Multi-modal noise generation in low Mach number orifice plates: An experimental investigation

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Keywords: Duct Acoustics, Orifice Plates, Higher-Order Acoustic Modes

Abstract. An experimental campaign on aerodynamic noise generation by orifice plates in rectangular ducts for low Mach number flows is carried. The test plant allows for the measurement of the total emitted acoustic power both upstream and downstream of the orifice plates for varying mass flow rates through the 2N-Port method. A modal decomposition for the first eight propagating higher-order acoustic modes is also performed. Keeping the free flow area and the plates' thickness constant, the tests allowed for a study of the influence of the number of circular orifices on the generated acoustic power as well as its modal composition. It is found that the orifices' number does not influence the overall pressure drop caused by the presence of the obstacle. The generated noise on the contrary is greatly affected by such a parameter both for the plane-wave frequency range and especially so in the multi-modal one.

Introduction

Heating, Ventilation and Air Conditioning (HVAC) systems play a fundamental role in ensuring a safe and comfortable environment in both buildings and vehicles. Part of the requirements for such systems is that they generate as less noise and vibrations as possible during operation. Amongst the various components concurring to the production of noise (e.g., fans, compressors…), flow singularities in ducts are one of the most common sources [1]. The flow is usually in the turbulent incompressible regime with very low Mach numbers ($Ma < 0.1$). In undisturbed flows (e.g., sufficiently long straight ducts), sound is aerodynamically generated by the turbulent boundary layer, and it is propagated inside the duct [2]. Whenever a singularity is present (e.g., valves, bends) intense turbulence is produced in its vicinity as the flow detaches from the ducts' walls. Part of the turbulence kinetic energy is converted into sound, which reaches largely higher values than in the case of undisturbed flows [3]. In unconfined low Mach number flows, previous studies have shown that in the presence of fixed surfaces noise generation can be predicted once the pressure fluctuations on such surfaces are known [4]. This amounts to equating the noise generation mechanism to a distributed dipole source. Addition of confinement (as in ducts) further modifies such noise generation mechanism. In particular, the fact that sound propagates in higher-order (or transversal) modes from a given cut-on frequency onwards fundamentally changes the propagation mechanisms compared to unconfined free-field conditions [5]. Obstacles perpendicular to the flow have received much attention due to their relatively simple geometry as well as their widespread use in duct systems (e.g., spoilers, orifice plates). A successful theory has been developed for aerodynamic noise prediction in the plane-wave frequency range by assuming that the pressure fluctuations over the obstacle's surface be proportional to the total drag force acting on it [6,7]. Attempts at models involving higher-order acoustic modes have been however somewhat less conclusive. Recent experimental work has shed more light on the phenomenon by directly measuring the fluctuating pressures over both sides of a circular orifice plate perpendicular to the flow [8]. It was found that the intensity of the pressure fluctuations was highest in the immediate vicinity of the orifice's edge, after which an exponential decrease was observed.

In the present paper, the results of an experimental investigation on noise production by ducted orifice plates are presented. The tests were performed at the Roberval Laboratory of the University of Technology of Compiègne (France), where an experimental bench allows for the measurement of the total internal aerodynamically generated acoustic power as well as its modal decomposition in the propagating higher-order acoustic modes through the 2N-port method [9]. The remainder of the paper is structured as follows. The basic theory of sound propagation in ducts and of aerodynamic sound production in ducts is first recalled. The experimental test plant is then briefly described, together with the tested orifice plate geometries. Finally, the results of the tests on the plates are discussed and some conclusions are drawn.

Theory

Acoustic pressure waves in ducts travel with a constant amplitude distribution over the cross-section until a particular "cut-on" frequency is reached. Above that, waves with a non-uniform sectional pressure distribution propagate alongside the plane wave form. The cut-on frequencies are usually referred to as f_{mn} where the subscripts m and n refer to the number of nodal lines along a particular direction depending on the type of cross section. For an obstacle inserted perpendicularly to a ducted low Mach number flow, the Fourier transform of the aerodynamically generated acoustic pressure in a point $(x_1, x_2. x_3)$ can be expressed as [10]:

$$\hat{p}(x_1, x_2, x_3) = \sum_m \sum_n \frac{1}{2A} \rho_0 \hat{c}_{mn} \psi_{mn}(x_1, x_2) e^{-i\hat{k}_{mn}x_3} \hat{Q}_{mn} \tag{1}$$

where A is the duct's area, ρ_0 is the density of the medium at rest, $\hat{c}_{mn} = 2\pi f / k_{mn}$ is the modal phase velocity, ψ_{mn} is the modal shape function of the duct, $\hat{k}_{mn}$ is the axial modal wave number and $\hat{Q}_{mn}$ is a coefficient which takes into account the coupling between the fluctuating force spatial distribution and the ducts' modal shape function. The expression of such a coefficient for the present case is [6]:

$$\hat{Q}_{mn} = \frac{1}{\hat{c}_{mn}} \int\int_{A_s} \hat{f}_3\,(x_1', x_2') \psi_{mn}(x_1', x_2') e^{i\hat{k}_{mn}x_3} dA \tag{2}$$

where $\hat{f}_3$ is the Fourier transform of the net fluctuating perpendicular force per unit area and per unit density over the obstacle's surface A_s. This expression shows that the value of the coefficient $\hat{Q}_{mn}$, and therefore of $\hat{p}$ through (1), increases the more the distribution of $\hat{f}_3$ follows that of the modal shape function ψ_{mn}.

Experimental setup

The experimental set-up for the results discussed in the present paper was conceived for the acoustic characterization and the estimation of noise emissions of HVAC components through the 2N-port method. Such experimental plant was used in several other publications on the subject (e.g., [2]) and the reader is referred to [9] for a more complete description both of the plant and of the 2N-port method.

The setup consists of a duct of rectangular cross section of width b equal to 200 mm and height h of 100 mm. Its total length is 4.1 m and anechoic terminations on both sides allow for a removal of end reflections starting from a frequency of 100 Hz. For such a cross section and neglecting the effect of the flow, the cut-on frequencies are computed from $f_{mn} = 1/c\sqrt{(m\pi/b)^2 + (n\pi/h)^2}$. The modal shape functions are instead given by $\psi_{mn} = N_{mn}\cos(m\pi x_1/b)\cos(n\pi x_2/h)$ with N_{mn} a normalizing factor ensuring that the average squared value of ψ_{mn} is 1 over the duct's cross section. The cut-on frequencies in the range of study [200 Hz, 3200 Hz] for the present configuration are reported in Table 1.

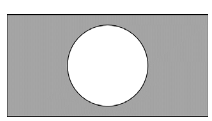
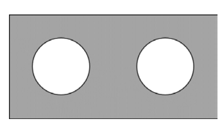
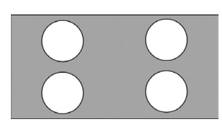
Table 1 - Cut-on frequencies

Mode (m,n)	(0,0)	(1,0)	(2,0)	(0,1)	(1,1)	(2,1)	(3,0)	(3,1)
f_{mn} **[Hz]**	0	849	1717	1717	1920	2428	2575	3095

Air is supplied to the system through a centrifugal fan powered by a variable-speed electric motor connected to a frequency handle for flow regulation. To reduce the disturbances by the machine, an in-line silencer is placed before a stabilization tank which is itself needed to compensate for the fluctuations of the incoming flow. The mass flowrate is then measured through a Venturi-like flow meter. Static pressure and temperature are also recorded at the stabilization tank through a pressure transducer and a Pt-100 RTD probe respectively. A total of 96 condenser microphones of 1/4" diameter is flush mounted along the duct between the two anechoic terminations in couples of twelve along a given cross-section, four of which upstream and four downstream of the mounted obstacles.

Three different orifice plate geometries have been experimentally tested. The flow to duct area ratio A_{flow}/A and the plates' thickness have been kept as constant for all three cases and equal to 0.25 and 8 mm respectively. The shape of the applied orifices was chosen as circular to avoid corners; all are sharp-edged. Table 2 reports the geometry of the tested orifices as well as their identification strings and the diameters of the applied holes d_h.

Table 2 - Orifice plate geometries

Plate ID	A1	A2	A4
Geometry			
d_h **[mm]**	80	56	40

Results

A preliminary measurement campaign was performed to characterize the pressure drop Δp_R caused by insertion of the orifice plates into the duct. This was necessary to understand whether differences in noise emissions could be due to such a factor, as previous literature highlights its importance. The pressure drop was measured varying the mass flowrate and keeping the outlet pressure at atmospheric level as the duct discharges into the outside environment. Figure 1 reports a dimensional and a nondimensional plot of the pressure drop due to the added resistance as a function of the mass flowrate. The nondimensionalization of Δp_R was made by computing the total drag force acting on the plate as $\bar{F}_3 = \Delta p_R A$ and expressing it in terms of a drag coefficient C_d as $\bar{F}_3 = 0.5\,\rho_0 U^2 C_d A_S$ where U is the average velocity of the flow in the axial direction. The Reynolds' number is defined as $Re = \rho_0 U D_h/\mu$ with D_h the hydraulic diameter of the duct ($D_h = 4A/P$, with P the duct's cross section perimeter). The pressure drop (or the drag coefficient) shows a weak dependence on the geometry of the plates having kept constant the flow area and the plates' thickness, with the A2 plate indicating a slightly higher resistance to the flow.

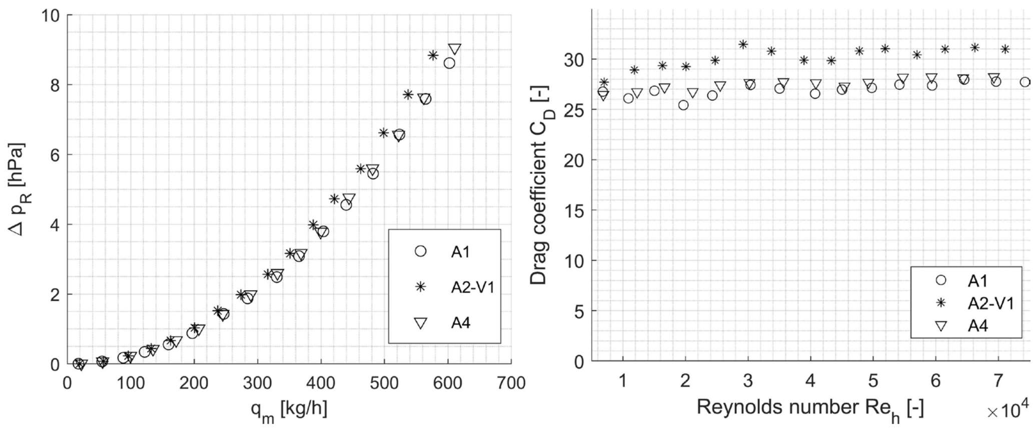


Figure 1 - (left) Pressure drop versus mass flowrate and (right) drag coefficient versus Reynolds' number.

The sound power level (SWL) in fine bands (Δf = 1.76 Hz) produced by the three orifice plates at a section 15 cm upstream of it for a mass flowrate of 505 kg/h (corresponding to a maximum local Mach number of ≈ 0.1) is reported in Figure 2. Differences of more than 10 dB are observed between, with the A2 plate producing the lowest noise and the A4 the highest outside of the plane-wave range. The A1 plate is particularly sensitive to the onset of certain higher-order modes (e.g. (2,0) and (1,0) modes). The modal decomposition of the SWL for the same tests resulting from application of the 2N-port method are reported in Figure 3. The amplitude of a given higher-order mode (m,n) in comparison to the corresponding plane-wave mode (0,0) depends greatly on the orifice plate geometry. The (2,0) mode for example has a higher value than its plane-wave counterpart for the A1 plate, a slightly lower value for the A2 plate and a much lower value for the A4 plate. Again, the (1,0) mode displays a relative amplitude with respect to (0,0) lower for the A1 geometry and essentially equal for the two plates A2 and A4.

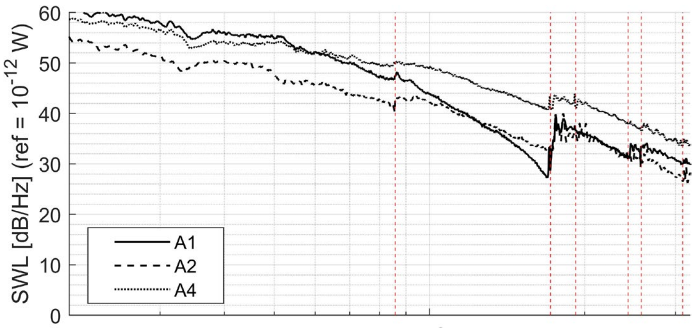


Figure 2 - Total upstream sound power level at 505 kg/h for the three geometries tested. Cut-on frequencies are highlighted as dashed red lines.

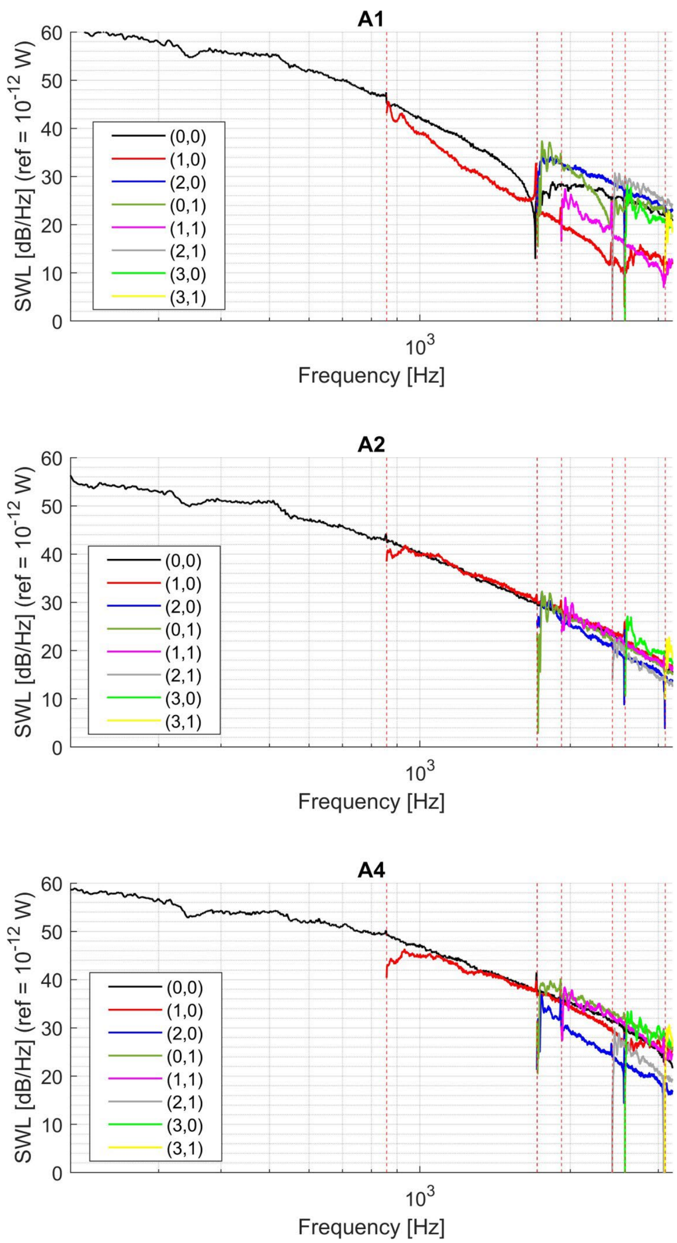


Figure 3 – Modal decomposition into propagating higher-order acoustic modes of the sound power level (SWL) for the different orifice plates tested at 505 kg/h. Cut-on frequencies are highlighted as dashed red lines.

Conclusions

In the present short paper, it has been shown that keeping a fixed flow area and plate thickness, the pressure drop caused by a low Mach number flow through circular-shaped sharp-edged orifices in a rectangular duct does not vary appreciably if the number of the holes is changed. On the contrary, the total emitted acoustic power is very sensitive to such parameter. A modal decomposition of such acoustic power into the first eight propagating higher-order acoustic modes has then been performed. It has been found that the contribution of a given higher-order acoustic mode (m,n) relative to the plane-wave mode (m,n) greatly varies depending on the plate geometry.

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