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Microphone-Array Measurements of the Floor Pressure in a Low-Speed Cavity Flow

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The objective of this paper is to highlight the significance of spatiotemporal data and associated analysis tools in the identification of oscillation modes in cavity flows. To this end, the unsteady wall-pressure field on the floor of a shallow, rectangular cavity is experimentally investigated at a low Mach number of 0.086. The pressure measurements are conducted by using an array of 16 microphones arranged in a line along the centerline of the cavity floor, which spans its full length. Data were acquired for two cavity configurations with a length-to-depth, L/D ratio of 5 and 8. Results show that for $L/D = 5$, the pressure oscillations are driven by the wake mode; whereas for $L/D = 8$, Rossiter-type modes are observed. The ability to contrast the wake and Rossiter-type oscillations was made possible through the unique, wall-pressure, wave-number-frequency signature of each of the modes.

NOMENCLATURE

f	=	frequency
D	=	cavity depth
k	=	ratio of convection velocity to freestream velocity
k_x	=	streamwise wave number
L	=	cavity length
M	=	Mach number
R_p	=	amplitude ratio
U_c	=	convection velocity
U_∞	=	freestream velocity
x	=	streamwise coordinate
y	=	wall-normal coordinate
θ_o	=	boundary layer momentum thickness at separation
θ	=	phase angle
ρ	=	fluid density
ϕ_{pp}	=	wall-pressure power spectrum

I. Introduction

CAVITY flows (see Fig. 1 for an illustration of the geometry) may be found in many engineering applications including aircraft landing-gear bays, dump combustors, and aerodynamic windows. In these applications, the flow is characterized by large, pressure fluctuations that can result in high levels of sound generation; strong vibration; and, in the extreme case, fatigue of the underlying surface. Moreover, the flow could also be associated with a substantial increase in the drag force on the object containing the cavity. The significance of cavity flows is reflected in the number of recent studies aimed at an attenuation of the flow unsteadiness through active-control methods. Examples include Williams et al. [1], Samimy et al. [2], Ziada et al. [3], Kegerise et al. [4] and Rowley et al. [5].

Although cavity flows have been investigated extensively over the years, only a few studies examined the behavior of such flows at low, Mach numbers (previous work has focused mostly on $M > 0.4$) and long cavities (large L/D). More important, none of the experimental studies have employed a sufficiently large sensor array for resolving the unstready, pressure field spatially *as well as* temporally. Because of the fairly complex nature of the cavity-oscillation modes (involving upstream and downstream, propagating disturbances; acoustic and hydrodynamic unsteadiness; and "shear-layer" as well as "wake" modes), a clear understanding of the nature of the cavity-oscillation modes requires spatiotemporal data. Therefore, this paper is intended to demonstrate the significance of using spatiotemporal analyses in the study (and ultimately feedback control) of cavity flows. However, to put the discussion in perspective, a brief account of the current understanding of cavity flows is given in the following paragraphs.

Rossiter [6], Sarohia [7], Gharib and Roshko [8], Rockwell and Knisley [9] are some of the more prominent early investigations that studied the behavior of cavity flow experimentally and classified the resulting flow field into two regimes depending on the cavity geometry (aspect ratio, or length-to-depth ratio L/D). The first regime occurs in deep-cavity flow, where the aspect ratio is less than 1, the flow field experiences a recirculation zone with one stationary, vortical structure and the shear layer covering the length of the cavity, whereas in the second regime, where the aspect ratio is greater than 1, the cavity is considered shallow and formation and rollup of vortices at the upstream edge of the cavity takes place.

Rossiter [6] studied the cavity flow experimentally and suggested that the periodic pressure fluctuations in a cavity flow appear due to acoustic resonance within the cavity. He proposed the following formula for identifying the frequencies (f) at which this resonance phenomenon takes place:

$$\frac{fL}{U_\infty} = \frac{m - \gamma}{M + 1/k} \tag{1}$$

m is an integer mode number (1, 2, ...) and γ is a parameter representing the time delay between the interaction of the shear-layer vortex structure with the downstream lip and subsequent generation of sound. γ and $1/k$ are treated as empirical parameters that are adjusted to fit the observed frequencies of self-sustained oscillation in a particular experiment. Equation (1) is based on the idea that for resonance to occur, the time duration for the travel of a disturbance

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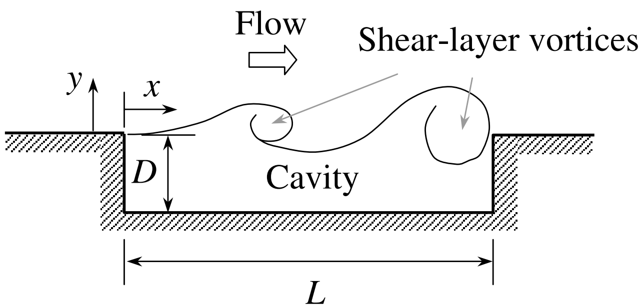

Fig. 1 Geometry and coordinate system for the cavity-flow problem.

from the upstream lip of the cavity to the downstream edge and back must equal an integer multiple of the period of the disturbance. Recently, Radhakrishnan et al. [10] studied the modified Rossiter formula for the frequency of the cavity, pressure oscillations and obtained a good agreement with the prediction of the formula.

Gharib [11] elucidated the modes of periodic pressure oscillations in shallow cavities and classified them according to the aspect ratio into nonoscillating mode, self-sustained-oscillations mode, and wake mode. In the case of the nonoscillating mode, the shear layer is smooth and covers the length of the cavity, whereas a standing, vortical structure is present in the cavity. Gharib and Roshko [8], Gharib [11], Sarohia [7], and Rockwell and Knisely [9] explained that there is a minimum required aspect ratio for the onset of the oscillations. Beyond this minimum aspect ratio the cavity oscillation becomes either in a self-sustained-oscillations mode or in the wake mode. For the self-sustained-oscillations mode, Gharib [11] suggested that the oscillations, originating from the shear layer, tend to be coherent in phase due to a feedback condition generated by the impingement of the shear layer on the downstream corner of the cavity. As the aspect ratio is increased even more, the cavity unsteadiness switched from being driven by the self-sustained-oscillation mode to the wake mode. This wake mode is characterized by a large-scale-vortex shedding with a Strouhal number nearly independent of the Mach number.

Najm and Ghoniem [12] divided the shallow cavity into short cavities and long cavities. Short cavities are defined as cavities that have an $1 < L/D < 2$, whereas long cavities are taken as those with $L/D > 2$. Najm and Ghoniem [12] studied the cavity flow numerically. They showed that the dynamics of cavity flows involves coexisting flow instabilities: the shear-layer instability and recirculation zone instability. If the recirculation zone was quiescent, the flow field over a cavity would resemble a shear-layer impinging on a downstream wedge, with the resulting organization due to disturbance feedback from eddy impingement downstream. They referred to this regime as short cavity, flow regime, which Gharib [11] named the self-sustained-oscillation mode. When the aspect ratio increases beyond the short-cavity limit of $L/D > 2$, that is, the cavity becomes a long cavity, the recirculation zone is not quiescent. The effect of the shear-layer impingement on the downstream edge becomes negligible, and the main mechanism that drives the pressure oscillations in the recirculation zone is the shedding of large-scale eddies within the cavity.

More recently, Rowley et al. [13] used direct numerical simulation of a cavity flow with a separating laminar boundary layer to demonstrate that cavity resonance may be associated with two fundamentally different modes depending on the length of the cavity relative to the initial momentum thickness of the boundary layer (θ_o). Specifically, for values of L/θ_o below 75, the shear-layer vortices represented convectively unstable Kelvin–Helmholtz (K–H) (or shear-layer) modes. These modes are essentially the ones considered in Rossiter's description of cavity resonance and those considered by most investigators of cavity flows. However, when L/θ_o was increased above 75, Rowley et al. [13] found that vortices at substantially larger scale than that of the K–H modes were shed from the cavity. This mode was referred to as the "wake" mode, which was first identified by Gharib and Roshko [8] and was found to be associated with a substantial increase in the cavity drag. As discussed above, Najm and Ghoniem [12] also observed this switching from K–H type vortex passage to shedding of larger-scale vortices from the recirculation zone within the cavity as they increased the cavity length from $L/D = 2$ to $L/D = 4$ in their vortex method simulation. Most recently, Murray and Ukeiley [14], using simultaneous wall-pressure and velocity measurements, also identified the wake mode in a cavity with $L/D = 5.16$ and $M = 0.2$ via a stochastic estimation analysis. The study seems to be the first to identify this mode when the separating boundary layer is turbulent. However, in a follow-up study, Ukeiley and Murray [15] revised their interpretation of the observations, preferring to refer to the observed mode as "breathing," rather than wake, mode.

II. Exprimental Setup

The experiments were completed in an open-return, wind tunnel. The tunnel is a low-turbulence-intensity (<0.1%), quiet facility with a $0.36 \times 0.36\ \mathrm{m}^2$ flow area. The measurements employed L/D ratios of 5 and 8 (see Fig. 1 for definition of geometrical parameters and coordinate system) for a freestream velocity of 30 m/s ($M = 0.086$).

The cavity was constructed from Plexiglas® with overall dimensions of 482×229 mm in length and width, respectively, and depth that can be varied continuously from 0 to 178 mm. The corresponding L/D ratio falls in the range of 2.7 to infinity (or zero depth). The cavity was mounted to the side of the wind-tunnel test section. An array of 16 WM-61A Panasonic, electret microphones were mounted in recessed holes on the backside of the cavity-bottom plate. The microphones were arranged inline on the centerline of the plate with their sensing holes connected to the flow side via short holes of matching diameter. The spacing between successive microphones was 25.4 mm with the most upstream microphone positioned at 49.4 mm downstream of the cavity lip.

All microphones were individually calibrated to obtain their sensitivity and phase response. The calibration was accomplished by subjecting the microphones, after mounting in the cavity floor, to sound in a plane wave tube (PWT), as depicted in Fig. 2. The PWT was 1.5 m long and had a cross section of 15.9×15.9 mm. A speaker placed at one of the open ends of the tube served as the source of planar sound waves traveling along the PWT axis. The characteristics of sound within the tube were verified using two Larson Davis microphones with known response that were mounted at the same cross section of the tube. The results are shown in Fig. 3. The data clearly demonstrate that the two microphones sense the same sound amplitude (within 1 dB) at practically no phase difference up to 10 kHz. Calibration results yielded Panasonic microphone sensitivities ranging from 9 to 13.4 mV/Pa (approximately −40 to −38 dB re 1 V/Pa) and phase discrepancy among the microphones that resulted in a maximum time delay of

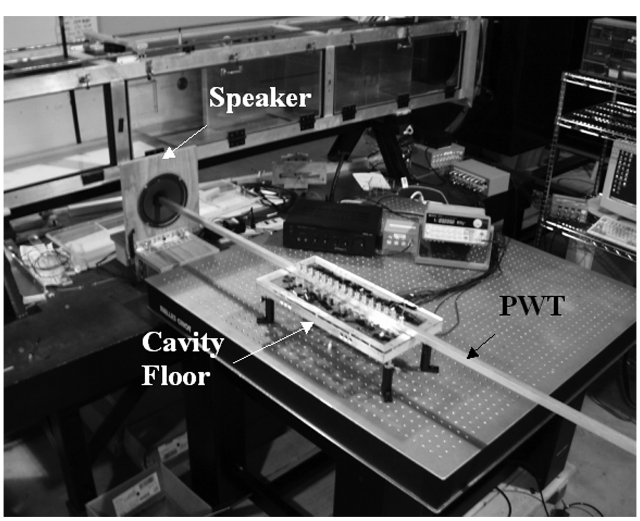

Fig. 2 Calibration of the microphones in the cavity floor using PWT.

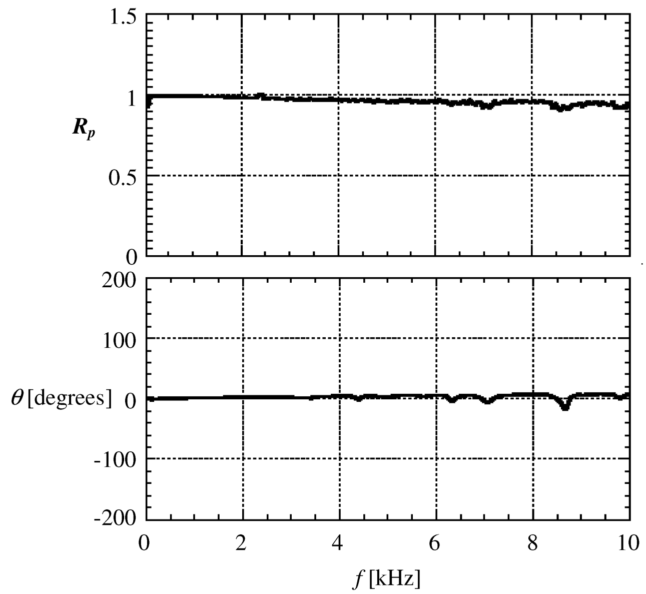

Fig. 3 Verification of the amplitude and phase characteristics of the plane wave tube sound field.

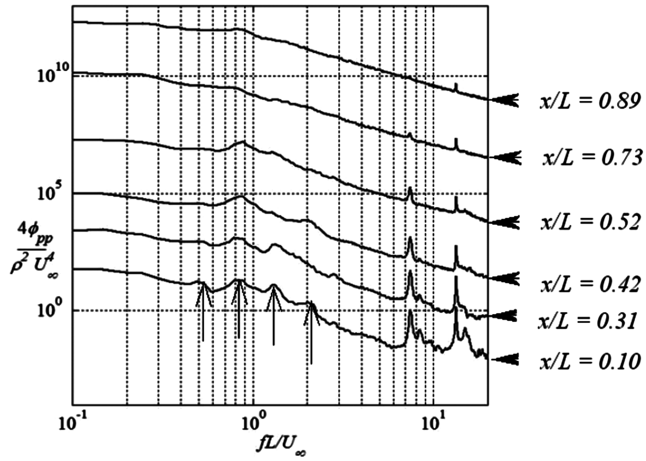

Fig. 4 Wall-pressure frequency spectra at different x locations along the cavity floor.

less than 5 μs. The latter is more than an order of magnitude smaller than the time taken by a pressure disturbance to propagate at the speed of sound over a distance equal to the intermicrophone spacing (about 70 μs).

All data were sampled using a National Instruments data acquisition, PC-based card (type NI-6020E). The card has a maximum sampling rate of 100 kHz and 16 single-ended channels that are sampled at a resolution of 12 bits. The sampling frequency used in acquiring the data was 6250 Hz per channel, which is the maximum possible when using all 16 channels. This frequency is substantially higher than the frequency content of the pressure fluctuations in the low-Mach-number flow examined here. Specifically, most of the pressure-fluctuation energy was below a few hundred hertz. Thus, the Nyquist frequency of 3125 Hz was well above that required to ensure aliasing-free sampling of data. Additionally, the interchannel time delay at the maximum rate of sampling was 10 μs, which was $\frac{1}{7}$th of the delay associated with propagation of sound over a distance equal to the intermicrophone spacing.

Finally, the deployment of 16 microphones across the full cavity length allows resolution of wave numbers up to that corresponding to mode number 8; that is, that containing eight full waves across the cavity. Any modes with higher wave number, or shorter wavelength, will contain less than two spatial, data points per wavelength; and, hence, their observed wave number will be an alias of the true one. However, given existing literature on the topic, it is highly unlikely that such a high mode number will exist. More important, for the dominant frequencies observed in this study, the existence of a mode number larger than 8 at those frequencies would require the mode to travel at a convection velocity of less than $0.1U_\infty$. Such slow-traveling flow structures have not been observed before in cavity-flow studies (typical convection speeds are of the order of $0.5U_\infty$).

III. Results and Discussion

A. Results for $L/D = 8$

Figure 4 displays frequency spectra of the measured pressure (p') at a number of x locations spanning the distance from 10–90% of the cavity length. Except for $x = 0.1L$, the spectra at the remaining locations have been arbitrarily shifted in the vertical direction to compare the results from different locations on the same plot without cluttering. Inspection of Fig. 4 shows that a number of localized peaks are found in the spectra. Those peaks, identified by arrows in the figure, are particularly visible at the location closest to the upstream lip of the cavity. As x increases, the peaks become obscure, except for the one at $fL/U_\infty \approx 0.83$, which remains visible throughout the range. The reduced visibility of the peaks with increasing streamwise distance is presumably caused by the increasing level of the broadband, hydrodynamic, pressure fluctuations with increasing x distance from the separation point. Near separation, the shear-layer vortices are smaller in size and less energetic and hence make little contribution to the pressure fluctuations. Therefore, it is suspected that the identified peaks at $x/L = 0.1$ are associated with an acoustic rather than hydrodynamic signature. In addition to the spectral peaks marked with arrows in Fig. 4, two other peaks are observed at the high-frequency end of the spectrum. The pressure-fluctuation energy associated with these peaks is substantially smaller than that associated with the peaks discussed above. Furthermore, it was found that the frequencies of these two peaks correspond to standing sound waves with wavelength equal to 1 and 2 times the distance between the cavity bottom and the opposite test-section wall.

Observation of localized peaks in the frequency spectrum is not sufficient to conclude that the peaks are associated with feedback resonance phenomenon. Kegerise et al. [16] used coherence between the pressure signals measured near the downstream and upstream cavity walls to identify frequencies that are taking part in the resonance. This, however, is a necessary but not sufficient condition for identification of resonance frequencies. For example, background sound waves in the tunnel or electronic noise could also produce high coherence between measurements conducted at two different points. A better identification can be achieved by using wave-number-frequency (k_x–f) spectra obtained from array-type measurements.

The k_x–f spectrum was obtained by partitioning the data into two-dimensional, x–t records, each containing 16 points in the x direction and 2048 points in time. The two-dimensional, Fourier transform was then used to obtain the k_x–f representation of the record. The result was multiplied by its own conjugate and averaged across all data records. Because the transformation involves a separable double-integral operation, it was accomplished by employing an integration with respect to time first, followed by an integration relative to x of the result. Each of the two transformations was implemented using Matlab's built-in one-dimensional, FFT function.

Figure 5 displays the k_x–f spectrum for the $L/D = 8$ case. In the figure, the magnitude of the spectrum is displayed using a gray scale. It should be noted that the results have been normalized by the largest spectrum magnitude, that is, the color scale spans a range between zero and 1.

An important feature of the k_x–f spectrum plot is that the slope of a straight line drawn from the origin to any point on the plot yields the convection velocity of the mode associated with the f and k_x values at that point. Because the slope is positive in the right-half plane and negative in the left-half plane, peaks found in the former are associated with downstream-traveling disturbances and vice versa. Figure 5 depicts two localized peaks at $fL/U_\infty \approx 0.25$ and 0.83 in

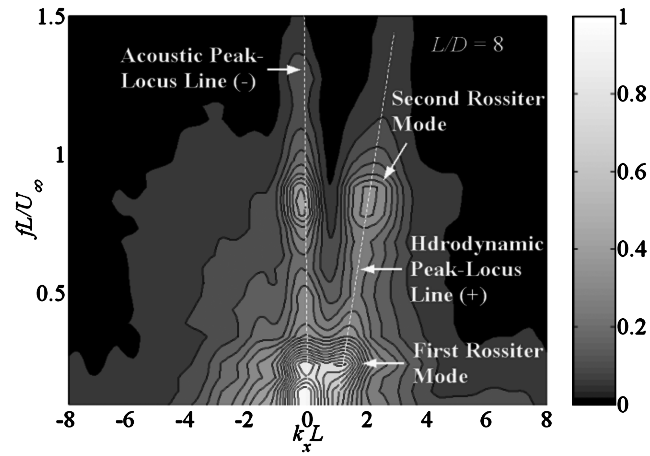

Fig. 5 Wave-number-frequency spectrum for $L/D = 8$.

the right-half plane (pointed to by arrows). The corresponding convection velocities (U_c) were found to be 0.24 and $0.4U_\infty$ respectively. One can readily associate those peaks with the hydrodynamic component of Rossiter-type-feedback resonance because 1) both peaks are associated with downstream convection velocity that is lower than U_∞; 2) each peak is associated with a "sister" localized peak at the same frequency but corresponding to disturbances propagating in the upstream direction at the speed of sound. The latter is seen from the finding that the sister peaks fall on a line drawn from the origin with a slope corresponding to the negative of the speed of sound.

Note that because the wavelength of the sound waves is substantially larger than L, spatial zero padding was used in the 2D-FFT analysis to interpolate in the k_x direction, making the back propagation of sound visible. Without zero padding, the acoustic peaks appear at $k_x = 0$. It is noted here that even in this case, the peaks deviate from the "acoustic propagation line" by an amount that is substantially smaller than the wave-number resolution of the spectrum. That is, with or without the use of zero padding, these peaks may be associated with acoustic propagation within the spectrum resolution uncertainty.

The observation of the coexistence of hydrodynamic and acoustic disturbances at the same frequency but propagating in opposite directions provides compelling evidence for the existence of Rossiter-type resonance at very low Mach numbers. This differs from the earlier conclusions by Tam and Block [17] who suggested that normal mode resonance is the mechanism responsible for self-sustained oscillations at Mach numbers less than 0.15. However, the largest L/D value investigated by Tam and Block [17] was approximately 2.4. The current results are obtained for a substantially larger L/D.

In contrast to the study of Tam and Block [17], Ziada et al. [3] observed the three, lowest Rossiter modes in their study of a confined cavity in the Mach number range of 0.1 to 0.3 and $L/D = 2.5$ and 4. Ziada et al. [3] commented on the weakness of the signature of the Rossiter modes at low Mach numbers and pointed out the inability of earlier studies to identify the fundamental (or first) Rossiter mode at low Mach numbers. They attributed the appearance of the mode in their study to the reflection of sound waves from the confinement plate, which seemed to promote the shear-layer oscillation at the fundamental frequency. These observations seem to not only be consistent with the current study but they also further highlight the significance of employing spatiotemporal analyses for identification of cavity modes. More specifically, as discussed earlier, the frequency spectra in Fig. 4 do not provide any evidence for the existence of the first Rossiter mode, the signature of which is seemingly buried beneath the influence of broadband turbulence. Since earlier studies relied primarily on frequency spectra in identifying cavity modes, it is not surprising that the first mode was not observed. The wave-number- frequency spectra in Fig. 5 clearly remedy this problem.

On the other hand, the recent study of Rowley et al. [13] showed that oscillations in long cavities are associated with wake mode (see Sec. I) rather than shear-layer resonance. This was observed for cavities with $L/D > 4$. Also, although not referred to as "wake mode," Najm and Ghoniem [12] also found earlier that for $L/D > 4$, the cavity-flow unsteadiness was driven by large-scale-vortex shedding from within the cavity. Both Rowley et al. [13] and Najm and Ghoniem [12] also noted that acoustic feedback of disturbances is not important for the dynamics of the wake mode. In this context, it is a bit surprising that Rossiter-type resonance is found here for a cavity with $L/D = 8$. This issue will be clarified after considering the shorter cavity results in the next section.

B. Results for $L/D = 5$

Frequency spectra of the wall pressure for the cavity with $L/D = 5$ are shown in Fig. 6 at different x/L locations. The streamwise locations of the spectra as well as the manner of plotting them are identical to those for the $L/D = 8$ case in Fig. 4. Comparison between the results for the two cases depicts general similarity between the qualitative features of the spectra and their overall level at similar x/L positions. In particular, for $x/L = 0.1$, a "corrugated" hump is observed for the $L/D = 5$ case in the frequency range $fL/U_\infty = 0.5$–2.0. Within the same range the $L/D = 8$ case also depicts a hump with multiple localized peaks (pointed to by arrows). As discussed above, of these peaks only the one at $fL/U_\infty = 0.83$ was found to take part in Rossiter-type resonance. (It is also the one peak that remains visible in the spectra obtained farther downstream.) Similarly, the corrugations in the spectral hump for the L/D case are believed to be a manifestation of multiple, albeit weaker, modes. Of these modes, only the one corresponding to $fL/U_\infty \approx 1$ seems to remain visible in the spectra at larger x/L locations. Thus, with the exception of the apparent weakening of the modes and some shift in the nondimensional frequency corresponding to the most dominant mode in the range $fL/U_\infty = 0.5$–2.0, the frequency spectra results suggest that the behavior of the $L/D = 5$ and 8 cavities are quite similar.

The wave-number-frequency spectra, however, tell a different story. Figure 7 displays the k_x–f spectrum for $L/D = 5$. Comparison with the corresponding data for $L/D = 8$ (Fig. 5) reveals a striking difference between the two cases, with the exception of the mode at $fL/U_\infty \approx 1$ ($L/D = 5$) and $fL/U_\infty = 0.83$ ($L/D = 8$). For this mode, an upstream, propagating, acoustic mode is found associated with a downstream, traveling, hydrodynamic mode at $k_xL \approx 2$; that is, the second Rossiter mode. This mode is weaker for the shorter cavity and is associated with a broad, spectrum distribution rather than the stronger localized peak seen for the longer cavity. The weakness of the hydrodynamic signature of the mode in the shorter cavity is believed to be caused by the larger distance between the shear layer and the bottom of the cavity where the p' is measured.

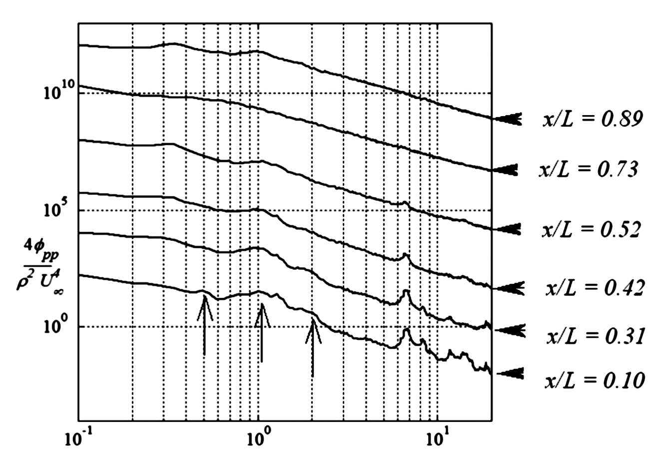

Fig. 6 Wall-pressure frequency spectra at different x locations along the cavity floor.

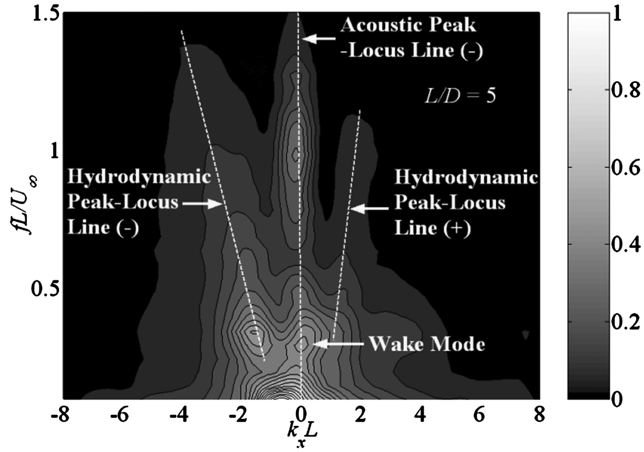

Fig. 7 Wave-number-frequency spectrum for $L/D = 5$.

The most striking difference between the wave-number-frequency spectra of the two cavity cases investigated here is that the dominant hydrodynamic pressure disturbances are seen to travel in the upstream direction for $L/D = 5$ versus the downstream direction for $L/D = 8$. A particularly strong upstream-traveling disturbance is found at $fL/U_\infty \approx 0.32$ and $k_x L \approx -1.5$, corresponding to a convection velocity of $-0.21U_\infty$. This peak is associated with another peak at the same frequency but at a wave number of $k_x L = 0$. It is quite interesting to note that the nondimensional frequency of 0.32 is equal to 0.064, when normalized using D instead of L. This value is precisely what Rowley et al. [13] found for the wake-mode shedding frequency. Furthermore, Rowley et al. [13] showed that the wake mode is independent of the Mach number and, hence, is not driven by acoustic feedback. Instead, they suggested that hydrodynamic feedback of disturbances plays an important role in the instability leading to the establishment of the wake mode. More specifically, Rowley et al. [13] suggested that when the mean, reverse velocity associated with the recirculation in the cavity became strong enough, an absolute instability sets in, resulting in the establishment of the wake mode. Both the strong hydrodynamic feedback of disturbances and the frequency at which this feedback occurs, as seen from the k_x–f spectrum results, give strong evidence that the wake mode is in fact the dominant oscillation mechanism in the $L/D = 5$ case.

The appearance of the wake mode itself at $k_x L = 0$, instead of positive wave number is believed to result from two reasons. First, inspection of the results showing temporal evolution of the wake mode in the studies of Rowley et al. [13] and Najm and Ghoniem [12] (who did not use the name wake mode but their large-scale-eddy shedding was in effect the same as the wake mode identified by Rowley et al. [13]) depict the vortical structure to start forming at the upstream edge of the cavity and grow in scale to a size comparable to D in the wall-normal direction and the cavity length in the x direction although moving very little in the downstream direction. The establishment of the large-scale vortex is followed by a fairly violent ejection from the cavity and its subsequent convection downstream. Thus, it is seen that before shedding, the vortex is practically stationary with a footprint that grows to register across most of the cavity length. This would give a stationary-mode-like signature, or at least one that is not harmonic in x with a substantial spatial dc signature (i.e., $k_x = 0$). Moreover, the interaction of the wake-mode vortices with the downstream lip of the cavity are also likely to produce sound disturbances (notwithstanding their benign influence on the wake mode) that would register at the same frequency and very near $k_x = 0$ in the wave-number-frequency spectrum, strengthening the signature of the mode at $k_x = 0$.

Finally, it is emphasized that without the use of the wave-number-frequency spectrum, it would have been quite difficult to establish that resonance is in fact taking place in the cavities investigated here (given the fairly weak amplitudes of the modes in the frequency spectra, or their obscurity due to the broadband turbulence). This may have contributed to the difficulty in identifying feedback-type resonance at very low Mach numbers in some of the previous studies involving air flow over a cavity (e.g., Tam and Block [17]). More significantly, as discussed above, the frequency spectra alone seem to indicate that the cavity behavior is similar for the two cases of $L/D = 5$ and 8. However, based on the k_x–f data, it is apparent that wake-mode resonance is taking place in the shorter cavity. As the cavity length increases, the oscillation switches to Rossiter-type resonance beyond a certain cavity length. It is not known if this switching takes place at a sharply defined length, but it is likely that the switch is gradual with the possibility of coexistence of both wake and Rossiter-type oscillations. This is evident in the $L/D = 5$ case, where a weak Rossiter mode at $k_x L \approx 2$ coexisted with the dominant wake mode, as pointed to earlier.

To put the present results in context with the current understanding of cavity flows, it is useful to consider how the cavity behavior changes with increasing cavity length. Both Sarohia [7] and Gharib and Roshko [8] showed that the cavity length must exceed a minimum threshold ($L_{\min}$) before any type of resonance takes place. Specifically, these two studies identified $L_{\min} \approx 800\theta_o Re_\theta^{-1/2}$ (θ_o being the momentum thickness of the boundary layer at separation and Re_θ is the corresponding Reynolds number based on momentum thickness). Once the minimum length is exceeded, Rossiter-type resonance takes place. As L increases beyond a *second* threshold, which was given by Rowley et al. [13] to be $L = 75\theta_o$ (for an Re_θ range of 40–80), cavity oscillations become wake-mode driven. This suggests that for a cavity length beyond this threshold, one should not observe Rossiter-type resonance. However, it is important to realize that the cavity-oscillation mode also depends on D/θ_o. In particular, Rowley et al. [13] found that at a given L/D, the dominant cavity-oscillation mode switched from shear-layer to wake mode as D/θ_o was increased. In other words, for a given upstream-boundary-layer condition, there is a minimum depth ($D_{\min}$) that is required for the onset of the wake mode. For this study, L/D was increased by reducing the cavity depth for the same cavity length and upstream-boundary-layer condition, resulting in a smaller D/θ_o for $L/D = 8$ than for $L/D = 5$. Therefore, the observation of the Rossiter mode for the larger L/D case is most likely caused by the corresponding smaller D/θ_o value.

IV. Conclusions

The wall-pressure field on the floor of a low-Mach-number, cavity flow was resolved *spatially* and *temporally* employing a 16-microphone array. The resulting space-time database coupled with wave-number-frequency analysis proved to be powerful in analyzing and understanding the oscillation modes of the flow.

Wake-mode and Rossiter-type oscillations were found in the low-Mach-number cavity for length-to-depth ratio values of 5 and 8, respectively. The ability to contrast the wake and Rossiter-type oscillations was made possible through the unique wave-number-frequency signature of each of the modes. The corresponding frequency spectra exhibited practically indistinguishable characteristics for the two cavities examined here, demonstrating the ineffectiveness of temporal data alone to clarify the oscillation mode type. This is particularly true for low Mach numbers where the resonance amplitudes may be weak and embedded within the broadband turbulence. Overall, the paper highlights the significance of employing spatiotemporal data and associated analyses for the investigation, and possibly feedback control of cavity flows.

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