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Numerical and experimental investigation of flow-acoustic resonance of side-by-side cylinders in a duct

Atef Mohany [a],*, David Arthurs [a], Michael Bolduc [b], Marwan Hassan [c], Samir Ziada [b]

[a] University of Ontario Institute of Technology, Oshawa, Ontario, Canada
[b] McMaster University, Hamilton, Ontario, Canada
[c] University of Guelph, Guelph, Ontario, Canada

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ABSTRACT

The phenomenon of flow-excited acoustic resonance is a design concern in many engineering applications, especially when wakes of bluff bodies are encountered in ducts, piping systems, heat exchangers, and other confined systems. In this paper, the case of self-excited acoustic resonance of two side-by-side cylinders in a duct with cross-flow is investigated both numerically and experimentally for a single spacing ratio of $T/D=2.5$, where D is the diameter of the cylinders and T is the centre-to-centre distance between them. The numerical investigation is performed using a finite-volume method at a Reynolds number of 3.0×10^4 to simulate the unsteady flow field, which is then coupled with an imposed resonant sound field of the first acoustic cross-mode of the duct calculated through the use of Finite Element Analysis (FEA). The experimental investigation has been performed using phase-locked Particle Image Velocimetry (PIV) of the flow field during the occurrence of a self-excited acoustic resonance condition in the duct. The results of both methods reveal that the flow-excited acoustic resonance produces a strong oscillatory flow pattern in the cylinder wakes, with strong in-phase vortex shedding being synchronized by the acoustic resonance. The distribution and strength of the aeroacoustic sources and sinks within the flow field have been computed by means of Howe's theory of aerodynamic sound for both the experimental and numerical cases, with the results of the two methods comparing favourably, showing comparable trends in the oscillating flow fields, and very similar trends in the distribution of net acoustic power.

1. Introduction

The phenomenon of flow-excited acoustic resonance, where fluid flow separated from bluff bodies couples with a resonant sound field of the volume enclosing the flow, is a design concern in many engineering applications such as tube bundles of heat exchangers and boilers, and cascades of compressor blades. This phenomenon can result in the excitation of intense self-excited noise and vibration, with fluctuating pressures often being several times the dynamic head in the main

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* Corresponding author.
E-mail address: atef.mohany@uoit.ca (A. Mohany).

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Nomenclature

c	speed of sound in air [343 m/s]
C_L	lift coefficient
C_D	drag coefficient
D	cylinder diameter [mm]
f_r	resonance frequency of the duct [Hz]
f_v	vortex shedding frequency [Hz]
h	height of the duct [m]
M	Mach number [U_o/c]
P_a	acoustic pressure distribution [Pa]
P_{RMS}	RMS acoustic pressure [Pa]
P^*	dimensionless pressure
Re_D	Reynolds number
SPL	sound pressure level [dB *re*: 20 μPa]
St_D	Strouhal number
T	transverse cylinder spacing [mm]
T/D	transverse cylinder spacing ratio
$\overrightarrow{u_a}$	acoustic particle velocity vector field [m/s]
$\overrightarrow{U}$	flow velocity vector field [m/s]
U_o	upstream flow velocity [m/s]
U_r	reduced velocity
$\overrightarrow{\varpi}$	vorticity vector field [1/s]
Π	acoustic source intensity [W/m^3]
ρ	density of air [1.204 kg/m^3]

flow, and may result in reduced efficiency and decreased component life due to vibration and fatigue failure. These flow-excited acoustic resonance conditions occur due to a coincidence of the vortex shedding frequency (f_v) and a resonant acoustic mode of the duct surrounding the cylinders (f_r), as shown in the schematic of Fig. 1. This process can result in a *lock-in* phenomenon, where the vortex shedding process is synchronized and enhanced by the sound field, and is found to occur at the resonant frequency of the duct over a significant range of flow velocity. The resonant sound field has the effect of triggering and enhancing the discrete frequency vortex shedding process occurring in the wake, with the vortex shedding acting as an amplifier, and the resonant sound field acting as a filter (Tonon et al., 2011). These two phenomena form a feedback mechanism in which the unsteady flow and sound fields augment one another, producing intense pressure pulsations in the duct, and strong self-excited flow oscillation in the wake. While this phenomenon is relatively well understood for the case of isolated cylinders (Blevins, 1985; Mohany and Ziada, 2005; Mohany, 2012), there are many unresolved issues for the more complex case of multiple cylinders in close proximity.

Mohany (2012) and Mohany and Ziada (2009a–c) have used both experimental and numerical techniques to investigate the excitation mechanism of acoustic resonance for the case of two tandem cylinders in cross-flow, i.e. where the cylinders are staggered in the stream-wise direction, finding that the aeroacoustic response of this system is considerably different from that of a single cylinder under similar flow conditions. For the tandem cylinder case, the acoustic resonance is excited over *two* different ranges of flow velocity: the pre-coincidence and coincidence resonance regimes, with the behaviour of the acoustic sources being significantly different within each of these distinct regimes. In the coincidence case, the main aeroacoustic sources are located immediately downstream of the second cylinder, similar to that of a single cylinder, however in the pre-coincidence range, additional acoustic sources are found to be located in the gap *between* the cylinders.

Cross-flow over two side-by-side circular cylinders has likewise been a popular topic of research for some time, because of its relevance to many engineering applications cited earlier. It is generally recognized that the behaviour of these flows is strongly dependent on the spacing ratio between the cylinders (T/D), defined as the transverse centre-to-centre distance between the cylinders (T) normalized by the cylinder diameter (D), and to a lesser extent, on the Reynolds number (Re_D). Many authors examining this geometry have observed a bistable flow phenomenon (Bearman and Wadcock, 1973; Kim and Durbin, 1988) in the cylinder wakes for small and intermediate spacing ratios, shown in the schematic in part (b) of Fig. 2, with these bistable flows being characterized by a wide wake region behind one cylinder, and a narrow wake region behind the other. These wide and narrow wakes have been found to intermittently switch between the two cylinders in an aperiodic fashion, and with the two separate wakes having been found to produce two individual vortex-shedding frequencies, with the higher frequency being associated with the narrow wake, and the lower frequency being produced by the wider wake (Hanson et al., 2009; Sumner et al., 1999). These results are summarized schematically in part (a) of Fig. 2, which has been recreated from the results of Sumner et al. (1999).

Mohany et al. (2011) conducted a numerical investigation of the flow-excited acoustic resonance for two side-by-side cylinders in cross-flow with a small cylinder spacing ratio of $T/D=1.25$. Before the excitation of acoustic resonance, the authors observed a bistable flow regime in the wake structure behind the two cylinders, with Strouhal numbers of $\mathrm{St}_D=0.24$ and $\mathrm{St}_D=0.11$ corresponding to vortex shedding in the narrow and wide wakes, respectively. Upon application of a resonant sound field at the first cross-mode of the duct, the flow-field was found to become synchronized to the applied acoustic field, showing synchronized vortex shedding for both cylinders at an intermediate Strouhal number between those observed prior to the onset of acoustic resonance, and with the numerical results comparing favourably with experimental acoustic measurements of Hanson et al. (2009), though no comparison of the flow fields was given for this case.

In his work on aerodynamic noise, Howe (1975) reformulated Lighthill's (1952) aerodynamic theory of sound to include the effects of a non-uniform mean flow on sound generation, concluding that acoustic sources within a given flow correspond to regions of non-zero vorticity. Howe (1980) later established a general expression to estimate the rate at which acoustic energy is produced per acoustic cycle due to interaction between the flow field, namely the flow velocity and vorticity fields, and the acoustic particle velocity of the sound field. This expression, given in Eq. (1), is the triple product of the instantaneous vorticity ($\overrightarrow{\varpi}$), flow velocity ($\overrightarrow{U}$) and acoustic particle velocity ($\overrightarrow{u_a}$) vector fields, where ρ is the mean fluid