Shear layer oscillation along a perforated surface: a self-excited large-scale instability

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SHEAR LAYER OSCILLATION ALONG A PERFORATED SURFACE:

A SELF-EXCITED LARGE-SCALE INSTABILITY

by

Emine Celik

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ABSTRACT

Self-sustained oscillations of a free-shear flow, i.e., a jet, mixing-layer or wake, can arise from its impingement upon a downstream boundary; these oscillations are well documented. The present experiments demonstrate existence of analogous oscillations for the case of a shear layer along a perforated plate. The spectrum of the pressure fluctuation at impingement shows sharply defined peaks. Moreover, the predominant frequency of oscillation exhibits a variation with either impingement length or inflow velocity that is remarkably similar to the case of the corresponding free-shear layer in absence of the perforated plate. Quantitative imaging yields patterns of large-scale vorticity concentrations and streamline topology, which have similar features for the shear layer along the perforated plate and the free-shear layer in absence of the plate. All of these observations indicate existence of a feedback mechanism for the shear layer along the perforated plate of finite length.
1. INTRODUCTION

The unsteady flow past a cavity, which is a form of self-sustaining oscillation, occurs in a variety of applications such as water tunnels, slotted-flumes, bellows type geometries, cavities in gasdynamic lasers, aircraft components, cavities in submarine and ship hulls, steam regulation and control valves. These types of oscillations are the origins of unsteady structural loading and fatigue, generation of noise and vibration.

In recent decades, considerable effort has been devoted to the study of self-sustained oscillations of free shear layers. The central features of these oscillations are described/reviewed by Powell (1961), Rockwell and Naudascher (1978, 1979), Rockwell (1998), Chomaz et al. (1988), Crighton (1992) and Howe (1998), and Kwan (1998). For persistent oscillations, the required elements are: amplification of an unstable disturbance in the free shear layer; impingement of the unsteady layer upon the corner/edge, which gives rise to an upstream influence; and conversion of this upstream influence to fluctuating vorticity at the receptive region of the separation corner, or lip. The consequence of this communication between the downstream and upstream edges of an impinging flow configuration is to yield stage-like variations of the predominant frequency $f_0$ of oscillation as a function of the inflow velocity $U$ and the streamwise length scale $L$. These self-excited oscillations are typically very coherent, and may be associated with the generation of higher harmonics, subharmonics, and nonlinear sum and difference frequencies, as summarized by Knisely and Rockwell (1982). It is important to note that flow oscillations can be grouped into three categories: fluid-dynamic (flow-boundary interaction), fluid-
resonant (due to excitation of a resonator associated with compressibility or free-surface wave phenomena), and fluid-elastic (due to elastic displacement of a solid boundary).

Undulations of the separated shear layer along a cavity are typical of the self-sustained oscillations described in the foregoing. Representative investigations include those of Sarohia (1977), Knisely and Rockwell (1982), and Gharib and Roshko (1987). Taken together, these studies clearly show the occurrence of well-defined spectral peaks of the velocity fluctuations in the oscillating shear layer; and the pressure fluctuations at the impingement (downstream) corner of the cavity. The frequencies of these peaks show stage-like characteristics when either the inflow velocity $U$ or the impingement length $L$ is varied.

If the unsteady shear layer past a cavity couples with an acoustic resonant mode of either the bounding cavity or the main duct, highly coherent oscillations can occur. Such coupled oscillations, which can occur in a wide variety of configurations, are reviewed by Rockwell et al. (2002). They can occur not only in air, as shown, for example, by DeMetz and Farabee (1977), but also in water systems, as demonstrated by Burroughs and Steinebring (1994). It should be emphasized that the present experiments do not involve coupling with a resonator, i.e., they are purely hydrodynamic.

Applications of flow through perforated surfaces can be found in the exhaust system of an automobile, within reciprocating engine systems, aircraft engines and compressors. Even though perforated surfaces are used for attenuation of sound in
flow systems, depending on the parameters of the perforated surfaces, they can create adverse effects like the onset of singing or pure tone noise generation.

Flow past a perforated plate, which contains a large number of individual cavities, has been investigated from several different perspectives. Tsui and Flandro (1977) address the case where vortices were shed over each of the individual holes; coupling of this vortex shedding with an acoustic mode(s) within the duct, gave rise to a "singing" phenomenon. The Strouhal number of this resonance varied directly with the diameter of the holes of the perforated plate. Ronneberger (1980) characterized in detail the oscillating interface along the mouth of a cavity, which simulated a single hole in a perforated plate. These results were used to aid interpretation of a model for the impedance of small holes subjected tangential, or grazing, flow. Dickey, Selamet and Ciray (2001) characterized the impedance of perforated plates with grazing flow. Instead of a self-excited oscillation, they induced tonal undulations via a controlled loudspeaker, which was located at the end of the side branch. Nelson (1982) focused on the generation of broadband noise, rather than discrete tones, due to flow past a perforated plate. The intent of their investigation was to establish a base level of noise due to insertion of various perforated liner configurations. The importance of noise generation due to flow past perforated plates extends to the transonic range, as demonstrated by Medved (1993), who addressed the attenuation of edge tone noise by splitter plates for perforated walls of the test section of a transonic wind tunnel. In all of the foregoing investigations, as well as related works cited therein, the possibility of a self-excited, coherent oscillation, which has a
wavelength much longer than the hole diameter of the perforated plate, has not been addressed. More specifically, the possible occurrence of a long wavelength, purely hydrodynamic oscillation, in absence of any acoustic or elastic effects, has not been pursued for shear flow past a perforated plate.

The separated, time-averaged shear layer along a cavity without a perforated plate has an inflectional velocity distribution and rapidly amplifies disturbances. In contrast, the time-averaged shear layer along a perforated plate has the form of a boundary layer without an inflection point. The issue arises as to whether the unsteady characteristics of this shear layer, when constrained by a streamwise length scale L, and in absence of acoustic resonant or elastic effects, effectively mimic the oscillating characteristics of the corresponding free shear layer in absence of a perforated plate.

The overall objectives of the present investigation are to determine: the spectral content of the oscillation; the manner in which the spectral peaks vary with changes in inflow velocity U and streamwise length scale L; and the detailed structure of the unsteady structure of the shear flow past the perforated plate under purely hydrodynamic conditions.
2. EXPERIMENTAL SYSTEM AND TECHNIQUES

2.1. INFLOW SYSTEM

Experiments were performed in a water channel with a test section 927 mm wide, 610 mm deep and 4,928 mm long. This test section is preceded by a stilling chamber and a flow conditioning section that involves a series of honeycomb and screens, followed by a contraction. The perforated plate assembly was housed in an insert located downstream of the contraction system. In order to allow a highly controlled boundary layer incident upon the perforated plate, two different arrangements were used:

(a) A special bleed arrangement was employed upstream of the perforations. With this configuration, a well-defined, quasi-laminar boundary layer profile was generated immediately upstream of the perforations, as shown in the plan view of Figure 1a. In this case, the freestream velocity was \( U = 12.6 \text{ cm/s} \), the boundary layer thickness was \( \delta = 6.8 \text{ mm} \) and the value of momentum thickness was \( \theta = 0.9 \text{ mm} \), as measured at a location 10mm upstream of the leading row of holes in the perforated plate. The value of Reynolds number based on \( \theta \) was \( Re_\theta = 113 \).

(b) An alternate arrangement, shown in Figure 1b, yielded a turbulent boundary layer profile. For this configuration, the free-stream velocity was maintained at a value \( U = 28.3 \text{ cm/s} \), the momentum thickness of the turbulent boundary layer was \( \theta = 1.45 \text{ mm} \), measured at the same location
as for (a). The Reynolds number based on θ was $Re_θ = 410$. The value of the boundary layer thickness was $δ = 15.1$ mm.

2.2 PERFORATED PLATE SYSTEM

The perforated plate system was bounded on the far side by a large, closed cavity shown in Figure 4, which was attached to the vertical plate that housed the perforated plate. The scale of this cavity was much larger than the surface length and width of the perforated plate, in order to preclude the influence of recirculation flow within the cavity. The length of the cavity in the streamwise direction was 610 mm, its height was 432 mm, and its depth was 432 mm, as can be seen in Figure 4. These dimensions compare with the length of the perforated plate in the streamwise direction, which was 203 mm; and its height was also 203 mm. The cavity was designed such that wall elasticity effects and fluid compressibility effects due to small bubbles were precluded. Furthermore, the acoustic wavelengths corresponding to the unstable frequencies of interest herein were approximately two orders of magnitude larger than the characteristic dimension of the cavity. All of these considerations ensure that the effect of the cavity is purely hydrodynamic, with no fluid-elastic or fluid-resonant effects.

The thickness of the perforated plate was 11 mm, and the diameter of each hole in the plate was $D = 0.64$ cm. As indicated in the side view of Figure 2, the holes of the perforated plate were arranged in a staggered pattern, with values of $Δ_a = 0.73$ cm and $Δ_b = 0.64$ cm. This arrangement corresponded to an open area ratio of 68.6 %. As indicated in Figure 2, the effective length $L$ of the perforated plate
exposed to the incident shear flow could be altered by sliding an impingement plate along its near surface.

2.3. PRESSURE SIGNAL ACQUISITION AND CALCULATION OF SPECTRA

The impingement plate housed a pressure transmission line, which was connected to a high sensitivity transducer, as indicated in the view of Figure 3. It allowed acquisition of pressure signals at the tip of the edge with negligible amplitude and frequency distortion. Spectra of the fluctuating pressure were obtained by sampling the signal at a frequency $\Delta f = 20$ Hz, which gives a Nyquist frequency $1/2\Delta = 10$ Hz, relative to the highest frequency of interest in this investigation $f = 6$ Hz.

2.4. IMAGING SYSTEM

In order to quantitatively interpret the flow patterns, a technique of high-image-density particle image velocimetry was employed. A laser sheet was generated from two Nd:Yag pulsed lasers ($\lambda = 532$ nm) in conjunction with a cylindrical-spherical lens combination. A collimated laser beam is transmitted through a cylindrical lens to diverge the beam in the height direction and a spherical lens is used to control the thickness of the light-sheet. The camera is focused near the light-sheet waist, at the focal length of the spherical lens, which is 1000 mm in this experiment. The maximum power rating of each laser was 90 mJ. The sheet was horizontal, such that it intersected the perforated plate at the midspan of the hole pattern. The flow was seeded with 12 micron hollow plastic spheres, which were metallic coated and essentially neutrally buoyant. The schematic of arrangement of the imaging system is given in Figure 5. The patterns of particle images were acquired using a digital
camera with a resolution 1,024 × 1,024 pixels. The camera is used at its maximum framing rate of 30 frames/sec, which gives 15 sets of cross-correlated images per second. For the first experimental setup which was given in Figure 1a, a lens of focal length 60 mm was used, providing a magnification of 1:13.6. For the case of the turbulent boundary layer, a 28 mm lens was used, with a magnification of 1:4.3. 

Each frame pair of the patterns of particle images was cross-correlated, in order to yield the pattern of velocity vectors. An interrogation window of 32 × 32 pixels was employed. The number of particle images within this interrogation window was approximately 15 to 25, in order to satisfy the high-image-density criterion. To ensure that the Nyquist criterion was met, these windows were overlapped by 50% during the interrogation process. The pattern of instantaneous velocity vectors attained using this approach extended over a field of view 3.2 cm × 6.5 cm for the case of the quasi-laminar inflow boundary layer. Over this region, a total of 1,568 velocity vectors were produced. In the case of the turbulent inflow boundary layer, the dimensions of the field of view were 7.2 cm × 18.2 cm. For the images shown herein, only the vorticity-bearing region of the original field of view is illustrated.

2.5. TIME AVERAGING OF PIV IMAGES

Time-averaged velocity, vorticity and velocity correlation were calculated by using the following formulas.

\[ <u(x,y)> = \frac{1}{N} \sum_{i=1}^{N} u_i(x,y) \]
\[
<v(x, y) > = \frac{1}{N} \sum_{i=1}^{N} v_i(x, y)
\]

\[
< \omega(x, y) > = \frac{1}{N} \sum_{i=1}^{N} \omega_i(x, y)
\]

\[
\sqrt{\frac{1}{N} \sum_{i=1}^{N} [u_i(x, y) - < u(x, y) >]^2}
\]

\[
\sqrt{\frac{1}{N} \sum_{i=1}^{N} [v_i(x, y) - < v(x, y) >]^2}
\]

\[
\sqrt{\frac{1}{N} \sum_{i=1}^{N} [\omega_i(x, y) - < \omega(x, y) >]^2}
\]

\[
< u'v' > = \frac{1}{N} \sum_{i=1}^{N} [u_i(x, y) - < u(x, y) >] [v_i(x, y) - < v(x, y) >]
\]

For the present experiments, \( N = 200 \); \( N \) is the number of images.

2.6. PHASE-AVERAGING OF PIV IMAGES

The equations employed for time-averaging can also be applied for phase-averaging, whereby images are averaged at a given phase of the oscillation cycle.

In determining the phase reference, the sequence of instantaneous PIV images is considered in order to identify a characteristic event that occurs at a given phase.

For the case of the low Reynolds number inflow boundary layer, i.e., case (a), a set of 200 images was analyzed. This set corresponded to 12 complete cycles of oscillation, and the period of oscillation was 17 PIV images, which represents 1.13 seconds.
3. LOW REYNOLDS NUMBER INFLOW BOUNDARY LAYER: PRESSURE SPECTRA

All of the pressure spectra given in this part were obtained using the first experimental arrangement, which is given in Figure 1a, and described in Section 2.1.

A representative spectrum of the fluctuating pressure at the tip of the impingement edge (see Figure 4) is given in Figure 6. Three spectral peaks are designated as $f_1$, $f_2$ and $f_3$.

The general form of the spectrum shown in Figure 6 persisted over a range of flow velocity extending from 9.4 to 24.2 cm/s. The frequencies of the predominant spectral peaks $f_1$, $f_2$, and $f_3$ were plotted as a function of flow velocity (given in Figure 7), and each frequency was shown to exhibit an approximately linear variation. The corresponding values of Strouhal number were, according to a linear best fit, $S_1 = f_1 L/U = 0.6$, $S_2 = 1.2$, and $S_3 = 1.9$. Remarkably, these types of multiple modes, with values of approximately $S_1 = 0.5$, $S_2 = 1.0$, and $S_3 = 1.6$, occur for the classical case of unstable flow past a cavity in absence of a perforated plate, as summarized by Rockwell and Naudascher (1978). This observation suggests the existence of a feedback mechanism for the unstable shear layer along the perforated plate. It promotes highly coherent oscillations that scale with inflow velocity $U$ in the same manner as undulations of the separated free shear layer along the cavity of length $L$.

The variations of the frequencies of the major spectral peaks $f_1$ and $f_2$ with impingement length $L$, at a constant value of inflow velocity $U$, are shown in Figure 8. The values of $f_1$ and $f_2$ decrease with increasing impingement length $L$ until, at a
critical value of \( L = 13.5 \) cm, they jump to a higher value, then again decrease for successively larger values of \( L \). This type of variation of \( f \) vs. \( L \), along with the frequency jump, is a basic characteristic of impinging free shear layers in absence of a perforated plate (Rockwell and Naudascher, 1979). The effect of the finite streamwise length scale \( L \) of the instability along the perforated plate is therefore indicative of an upstream influence similar to that for the undulating free shear layer.

In addition to the above measurements, data were obtained by varying the free-stream velocity \( U \) at a constant value of impingement length \( L \) (not shown here), in order to further analyze the oscillation process. The variation of \( f \) versus \( U \) showed characteristics similar to oscillations in absence of a perforated plate (Knisely and Rockwell, 1982). The frequency \( f \) increased linearly with \( U \).

4. LOW REYNOLDS NUMBER INFLOW BOUNDARY LAYER: FLOW PATTERNS

Figures 9 and 10 show patterns of vorticity and streamline topology for a free-shear layer along the opening of a cavity of streamwise length \( L \) (left column), in comparison with the instability along the perforated plate of effective length \( L \) (right column), which is bounded by the same cavity.

In absence of the perforated plate, the time sequence of patterns of phase-averaged vorticity \( \langle \omega \rangle_p \) show a highly-ordered series of vorticity concentrations, similar to those described by Sarohia (1998), Knisely and Rockwell (1982) and Gharib and Roshko (1987) using smoke and dye visualization. The patterns of phase-averaged streamlines \( \langle \Psi \rangle_p \), shown in the left column of Figure 10, are in a reference
frame moving with the convective speed of the vorticity concentrations. They indicate well-defined foci (centers of vortices) and saddle points (intersecting streamlines). The patterns of both streamline topology and vorticity are substantially distorted along the leading portion of the impingement plate.

In the right column of Figure 9, the phase-averaged patterns of vorticity $\langle \omega \rangle_p$ show development of a single concentration, which is also distorted upon encounter with the leading region of the impingement plate. The corresponding pattern of streamline topology shows well-defined foci and saddle points. The middle image of the streamline topology in the right column shows that the streamwise distance between successive saddle points is larger than the case of no perforated plate given in the left column; this observation corresponds to the elongated nature of the vorticity concentrations. Furthermore, distributions of time-averaged vorticity are indicated on Figure 11. These distributions have the form of a bounded shear layer with no inflection point, in contrast to the well known inflexional shape of the separated shear layer in absence of the perforated plate.

Also, contours of time-averaged $u$ and $v$, i.e., $\langle u \rangle$ and $\langle v \rangle$, were investigated for unstable flow past a cavity in absence of the perforated plate and with perforated plate. These patterns, which are given in Figures 11 and 12, show similar patterns for cases with and without the perforated plate case.

Corresponding patterns of the velocity fluctuations and their correlation are given in terms of $u_{rms}/U$, $v_{rms}/U$, and $\langle u'v' \rangle/U^2$ in the images of Figures 14.
through 17. The contours of $u_{rms}/U$ and $v_{rms}/U$ are concentrated in a region close to the perforated plate.

Figure 17 compares patterns of time-averaged Reynolds stress $<u'v'>/U^2$ for unstable flow past a cavity in absence of a perforated plate, and in presence of a perforated plate. For the case of the perforated plate, represented by the top set of contours, high levels occur in the region close to the plate perforation. In absence of the perforated plate, contours are much more broadly distributed, but highly concentrated regions occur at approximately $x=20$ mm and 50 mm.

5. MODERATE REYNOLDS NUMBER (TURBULENT) INFLOW BOUNDARY LAYER: FLOW PATTERNS

The flow structure for the case of an initially turbulent boundary layer, which has the characteristics described in Section 2.1, is particularly complex, relative to the case of the low Reynolds number (quasi-laminar) boundary layer described in the preceding section. In view of this complexity, entire time sequences of instantaneous images of vorticity $\omega$, Reynolds stress correlation $u'v'$ and transverse velocity fluctuation $v$ are given in the image layouts of Figures 18, 19 and 20. For all images shown in Figures 18 through 20, the flow is from right to left, in contrast to the usual flow direction, i.e., from left to right. Despite the fact that the inflow boundary layer is turbulent, organized patterns of the flow structure are detectable for each of these representations. In the following, the major features of the instantaneous flow structure are described by referring to selected images of the instantaneous patterns.
5.1. PATTERNS OF INSTANTANEOUS VORTICITY

Patterns of instantaneous vorticity $\omega$ are given as a sequence of 90 images, designated in Figure 18 as frames 1 through 90. The minimum and incremental values of vorticity for the designated contours are given in the caption of Figure 18.

Viewing the patterns of vorticity of Figure 18 as a whole, i.e., considering frames 1 through 90, it is evident that a vertical deflection of the maximum level of vorticity occurs as the tip of the impingement edge is approached. For example, in frames 13 and 25, the layer of vorticity is essentially flat, even in the immediate vicinity, i.e., immediately upstream, of the impingement edge. Between these frames, the vorticity pattern in this region experiences substantial vertical deflection in the form of undulations of the shear layer. Note that the time elapsed between frames 13 and 25 corresponds to a total of 12 frames. In view of the fact that the framing rate of the imaging system is 15 frames per second, a total of twelve frames corresponds to a frequency of 1.25 Hz, which is approximately equal to the frequency of the spectral peak obtained from pressure measurements. For later frames in this sequence, so-called "flat" patterns, similar to the patterns of frames 13 and 25, can be observed in frames 36, 48, and 61. Although the difference in number of frames is not the same as between frames 13 and 25, it is clear that it is indeed approximately 12 frames, which, as indicated in the foregoing, is in accord with the measured frequency of oscillation.

Further details of the flow patterns in frames 13 through 25 are as follows. As the flow structure progresses from frames 13 through 15, the relatively uniform layer
of maximum vorticity in frame 13 transforms to a less organized form over the left half of the image, i.e., as the flow approaches the impingement edge. At later times the overall layer of vorticity appears to deflect downward (away from) the surface of the perforated plate. This deflection is particularly evident in frame 19. Thereafter, in frames 20 through 23, this downward deflection is still very evident, and eventually in frames 24 and 25, the vorticity layer again takes a relatively undisturbed, flat form. A similar cycle of events can be seen for frames 25 through 36.

Finally, as an overall observation, it should be noted that the layers of vorticity in the sequence of images shown in Figure 18 extend a distance of the order of 15 to 25 mm from the surface of the perforated plate. This overall thickness of vorticity layer compares with the momentum \( \theta \) and boundary layer \( \delta \) thicknesses, which have values of \( \theta = 1.45 \text{ mm} \) and \( \delta = 15.1 \text{ mm} \).

5.2. PATTERNS OF INSTANTANEOUS REYNOLDS STRESS

Patterns of instantaneous Reynolds stress \( u'v' \), which correspond to the patterns of instantaneous vorticity \( \omega \) given in the preceding section, are provided in the images of Figure 19, which extend from frame 1 to frame 90. Generally speaking, these patterns of \( u'v' \) are not as distinct and coherent as the patterns of instantaneous vorticity. Nevertheless, it is possible to detect certain, overall features, as described in the following. In frames 52 through 54, for example, it is apparent that the dominant Reynolds stress is indicated by the black regions, which correspond to negative values of \( u'v' \). On the other hand, for frames 59 through 61, the value of
positive (white) regions of Reynolds stress starts to become significant, and appears to have values that are as large as the aforementioned negative (black) regions.

Further observations concerning the contours of constant $u'v'$ are evident in Figures 41 through 44. The predominant cluster of negative (black) $u'v'$ moves from right to left in images 40 to 44, which apparently corresponds to the phase speed of the disturbance. Similar types of movement of reasonably well-defined concentrations of $u'v'$ are evident, for example, in frames 76 through 79, as well as in other sets of frames in this sequence.

5.3. **CONTOURS OF CONSTANT TRANSVERSE (VERTICAL) VELOCITY**

Patterns of instantaneous contours of transverse velocity $v$ are given in Figure 20, which again extends over frames 1 through 90, in direct correspondence with the corresponding patterns of instantaneous vorticity and instantaneous Reynolds stress correlation $u'v'$ given in Figures 18 and 19.

Consider, for example, the patterns of black concentrations shown in frames 13 through 24. These black regions correspond to instantaneous vertical velocity $v$ oriented in the downward direction (away from the perforated plate). Unlike the representations of instantaneous vorticity $\omega$ and Reynolds stress correlation $u'v'$, these negative (black) contours are not located close to the surface of the perforated plate. They can extend to a distance of approximately $120 - 60 \text{ mm} = 60 \text{ mm}$ from the surface of the perforated plate.

Regarding positive (white) contours of constant vertical velocity $v$, they can be tracked with reasonable effectiveness in frames 5 through 64. During the initial
part of this image sequence, it is evident that the positive (white) contours, which correspond to upward oriented vectors, originate at the surface of the perforated plate and move downstream, i.e., from right to left.

Concerning negative (black) regions, which correspond to downward oriented vectors of instantaneous vertical velocity \( v \), consider either frame 13 or 48. It is evident that there is no negative (black) contour of instantaneous \( v \) and the corresponding vorticity pattern is flat. On the other hand, when the negative (black) contours are close to the surface of the plate as shown, for example, in images 30 and 79, the vorticity pattern exhibits significant undulations as it approaches the tip of the impingement edge.
6. CONCLUSIONS

An unsteady shear flow along a perforated plate of finite streamwise extent can exhibit highly coherent, self-sustaining oscillations, which have been characterized using pressure spectra and quantitative visualization. The variations of the frequencies of the spectral peaks of pressure, with both inflow velocity and plate length, are remarkably similar to those observed for the classic cases of flow past cavities, and in jet-edge configurations, in absence of a perforated plate. This observation indicates that the finite length of the perforated plate allows existence of a feedback mechanism between its downstream and upstream edges.

Quantitative imaging of the unstable shear flow along the perforated surface confirms the remarkably organized oscillations evident in the pressure spectra. Repetitive formation of vorticity concentrations occurs in conjunction with well-defined foci and saddle points in the corresponding streamline topology. These features are generally similar to those of the corresponding unstable free-shear layer past the cavity opening in absence of the perforated plate.

Fully turbulent inflow past a perforated plate also can give rise to highly coherent, self-sustained oscillations. This type of long wavelength instability is different from the instability typically associated with the local instabilities past individual holes in a perforated plate.
7. REFERENCES


Howe, M. S. 1997, "Edge, cavity and aperture tones at very low Mach numbers", *J. Fluid Mech.* 33, 61-84.


Figure 1a: Overview of submerged perforated plate-cavity system for low Reynolds number inflow boundary layer. (All dimensions are in mm.)
Figure 1b: Overview of submerged perforated plate-cavity system for turbulent inflow boundary layer.
Figure 2: Perforated plate.
Figure 3: Closeup of impingement plate showing pressure tap, transmission line, and transducer housing system. (All dimensions are in mm.)
Figure 4: Closed cavity with access ports. (All dimensions are in mm.)
Figure 5: Views of perforated plate test section showing orientation and location of laser, generated laser sheet, camera and field of view for laser sheet.
Figure 6: Spectra of pressure fluctuations. Impingement length $L = 9.16$ cm. Perforated plate has holes of diameter $D = 0.64$ cm.
Figure 7: Variation of spectral peaks of pressure fluctuation with inflow velocity $U$. Impingement length $L = 9.16$ cm. Perforated plate has holes of diameter $D = 0.64$ cm.
Figure 8: Spectra of pressure fluctuations. Perforated plate has holes of diameter $D = 0.64$ cm.
Figure 9: Phase-averaged vorticity patterns in absence of perforated plate and with perforated plate. The minimum contour level is $-25 \, \text{sec}^{-1}$ and the incremental value is $2.166 \, \text{sec}^{-1}$. 
Figure 10: Phase-averaged streamlines in the moving frame with $U_{ref}$ at successive phases of the oscillation cycle.
Figure 11: Time-averaged vorticity distributions for unstable flow past a cavity of length L in absence of a perforated plate and with a perforated plate of effective length L, which is defined as the distance from the upstream boundary of the perforated plate to the impingement edge. $\omega_{\text{min}} = -20.6 \text{ sec}^{-1}$, $\Delta \omega = 1.5 \text{ sec}^{-1}$. In both cases, the field of view corresponds to $0.7L$, $U = 12.6 \text{ cm/s}$, $Re_\theta = U\theta/\nu = 113.4$, $D = 0.64 \text{ cm}$, $D/\theta = 7.11$, $L = 9.16 \text{ cm}$, $L/\theta = 101.76$. 

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Figure 12: Contours of time-averaged streamwise velocity with perforated plate and in absence of perforated plate. The minimum contour level is 0.924 cm/s and the increment is 0.85 cm/s.
Figure 13: Contours of time-averaged transverse velocity with perforated plate and in absence of perforated plate. The minimum contour level is -1.07 cm/s and the increment is 0.16 cm/s.
Figure 14: Contours of time-averaged root-mean-square values of streamwise velocity fluctuation $u_{rms}/U_{ref}$ and transverse velocity fluctuation $v_{rms}/U_{ref}$ for perforated plate case. The minimum contour level is 0.03 and the increment is 0.01 for both cases.
Figure 15: Contours of time-averaged root-mean-square values of streamwise velocity fluctuation $u_{rms}/U_{ref}$ and transverse velocity fluctuation $v_{rms}/U_{ref}$ in absence of perforated plate. The minimum contour level is 0.06 and the increment is 0.01 for both velocity fluctuations.
Figure 16: Contours of phase-averaged root-mean-square values of transverse velocity fluctuation $v_{rms}/U_{ref}$ for with perforated plate case and in absence of perforated plate. For the first case, $(v_{rms}/U_{ref})_{\min} = 0.02$ and $\Delta(v_{rms}/U_{ref}) = 0.005$. For the case of without perforated plate, $(v_{rms}/U_{ref})_{\min} = 0.02$ and $\Delta(v_{rms}/U_{ref}) = 0.01$. 
Figure 17: Time averaged Reynolds stress distributions for unstable flow past a cavity in absence of a perforated plate and with a perforated plate. For the first image, \( \langle u' v' / (U_{ref})^2 \rangle_{\text{min}} = -0.014 \) and \( \Delta(\langle u' v' / (U_{ref})^2 \rangle) = 0.001 \). For the second image, \( \langle u' v' / (U_{ref})^2 \rangle_{\text{min}} = -0.012 \) and \( \Delta(\langle u' v' / (U_{ref})^2 \rangle) = 0.001 \).
Figure 17: Time averaged Reynolds stress distributions for unstable flow past a cavity in absence of a perforated plate and with a perforated plate. For the first image, \( (u'v')_{min}/U_{ref}^2 = -0.014 \) and \( \Delta(u'v')/U_{ref}^2 = 0.001 \). For the second image, \( (u'v')_{min}/U_{ref}^2 = -0.012 \) and \( \Delta(u'v')/U_{ref}^2 = 0.001 \).
Figure 18a: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3$ cm/s, $D = 0.64$ cm. The minimum and incremental values of vorticity are $\omega_{\text{min}} = -47$ sec$^{-1}$, $\Delta \omega = 3.84$ sec$^{-1}$.
Figure 18a: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3 \text{ cm/s, } D = 0.64 \text{ cm}$. The minimum and incremental values of vorticity are $\omega_{\text{min}} = -47 \text{ sec}^{-1}$, $\Delta \omega = 3.84 \text{ sec}^{-1}$. 
Figure 18b: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3 \text{ cm/s}, D = 0.64 \text{ cm}$. The minimum and incremental values of vorticity are $\omega_{\text{min}} = -47 \text{ sec}^{-1}$, $\Delta \omega = 3.84 \text{ sec}^{-1}$. 
Figure 18b: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. \( U = 28.3 \text{ cm/s}, \ D = 0.64 \text{ cm} \). The minimum and incremental values of vorticity are \( \omega_{\text{min}} = -47 \text{ sec}^{-1}, \ \Delta \omega = 3.84 \text{ sec}^{-1} \).
Figure 18c: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3\ \text{cm/s}, \ D = 0.64\ \text{cm}$. The minimum and incremental values of vorticity are $\omega_{\min} = -47\ \text{sec}^{-1}, \ \Delta \omega = 3.84\ \text{sec}^{-1}$. 
Figure 18c: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3$ cm/s, $D = 0.64$ cm. The minimum and incremental values of vorticity are $\omega_{\min} = -47$ sec$^{-1}$, $\Delta \omega = 3.84$ sec$^{-1}$. 
Figure 18d: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3 \text{ cm/s}$, $D = 0.64 \text{ cm}$. The minimum and incremental values of vorticity are $\omega_{\text{min}} = -47 \text{ sec}^{-1}$, $\Delta \omega = 3.84 \text{ sec}^{-1}$. 
Figure 18d: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3$ cm/s, $D = 0.64$ cm. The minimum and incremental values of vorticity are $\omega_{\text{min}} = -47$ sec$^{-1}$, $\Delta \omega = 3.84$ sec$^{-1}$. 
Figure 18e: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3$ cm/s, $D = 0.64$ cm. The minimum and incremental values of vorticity are $\omega_{\text{min}} = -47$ sec$^{-1}$, $\Delta \omega = 3.84$ sec$^{-1}$. 
Figure 18e: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3 \text{ cm/s}, D = 0.64 \text{ cm}$. The minimum and incremental values of vorticity are $\omega_{\text{min}} = -47 \text{ sec}^{-1}, \Delta \omega = 3.84 \text{ sec}^{-1}$. 
Figure 18f: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3 \, \text{cm/s}$, $D = 0.64 \, \text{cm}$. The minimum and incremental values of vorticity are $\omega_{\min} = -47 \, \text{sec}^{-1}$, $\Delta \omega = 3.84 \, \text{sec}^{-1}$. 
Figure 18f: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3$ cm/s, $D = 0.64$ cm. The minimum and incremental values of vorticity are $\omega_{\text{min}} = -47$ sec$^{-1}$, $\Delta \omega = 3.84$ sec$^{-1}$. 
Figure 18g: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3$ cm/s, $D = 0.64$ cm. The minimum and incremental values of vorticity are $\omega_{\text{min}} = -47$ sec$^{-1}$, $\Delta \omega = 3.84$ sec$^{-1}$. 
Figure 18g: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3 \text{ cm/s}$, $D = 0.64 \text{ cm}$. The minimum and incremental values of vorticity are $\omega_{\text{min}} = -47 \text{ sec}^{-1}$, $\Delta \omega = 3.84 \text{ sec}^{-1}$. 
Figure 18h: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3$ cm/s, $D = 0.64$ cm. The minimum and incremental values of vorticity are $\omega_{\text{min}} = -47$ sec$^{-1}$, $\Delta \omega = 3.84$ sec$^{-1}$. 
Figure 18h: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. \( U = 28.3 \text{ cm/s}, D = 0.64 \text{ cm} \). The minimum and incremental values of vorticity are \( \omega_{\text{min}} = -47 \text{ sec}^{-1} \), \( \Delta \omega = 3.84 \text{ sec}^{-1} \).
Figure 18j: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3$ cm/s, $D = 0.64$ cm. The minimum and incremental values of vorticity are $\omega_{\text{min}} = -47$ sec$^{-1}$, $\Delta \omega = 3.84$ sec$^{-1}$. 
Figure 18j: Time sequence of instantaneous patterns of vorticity for turbulent boundary layer at the leading edge of the perforated plate. \( U = 28.3 \text{ cm/s}, D = 0.64 \text{ cm} \). The minimum and incremental values of vorticity are \( \omega_{\min} = -47 \text{ sec}^{-1}, \Delta \omega = 3.84 \text{ sec}^{-1} \).
Figure 19: Time sequence of instantaneous patterns of Reynolds stresses for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3$ cm/s, $D = 0.64$ cm.
Figure 19: Time sequence of instantaneous patterns of Reynolds stresses for turbulent boundary layer at the leading edge of the perforated plate. $U = 28.3 \, \text{cm/s}$, $D = 0.64 \, \text{cm}$. 
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Figure 20: Time sequence of instantaneous contours of transverse velocity $v$ for turbulent boundary layer at the leading edge of the perforated plate. The minimum contour level is $-2.2$ cm/s and the increment is 0.34 cm/s.
9. VITA

The author was born to Ummu and Sinan Celik in Adana, Turkey in April 1979. She received a Bachelor of Science degree in Mechanical Engineering from Cukurova University in 2000. She continued her education at Lehigh University to obtain a Master of Science degree in Mechanical Engineering.
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