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Numerical Study of Drag and Noise Reduction of Electric Cable

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Abstract

To develop the code of predicting flow-field and aeroacoustic noise by an electrical cable, a combined CFD-Acoustic analogy approach is selected. The two dimensional, unsteady and incompressible Reynolds-averaged Navier-Stokes solver with κ-ω and κ-ω SST turbulence modeling is used to calculate the near flow-field around an electric cable. Near-field results are then coupled with two-dimensional Curle's integral formulation based upon Lighthill's acoustic analogy with the assumption of acoustic compactness. To validate this code, numerical results are compared with experimental data for a circular cylinder. The simulation shows an overprediction on acoustic amplitudes, but overally speaking, the spectrum pattern of sound pressure agrees well with experiment within an acceptable amount of error. In addition, a few cross-sections of the cable were selected and tested with each other in terms of drag and radiated noise

Keywords: *Electric cable, Navier-stokes solver, Curle's integral formulation, Aeolian tone*

I. Introduction

Aerodynamic design of a low-drag electric cable which is responsible for the transmission of electric power may prevent short-circuit of the cable or breakdown of power transmission tower by a windstorm. It can reduce the possible cost due to accident of a power failure. Therefore the aerodynamics around the electrical cable should not be ignored. Also, recently, the concern about environmental issue for noise is increasing with public regulation of noise level for various sources of sound. The research for reduction of noise is briskly being progressed.

Sound may be emitted whenever a relative motion exists between two fluids or between fluid and surface. The sound radiated by flow across a circular cylinder like the electric cable, well-known as the aeolian tone, is one of the most fundamental phenomena of aeroacoustics, which contains the problems of vortex shedding, Reynolds number dependence and spatial correlations of the forces, etc. Even though it is such a basic problem, it is still very difficult to simulate the sound field directly using CFD (Computational Fluid Dynamics) techniques due to the required numerical accuracy and computation time[13-15]. Considering the available computing power, the most appropriate prediction method of sound field is a combination of CFD with an acoustic solver based upon acoustic analogy[5] or Kirchhoff formulation[11].

Nowadays the environmental noise is conceived as one disturbing our daily lives. Aerodynamic noise by an interaction between air-flow and an electric cable may bother residents seriously. Therefore it is necessary to apply aerodynamics and aeroacoustics simultaneously about

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this problem.

In this study, the objective is the development of code to analyze the flow field around the electric cable and flow-induced noise. To numerically simulate the flow field, the two dimensional, unsteady and incompressible Navier-Stokes equation with two equation turbulence modeling is used. And the near-field data obtained by using the Navier-Stokes equation is used to predict the acoustic far-field. The governing equation to predict far field is Curle's formulation based upon the Lighthill's acoustic analogy[5]. To validate the code, the numerically predicted results are compared with the experimental data for a circular cylinder. And the numerical study is also performed for the electric cable having a different cross-section configuration.

II. Near-field Analysis

The two-dimensional, unsteady and incompressible Navier-Stokes equation is used to predict the near-field around a circular cylinder. The governing equation is as follows.

$$\frac{\partial u_i}{\partial x_i}=0 \tag{1}$$

$$\frac{\partial u_i}{\partial t}+\frac{\partial}{\partial x_j}(u_i u_j)= -\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left\{\nu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right)\right\} \tag{2}$$

As shown in Eq. (1) and (2), the continuity and momentum equation are perfectly decoupled in the incompressible Navier-Stokes equation. Therefore great care is required to obtain the pressure field. In present study, pseudo-compressibility method is used to acquire the pressure field. The pseudo-compressibility relation is introduced to relate pressure field with velocity field and pseudo-time derivative of velocity is added too. This procedure is called dual-time stepping. At each time level, discretized governing equation is solved as pseudo-time goes on until convergence is obtained[1,2]. The finite volume approach is employed with a third order upwind spatial differencing for the inviscid flux and a second order central differencing for viscous flux term. The calculation is advanced implicitly in time using LU-SGS (Lower Upper - Symmetric Gauss Siedel) methods. The turbulence modelings used in this study are κ-ω and κ-ω SST (Shear Stress Tranport) model[3-4]. No-slip conditions and Riemann boundary conditions are imposed on the body surface and the outflow boundary, respectively. Computations are carried out on a O-type mesh configuration. A total of 129×65 mesh cells are used in these simulations.

III. Acoustic Prediction

Aerodynamic sound generated by flow around the body such as the electric cable can be divided by dipole term due to aerodynamic loads on the body surface and quadrupole term due to fluctuations of fluid stress around the body. The singing of the wind through the electric cable is called as aeolian tones. The nature of the flow around the cylinder moving through a fluid with a subsonic velocity is largely determined by the Reynolds number based on the cylinder diameter. When this quantity is sufficiently small, the flow is steady and its main effect is to cause a drag force on the cylinder. However, the flow becomes unstable to small disturbances at a Reynolds number of 50, and the wake starts to oscillate beginning at a point some distance downstream of the cylinder. Further increase of this parameter causes the oscillations in the wake to move upstream until, when the Reynolds number reaches about 60, the oscillations appear as the alternate shedding of lumps of fluid from the top and bottom of the cylinder. Most of vorticity in the wake is now concentrated in these lumps, which move downstream in a regular array called the Kármán vortex street. The periodic shedding of vorticity into the wake exerts a periodic lift force on the cylinder and it is this oscillating force which is mainly responsible for the aeolian tones. The vortex shedding also induces a periodic drag force on the cylinder, which turns out to be quite small compared with the fluctuating lift. The unsteady flow-field information from two-dimensional incompressible Navier-Stokes solver is used as an input for acoustic far-field prediction. Curle's integral formulation, which represents the sound generated by a solid surface in uniform velocity, can be expressed as following[5,6]

$$4\pi p'(\boldsymbol{x},t) = -\frac{\partial}{\partial x_i}\int_S\left[\frac{p_{ij}n_j}{r}\right]_\tau dS(y) + \frac{\partial}{\partial x_i \partial x_j}\int_V\left[\frac{T_{ij}}{r}\right]_\tau dV(y) \qquad (3)$$

where τ is the retarded time, t is sound receiving time, y is the coordinates of source of sound, x is the position of observer and r is the distance between source and observer. If both the body and the aerodynamic flow region are small compared with the typical acoustic length, the source region is assumed to be acoustically compact. The far-field acoustic pressure can be approximated by

$$p'(\boldsymbol{x},t) = \frac{1}{4\pi}\frac{1}{c_0}\frac{x_i}{|\boldsymbol{x}|}\dot{D}_i\left(t-\frac{|\boldsymbol{x}|}{c_0}\right) + \frac{1}{4\pi}\frac{1}{c_0^2}\frac{x_i x_j}{|\boldsymbol{x}|^2}\ddot{Q}_{ij}\left(t-\frac{|\boldsymbol{x}|}{c_0}\right) \qquad (4)$$

where

$$\dot{D}_i\left(t-\frac{|\boldsymbol{x}|}{c_0}\right) = \frac{\partial}{\partial t}\int_S n_j P_{ij}\left(\bar{y}, t-\frac{|\boldsymbol{x}|}{c_0}\right)d^2\bar{y}$$

$$\ddot{Q}_{ij}\left(t-\frac{|\boldsymbol{x}|}{c_0}\right) = \frac{\partial^2}{\partial t^2}\int_V T_{ij}\left(\bar{y}, t-\frac{|\boldsymbol{x}|}{c_0}\right)d^3\bar{y}$$

$$P_{ij} = p\delta_{ij} - \tau_{ij} \qquad (5)$$

are, respectively, point dipole and quadrupole sources which are representative of volume and compact surface radiation. Curle's three dimensional results can be transformed into two dimensional version by integrating Eq.(4) over a infinite span[7]. The result is

$$p'(\boldsymbol{x},t) = \frac{1}{2\pi}\frac{1}{c_0}\frac{x_i}{|\boldsymbol{x}|}\int_0^\infty \dot{D}_i(t^*)\,d\zeta + \frac{1}{2\pi}\frac{1}{c_0^2}\frac{x_i x_j}{|\boldsymbol{x}|^2}\int_0^\infty \ddot{Q}_{ij}(t^*)\,d\zeta \qquad (6)$$

where

$$t^* = t - \frac{|\boldsymbol{x}|}{c_0}\cosh\zeta \quad (\ retarded\ \ time\ ).$$

IV. Results

4.1. Validation of Code

To validate the developed prediction code, the numerical results for the circular cylinder are compared with the experimental data. Figure 1 shows the grid system for computation of near field aerodynamics.

The time histories of lift and drag coefficients of laminar and turbulent flow simulations at a Reynolds number of 54000 are shown in Figure 2 and Figure 3. For laminar flow simulation, the physical time step (Δt) of 0.02, 30 times sub-iteration and β (pseudo-compressibility) of 800 are used and for turbulent flow case, same numerical inputs are applied except the case of compressibility factor β of 400.

From the result of Figure 2, the history of lift coefficient shows a sinusoidal form corresponding to Strouhal number ($St=fD/U$) of 0.2 for laminar, 0.192 for κ-ω turbulence modeling and 0.194 for κ-ω SST turbulence modeling. These results for turbulence modeling agree well with the experimental data in terms of Strouhal number[8]. There is a maximum difference of 86% in amplitude of lift and drag coefficients as compared with each other. When compared with experiment, the prediction of flow-field using the κ-ω SST model gives the best result. This is because the modified κ-ω model improves the prediction capability of flow with strong adverse pressure gradient.

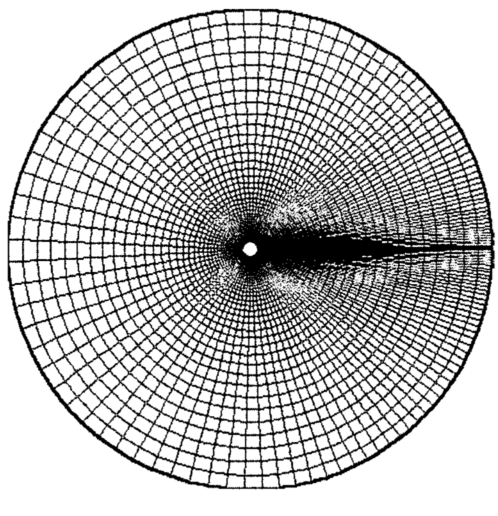


Figure 1. Grid system for computation.

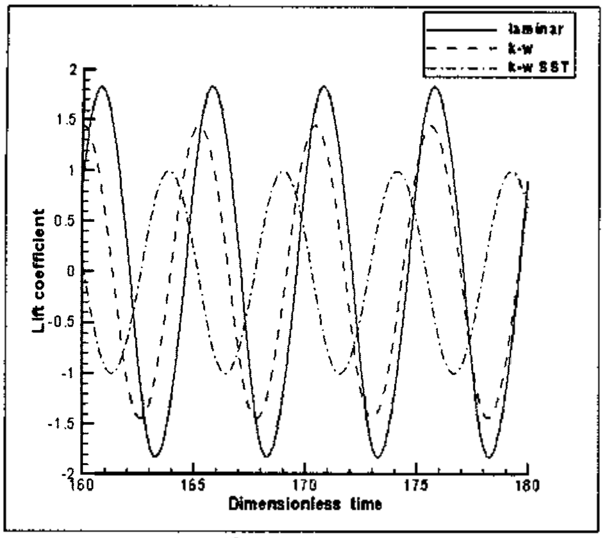


Figure 2. Lift coefficient for reynolds number of 54000.

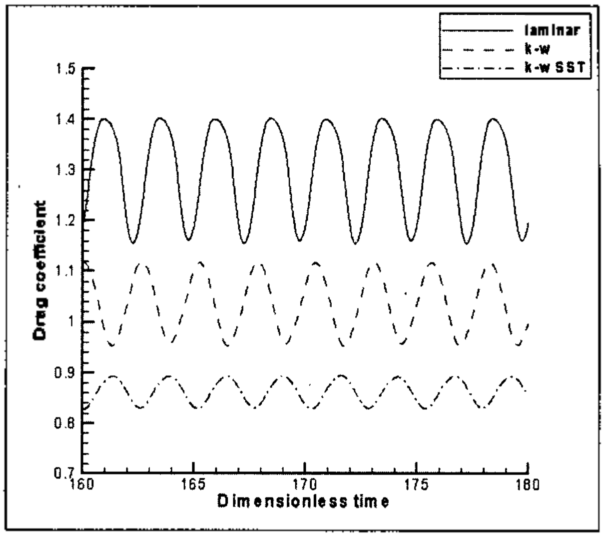
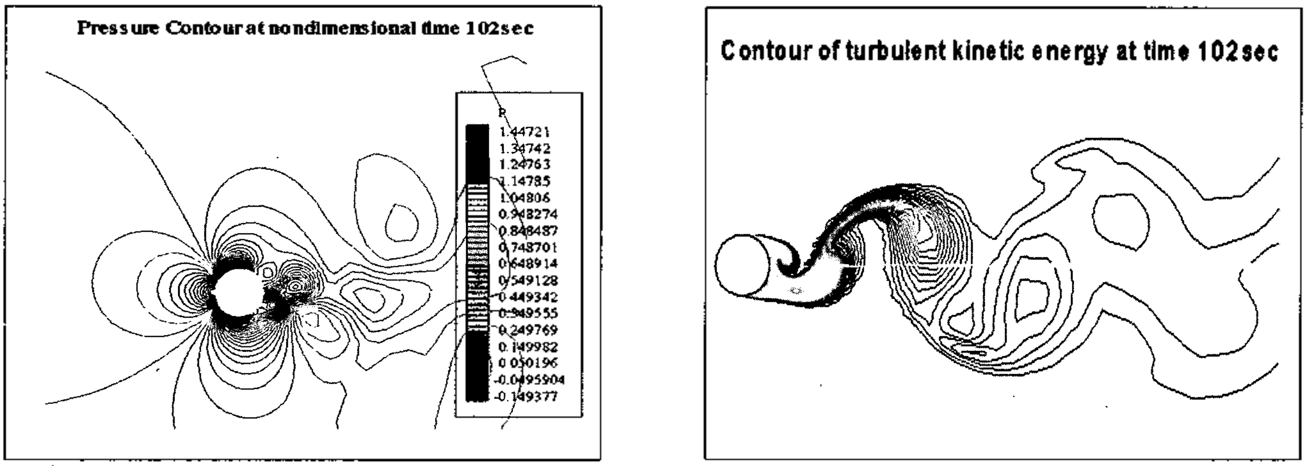
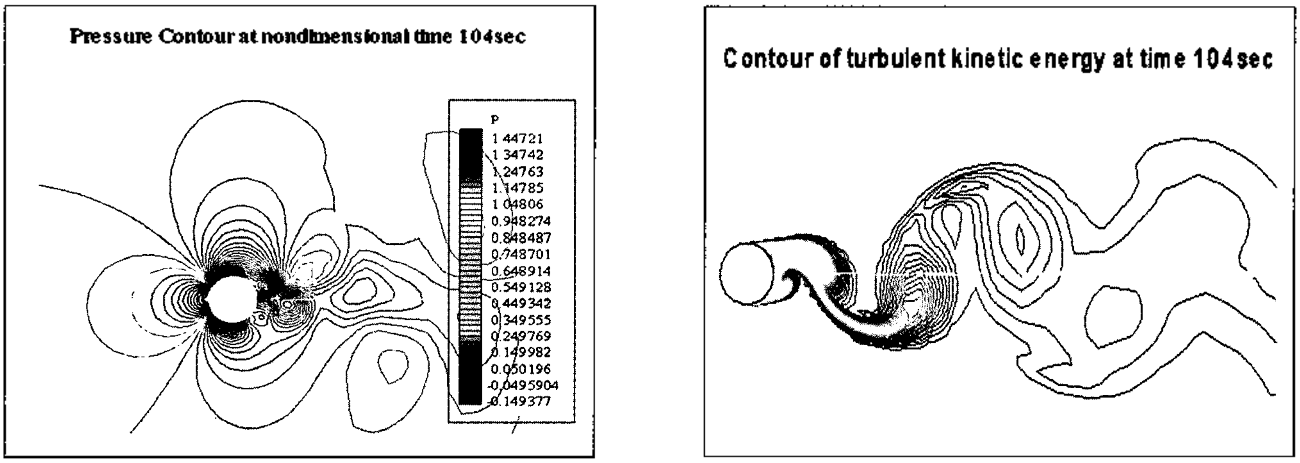


Figure 3. Drag coefficient for reynolds number of 54000.



(a)



(b)

Figure 4. Contours of pressure and turbulent kinetic energy at instantaneous time 100 and 102 sec.

Figure 4(a) and 4(b) depict contours of turbulent kineticenergy of simulation with κ-ω SST model at instantaneous times

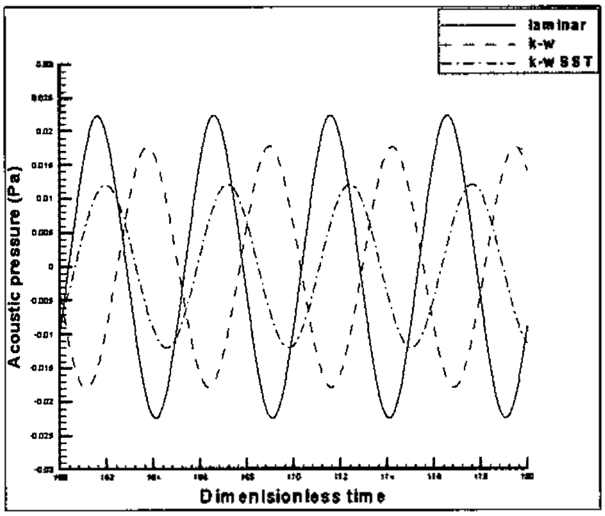


Figure 5. One point acoustic pressure time history at reynolds number of 41000 at 90 degrees position.

100 (maximum lift) and 102 (minimum lift).

The Figure 5 represents the one point acoustic pressure time history from calculation with Eq. (6) at Reynolds number of 54000 by coupling CFD and acoustic codes.

Unlike the two-dimensional flow-field calculation, the acoustic solver is calculated by integration over infinite span. And the wavelength is very large compared to the body diameter, so source of sound is considered as a compact. In this simulation spanwise correlation length for the effect of randomly varying phase along the span is not considered. This is because vortex shedding is correlated only over finite span length. If a model having a span length smaller than ten times diameter is used, a consideration of spanwise correlation is essential to the simulation of the sound field. The calculation is carried out at 90 degrees from the cylinder and 25 times the diameter away. The predicted, one-point far-field acoustic pressure has a sinusoidal waveform. Figure 6 shows the directivity pattern of sound. These results represent the dipole nature of the acoustic radiation due to lift variation with a symmetry about x-axis and show that the coupling of CFD and acoustic solver using Curle's integral formulation predicts sound directivity pattern, correctly.

Predicted sound pressure level using Fourier transformation is compared with experimental data in Figure 7[9]. The observer position is the same as the case of Figure 5. The amplitudes are overpredicted by about 15 dB at a fundamental frequency for the case of the κ-ω SST turbulence modeling which predicts the smallest values of force coefficients. The discrepancy of amplitude between simulation and experiment can be explained by three- dimensional effect as follows. The vortex shedding is not two dimensional in nature[10]. In CFD calculation, the vortex shedding is modeled as a completely coherent structure. Overestimation of force coefficients has a significant effect upon amplitudes of noise spectrum. In other reason, Curle's formulation in present study is integrated over infinite span. Therefore wrong signals due to the infinite span appeared. But overally speaking, the spectrum pattern of sound pressure level

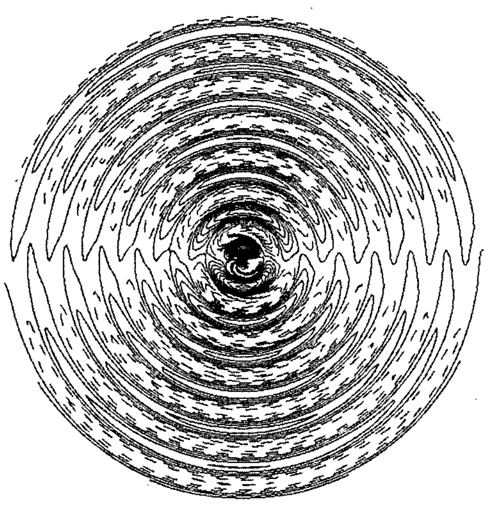


Figure 6. Directivity of sound (dipole is dominant).

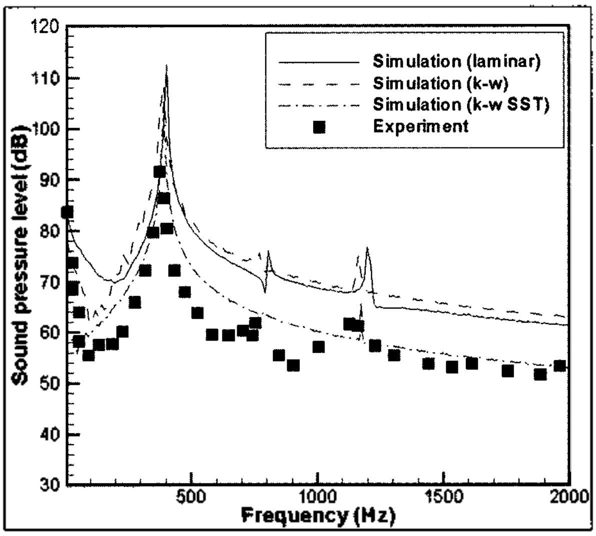


Figure 7. Sound pressure level at Reynolds number of 54000.

agrees well with that of experiment within an acceptable bound of error.

4.2. Drag and Noise Due to Change of Cross-sectional Shape

The numerical simulation of effect of cross-sectional shape upon sound pressure level is performed. The diameter of electric cable is 0.05 m and the flow velocity is 20 m/s (Reynolds number of 66000). The circular and elliptic shapes are considered. In fact, if the body takes on the streamlined shape, the drag and noise will be reduced. But this situation is not realistic by technical and economical restriction. Also the flow direction may be randomly changed. In present study, the incoming flow direction is same with the case of circular cylinder.

The cross-sectional area of elliptic shape is larger than that of circular cylinder about 20 %. Figure 8 shows the time histories of lift and drag coefficients for circular and elliptic cylinder. The mean drag for elliptic cylinder is smaller than the case of circular cylinder. The Strouhal numbers are 0.198 for circular shape and 0.206 for elliptic cylinder, respectively. The fluctuating lift is also small for elliptic cylinder. Figure 9 represents the predicted noise spectrum, which is based upon the results of Figure 7. For elliptic shape, the amplitude at the fundamental frequency is 90 dB compared to the case of circular cylinder 93 dB. Therefore we may conclude that the elliptic shape is efficient for drag and noise reduction.

V. Conclusion

In present study, the code for numerical prediction of near field aerodynamics and far field acoustics was developed for the simulation of low drag/noise electric cable. The two-dimensional, unsteady and incompressible Reynolds averaged Navier-Stokes solver was used to calculate the flow field. And Curle's integral formulation based on the acoustic analogy was used to compute the aerodynamic sound.

To validate the code, the prediction results were compared with the experimental data. The frequency characteristics match well with those of experiment in terms of Strouhal number. But amplitudes at the fundamental frequency were overpredicted. The difference between experiment and simulation can be explained by the characteristics of Curle's formulation being integrated over infinite span and three-dimensional vortex shedding characteristics. If three-dimensional flow-field calculation is carried out, the better results will be expected.

And the preliminary study about low drag/noise of electric cable due to change of cross-sectional shape was also performed.

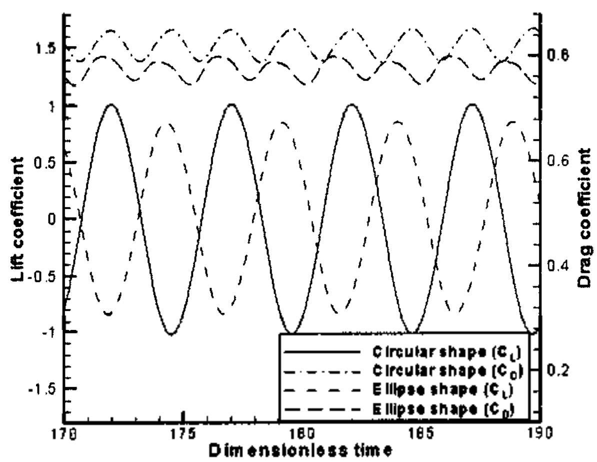


Figure 8. Lift and drag coefficient for circular and elliptic cylinder.

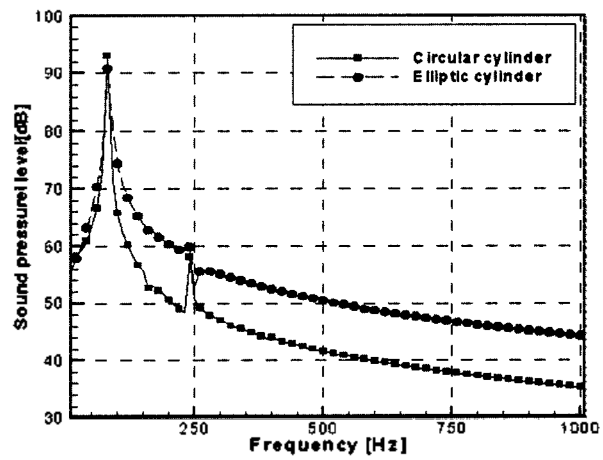


Figure 9. Sound pressure level for circular and elliptic cylinder.

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Nomenclatures

δ_{ij}	delta function
ρ	density
ν	kinematic viscosity
τ	retarded time
ζ	integration variable
c_0	speed of sound
n_j	surface normal vector
p	pressure
p'	acoustic pressure
u_i	velocity component
r	distance between observer and source ($r=\lvert x-y \rvert$)
t	time
T_{ij}	Lighthill stress tensor
x_j	cartesian coordinate
y	source coordinate

References

1. Honam, Ok, "Development of an incompressible Navier-Stokes Solver and Its application to the Calculation of Separated Flows," Department of Aeronautics and Astronautics, University of Washington.
2. Stuart E. Rogers, Dochan Kwak and Cetin Kiris, "Steady and Unsteady Solutions of the Incompressible Navier-Stokes Equations," *AIAA J.*, Vol. **29**, No. 4, 1991.
3. F. R. Menter, "Two-Equation Eddy-Viscosity Turbulence Models for Engineering Application," *AIAA J.*, Vol. **32**, No. 8, 1994.
4. D. C. Wilcox, "Turbulence modeling for CFD," DCW Industries, Inc., 1993.
5. M. J. Lighthill, "On sound generated aerodynamically; I. General theory," *Proc. Roy. Soc. London Ser. A.*, 211, 564-587, 1952.
6. Curle, N., "The influence of solid boundaries upon aerodynamic sound," *Proc. Roy. Soc. London Ser. A.*, 213, 505-514.
7. Mitchell, B. E., Lele, S. K. and Moin, P., "Direct computation of the sound from a compressible co-rotating vortex pair," *Journal of Fluid Mechanics*, 1995.
8. Blake, W. K., "Mechanics of Flow-induced Sound and Vibration: Volume I," Academic Press, 1986.
9. H. B. Hong, J. S. Choi, "Experimental Study of vortex shedding noise around a circular cylinder," Proceedings of the Korean Society for Aeronautical and Space Sciences Annual meeting, 1997.
10. Alemdaroglu, N., Rebillat, J. C., and Geothals, R., "An aeroacoustic Coherence Function Method Applied to Circular cylinder flows", *Journal of Sound and Vibration*, Vol. **69**, No. 3, pp. 427-439, 1980.
11. S. Lee, J. Kim, Y. H. Yu, and M. P. Isom, "Prediction of Rotor High-Speed Impulsive Noise with a Combined CFD-Kirchhoff Method," *Journal of Sound and Vibration*, Vol. **207**, No. 4, pp. 453-464, 1997.
13. J. Kim and D. J. Lee, "Generalized Characteristic Boundary Conditions for Computational Aeroacoustics," *AIAA Journal*, Vol. **38**, No. 11, pp. 2040-2049, 2001.
14. C. Seror, P. Sagaut, C. Baily, and D. Juve, "On the radiated noise computed by large-eddy simulations," *Physics of Fluids*, Vol. **13**, No. 2, pp. 476-487, 2001.
15. S. Mittal, "Computations of three-dimensional flows past circular cylinder of low aspect ratio," *Physics of Fluids*, Vol. **13**, No. 1, pp.177-191, 2001.

[Profile]

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