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Strouhal number dependency of the aero-acoustic response of wall perforations under combined grazing-bias flow

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ABSTRACT

The influence of low Mach number grazing-bias flow on the linear acoustic response of slit shaped wall perforations is determined in terms of a dimensionless acoustical impedance for Strouhal numbers based on the perforation width of order unity. The influence of edge geometries is studied by experiments. In particular, slanted slits under an angle of 30° with respect to the grazing flow direction are considered. Sound production, i.e. whistling potentiality corresponding to a negative real part of the impedance, is observed for various geometries and flow conditions. Sound production restricts the largest perforation size which can be used in practice for acoustical liners. Whistling in the limit cases of purely bias and purely grazing flows can be explained qualitatively in terms of Vortex Sound Theory. For combined bias/grazing flow, most of the oscillations in the impedance as a function of the Strouhal number are related to these limit behaviours. A configuration with thin sharp edges both upstream and downstream corresponds to commonly used theoretical models assuming an infinite thin wall. This configuration displays a behaviour drastically different from a more realistic perforation geometry with sharp square edges.

1. Introduction

Perforated walls are often used as acoustical liners [1]. In Micro-Perforated Plates [2,3] the size of the perforations is comparable to the Stokes viscous boundary layer thickness. Acoustic wave dissipation is dominated by viscous effects within the perforations. We consider here larger wall perforations. In that case dissipation is mainly due to vortex shedding [4]. At low amplitudes of the acoustic perturbations, in the linear regime, this vortex shedding is a consequence of the modulation of the steady main flow by acoustical forcing at the points where flow separation occurs. Vortex Sound Theory [5–7] predicts that sound absorption will be most effective at sharp edges. Hence, one expects the geometry of the edges of the perforations to be essential for the sound absorption performance of liners. The studies of Heuwinkel et al. [8] and Kooijman et al. [9] confirm this. Furthermore, Vortex Sound Theory [5,6,10] predicts that shed vortices do not only absorb sound. Depending on the sign of the triple product $(\vec{\omega} \times \vec{v})\cdot\vec{u}\,'$, the vorticity $\vec{\omega} = \nabla \times \vec{v}$ in a flow field $\vec{v}$ can produce or absorb

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sound as a result of its interaction with the acoustic velocity field $\vec{u}\,'$. The acoustic velocity $\vec{u}\,'$ is defined by Howe [5] as the unsteady component of the flow velocity $\vec{v}$, which can be described by a scalar potential. At low Mach numbers a net sound production is found when the time average of the acoustic power $\langle P \rangle = -\rho_0 \int_V \left\langle (\vec{\omega} \times \vec{v})\cdot\vec{u}\,' \right\rangle dV$ is positive, where the brackets $\langle\ldots\rangle$ indicate time averaging and the volume integral is taken over the volume V in which $\vec{\omega}$ is non-vanishing.

Using the approximation of Howe described above, one can explain the whistling of nozzles [11], human whistling [10,12] and whistling of orifices due to bias flow [13–16]. For orifices with sharp orthogonal edges, there appear to be critical Strouhal numbers $Sr_H = fH/U_B \simeq 0.2$ and $Sr_H \simeq 0.6$ based on the wall thickness H, frequency f and bias velocity U_B for maximum whistling potentiality [13,15]. Flow visualization of the vortex shedding within a whistling orifice is provided by Karthik et al. [14]. Recently numerical simulations of the aeroacoustical response of orifices with pure bias flow have been carried out [17–22]. Such simulations are still quite computationally demanding. The availability of experimental data remains essential to check the physical relevance of such calculations.

The whistling of a resonator due to a grazing flow was also explained in terms of Vortex Sound Theory [7,23,24]. Whistling occurs for pure grazing flow at Strouhal numbers $Sr_W = fW/U_G \simeq 0.4$, based on the perforation width W in the direction of the grazing flow U_G. The exact value of this Strouhal number depends among others on the depth of the cavity and the ratio of boundary layer momentum thickness θ to perforation width W [25,26]. In early literature, the sound production was qualitatively explained as a result of the impingement of the vortices on an edge [27]. The Vortex Sound Theory provides a more quantitative description. In particular, it indicates that vortex shedding at a sharp edge will induce a strong absorption of acoustic energy due to the singularity of the potential flow (acoustic flow $\vec{u}\,'$) at the edge. This absorption will for example be stronger at a sharp edge with a small angle than for a square edge with a $\pi/2$ angle, because the singularity increases with decreasing edge angle. Hence, rounding-off or chamfering this edge should decrease its sound absorption characteristics. Rounding of the upstream edge results indeed into a strong increase of whistling amplitude for the case of grazing flow along a cavity [7,28]. In some cases the vortex will not impinge at all on a downstream wall. Aeolian tones due to vortex shedding in the wake of blunt bodies in cross-flow [29,30], human whistling [12] and sound production by a flow through a horn [10,31] are extreme examples of this, indicating that sound production is not necessarily due to an "impingement" of the vortices on a downstream wall or edge. The influence of the geometry of the orifice on the whistling of a Helmholtz resonator in grazing flow has been studied by Panton et al. [32] and Dequand et al. [24]. Their results can be qualitatively explained on the basis of the Vortex Sound Theory. The ratio u'/u_G of the acoustic velocity amplitude u' in the orifice (due to whistling of a Helmholtz resonator) to grazing flow velocity u_G is less than 0.1 for edge angles less than $\pi/2$ while one reaches 0.6 for rounded edges [24]. The present work considers the linear response of the flow to acoustical forcing rather than self-sustained oscillations. The influence of the orifice geometry on the linear response to acoustical forcing of a wall perforation in grazing flow was studied by Kooijman et al. [9]. His results clearly show hydrodynamic critical Strouhal numbers for strong whistling potentiality. Analytical models for the prediction of the linear response of an orifice to acoustic forcing have been proposed by Howe [16], Howe et al. [33] and Grace et al. [34,35]. An asymptotic analysis of the acoustic response of perforated plates backed by a cavity at low and high Strouhal numbers was described by Scarpato et al. [36,37]. Numerical simulations of the aeroacoustic response of an orifice in pure grazing flow have been carried out by Toulorge [38] using a linear model, and by Dai [39] and Zhang and Bodony [40] based on non-linear models. These models do provide insight, but do not predict accurately the response of orifices in pure grazing flow [9].

Some experimental data on the damping performance are available for different types of acoustic liners with combined bias and grazing flows and various perforation geometries, porosity and distribution of the perforations of the liner [41–43]. In the present study, a combination of bias and grazing flows is considered for a single wall perforation. The fact that we focus on single perforations is a significant limitation of the validity of the present results to the case of perforated walls as used in liners or mufflers. When considering a perforated wall, one should be aware of possible interactions between perforations. In the case of pure bias flow and normal acoustic wave incidence the interaction between perforations has the same effect as the confinement of an orifice within a pipe. This effect is discussed for low frequencies by Hofmans et al. [44], Durrieu et al. [45], and Tayong et al. [46]. In the case of pure grazing flow, strong hydrodynamic interaction has been observed between perforations for a wall liner consisting of an array of resonating quarter wavelength tubes [47–49]. This can be related to the instability of a grazing flow along a locally reacting impedance wall predicted by Vilenski and Rienstra [50]. Long range hydrodynamic instabilities were also observed by Ozalp et al. [51] for a perforated plate covering a large cavity. The large porosity of the plate in these experiments could explain this spectacular effect [51]. For a row of Helmholtz resonators aligned normal to the flow direction acoustic synchronization has been observed by Flynn and Panton [52]. Oscillation of neighbouring resonators appears to be in the opposite phase, this reduces the radiation losses of the resonators. Two acoustic modes (oscillation in phase or in opposite phase) and hydrodynamic interaction have been observed in experiments on Helmholtz resonators in tandem configuration: a pair of resonators in close proximity aligned with the grazing flow [53]. In this tandem configuration, the choice of the oscillation mode, in- or out-of-phase, can be determined by perturbation of the grazing flow upstream or downstream of the resonators. Strong hydrodynamic interaction was also observed between coaxial axisymmetric cavities placed along a pipe at distances comparable to the width of the cavity opening [54].

In acoustic liners for aircraft engines one often uses circular sharp edged perforations with an axis normal to the wall and a diameter comparable to the wall thickness [8,55]. Typically, the flow is a pure grazing flow. It is however interesting to

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