Chinese Journal of Aeronautics, (2017), **xxx**(xx): xxx–xxx

CSAA

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Chinese Journal of Aeronautics

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Self-sustained oscillation for compressible cylindrical cavity flows

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Received 16 June 2016; revised 10 October 2016; accepted 18 October 2016

KEYWORDS

Cavity flow;
Compressible flow;
Convection velocity;
Open cavity;
Oscillation

Abstract The presence of a cavity changes the mean and fluctuating pressure distributions. Similarities are observed between a cylindrical cavity and a rectangular cavity for a compressible flow. The type of cavity flow field depends on the diameter-to-depth ratio and the length-to-depth ratio. The feedback loop is responsible for the generation of discrete acoustic tones. In this study, the self-sustained oscillation for a compressible cylindrical cavity flow was investigated experimentally. For open-type cavities, the power spectra show that the strength of resonance depends on the diameter-to-depth ratio (4.43–43.0) and the incoming boundary layer thickness-to-depth ratio (0.72–7.0). The effective streamwise length is used as the characteristic length to estimate the Strouhal number. At higher modes, there is a large deviation from Rossiter's formula for rectangular cavities. The gradient-based searching method was used to evaluate the values of the empirical parameters. Less phase lag and a lower convection velocity are observed.

1. Introduction

Cavities occur in a large number of flight vehicles.[1,2] Flow over a cavity changes the distributions of the mean and fluctuating pressures inside and near the cavity.[3–5] Near the front edge of a cavity, an unsteady pressure difference between the high-speed external flow and the vortex structure in the cavity is responsible for the generation of shedding vortices. When the shedding vortices propagate downstream and impinge the rear edge, there is a trailing edge vortex and acoustic waves. This induces high-intensity oscillation at predominant frequencies.[6–8] Tracy and Plentovich[9] investigated the flow characteristics of rectangular cavities with variable geometry at Mach numbers ranging from 0.2 to 0.95. Their results show the length-to-depth ratio, L/H, of a cavity is an important parameter to characterize cavity flows. A closed type cavity occurs for $L/H > 10–13$, in which the shear layer separates from the leading edge, attaches to the bottom of the cavity, and then separates again before the trailing edge. There is a strong streamwise pressure gradient along the cavity floor. For $L/H < 6–8$, known as an open-type cavity, the shear layer spans the entire cavity and the impingement of the shear layer around the rear corner of

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Peer review under responsibility of Editorial Committee of CJA.

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http://dx.doi.org/10.1016/j.cja.2017.05.013
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the cavity induces high pressure fluctuations. A transitional-type cavity exhibits combined characteristics of both open- and closed-type cavities. The boundaries between different types of cavity flow also depend on the cavity's width-to-depth ratio, the freestream Mach number, the Reynolds number, and the incoming boundary layer thickness.[4,9–11]

For an open-type cavity flow, the cavity can be classified as a shallow or a deep cavity, in which oscillation propagates in longitudinal and transverse directions. Rockwell and Naudascher[12] demonstrated the transition between longitudinal and transverse oscillation occurs at $L/H \approx 1$. For a shallow cavity, Rossiter[7] proposed that a feedback loop between vortex shedding and acoustic disturbance is responsible for the generation of discrete acoustic tones. Vortices shed periodically from the upstream lip of the cavity to the downstream end of the cavity. Acoustic pulses were then generated and propagated upstream inside the cavity. A semi-empirical formula is derived by Rossiter:

$$St_n = \frac{f_n L}{U_\infty} = \frac{n-\alpha}{Ma + 1/k_c} \qquad (1)$$

where n is the oscillation mode number for the corresponding Strouhal number, St_n. f_n and U_∞ are the oscillation frequency and freestream velocity, respectively. Ma is the freestream Mach number. α corresponds to the lag time between the passage of a vortex and the emission of a acoustic pulse. k_c is the ratio of the convection velocity of vortices to U_∞. The empirical parameters were determined by the measured data, in which $\alpha = 0.25$ ($L/H = 1, 2, 4$) and $k_c = 0.57$ for rectangular cavities.[7] However, Unalmis et al.[13] indicated that values of the empirical parameters depend on flow conditions and L/H. The suggested values of k_c range from 0.5 to 0.75[7,14,15] and $\alpha = 0.062(L/H)$.[16]

For cylindrical cavities, Hiwada et al.[17] found two unstable flow behavior, that is, flapping and switching, occurs at diameter-to-depth (D/H) = 1.43–2.5 and 2.5–5.0, respectively (U_∞ = 10–25 m/s). Dybenko and Savory[18] verified an asymmetric flow pattern inside cylindrical cavities ($D/H = 0.47$ and 0.7 at $U_\infty = 27$ m/s) and showed a significant pressure drop because of the asymmetric disturbance of upstream velocity or pressure profiles. Detailed information of the flow topology and the turbulent structure of the asymmetrical flow pattern inside a cylindrical cavity ($D/H = 2.0$ at $U_\infty = 12$ m/s) with stereo and tomographic particle image velocimetry is also presented by Haigermoser et al.[19] For oscillation characteristics in cylindrical cavities, previous studies[18,20] for incompressible flows showed that the first resonant frequencies can be predicted by classical Rossiter's semi-empirical formula. Furthermore, Czech et al.[20] suggested that the characteristic length used in Rossiter's formula can be represented by the streamwise effective length, corresponding to the equivalent area for a cylindrical cavity and a square cavity. On the other hand, Verdugo et al.[21] evaluated the first three modes of oscillation frequencies, in which the diameter of a cylindrical cavity was chosen to be the characteristic length. The values of St_n were well predicted with modified empirical parameters α and k_c. For compressible flows, the distributions for mean and fluctuating pressure show similar characteristics for cylindrical and rectangular cavities.[22] A transitional cavity flow is observed at $D/H = 8.60 - 21.00$. The effect of the incoming boundary layer thickness-to-depth ratio, δ/H, is only evident near the rear face of the open and transitional cavities, in which the trailing-edge expansion and the amplitude of the peak pressure fluctuations decrease as δ/H increases.[23] This study aims to investigate the self-sustained oscillation of cylindrical cavities for compressible flows. The distributions of power spectral density (PSD), based on surface pressure fluctuations, are presented. For an open-type cavity flow, the resonant frequencies and their amplitudes are evaluated. The Strouhal numbers based on the streamwise effective length are presented and compared with the prediction of Rossiter's semi-empirical formula, including a best fit to the measured data for α and k_c.

2. Experimental technique

2.1. Transonic wind tunnel and instrumentation

Experiments were conducted in the blowdown transonic wind tunnel at the Aerospace Science and Technology Research Center in National Cheng Kung University (ASTRC/NCKU), as shown in Fig. 1. The test section has a constant cross-section area of 600 mm square and a length of 1500 mm with solid side walls and perforated top/bottom walls. The perforated test-section walls of a transonic wind tunnel induce strong acoustic waves. For the flat plate cases, the spectra show the existence of high-level discrete peaks, in which an increase in Ma results in a high frequency (4.2–4.8 kHz for Ma = 0.64–0.83).[24] The stagnation pressure was controlled by a rotary perforated sleeve valve and the test Mach number in a subsonic condition was monitored by two choked flaps. In this study, the stagnation pressure was (172 ± 1) kPa ((25.0 ± 0.15) psia) while the stagnation temperature was at room temperature, Ma = 0.64, 0.70, 0.83 ± 0.01.

The NEFF 620 system was used to record test conditions and a National Instruments (NI-SCXI) system recorded the output signals of the dynamic pressure transducers (Kulite XCS-093-25A, B screen). The transducers were flush-mounted and powered by a DC power supply (GW Instek PSS-3203) of 10.0 V. The natural frequency of the transducers is 200 kHz, as quoted by the manufacturer. The Ectron amplifiers (753 A) were used to improve the signal-to-noise ratio, with a roll-off frequency of approximately 140 kHz at a gain of 20. Each sample record has 131,072 data points and is measured with a 5 µs sampling rate. For the spectral analysis, one sample record was divided into 31 segments with 50% overlap, resulting in 8192 data points for each segment. The frequency

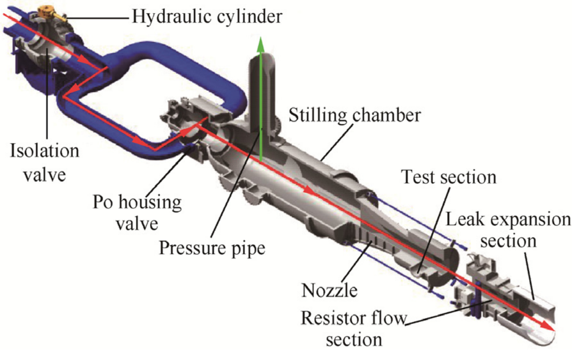

Fig. 1 ASTRC/NCKU transonic wind tunnel model.

Please cite this article in press as: Chung K-M et al. Self-sustained oscillation for compressible cylindrical cavity flows, *Chin J Aeronaut* (2017), http://dx.doi.org/10.1016/j.cja.2017.05.013