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SIMULATION OF TURBULENT WIND NOISE REDUCTION BY POROUS WINDSCREENS USING HIGH-ORDER SCHEMES

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The purpose of the study is to investigate the wind noise reduction provided by microphone windscreens at different frequencies of the impinging turbulence. The windscreen is assumed to be a cylindrically shaped porous medium. This paper uses a high-order scheme to improve the accuracy at the interface between air and porous medium. The computational scheme is based on a modified immersed-boundary method with distributed forcing terms. The simulation results show that, for low-frequency turbulence, the windscreens with low flow resistivity are more effective in noise reduction, while for high-frequency turbulence, the windscreens with high flow resistivity are more effective.

Keywords: Wind noise; porous medium; high-order scheme; windscreen.

1. Introduction

This paper examines turbulent flow over a porous windscreen and the resulting attenuation of *wind noise*, i.e., the turbulent pressure fluctuations occurring on a microphone placed within the screen. Windscreens are widely used on microphones, particularly for outdoor acoustic measurements. In many such applications, wind noise interferes with the signals of interest, particularly at frequencies low in the audible range. The performance of measurement microphones thus heavily depends on correct windscreen designs. Production of wind noise inside a windscreen is a complicated aerodynamic noise problem because of the interaction with the atmospheric turbulence with the porous windscreen. Currently, windscreen design practice is mostly heuristic in nature. Therefore, there is a need to fully understand the mechanisms involved in flow/pressure fluctuations around a screened microphone. Such understanding can lead to optimized windscreen designs. In this study, the effects of turbulence and the windscreen material properties (specifically its flow resistivity) are investigated. Time-domain computational techniques are developed to study the detailed flow mechanisms around the windscreen as well as the flow inside the windscreen.

With the advent of time-domain methods,[1] numerical simulations for acoustic problems can be combined with computational fluid dynamics. This provides powerful new tools to tackle acoustic problems. Recently, Wilson *et al.* used the finite-difference, time-domain (FDTD) method to simulate turbulence-induced pressure fluctuations around a porous microphone windscreen.[2] The unsteady, incompressible fluid flow equations were solved outside the windscreen, whereas an incompressible form of the Zwikker-Kosten[3] (ZK) equation was solved within the porous medium, which (as for the case of an impermeable, flexible membrane) resulted in a Laplace equation for the pressure field. However, the flow within the porous medium does not vanish. In this paper, an improved, coupled simulation is developed for solving these same equations.

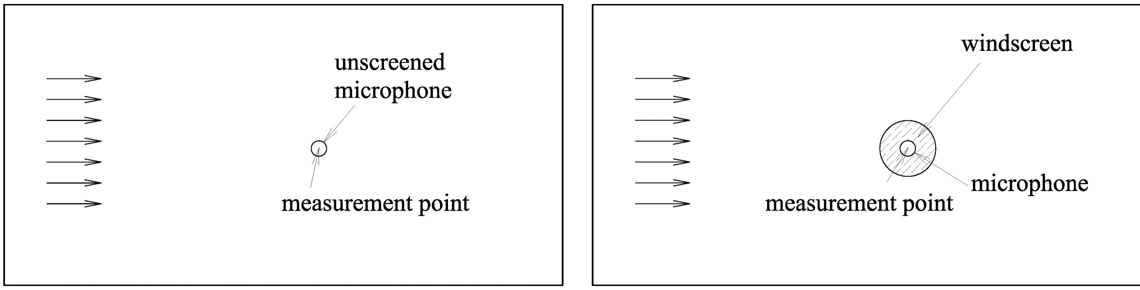
Recently numerical simulations of flow over porous media have aroused much interest and attention.[4] Specifically, the presence of a porous medium introduces a discontinuity at the interface between the fluid and porous medium, and also has been found to decrease computational accuracy. Therefore, accuracy at the interface is a key point in simulating such problems. Consequently, finding accurate and efficient ways to increase the accuracy and decrease the discontinuity at the interface is very important in simulations. One of the most effective ways to overcome the discontinuity is to apply high-order schemes such as upwind schemes or weighted essentially nonoscillatory (WENO) schemes.[5,6]

While stability of first-order upwind schemes is often acceptable, such schemes have a strong diffusive effect similar to the molecular viscosity.[7] We thus consider and compare second-order upwind, third-order upwind, and fifth-order WENO schemes.

High-order schemes have previously been used for viscous flow around steady and moving solid bodies,[8] but not for flow involving different types of media. Thus, in this paper, the high-order scheme will be used in the regions near the interface between fluid and porous media for the first time. The high-order scheme is combined with a modified immersed-boundary method.[8,9]

2. Formulation and Numerical Schemes

The two-dimensional model problem is shown in Fig. 1, where a stream of unsteady and/or turbulent flow approaches a cylindrical unscreened or screened microphone. The windscreen, when present, is made of a porous material. Because of the unsteadiness and surface conditions, flow fluctuations and vortical structures are generated around the surface and in the wake region. The pressure fluctuations sensed by the microphone, which is assumed to



(a) Unscreened microphone (b) Screened microphone

Fig. 1. Illustration of the model problem and the computational domain: (a) An unscreened microphone; (b) A screened microphone.

be at the center of the screen, result from near-field, incompressible disturbances. The flow fluctuations, both internal and external to the windscreen, are investigated based on coupled flow simulation between the outside and inside of the windscreen. We have developed an immersed-boundary (IB) computational method[8,9] suitable for simulations in which a windscreen is immersed in a background flow. While the IB methods for fluid-structure interaction problems typically discretize the equations of motion for fluid on a Cartesian grid, the methods generally do not require that the geometry of the structure to conform in any way to this Cartesian grid.

The model equations are the Navier-Stokes (NS) equations for incompressible flow, with the modified ZK equation for flow inside the porous medium. It should be noted that although sound waves measured at a microphone are compressible disturbances, the wind noise interfering with the sound waves consist, in general, of incompressible turbulence. The pressure fluctuations of interest are near the surface of an object or inside a porous medium. These fluctuations are associated with near-field, as with the surface pressure fluctuations produced by a turbulent boundary layer over the surface (as discussed by Kraichnan[10]), for which the incompressible flow assumption is well justified.

For the convenience of numerical computation and flow characterization, the governing equations are nondimensionalized with the incoming wind speed, U, the diameter of the cylindrical windscreen, D, and the air density, ρ. The governing equations for the airflow for unsteady, incompressible flow can be generally written as:

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}(u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{1}{\mathrm{Re}}\frac{\partial^2 u_i}{\partial x_j \partial x_j} + f_i \tag{1}$$

and

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{2}$$

where all the variables are dimensionless, and the Reynolds number, Re, is defined as UD/ν, with ν being the kinematic viscosity of the air. The body force, f_i, is a fictitious force that is introduced to enforce the flow outside the cylinder (either porous or solid) to accommodate the cylinder boundary condition,[8] so that the flow both outside and inside the cylinder can be simulated using the same format of the governing equation.

We begin by discretizing the momentum equation Eq. (1) as:

$$\frac{u_i^{n+1} - u_i^n}{\Delta t} = RHS_i + f_i \tag{3}$$

where $RHS_i = -(\partial/\partial x_j)(u_i u_j) - (\partial p/\partial x_i) + (1/\mathrm{Re})(\partial^2 u_i/\partial x_j \partial x_j)$, and the f_i is given by,

$$f_i = \begin{cases} 0 & \text{outside the windscreen} \\ \sigma u_i & \text{inside the windscreen} \\ -RHS_I + (v_{bi}^{n+1} - u_i^n)/\Delta t & \text{inside solid body} \end{cases} \tag{4}$$

where v_{bi}^{n+1} is the velocity of the solid body at the $n+1$ time step; therefore, the condition $u_{bi}^{n+1} = v_{bi}^{n+1}$ will be satisfied inside the solid body.

The airflow outside the windscreen is modeled with the incompressible NS equation expressed in Eq. (1) as $f_i = 0$. For simplicity, the windscreen is assumed to have porosity and structure constant equal to 1. The air flow inside the windscreen is modeled with the ZK equation,[3] which is the low-frequency limit of more general forms of porous media equations.[11] In addition, incompressibility is assumed for flow inside the porous medium. The governing equations for airflow inside the windscreen are expressed in Eq. (1) as $f_i = \sigma u_i$, where σ is the dimensionless flow resistivity of the porous medium, nondimensionalized by ρU/D. The convection and diffusion terms are neglected in the original ZK equation because the velocity is low in the porous medium. We still retain them here so that the same solver can be used for both the NS equation and ZK equation, as the effect of convection and diffusion automatically becomes small when the velocity is low. Moreover, we also want to test the cases when the flow resistivity is small, and then the convection effect may not be very small. However, the Forchheimer term, which represents the flow resistivity caused by the second-order effect of the velocity, is neglected due to the small magnitude of velocity in the porous medium.

By applying a divergence operator to both sides of Eq. (1) and invoking the incompressibility condition of Eq. (2), a Poisson equation for the pressure can be obtained as

$$\nabla^2 p = -\frac{\partial}{\partial x_i \partial x_j}(u_i u_j) \tag{5}$$

The presence of the porous media introduces a discontinuity in some of the flow variables or their derivatives around the flow/porous interface. Under these circumstances most conventional finite-difference schemes would generate spurious numerical oscillations. Here we introduce three approaches to addressing this problem: a second-order upwind scheme, a third-order upwind scheme, and a fifth-order WENO scheme.