Time Resolved PIV Measurements Elucidate the Feedback Mechanism that Causes Low-Frequency Undulation in an Open Cavity Shear Layer

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ABSTRACT

Time resolved 2D PIV measurements with an image-sampling rate of 4500 fps have been used for studying the unsteady flow structure in an open cavity shear layer. The Reynolds number based on cavity length is 4.0×10^5. The present paper focuses on elucidating the feedback mechanism that causes the self-organized low-frequency vertical undulation of the shear layer. Data analysis includes calculations of the instantaneous pressure distribution by spatially integrating the measured material acceleration (Liu and Katz 2006). Two primary mechanisms with distinctly different characteristic frequencies affect the vorticity flux and generation as well as pressure variations around the trailing corner. The first mechanism involves interactions of the large-scale, organized shear layer vortices with the corner. The velocity field induced by these vortices causes periodic formation of pressure maxima in front of the cavity corner, and pressure minima above it, which in turn, cause periodic variations in surface vorticity production above the corner. The second unsteady flow mechanism is characterized by low frequency undulation in the elevation of the shear layer, which periodically strengthens and weakens all of the mean flow and turbulence quantities around the trailing corner. Entrainment of high momentum fluid into the cavity when the shear layer is low increases the pressure near the forward-facing surface of the cavity corner, and results in a jetting flow into the cavity, which recirculates back to the vicinity of the backward facing surface at the beginning of the cavity. This jet increases the pressure at the upstream corner of the cavity, increasing the pressure-gradients that the boundary layer upstream of the cavity corner is facing. Consequently, the boundary layer thickness increases, causing the shear layer to roll up at a higher elevation. This process lifts the entire shear layer, and reduces the pressure and jetting into the cavity at the downstream corner. The reduced backflow decreases the pressure at the inlet corner and incoming boundary layer thickness, causing a downward shift in the vertical location of the shear layer. This low frequency undulation has substantial impact on the turbulence and noise generations by the cavity corner.

1. INTRODUCTION

Shear layer flows past a cavity have been investigated extensively over the past several decades due to its simple geometry, richness in flow physics and relevance to practical applications (Rockwell and Naudascher 1978 and 1979, Rockwell 1983 and 1998, Rowley and Williams 2006, Morris 2010). One intrinsic feature of this flow is periodic oscillations that persist over a large range of Mach numbers and Reynolds numbers, with both laminar and turbulent boundary layers, and over a wide range of cavity length-to-depth ratios (Sarohia 1977). For open cavity flows (see Sarohia 1977 for definition of “open” and “close” cavity flows), where a “stable” (Pereira and Sousa 1995) recirculation zone exists, Rockwell (1983) and Najm and Ghoniem (1991) point out that the shear layer oscillations may be classified into two categories according to the mechanisms responsible for their generation: (a) Inherent hydrodynamically unstable instabilities that are responsible for the roll-up of the large scale vortices in the shear layer, with Strouhal numbers (St= fL/Ue, where f is frequency, L the opening of the cavity, and Ue the external velocity) in the range of 0.5-2.5, and (b) oscillations associated with “low-frequency mechanisms” (Rockwell 1983) or recirculation zone instability (Najm and Ghoniem 1991), with a Strouhal number in the order of 0.1, which modulates and causes a low frequency flapping (“jitter”) of the shear layer.

Kelvin-Helmholtz instabilities cause rollup of well-known periodic vortical structures in the shear layer (Rockwell and Naudascher 1978, Knisely and Rockwell 1982, Ashcroft and Zhang 2005, Rowley and Williams 2006). As described in Rockwell (1983), impingement of these vortical structures on the trailing corner of the cavity generates a feedback mechanism, either due to Biot-Savart induction or upstream pressure waves, which keeps the shear layer oscillations self-sustainable. Extensive studies of this feedback mechanism have established that the characteristic frequency of these oscillations for an incompressible flow can be predicted from fL/Ue=0.5(πn±0.25), with n the number of large-scale vortices within the shear layer, based on inviscid stability theory (Rossiter 1964, Martin et al. 1975, Blake 1986, Lin and Rockwell 2001).

However, as far as the low-frequency oscillations are concerned, the mechanisms involved are not clearly understood, though significant advancements have been made in clarifying the associated flow phenomena and their underlying mechanisms (Rockwell and Knisely 1979, Knisely and Rockwell 1982, Najm and Ghoniem 1991, Pereira and Sousa 1995, and Lin and Rockwell 2001). Hydrogen bubble visualizations at low Reynolds numbers by Rockwell and Knisely (1979) have led them to describe the low-frequency oscillation as “jitter” of the shear layer flow. They show that as the jittering shear layer impinges on the trailing corner it could be completely clipped, i.e. swept down back into the cavity, partially clipped, or escape from the cavity. These events have been replicated recently in large eddy simulations (Chang et al. 2006). As a follow-up of their earlier work, Knisely and Rockwell (1982) use hot-film flow velocity and surface pressure measurements along with flow visualization to investigate the low-frequency oscillations. They conclude that the characteristic frequency of these cyclic oscillations is equal to the cavity length, and that the transverse displacement of the shear layer could be interpreted as low-frequency flapping. Najm and Ghoniem (1991), use results of vortex method simulations to argue that the dynamics of the cavity flows involve two coexisting flow instabilities: shear-layer instability and low-frequency recirculation zone instability, and that the latter
causes the shear layer flapping. Pereira and Sousa (1995), while confirming Najm and Ghoniem's observation about the role of the recirculation region in causing the flapping, do not exclude the possibility that the feedback is caused by upstream influence of shear layer impingement on the downstream corner of the cavity. With PIV measurements, Lin and Rockwell (2001) show that the large-scale vortical structures induce ordered pressure fluctuations at the impingement corner of the cavity. They also observe a jet-like return flow that develops along the cavity walls, leading them to suggest that this backflow modulates the separating shear layer at the leading corner of the cavity. They further notice that this jet is produced when portion of the unsteady shear layer is deflected downward into the cavity near the impingement corner. They conjecture that this jet plays a role in the process of shear layer flapping, but do not explain how. Thus, the underlying mechanism causing the periodic, low frequency flapping of the shear layer is still not understood. As shown in this paper, the jet described by Lin and Rockwell (2001) is part of a process that involves pressure fluctuations on both corners of the cavity, the above mentioned jet as well as changes to the boundary layer upstream of the cavity along with vertical undulations/flapping of the shear layer. In explaining this process, we rely on time resolved measurements of the pressure distribution within the cavity along with the associated flow structure.

A few years ago, we introduced a PIV-based technique for measuring the instantaneous spatial pressure distribution in a sample area (Liu and Katz 2006). This technique originally utilized four-exposure particle image velocimetry (PIV) to measure the distribution of the in-plane components of the material acceleration, and then integrating them by means of virtual boundary omni-directional integration algorithm to obtain the pressure distribution. The robustness of this integration method has been confirmed recently by Charonko et al (2010). Integration of the acceleration field to obtain the pressure distribution has also been used recently by van Oudheusden (2008) and Ragni et al (2009) using spatial integration, and Violato et al (2011) using a Poisson equation solver. Using time resolved measurements, Haigermoser (2009), Koschatzky et al (2010), Li et al (2010) and Moore et al (2011) use the measured pressure field to estimate the acoustic pressure radiated from a cavity flow. We have also replaced the four-exposure setup with a high-speed PIV system, and used it to acquire the data described in this paper. We focus here on the mechanisms involved with the low frequency undulations. A discussion about flow phenomena involved with interactions of the shear layer eddies with the trailing corner, and the associated acoustic radiation can be found in Liu and Katz (2011). With the critical information on the time-resolved instantaneous pressure and velocity distributions available, we show that a clear picture about the feedback mechanism of the low-frequency undulation can be depicted.

2. EXPERIMENTAL SETUP AND PROCEDURES

2.1 Testing model and facility

The experiment has been conducted in a small water tunnel described in Gopalan and Katz (2000) and Liu and Katz (2006). As sketched in Fig. 1, the 38.1 mm long, 50.8mm wide and 30.0 mm deep 2-D cavity is constructed of a transparent acrylic insert that is installed in the 50.8×63.5 mm test section. The test model has a contraction ramp leading to the cavity, and a diffusing ramp downstream of the cavity. A 13 mm long region with tripping grooves, each with a notch depth of 0.46 mm and width of 1.00mm is machined at the beginning of the contraction ramp in order to trip the boundary layer. Thus, the separating boundary layer at the beginning of the
Figure 3. Mean velocity and pressure distributions within the two fields of views around the leading and trailing corners of the 2-D open cavity flow: (a) Ensemble averaged horizontal velocity distribution; (b) Ensemble averaged vertical velocity distribution; (c) Ensemble averaged pressure distribution.

cavity is turbulent. The mean velocity above the cavity is 1.20 m/s, corresponding to Reynolds numbers of 4.0×10⁴ based on cavity length. The origin of the coordinate system used in this paper is placed at the leading edge of the cavity, with the x and y axes pointing downstream and upward, respectively.

2.2 Instrumentation

To perform the time-resolved, 2D PIV measurements, we utilize a Photonics DM60-527 Nd:YLF laser that has a maximum pulse rate of 10 kHz, and pulse width of 100 ns. The images are recorded at 4500 frames per second by a PCO.dimax, CMOS camera, at a resolution of 1008×1000 pixels, giving a Nyquist frequency of 2250 Hz for the velocity. To synchronize the laser with the camera, we use Quantum Composer model 9618 pulse generator. The selected temporal resolution is sufficient for resolving the Kolmogorov time scale, found to be 673 µs, based on curve fits to the spatial energy spectra to estimate the dissipation rate. The size of the field of view is 25×25 mm. With an appropriate concentration of seed particles, 8-12µm diameter hollow glass spheres with specific gravity of 1.05-1.15, we are able to use an interrogation window size of 16×16 pixels, corresponding to 0.4×0.4 mm. This size is similar to the estimated Taylor transverse microscale of 0.5 mm, but is an order of magnitude larger than the Kolmogorov length scale of 26 µm. A 50%...
The overlap between the interrogation windows gives a vector spacing of 0.2 mm. We use an in-house developed software (Roth 1998 and Roth and Katz 2001) for calculating the velocity. The entire dataset for each field of view consists of 10,000 sequentially obtained instantaneous realizations over a period of 2.22 sec.

2.3 Material acceleration measurement and pressure reconstruction procedures

The procedures for obtaining the velocity and the material acceleration, though still following the principle described in [15], have been modified to take advantage of the continuous data series. Analysis of each pair of consecutive images provides an instantaneous velocity distribution, and the entire set provides a time series \( \mathbf{U}_t \), \( \mathbf{U}_{t+1} \), \( \mathbf{U}_{t+2} \), ... \( \mathbf{U}_{t+N} \). Five consecutive images are used for calculating the acceleration. To calculate the velocity field at time \( t \), we use

\[
\mathbf{U}_i = \left( \mathbf{D}_{i+1} - \mathbf{D}_{i} \right) / (2\delta)
\]  

(1)

where \( \mathbf{D}_{i+1} \) is the result of cross correlating image \( i \) with image \( i+1 \). The in-plane projection of material acceleration is calculated using

\[
\frac{D\mathbf{U}_i}{Dt}(x_i,t_i) = \frac{\mathbf{D}_{i+1}(x_i + \mathbf{D}_{i+1}t_{i+1}) - \mathbf{D}_{i}(x_i + \mathbf{D}_{i}t_i)}{2\delta}
\]

(2)

A similar approach is used in de Kat and van Oudheusden (2010). We have also adapted an improved virtual boundary, omnidirectional integration method featuring circular virtual boundary instead of the rectangular one described in [15]. This same approach is also applied in a study of turbulent boundary layer in favorable pressure gradients (Joshi et al., 2011).

3. BASELINE MEAN FLOW QUANTITIES

3.1 Incoming flow conditions

Fig. 2 shows several incoming boundary layer profiles upstream of the cavity, at \( x/L = -0.26, -0.13 \) and \(-0.0007\). The associated calculated parameters are presented in Table 1. Both the log fit in Figure 2b and a shape factor of 1.8 indicate that this boundary layer is turbulent. The Reynolds number based on the momentum thickness, \( \Theta \), at the cavity inlet is \( Re_\Theta = 316 \).

<table>
<thead>
<tr>
<th>Location x/L</th>
<th>Displacement thickness ( \delta^* ) (mm)</th>
<th>Momentum thickness ( \Theta ) (mm)</th>
<th>Shape factor ( H ) (= ( \delta^*/\Theta ))</th>
<th>Skin friction coefficient ( C_f )</th>
<th>Friction velocity ( u_\tau ) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.0007</td>
<td>0.55</td>
<td>0.30</td>
<td>1.8</td>
<td>0.00715</td>
<td>0.0717</td>
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<tr>
<td>-0.13</td>
<td>0.53</td>
<td>0.27</td>
<td>2.0</td>
<td>0.00715</td>
<td>0.0717</td>
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<tr>
<td>-0.26</td>
<td>0.52</td>
<td>0.25</td>
<td>2.1</td>
<td>0.00715</td>
<td>0.0717</td>
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Table 1. Parameters of the boundary layer profiles.
small secondary recirculation region persistently resides just upstream of the trailing corner, and therefore decelerates, forming a mean "stagnation" point. This high pressure peak appears in front of the corner, and a high pressure gradient develops along the cavity vertical trailing wall (Fig. 3b). When this jet returns back to the beginning of the cavity, the associated vertical velocity along the upstream wall decreases to \(0.2U_e\). In the rest of the cavity, the velocity is significantly lower, remaining typically in the order of 10-15% of \(U_e\).

In agreement with Lin and Rockwell (2001), a downward "jetlike" flow, with velocity as high as 40% of the freestream level, develops along the cavity vertical trailing wall (Fig. 3b). This jet impinges on the trailing corner, where it is deflected and broken, periodically feeding vorticity to the flow. The pseudo-streamlines are obtained subtracting half of the external velocity from the velocity vector. As the large shear layer eddies impinge on the trailing corner, they are deformed, sheared, and broken, periodically feeding vorticity to the flow along the horizontal and vertical corner walls (Fig. 5d1). At the instants corresponding to Fig. 5(a1) and (b1), a local region of high vorticity forms right above the corner, and remains attached for part of the cycle. During this phase, a high pressure peak appears in front of the corner, and a negative one above it, indicating that the flow is subjected to high pressure gradients (Fig. 5a2 and b2). In [18], we show that this high vorticity is originated in part from advection of shear layer vorticity, and in part is generated locally due to the high pressure gradients near the corner.

The high positive and negative pressure peaks near the corner disappear periodically when the shear layer eddy is located just upstream of the corner or starts climbing around it (Fig. 5 c and d). These peaks reappear when the eddies are located further upstream (Fig. 5 a and b). The magnitude of these peaks is also affected by the low frequency undulations of the entire shear layer, as discussed in Section 5.2. Disappearance of the pressure peaks, especially the negative one, which also eliminates the cavitation above the corner, occurs as a result of vortex-induced downwash [17, 18]. The positive peak

\[\lambda_{ci}\]

\[C_p\]

\[\lambda_{ci}\]

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\[C_p\]
disappears when the vortex occupies the space upstream of the corner, and reappears when it evacuates this area.

4.2 Characteristic spectra of the shear layer flow oscillations
To investigate the characteristic frequencies embedded in the unsteady flow field, we perform spectral analysis at three representative locations, which are indicated in Fig. 6 (b), the distribution of rms values of pressure fluctuations shown in (b).

Figure 6. Power spectra of horizontal velocity component (left column, c, f, i), vertical velocity component (middle column, d, g, j) and pressure (right column, e, h, k) for points A (first row), M (second row), and C (third row) indicated in the distribution of rms values of pressure fluctuations shown in (b).
Power spectral density functions of horizontal velocity component $\Phi_\nu$ (Fig. 6 c, f, i) and pressure $\Phi_p$ (Fig. 6 c, h, k) for points A (first row), M (second row), and C (third row) are presented in Fig. 6 (c-k). Examination of all the power spectra indicates that the characteristic frequencies of the shear flow oscillations can be categorized into the following three groups: (i) Low frequency, e.g., the peak at 4.4 Hz and others below 20Hz, which, as shown later, are associated with vertical undulations of the entire shear layer. (ii) Peaks within the range of 20-100Hz, which are associated with convection of large eddies in the shear layer. The frequency of these peaks agrees (within the frequency resolution of the spectral analysis, 2.2 Hz) with theoretical predictions of the cavity shear layer modes calculated using (Martin et al 1975, Blake 1986 and Rossiter 1964):

$$fL/U_c = n \pm 0.25, \quad n = 2,3,4,5,6.$$  (3)

Here, $U_c$ is the convection speed of shear layer eddies, estimated as 50% of the freestream velocity. We do not include the $n=1$ modes since they merge with those of the shear layer undulations. Deviation of some spectral peaks from the theoretical values at points M and C might be associated with fragmented eddies during their impingement on the corner; (iii) High frequency fluctuations at frequencies exceeding 100 Hz, extending to the entire range of resolvable time scales. These fluctuations are associated with shear layer broadband turbulence.

Although all the velocity and pressure spectra at the locations share the roughly same characteristic frequencies, the relative magnitude of these peaks vary, depending on which flow phenomenon dominates. For example, the horizontal velocity in point A is most affected by low frequency flapping of the shear layer, while the vertical component and pressure are mostly affected the shear layer eddies. Conversely, at point M, the low frequency part of $\Phi_\nu$ is suppressed and $\Phi_\nu$ increases (Fig. 6f), as the streamwise velocity decreases upstream of the corner, while the vertical fluctuations are strongly affected by the flapping. In this area, $\Phi_\nu$ and $\Phi_p$ have similar shapes, indicating that fluctuations of pressure and vertical velocity component are closely related. It is also worth mentioning that upstream of the trailing corner $\Phi_p$ has the highest low-frequency peak in the entire flow field, indicating the substantial contribution of low-frequency shear layer undulations to the unsteady pressure there. Above the corner (point C), the low-frequency peaks are prominent in all spectra.

5. EVIDENCE FOR AND EFFECTS OF THE LOW-FREQUENCY UNDULATION

5.1 Evidence

To explain the origin of the low frequency peaks, we start by examining the time series of $u$, $v$ and $p$ at point A. Consistent with the power spectra, the time series of $u$, shown in Fig. 7(a), exhibits high amplitude, low frequency fluctuations, with magnitude varying between 40 to 100% of $U_c$. These fluctuations are not associated with the transport of shear layer eddies that occur at much higher frequencies and cause the spiky appearance of the long time series in Fig. 7(a). In contrast, $v$ and $p$ do not exhibit the same high amplitude, low-frequency fluctuations at this location.

To associate the typical flow patterns with the low-frequency fluctuations, Fig. 7(b) and (c) display two typical swirling strength and pressure distributions when the streamwise velocity at point A is low and high, respectively. As is evident,
the location of the entire shear layer fluctuates vertically. When the shear layer is high (Fig. 7b), the velocity at point A is low, and when the shear layer is low, the same point is located at the top of the shear layer, and the velocity there is almost equal to the freestream value. This phenomenon has been referred to before as “jitter” (Rockwell and Knisely 1979, Najm and Ghoniem 1991 and Pereira and Sousa 1995), and attributed to instabilities of the large recirculation motion within the cavity (Najm and Ghoniem 1991).

5.2 Effects
To characterize the vertical undulation of the shear layer, we examine the low-pass filtered (cut-off frequency 20Hz) vertical location of the vorticity center, \( Y_c \), within the area enclosed by the square shown in Fig. 8(a). The size of this control area is selected to approximately cover an entire large-scale eddy. The original as well as the low-pass filtered time variations of \( Y_c \), shown in Fig. 8(b), represent the vertical position of the shear layer. The filtered and unfiltered spectra of \( Y_c \), which are presented in Fig. 8(c), have a clear peak at 4.4Hz. The correlation between the low-pass filtered \( Y_c \) and the low-pass filtered pressure at the points labeled as B, C, D, E, F, M in Fig. 8(a) are shown in Fig 8(d-i). It can be seen that the highest correlation of -0.81 is measured close to the impingement point. The pressure at points B and E, which are located in the vicinity of point M, remains negatively correlated with \( Y_c \), but at a reduced magnitude. In contrast, at points C and F, where the pressure coefficient is predominantly negative, the pressure is positively correlated with the filtered \( Y_c \). These trends indicate that when the shear layer is low, the pressure around the impingement location is high, and the pressure coefficient above the trailing corner is more negative, maximizing the streamwise pressure gradients there. Conversely, when the shear layer is high, the pressure
Figure 9. Conditionally averaged distributions of (a-b) pressure, (c-d) vertical velocity, and (e-f) rms value of vertical velocity fluctuations corresponding to conditions of (a, c, e), the low-pass filtered \( Y_c \) located in its lower 30% range; and (b, d, f), the low-pass filtered \( Y_c \) located in its upper 30% range around the trailing corner.

around the impingement point is low, and the pressure coefficient above the trailing corner is less negative, minimizing the streamwise pressure gradients.

The high correlation values imply that the pressure fluctuations around the corner are strongly influenced by the vertical shear layer flapping. With increasing distance from the corner, the trends persist, but the correlation levels
upstream field of view. First of all, with changing elevation, the downstream field of view, or the lowest 40%, for the corner significantly, as demonstrated in Fig. 9, where the shear layer changes its interaction with the downstream trailing corner, are lower by 48% and 40%, respectively, when the magnitudes of the pressure peaks upstream and above the corner are high (Fig. 9c, d). This trend indicates, as expected, that larger fractions of the shear layer are entrained as the flow impinging on it, i.e. when the shear layer is low. The stronger negative pressure peak on top of the corner at nearly the same phase is directly associated with the increasing momentum in the local flow accelerating and curving around the corner. The higher pressure-gradient when $Y_c$ is low, in turn, would force this boundary layer to become thicker.

To explain the processes causing the shear layer undulations, we return in Fig. 12 to the vicinity of the upstream corner, and compare the conditionally averaged distributions of streamwise velocity (Fig. 12a-b), vertical velocity (Fig. 12c-d), and pressure (Fig. 12e-f). Here, $Y_c$, is defined based on the centre of vorticity distribution within the square area indicated in Fig. 12d. Consistent with the previous result, the entire boundary layer upstream of the cavity widens when $Y_c$ is high (Fig. 12a-b). The vertical velocity distribution shows another important effect in the broad region of high velocity along the backward-facing vertical wall. This velocity is clearly higher when $Y_c$ is low, as is also demonstrated by a series of profiles shown in Fig. 13. Thus, when the shear layer is low, there is faster downward jetting along the forward-facing vertical wall of the cavity, and a faster upward jet along the backward-facing vertical wall. Associated with this higher momentum, is a higher pressure just downstream of the separation point in the cavity leading corner (Fig. 12e). This higher pressure inherently exposes the boundary layer upstream of the leading corner to higher adverse pressure gradients, and consequently, would force this boundary layer to become thicker.

The correlations between the shear layer height and the pressure in several locations near the upstream vertical wall, which are marked in Fig. 12d, are shown in Fig. 14. All of the plots show very similar trends, namely that the pressure is negatively correlated with $Y_c$ at $x/L = 0.13$ (Fig. 11d-f), when the shear layer is still thin, the differences in thickness are still of the same order as those observed in the boundary layer. However, trends of the shear stress change, as the shear layer becomes thinner, and the shear stress becomes higher when the shear layer is low (Fig. 11e, f). This trend is consistent with the previously shown plots, that the pressure is high when the shear layer is low. However, 0.4 s later, the pressure would become also become low, at the same time that $Y_c$ reaches its high peak.

Figure 10. Development of the vertical velocity profiles along the trailing vertical wall at selected locations when the shear layer is high (indicated by hollow symbols on plot) and low (indicated by dark symbols).
Figure 11. Effect of low-frequency undulation on (a, d, g, j), mean streamwise velocity; (b, e, h, k), rms values of streamwise velocity fluctuations and (c, f, i, l), Reynolds stress profiles at different streamwise locations.

6. THE CLOSED-LOOP FEEDBACK MECHANISM OF THE LOW-FREQUENCY UNDULATION

The data and trends presented in the previous sections enable us to clarify the feedback mechanism that causes the low-frequency undulation of the shear layer. This process is illustrated by the sketches presented in Fig. 15. Suppose initially the shear layer is low. As a result, higher momentum flow is entrained into the cavity, increasing the pressure near the downstream corner, as well as the vertical pressure gradients and the associated downward jetting along the trailing vertical wall. When this faster jet recirculates back, it increases the pressure near the leading corner of the cavity. This elevated pressure, though one order of magnitude smaller than its counterpart at the downstream impingement region, plays a pivotal role in the entire feedback loop associated with the low-frequency undulations. The resulting increased adverse streamwise pressure gradient, forces the upstream boundary layer to thicken, and the shear layer to roll up at a
higher elevation. Once the shear layer shifts to a higher elevation, both the high pressure peak near the downstream corner and the downward jetting into the cavity decrease. Consequently, the returning jet, and the pressure peak near the upstream corner also decrease, reducing the adverse pressure gradient facing the boundary layer prior. The more favorable (but still adverse) pressure gradients result in a thinner boundary layer, and a downward shift in the vertical location.

Figure 12. Conditional averaged distributions of (a-b) streamwise velocity, (c-d) vertical velocity, and (e-f) pressure corresponding to conditions of (a, c, e) the low-pass filtered shear layer height $Y_c$ located in its lowest 40% range, and (b, d, f) the low-pass filtered $Y_c$ located in its upper 30% range. The shear layer height $Y_c$ is represented by the vorticity center of the orange control area indicated in (d).
development of the vertical velocity profiles along the leading vertical wall at selected locations when the shear layer is high (indicated by hollow symbols on plot) and low (indicated by dark symbols).

Figure 14. Correlation of the low-pass filtered $\gamma_c$ and the pressure at points A1-A9 as indicated in Fig. 12(d).

Figure 15. The closed-loop feedback mechanism for the low-frequency undulation of the cavity shear layer.

of the entire shear layer, thus initializing another round of the low-frequency undulation.

7. CONCLUSIONS

Time resolved PIV data are used for calculating the pressure distribution and resolving the unsteady flow structure in an open cavity shear layer. Conditional sampling, low pass filtering and correlations among variables enable us to elucidate two primary mechanisms, each with a distinctly different frequency range, that dominate this unsteady flow. The first involves Kelvin Helmholtz shear layer eddies and their interactions with the trailing corner of the cavity. The associated Strouhal numbers are in the 0.6-3.2 range, consistent with results of prior studies. The second mechanism involves low frequency undulations/flapping of the entire layer and has a characteristic Strouhal number of 0.10. The data show that interactions of the undulating shear layer with the trailing corner of the cavity cause substantial changes to all the mean flow and turbulence quantities over the entire cavity, but particularly around and downstream of the trailing corner. Measurements of the intrinsic high correlations between the shear layer elevation and flow variables, such as pressure and velocity at different locations, enables us to present a clear picture about the feedback mechanism that sustains these low-frequency undulation. This feedback process involves pressure fluctuations on both corners of the cavity along with associated internal backflow and changes to the boundary layer upstream of the cavity.

Briefly, when the shear layer is low, a high momentum fluid impinges on the trailing corner, generating a high pressure peak and a relatively fast downward jet along the trailing wall. When this flow circulates and returns to the beginning of the cavity along the upstream wall, it increases the pressure near the upstream corner of the cavity. The resulting increase in adverse pressure gradients upstream of this corner increases the thickness of the boundary layer there, causing an upward shift in the location and orientation of the shear layer that evolves from this boundary layer. As the elevated shear layer arrives to the downstream corner, the pressure peak and downward jetting weaken, leading to a reduced pressure in the upstream corner, thinning of the boundary layer, and a downward shift in the shear layer. This sequence of flow phenomena constitutes a closed-loop feedback system that
sustains the low-frequency shear layer undulations, and has substantial impact on the flow structure, turbulence and noise radiated from the downstream corner of the cavity. Identification of the processes involved with this feedback mechanism might be utilized for developing control strategies or devices for alleviating/suppressing the low-frequency components of turbulence and noise generated by the cavity shear layer.

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