Boundary-Layer Noise Due to Surface Irregularities

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Contents

1 Introduction

Turbulent boundary-layer flows over a smooth, rigid and plane surface are known to be acoustically inefficient. The fluctuations in surface pressure, once thought of as acoustic dipoles, are in reality specular images of quadrupole sources arising from the fluctuating Reynolds stress in the boundary layer (Powell, 1960). While the fluctuating viscous shear stress on a wall is a valid dipole sound source (Morfey, 2003; Shariff and Wang, 2005; Hu et al., 2006), its magnitude is generally small in high-Reynolds-number boundary layers of practical interest.

The presence of irregular surface features such as roughness, steps and gaps can, however, drastically enhance boundary-layer noise. One way for surface irregularities to generate enhanced noise is through diffraction. The surface inhomogeneity facilitates the conversion of flow energy to acoustic energy and thereby causes a significant increase in radiated noise levels even if the flow field (structure) is unchanged. Another mechanism for noise generation is the modification of near-wall turbulence. When the height of surface roughness exceeds the buffer layer thickness, it interacts nonlinearly with the flow to distort incoming turbulence and generate new noisy flow features such as horseshoe vortices, unsteady separation, vortex shedding, and reattachment. For acoustically small roughness features, diffraction and turbulence generation collectively exert unsteady drag forces on the rough surface, which constitute in-plane acoustic dipoles as described by Curle (1955) and Howe (1984, 1986). In addition to directly radiated sound, the enhanced surface pressure fluctuations are of significant concern because they can cause structural vibration and hence additional noise.

We have recently performed fundamental studies of noise generation by surface roughness and steps, two types of surface irregularities underneath turbulent boundary layers. Both forward and backward facing steps are considered, and roughness effects are examined with a single hemispherical roughness element and a pair of elements. For low Mach number flows of primary interest, a hybrid method, which computes the turbulent source field separately from the radiated acoustic far field, provides the most efficient and accurate approach (Wang et al., 2006). The turbulent boundary layers are computed with large-eddy simulation (LES), and the far-field sound is calculated using Lighthill's aeroacoustic theory (Lighthill, 1952). Detailed computational procedures and major findings for roughness noise and step noise are discussed in Sections 2 and 3, respectively.

2 Roughness-Induced Noise

Noise generated by flow over rough surfaces is of particular concern in naval applications since underwater vehicles inevitably develop rough surfaces due to continual exposure to seawater. Such noise can not only affect the stealth operation of a submarine but also obscure the weak signals from a remote source that a passive sonar system aims to detect (Crighton et al., 1991). In aeronautical applications, roughness noise is a significant part of the airframe noise in clean configuration, when high-lift devices such as flaps and slats are retracted. Based on experimental measurements and empirical correlations, Liu and Dowling (2007) estimated that roughness noise may exceed trailing-edge noise at high frequencies for a Boeing 757 sized aircraft wing.

In a series of theoretical investigations, Howe (1984, 1986, 1989) examined rough-wall noise in the framework of diffraction theory. By using Lighthill's aeroacoustic theory (Lighthill, 1952) with an approximate hard-wall Green's function for acoustically compact roughness elements, the dipole nature of the roughness noise source was revealed explicitly. The sound intensity was found to vary as the sixth power of flow velocity. In Howe's theory wall roughness is modeled by a distribution of hemispherical bosses. The dominant turbulent pressure sources (fluctuating Reynolds stress) are assumed to lie above the roughness elements and are not directly affected by the roughness elements. This effectively limits the height of roughness elements to within the buffer layer.

There have been only a few experimental investigations of roughness noise. Earlier experiments involved turbulent boundary layers (Cole, 1980; Farabee and Geib, 1991) and pipe flows (Hersh, 1983), and were focused on radiated noise, wall pressure spectra, and their correlations with the mean velocity. Considerable discrepancies exist among the data even in terms of basic scaling laws, i.e., the velocity scaling of the noise spectrum. A quantitative comparison of the experimental results is difficult because of disparate flow conditions and configurations. Overall, the source mechanisms and radiation characteristics of roughness noise are still not well understood, and there is a lack of predictive tools.