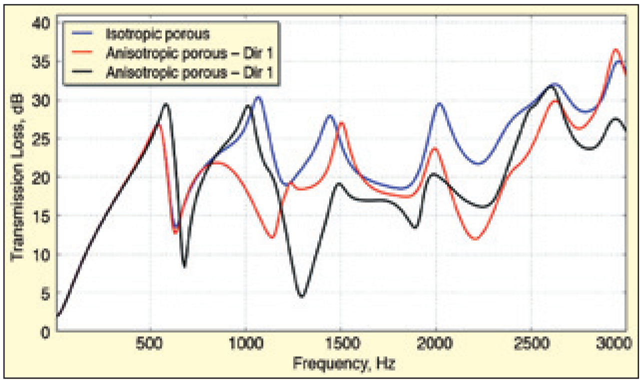


*Figure 9. Transmission loss of air filter with different porous formulations.*

correctly address the acoustic performance through simulations Both models have been implemented within Actran software.

## References

1. Ze Zhou, Diego Copiello, "Simulation of Exhaust Line Noise Using FEM and TMM," *Sound & Vibration,* www.sandv.com/downloads/1309zhou.pdf.
2, MUMPS Solver: http://mumps.enseeiht.fr/.
3, PARDISO: Parallel Direct Sparse Solver. https://software.intel.com/en-us/node/470282.
4, Mitsubishi Motors, "Exhaust System Modeling Using a Transfer Matrix Method Coupled to Actran" Actran Users Conference 2010, Belgium.
5, T. Le Bourdon , et al, "Vibro-Acoustic Simulation of an Intake Air Filter Using a Hybrid Modal Physical Coupling," ISNVH 2012-01-1549
6, D. Copiello, Z. Zhou, G. Lielens, "Acoustic Simulation of a Vehicle Exhaust System using High Order Transfer Matrix Method Coupled with Finite Element Method," SAE Int. J. Engines 8(1):258-265, 2015.
7, C. Sambuc, "Refined Damped Equivalent Fluid Models for Acoustics," Ph.D. Thesis, Université Libre de Bruxelles, 2015.
8, G. Lielens and Z. Zhou, "Numerical Investigation of the Different Dissipation Mechanisms Within a Typical Multilayered Trim Panel," Symposium on the Acoustics of Poro-Elastic Materials, 2014. SV

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