Predicting the Aerodynamically Generated Noise in 2D-Mufflers and its Far-Field Propagation Using a Combined LES/LEE Approach

De Roeck Wim, Desmet Wim, Sas Paul

K.U.Leuven, Dept.Mech.Eng., Celestijnenlaan 300B, B-3001 Leuven, Belgium, Email: wim.deroeck@mech.kuleuven.ac.be

Introduction

Mufflers are commonly installed in exhaust systems to attenuate the noise emitted by e.g. a combustion engine. The energy of this engine noise is concentrated around the harmonics of the engine firing frequency. Their contribution is dominant for low to medium engine speeds. When the engine speed increases, flow noise effects become more important and can even become the dominant source of exhaust noise [1]. In this framework, expansion chambers can even become flow-excited sound generators rather than silencers.

A first objective of the research project is to gain insight in the noise generating mechanisms of automotive muffler and expansion chamber applications, and to identify possible resonance effects in the expansion chamber cavity and/or tailpipe section. Secondly, the project aims at developing and validating numerical methodologies for subsonic confined flows. In the present paper, two different approaches of a combined Large Eddy Simulation-Linearized Euler Equation (LES/LEE) calculation are presented.

The first approach [2] performs an LES to obtain the acoustic pressure on an imaginary surface, surrounding all acoustic sources. The propagation of the pressure on the surface is then calculated with a LEE-calculation. In the second approach [3], an LES is performed to obtain equivalent acoustic source terms that drive a second LEE-calculation to obtain the acoustic near- and far-field propagation of the generated noise through the flow.

Method Description

Large Eddy Simulation

The generation and propagation of aerodynamically generated noise is described by the compressible Navier-Stokes equations. Due to the fact that there is a large disparity between the energy and length scales of the acoustic and flow variables and the fact that acoustic waves propagate over large distances, the use of the direct numerical solution of the Navier-Stokes equations (DNS) or LES to compute the entire acoustic field is only possible when the total domain is small and/or at low frequencies.

In this paper, LES with a Smagorinsky-model is used. Since LES-results are not very accurate near walls, Van Driest wall damping is applied in the vicinity of the walls. LES-calculations are carried out with the commercial finite-volume CFD-code CFX 5.5. For space integration, a 2nd-order central difference scheme is used and for time integration, a 2nd-order backward Euler scheme. The calculations are carried out on an unstructured grid.

Linearized Euler Equations

LEE can be used to predict the propagation of sound waves in a moving medium. Convection and refraction effects are taken into account. On the right hand side of the LEE, a source term S is needed when the approach of the equivalent sources is used, while the source term is absent when pressure B.C. are used. In the present paper, only the self-noise term of the Lighthill source term [4] is used. This results in the following expression for the source term in the momentum equations:

$$S_i = \frac{\partial \rho_0 u'_{ti} u'_{tj}}{\partial x_j} \tag{1}$$

The LEE are discretized with a finite difference method. The space derivatives are calculated with the 4th-order 7-point stencil DRP-scheme [5]. In order to filter out spurious grid-to-grid oscillations an artificial selective damping [6] is added to the equations. The time advancing is carried out with the 6-stage low dispersion-dissipation Runge-Kutta (LDDRK) scheme of Hu et al. [7]. Non-reflective B.C. derived by Tam and Dong [8] are used at the borders of the computational domain.

Discussion of the Results

Problem Description

The geometry of the 2D-expansion chamber is shown in Fig. 1. The inlet pipe has a height of 50 mm and a length of 100 mm. For the LES-calculations the inlet pipe is extended by 150 mm in order to generate some turbulence in the inlet conditions. The expansion chamber is square and has a height and length of 300 mm. The outlet pipe has a height of 50 mm and a length of 150 mm. For the LES-calculation an unstructured grid, containing 69.344 cells, with a maximum length of 2 mm is chosen. This length is also the filter length of the LES, so that the whole frequency range of interest is captured. The inlet velocity equals 100 m/s. At the end of the tailpipe

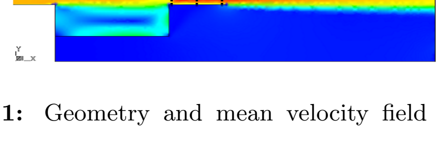

Figure 1: Geometry and mean velocity field of the 2D-muffler.

a $p' = 0$ outlet B.C. is imposed, which might result in wrong results in the vicinity of the outlet.

The LES-calculation is carried out over 50.000 time steps with a time resolution of 1e-5 s. The results of the last 15.000 time steps are used for the evaluation of the acoustic pressures and the calculation of the acoustic sources for the LEE, since the flow results are fully converged after 35.000 time steps. LEE-calculations are carried out on a Cartesian, equidistant grid with a grid size equal to 5 mm in both x- and y-direction.

Pressure Boundary Conditions

In the first approach, the acoustic field inside the muffler is calculated with a compressible LES. In this way, all flow-acoustic resonances inside the muffler can be predicted. In a second stage, the acoustic pressure on a surface inside the tailpipe is propagated with LEE. The noise generated by the outflow of the tailpipe is thus not taken into account. Three different calculations are carried out with different positions of the "pressure surface": one with the surface at the beginning, one in the middle and the last at the end of the tailpipe (black lines on Fig. 1). The acoustic pressure spectra for a point inside the expansion chamber and a point outside the muffler (black dots on Fig. 1) are shown in Fig. 2.

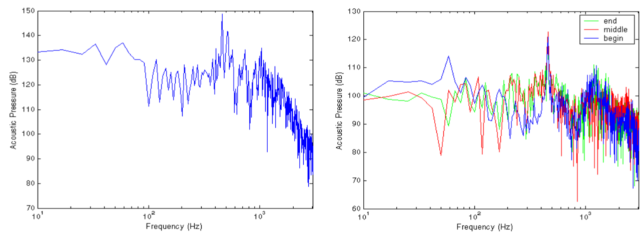

Figure 2: Acoustic pressure spectra inside (left) and outside (right) the muffler, calculated with LES and pressure B.C.

The first two chamber resonances (455 Hz and 520 Hz) are predicted correctly inside the muffler, outside the muffler the second resonance is not predicted since this is a transversal mode with a nodal line inside the tailpipe. The small difference between the different calculations indicates that there is not much noise generated inside the tailpipe, which is contradictionary to experimental research [1] where tailpipe resonances are found to be quite important. Further research is needed to investigate the absence of tailpipe resonances.

Equivalent Sources

The second approach uses the same LES-results to calculate equivalent sources inside the muffler which are then propagated with LEE. A comparisson between these results and those obtained with pressure boundary conditions is made in Fig. 3.

Inside the muffler the resonances are poorly predicted which can be explained by the artificial sound field that is imposed there, which generates also entropy and vorticity waves. Outside the muffler, these spurious entropy and

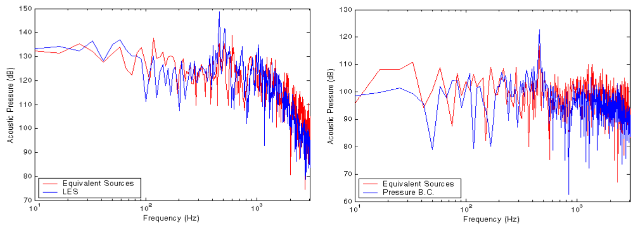

Figure 3: Comparison of acoustic pressure spectra inside (left) and outside (right) the muffler between calculation with pressure B.C. (blue) and sources (red)

vorticity waves are cancelled out and the results are in much better agreement. The broadband component of the generated noise is fairly well predicted inside and outside the muffler.

Conclusions

This paper presents some preliminary results of a CAA-research project to predict the aerodynamically generated noise in expansion chambers. A combined LES/LEE approach is being explored with pressure boundary conditions and a quadrupole description of source terms in the LEE. Inside the muffler the approach with the equivalent sources predicts the acoustic field poorly. Outside the muffler, there is a fairly good agreement between both approaches. Further research will be focused on the further validation of the LES-results and the use of other sources terms.

Acknowledgements

The research work of Wim De Roeck is financed by a scholarship of the Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT).

References

[1] Desantes J.M., Torregosa A.J., Broatch A., *"Experiments on Flow Noise Generation in Simple Exhaust Geometries"*, Acustica **87** (2001), 46-55.

[2] Terracol M., Manoha, E., Herrero C., Sagaut P., *"Airfoil Noise Prediction using Large Eddy Simulation, Euler Equations and Kirchhoff Integral"*, Proceedings LES for Acoustics (2002), Göttingen, Germany.

[3] Bailly C., Juvé D., *"Numerical Solution of Acoustic Propagation Problems Using Linearized Euler Equations"*, AIAA-journal **38** (2000), 22-29.

[4] Lighthill M.J., *"On Sound Generated Aerodynamically: I. General Theory"*, Proc. Roy. Soc.**A231** (1952), 564-587.

[5] Tam C.K.W., Webb J.C., *"Dispersion-Relation-Preserving Schemes for Aeroacoustics"*, Proc. of the 14th DGLR/AIAA Aeroacoustics Conference (1992), Aachen, Germany.

[6] Tam C.K.W., Webb J.C., Dong Z., *"A Study of the Short Wave Components in Computational Aeroacoustics"*, Journal of Computational Acoustics **1** (1993), 1-30.

[7] Hu F.Q., Hussaine M.Y., Manthey J.L., *"Low-Dissipation and Low-Dispersion Runge-Kutta Schemes for Computational Aeroacoustics"*, Journal of Computational Physics **124** (1996), 171-177.

[8] Tam C.K.W., Dong Z., *"Radiation and Outflow Boundary Conditions for Direct Computation of Acoustic and Flow Disturbances in a Non-Uniform Mean Flow"*, Journal of Computational Acoustics **4** (1996), 175-201.