

Prediction of Muffler Insertion Loss by a Hybrid FE Acoustic-SEA Model

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ABSTRACT

A reactive aftermarket automotive style muffler was considered for development and validation of a procedure to numerically predict and experimentally validate acoustic performance. A CAD model of the silencer was created and meshed. The silencer interior included two sections of perforated pipe, which were included in the cavity mesh. A hybrid FE-SEA (Statistical Energy Analysis) numerical model consisting of a finite element acoustic cavity excited by a diffuse acoustic field at the inlet and coupled via hybrid junctions to SEA semi-infinite fluids on both the inlet and outlet. The hybrid FE-SEA model solves very rapidly on a desktop PC making iterative numerical design a realistic option.

To validate the predictions, an experimental setup was created to directly measure the muffler insertion loss. This was done by using a broadband acoustic source piped into a hemi-anechoic chamber. A straight pipe with simple bends to recreate the path from muffler inlet to outlet was fabricated for comparison. Muffler insertion loss was calculated by means of a simple level difference between the silencer and the straight pipe. Agreement between experimental measurement and numerical prediction are excellent. A simple procedure allowing high confidence numerical evaluation of design iterations based on CAD models is outlined.

INTRODUCTION

The design of automotive mufflers is important to effectively attenuate engine noise. Typically the insertion

loss or transmission loss of the muffler is used to assess the performance of the muffler at the component level. The acoustic design of mufflers have has been studied extensively and there have been numerous methods and techniques developed to predict the performance of dissipative, reactive and hybrid silencers which are summarized in Munjal¹ and Beranek². These can be categorized into 1D methods such as transfer matrix methods^{1,2,3,4} via four-pole methods, boundary element methods^{5,6}, and finite element methods. When designing and performing acoustic analysis on mufflers, there are tradeoffs in modeling effort, solution time and modeling accuracy that are involved when selecting a particular analysis technique. The transfer matrix method can provide the low-pass filter characteristics of a muffler and exhaust system with gross geometric details without the need for full CAD data. The limitation is that the model is based on one-dimensional plane wave behavior and the predictions are inaccurate once the acoustic wavelengths approach the physical dimensions of the muffler and pipe work. Full three-dimensional wave behavior can be predicted and accounted for in boundary element models and finite element models. Typically FE acoustic models are significantly faster to solve because sparse symmetric matrices are solved compared with BEM where the solution of fully populated non-symmetric matrices is required. FE models are limited by the element size and the number of elements required to adequately represent the physics of the acoustic modes in the fluid. For BE models the limitation is the number of wetted nodes that can be solved for in the available memory. In this paper the basic CAD data is used to create FE acoustic models to rapidly evaluate automotive muffler design and the accuracy of the modeling approach is compared to measured data.

OVERVIEW

The acoustic performance criteria for evaluating the effectiveness of mufflers are Insertion Loss (IL), and Transmission Loss (TL) after Beranek². The Insertion Loss is the simplest performance metric that can be assessed by measuring the change in the radiated sound pressure level at the muffler outlet with and without the muffler in place as shown in Figure 1. The TL is defined as the ratio of the power transmitted (W_t) to the incident power (W_i). Typically a Boundary Element Model is used to predict the TL by calculating the incident and transmitted power.

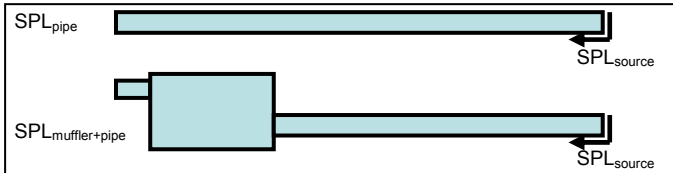


Figure 1: Insertion Loss Measurement

$$\text{Insertion Loss} = \text{SPL}_{(\text{pipe})} - \text{SPL}_{(\text{muffler+pipe})} \quad \text{dB} \quad (1)$$

$$\text{Transmission Loss} = 10 \log_{10} (W_t/W_i) \quad \text{dB} \quad (2)$$

For this study a typical aftermarket muffler was chosen as a candidate for the evaluation of a finite element based methodology to predict muffler acoustic performance analytically and verify the acoustic performance experimentally. The silencer used in this evaluation is a three chamber design, with perforated sections on both inlet and outlet pipes. The perforations allow interaction between the inlet and outlet pipes through the middle chamber. The sectioned silencer is shown in figure 2 for clarification and is manufactured from 0.0325" galvanized steel.



Figure 2: Automotive Style Muffler

NUMERICAL MODELING METHODOLOGY

The numerical modeling procedure is based on a workflow that begins with CAD geometry. The geometry based on an idealized version of the sheet metal

geometry. The geometry is ideal and simplified so that the sheet metal walls intersect perfectly and no attempt is made to model local details such as hems or spot welds that are required in manufacturing. The CAD geometry is transferred to an FEA pre-processor to generate a fluid volume and create the Finite Element mesh of the acoustic fluid. The volume mesh is exported as a Nastran bulk data file and imported into the numerical acoustic software, where additional acoustic cavities, boundary conditions, load are defined. The workflow is shown in the flowchart in figure 3.

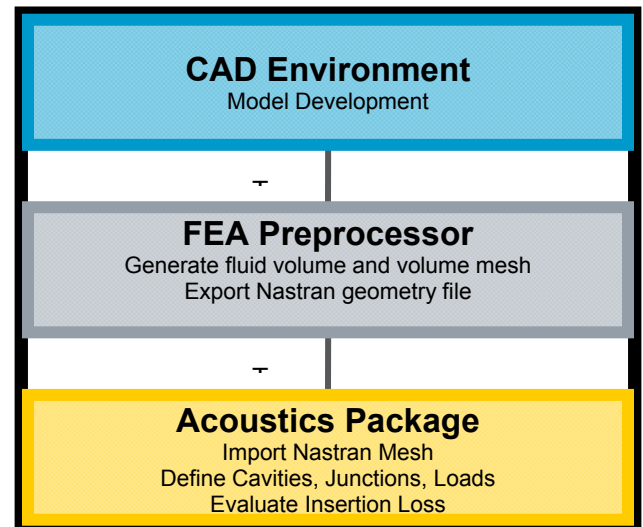


Figure 3: Numerical modeling workflow

CAD MODEL DEVELOPMENT

The muffler shown in figure 2 is an assembly of end caps, an outer shell, tubes, and baffles. Many of these components have features such as spot welds, hems, weld tabs, and expansion joints that ease the manufacturing of the muffler, improve thermal expansion, and make a durable muffler; however they have negligible effect on the internal acoustics. Including these features in the model complicates meshing and result in large element counts which would extend solution times for negligible benefit. For these reasons these features are not included in the CAD model. Complicated features such as tube perforations are important to the acoustic function of the silencer and require being included in the model; however they complicate the meshing procedure and increase the element count. In this case the feature must be included in the analysis to accurately predict the acoustic performance of the silencer.

For an FE representation of the model, the requirement in developing any model for acoustic analysis is to have a continuous fluid volume. Therefore, a single CAD part functions better than an assembly of parts in most cases as a single CAD part can be created without seams and with ideal feature intersections. The CAD model shown in figure 4 was used as the basis for creating the FE acoustic model. The time required to create this CAD

model was approximately two hours, however the time to create the model varies depending on the complexity of the model.

FLUID VOLUME GENERATION AND MESHING

The next step in creating an acoustic model is to use the muffler CAD geometry to define the internal fluid volume of the muffler and then mesh the corresponding volume using an FE preprocessor. The fluid volume is defined by selecting two bounding surfaces, the inlet and outlet pipes, and an internal seed surface. Because the CAD geometry was simplified as described previously, the fluid volume is created automatically. Unless radiation from the muffler shell is being considered, only the fluid volume is needed and an FE structural mesh for the sheet metal is not required.

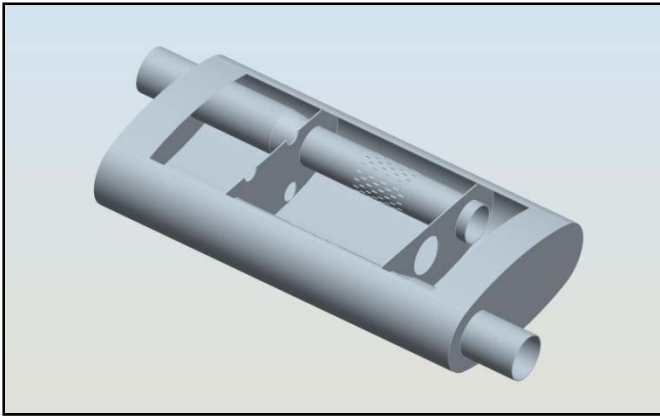


Figure 4: NAPA Muffler geometry created in CAD Package

to the smallest relevant CAD features. When meshing the fluid volume, a mesh density based on approximately 6 elements per acoustic wavelength is typical. Since the upper frequency bound in the model is 2 kHz, a mesh size of 0.009m was specified which satisfies the six elements per wavelength requirement to 6.3 KHz. This may seem excessive, but allows good spatial resolution at the perforations and ensures sufficient modes are calculated for a converged solution.

The final step of the fluid mesh generation is to export the meshed model as a Nastran file. The time required for fluid generation, volume meshing, and Nastran export is approximately 1 hour, but can vary depending on the complexity of the geometry.

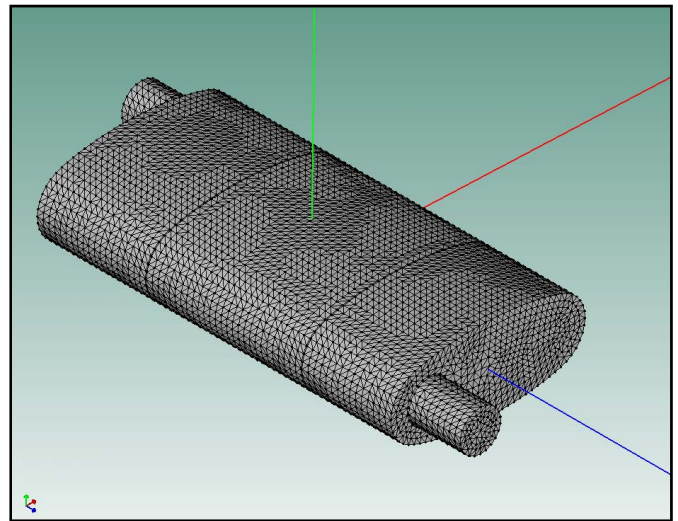


Figure 6: FE cavity defined using Nastran mesh

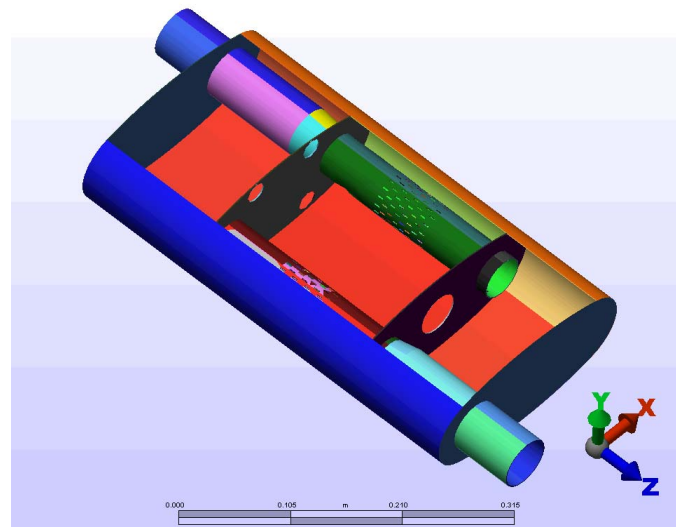


Figure 5: Geometry imported to FEA preprocessor

With clean CAD geometry and the current auto meshing technology, creating an FE mesh of the fluid volume is straightforward with minimal user interaction. The mesh size must be specified, either explicitly or by relationship

ACOUSTIC FEA MODEL DEVELOPMENT

The Nastran model file is imported into the acoustic software VA-One for definition of cavities, boundary conditions, and loads for model solution. All imported solid elements are selected and used to define an acoustic FE cavity. The cavity requires the definition of fluid properties, in this case air at room temperature, although in practice the effect of the elevated operating temperatures will change the fluid properties and muffler performance. The surface of the elements on the inlet and outlet of the muffler are defined as FE faces by selecting all surface elements belonging to the round terminating surfaces of the pipes. The faces provide a means to couple SEA infinite fluids and diffuse acoustic fields to the muffler inlet and outlet. Solution parameters are defined as either constant bandwidth or third octave bands. The solution in this paper is computed from 20 Hz to 2 kHz at 5 Hz intervals. The solution sequence includes a modal eigenvalue solution and factorization for the requested solution bandwidth as well as a forced response solution considering applied loads. This solution sequence takes approximately twenty minutes on a 32 bit dual core processor with 2GB of RAM.