Direct Aeroacoustic Simulation with Volume Penalization Method

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Abstract. Flow and acoustic fields around a circular cylinder and a cascade of flat plates are clarified by direct simulations with a volume penalization method, which is a useful method to predict flow and acoustic fields around a complex geometry in a flow. The predicted results are compared with our experimental results or those of literatures. It is also clarified that the acoustic resonance occurs between the plates for a cascade of flat plates. The phase-averaged predicted flow fields present that the vortices shed from neighboring plates is synchronized in an anti-phase mode. As a result, the intense standing waves are generated between plates.

Introduction

Intense tonal sound often radiates from flows around a cascade of flat plates, as shown in figure 1. These configurations exist in many industrial products, such as transportation vehicles and architectures. In order to establish methods to suppress this noise, the acoustic radiation mechanism must be clarified. Parker [1] measured the sound pressure level for the flows around a cascade of flat plates and clarified that the sound pressure level becomes intense at a specific velocity and that this phenomenon is due to the coupling between the vortex shedding in the wakes and the acoustic resonance between plates.

The preliminary experiments and computations have showed that the tonal sound becomes more intense for the rounded upstream edges than for the rectangular edges. In the present paper, the flow and acoustic fields around the cascade of the flat plates with rounded upstream edges are clarified. To do this, the direct computations of flow and acoustic fields were performed by using the volume penalization method [2-3], which is one of the various immersed boundary methods [4]. To validate the present computational methods using the volume penalization method, the flow and acoustic fields around a circular cylinder as shown in figure 1 were also predicted, and the results are compared with the past results by Inoue and Hatakeyama [5].

Figure 1. Configurations of flow around a cascade of flat plates and that around a circular cylinder.
Computational Methods

Flow Configurations

Flow around a Cascade of Flat Plates. Table 1 shows the computational parameters. The plate thickness, $b$, is 2 mm, and the aspect ratio, $C/b$, is 15.0. The separation-to-thickness ratio, $s/b$, is 6.0 for the cascade of flat plates. Preliminary experiments have confirmed that acoustic resonance occurs in a half-wavelength mode along the chord length at $U_0 = 44$ m/s. At $U_0 = 44$ m/s, the Reynolds number based on the thickness and the freestream velocity is $5.8 \times 10^3$, and the freestream Mach number is $M = U_0/a_0 = 0.13$.

The plates are hereinafter referred to as plates A, B, C, D, and E starting from the top, as shown in Figure 1. As shown in figure, the $x$, $y$, and $z$ axes were set in the flow, normal, and spanwise directions, respectively. The origin of the coordinate system is located on the spanwise middle $x$-$y$ plane and at the midpoint between the upper and lower edges of plate C.

Table 1. Computational parameters.

<table>
<thead>
<tr>
<th>Thickness $b$ [m]</th>
<th>Length $C/b$</th>
<th>Velocity $U_0$ [m/s]</th>
<th>Number of plates $N$</th>
<th>Distance $s/b$</th>
<th>$Re_b$ $(U_0 = 44$ m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.0 \times 10^{-3}$</td>
<td>15.0</td>
<td>44</td>
<td>5</td>
<td>6.0</td>
<td>$5.8 \times 10^3$</td>
</tr>
</tbody>
</table>

Flow around a Circular Cylinder. To validate the present computational methods, the flow and acoustic fields around a circular cylinder as shown in Figure 1 were predicted. The Reynolds number based on the freestream velocity $U_0$ and the circular diameter $d$ is $Re = 150$. The freestream Mach number $M = U_0/a_0$ is 0.2.

Governing Equations and Finite Difference Scheme

Flow and acoustic fields were simulated simultaneously by directly solving the three-dimensional compressible Navier-Stokes equations with the penalization term $V$ in the conserved form:

$$Q_i + \frac{\partial}{\partial x_i} (F_k - F_{vk}) = V,$$

(1)

$$V = -(1/\phi - 1) \chi$$

$$\begin{pmatrix}
\frac{\partial \rho u_i}{\partial x_i} \\
0 \\
0 \\
0
\end{pmatrix},$$

(2)

$$\phi = 0.25, \quad \chi = \begin{cases}
1 \text{ (inside object)} \\
0 \text{ (outside object)}
\end{cases}$$

(3)

where $Q$ is the vector of the conserved variables, $F_k$ is the inviscid flux vector, and $F_{vk}$ is the viscous flux vector. The coefficient $\phi$ is the porosity of a porous medium, determined so that the sound wave can be reflected almost completely (reflectivity: 99%), and a weighted function is multiplied for treating moving objects. The spatial derivatives were evaluated using the sixth-order-accurate compact finite difference scheme (fourth-order-accurate on the boundaries) [6]. The time integration was performed using the third-order-accurate Runge-Kutta method. It has been confirmed that the aerodynamic sound can be correctly predicted by using methods [7].

In order to reduce the computational cost, large-eddy simulations (LES) were performed for the flow around cascade of flat plates, while the flow is laminar for the flow around a circular cylinder.
No explicit SGS model was used. The turbulent energy in the GS that should be transferred to SGS eddies is dissipated by a 10th-order spatial filter.

Results

Flow and Acoustic Fields around a Circular Cylinder

Figure 2 shows the distributions of the time-averaged pressure coefficient predicted by the present computational method compared with those by Inoue and Hatakeyama [5]. As a result, it is clarified that the present result is in good agreement with their result.

![Figure 2. Distributions of time-averaged pressure coefficient Cp.](image)

Figure 3 shows the time histories of the lift and drag coefficients on the circular cylinder and the sound pressure at the point of the distance $r/d = 75$. The Strouhal number of the lift coefficient $C_L$ and the sound pressure is $St = fd/U_0 = 0.181$, which is in good agreement with the value in the literature, $St = 0.183$ [5]. Moreover, this value approximately agrees with the experimental values (0.18 at $Re = 150$ in Williamson [8]; 0.185 at $Re = 155$ in Williamson and Prasad [9]). The amplitude of the fluctuations of the lift coefficient is 0.44, which is slightly lower than the value predicted in the past studies (0.52 at $Re = 150$ in the literature [5]; 0.48 at $Re = 140$ Kwon and Choi [10]). The time-averaged drag coefficient $C_{D,ave}$ predicted in the present computation is 1.27, which is approximately in good agreement with the value in the literature, $C_{D,ave} = 1.34$ [5].

Figure 3 also shows that the amplitude of the sound pressure in the far field ($r/d = 75$) is in good agreement with that in the literature. The error of the level was approximately 0.1 dB. It has been
concluded that the flow and acoustic fields can be correctly predicted by the present computational methods.

Flow and Acoustic Fields around a Cascade of Flat Plates

**Comparison with Experiments.** The predicted flow and acoustic fields around the above-mentioned cascade of flat plates are compared with experimental data [11]. Figure 4 shows the predicted and measured profiles of the mean values of $u_h = (u^2 + v^2)^{0.5}$ in the wake along $x/b = 2.5$ and the sound pressure level at $x = 0$ and $y/b = 215$. The duration time for the calculation of these statistical values in the computation was 0.015 s, which is shorter than that in the experiment, 30 s. In order to take this difference into consideration, the variations of the statistical values of the experimental data were estimated with the duration time shortened to the above-mentioned computational duration time and are shown as bars in Figure 4.

The predicted mean values are in good agreement with the measured values. It is also shown that the level and the Strouhal number of the radiating tonal sound ($St = fb/U_0 = 0.21$) are in good agreement with the measured values.

![Figure 4](image)

**Figure 4.** Comparison with experimental data. (a) Profiles of mean velocity, $u_h$ along $x/b = 2.5$. (b) Sound pressure spectra at $x = 0$ and $y/b = 215$.

![Figure 5](image)

**Figure 5.** Iso-surfaces of the second invariant ($Q/(U_0/b^2) = 0.02$) and fluctuation pressure $p'/(0.5pU_0^2)$ for phase-averaged flow fields.

**Phase-averaged Fields.** Phase-averaging process was performed for the predicted flow and acoustic fields around a cascade of flat plates. The normal velocity in the wake of plate C ($x/b = 2.5$, $y/b = 0.5$, $z = 0.0$) was used as the reference signal. The flow fields are averaged 64 times for each
phase of the fundamental frequency. Figure 5 shows the iso-surfaces of the second invariant and fluctuation pressure for the phase-averaged flow fields.

Two-dimensional vortices are apparent in the wake of the plates and form low-pressure regions around the vortices. The two-dimensional vortices in the wakes of the other plates than plate C are also apparent because the vortex shedding of one plate and the neighboring plates are synchronized for the resonant condition [11]. It is also clarified that the mode of vortex shedding between neighboring plates is an anti-phase mode. Vortex shedding in this mode contributes to the intensification of the standing waves.

Summary
Direct aeroacoustic simulations with volume penalization method were performed for the flow around a circular cylinder and that around a cascade of flat plates, where acoustic resonance occurs. It was found that the present simulations correctly predict flow and acoustic fields in both cases. The phase-averaged predicted flow fields for the plates presented that the vortices shed from neighboring plates are synchronized in an anti-phase mode. The presented numerical method is a useful method to predict flow and acoustic fields around a complex geometry and moving objects in a flow.

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References