

# Development of Computational Fluid/Aeroacoustic Coupling Code

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## ABSTRACT

A rather novel coupling method is developed for predictions of aerodynamic sound fields. The flow fields are predicted by Reynolds Averaged Navier-Stokes (RANS) and the sound propagations are computed by Linearized Euler Equations (LEE). This method enables wide range aeroacoustic analyses with the lower computational cost. All simulations are performed using unstructured grid methods because of their flexibility to fit complex geometries. To validate this method in the present work computational aeroacoustic analysis around an airfoil was carried out. Sound sources are treated universally by using turbulent vortex fluctuations which induce aeroacoustic phenomena, not by the secondary pressure fluctuations on the body surfaces. This suggests a new guidance in computational aeroacoustics.

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## 1. Introduction

The term “aerodynamic sound” refers to the acoustic fields caused by air flows. The noise from home air conditioners, computer cooling fans, and exterior mirrors and sun roofs on automobiles are everyday examples of this; noise from engine compressors, turbines, engine jet mixing, and wing flaps are examples in aircraft. Because aerodynamic sound increases sharply with flow speed, it is of growing interest to be able to predict noise levels. Recently, aerodynamic noise has become the dominant factor in the noise emitted by automobiles, aircraft, and other vehicles as operating speeds increase. There is heightening demand from society to reduce such noise so as to preserve physical comfort and the livability of the environment.

Conventionally, predictions of aerodynamic noise levels have relied mainly on experiments and theory, but the recent advances in the techniques of Computational Fluid Dynamics (CFD) have allowed researchers to publish many numerical studies on prediction of the noise<sup>(1)</sup>. However, the conventional methods of aeroacoustic simulation have been hindered by the following issues:

- (1) Precise simulation of time-dependent components of flow fluctuations require costly numerical approaches such as Direct Numerical Simulation (DNS) or Large Eddy Simulation (LES).
- (2) Methods employing acoustic analogies, such as that of Lighthill, are limited to sources and propagation in homogeneous media with no velocity gradients.
- (3) Analytical objects must have simple shapes.

The above issues were successfully solved with the Reynolds Averaged Navier-Stokes (RANS) and Stochastic Noise Generation and Radiation (SNGR) models, which were used to extract sound sources while suppressing computational costs. Linearized Euler equations (LEE) were used to handle acoustic simulation of various applications including non-homogeneous media. For the third concern, a new code for the coupled solution of flow and acoustic fields was developed exploiting the possibilities of an unstructured grid method, due to its superior adaptability to shapes and ability to analyze both fluids and acoustic fields. These methods together have enabled to carry out the numerical simulation of several aerodynamic noise issues in practical time frames and in several computation environments.

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## 2. Computational Method

### 2.1. Computational Procedure

Figure 1 diagrams the computational method used in this research. The procedure was as follows:

- Step 1. The flow in the vicinity of the sound sources was analyzed using RANS and a turbulence model.
- Step 2. The SNGR model was used to calculate the instantaneous turbulent flow velocity field from the turbulent kinetic energy and its dissipation rate obtained in Step 1.
- Step 3. The turbulent flow velocity field obtained in Step 2 was treated as the sound source and combined with the flow field found in Step 1 for simulation by LEE.

If the RANS solution at the boundary of propagation space can be considered to be uniform, an integral equation based on theoretical analysis is solved to obtain the far-field solution.

This procedure can be broadly divided into the flow simulation by RANS and the turbulence model and the acoustic simulation with the SNGR model and LEE.

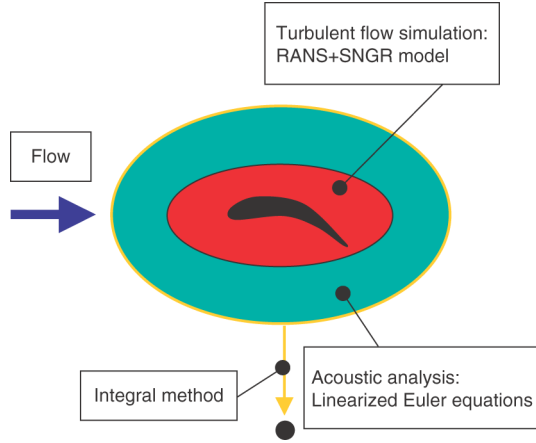


Fig. 1 Aeroacoustic simulation methods in different domains

### 2.2. Flow Simulation

The compressible Navier-Stokes equation is the governing equation for this flow field:

$$\frac{\partial \mathbf{Q}}{\partial t} + \frac{\partial (\mathbf{F}_j - \mathbf{G}_j)}{\partial x_j} = 0 \quad (1)$$

Here,  $t$  is time and  $x_j$  are the coordinate axes. The vector of conservative variables  $\mathbf{Q}$ , inviscid flux vector  $\mathbf{F}_j$ , and viscous flux vector  $\mathbf{G}_j$  are defined as follows:

$$\mathbf{Q} = [\rho \quad \rho u_i \quad \rho E]^T \quad (2)$$

$$\mathbf{F}_j = \begin{bmatrix} \rho u_j \\ \rho u_j u_i + p \delta_{ij} \\ \rho H u_j \end{bmatrix} \quad (3)$$

$$\mathbf{G}_j = \begin{bmatrix} 0 \\ \tau_{ji} \\ u_i \tau_{ij} - q_j + (\mu + \sigma \mu_T) \frac{\partial k}{\partial x_j} \end{bmatrix} \quad (4)$$

where  $\rho$  is density,  $u_i$  are the velocity components in the  $x_i$  directions,  $p$  is pressure,  $\mu$  is the coefficient of viscosity in laminar flow,  $\tau_{ij}$  is the viscous stress tensor, and  $q_j$  are the heat flux components.  $E$  and  $H$  are the total energy and total enthalpy per unit mass, respectively.

The turbulent kinetic energy  $k$  and coefficient of viscosity in turbulent flow  $\mu_T$  are found using the turbulence model. Here, the distance from the wall is unnecessary; Wilcox's low Reynolds number  $k$ - $\omega$  model<sup>(2)</sup> was used due to its convenience for the storage of unstructured data. The turbulent model constant is  $\sigma$ .

### 2.3. Acoustic Simulation

LEE simulation with sound source terms is not limited by any assumptions of homogeneous media; it can also handle diffraction and wall reflection. In comparison to scalar wave equation, which can only handle acoustic waves, LEE may be used for examining entropy and vorticity waves.

The LEE is derived from the compressible Euler equation, and is shown in Eq. (5):

$$\frac{\partial \mathbf{Q}_a}{\partial t} + \frac{\partial \mathbf{F}_{aj}}{\partial x_j} = \mathbf{S}_a \quad (5)$$

where the vector of conservative variables  $\mathbf{Q}_a$  and the inviscid flow velocity vector  $\mathbf{F}_{aj}$  are as follows:

$$\mathbf{Q}_a = [\rho' \quad (\rho u_i)' \quad (\rho E)']^T \quad (6)$$

$$\mathbf{F}_{aj} = \begin{bmatrix} (\rho u_j)' \\ u_j (\rho u_i)' + u_i (\rho u_j)' - \rho' u_i u_j + p' \delta_{ij} \\ u_j (\rho H)' + H (\rho u_j)' - \rho' H u_j \end{bmatrix} \quad (7)$$

The primed quantities ( $'$ ) are the fluctuating components; here, they are acoustic components. The quantities  $u_i$  and  $H$  are values intrinsic to the flow field and were obtained with RANS in this study.

The noise arising from interference with the turbulent flow is expressed by the sound source term  $\mathbf{S}_a$  below. It is employed as the formation term on the right side of the LEE equation.

$$\mathbf{S}_a = \begin{bmatrix} 0 \\ -\frac{\partial}{\partial x_j} (\rho u_i' u_j' + \overline{\rho u_i' u_j'}) \\ -\frac{\partial}{\partial x_j} (\rho H u_i' u_j' - \overline{\rho H u_i' u_j'}) \end{bmatrix} \quad (8)$$

When a flow field is simulated with RANS, the obtained solution is the time average of the turbulent flow field; it contains no information about the unsteady components of the sound source. The SNGR model proposed by Bechara et al.<sup>(3)</sup> was used here to extract the sound source from the turbulent flow field. In this model, the instantaneous turbulent velocity  $\mathbf{u}_t$  at location  $\mathbf{x}$  was found using the expression below, based on the random Fourier mode.

$$\mathbf{u}_t(\mathbf{x}) = 2 \sum_{n=1}^N \hat{u}_n \cos(\mathbf{k}_n \cdot \mathbf{x} + \psi_n) \sigma_n \quad (9)$$

Here,  $\hat{u}_n$ ,  $\psi_n$ ,  $\sigma_n$ , and  $\mathbf{k}_n$  mean the amplitude, phase angle, directional vector, and wave number vector of the  $n$ th Fourier

mode, respectively, and  $N$  is the total number of modes. Figure 2 shows the relations between these quantities in the wave number space for the  $n$ th mode.  $\hat{u}_n$  was found from the turbulent kinetic energy spectrum of the von Karman-Pao spectrum<sup>(4)</sup>. The SNGR model requires input of the turbulent kinetic energy, integral length scale, and time scale. The turbulent kinetic energy is obtained from RANS, and the integral length scale and time scale are found from the turbulent kinetic energy and the dissipation rate. Once the turbulent shear stress has been calculated using the results from the SNGR model, the propagation calculations are carried out by inputting this into LEE as the sound source term.

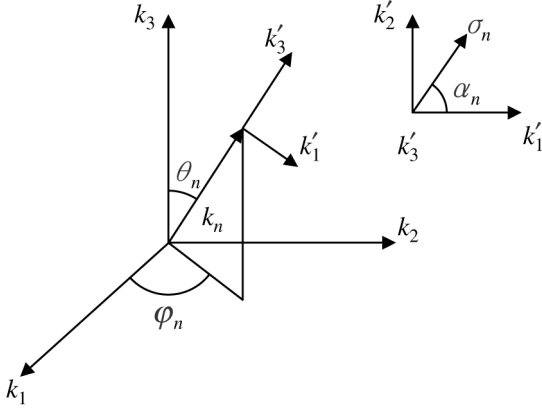


Fig. 2 Wave vector geometry for the  $n$ th Fourier velocity mode ( $\varphi_n$ ,  $\theta_n$ , and  $\alpha_n$ : random functions)

### 3. Validation of Simulation Code

The acoustic simulation code developed in this study was tested to verify its accuracy. The LEE code was examined in a prediction of acoustic pulse propagation in a uniform flow field<sup>(5)</sup> as shown in Fig. 3. The initial conditions were as follows:

$$\begin{bmatrix} p' \\ u'_i \\ p' \end{bmatrix} = \begin{bmatrix} 0.03 \exp[-(\ln 2)(x_1^2 + x_2^2)/5^2] \\ 0 \\ 0.03 \exp[-(\ln 2)(x_1^2 + x_2^2)/5^2] \end{bmatrix} \quad (10)$$

Here, the Mach number of the uniform flow was 0.5. Figure 4(a) shows the calculation results for the acoustic pulse. The pulse diffuses through the space with the passage of time while transported downstream by the uniform flow. These results compare well with the analytical solution, as shown in Fig. 4(b). Thus, the LEE code developed in this research correctly describes the propagation of pulses in a uniform flow.

A turbulent velocity field solution<sup>(3)</sup> was sought to verify the results of SNGR. Figure 5 presents the calculated instantaneous turbulent flow field. This is dimensionless; the axes have been normalized to the turbulence scale. Some vortices with a size of approximately 1 are outlined in the figure, indicating that these results are reasonable. Figure 6 presents the spatial correlation of velocities in the turbulent flow field. The calculated results indicated that the correlation between any two points diminished with the distance between the points; this agreed with the analytical prediction. Figure 7 shows autocorrelation; this also diminished with the passage of time, in agreement with analytical predictions. The above results show that this SNGR simulation has a good correlation in both the time and space domains.

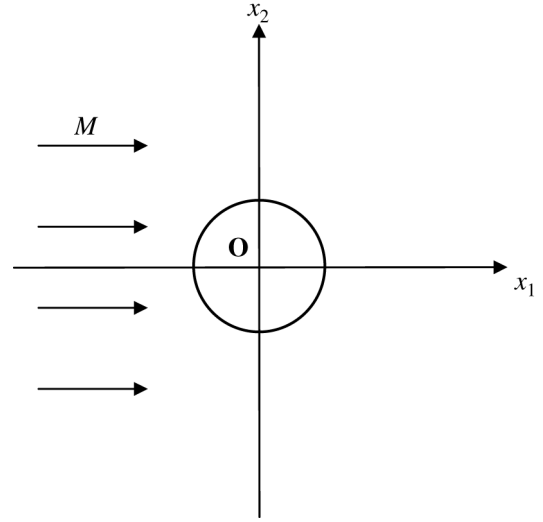


Fig. 3 Two-dimensional acoustic pulse in a uniform flow. The sound source is located at (0,0). The circle indicates the "edge" of the pulse.

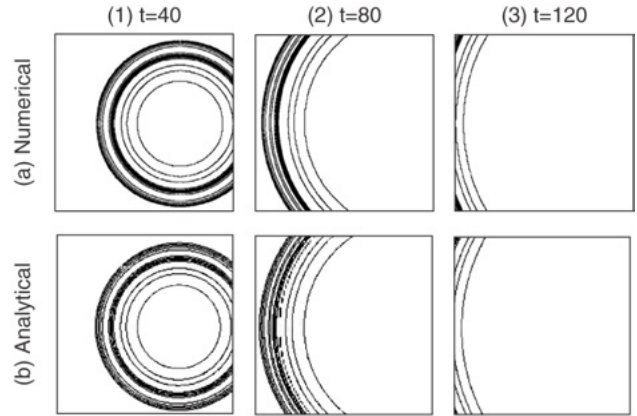


Fig. 4 Pressure fluctuation of acoustic pulse in a two-dimensional uniform flow

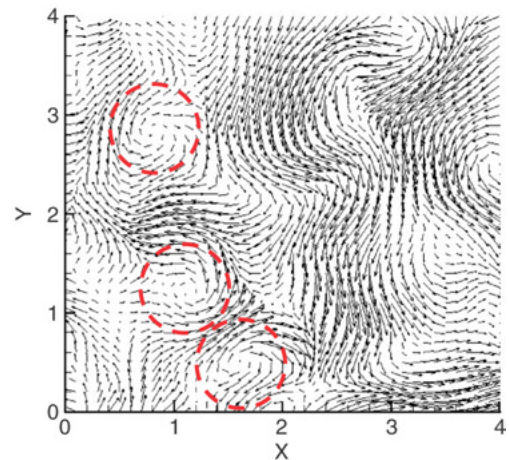


Fig. 5 Spatial distribution of the simulated turbulent velocity field ( $k=1714\text{m}^2/\text{s}^2$ ,  $\varepsilon=44.8 \times 10^6\text{m}^2/\text{s}^3$ ,  $N=200$ ). Several eddies are visible in the spots of red circles.

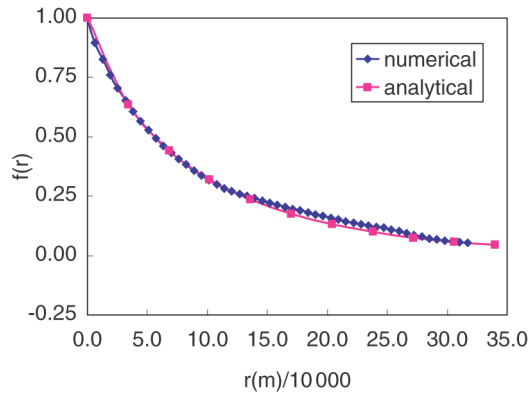


Fig. 6 Spatial two-point correlation function  $f(r)$  with a distance variable

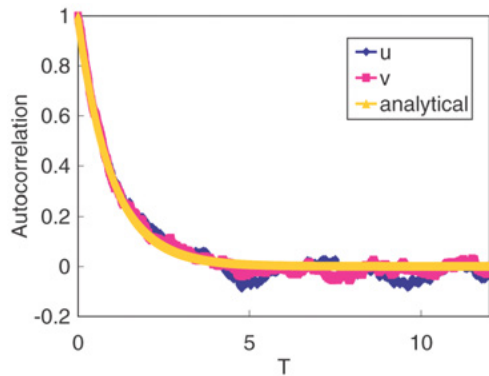


Fig. 7 Autocorrelation for generated turbulence as a function of normalized time separation

#### 4. Coupled Aeroacoustic Simulation around an Airfoil

An aeroacoustic simulation of the flow around an airfoil was carried out to show the effectiveness of this simulation code. The object was an NACA0012 wing section with a thickened trailing edge, from which the noise has already been experimentally observed<sup>(6)</sup>. The inflow Mach number was  $M_\infty = 0.205$  and the Reynolds number was  $Re = 2.86 \times 10^6$ . Turbulent flow was assumed over the whole region. Inflow turbulence intensity at the entrance portion of the boundary was set at  $Ti = 0.3\%$ , turbulent flow length scale at  $0.2\%$  chord, and angle of attack at  $5^\circ$ . An unstructured hybrid grid was used for the simulation (Fig. 8).

Figure 9 presents the results of the simulation. Figure 9(a) is the Mach number distribution, Fig. 9(b) the turbulent kinetic energy distribution. High turbulent kinetic energies were generated by the thickened portion of the trailing edge.

Figure 10 shows the instantaneous velocity vectors, excluding the time average component, obtained by the SNGR model. Many large and small vortices were generated downstream. All in all, the figure indicates a very complicated flow situation. Notable is the turbulent boundary layer's interference with the trailing edge, which gives rise to high turbulence. This agrees with the high turbulent kinetic energy predicted by fluid mechanics.

Figure 11 depicts the results of the LEE acoustic simulation [(a) through (d) occur simultaneously with the conditions shown in the corresponding parts of Fig. 10]. The propagation of small pressure fluctuations away from the

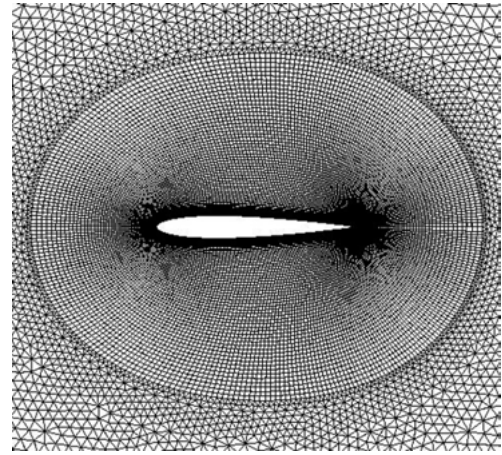


Fig. 8 Unstructured hybrid mesh around NACA0012 airfoil with the blunt trailing edge. Structured mesh are generated around the solid surface, surrounded by unstructured triangular mesh.

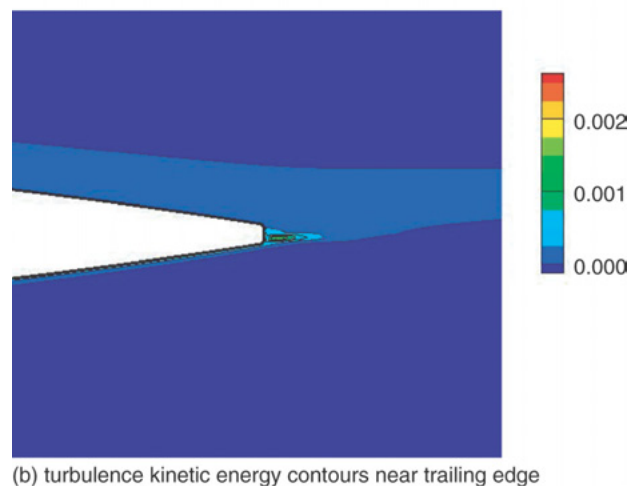
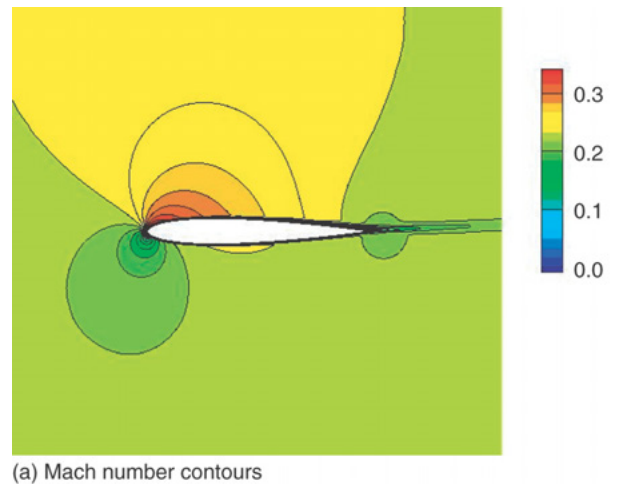


Fig. 9 Results of flow simulation around NACA0012 airfoil ( $M_\infty = 0.205$ ,  $Re = 2.86 \times 10^6$ ,  $Ti = 0.3\%$ ,

vicinity of the airfoil trailing edge is clearly shown here. This shows the unique dipolar character of the dispersion of acoustic waves from the interface with a solid body. The Doppler effect of a shorter wavelength on the upstream side also appears.

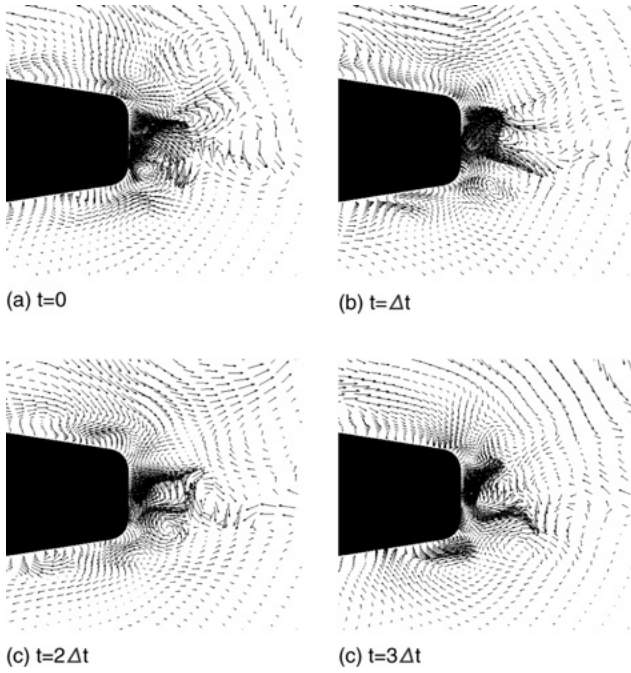


Fig. 10 Distributions of instantaneous velocity fluctuation near trailing edge ( $\Delta t$ : time increment)

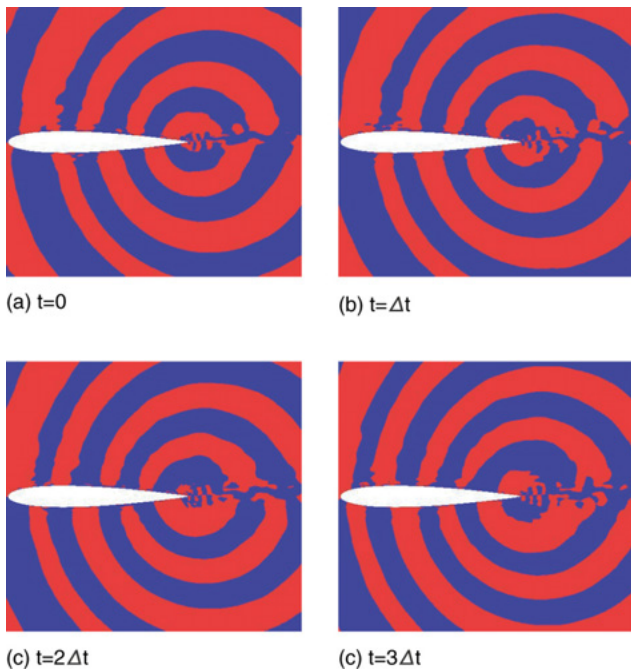


Fig. 11 Sound pressure field around NACA0012 airfoil (red:  $p' > 0$ , blue:  $p' < 0$ ,  $\Delta t$ : time increment)

Figure 12 shows the large fluctuations in density in the vicinity of the trailing edge. Density showed periodic positive and negative fluctuations near the corners of the trailing edge. The greater tendency to occurrence at the bottom of the airfoil was considered to be due to the angle of attack. This study confirmed the generation of acoustic waves throughout the turbulent boundary layer, but most of the waves were generated at the trailing edge, and these often cancelled out the other waves.

The results of simulation described herein indicate that airfoil-generated noise is caused by fluctuations in density

and pressure due to complex interference among trailing-edge vortices, and propagates into the surroundings as acoustic waves. RANS was used for this research because of its low cost, but this study confirmed that the same results are obtained by LES and other methods (Fig. 13). The new simulation code has been shown to be effective.

Previous research methods have shown that surface pressure fluctuations are the main sound source when a wing or other physical object is exposed to a fluid flow. In this study, turbulence fluctuations were used as the direct inputs, and the simulation correctly predicted the resulting dipole sound. This is due to the excitation of surface pressure fluctuations by fluctuations in the turbulent flow field, which shows that this approach makes more accurate assumptions about the mechanisms of these phenomena. It is, therefore, clear that the application of this method to acoustic simulation, in which the secondary surface pressure fluctuations are the main sound source, allows a better grasp of the mechanisms of sound from airfoils. In addition to the considerations of surface pressure fluctuations, using this technique enables simulation of the turbulence fluctuations themselves, and the proper model for sound sources. Sound sources can now be handled in general simulations.

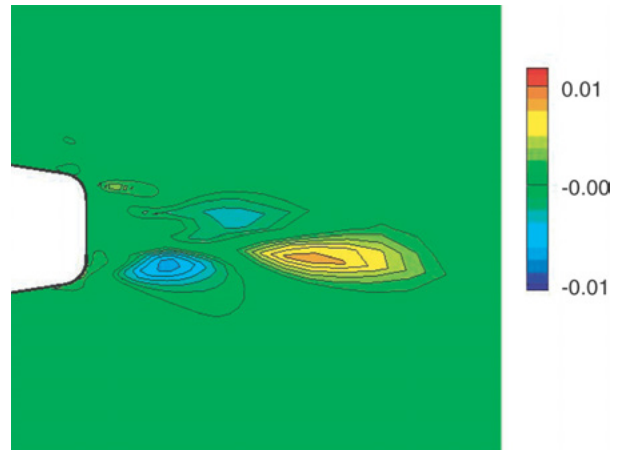


Fig. 12 Density fluctuation near trailing edge

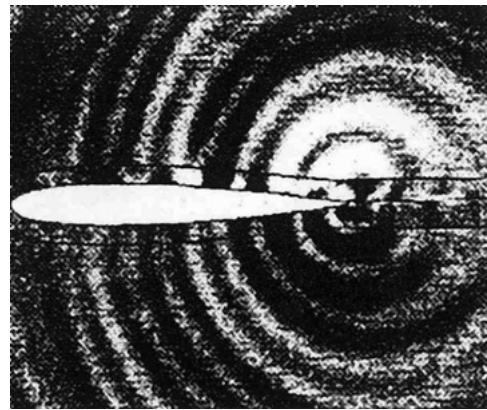


Fig. 13 Instantaneous pressure fluctuation field using LES data taken from the computational result by Manoha E. et al.<sup>(7)</sup>

## 5. Conclusion

A code has been developed for simulation of aerodynamic sound to overcome the longstanding shortcomings of high cost and limited applications of previous models. The following results were obtained:

- (1) A combination of RANS and LEE was used to solve the flow field and the acoustic field, respectively, in a newly developed coupled method for aeroacoustic simulation. This method enables simulation of aerodynamic sound over a wide range of variables at low cost. An unstructured grid was used in all simulations and successfully accommodated complicated shapes.
- (2) The validity of the code was verified by simulation of acoustic pulse propagation and turbulent velocity field solution.
- (3) The code was applied to simulation of the flow around an airfoil. Results indicated that acoustic waves are generated at the trailing edge and propagate away to the surroundings. This result verified the effectiveness of this method. In addition, the direct use of turbulence fluctuations themselves, rather than of the secondary fluctuations in surface pressure, allows general handling of sound sources. This method points to a productive new direction in simulation of aerodynamic sound.

## References

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