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The acoustics of short circular holes opening to confined and unconfined spaces

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ABSTRACT

The sound generated or absorbed by short circular holes with a mean flow passing through them is relevant in many practical applications. Analytical models for their acoustic response often ignore the fact that such holes open to a confined or finite space either side, or account for this effect simply by adding an end mass inertial correction. The vortex–sound interaction within a short hole has been recently shown to strongly affect the acoustic response at low frequencies (D. Yang, A.S. Morgans, *J. Sound Vib.* 384 (2016) 294–311 [19]). The present study considers a semi-analytical model based on Green's function method to investigate how the expansion ratios either side of a short hole affect the vortex–sound interaction within it. After accounting for expansions to confined spaces using a cylinder Green's function method, the model is substantially simplified by applying a half-space Green's function for expansions to large spaces. The effect of both the up- and downstream expansion ratios on the acoustics of the hole is investigated. These hole models are then incorporated into a Helmholtz resonator model, allowing a systematic investigation into the effect of neck-to-cavity expansion ratio and neck length. Both of these are found to affect the resonator damping.

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1. Introduction

The sound generated or absorbed by a short¹ circular hole with a mean flow passing through it is relevant to many engineering applications. This includes Helmholtz resonators, perforated liners or plates with cooling flow passing through them in aero-engine or land-based gas turbine combustors [1–4]. At high mean hole Reynolds numbers, beyond the hole inlet a shear layer is formed. When an acoustic wave is incident on the hole, viscous dissipation is mainly localised at the hole edge where the action of viscosity brings about the generation of vortices. Significant acoustic attenuation occurs at low frequencies due to the conversion of acoustic energy into this unsteady shed vorticity [5,6].

Many theoretical models dealing with this vortex–sound interaction [6–8] assume that the shed vortices at the hole inlet edge are convected downstream by the mean flow to form a thin vortex sheet within the mean shear layer. Instabilities of the mean shear layer can be avoided when the thickness of the vortex sheet near the edge can be assumed to be much smaller than that of the shear layer [5,6,9–11]. This approach has the advantage that it allows the Kutta condition – imposing finite velocity oscillations near the vortex shedding edge [8] – to be applied at the sharp edge without the introduction of

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¹ In this paper, “short” hole implies a hole which is not infinitely short but is not long enough to allow the separated mean flow from its inlet edge to reattach its inner wall.

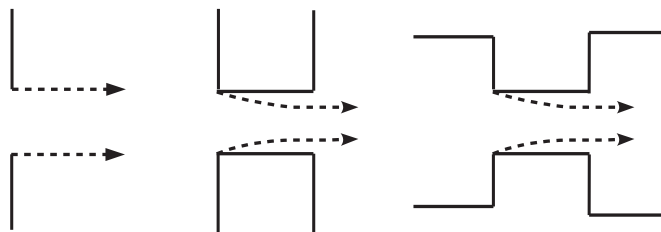


Fig. 1. (Left) Schematic of an infinitesimally short circular hole opening to semi-infinitely large spaces either side, and with a mean flow left to right which yields a cylindrical vortex sheet downstream. (Middle) A short circular hole opening to semi-infinitely large spaces either side and with a convecting vortex sheet path within and downstream of it. (Right) A short circular hole opening to finite expansion cylinders either side and with a convecting vortex sheet path within and downstream of it.

exponentially growing shear layer instabilities. Based on this assumption, Howe [6] derived an analytical Rayleigh conductivity expression (which denotes the relation between the oscillating mass flux through the hole and the oscillating pressure difference across it) for an infinitesimally short circular hole opening to semi-infinitely large spaces either side, as shown in Fig. 1 (left). A semi-infinitely long cylindrical vortex sheet with the same radius as the hole was assumed to be shed from the hole edge. Howe's model can be slightly modified by adding a small mass inertial term to account for a small hole length; this approach has been widely used to predict the acoustic response of very short holes over recent years [1,2,12–16]. Another approach which does not explicitly consider the shed vorticity was proposed by Bellucci et al. [3]. The hole acoustic resistance is assumed to be mainly associated with the pressure loss caused by the flow contraction and the reactance with the acoustic scattering either side of the hole.

When the hole length is of the same order as the hole radius but not long enough to allow the separated mean inlet flow to reattach within it (the situation shown in Fig. 1 (middle)), the hole impedance was experimentally found to differ substantially from both Howe's and Bellucci's predictions [17,18]. Such holes were found to have the potential to generate as well as absorb acoustic energy, even in the low Strouhal number region. A theoretical model was recently developed based on Green's function method to take the vortex–sound interactions both within and after the hole into consideration [19]. This model was able to predict the experimentally measured trends. Accurately capturing the path of the shed vorticity was found to be important, and to this end models matching the experimentally measured vortex path [20] were used. It was found that both the hole length and the vortex sheet shape near the shedding edge significantly affect the acoustic response of the hole.

The above models deal with holes opening to an unconfined space either side. However, in many practical situations, the holes open to confined spaces (as shown in Fig. 1 (right)) and this may have a strong effect. One example is the expansion between the neck and cavity volume of a Helmholtz resonator. For a semi-infinitely long circular pipe undergoing an area expansion in the absence of a mean flow, Ingard [21] showed that the mass inertial end correction decreased as the expansion ratio² decreased at low frequencies. This was due to the fact that the finite expansion ratio modulates the plane acoustic wave scattering near the expansion interface. In the presence of a mean flow, the low frequency interaction between the vorticity shed from the smaller pipe edge and the acoustic waves was found to affect the mass inertial end correction significantly [22,23].

For a Helmholtz resonator with no mean flow passing through its neck, a fixed mass inertial correction length of $8R_h/3\pi$ (where R_h is the neck radius) has been used widely for unconfined openings either side of the neck [14,24,25]. A varying correction length can be used to account for different confinements [21]. In the presence of a mean flow, analytical models [14,26] based on Howe's model [6] neglect the vortex–sound interaction within the neck and assume unconfined openings on either side of the neck hole. More recent models based on the Cummings–Fant equation [27] use numerical solutions of Laplace's equation to obtain the hole Rayleigh conductivity in the absence of mean flow – they are thus able to consider the effects of any confinement on the Rayleigh conductivity in the absence of a mean flow [28,29]. These models assume that the frequencies of interest are sufficiently low for the “wavelength” of the vorticity variations along the vortex sheet to be large compared to the hole length and radius. This implies that there is no need to consider vorticity variations or detailed vortex–sound interaction inside the hole or downstream of it, allowing the vorticity induced force term to be linearised using a quasi-static approximation [27–30]. Other commonly used empirical models also neglect vortex–sound interaction within the neck and assume unconfined openings either side of it [3]. The analytical model developed in [19] uses cylinder Green's functions to calculate the acoustic field within and either side of a hole. It is therefore highly suitable for studying the effect of confined space on the overall acoustic response of short holes.

For holes opening to very large spaces (for example, the holes of perforated liners or screens [1,2,4,16,18]), the above cylinder Green's function method requires a very large number of Fourier–Bessel expansion modes to be retained to accurately capture the acoustic scattering and vortex shedding, making the model complex. As the predicted acoustic response converges with expansion ratio for large expansions, model simplification for large expansion ratios would be attractive.

² In this paper, “expansion ratio” denotes the ratio between the radii of the large and the small coaxial cylinders which are connected at a sudden expansion interface.

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