Aeroacoustics of Wall-Bounded Flows: Overview of Computational Methods

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1 Introduction

The study of flow-induced noise, known as aeroacoustics or hydroacoustics depending on the fluid medium, is concerned with the sound generated by turbulent and/or unsteady vortical flows. Such flows are prevalent in engineering applications. Historically, aeroacoustics was dominated by the noise from aircraft jet engines, which was treated as a free-space problem; the effect of nozzle and other solid objects was largely neglected. Most flow-noise problems, however, involve flow interaction with solid boundaries. With advances in jet-noise reduction, fan-noise from the turbo-fan engines rises in significance, and airframe noise, including the noise from the landing gear, slats and flaps, becomes a significant component of overall noise when landing. In the automotive industry, increasing attention is being paid to reducing wind noise, typically dominated by flows past sideview mirrors, A-pillars, and windshield wipers. In naval applications, the noise generated by marine propellers, hydrofoils, and even transitional and turbulent boundary layers are serious concerns. Other examples include the noise from wind turbines, axial and centrifugal fans in rotating machines, and helicopter rotors.

The presence of solid boundaries generally makes aerodynamic sound radiation more efficient. They can enhance noise radiation in two ways: by creating or augmenting noisy flow features such as unsteady separation and vortex shedding and by imposition of a boundary inhomogeneity which promotes efficient conversion of flow energy to acoustic energy. An illustrative example of this is the noise of flow past an airfoil. In the small airfoil (relative to the acoustic wavelength) limit, Curle's (1955) solution to the Lighthill equation (Lighthill, 1952) reveals the dipole nature of the sound source as compared with the less efficient quadrupole sources in free space. For long and thin airfoils relative to the sound wavelength, scattering of flow disturbances by the leading and trailing edges dominates sound radiation, which has an even more efficient non-multipole (or "3/2-pole") character (Ffowcs Williams and Hall, 1970; Crighton and Leppington, 1971).

Computation of the generation and propagation of flow-induced sound presents a number of distinct challenges relative to general computational fluid dynamics (CFD), as pointed out early on by Crighton (1993) and recently discussed in detail by Colonius and Lele (2004). First, the noise generating flow is inherently unsteady, which renders the traditional CFD methods based on steady Reynolds-averaged Navier-Stokes (RANS) equations alone unsuitable. The second difficulty is the vast disparity in the magnitudes of fluid dynamic and acoustic disturbances. With the exception of high-speed flows involving shock waves, only a small fraction ($\sim$ fourth power of fluctuating Mach number M for small M) of flow energy radiates to the far field (Crighton, 1993). Since the ratio of acoustic wavelength to its source flow scale is inversely proportional to the fluctuating Mach number, the disparity in acoustic and flow length scales at low Mach numbers presents a third challenge. In addition, acoustically nonreflecting boundary conditions remain a difficult issue in the presence of complex turbulent shear flows (Colonius, 2004).

Two additional computational challenges arise in connection with solid boundaries. The first is the large computational expenses required to resolve near-wall flow structures at high Reynolds numbers in a time-accurate turbulence simulation. These structures are small but energetic and therefore can contribute to sound generation. The second issue concerns the reflection and scattering of sound waves by the solid surfaces, which can be computationally demanding in complex geometries and for high frequency waves.

In addition to the sound radiated to the far field, the study of fluctuating pressure on a solid surface, also known as "pseudo-sound", has traditionally been a part of aeroacoustics and hydroacoustics (Blake, 1986). It is of interest not only because it is considered a sound source in many aeroacoustic theories, but also because it can excite structural vibrations and lead to potentially more efficient sound radiation.

The lecture notes presented here give an overview of the computational techniques for predicting flow-generated sound, with an emphasis on hybrid techniques which combine Lighthill's theory and its extensions with high-fidelity flow simulations. This includes advanced turbulence simulation methods suitable for computing acoustic source functions and techniques for calculating the acoustic field through analytical and numerical means.