

Direct Aeroacoustic Simulation of Flow Impingement Noise in an Exhaust Opening

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ABSTRACT

Unusual noises during vehicle acceleration often reflect poorly on customer perception of product quality and must be removed in the product development process. Flow simulation can be a valuable tool in identifying root causes of exhaust noises created due to tailpipe openings surrounded by fascia structure. This paper describes a case study where an unsteady Computational Fluid Dynamics (CFD) simulation of the combined flow and acoustic radiation from an exhaust opening through fascia components provided valuable insight into the cause of an annoying flow noise. Simulation results from a coupled thermal/acoustic analysis of detailed tailpipe opening geometry were first validated with off-axis microphone spectra under wide open throttle acceleration. After studying the visualizations of unsteady flow velocity and pressure from the CFD, a problem that had proved difficult to solve by traditional “cut and try” methods was corrected rapidly.

INTRODUCTION

Customer expectations of vehicle quality are steadily increasing. Interior noise levels are being continually reduced in response to this competition, which often reduces the overall masking levels of noise, vibration and harshness (NVH) and makes unusual noises more noticeable. Sound quality is particularly important for acceleration NVH, as drivers wish to get rewarding aural feedback from their occasional requests for rapid speed increases. Any deviations from smooth and pleasing increases in sound level and pitch as engine speed rises during wide open throttle (WOT) acceleration may be perceived as “unusual noises,” which

detract from the feeling of vehicle quality. Expressions of dissatisfaction sometimes attributed to acceleration sound are “roughness,” “coarseness,” “strain” and “boominess.” The perceived direction of powertrain sound can also be an issue, as pressure fluctuations from intake and exhaust valves can be attenuated by the design of induction and exhaust systems, with a design goal being to avoid shifts in directionality as engine speed increases. Presence of flow noise in the intake or exhaust systems can upset this balance. The strong dependency of aeroacoustic noise on flow velocity can set up speed ranges where both character and perceived directionality of powertrain sound changes, detracting from the goal of a smooth steady increase in sound with speed.

Traditional methods of achieving noise control rely on identifying and treating sources and paths. The speed-dependent nature of flow noise sources argues for source treatment, as there are increasing costs associated with the weight of path treatments. At the same time that improved noise performance and weight reduction are being required, product development cycles are being reduced to accelerate delivery of new designs to the market. Creating expressive designs to increase customer satisfaction is certainly a requirement for new passenger vehicles. Often, design requirements lead to engineering issues that must be addressed to make the expressive styling available while avoiding dissatisfying side effects, such as unusual noises. Cost pressures have significantly reduced the number of high quality hardware prototypes that are available for reliable assessment of vehicle interior noise performance. For the limited number of such prototypes that are produced, testing time must be shared between different attribute groups. Still, there is an opportunity to influence the design if timely and

accurate feedback about interior noise impact can be provided to the design team.

As simulation methods are improved and confidence in using them is gained, there is an opportunity to influence the design in earlier development phases, prior to hardware prototype availability. Computational Fluid Dynamics (CFD) simulations are particularly helpful for wind noise assessment, contributing flow visualization images that enhance understanding of the effect of vehicle shape features on air flow. An exhaust flow noise issue encountered in developing a high output powertrain option for a new vehicle raised the question of whether CFD tools and experience from earlier exterior wind noise simulations could be applied to assess flow noise sources and to diagnose potential fixes. This paper describes a case study of such a simulation, including validation with experimental data. Diagnostic images of simulated flow variables were found to be quite useful in explaining the causes and suggesting potential improvements in the design to reduce flow noise. The body of the paper is divided into sections discussing geometry, experimental results, simulation method and results, validation and improvements.

GEOMETRY

A vehicle under development with a new high-output engine option was found to have an unexpected exhaust sound at high speed and load combinations. The subjective nature of the sound suggested that it was originating from high-speed flow out of the tailpipe opening and through rear fascia components. [Figures 1](#) and [2](#) illustrate the geometry of the subsystem components in this area. The single exhaust pipe feeds into a central muffler, with symmetric left and right tailpipe openings through the rear fascia. In order to protect the plastic fascia from exhaust gas temperatures, a bezel is attached to each fascia opening. The rear opening of the tailpipe is inside the bezel, but there is no mechanical contact between the tailpipes and the bezels.

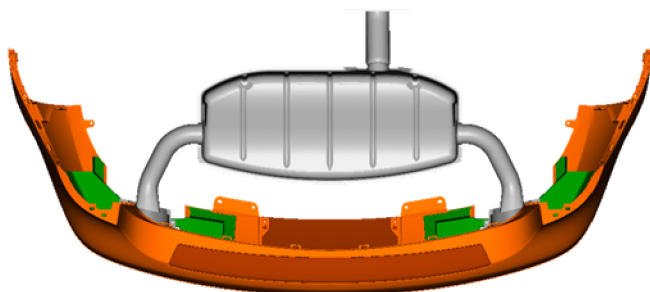


Figure 1. Plan view of muffler, tailpipes and rear fascia.



Figure 2. Rear view of right tailpipe opening, bezel and rear fascia.

EXPERIMENTAL RESULTS

A ½" microphone was fixtured to the prototype vehicle exterior so as to be in the plane of the tailpipe openings, 45° outboard of a fore/aft axis at the opening and 0.5 m from the center of the opening. This location was at the same height above ground as the tailpipe openings. A foam windscreen was used to reduce self-noise from wind. An LMS Test.Lab system was used to acquire pressure time histories during wide open throttle run-ups and to analyze these into RPM/frequency spectrograms.

With the flow noise issue present, a 1st gear run-up spectrogram was produced with color indicating sound pressure level (SPL), as shown in [Figure 3](#). The horizontal axis here is narrowband frequency from 0 to 1500 Hz on a linear scale, while the vertical axis shows engine speed, also on a linear scale from 2000-6400 RPM. A-weighted SPL of the exterior exhaust microphone is encoded in color, with approximately 90 dB range. The slanted yellow lines of higher SPL represent combustion orders (firing rate and harmonics) of the V-6 engine, as well as other sources tied to engine speed. These lines produce the desired acceleration sound, increasing smoothly with rising speed. The unusual noise in this case appears as the nearly-uniform yellow color across most frequencies in the top RPM range, as indicated by the horizontal black cursor line around 6000 RPM. It was noted that the broadband level rose above 5500 RPM, but then was nearly constant with engine speed from 5500-6400 RPM.

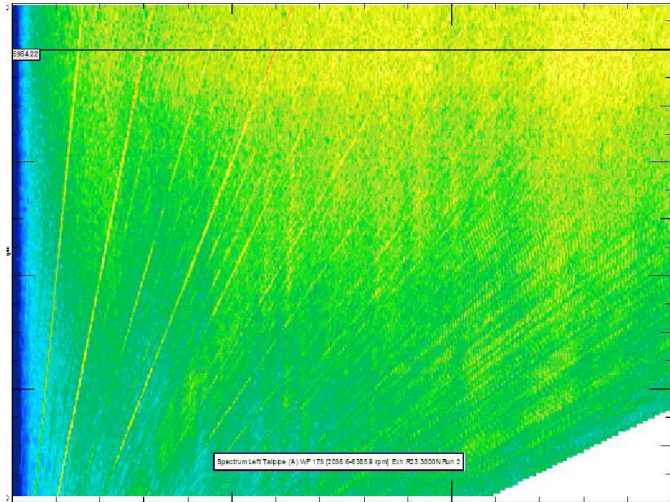


Figure 3. Wide open throttle exterior spectrogram, 0-1500 Hz horizontal scale, 2000-6400 RPM vertical scale, 90 dB A-weighted SPL scale from blue to orange.

Spectra from 6000-6400 RPM were extracted from the run-up data and power-averaged to provide a quasi-steady spectrum for comparison to CFD simulation of the flow noise. In [Figure 4](#), three individual narrowband spectra are compared to the speed-average calculated result. It can be observed that the individual narrowband spectra vary considerably from band to band, but that these variations are significantly reduced by averaging mean-square pressure over the speed range. Combustion orders are prominent as localized SPL peaks in the vicinity of 300 Hz (3rd engine order) and 600 Hz (6th engine order).

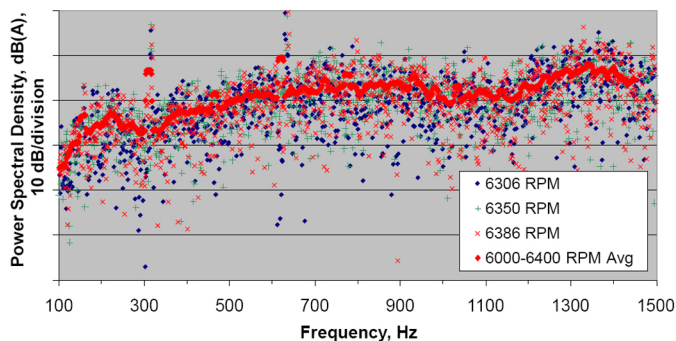


Figure 4. Narrowband power spectral density calculated from spectrogram data, three individual speeds compared to power average from 6000-6400 RPM.

Interior sound in the center rear seat position was also measured, using a Head Acoustics artificial head system for recording. This data was analyzed into 1/3rd octave band SPL spectra. The comparison of interior noise before and after correction of the flow noise issue will be shown in the Improvements section below.

SIMULATION METHOD

CFD modeling of exterior airflow is an accepted simulation method for assessing aerodynamic and cooling performance of vehicles of many types [1,2], and has been applied more recently for aeroacoustic assessments [3, 4, 5]. Key performance factors for successful flow noise simulation include:

- Transient solution mode to capture pressure fluctuations
- Compressible flow to allow acoustic propagation
- Extremely low numerical dissipation to allow realistic convection of small length scales

Simulations of exhaust outlet flow will also be more realistic in pressure and velocity distribution if density variations due to temperature changes can be captured in the solution. In addition, high frequencies in flow simulations are sensitive to small geometry features that imply a very high quality of CAD geometry is needed to correspond to hardware features as present in test articles.

Flow simulations for the exhaust system in this paper were performed using the PowerFLOW 4.1 commercial CFD solver. The simulation kernel of this software is based on a numerical scheme known as the Lattice Boltzmann Method (LBM), combined with a 2-equation renormalization group (RNG) turbulence model [5]. Ideally, direct numerical simulation (DNS) would allow all important length scales of the flow to be calculated, but practical considerations of turnaround time within available computing resources make it necessary to apply a turbulence model for unresolved length scales in practice. Temperature distribution in the fluid is calculated simultaneously with the flow - in coupled scalar energy transport equations - using a modified Lax-Wendroff-like explicit time marching finite difference scheme [2]. The title of this paper uses the term “direct aeroacoustic simulation” to emphasize that both flow and acoustic results are calculated simultaneously in the CFD solver. Additional details and bibliography about the LBM method are available in references [2,5].

Simulations were performed by placing the fully detailed faceted vehicle subsystem geometry, as shown in [Figure 5](#), into the Digital Wind Tunnel (DWT). Simplifications over the vehicle track test geometry were extensive, but not expected to affect the flow noise source excessively:

- Vehicle body and chassis excluded, as test speed was low
- Muffler internal baffles excluded, as geometry was not available
- As-designed location of tailpipe opening relative to bezel assumed, simulating a cold exhaust system and no inertial kinematics