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Direct numerical simulation of turbulent flow with an impedance condition

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ABSTRACT

DNS solutions for a pipe/jet configuration are re-computed with the pipe alone to investigate suppression of previously identified internal noise source(s) with an acoustic liner, using a time domain acoustic liner model developed by Tam and Auriault (AIAA Journal, 34 (1996) 913–917). Liner design parameters are chosen to achieve up to 30 dB attenuation of the broadband pressure field over the pipe length without affecting the velocity field statistics. To understand the effect of the liner on the acoustic and turbulent components of the unsteady wall pressure, an azimuthal/axial Fourier transform is applied and the acoustic and turbulent wavenumber regimes clearly identified. It is found that the spectral component occupying the turbulent wavenumber range is unaffected by the liner whereas the acoustic wavenumber components are strongly attenuated, with individual radial modes being evident as each cuts on with increasing Strouhal number.

1. Introduction

The noise generated by internal flows has recently received attention in the aeronautical field as well as in the industrial field. Noise generated by turbulent pipe flows represents a significant problem for industrial applications such as ventilation and piping systems. Furthermore, in the aeronautical field the aircraft's engine is an important source of noise. More specifically turbofan engines are characterized by internal turbulent flows such as by-pass duct flow and nozzle flow through which noise internally generated by the fan, turbine or combustion propagates out to the external observer. Acoustic liners are a common solution to reduce the noise propagating through internal flows. Acoustic liners are passive control devices that convert sound energy into heat through viscous and thermal diffusion processes. They are typically designed as porous surfaces and installed on pipe walls and internal engine ducting walls. Acoustic liners are usually modelled as a mass–spring–damper system and are therefore characterized by a resonance frequency. Previously, researchers had developed mathematical models in order to simulate the performance of acoustic liners [1]. In classical acoustics, where typically no flow is present in the acoustic domain, the liner modelling is quite simple in terms of development and numerical implementation. In contrast, when a viscous flow grazes the acoustic liner surfaces, the mathematical modelling and numerical implementation becomes far more complex [2]. A grazing flow over an acoustic liner represents a more realistic situation in applications such as ventilation, piping and aero-engines. A boundary layer over an acoustic liner is typically modelled as infinitely thin shear layer on the impedance surface. However, the Myers boundary condition can cause numerical instability when applied to reacting surfaces with slipping flow (*e.g.* [3–5]). In contrast there

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have been attempts to model a finite thickness shear layer applying a no-slip boundary condition over the reacting surface (*e.g.* [6–8]). Difficulties in developing a liner model that includes a viscous grazing flow might be due to the lack of knowledge regarding the physical interaction between the flow field and liner cavities. In order to provide such insight, Tam et al. [9] performed a computational and experimental investigation of the acoustic properties of a three-dimensional acoustic liner with rectangular apertures. It was observed that shed vortices appear on the apertures of the cavities and tend to evolve into rings and align themselves into two regularly spaced vortex trains moving away from the resonator opening in opposite directions. More recently, Zhang and Bodony [10] demonstrated that direct numerical simulation has the potential to provide validated numerical results for acoustic liners with complex geometries. They simulated a locally reacting honeycomb liner with circular apertures at a variety of sound pressure levels and frequencies. Although computational resources are available to accurately simulate the flow interaction with a single resonating cavity, it is till not possible to extend this analysis to a fully lined wall.Therefore, in order to investigate the effect of acoustic liners on turbulent flows, a CFD solver combined with a time-dependent impedance condition is a possible alternative. Thus, in the current work a time domain impedance model, given by Tam and Auriault [3], is implemented into an in-house viscous flow solver. The liner model incorporates a frequency independent acoustic resistance and a frequency dependent reactance. Acoustic impedance conditions have previously been applied to CFD solvers, see for example Zheng and Zhuang [11] and Baelmans and Desmet [12]. However, they used artificial profiles for the boundary layer generating an artificially thickened boundary layer. In consequence, the modelling error due to the large boundary layer thickness leads to a wrong prediction of the NASA flow tube experiment [13]. Realistic boundary layers from a CFD simulation were used by Eriksson and Baralon [14]. They showed that a correct prediction of the NASA grazing flow tube experiment could be obtained by using a high-order accurate CFD code. In the present work a DNS solver is used to simulate a fully turbulent subsonic pipe flow. The Tam and Auriault [3] model has been implemented to simulate the acoustic effect of an acoustic liner on the internally generated noise. The main objective of this study is to investigate the internal noise reduction potential of the liner model and to assess its effect on the turbulent flow. The DNS solver has already been used by Sandberg et al. [15] for simulations on jet noise which motivated the present work. It is important to state that in the present work the liner is modelled as a uniform, constant, linear impedance surface so there is no need to incorporate a detailed model of the unsteady flow through individual holes unlike Zhang and Bodony [10] and Tam et al. [9] who study a grazing flow over a single and multiple meshed holes.

In this paper the second section introduces the governing equations implemented in the DNS solver. The third section introduces the liner model and its implementation. In the fourth section the Tam and Auriault [3] model is applied to a fully turbulent subsonic pipe flow. In the fifth section the attenuation capability of a particular liner design is tested and analysed, along with modifications to the inflow perturbations. In the sixth section a wavenumber analysis (equivalent to beamforming) is carried out, in order to separate out the acoustic and hydrodynamic components of the DNS wall pressure and hence more clearly assess the liner performance in suppressing the acoustic noise.

2. Governing equations

The flow under consideration is governed by the full compressible Navier–Stokes equations. The fluid is assumed to be an ideal gas with constant specific heat coefficients. All quantities are made dimensionless using the nozzle radius and the bulk velocity, U, within the nozzle. For simplicity, all equations in this section are presented in tensor notation. The non-dimensional continuity, momentum and the energy equations are

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_k}(\rho u_k)=0, \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_k}[\rho u_i u_k+p\delta_{ik}-\tau_{ik}]=0, \tag{2}$$

$$\frac{\partial}{\partial t}(\rho E)+\frac{\partial}{\partial x_k}\left[\rho u_k\left(E+\frac{p}{\rho}\right)+q_k-u_i\tau_{ik}\right]=0, \tag{3}$$

where the total energy is defined as $E=T/\left[\gamma(\gamma-1)M_\infty^2\right]+0.5u_iu_i$. The stress tensor and the heat-flux vector are computed as respectively

$$\tau_{ik}=\frac{\mu}{Re}\left(\frac{\partial u_i}{\partial x_k}+\frac{\partial u_k}{\partial x_i}-\frac{2}{3}\frac{\partial u_j}{\partial x_j}\delta_{ik}\right), \quad q_k=\frac{-\mu}{(\gamma-1)M_\infty^2 PrRe}\frac{\partial T}{\partial x_k}, \tag{4}$$

where the Prandtl number is assumed to be constant at $Pr=0.72$, and $\gamma=1.4$. The molecular viscosity μ is computed using Sutherland's law [16] setting the ratio of the Sutherland constant over freestream temperature to 0.36867, implying a reference temperature of 300 K and a reference speed of sound $c_\infty=347.2$ m/s. Furthermore, the Mach number is defined such that $M_\infty=U/c_\infty$. Assumed to be constant at $Pr=0.72$, $\gamma=1.4$, the bulk viscosity is neglected. To close the system of equations, the pressure is obtained from the non-dimensional equation of state: $p=(\rho T)/(\gamma M_\infty^2)$.

At the pipe inflow velocity perturbations are calculated using a compressible version of the digital filter technique according to Touber and Sandham [17], with parameters specified from precursor periodic pipe simulations, and superposed