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Technical Notes

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Effect of Cavity Width on the Unsteady Pressure in a Low-Mach-Number Cavity

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Introduction

THE flow over a cavity (Fig. 1) has drawn the attention of many researchers (e.g., see the review articles by Rockwell and Naudascher [1] and Colonius [2]) because of its relevance to a range of engineering applications. These include the flow past windows and sunroofs in automobiles, airplane wheel wells, and dump combustors. The flow in these circumstances is characterized by *self-sustained*, high-pressure fluctuations, which can produce vibration and fatigue of the underlying structure, a high level of noise, and drastic increase in the drag force on the body containing the cavity. Hence, understanding and controlling the unsteadiness associated with cavity flows are important.

Rossiter [3] identified the basic mechanism leading to strong, self-sustained oscillations in cavities. More specifically, he proposed that small disturbances in the shear layer separating at the upstream edge of the cavity are amplified, forming *periodic vortex structures* that travel downstream and interact with the aft edge of the cavity, generating strong pressure fluctuations. These fluctuations propagate ("feedback") acoustically to the separation edge and reexcite the shear layer, hence, sustaining the cavity oscillations.

A notable deviation from the Rossiter mechanism is the case where the vortex structures do not form upstream of the cavity's aft edge. In this situation, self-sustained oscillations could still exist, but they are driven by convective waves, which cause large lateral motion (or "flapping") of the shear layer near the downstream lip of the cavity (e.g., Sarohia [4] and Chatellier et al. [5]). Another important aspect of self-sustained oscillations of a cavity is the nature of the feedback. As $M \to 0$, the disturbance-edge interaction is inefficient in producing acoustic disturbances and the feedback is driven by the conservation of the fluid mass within the cavity (e.g., see Martin et al. [6] and Rockwell [7]).

Although there is a large body of literature on cavity flows, very few studies have focused on three-dimensional aspects of the flow. Cell structures along the span of the cavity were found in the experiments of Maull and East [8]. Rockwell and Knisely [9] found that secondary, spanwise-periodic, streamwise vortices formed and distorted the primary spanwise vortex structures. More recently, three-dimensional instability analysis of a *two-dimensional* cavity flow was carried out by Bres and Colonius [10]. It was found that the most amplified three-dimensional mode had a typical frequency that was an order of magnitude smaller than the frequency of the self-sustained cavity oscillations. This mode was linked to the centrifugal instability of the primary recirculation flow inside the cavity.

The objective of this study is to examine the influence of the cavity width on the behavior of the unsteady pressure acting on the cavity floor and how this behavior depends on Reynolds number. A unique aspect of the present investigation is that an axisymmetric cavity geometry is employed to establish a "reference" condition that is free of any end-wall influences. The behavior of this cavity flow can then be compared against that of finite-width cavities by filling portions of the axisymmetric cavity (see the next section for further details). It is significant to contrast the present work to the study of Maull and East [8], who employed a rectangular cavity geometry that had to be terminated with end walls (even for the widest cavity). In addition, Maull and East did not report any quantitative measurements of the cavity unsteadiness. As will be seen, the present findings show that, as $M \to 0$, the accepted criteria, based on cavity depth and length as well as boundary layer thickness, for the occurrence of self-sustained oscillation are not sufficient to guarantee the establishment of the oscillation. The cavity width must also be accounted for; this offers a possible explanation for the discrepancy between recent (Grace et al. [11] and Ashcroft and Zhang [12]) and earlier studies at a low Mach number.

Experimental Setup

The present experiment was conducted in a low-speed, open-circuit wind tunnel. The tunnel had a $0.610 \times 0.610 \times 1.83\ m^3$ test section and the freestream turbulence intensity was less than 0.5%. An axisymmetric model containing a 12.2-mm-deep cavity was mounted in the test section. General dimensions of the model can be found in Zhang and Naguib [13]; only essential details are provided here. The downstream wall of the cavity was movable along the model's axis to enable variation of the aspect, or L/D, ratio of the cavity. In addition, inserts were employed to fill a portion of the cavity along the azimuthal direction to create finite-width cavities with different width-to-depth (W/D) ratios (see Fig. 2). Note that W is defined here as the azimuthal arc length at a height of $D/2$ above the cavity floor. Each insert was made from two parts that could be assembled around the central shaft inside the cavity. By varying the length and azimuthal extent of the insert it was possible to vary L/D and W/D.

A surface-pressure sensor array consisting of 32 Emkay FG-3629 microphones was embedded in the top surface of the model downstream of the fore lip of the cavity, as shown in Fig. 2, to measure the unsteady pressure along the cavity floor. The sensors, which had an outside diameter of 2.54 mm and sensing diameter of 0.75 mm, were spaced 4.75 mm apart in the streamwise direction, starting from 5.3 mm downstream of the cavity lip. These microphones were calibrated individually in situ against a B&K 4938-A-011 $\frac{1}{4}$-in. microphone with known sensitivity in a custom-made plane wave tube. Details of the calibration can be found in Zhang and Naguib [13].

All data were acquired digitally at a sampling frequency of 1000 Hz per channel, resulting in a Nyquist frequency of 500 Hz, which was sufficiently higher than the highest frequency of interest (approximately 300 Hz) in the low-Mach-number cavity flow

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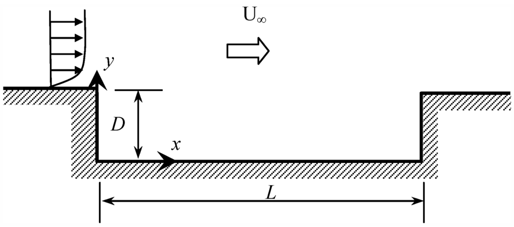

Fig. 1 Illustration of the cavity geometry and coordinate system.

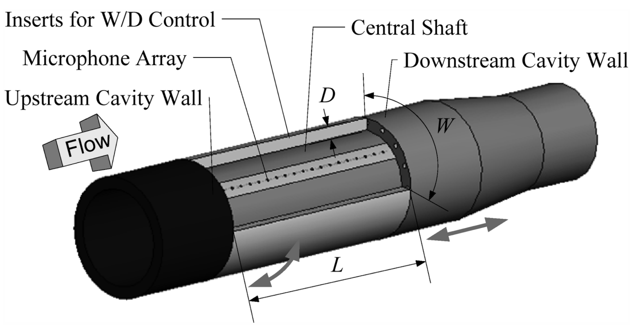

Fig. 2 Three-dimensional drawing of the cavity model.

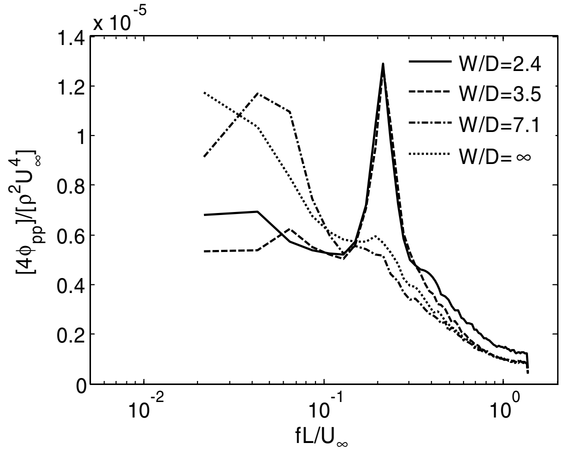

Fig. 3 Cavity-width effect on wall-pressure spectra at $x/L = 0.95$ ($Re = 12,200$).

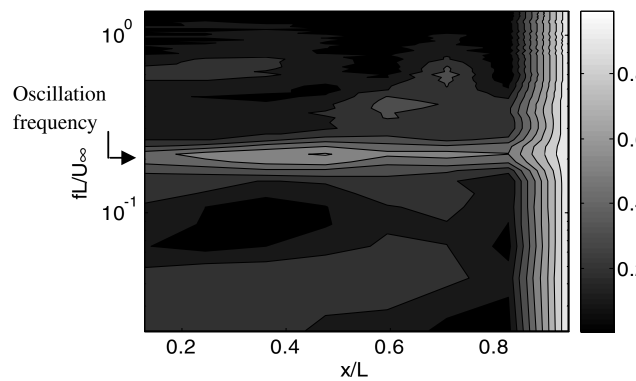

Fig. 4 Coherence of pressure fluctuations across the cavity length for $W/D = 2.4$ ($Re = 12,200$).

examined here. Moreover, no frequency aliasing was found by comparing the resulting pressure spectra to those produced from acquisition at a higher sampling frequency. In addition to signals from the floor microphones, data from a microphone embedded under the downstream wall of the cavity were acquired. These data were used to provide a reference signal for cancellation of any electrical or acoustic fan noise using the optimal filtering technique described by Naguib et al. [14].

Finally, data shown here were obtained for a cavity with fixed L/D of 3.4 but different widths. The specific W/D values were 2.4, 3.5, 7.1, and ∞ (end-wall free, or axisymmetric). For each of the cases, the unsteady pressure on the floor was investigated at two different freestream speeds, 5 and 15 m/s, resulting in Reynolds numbers (Re), based on cavity depth, of 4067 and 12,200, respectively. In both cases, the boundary layer was turbulent at the point of separation with corresponding momentum thicknesses of $\theta/D = 0.252$ and 0.169, as measured using a single hot wire. Recently, Morris and Foss [15] showed that "an effective momentum thickness" of $\theta_{\text{eff}} = 0.052\theta$ is the appropriate length scale characterizing turbulent separation rather than θ, as in the laminar case. They demonstrated that *only* the near-wall, or inner-layer, vorticity participated in the initial shear layer instability in the turbulent case. In the current study, $\theta_{\text{eff}}/D = 0.013$ and 0.009 for the low and high Reynolds numbers, respectively. This yields $L/\theta_{\text{eff}} = 262$ and 378.

Results and Discussion

Figure 3 shows the frequency spectra of the unsteady pressure measured near the downstream lip ($x/L = 0.95$) on the cavity floor at $Re = 12,200$ for different values of W/D. There is a striking change in the nature of cavity oscillations as the cavity becomes wider. For the narrower cavities ($W/D = 2.4$ and 3.5), a clear harmonic peak is observed at $fL/U_\infty \approx 0.21$, suggesting the establishment of self-sustained oscillations. On the other hand, there is no evidence of such oscillations in the spectra for the wider cavities ($W/D = 7.1$ and ∞) *and* the spectra are instead dominated by unsteadiness at low frequency.

The harmonic oscillations found in the narrower cavities exhibit a large degree of phase locking across the entire cavity length. This can be seen from the contour plot of the coherence between the wall-pressure fluctuations measured near the cavity downstream edge and those at different locations on the cavity floor, shown in Fig. 4 for a cavity with $W/D = 2.4$ and $Re = 12,200$. As seen from the figure, substantial coherence magnitude is sustained across the length of the cavity at $fL/U_\infty \approx 0.21$. This confirms the global organization of the flow unsteadiness at this frequency and the establishment of self-sustained oscillation.

The frequency of the oscillation ($fL/U_\infty \approx 0.21$) is lower than the typical value for the lowest Rossiter mode ($fL/U_\infty \approx 0.4$–0.5). This suggests that the self-sustained oscillations observed here are not of the Rossiter type. On the other hand, $fL/U_\infty \approx 0.21$ matches one-third of the frequency of Sarohia's [4] first mode of self-sustained oscillations ($fL/U_\infty \approx 0.67$, see his Fig. 8 and associated discussion), suggesting that the cavity mode found here has a wavelength (λ) 3 times longer than that of Sarohia's. More specifically, the present oscillations appear to correspond to $n = 0$ in Sarohia's equation for the wavelength of cavity modes $\lambda/L \approx 1/(n + 1/2)$; $n = 0, 1, 2$, etc. (note that the wavelength ratio for modes 0 and 1 is 3). This provides strong evidence that the self-sustained oscillations found here are similar to those of Sarohia [4] and Chatellier et al. [5] where large lateral oscillations of the shear layer are self-sustained through conservation of the fluid mass within the cavity, as discussed in the Introduction.

The results of Fig. 3 may, in fact, explain the apparent dilemma found by Grace et al. [11] for a low-Mach-number cavity with $L/D = 4$. Although the cavity of Grace et al. satisfied well-known resonance criteria, no self-sustained oscillations were observed. These criteria, however, are based solely on the cavity length and depth as well as boundary layer thickness *but not* the cavity width. Based on Fig. 3, the cavity of Grace et al., with $W/D = 36$, is too wide for self-sustained oscillations to occur at a low Mach number. Similar reasoning could explain the absence of cavity oscillations in the study of Ashcroft and Zhang [12] whose cavity had a W/D of 18.

Interestingly, the dominance of the low-frequency unsteadiness for wider cavities is only found at the higher Reynolds number. This may be seen by inspecting the results shown in Fig. 5, which are similar to those shown in Fig. 3 but for $Re = 4067$. Although in this

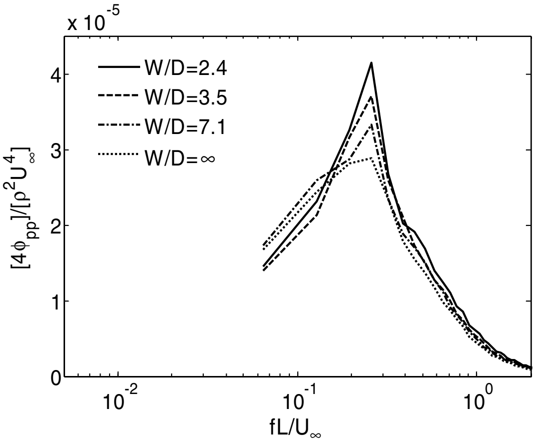

Fig. 5 Cavity-width effect on wall-pressure spectra at $x/L = 0.95$ ($Re = 4067$).

case the harmonic peak is not as pronounced as in the higher-Reynolds-number case, it remains discernible for the narrower cavities. The peak gets weaker with increasing cavity width, but the attenuation is not as strong as in the higher-Reynolds-number case, *and* the dominant unsteadiness never switches to low frequencies.

The finding that the low-frequency unsteadiness appears above a certain Reynolds number leads us to believe that this unsteadiness is related to some form of instability. As discussed in the Introduction, Bres and Colonius [10] discovered that a three-dimensional centrifugal instability of the two-dimensional recirculating flow inside a cavity "kicks in" above a critical Reynolds number. Furthermore, the frequency of this instability was found to be much smaller than that of the self-sustained cavity oscillations. These characteristics agree with the present observations, where the rise in the spectra at the low-frequency end for the wide cavities is only found at the higher Reynolds number and at frequencies that are substantially lower than that of the harmonic oscillations (see Fig. 3). Thus, it is reasonable to speculate that the low-frequency disturbances observed hear are caused by the three-dimensional instability of the flow inside the cavity. Perhaps such instabilities could interfere with the shear layer structure, causing the weakening/disappearance of the self-sustained oscillations. Further research of the three-dimensional structure of the flow is required to validate/refute this hypothesis. However, the purpose of this Note is to underscore a new and significant finding: the occurrence of self-sustained, fluid-dynamic cavity oscillations depends on the cavity width as $M \to 0$ (i.e., the traditional criteria, based on cavity length and depth as well as boundary layer thickness, represent *necessary but not sufficient* conditions for the occurrence of the oscillations); this width effect becomes more pronounced with increasing Reynolds number.

Conclusions

The effect of the cavity width on the unsteady pressure acting on the bottom of a low-Mach-number cavity was investigated for different Reynolds numbers. An axisymmetric cavity geometry was used to enable the unique comparison of the cavity behavior with and without end walls. It was found that the increase of the cavity width caused the cavity's self-sustained oscillation to be attenuated or disappear altogether. At a *high* Reynolds number, the cessation of the oscillation was accompanied by increased unsteadiness at very low frequencies. Additional investigations will be done to understand the nature of the low-frequency disturbances in wide cavities at high Reynolds number and their interaction with the cavity's self-sustained oscillation.

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