

A Proposed Coupled Vibro-Acoustic and CFD Modeling Solution for Complex-Shaped Mufflers Subject to Mean Flow

Abderrazak Mejdí¹, Tiago Macarios², Bryce Gardner³, Sébastien Chaigne⁴ and Chad Musser⁵

¹ ESI US R&D, 12555 High Bluff Drive, Suite 175, San Diego, CA 92130, USA, E-Mail: Abderrazak.Mejdi@esi-group.com

² ESI US R&D, 12555 High Bluff Drive, Suite 175, San Diego, CA 92130, USA, E-Mail: Tiago.Macarios@esi-group.com

³ ESI US R&D, 12555 High Bluff Drive, Suite 175, San Diego, CA 92130, USA, E-Mail: Bryce.Gardner@esi-group.com

⁴ ESI Group, Parc d'Affaires SILIC, 99 rue des Solets, BP 80112, 94513 Rungis cedex, France, E-Mail: Sebastien.Chaigne@esi-group.com

⁵ ESI US R&D, 12555 High Bluff Drive, Suite 175, San Diego, CA 92130, USA, E-Mail: Chad.Musser@esi-group.com

Abstract

Flow within a duct strongly affects the propagation of acoustic waves. This effect must be addressed by the vibro-acoustic modeling of duct systems that are subject to flow. The effective sound propagation speed in a duct is changed and the sound is refracted towards or away from the duct walls depending on flow direction. Narrowband acoustic sources from the engine must be attenuated by the muffler system. Because flow will shift the frequencies of the muffler system acoustic resonances, accurate modeling of acoustic propagation within a duct is crucial for design and “tuning” of muffler systems. For many actual muffler systems which have arbitrary or complex geometry, flow patterns do not have an analytical solution and must be determined through computational fluid dynamics (CFD) simulations. This paper describes an automated process for coupling an acoustic finite element (FE) muffler vibroacoustic design to an open source computational fluid dynamics (CFD) solver to obtain noise attenuation predictions accounting for flow effects, saving test effort and time. A validation case study showing the ability for a non-CFD expert modeler to obtain accurate muffler predictions for cases of uniform and non-uniform flow is presented. Limitations and future steps for this modeling approach are discussed.

Introduction

Mufflers are designed with the intention to attenuate certain important frequencies from the engine as it passes through the exhaust system. Because this type of noise is quite tonal in nature, mufflers are often designed to provide large amounts of attenuation at certain narrowband frequency ranges at important RPM conditions. To support this type of noise reduction, mufflers are designed with series of expansion chambers (tuned to attenuate certain frequencies by the selection of chamber volumes and pipe lengths), perforations, and the use of porous materials.

A reactive type of muffler design as shown in Figure 1 contains no porous materials and relies on cancellation of sound waves due to tuned chambers to attenuate noise at key frequencies and RPM. [1], [2] This type of design may have a larger back pressure when perforations are involved and so the tradeoff of acceptable back pressure and noise attenuation performance of the perforations must be considered.

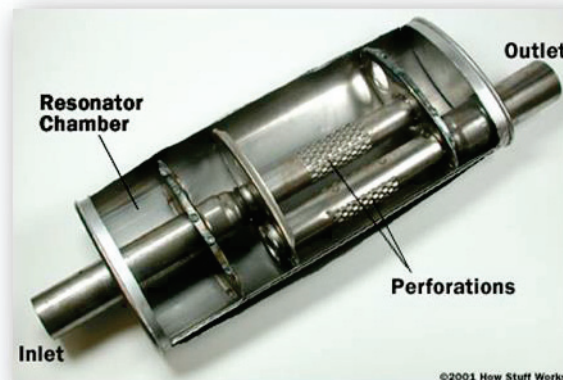


Figure 1: Typical Reactive Muffler Design

In contrast, an absorptive muffler design employs porous materials (fiber or foam), commonly located at the edge of the muffler behind a facing perforated layer, which dissipates sound energy within the material. [2] This muffler design, shown in Figure 2, generally has less back pressure but the porous materials must be designed for optimum performance and must be able to withstand high temperature conditions to which they may be subjected.

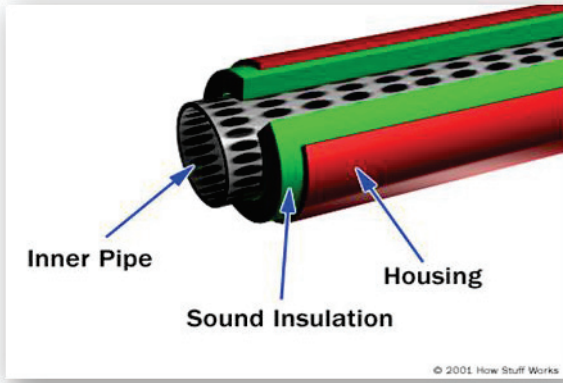


Figure 2: Typical Absorptive Muffler Design [1]

Muffler Acoustic Performance Metric

The acoustic performance metric for these mufflers designs is the same and is defined as muffler Transmission Loss. This is the ratio of transmitted acoustic power (at the outlet) to the incident acoustic power (at the inlet) and may be expressed mathematically as the dimensionless quantity:

$$TL = 10 \log_{10} \left(\frac{\Pi_{in}}{\Pi_{trans}} \right) = -20 \log_{10} \left(\frac{p_2}{\frac{\rho c}{2} v_0 \sqrt{\frac{S_1}{S_2}}} \right) \quad (1)$$

where v_0 is the applied inlet (acoustic) velocity, ρ is the fluid density, c is the wavespeed of sound, S_1 and S_2 are the inlet and outlet surface areas, respectively, and p_2 is the acoustic pressure at the outlet. A further assumption for this equation to hold is that both the inlet and outlet have non-reflective boundary conditions.

In the special case where the input velocity is normalized to a unit input and the inlet and outlet surface areas S_1 and S_2 are equal, Equation (1) takes the simpler form:

$$TL = -20 \log_{10} \left(\frac{2p_2}{\rho c} \right) \quad (2)$$

Muffler Acoustic Performance Baseline Test Case Modeling and Validation

Knowing that the flow in a muffler impacts the acoustic properties and hence the modal response of the acoustic modes in the muffler, there are two possible ways in which the flow can be modeled: uniform or non-uniform flow type. [3] Either method will change the local properties of the acoustic wavespeed and density which will lead to changes

in acoustic response for the system. When the flow is assumed to be uniform so are the acoustic properties everywhere in the muffler and a Boundary Element (BEM) approach or Finite Element (FEM) approach can both be used and should yield similar results as shown in Figure 3 for uniform flow (or no flow). Excellent agreement for the acoustic response of a simple duct is shown.

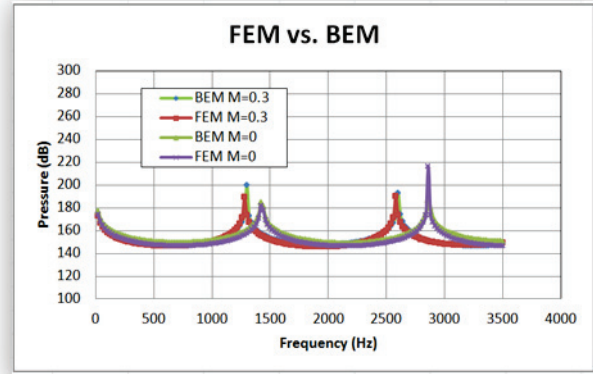


Figure 3: Comparison of Finite Element (FEM) and Boundary Element (BEM) Pressure Results for a Simple Duct with Uniform Flow (M=0.3) and No Flow (M=0)

For a next level of model validation complexity, a simple muffler consisting of an expansion chamber with measured response data available from the literature is chosen for a validation study as shown in Figure 4. [4]

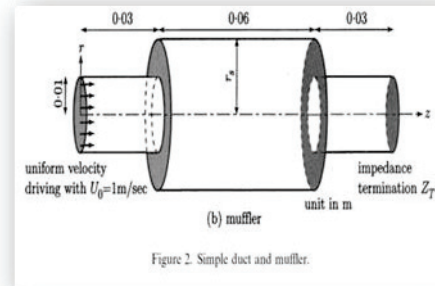


Figure 4: Simple duct and muffler test case from reference for comparison studies

This muffler has no perforations or porous materials inside and is suitable for comparison to an acoustic Finite Element modeling approach for both uniform or non-uniform flow. A comparison of the FE acoustic prediction of the acoustic response of this system with uniform flow at M (Mach number) = 0.3 is shown in Figure 5. The comparison between prediction with uniform flow and test data from the reference is excellent.

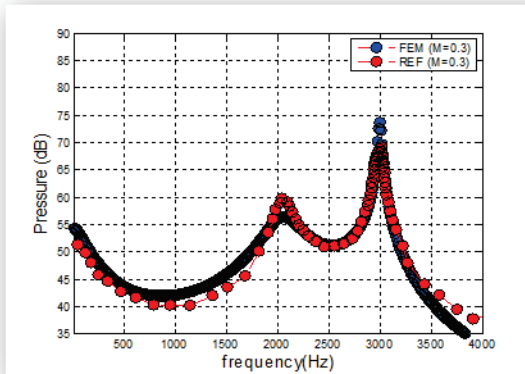


Figure 5: Comparison of FEM prediction (FEM) to reference test data (REF) for uniform flow at $M=0.3$

Muffler Acoustic Performance Validation for Non-Uniform Flow

The same system can be modeled with a non-uniform flow which accounts for the locally-varying characteristics in a muffler due to complex flow. With a suitably complex CFD model these local effects can be modeled. However, setting up a suitable CFD model and its parameters which is capable of providing the necessary flow characteristics which can be translated into locally-varying acoustic properties is often beyond the scope of experience or time and resources available to an acoustic analyst. Therefore a new methodology was explored in which the acoustic FE model and mesh within the VA One software is automatically used to generate a model, run an analysis and import the results back into the acoustic FE model to update the local acoustic properties. [3,5] An open source CFD solver, OpenFOAM, was utilized to perform the CFD analysis and obtain the information needed to update the acoustic model through a robust automation procedure.

Note that the locally-varying characteristics of the interior acoustics create a situation in which a Boundary Element (BEM) model is not appropriate or accurate for modeling; when a non-uniform flow is present an acoustic FE model must be used to calculate the flow effect on the acoustics as shown in Figure 6. The correlation between FE prediction with non-uniform flow following this new automatized method and test data from the reference is excellent, giving confidence that for this simple test case the proposed procedure for accounting for locally varying acoustic properties is working properly.

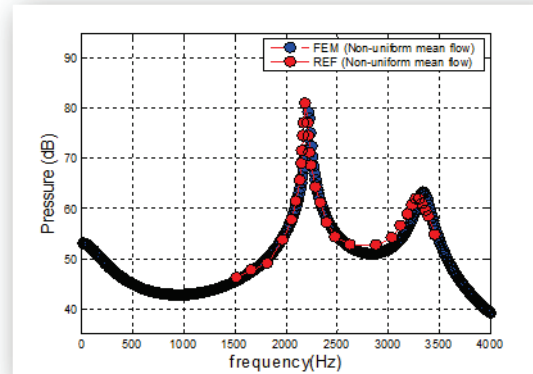


Figure 6: Comparison of FEM prediction (FEM) with acoustic properties obtained by OpenFOAM simulation to reference test data (REF) for non-uniform flow at $M=0.1$

Non-Uniform Flow Results for Typical Automotive Muffler

With the confidence for the validation comparisons, an actual automotive muffler was studied following the same method of automatically using OpenFOAM analysis to model the non-uniform flow in an acoustic FE model. The muffler design is as shown in Figure 7 and consists of an inlet and outlet chamber with a direct connection and a secondary intermediate chamber connected to the outlet chamber and acting as a Helmholtz resonator.

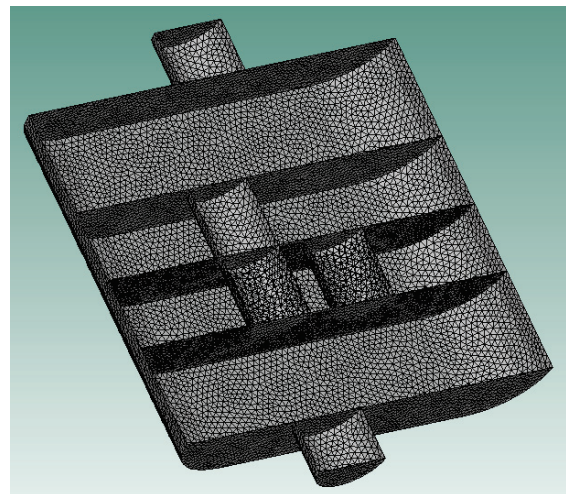


Figure 7: Typical automotive muffler being modeled for non-uniform flow

The OpenFOAM CFD results from the acoustic FE model shows flow results indicating a fairly direct flow from inlet to outlet with a total pressure drop of around 5% (relatively little back pressure), as visualized in the streamlines shown in Figure 8.

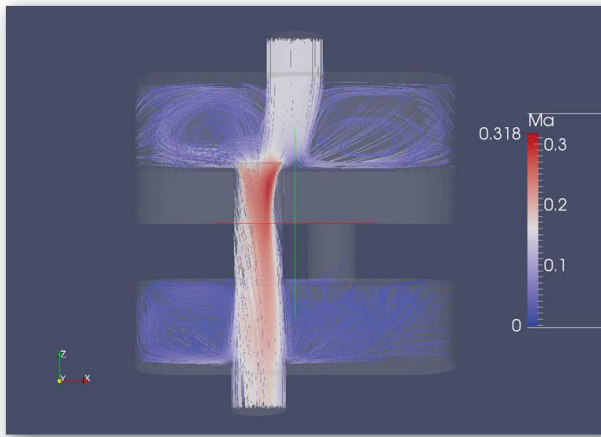


Figure 8: Visualization of streamlines in the typical muffler model from OpenFOAM

The FE acoustic results for no flow and for non-uniform flow the first mode are shown in Figure 9, showing just a small shift in frequency due to the non-uniform flow.

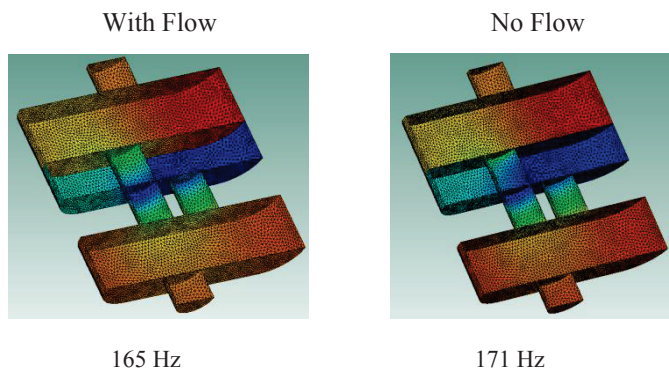


Figure 9: Visualization of 1st acoustic mode

However, with increasing frequency the acoustic modes shift more in frequency due to the flow. Mode 18, showing a strong response in the middle chamber functioning as a Helmholtz resonator, shifts in frequency by almost 100 Hz at this frequency range as shown in Figure 10.

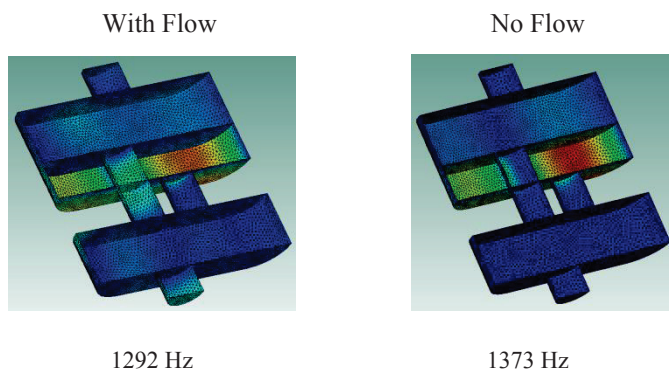


Figure 10: Visualization of 18th acoustic mode

The overall shift in frequencies for the case of no flow and the non-uniform flow case simulated can be seen in Figure 11 which shows the muffler TL versus frequency from 100 to 2000 Hz. The case with flow is generated with automatically calculated and imported locally varying acoustic properties from OpenFOAM.

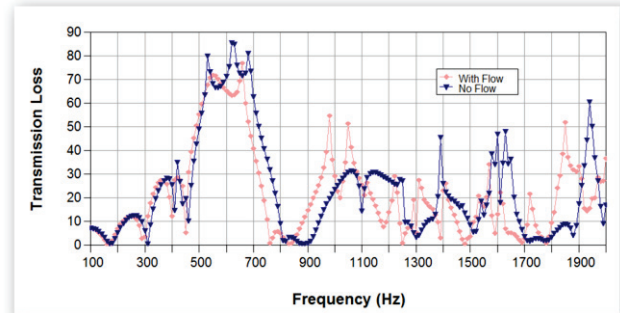


Figure 11: Predicted muffler TL with flow (pink) and no flow (blue)

Conclusions and Next Steps

The method described above, starting with simple test cases, shows how an acoustic FE approach taking into account locally varying acoustic properties due to flow via an automatized CFD analysis can accurately model the flow effects on the muffler acoustic response and be used as a muffler acoustic design tool. Studies subjecting the side wall boundary conditions to a range of temperatures that would be encountered during typical vehicle operation are underway. Also underway is work to establish a similar procedure when perforated muffler sections are involved and initial results versus simple reference test cases and test data are promising. Further work will address the modeling of porous materials included in absorptive type mufflers.

References

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- [5] "OpenFOAM User Guide," The OpenFOAM Foundation, 2015.