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Direct Numerical Simulation of Aeolian Tones

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Abstract

Direct numerical simulation results of aeolian tones generated by a two-dimensional obstacle (circular cylinder, square cylinder, NACA0012 airfoil) in a uniform flow are presented and the generation and propagation mechanisms of the sound are discussed. The unsteady compressible Navier-Stokes equations are solved by a highly-accurate finite difference scheme over the entire region from near to far fields. The direct numerical simulation results are also compared with the results obtained by Curle's acoustic analogy.

Keyword: *Sound, Aeolian Tones, CAA, DNS*

1. Introduction

Aeolian tone is sound generated by an obstacle in a flow. Research of aeolian tone has a long history of more than one hundred years. Strouhal [1] experimentally found that the frequency f of the sound radiated from a cylinder of diameter D is related to the velocity U of a uniform flow as fD/U = const. The constant is now known as the Strouhal number, *St.* Since the work of Strouhal, a number of studies on aeolian tones have been made. A brief survey for a circular cylinder has been given by Inoue and Hatakeyama [2].

Works in the field of computational aeroacoustics (CAA) can be categorized into three groups depending on the method to use: hybrid method, acoustic/viscous splitting method and direct numerical simulation (DNS) method. The first group (hybrid method) makes use of an acoustic analogy, under the assumption of a compact source, to predict the far-field sound. The source terms are evaluated using the near-field flow quantities, which are obtained by solving the incompressible Navier-Stokes equations for low-Mach-number flows. This method saves computational time as well as memory storage compared with DNS, because the flow in the far field is assumed to be stationary or uniform and thus not solved numerically. The second group (acoustic/viscous splitting method) assumes that flow quantities are represented, under the assumption of low Mach number, by an incompressible mean flow and a perturbation about the mean. In the far field, the perturbation quantities are equivalent to acoustic quantities. This method may possibly be a convenient method of predicting sound field resulting from low-Mach-number, non-compact source region. So far the results obtained by this method are qualitative, and detailed descriptions of sound fields have not yet been given. The third group makes use of DNS, where both the fluid motion and the sound which it generates are directly computed. Recent development of a high-performance supercomputer and highly-accurate numerical schemes makes it possible to simulate a sound field by directly solving the compressible Navier-Stokes equations over the entire region from near to far fields. This method does not suffer from restrictions such as low Mach number and compactness of the source region, but requires a large amount of computer resources; the studies using DNS are very few.

In this paper, DNS results of aeolian tones generated by a two-dimensional (2D) obstacle in a uniform flow are presented and the generation and propagation mechanisms of the sound are discussed.

2. Numerical Method

The 2D, unsteady, compressible Navier--Stokes equations are solved by a finite difference method. For spatial derivatives, a sixth-order-accurate compact Pade scheme (fourth-order-accurate at the boundaries) is adopted [3]. The fourth-order Runge--Kutta scheme is used for time-integration. Non-reflecting boundary conditions are used for the outer boundary of the computational domain [4]. The Mach number, *M*, of the uniform flow is prescribed to be $M = 0.05$ to 0.3. The Reynolds number *Re* is prescribed to be $Re = 150$ to 2000. For more details about the numerical method, readers are referred to Inoue and Hatakeyama [2] for a circular cylinder case.

3. Results

A typical example of computational results is presented in Fig. 1, where an instantaneous fluctuation pressure field superimposed on a vorticity field is shown for the case of an NACA0012 airfoil at an angle of attack 20 degree. The Mach number is $M = 0.2$ and the Reynolds number is $Re = 300$. In the figure, positive fluctuation pressures and vortices with anticlockwise rotation are shown by red; negative fluctuation pressures and vortices with clockwise rotation are shown by blue. We can see from the figure that sound pressure pulses are generated in response to vortex shedding and that the generated sound has a dipolar nature. When a vortex is shed from the leading edge, a negative pressure pulse is generated on the upper side of the airfoil whereas a positive pressure pulse is generated on the lower side. On the other hand, when a vortex is shed from the trailing edge, a negative pressure pulse is generated on the lower side whereas a positive pressure pulse is generated on the upper side. The generated pressure pulses propagate upstream under the Doppler effect.

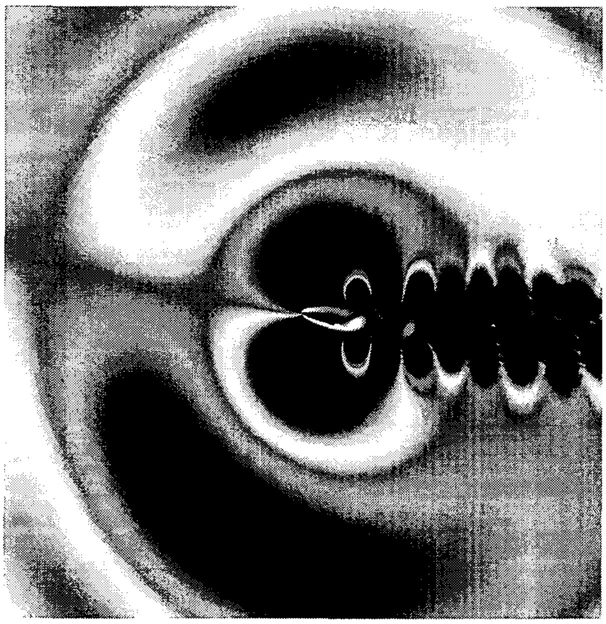

Fig. 1. Fluctuation pressure superimposed on vorticity. NACA0012. $M = 0.2$, $Re = 300$.

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