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A Frequency Domain Immersed Boundary method and its Application to 2-dimensional Acoustic Problems

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Abstract

A frequency domain Immersed Boundary (IB) method was developed and validated in the present paper using 2-dimenstional acoustical radiation and scattering cases. The IB method was incorporated with Linearized Euler Equations (LEE) in the frequency domain in the present work. The governing equations were spatially discretisized using the DRP scheme. A pseudo time dependant term was added to the frequency domain equations, allowing the use of a conventional time-marching algorithm to converge the solutions in the pseudo-time domain. Perfectly Matched Layers (PML) were placed at boundaries of computational domain where non-reflective conditions were expected. PML technique was also implemented inside the rigid body to stabilize the computation. The impermeable boundary condition on the surface of the geometry is guaranteed by finding the inverse of an influence matrix, which establishes the relationship between boundary forces and induced velocity. Numerical computations were performed for 2-dimensional acoustic radiation and scattering problems. Computational results were compared with exact solution and yielded good agreement, providing a solid validation of the current method. The method is expected to extend to higher dimension and applied to more complex problem like wake/airfoil interaction simulations in turbomachinery.

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Keywords: Immersed boundary method; Frequency domain; Linearized Euler equation; Computational Aeroacoustics; Acoustic scattering

Nomenclature

A	coefficient matrix of linearized Euler equations

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$\mathbf{B}$	coefficient matrix of linearized Euler equations
$\mathbf{F}$	source term added to linearized Euler equations
$\mathbf{M}$	influence matrix
$\mathbf{U}$	state variable vector of linearized Euler equations
$\hat{\mathbf{U}}$	state variable vector of linearized Euler equations in frequency domain
$\delta(x)$	Dirac delta function
ω	angular frequency
τ	pseudo time variable
σ_x	PML coefficient
σ_y	PML coefficient

1. Introduction

Aircraft noise has always been a great issue accompanying the rapid development of civil aviation. The need of noise prediction and reduction has been impelling the development of aeroacoustics discipline, in both aspect of theory and application. In the early ages with limited computational ability, aircraft noise analyses generally rely on empirical models and analytical models. ANOPP (Aircraft NOise Prediction Program), which was developed under the organization of NASA, integrates various empirical models for main noise sources of modern aircraft like fan noise models[1], jet noise models[2-4] and so forth. TFaNS[5] and BFaNS[6, 7] are good examples for analytical models, which predicts fan tone noise and broadband noise respectively.

In the recent decades, CFD has gradually become a common tool routinely used in aircraft and its engine design. Tempted by the success of CFD, people were considering the application of numerical simulations for acoustic problems. After a short period of attempt to use CFD schemes directly for acoustical simulation, people started to realize that some important issues, including the reflection of computational boundaries, numerical dispersion and dissipation, must be taken good care of before accurate result can be acquired. Research efforts on those aspects then led to the emergence of a new discipline named Computational Aeroacoustics, or CAA. Lele[8] proposed a compact differential scheme for spatial discretization while Tam and Webb[9] developed an explicit DRP scheme. For time marching schemes, modified Adams-Bashforth[9] and modified Runge-Kutta[10] schemes were developed to minimize the dispersion and dissipation in temporal dimension. Various versions of characteristic [11, 12], asymptotic [9] and absorbing[13] boundary conditions were introduced to prevent sound, vorticity and entropy waves from reflecting back into computational domain.

Complex and/or moving geometries are great challenges in both CFD and CAA. In order to simplify the grid generation procedure and improve grid quality, computational techniques based on simple grids are of great research interests. Besides the traditional body-fitted grid, several other options for complex geometries are available. One possibility is the Chimera grid (also called overset grid) method[14-16], which generates a simple (e.g. Cartesian) grid as background and a body-fitted grid for each geometry. Another concept is to treat the boundaries inside the computational domain as force distributions and include the force term to the momentum conservation equation. That idea was first proposed by Peskin et al.[17, 18] in 1970s and named the Immersed Boundary (IB) method. The IB method has evolved much since its emergence. LeVeque et al.[19] described the boundaries as discontinuities of function value and/or it derivatives and modified spatial discretization schemes to enforce the jump condition. LeVeque's method promoted the IB method from 1st order accuracy across boundaries to higher order. To make a distinction, it was titled the Immersed Interface Method (IIM). Some researchers use ghost cell technique[20-22] instead of singular force to treat complex geometries in simple background grid and sometime these methods are also classified as IB methods.

The IB methods, including its varieties, has been applied to broad categories of fluid flow problems like flow around heart valves[17, 18, 23], aquatic animal locomotion[24, 25], multi-phase flow[26-28], fluid-structure interaction in turbomachinery[29] but very little attention was paid to inviscid acoustic applications[21, 22, 30]. Moreover, most realizations of the IB concept were carried out in time domain instead of frequency domain. However, studying acoustic problems in frequency will bring great convenience in treating boundary conditions like