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A high-order immersed boundary method for acoustic wave scattering and low-Mach number flow-induced sound in complex geometries

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ABSTRACT

A new sharp-interface immersed boundary method based approach for the computation of low-Mach number flow-induced sound around complex geometries is described. The underlying approach is based on a hydrodynamic/acoustic splitting technique where the incompressible flow is first computed using a second-order accurate immersed boundary solver. This is followed by the computation of sound using the linearized perturbed compressible equations (LPCE). The primary contribution of the current work is the development of a versatile, high-order accurate immersed boundary method for solving the LPCE in complex domains. This new method applies the boundary condition on the immersed boundary to a high-order by combining the ghost-cell approach with a weighted least-squares error method based on a high-order approximating polynomial. The method is validated for canonical acoustic wave scattering and flow-induced noise problems. Applications of this technique to relatively complex cases of practical interest are also presented.

1. Introduction

Low-Mach number, flow-induced sound plays a critical role in engineering applications such as transportation systems, engineering appliances and turbo-machines. In many of these applications, flow-induced noise is undesirable and engineers seek to identify noise source(s) with the objective of eliminating or diminishing the same. One examples of this is the cabin noise in automobiles associated with external air-flow and another is the aeroacoustics sound associated with the flow from an air-conditioning vent. Flow-induced sound also plays an important role in biomechanics. Human speech and animal vocalization is enabled by the generation of flow-induced sound in the larynx [1]. In the cardiovascular system, sounds such as "bruits" [2], heart murmurs [3], and Korotkoff sounds [4] are blood-flow-induced sounds that carry important information about the health of the individual. Finally, hydroacoustic sound generation [5–7] associated with wakes, shear layers, jets, tip-vortices, etc. are also low-Mach number flows phenomena which have tremendous importance in naval hydrodynamics and ocean acoustics.

The ability to predict flow-induced sound in these various applications can advance the design of quieter devices/machines and also lead to insights and non-invasive diagnostic techniques for pathologies associated with phonation, speech and the cardiovascular system. However, all of the above aeroacoustic problems are associated with very complex geometries, and accurate prediction of sound generation and propagation in such complex geometries is a challenging proposition. Although sound wave propagation and scattering by a complex geometry can be modeled with a boundary element method (BEM) [8,9], the prediction of flow-induced sound generation requires more direct approach such as the direct computation of compressible conservation equations (see [10,11]). Computation of sound wave generation/propagation requires a

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method that has very low dispersion and dissipation and is therefore best accomplished by high-order finite-difference schemes such as compact schemes [12] or DRP (Dispersion–Relation-Preserving) scheme [13]. Most of these high-order, finite-difference numerical method used in computational aeroacoustics (CAA) are formulated on structured grids and are usually very sensitive to the quality of the computational grid and the formulation of the boundary conditions. However, it is difficult to generate high-quality structured grids around complex geometries and this has mostly limited CAA to relatively simple geometries.

There are however a few approaches that have been used with some success for CAA in relatively complex geometries. A high-order overset grid method [14,15] has been developed to solve the compressible flow and acoustics over complex geometries. However the level of geometric complexity that this solver can handle is still limited. Furthermore, while the method is well suited for high-Mach number sound, computations at low Mach numbers ($M < 0.1$) are difficult. The high-order discontinuous Galerkin method [16–19] could be an alternative to solve for the aeroacoustic field around complex geometries, but this method is computationally expensive. Thus, there is a clear need for developing a method that can compute low-Mach number flow-induced sound in geometrically complex configurations.

The immersed boundary method (IBM) [20] is well suited for dealing with complex geometries. With IBM, all the equations can be solved on a body non-conformal, Cartesian grid, and also the grid does not need to be re-generated for moving or deforming bodies. Due to this flexibility, many different types of IBM are used in compressible and incompressible flow solvers. A few IB based approaches for acoustic wave propagation/scattering problem in frequency [21,22] and time domain [23,24] have also been developed. In these studies, however, only the linear wave propagation and scattering with prescribed acoustic source is considered. The key to IBM is the treatment of boundary condition at the body surface and the vast majority of immersed boundary formulation are first or second-order accurate (one exception is the high-order immersed-interface method of Linnick and Fasel [25]). For example, in the IB method of de Tullio et al. [26] and de Palma et al. [27] for compressible flows, a direct forcing with a linear or inverse-distance weighted interpolation is employed and this leads to a locally first-order accurate method. In the compressible IB method of Ghias et al. [28], a ghost-cell method is used with two-point centered scheme, which results in local and global second-order accuracy.

Acoustic field computations however require high-order boundary formulations so as to minimize the dispersion/dissipation errors. Additionally, not only the order of accuracy of boundary formulation, but also the sharpness of interface would be very important in order to limit the phase and amplitude errors generated by a wave interacting with the boundary. Recently, Liu and Vasilyev [29] applied a Brinkman penalization method, which is an immersed boundary method based on a porous media model equation, to the compressible Navier–Stokes equations and considered an acoustic wave scattering problem. Although the order of accuracy of numerical scheme could be maintained near the immersed boundary, the immersed interface is not sharp.

In the present study, we propose a sharp-interface, higher-order immersed boundary method to solve aeroacoustic problems with complex bodies in low-Mach number flows. For the efficient computation of low Mach number aeroacoustics, a hybrid method based on the hydrodynamic/acoustic splitting technique [30–32] is employed. In this approach, the flow field is obtained by solving the incompressible Navier–Stokes equations (INS), and the acoustic field is predicted by the linearized perturbed compressible equations (LPCE) proposed by Seo and Moon [32]. The INS/LPCE hybrid method is a two-step/one-way coupled approach to the direct simulation of flow -induced noise. In the method proposed here, we couple an existing immersed boundary solver for incompressible flows [33] with a new high-order immersed boundary method for solving the LPCE equations with complex immersed boundaries. The high-order immersed boundary method proposed here also employs ghost-cells as in Refs. [28,33] but the method is extended to higher-orders by using an approximating polynomial method originally proposed by Luo et al. [34] for the solid mechanics equations. Dirichlet as well as Neumann boundary conditions can be applied with a high order of accuracy on the solid surface using the method. Thus dispersion/dissipation errors caused by the boundary condition formulation can be minimized thereby ensuring highly accurate representation of wave reflection on the solid walls.

The current method therefore combines the flexibility of the immersed boundary method with the capability offered by the INS–LPCE hydrodynamic/acoustic splitting technique for computing low-Mach number ($M < 0.3$) flow-induced sound. It should be pointed out that the sound generation and propagation is modeled here in a natural way and unlike acoustic analogy methods (e.g. Lighthill's analogy [35]), the predicted acoustic field is valid for both the far and near-fields. The time-dependant base flow effects on the sound generation and propagation are also fully taken into account. Additionally, the LPCE secures a consistent acoustic solution by suppressing the evolution of the unstable perturbed vortical mode [32]. Finally, since this method is based on the incompressible flow solution, it is very effective for the flows at low Mach numbers which are of particular relevance to the applications of interest to us.

The paper is organized as follows: In Section 2, the governing equations and numerical methods including the present immersed boundary approach are described. In Section 3, several canonical acoustic wave scattering problems and a fundamental flow-induced noise problem are considered in order to validate the present method. The acoustic wave scattering results are compared with analytical solutions while the flow-induced noise simulation is validated against data from a highly resolved direct compressible flow simulation performed on a body-fitted grid using a different solver. Finally, the capability of the present approach for modeling flow-induced sound in complex geometries is demonstrated by computing the generation and propagation of sound in a modeled human vocal-tract as well as that from a modeled air-conditioning vent.