

Numerical Simulations of Aeroacoustic Fields around Automobile Rear-View Mirrors

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ABSTRACT

A numerical method to simulate aeroacoustic fields around automobiles is proposed in the present paper. The proposed method can be used to compute sound emissions directly in both far fields and near fields. Sound passes through body structures near A-pillars and rear-view mirrors. The direct predictions of the sound to passengers therefore require solutions of acoustic near fields. Most aeroacoustics simulations around automobiles are based on Lighthill's analogy. Strictly speaking, Lighthill's analogy is not consistent in near fields because near fields are not governed by a simple wave equation. In the present paper, a proper approach is proposed to achieve further progress in the simulation of aeroacoustic fields around automobiles. The difficulties occur because the sound pressure is much smaller than the vortical flow pressure. The present method uses a flow/acoustics splitting technique that derives the modeled acoustic equations under the assumption that there is no acoustic feedback to the flows. The present acoustic equations are defined based on the difference between the compressible and incompressible flow equations. The acoustic equations are calculated with the fourth-order weighted essentially non-oscillatory scheme for the finite volume method, and a number of techniques are used to reduce the calculation time. These techniques use different meshes, time-step sizes, and computational regions in each flow and acoustics calculation. As a result, the present method makes it possible to simulate the acoustic near fields around the rear-view mirrors mounted on a vehicle. The acoustic fields for three different mirror shapes, namely, a baseline mirror, a mirror with a sharp edge around its stay, and a mirror with a sharp edge around its tip, are considered in the present paper. Consequently, the sound emissions from the mirrors and A-pillars are clearly visualized in the near fields as well as the far fields, and differences in the acoustic fields among the mirror shapes are clarified.

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INTRODUCTION

The reduction of wind noise has become essential in the development of automobiles. During high-speed driving, vortices are generated around A-pillars and rear-view mirrors and emit aerodynamic sound. The aerodynamic sound generated by these vortices is generally referred to as wind noise. The wind noise around A-pillars and rear-view mirrors is especially significant because these objects are mounted near passengers.

Computational aeroacoustics (CAA) involves the simulation of aerodynamic sound and is essentially an extension of computational fluid dynamics (CFD). The trend toward virtual design has come to include the simulation of wind noise using CAA.

The wind noise around automobiles is too complicated to simulate precisely. The aerodynamic sound that is emitted from A-pillars and rear-view mirrors propagates along the body surface, passes through the body structures, and

eventually reaches the passengers. Despite recent progress in CFD and CAA, complete simulations are quite difficult, and a number of problems remain.

Most CAA methods for automobiles are based on Lighthill's analogy [1], which assumes the governing equation of acoustic fields to be the wave equation. The analogy assumes that observers are located in far fields. In other words, the analogy is inconsistent in near fields, which include vortex fluctuations. With respect to acoustic fields around an automobile, noise is generated, for example, around rear-view mirrors, which then vibrates the front and side windows near the noise sources. In industrial applications, since the sound pressure levels observed by passengers may be equivalent to those in far fields, Lighthill's analogy appears to be valid. However, direct simulation of acoustic fields around A-pillars and rear-view mirrors requires appropriate methods.

In order to calculate near fields, the compressible flow equations must be solved. However, the compressible flow equations are difficult to solve in low-Mach-number flows, because the speed of sound is much greater than the speed of the flow. This means that high resolution is required for time discretization. In other words, the calculation cost is high because the time-step size of the calculation must be very small. Moreover, extremely precise numerical solutions are required because the pressure of acoustic waves is much smaller than that of flows.

In the present study, an approach to calculate the aeroacoustic near fields around automobiles is proposed. The present approach uses a flow/acoustics splitting technique to derive the modeled acoustic equations. This technique is based on the assumption that flows are not related to the compressibility of fluids. That is to say, there is no feedback from acoustics to flows. For example, the wind-throb noise around sunroofs and front-grille noise, which have significant peaks, cannot be simulated using the present approach. The applicability depends on whether the target vortical flows are governed by the incompressible flow equations. Generally, flows that emit broadband noise around automobiles can be assumed to be incompressible. The primary target of the present method is broadband noise. The wind noise around A-pillars and rear-view mirrors is typical broadband noise.

In the present paper, we refer to the technique, which is based on Lighthill's analogy, as the split technique. However, the present approach differs from that based on Lighthill's analogy. In the present technique, the governing equations are applicable in near fields. In the following, previous research [2,3,4], in which basic applications are validated using calculations around a circular cylinder and a three-dimensional rectangular cylinder, is first discussed. The results for a circular cylinder indicate the fundamental characteristics of split aeroacoustic fields. The results obtained for a rectangular cylinder are then compared with the measurement results.

The primary goal of the present paper is to reveal the aeroacoustic fields around A-pillars and rear-view mirrors mounted on an automobile body. A case study with different mirror shapes is performed in order to investigate the difference in sound emission. The present results clarify how sound is emitted and propagated depending on the vortices generated around the mirrors, and consequently the effectiveness of the present approach is demonstrated.

NUMERICAL METHODS

GOVERNING EQUATIONS

Numerical simulation methods that use split acoustics equations have been proposed [5] [6]. In the present study, the governing equations of the flow field are determined based on the leading terms of the Mach number (M) expansion discussed in Reference [7]. The flow equations obtained from the mass conservation equation and the momentum equation are identical to the incompressible flow

equations. Thus, flow field calculations can be performed by conventional numerical methods assuming incompressible flows.

In addition, the energy equation is also split by the Mach number expansion. The leading term defines the density in the flow field. Therefore, in the present study, the density in the flow field is a variable, although the flow field is assumed to be incompressible.

The compressible flow field (u, p, ρ) is assumed to be the sum of the incompressible flow field (u_*, p_*, ρ_*) and the acoustic field (u', p', ρ') as follows:

$$u_i = u_{*i} + u'_i, \quad p = p_* + p', \quad \rho = \rho_* + \rho', \quad (1)$$

where u_i , p , and ρ are velocity, pressure, and density, respectively. This model of the acoustic field depends on the definition of the flow field and is not governed by a wave equation. In the present study, for convenience, (u'_i, p', ρ') is considered to be an acoustic field, although (u'_i, p', ρ') is not governed by a wave equation. Here, (u'_i, p', ρ') is the perturbation that is split from the compressible flow variables by order estimation. The order of (u'_i, p', ρ') is $O(M^2)$ relative to (u_*, p_*, ρ_*). This definition of acoustics is required in order to simulate near fields, although the field is not actually produced by waves alone. The present approach is almost equivalent to solving the compressible equations under the assumption of no feedback. Therefore, acoustic fields can be simulated over entire regions, which include sound sources in near fields.

Here, dimensional values, which are denoted by tildes, are normalized to the following non-dimensional values:

$$u_i = \frac{\tilde{u}_i}{\tilde{U}_\infty}, \quad p = \frac{\tilde{p} - \tilde{p}_\infty}{\tilde{\rho}_\infty \tilde{U}_\infty^2}, \quad \rho = \frac{\tilde{\rho} - \tilde{\rho}_\infty}{\tilde{\rho}_\infty}, \quad (2)$$

where $\tilde{U}_\infty$, $\tilde{p}_\infty$, and $\tilde{\rho}_\infty$ are velocity, pressure, and density of main flow, respectively.

Using the above-described definitions of flow fields, the density and the momentum equations for acoustics are as follows:

$$\begin{aligned} \frac{\partial \rho'}{\partial t} + \frac{\partial f_j}{\partial x_j} &= -\frac{D_* \rho_*}{Dt}, \\ f_j &= (1 + \rho_* + \rho') u'_j + \rho' u_{*j}, \\ \frac{D_*}{Dt} &= \frac{\partial}{\partial t} + u_{*j} \frac{\partial}{\partial x_j}, \end{aligned} \quad (3)$$

$$\frac{\partial f_i}{\partial t} + \frac{\partial h_{ij}}{\partial x_j} = -\frac{D_* \rho_* u_{*i}}{Dt},$$

$$h_{ij} = f_i(u_{*j} + u'_j) + (1 + \rho_*)u_{*i}u'_j + p'\delta_{ij}. \quad (4)$$

The viscous terms in the momentum equation are neglected here. Generally, the viscous terms can be neglected for acoustic fields such as those around automobiles.

The acoustic field is assumed to be isentropic, and the following relation is used:

$$p' = c_*^2 \rho'. \quad (5)$$

The speed of sound c_* is a non-dimensional variable normalized by the reference velocity and is given as follows:

$$c_*^2 = \gamma \frac{1}{1 + \rho_*} \left(p_* + \frac{1}{\gamma M_\infty^2} \right), \quad (6)$$

where γ is ratio of specific heat, and M_∞ is the Mach number of the main flow. As mentioned above, the density in the flow field is obtained from the energy equation using the Mach number expansion. However, in the present study the density in the flow field is approximated by

$$\rho_* = M_\infty^2 p_*. \quad (7)$$

Solutions of the incompressible flow equations are substituted into the above equations, which are then integrated using the time marching scheme.

NUMERICAL SCHEMES

The numerical method proposed for the present equations is the finite volume method (FVM) with the weighted essentially non-oscillatory (WENO) scheme [8]. The solution vectors on both sides of the cell face are calculated using the fourth-order WENO scheme, and the Harten, Lax, van Leer, and Einfeldt (HLLC) method [9], which is an approximate Riemann solver, is used to calculate the numerical flux on cell faces. The two-step Runge-Kutta scheme is used for integration with respect to time. The outer boundaries in acoustics simulations require a non-reflecting condition. The perfectly matched layer (PML) [10] is used for this non-reflecting condition. The solver, which was developed in-house, uses a structured grid system. By setting more than 15 grid points per wave length, the wave profiles are well predicted by these schemes. At least 10 points per wave length are required in order to predict the wave amplitudes.

CHARACTERISTICS OF AEROACOUSTIC FIELDS

AEOLIAN TONE OF A CIRCULAR CYLINDER [2]

The wind noise generated by circular cylinders is referred to as Aeolian tone. The present method is applied to Aeolian tone in order to investigate the characteristics of the acoustic field defined herein. The numerical scheme used to obtain the incompressible flow is the QUICK scheme, which is an upwind scheme. The Reynolds number is 300, and the Mach number is 0.3. [Figure 1](#) shows the grid near the cylinder and the calculated acoustic pressure field.

The pressure field around a circular cylinder can be approximated analytically. Hatakeyama et al. [11] proposed the following improved approximation of Curl's dipole solution [12]:

$$p(\vec{x}, t) = \Delta p_1 + \Delta p_2 + \Delta p_3,$$

$$\Delta p_1 = \frac{1}{2^{1.5} \pi c^{0.5} r^{0.5}} \int_{-\infty}^{\tau} \frac{x_j}{\sqrt{\tau - t'}} \frac{\partial F_j(t')}{\partial t} dt',$$

$$\Delta p_2 = \frac{x_j \bar{F}_j}{2\pi r},$$

$$\Delta p_3 = \frac{c^{0.5}}{2^{2.5} \pi r^{1.5}} \int_{-\infty}^{\tau} \frac{x_j}{\sqrt{\tau - t'}} \{F_j(t') - \bar{F}_j\} dt',$$

$$\tau = t - r/c,$$

$$c = c_\infty (\sqrt{1 - M_\infty^2 \sin^2 \theta} + M_\infty \cos \theta),$$

$$\cos \theta = x_1 / r,$$

(8)

where F_j is the aerodynamic force of the cylinder, t is the time, and r is distance from the origin. The overbar indicates time averaged values. The length is normalized by the diameter in these equations. [Equation \(8\)](#) includes the pseudo-sound terms, Δp_2 and Δp_3 , which do not propagate to far fields, because Δp_1 , Δp_2 , and Δp_3 are proportional to $r^{-0.5}$, r^{-1} , and $r^{-1.5}$, respectively. Furthermore, this improves the speed of sound due to the main flow. Therefore, [Equation \(8\)](#) gives equivalent results relative to the direct numerical simulations (DNS), except near and in the wake of the cylinder.

[Figure 2](#) shows the pressure distributions along $\theta = 135^\circ$, as shown in [Figure 1](#). The lift of the cylinder changes periodically. The distributions in [Figure 2](#) are instantaneous when the lift is 0 and increasing. The calculated $p_* + p'$ is in

good agreement with $\Delta p_1 + \Delta p_2 + \Delta p_3$, except around $r < 1.3$, which seems to be the limit of application for Equation (8). In Figure 2, on the wall, $p_* + p' = -0.117$ (out of range) at $r = 0.5$. Near the wall, $p_* + p'$ conforms to p_* , which is the fluid dynamic pressure. On the surface, at $r = 0.5$, the sign of $p_* + p'$ is opposite to the sign of $\Delta p_1 + \Delta p_2 + \Delta p_3$ due to slight difference caused by errors, because the sign of pressure reverses around $\theta = 135^\circ$.

Thus, this split method can simulate fields that are approximately equivalent to the compressible flows for a circular cylinder from the comparison of $p_* + p'$ and $\Delta p_1 + \Delta p_2 + \Delta p_3$. On the other hand, the comparison of p' and Δp_1 reveals a discrepancy for $r < 10$. Thus, p' differs from Δp_1 , which is the term for the minimum decay at distance r . In other words, p' includes not only the sound that propagates to far fields, but also pseudo-sound components.

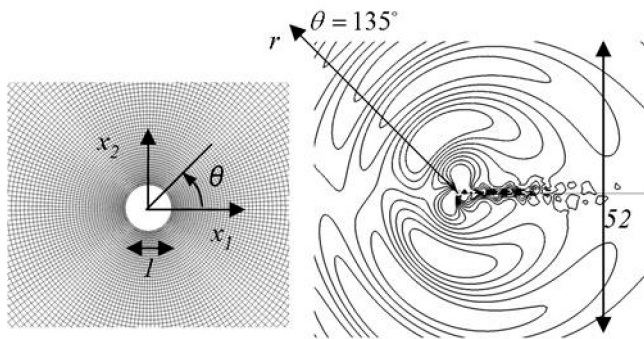


Figure 1. Simulation around a circular cylinder. The figure on the left shows the computational grid, and the figure on the right shows the distribution of p' (-0.01 to 0.01 by 8 lines).

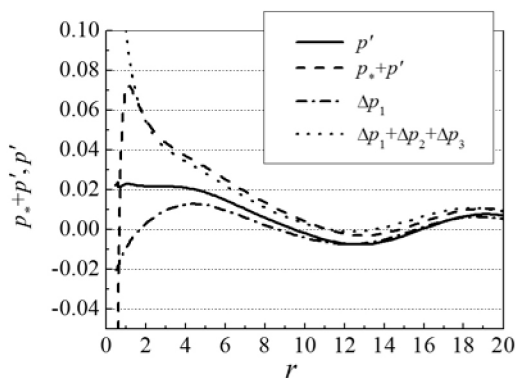


Figure 2. Pressure distributions.

RECTANGULAR CYLINDER ON A FLAT PLATE [3]

For validation of the present method, the numerical and measurement results are compared. The test specimen is the rectangular cylinder shown in Figure 3. Since the width (W) is finite ($= 100$ mm), the flow is three-dimensional. The case study is performed using heights (H) of 10, 30, and 50 mm. The flow fields are calculated by large eddy simulation (LES) using a mixed-time-scale SGS model [13]. The calculations for flows are performed using an in-house code. The other applications, i.e., rear-view mirrors, in the present paper are investigated using the same LES. A different grid spacing is used for each flow and acoustics calculation, as is described in the following section. The grid spacing normal to the wall for the first points is 0.5 mm for flows and 2 mm for acoustics.

Example numerical results are shown in Figure 4, which shows the distribution of p' on the symmetric plane. This visualization reveals how sound is emitted and the propagation paths of the sound.

The sound pressure level (SPL) was measured in a low-noise wind tunnel. Figure 5 shows the calculation and measurement results obtained at the microphone in the setup shown in Figure 3. An A-weighted filter and a 1/3-octave band filter are used for the SPL.

Figures 5(a) and 5(b) cannot be compared below 500 Hz, because the background noise is dominant in that frequency band. Over 500 Hz, the calculations tend to provide higher predictions (by several dB) than the measurements. However, the increment levels with H are in good agreement with the measured levels. As a result, the present numerical method can simulate physically reasonable acoustic fields.

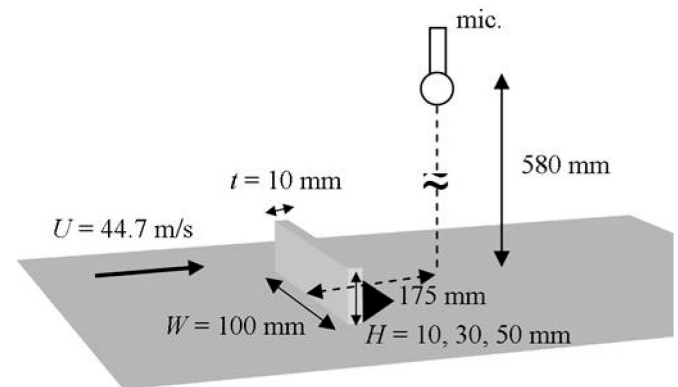


Figure 3. Shape and configuration.