Simulation of aeroacoustics of low Mach number flow with the use of wave equation model

E K Guseva¹ and Y Egorov²

¹ Peter the Great St. Petersburg Polytechnic University (SPBPU), Polytechnicheskaya Str. 29, 195251 St. Petersburg, Russia
² ANSYS Germany GmbH

E-mail: katia.guseva@inbox.ru

Abstract. Results of simulations of the noise generated by a turbulent flow around a simplified rain gutter of a car windshield are presented. The hybrid approach of ANSYS FLUENT used the scale-resolving SBES model for calculating a turbulent flow under an incompressible flow assumption, and the wave equation model for the propagation of acoustic perturbations. The mean static pressure and the sound intensity obtained in the simulations were compared with experimental data and were found to be well predicted.

1. Introduction

Prediction of the flow-induced noise is a challenging task requiring both accurate flow simulation and modelling of sound propagation. While turbulence modelling itself remains a complicated task nowadays, the need in noise prediction adds up even more challenges into the problem. This resulted in the existence of multiple approaches that differ in complexity of the model, computational requirements, accuracy, and other aspects.

Within the direct method of noise simulation, a joint computation of the noise generation by turbulence structures and the propagation of sound waves through a computational domain is performed using the full system of compressible gas equations. This approach is the most accurate one provided that all important scales are resolved well enough in the whole domain up to the observer’s position, which could be located quite far. This, however, often requires excessively high computational costs.

Apart from this, there is a big family of hybrid approaches, which use different equations for computing noise generation and for computing noise propagation. The most popular ones among them are the integral hybrid approaches, such as the method by Ffowcs Williams and Hawkins (FWH) [1]. These approaches, however, can only be used if there are no obstacles between the integration surfaces and the receivers. Relatively new differential hybrid approaches do not have this limitation. These methods use differential models to compute the sound propagation.

For low Mach number flows, typical for the car aeroacoustics applications, an assumption of non-compressible fluid can be used to compute a fluid flow and sound sources. A differential hybrid method, which is suitable to simulate aeroacoustics of such flows, was recently implemented in ANSYS FLUENT code. This method applies the wave equation model [2] for the calculation of sound propagation. The present paper outlines results of its application to the simulation of noise generated by the flow around a simplified automobile A-pillar rain gutter. It is organized as follows.

In Section 2, a brief description of the wave equation model is presented. Then, in Section 3, flow description is given as well as the computational problem formulation, and the numerical aspects of the
performed computations. After that, in Section 4, results of the computations are presented and discussed. Finally, in Section 5 some conclusions based on the performed studies are drawn.

2. Wave Equation Model

Within this model, transient fluid flow and propagation of noise are calculated concurrently on the same domain and mesh. The sound sources are calculated using the scale-resolving simulation (SRS) approach for turbulent flow of incompressible fluid, whereas the sound propagation is computed using the wave equation, which is formulated for the sound potential \( \phi \):

\[
\frac{\partial^2 \phi}{\partial t^2} - c^2 \nabla^2 \phi = \frac{1}{\rho} \frac{\partial}{\partial t} p_{\text{flow}}
\]

Here \( p_{\text{flow}} \) is the local static pressure, obtained by solving the equations of fluid motion, \( \rho \) is the constant fluid density, and \( c \) is the constant speed of sound.

The source in the right part of (1) can be masked out in space which allows only the desired part of the turbulent flow region to generate sound, where the solution is known to be well resolved. During the initial phase of the sound simulation the source term is multiplied with a slowly ramping factor to avoid start-up disturbances. Filtering procedures in time and space, which are also applied to the sound source, help to suppress the under-resolved high-frequent noise. In many practical cases only a part of the computational mesh is relevant for the simulation of sound propagation. In order to prevent undesirable reflections and other solution distortions in the insufficiently smooth and fine mesh parts, a viscous damping term is added to the equation (1). The coefficient of this term can be used to cover the mesh parts outside the acoustics-relevant zone by a sponge layer. An example of applying such a sponge layer is provided in the next section.

The available boundary conditions for the wave equation are the following: the walls are considered acoustically hard, ideally reflecting sound, and the permeable boundaries (velocity inlets and pressure outlets) are handled using the non-reflective conditions. A second order accurate finite volume method is applied to the discretization of the Laplacian term, and a second order accurate scheme by Newmark is used for the integration in time.

The sound pressure \( p' \) is computed using the following relation:

\[
p' = -\rho \frac{\partial \phi}{\partial t}
\]

This model has been derived from the “Acoustic Perturbation Equations 2” model of Ewert and Schroeder [3] under the assumption of the constant density in the background flow and neglecting the effect of convection. Thus, it is only valid for low Mach number flows.

3. Flow description and numerical setup

The simplified rain gutter model is a forward-facing corner mounted on a flat plate. The geometry of the model and the computational domain are based on the experimental setup of Kumarasamy and Karbon [4] and are shown in Figure 1 (only a half of the geometry is shown). The height as well as the width of the rain gutter is \( h = 0.0127 \text{ m} \), the length is \( 0.162 \text{ m} \), and it’s surface is considered to be infinitely thin. The domain consists of a rectangular box representing the experimental anechoic chamber, as well as the inlet section with the inlet shaped as a half of an octagon, with the same geometric parameters as in the experiment. The air speed at the inlet is \( 22.35 \text{ m/s} \), which correspond to a Reynolds number of \( 20,000 \) based on the height of the rain gutter. The calculated pressure signals are compared with the experimental data recorded at two locations: a flush-mounted transient pressure sensor on the plate upstream from the center of the rain gutter \((x = -0.0127 \text{ m}, y = 0, z = 0, \) where \( x = 0 \) corresponds to position of the leading edge of the rain gutter\), and a microphone directly above it \((x = 0, y = 0.12 \text{ m}, z = 0)\).

A nearly Cartesian mesh with 5 refinement levels, each having twice finer cells, was used in the simulations. The finest mesh with the cell size \( \Delta = 4 \times 10^{-4} \text{m} = h/32 \) is used in the SRS region, which includes the major sources of the noise (the small separation region upstream of the rain gutter and the long recirculation zone downstream of the rain gutter). As shown in [4], the free shear layer originating
from the nozzle inlet does not noticeably contribute to the noise level, therefore it was treated in RANS mode and was not covered with the SRS grid.

In the acoustic region, where the sound propagates to the microphone positions, cell size was 4 times coarser ($\Delta = 1.6 \times 10^{-3} \text{m} = h/8$), which allows to resolve the smallest wavelength, which were accurately measured in the experiment. In the rest of the domain the grid step was increased 4 times more ($\Delta = 6.4 \times 10^{-3} \text{m} = h/2$). Thanks to this strategy a mesh of the affordable size (22 million cells) with the sufficiently fine resolution was build.

The boundary conditions used in the flow simulations were as follows.

Walls of the inlet section were considered as slip, since no details about the inlet boundary layer were available from the experiment. At the inlet plane the constant uniform velocity of 22.35 m/s, the turbulence intensity of 0.4% and the turbulence viscosity ratio of 1 were set, while the pressure was extrapolated from the domain. On the rain gutter surface and on the plate the non-slip wall conditions were used. At other boundaries a constant pressure value was set, while other variables were extrapolated from the domain.

Scale-resolving simulation of a turbulent flow is performed using the Stress-Blending Eddy Simulation method by Menter [5] (SBES), which is a global hybrid RANS-LES turbulence model that uses the shielding function to switch from the underlying SST RANS model directly to the algebraic WALE LES model. Unlike some others hybrid approaches, SBES does not suffer from slow RANS-LES transition in separated shear layers [5], which is important in the simulations of separated flows, such as a considered flow around the rain gutter. Another merit of SBES is a possibility to use it in a zonal mode by changing the shielding function using a user-defined function tool of ANSYS FLUENT. This approach was used to ensure the RANS treatment in the free shear layer coming from the inlet.

The source term of the wave equation was deactivated (masked out) with the use of a mask marker shown in Figure 2. In order to ensure the absence of wave reflection from the outer boundaries and from mesh interfaces, the solution of wave equation was damped in the outer part using the sponge layer marker also shown in the Figure 2.

The computational strategy was the following. First, RANS solution was obtained and used as an initial field for the unsteady computations with SBES. Then after a transient period of 0.05s, when the solution had become well established, the acoustics wave equation model was activated and the coupled flow-acoustics computations were continued. Statistics for spectra and averaged data were gathered for

Figure 1. Left frame: half of the computational domain, cut by XY central plane. Right frame: computational domain and grid in the central XY-plane. Microphone positions are shown by the black circles.

The boundary conditions used in the flow simulations were as follows.

Walls of the inlet section were considered as slip, since no details about the inlet boundary layer were available from the experiment. At the inlet plane the constant uniform velocity of 22.35 m/s, the turbulence intensity of 0.4% and the turbulence viscosity ratio of 1 were set, while the pressure was extrapolated from the domain. On the rain gutter surface and on the plate the non-slip wall conditions were used. At other boundaries a constant pressure value was set, while other variables were extrapolated from the domain.

Scale-resolving simulation of a turbulent flow is performed using the Stress-Blending Eddy Simulation method by Menter [5] (SBES), which is a global hybrid RANS-LES turbulence model that uses the shielding function to switch from the underlying SST RANS model directly to the algebraic WALE LES model. Unlike some others hybrid approaches, SBES does not suffer from slow RANS-LES transition in separated shear layers [5], which is important in the simulations of separated flows, such as a considered flow around the rain gutter. Another merit of SBES is a possibility to use it in a zonal mode by changing the shielding function using a user-defined function tool of ANSYS FLUENT. This approach was used to ensure the RANS treatment in the free shear layer coming from the inlet.

The source term of the wave equation was deactivated (masked out) with the use of a mask marker shown in Figure 2. In order to ensure the absence of wave reflection from the outer boundaries and from mesh interfaces, the solution of wave equation was damped in the outer part using the sponge layer marker also shown in the Figure 2.

The computational strategy was the following. First, RANS solution was obtained and used as an initial field for the unsteady computations with SBES. Then after a transient period of 0.05s, when the solution had become well established, the acoustics wave equation model was activated and the coupled flow-acoustics computations were continued. Statistics for spectra and averaged data were gathered for
about 0.2 s. The time step in the simulations was $1 \cdot 10^{-5}$ s, corresponding to the flow Courant number in the SRS region of about 0.5.

4. Results and Discussion

Distribution of the mean pressure along the central line of the plate ($z = 0$) in comparison with the experimental data [4] is presented in Figure 3. Results of the simulations match with the data within the range of the measurements uncertainty. This suggests that in the present simulations the main features of the flow are modelled accurately.

Figure 4 presents flow visualizations in the form of vorticity magnitude contours at the central XY-plane and several YZ-planes downstream of the rain gutter. The visualizations clearly reveal complex 3-dimensional structure of the flow with a large and highly turbulent wake. Other than that, the figure visibly displays quick formation of the turbulent structures in the separated shear layer and finely resolved turbulent structures in the recirculation area, thus suggesting plausible work of the SBES in resolving major noise sources.
Figure 4. Vorticity magnitude contours at the central xy-plane and at 4 zy-planes at sections x = 0 (trailing edge of the rain-gutter), x = 0.02m, x = 0.05m and x = 0.1m.

A snapshot of the sound pressure from the wave equation solution in the central XY-plane is shown in Figure 5. It is well seen that the main source of the sound is the rain gutter itself, and sound waves propagate from the rain gutter through the domain without any visible unphysical reflection.

Figure 5. Contour of the sound pressure at the central XY plane.

Computed sound pressure levels (SPL) at the experimental microphone positions on the plate and above the rain gutter are shown at Figure 6. Sound spectra at the far field (above the rain gutter) were also computed with the use of the FWH approach with the plate and rain gutter used as the control surfaces.

SPL on the plate is close to the measured level at the high-frequency part of the spectrum, while at low frequencies (<2000Hz) it is underpredicted by ~20 dB. A small peak observed in the experimental spectrum at approximately 2500Hz is not reproduced in the present simulations. A possible reason for that is the unsteadiness of the separation region upstream of the rain gutter. It should be noted, however, that the flow properties in this separation region could depend on the parameters of the incoming boundary layer, the characteristics of which are not reported in [4].

The high frequency part of the far-field sound spectrum, predicted with the use of the wave equation model, agrees with the experimental data reasonably good, and about 10 dB more accurately than with the use of the FWH approach. The lower frequency part of the SPL spectrum is, however, underpredicted compared to the experiment. The reason for this disagreement is unclear. Possible reasons are the unsteadiness of the separation region upstream of the rain gutter discussed previously and the interaction of the free shear layer coming from the nozzle with the rain gutter wake, which is not resolved in the present simulation.
Figure 6. Sound spectra at two locations: on the plate upstream from the rain gutter (left) and above the rain gutter (right).

5. Conclusions and outlook
Simulation of the low Mach number flow over the simplified model of the A-pillar rain gutter and the noise generated by this flow was conducted with the use of a hybrid approach: the incompressible flow simulations with the SBES model, and the sound propagation simulation with the wave equation model. Accuracy of the mean flow prediction is confirmed by the comparison of the calculated mean pressure on the plate with the experimental data. Rapid formation of the turbulent structures in a shear layer after the rain gutter and finely resolved turbulent structures in the separated region suggest plausible work of SBES in resolving major sound sources. Far field sound predicted by the wave equation agrees with experiments reasonably well at the frequencies of 2kHz and higher and about 10 dB more accurately, than with the FWH approach. The sound in the low frequency part of the spectrum is under predicted, the reasons are to be investigated in further work.

Acknowledgements
This research work was supported by the Academic Excellence Project 5-100 proposed by Peter the Great St. Petersburg Polytechnic University, computations were performed with the use of resources of the Supercomputer Center “Polytechnichesky”.

References
[1] Ffowcs-Williams J E and Hawkings D L 1969 Sound generation by turbulence and surfaces in arbitrary motion Proc. Roy. Soc. London 264 321–42
[2] ANSYS Fluent 2019R3 Theory Guide 2019 15.2.2. Wave Equation Model
[3] Ewert R and Schroeder W 2003 Acoustic perturbation equations based on flow decomposition via source filtering J. of Computational Physics 188 365-98
[4] Kumarasam S and Karbon K 1999 Aeroacoustics of an Automotive A-Pillar Rain Gutter: Computational and Experimental Study SAE 1999-01-1128
[5] Menter F 2018 Stress-Blended Eddy Simulation (SBES)—A New Paradigm in Hybrid RANS-LES Modeling Progress in Hybrid RANS-LES Modelling, HRLM 2016. Notes on Numerical Fluid Mechanics and Multidisciplinary Design vol 137 ed Y Hoarau et al. (Springer, Cham)