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Experimental investigation of a cylindrical cavity in a low Mach number flow

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ABSTRACT

The aeroacoustics of a cylindrical cavity with aspect ratio (Depth/Diameter) 1.357 is investigated through experimental measurements conducted in a low speed recirculating wind tunnel. The aim of the study is to characterize the velocity field outside of the cavity and to determine the major acoustic modes influencing both the velocity and the wall pressure statistics. Aerodynamic and wall pressure measurements are carried out at different Reynolds numbers using a hot wire anemometer and wall mounted microphones. The reattachment region of the shear layer and the presence of the vortices in the wake region are identified. Pressure and velocity Fourier spectra evidenced the presence of three resonance modes at frequencies well predicted by classical theoretical formulations developed in literature for rectangular cavities. Results obtained through a Finite Element (FE) simulation are in agreement with the measured lock-on frequencies. The effect of the flow structures upon the wall pressure statistics is evaluated by wall pressure measurements conducted in several positions over the cavity. By a separation of the wall pressure spectra into specific frequency bands, the nature (acoustic or hydrodynamic) of the dominant modes is identified. An overall description of the flow physics inside the cavity is proposed.

1. Introduction

Cavities exposed to grazing flows can be found in many industrial applications, especially in ground, air and maritime transportation. The research of the unsteady fluid mechanical phenomena generated by cavities includes, for instance, the study of the shear layer developing from the upstream edge of the cavity, the consequent vortex shedding and the generation of recirculation zones. These phenomena play a relevant role into the generation of noise, drag, pressure fluctuations and structural vibrations.

To date, most of the studies have focused on rectangular cavities and little attention has been given to cylindrical cavities despite their widespread use in aerospace applications: pressure relief valve of the fuel vents, circular anti-icing vent holes, cylindrical landing gear wheel wells are only a few examples among many. The purpose of the present work is to gain knowledge on the flow physics of a cylindrical cavity mounted in a wind tunnel through velocity and wall pressure measurements.

From the aerodynamic viewpoint, it is known from literature that the generated flow depends on the cavity shape, and in the cylindrical case, exclusively on the aspect ratio H/D, where H and D denote, respectively, the depth and the diameter

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of the cavity. Gaudet and Winter (1973), Hiwada et al. (1983) and Dybenko and Savory (2008) showed that for aspect ratios between 0.2 and 0.8 the flow both inside the cavity and in its wake is asymmetric. Through the analysis of long pressure measurements, Hiwada et al. (1983) identified two different flow dynamics: a flapping flow for $H/D = 0.2–0.4$ and a switch flow for $H/D = 0.4-0.7$. For aspect ratios such as $H/D < 0.2$ or $0.8 < H/D$, the flow inside the cavity was found to be stable and symmetric.

From the viewpoint of the aeroacoustics, a relevant role is played by the so-called self-sustaining oscillations consisting in the coupling between a hydrodynamic mode of the shear layer and an acoustic mode of the cavity. This flow–acoustic mechanism has been extensively studied for rectangular cavities (see among many Rockwell and Naudascher, 1978, for a general review). Over the years, the semi-empirical formula proposed by Rossiter (1964) for the frequency prediction of the rectangular cavities oscillations has been subjected to small changes introduced after analytical developments (see for instance Bilanin and Covert, 1973; Block, 1976; Heller and Bliss, 1975; Howe, 1997). Usually, the characteristic length chosen to nondimensionalize the frequency is the length of the cavity in the streamwise direction. Since for cylindrical cavities this dimension is not constant Bruggeman et al. (1991) and Czech et al. (2006) introduced their own expressions for the effective length of the cavity in order to accommodate Rossiter's formula.

Depending on the geometry of the cavity, the shear layer hydrodynamic modes can excite different acoustic modes. Plumblee et al. (1962) showed that in the case of shallow rectangular cavities the predominant excited acoustic mode is the lengthwise mode whereas for cavities of aspect ratio higher than unity the depth mode is the one excited. Ziada et al. (2003) noticed that when a shallow rectangular cavity is mounted in a wind tunnel closed test-section a flow–acoustic coupling can occur between the shear layer modes and the acoustic modes of the cavity-test-section. Alvarez and Kershen (2005) analytically evaluated the influence of the wind tunnel confinement on the acoustic resonances of two-dimensional cavities. Similar flow–acoustic coupling mechanisms exist in the case of coaxial side branches (Arthus and Ziada, 2009; Dequand et al., 2003; Oshkai and Yan, 2008; Ziada and Shine, 1999) or in the case of axisymmetric internal cavities mounted on pipes (Aly and Ziada, 2010). In order to avoid the influence of the closed test-section, Yang et al. (2009) studied a deep rectangular cavity mounted at the outlet of a duct. Similarly, Marsden et al. (2008) used an anechoic wind tunnel to investigate the coupling mechanism taking place between the shear layer modes and the depth acoustic modes of a cylindrical cavity of various aspect ratios.

In the present study, the analyzed cylindrical cavity has an aspect ratio of 1.357. The choice of the geometry was dictated by the need of reproducing typical geometries present on commercial aircraft. According to the above mentioned literature studies, the selected aspect ratio should guarantee the symmetry of the flow properties with respect to the streamwise wall-normal symmetry plane. In order to describe the flow field, the shear layer and the wake are investigated in a 3D volume surrounding the cavity. Inside the cavity, the dynamic is investigated through wall pressure measurements and a detailed statistical analysis is presented. As the cavity is mounted inside the closed test-section, the effect of the confinement on the shear layer modes is discussed therein. In addition to contribute to clarify of the flow physics, the data base achieved can also be considered as a useful test bench for the validation of numerical simulations of similar geometries (see e.g. Grottadaurea and Rona, 2008).

The experimental set-up and the flow conditions analyzed are presented in Section 2. The acoustic mode prediction is given in Section 3. Results concerning velocity measurements are given in Section 4 while Section 5 provides a spectral analysis of the cavity oscillations.

2. Experimental set-up

The experimental investigation has been conducted in a recirculating low speed wind tunnel designed by the Mechanical and Industrial Engineering Department (DIMI) of 'Roma Tre' University. The facility is located in the Italian National Agency for New Technology Energy and Environment (ENEA) research center of Cassacia, 28 km from Rome. The closed test-section is 2.49 m long and has a $0.89 \times 1.16\,m^2$ cross-section. The fan can generate flows ranged from 0 to 90 m/s in the centreline of the test-section with a relative turbulence level of 0.1% at a velocity of 40 m/s. Further details on the wind tunnel properties can be found in Camussi et al. (2006a, b). The background noise in the test-section has been characterized (Camussi et al., 2000). In particular, a tone of 300 Hz, which can also be identified in the present results (Section 5), has been ascribed to the constant speed fan installed for cooling the wind tunnel blower. However, it has been checked that the level of the background noise, including this tonal noise, at the walls of the cavity is lower than the pressure fluctuations generated by the cavity flow itself. This will be clarified in Sections 4 and 5 through the spectral analysis of the velocity and pressure data.

A Perspex cylindrical pipe with an interior diameter (D) of 210 mm was flush mounted to the bottom wall of the test-section, 1780 mm downstream the end of the convergent section. A flat Perspex disk sealed the cylinder from underneath, creating a 285 mm deep (H) cavity. These dimensions lead to cavity aspect ratio of 1.357 (Fig. 1).

The flow velocity in the test-section was monitored with a Pitot tube connected to a *Kavlico* pressure transducer model P592. The calibration of the transducer was done with a pressure pump and a U-tube manometer. Velocity fluctuations in the shear layer and in the wake of the cavity were measured with a 55P11 single component Dantec probe connected to a constant temperature hot-wire anemometer (A.A. Lab System AN-1003). To reach the desired positions, the probe was mounted on a 2D traverse system equipped with stepping motors (Rexroth Compact Module CKK).