



# Measurements and computational fluid dynamics predictions of the acoustic impedance of orifices



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## ABSTRACT

The response of orifices to incident acoustic waves, which is important for many engineering applications, is investigated with an approach combining both experimental measurements and numerical simulations. This paper presents experimental data on acoustic impedance of orifices, which is subsequently used for validation of a numerical technique developed for the purpose of predicting the acoustic response of a range of geometries with moderate computational cost. Measurements are conducted for orifices with length to diameter ratios,  $L/D$ , of 0.5, 5 and 10. The experimental data is obtained for a range of frequencies using a configuration in which a mean (or bias) flow passes from a duct through the test orifices before issuing into a plenum. Acoustic waves are provided by a sound generator on the upstream side of the orifices. Computational fluid dynamics (CFD) calculations of the same configuration have also been performed. These have been undertaken using an unsteady Reynolds averaged Navier–Stokes (URANS) approach with a pressure based compressible formulation with appropriate characteristic based boundary conditions to simulate the correct acoustic behaviour at the boundaries. The CFD predictions are in very good agreement with the experimental data, predicting the correct trend with both frequency and orifice  $L/D$  in a way not seen with analytical models. The CFD was also able to successfully predict a negative resistance, and hence a reflection coefficient greater than unity for the  $L/D = 0.5$  case.

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## 1. Introduction

Perforated liners are used to absorb unwanted sound within engineering applications that can range from architectural acoustics to use within internal combustion or aircraft engines. Furthermore, depending on the application the incident acoustic energy may be in the form of plane waves (of a specific frequency) or more broadband. With no bias (or mean) flow through the liner there are no damping mechanisms associated with the linear acoustic equations and so sound dissipation is nonlinear [1]. In other words the energy absorbed, relative to the incident acoustic energy, is not constant. Alternatively in many applications a mean (or bias) flow through the aperture may be introduced. This can improve the amount of acoustic energy absorbed and/or may be required to protect the mechanical integrity of a liner in harsh operating environments (e.g. in high temperature regions such as present within an internal combustion engine or the afterburner duct of a gas turbine

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engine). If the amplitude of the incident wave is not high enough to induce reverse flow through the liner, the absorption is typically linear (i.e. the absorbed energy relative to the incident acoustic energy is constant). In such a case the ratio between the fluctuations of pressure and flow rate across the perforated liner is a constant complex number. This is generally referred to as the acoustic impedance, and in the linear regime, this is independent of the amplitude of pressure fluctuation. This paper is concerned with the linear absorptive properties of a range of aperture geometries with bias flow in the presence of plane incident waves.

An approach is required that accurately captures the flow mechanisms and absorption properties of aperture geometries that are typically used within engineering applications. For the approach to provide a useful design tool it must be capable of providing results within a relatively short time frame (e.g. days) and, in the long term, must be capable of applying to a whole range of aperture shapes and sizes. In this paper experimental and computational methods are presented that have been used to obtain the acoustic impedance of circular orifices subjected to incident plane acoustic waves over a range of frequencies. The results from these methods are then presented for comparison. This is done for apertures of length to diameter ratio 0.5, 5 and 10. This is thought to reflect the range of geometries likely to be encountered in practice. It includes cases in which the flow forms a vena-contracta downstream of the aperture ( $L/D = 0.5$ ) to flow reattachment inside the aperture, with the flow then remaining attached over a significant portion of the aperture length ( $L/D = 10.0$ ). The numerical method employed here uses unsteady Reynolds Averaged Navier–Stokes (URANS) modelling to produce time resolved simulations of the unsteady flow induced by the acoustic waves. Before describing the experimental and numerical methods in detail, we first discuss the relative advantages of the numerical methods available.

It is typically assumed that the apertures within a porous plate are sufficiently separated so they behave as if operating in isolation. In this way the various investigations undertaken on a single orifice can be used to help understand the performance of perforated liners. For example Howe [2] developed an expression for the Rayleigh conductivity of an aperture through which a high Reynolds number bias flow passed. The theoretical model provided an exact analytical solution for an infinitely thin aperture. This was based on the harmonic pressure difference across the aperture causing the unsteady shedding of vorticity from the aperture rim. In this way acoustic energy is converted into turbulent flow energy that is subsequently dissipated as heat. This has been used as the basis for many predictions relating to perforated liners, for example [3,4] and Rupp and Carrotte (2011) [5]. However, for practical engineering applications the aperture must be of finite thickness (or length) and so an additional term was typically included. As indicated by [3] the thickness of the aperture (or its effective acoustic length) can be crucial in determining the performance of the aperture. However, it should be acknowledged that in many engineering applications the aperture length will significantly affect the flow field that is inherent to the model developed by Howe. For example, downstream of an infinitely thin orifice the flow will form a vena-contracta, but at greater orifice length to diameter ratios (e.g.  $L/D > 2$ ) the flow reattaches inside the aperture. The mechanisms by which acoustic energy is absorbed will therefore be affected and the addition of a single term to capture this may be somewhat simplistic. Alternative strategies to those based on Howe include, for example, the use of a momentum balance across the aperture such as that outlined by Bellucci et al. [6]. In this case the model requires an aperture loss (or discharge) coefficient, along with an effective length, to enable the prediction of damping performance. The limitations associated with both of the above approaches are reflected in the fact that in conjunction with an effective length, the discharge coefficient that provides the best match with experimental acoustic absorption measurements does not often agree with the experimentally measured discharge coefficient obtained from the mean flow [7]. Zhong and Zhao devised a time-domain numerical tool for acoustic damping of a perforated liner with bias flow by transforming the frequency-domain analytical models into the discrete time-domain through z-transform [8]. Satisfactory agreements with the experimental data were obtained. However, as this method is based upon a 1D acoustic wave model, a suitable analytical model must already be known. This approach will have the limitations associated with such a model in that its use is restricted only to those flows for which the assumptions behind the model are valid.

CFD methods offer an attractive solution for predicting acoustic behaviour, as CFD calculations of mean flow fields are already a routine part of engineering design. Linearised methods for calculating acoustic behaviour have been used, for example Gikadi et al. [9] used this method to investigate a swirl burner. They used a technique whereby a RANS simulation was produced of the steady field before a method using Linearised Navier–Stokes Equations (LNSE) was used to find the magnitude and phase of reflected and transmitted waves through a swirler. The LNSE part of the calculation was carried out using a finite element method using a much coarser mesh than the RANS calculation.

Time resolved CFD methods offer the ability to reveal details of the unsteady flow as well as removing some modelling assumptions. Orifice flows of engineering interest will typically be at Reynolds numbers where the flow is turbulent. This turbulence will both determine the behaviour of the mean flow and play a key role in dissipating the energy put into the flow by acoustic forcing. As with the simulation of any turbulent flow a choice must be made as to how to treat this turbulence. At one extreme is the approach of using Direct Numerical Simulation (DNS) to resolve all temporal and spatial scales of turbulence. Zhang et al. performed DNS to study the acoustically excited flows through a circular orifice backed by a hexagonal cavity [10]. Accurate results were obtained up to a frequency of 2.5 kHz. Tam et al. also used DNS in their numerical investigation of resonators in three dimensions [11]. By virtue of its high-fidelity non-modelling approach, DNS is able to reproduce the small scale details of acoustic phenomena (such as dissipation mechanisms) accurately, even for high frequency ranges. However, the computational resources required by DNS limited both Zhang and Tam's works to only a small number of data points. For studies in lower frequency ranges (e.g. the one considered in the present work) the computational cost is expected to be excessively high. Another popular choice for academic research is Large Eddy Simulation (LES) in which the smaller spatial scales of

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