

Exhaust and Muffler Aeroacoustics Predictions using Lattice Boltzmann Method

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ABSTRACT

Exhaust and muffler noise is a challenging problem in the transport industry. While the main purpose of the system is to reduce the intensity of the acoustic pulses originating from the engine exhaust valves, the back pressure induced by these systems must be kept to a minimum to guarantee maximum performance of the engine. Emitted noise levels have to ensure comfort of the passengers and must respect community noise regulations. In addition, the exhaust noise plays an important role in the brand image of vehicles, especially with sports car where it must be tuned to be “musical”. However, to achieve such performances, muffler and exhaust designs have become quite complex, often leading to the rise of undesired self-induced noise. Traditional purely acoustic solvers, like Boundary Element Methods (BEM), have been applied quite successfully to achieve the required acoustic tuning. However, they fail at predicting all of flow-induced noise, as well as non-linear noise dissipation mechanisms. A natural candidate for this type of problem is the use of a Lattice-Boltzmann Method (LBM) solver as a CFD tool. It has already been successfully applied and validated to quantify self-induced noise of mufflers as well as complex acoustic devices performance like acoustic liners. In this paper, a muffler baseline geometry self-induced noise is assessed using the commercial LBM solver PowerFLOW. Noise generation mechanisms are identified and design modifications are proposed to atone it. The given baseline and iterations designs noise mechanisms are analyzed and the obtained noise reductions are compared and discussed.

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INTRODUCTION

The main noise source in the exhaust systems of combustion engines is generally located, for an outside observer, at the outlet orifice. However, this source is not the original source of noise, which is actually a combination of multiple sources within the system itself. The acoustic waves are then propagated towards its exits. There are two types of sources which are dominant in such systems: 1) the acoustic pulses originating from the periodic explosion within the engine and 2) the self-induced flow noise within the exhaust system due to the complex geometries and flow paths. If the main purpose of mufflers is to reduce the intensity of the acoustic pulses via complex acoustic resonances, interferences and diffractions [1], the high complexity of the geometry design also tends to induce flow disturbances that may create flow noise. The exhaust mass flow from the engine is often quite high and the self-induced noise is consequently not negligible, especially when tonal noise arises. A perfect acoustic muffler design would consequently allow no acoustic pulse transmission and induce minimum noise. However, the back pressure induced by the exhaust system must be kept small to maximize the engine mass flow output. This constraint generally limits the ability of the muffler as a perfect noise cancellation device and a compromise often has to be found.

For muffler design, the most numerically challenging part is the determination of the noise sources within the muffler. The acoustic efficiency of the system is usually correctly recovered with Boundary Element Methods (BEM) [3, 4, 5] or simpler semi-empirical tools [6], and the acoustic pulse intensity and flow are estimated with simple 1-D gas dynamics programs [7]. However, to recover correctly the self-induced noise of the muffler, flow and acoustics must be simultaneously calculated, often in a complex geometry containing very small scale elements, such as perforated baffle holes. Such elements tend to drive the maximum resolution of the numerical simulation. At early stage design, prototypes are not available and cannot yet be tested experimentally, giving an advantage for a numerical investigation. The traditional approach of Computational Fluid Dynamics (CFD) + Computational Aero Acoustics (CAA) has been explored in the past for this application [8]. But the complexity of the design, the small length scales, and the consequent human and computation time cost remains challenging for industrial applications.

The presented study explores a different approach using the Lattice Boltzmann Method (LBM). This method has already been applied to many types of applications [9, 10, 11, 12, 13], including automotive muffler systems [14, 15, 16], to a limited extent. It has a very low

numerical dissipation which allows a single solver for a full CFD/CAA simulation, and its automatic grid generation makes it very convenient for engineering purposes. In this study, a complex generic muffler geometry was generated numerically, inspired by real-world designs. After reviewing validation results obtained in a previous paper [15] with a real geometry, the self-induced noise of this baseline numerical geometry is investigated. The main noise source is identified and an iteration aiming at reducing self-induced noise is proposed. This iteration is also investigated to confirm the expected improvements. A second iteration is proposed based on the first one, which is also investigated to confirm and conclude the work.

PREVIOUS WORK SUMMARY

Previously to this paper, a study on muffler/exhaust self induced noise using Lattice Boltzmann Method was performed by Rose et al [15]. The goal of that study was to investigate first the broadband flow noise at the exit orifice of a particular muffler and then to identify the noise sources and propose design improvements. Experimental data was also used to validate the numerical method results. A quiet source of steady air flow was applied at the muffler inlet. The used muffler geometry is presented in Figure 1. In this and most subsequent geometry figures, the muffler outer shell is rendered invisible so that internal structure may be seen. The baseline and its iteration are presented in Figure 2, highlighting the iteration part change in red. The iteration was obtained by shortening the inlet duct in the last compartment and by removing two rows of slotted holes in the third compartment. It is important to note that these changes could have an impact on the acoustic efficiency of the design, which is not investigated here.

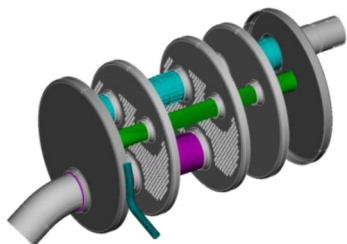


Figure 1. Muffler internal geometry used in Rose et al [15].

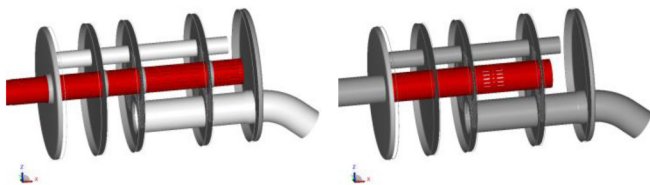


Figure 2. Muffler internal geometries used in Rose et al [15]. Left: Baseline. Right: Iteration.

The 1/12th octave band Sound Pressure Levels (SPL) results are presented in Figure 3 for the baseline and Figure 4 for the iteration. For the baseline, 3 different mass flows were investigated, both numerically and experimentally. An excellent correlation between experiment and simulation results, both in terms of broadband and tonal noise, is observed over the whole range of frequency from 500

Hz to 8 kHz. Tonal noise is especially present at 1.5 KHz at the second highest mass flow. For the iteration, 2 mass flows were investigated, showing similar excellent correlation. Because the same LBM code was employed, these results are used as validation for the numerical study proposed in the present paper.

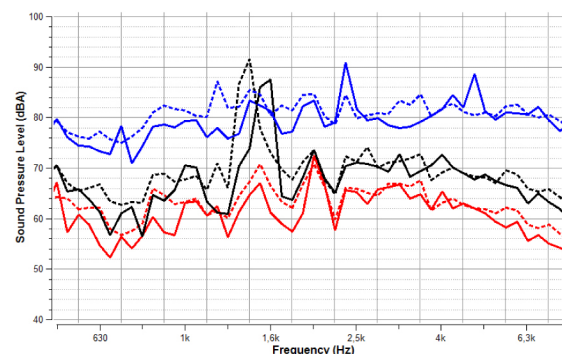


Figure 3. 1/12th Octave Band Sound Pressure Levels (dBA) for baseline geometry, at 3 different mass flows (red, black and blue). Experimental results (dotted line) and LBM results (line). Results from Rose et al [15].

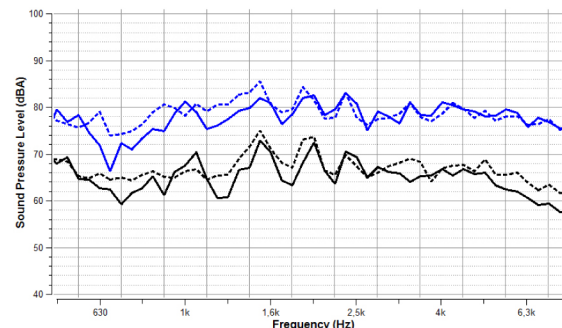


Figure 4. 1/12th Octave Band Sound Pressure Levels (dBA) for iteration geometry, at 2 different mass flows (black and blue). Experimental results (dotted line) and LBM results (solid line). Results from Rose et al [15].

NUMERICAL APPROACH DESCRIPTION

The CFD/CAA solver PowerFLOW 5.0 based on the Lattice Boltzmann Method (LBM) is used to calculate unsteady flow physics and the corresponding flow-induced noise generation and radiation. Lattice-based methods are by nature explicit, transient and compressible, and are an alternative to traditional CFD methods based on the discretization of the Navier-Stokes equations and derived variations [17, 18, 19, 20, 21, 22]. The basic idea of LBM is to track the advection and collisions of fluid particles. Since the average number of particles in a representative volume of fluid far exceeds the compute power required to track them individually, the particles are grouped into an integer number of discrete directions with index i . The computation follows the particle distribution function f_i which represents the number of particles per unit of volume, also called voxel, at a specific time and location moving with velocity c_i . As in statistical physics, the flow variables such as density and velocity are determined by taking the appropriate moments, i.e. summations over the set of discrete directions, of the particle distribution function [23, 24, 25, 26, 27, 28, 29, 30, 31]. LBM is used

and validated across many aeroacoustics applications such as automotive wind-noise [9], HVAC system noise [10], acoustic propagation [11,12], airframe noise [13,32] and sunroof buffeting [33]. Further details on LBM can be found in the cited references.

The CAD of the generic muffler used in the present study was generated based on typical geometrical features observed in mufflers from the transportation industry. The baseline version is presented in [Figure 5](#). The flow enters the muffler via the inlet duct which is perforated with slotted holes in the 3rd compartment, flows through the intermediate duct, which is perforated in the 2nd compartment, as well as through the single holes in each baffle. The flow then exits through the outlet duct. The slotted holes have a 3 mm diameter. To solve the correct flow and acoustics, a minimum of 15 points is needed across the slotted holes diameter. This number of points was practically determined, for example, with acoustic liners in Mann et al [16,34] and is enforced in the present study. The inlet duct is extended in the x-direction in order to set acoustic sponge zones preventing acoustic reflections and resonance modes in the inlet ducts. The inlet boundary condition is set to a velocity of 56.76 m/s for a targeted volume flow of 325 m³/h with an inlet duct diameter of 4.5 cm. In the far field, acoustic sponge zones are also created to avoid reflections from the simulation volume limits. Pressure boundary conditions set at 101325 Pa are applied on the simulation volume walls. All muffler walls are then treated as standard walls. A cloud of 45 probes located near the outlet orifice of the muffler is created. The SPL results presented in this paper are obtained from the spatial averaging of these 45 microphones. The spatial location of the microphones is presented in [Figure 6](#). Measurement planes are also added at various locations in order to record the instantaneous flow and acoustic fields. The simulation is run for 0.2 seconds, with the first 0.1 seconds being discarded. The remainder of the simulation, i.e. 0.1s, is used for post-processing as all physical quantities are converged after 0.1s of simulation. As this geometry is digital and has never been physically crafted, validation results are not presented in this paper. However, thorough validation work was performed by Rose et al. [15] as presented in the previous section. Therefore the methodology is considered validated and this study aims at investigating further the physical phenomena responsible for self-induced noise, and how to reduce or cancel them.

BASELINE RESULTS

The baseline results are obtained as discussed previously. For this configuration, the achieved mean pressure drop through the muffler is 10.2 kPa. This quantity will be investigated each time a new geometry is simulated in order to ensure some consistency for the aerodynamic performance of the muffler. If the change in this value brought by the design modifications is kept negligible, then the performance of the engine will not be affected by replacing the baseline muffler by its iteration. If the value decreases, the aerodynamic performance is improved, and vice-versa. Also the mean mass flow is 0.11 kg/s. This value will also be checked across the simulations to ensure the noise levels are comparable. Generally, a lower mass flow for the same geometry introduces weaker noise sources, without accounting for the cavity resonances.

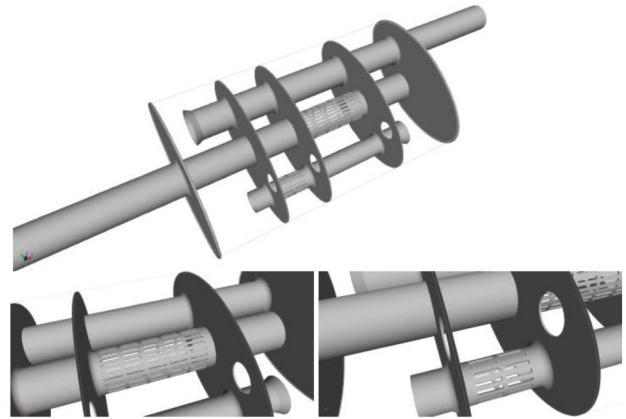


Figure 5. Baseline geometry. Global view and zoomed in views on perforated ducts and baffles.

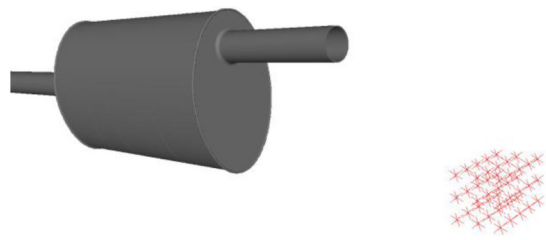


Figure 6. Muffler geometry with the 45 microphones location.

The 1/12th octave band SPL results of the baseline muffler are presented in [Figure 7](#). Frequency is limited to the range 500 Hz - 8 kHz, similarly to the presentation in Rose et al [15]. As mentioned in this previous work, the additional sound generated from the flow through the muffler is typically in the mid to high frequency range, i.e. above 500 Hz. An additional reason for looking at frequencies over 500 Hz is to minimize the contamination of the microphone signals due to the pseudo-noise generated by the hydrodynamic fluctuations of the jet exhaust plume. This is illustrated by standard deviation values of the spatially averaged SPL above 5 dBA below 500 Hz. This contamination could be cancelled by distancing the microphones from the jet or using CAA approach such as a Ffowes Williams Hawkins (FWH) calculation.

In this frequency range, the maximum SPL value is achieved around 1.9 kHz at 98 dBA. Overall, the highest values are observed between 1.5 kHz and 6 kHz with several peaks above 90 dBA, including two at 2.8 kHz and 4.1 kHz. The overall SPL value between 500 Hz and 8 kHz is 103 dBA. In [Figure 8](#), the snapshot of pressure time derivative shows that the acoustic field apparent source is the muffler exhaust duct. It is consequently important to focus on the investigation of the noise sources within the muffler and not the outside ones such as the exhaust jet which are less relevant for the moment. In [Figures 9, 10, and 11](#), the 1/3rd Octave Band dB-Maps of the muffler surface as well as a z-aligned plane and a y-aligned plane crossing the muffler geometry, at 4 different frequency ranges, are presented. The 4 frequency ranges are chosen according to the maximum SPL values observed to identify the noise sources responsible for the maximum noise radiation.