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Special Brief Note

Self-sustained oscillations of shear flow past a slotted plate coupled with cavity resonance

A. Ekmekci, D. Rockwell*

Department of Mechanical Engineering and Mechanics, 354 Packard Laboratory, 19 Memorial Drive West, Lehigh University Bethlehem, PA 18015 3085, USA

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Abstract

Shear flow past a slotted plate configuration can give rise to highly coherent, self-sustained oscillations when coupling occurs with a resonant mode of an adjacent cavity. The distinctive feature of these oscillations is that the wavelength of the coherent instability along the plate is of the order of the plate length. This observation is in contrast to previous investigations of flow past perforated or slotted surfaces, where the instability scales on the diameter of the perforation or the gap length of a slot. The present oscillations occur even when the inflow boundary layer is turbulent and an inflectional form of the shear flow cannot develop along the cavity opening, due to the presence of the slotted plate. Instigation of a resonant mode of the cavity, in conjunction with an inherent instability of the shear flow along the plate, gives rise to ordered clusters of instantaneous vorticity and instantaneous velocity correlation. During the oscillation, ejection of flow occurs from the cavity to the region of the shear flow; this ejection is in accord with the convection of the large-scale cluster of vorticity along the slotted plate. This oscillation can be effectively detuned by adjusting the inflow velocity, such that the inherent instability of the shear flow past the slotted plate is no longer coincident with the resonant frequency of the cavity. Certain features of this self-sustained oscillation are directly analogous to recent findings of oscillations due to shear flow past a perforated plate bounded by a cavity, but in the absence of cavity resonance effects.

1. Introduction

Partially open surfaces, such as perforated plates or slotted plates, are often deployed with the intent of precluding flow-induced oscillations due to flow past openings of cavities. Furthermore, perforated liners have been successfully employed as a means of absorbing sound generated within internal flow systems. It is well recognized, however, that flow past a perforated surface or liner can give rise to undesirable tone generation, which usually occurs in conjunction with an excited resonant mode of a cavity(ies) on the backside of the perforated surface. This effect has been documented by Meyer et al. (1958), Dean (1972), Adams (1974), Tsui and Flandro (1977), and Bauer and Chapkis (1977). The self-excited, tonal noise in these investigations was attributed to a local instability along an individual perforation, or hole, in the plate. The physics of vortex shedding past a single hole was pursued in a simulated water experiment by Ronneberger (1980), with the intent of modelling the key physics during self-generation of tones in airflow. Not all flow-induced excitation is purely tonal; Nelson (1982) and Howe (1997a) modelled the broadband noise generation due to flow along a perforated surface. A further related investigation is the work of Dickey et al. (2001), who determined the plate impedance via experiments involving controlled excitation.

*Corresponding author. Tel.: +1-610-758-4107; fax: +1-610-758-4041.
E-mail address: dor0@lehigh.edu (D. Rockwell).

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Flow past a wall with longitudinal (streamwise) slots, whereby the wall is bounded by a closed cavity, can give rise to a self-excited instability, as described by King et al. (1958). This slotted-wall configuration formed the test section of a closed water tunnel. A free-surface analogy of this configuration was addressed by Betts (1972), who considered the flow past a slotted wall bounded by a cavity, whereby the slots were again aligned in the streamwise direction. The oscillations in this system were reinforced by occurrence of a free-surface, standing-wave resonance within the cavity, which apparently coupled with a type of instability of the shear layer along the slotted surface. In both of the foregoing investigations, the underlying physics of the finite-thickness shear flow past the longitudinal slots was not addressed.

Flow past louvers, i.e., inclined slats (rectangular plates), located along the mouth of a bounding cavity, has been addressed by Bruggeman et al. (1991) and Looijmans and Bruggeman (1997). The emphasis of these investigations was on the sound generation. Bruggeman et al. (1991) provide models for the aeroacoustic source, in conjunction with wind tunnel experiments. Looijmans and Bruggeman (1997) employ vortex models for both rigid and elastic louvers, as well as for a cavity opening without louvers, and define a resonance condition of self-sustained flow oscillations that involves energy input by vortices past the louvers. For both of the foregoing investigations, the unsteady phenomena (in presence of louvers) scaled on the gap distance between successive louvers. Zoccola (2002) experimentally investigated the consequence of one or three spanwise (two-dimensional) obstacles across the opening of a cavity, whereby an acoustic resonant mode was excited in conjunction with the onset of pronounced oscillations. In this case, as for the foregoing louvers, the slots of relatively wide opening were oriented transversely to the flow direction.

A fundamental issue regarding the self-excited oscillation of flow past a partially open plate or surface is whether a self-excited, long-wavelength instability can be generated in the absence of excitation of a resonant (Helmholtz or standing wave) mode of the cavity that bounds the plate. Celik and Rockwell (2002) and Ozalp et al. (2003) have demonstrated, for different conditions of the inflow boundary layer, occurrence of a long-wavelength instability. It scales according to f_0L/U, in which f_0 is a well-defined peak in the spectrum of velocity and pressure, L is the effective length of the plate and U is the free-stream velocity of the inflow. In their investigations, the value of f_0L/U was of the order of 0.5–0.6, which, in fact, corresponds approximately to the first self-excited, purely hydrodynamic mode of flow past a nonresonant cavity of length L without a perforated plate, as described by Rockwell and Naudascher (1978) and Howe (1997b, 1998).

The foregoing observations of Celik and Rockwell (2002) and Ozalp et al. (2003) indicate that a purely hydrodynamic, long-wavelength instability can arise from shear flow past a partially open surface with circular holes bounded by a cavity, and presumably, it can also occur for a plate with transverse, closely spaced slats. If the bounding cavity is susceptible to undergoing resonance in either a free-surface or acoustic resonant mode, this long-wavelength instability may couple with such a mode to yield highly coherent oscillations, as reported by Ekmekci and Rockwell (2002). That is, the oscillation will scale according to f_0L/U, in which L is the effective length of the plate; f_0L/U will have a value corresponding to a wavelength of the order of the plate length L.

The present investigation addresses the coupling between the self-excited instability past a slotted plate and a resonant mode of a bounding cavity, with particular emphasis on the flow physics. A technique of high-image-density particle velocimetry is employed to provide whole field representations of the instantaneous flow structure during an oscillation cycle.

2. Experimental system and techniques

Experiments were performed in a large-scale water channel having a test section 5484 mm long, 610 mm wide and 610 mm deep. A horizontal plate was placed at an elevation of 232 mm from the floor of the test section in order to create a shallow water layer of height 38.1 mm along the upper surface of the plate. This shallow water layer was bounded on its lower side by the solid surface of the plate and on its upper side by a free-surface. It flowed through a contraction, which had an inlet width of 610 mm and an outlet width of 152.4 mm. From the outlet of the contraction, the shallow layer flowed through a channel of constant cross-section with a width of 152.4 mm and a length of 1790 mm. This inflow channel ensured that the shallow, free-surface layer had a turbulent inflow boundary layer at the inlet of the slotted plate–cavity system.

Detailed schematics of the slotted plate–cavity arrangement are shown in Fig. 1. The top schematic shows a plan view and the bottom schematic gives a side view in the form of the sectional cut A–A. In the top schematic, cavities of length L_c and width W_c are designated; the corresponding values are $L_c = 304.8$ mm and $W_c = 76.2$ mm. A slotted plate is placed along the opening of the cavity as indicated. A sharp-edged (solid) plate could be moved along the high-speed side of the slotted plate, in order to produce an effective length L of the slotted plate. For all experiments performed herein, $L = 53.2$ mm. Each individual slat had a width ℓ (in the streamwise direction) of 3.81 mm and a thickness t (in the cross-stream direction) of 5.8 mm. The gap distance between slats was $G = 6.35$ mm.

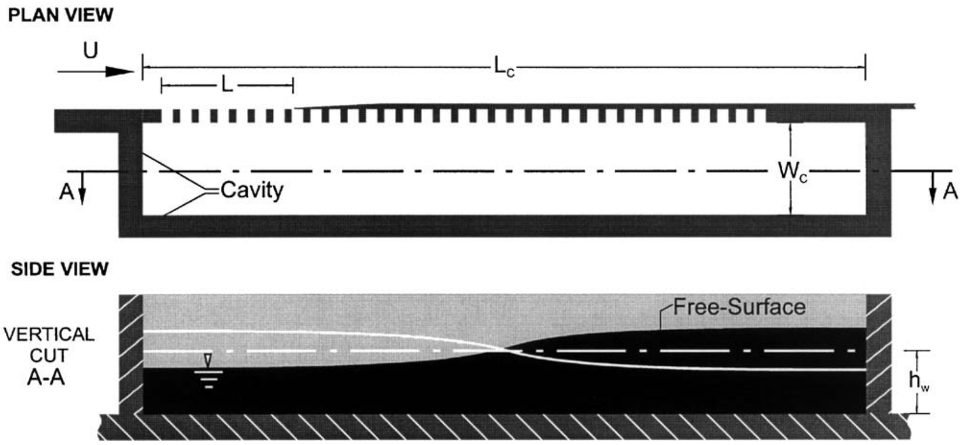

Fig. 1. Schematic of slotted plate–resonant cavity system showing first mode of free-surface resonance at section A–A. For purposes of illustration, vertical deflection of free-surface is magnified.

The bottom schematic of Fig. 1 shows the instantaneous deflection of the free-surface (gravity) standing wave. The nominal elevation of the free-surface is designated as h_w. Furthermore, the deflection of the free-surface one-half cycle later is indicated by the solid white line. This representation therefore corresponds to excitation of the first longitudinal, free-surface (gravity wave) mode of the cavity. The resonant frequency of this mode was $f_r = 1.44\,\mathrm{Hz}$. This value agrees within 5% of the theoretically predicted value of the standing gravity wave in cavity, which involves the free-surface wave celerity c, for the nominal depth of the free-shear surface layer (Blevins, 1979; Naudascher and Rockwell, 1994). During fully coupled oscillations, the maximum vertical deviation of the free-surface from its nominal elevation of 38.1 mm was 2.0 mm. This resonant-coupled oscillation occurred at a value of inflow velocity $U = 315.4\,\mathrm{mm/s}$; this value of U is designated as U_r. Inflow velocities are scaled according to U/U_r, with $U/U_r = 1.00$ corresponding to the fully coupled resonance condition. At the resonance velocity U_r, the Reynolds number based on channel width was $\mathrm{Re}_w = 47{,}942$ and on momentum thickness of the inflow was $\mathrm{Re}_\theta = 701$.

The fact that the present oscillations of flow past the slotted plate represent coupling between the instability of the shear flow past the plate and the first longitudinal (free-surface) mode of the cavity was verified by varying the inflow velocity U and observing the amplitude $\tilde{h}$ of the free-surface undulation and the frequency ratio f_0/f_r. With increasing U, f_0 took on larger values, until a value of $f_0/f_r = 1$ and the maximum $\tilde{h}$ were attained at $U/U_r = 1$ (Ekmekci and Rockwell, 2002).

Furthermore, this resonant-coupled oscillation was isolated from the flow system, as verified by acquisition of velocity spectra in the free-stream. These spectra showed no organized components in contrast to the sharply defined, large-amplitude spectral peaks evident in the immediate vicinity of the slotted plate.

Quantitative, instantaneous images of the flow patterns were acquired using a technique of high-image-density particle image velocimetry. A horizontal laser sheet illuminated a plane that included the front and back sides, as well as the gap regions of the slotted plate. This laser sheet was generated using a dual laser system with a double-pulsed capability. The maximum output of each laser was 90 mJ. The desired laser sheet was generated using a cylindrical–spherical lens arrangement. The flow was seeded with hollow, metallic-coated spheres, having a diameter of 14 μm. Patterns of particle images were acquired via a CCD camera with an array of 1008×1018 pixels, and at a rate of 15 frames/s. These image patterns were evaluated using a frame-to-frame correlation technique. The size of the interrogation window corresponded to 32×32 pixels. In order to satisfy the Nyquist criterion, an overlap of 50% was employed during the interrogation process. This resulted in an effective grid size of 1.93 mm.

3. Time traces and spectra of fluctuating velocity field

Acquisition of images of the flow pattern in a cinema sequence allowed, in effect, simultaneous records of the time-dependent velocity fluctuation at all locations on the grid of the fluctuating velocity field. In turn, these velocity records were used to determine time-averaged spectra of the velocity fluctuations at all locations. Representative time traces $u(t)$ and spectra $S_u(f)$ of the streamwise (longitudinal) velocity fluctuation are indicated in Fig. 2 for critical locations a, b

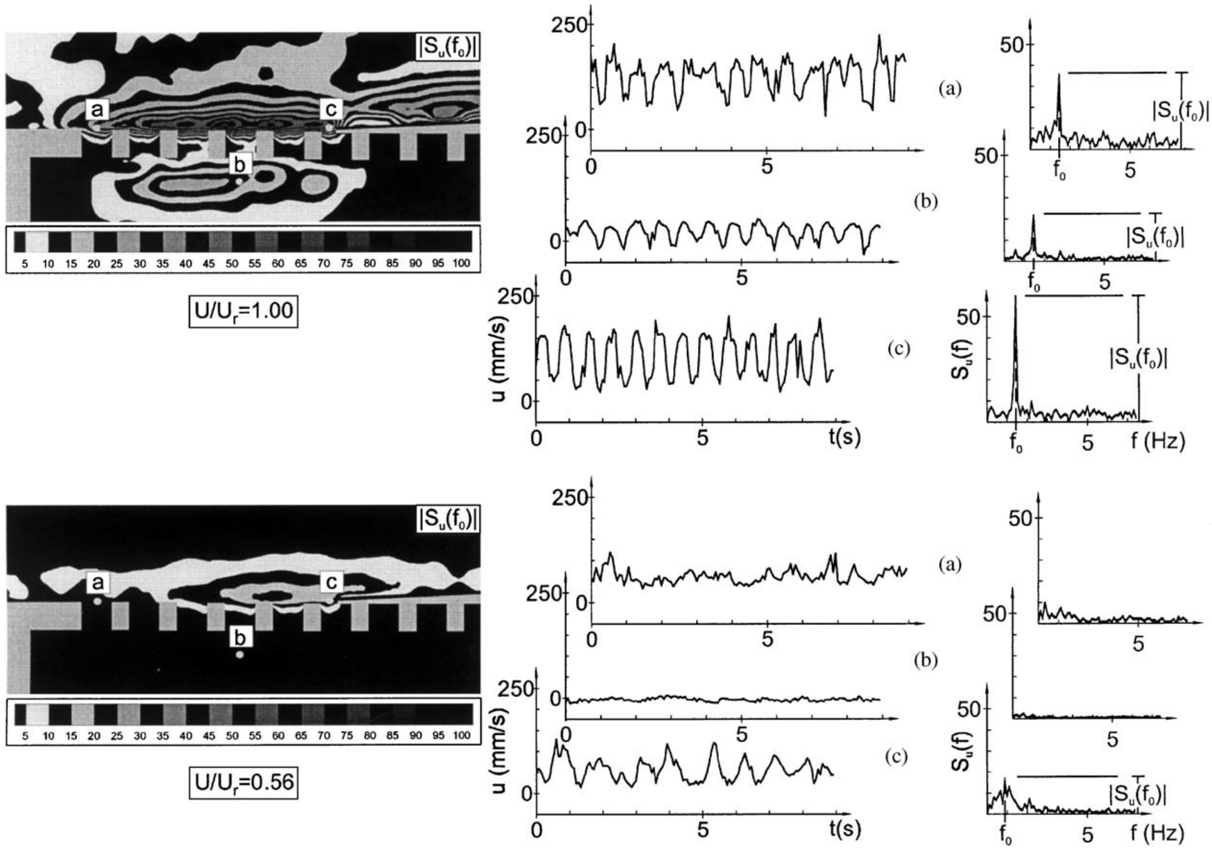

Fig. 2. Images showing contours of constant peak amplitude of autosprectal density $|S_u(f_0)|$ of fluctuating streamwise velocity u at predominant frequency f_0 and representative values of time traces of streamwise velocity u and spectra $S_u(f)$ in the presence of the slotted plate. These images and plots are shown for three values of velocity ratio U/U_r, in which U is the free-stream velocity and U_r corresponds to its value at the resonance condition. Minimum and incremental values are $[|S_u(f_0)|]_{\min} = 5$ and $\Delta[|S_u(f_0)|] = 5$.

and c on the high- and low-speed sides of the slotted plate arrangement. These time traces and spectra are shown for two values of the normalized inflow velocity $U/U_r = 1.00$ and 0.56, represented by the images and plots at the top and bottom of Fig. 2. Consider first the case of the fully coupled oscillation at $U/U_r = 1.00$. The time histories of the velocity fluctuation $u(t)$ show an ordered form at locations a, b and c. The corresponding spectra show peaks designated as $|S_u(f_0)|$. The occurrence of sharp spectral peaks at all three locations a, b and c indicates that the oscillation is globally coupled, and involves regions on the high- and low-speed sides of the slotted plate. The largest spectral peak occurs at location c, which suggests interaction of a large-scale instability with the tip of the impingement edge, i.e., the effective trailing edge of the slotted plate. The corresponding image at $U/U_r = 1.00$ shows contours of constant $|S_u(f_0)|$ throughout the entire flow field. The highest contour levels of $|S_u(f_0)|$ occur along the upper edge of the slotted plate, i.e., along the high-speed side, though a detectable level of $|S_u(f_0)|$ occurs beneath the slotted plate.

If the above-mentioned oscillations are indeed due to coupling with the resonant mode of the cavity, then a decrease in the inflow velocity U should effectively decouple the system and reduce the coherence of the oscillation. The time traces and image at $U/U_r = 0.56$, shown at the bottom of Fig. 2, indicate that this is the case. The time traces $u(t)$ exhibit a quasi-ordered form only at location c at the impingement edge. Corresponding spectra show only a broadly defined peak at f_0 at this same location c. This frequency f_0 is proportionately lower than the corresponding value at $U/U_r = 1.0$; this observation suggests occurrence of an inherent hydrodynamic instability along the slotted plate.

The instantaneous physics of the flow associated with the coupled oscillation at $U/U_r = 1.0$ is described in the following section.

4. Patterns of instantaneous velocity

Patterns of instantaneous velocity V normalized by the inflow velocity U, i.e., V/U, are shown for sequential instants of time t/T in the left column of Fig. 3; T corresponds to the period of the coherent oscillation, i.e., $T = 1/f_0$, where f_0 is defined in the spectra of Fig. 2. Corresponding patterns of instantaneous velocity fluctuation V'/U are given in the right column of Fig. 3. Values of V' were determined by subtracting the time-averaged velocity from the patterns of V/U given in the left column of Fig. 3.

Consider the pattern of V/U at $t/T = 0.1$. During selected parts of the oscillation cycle, fluid is ejected vertically toward the high-speed side. This ejection through the slats is particularly evident in the gap close to the impingement edge at $t/T = 0.1$. Similarly, an ejected pattern is also detectable at $t/T = 0.3$. At $t/T = 0.5$, however, ejection is not evident along the entire length of the slotted plate, while at a later time, $t/T = 0.7$, a region of reverse flow exists beneath the slotted plate, accompanied by low-speed ejection to the high-speed side; these events occur near the leading edge of the slotted plate. At later times $t/T = 0.9$ and 1.0, the process of well-defined ejection to the high-speed side develops in such a fashion that it eventually leads to the type of pattern described at the beginning of the cycle at $t/T = 0.1$.

Corresponding patterns of instantaneous velocity fluctuation V'/U given in the right column of Fig. 3 define the relationship between: (i) the upward-ejected fluid through the gaps; and (b) the pronounced regions of upward-oriented patterns of velocity vectors that penetrate well into the stream on the high-speed side of the slotted plate. At certain times t/T, these patterns of velocity vectors occur in conjunction with a large-scale swirl on the upper side of the plate, most notably at $t/T = 1.0$.

These patterns of V/U and V'/U of Fig. 3 are intimately related to patterns of instantaneous vorticity and velocity correlation, as described in the following section.

5. Patterns of instantaneous vorticity and velocity correlation

Coherent clusters of instantaneous vorticity ω and velocity correlation $u'v'/U^2$, which correspond to the images of Fig. 3, are indicated in the left and right columns of Fig. 4. A large-scale cluster of vorticity ω is evident at $t/T = 0.1$ immediately adjacent to the tip of the impingement edge, i.e., at the effective trailing edge of the slotted plate. At subsequent times $t/T = 0.3$ and 0.5, this large-scale cluster moves out of the field of view. At $t/T = 0.7$, the next large-scale cluster forms in the leading (upstream) region of the slotted plate and develops in a more distinct fashion at $t/T = 0.9$ and 1.0. As this development occurs, the apparent center of the large-scale cluster of ω moves downstream.

Patterns of instantaneous velocity correlation $u'v'/U^2$ given in the right column of Fig. 4 show the same trend with increasing values of t/T. Particularly remarkable is the penetration of a relatively large-scale cluster of $u'v'/U^2$ well into the high-speed stream at $t/T = 0.7$; it occurs at a location near the leading edge of the slotted plate. This extended cluster of $u'v'/U^2$ above the slotted plate occurs in conjunction with the initial stage of formation of the long and narrow cluster of instantaneous vorticity near the leading region of the plate. At subsequent times $t/T = 0.9$ and 1.0, the well-defined region of $u'v'/U^2$ convects downstream, in accord with the large-scale cluster of vorticity ω.

Comparison of patterns of instantaneous vorticity ω with the patterns of instantaneous velocity V/U in Fig. 3 indicates that the ejection of fluid through the gap region towards the high-speed shear layer occurs in accord with the onset and propagation of the large-scale cluster of vorticity ω. Compare, for example, the patterns of V/U and ω at $t/T = 1.0$.

6. Concluding remarks

The free-shear flow along a slotted plate can give rise to highly coherent oscillations when coupling occurs with a mode of a resonant cavity located adjacent to the slotted plate. These oscillations occur when the inflow velocity is adjusted such that the inherent instability of the shear flow along the slotted plate coincides with the first resonant mode of the cavity. This oscillating system can be effectively detuned by decreasing the inflow velocity; in this case, organized oscillations are barely detectable. A technique of quantitative imaging allows, in effect, acquisition of time traces of velocity at a large number of points in the flow field. Using these traces, spatial distributions of spectral amplitude were determined for the fully coupled and detuned states of the oscillation. For the fully coupled state, well-defined spectral peaks occur at critical locations on either side of the slotted plate, which indicates a globally coupled phenomenon. On the other hand, for the detuned state, only a broadly organized fluctuation is evident at the trailing edge of the slotted plate.

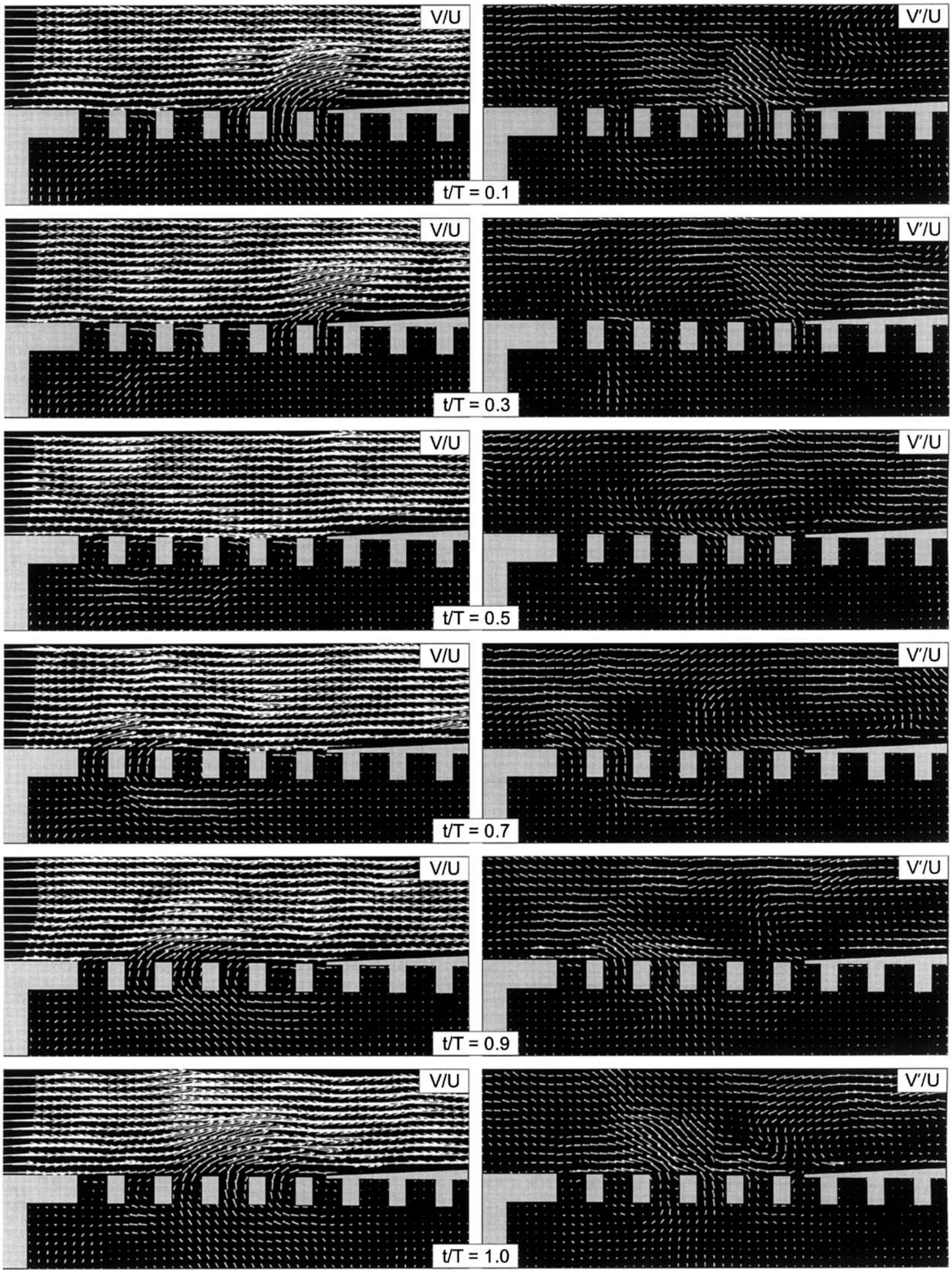

Fig. 3. Patterns of the sequence of instantaneous velocity V/U and velocity fluctuation V'/U. The dimensionless time interval extending from $t/T = 0$ to 1.0 represents one cycle of oscillation.

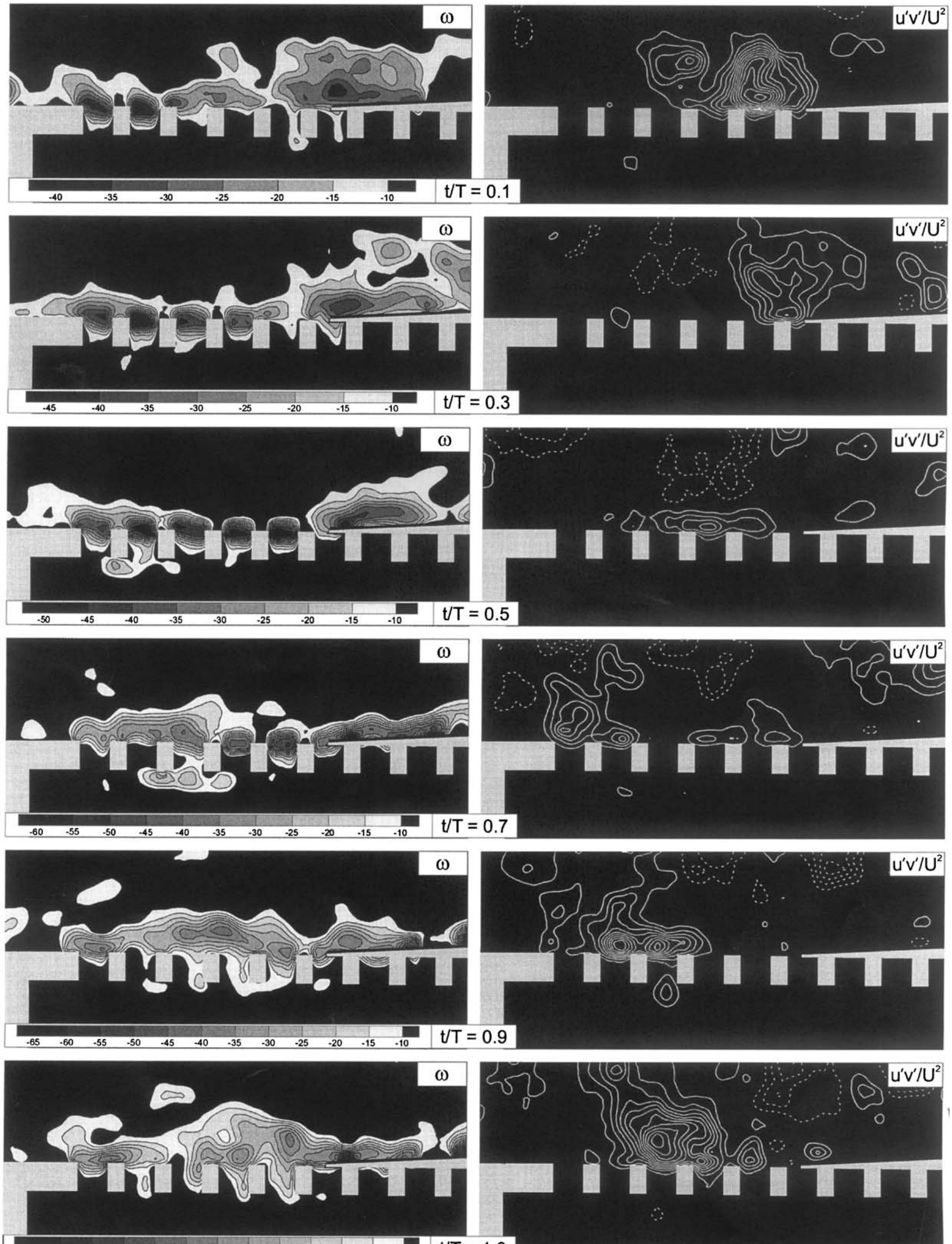

Fig. 4. Patterns of the sequence of instantaneous vorticity ω and instantaneous velocity correlation $u'v'/U^2$. Minimum and incremental values of vorticity are $\omega_{\min} = -10\,\mathrm{s}^{-1}$ and $\Delta\omega = -5\,\mathrm{s}^{-1}$. Minimum and incremental values of velocity correlation are $|[u'v'/U^2]_{\min}| = 0.005$ and $|\Delta[u'v'U^2]| = 0.005$; solid lines are negative and dashed lines are positive values.

Patterns of instantaneous velocity for the fully coupled state indicate ejection from the cavity region through selected gaps of the slotted plate towards the high-speed side. Related patterns of instantaneous vectors of velocity fluctuation show that vertically oriented patches exist up through the high-speed shear flow region. This type of physics is associated with the development and propagation of large-scale clusters of vorticity along the high-speed side of the plate. Correspondingly, patterns of instantaneous velocity correlation occur in conjunction with the development of the large-scale clusters of vorticity.

This long-wavelength oscillation involves development of large-scale clusters of instantaneous vorticity and Reynolds stress correlation that have a scale much larger than the gap distance between slats. In other words, this resonant-coupled oscillation is in accord with the streamwise length L of the slotted plate. In fact, the dimensionless frequency $f_0L/U = 0.244$, which compares with the value $f_0L/U = 0.320$ observed for the corresponding resonant-coupled oscillations of free-shear flow along the cavity in absence of a slotted plate.

The fully coupled oscillation described herein exhibits certain features in common with purely hydrodynamic oscillations past a perforated plate bounded by a closed cavity, recently described by Celik and Rockwell (2002) and Ozalp et al. (2003) for inflow boundary layers that are, respectively, laminar and turbulent. For those experiments, the possibility of cavity resonance was precluded, and therefore the instability was purely hydrodynamic. The physics of formation of large-scale, elongated clusters of vorticity on the high-speed side of the perforated plate shows a remarkable degree of similarity to patterns of vorticity described herein. Furthermore, the wavelength of this oscillation is also an order of magnitude longer than the effective gap size (diameter) of the perforation; in fact, it scales on the length L of the perforated plate. This observation suggests a similar type of hydrodynamic instability to that observed herein for shear flow along a slotted plate. For the present case, the instability couples with a free-surface resonant mode of the cavity. Analogous coupling is expected to occur for cavities undergoing acoustic resonance in either a compressible standing wave or Helmholtz mode. Irrespective of the type of resonance, an issue that deserves further investigation is the effect of the gap distance between slats of the slotted plate. Preliminary studies of this effect by Ekmekci and Rockwell (2002) indicate that the oscillation can be detuned by gap variations.

Finally, one might draw useful analogies between the present long-wavelength instability and the resonant vibrations of an elastic plate mounted on an otherwise rigid wall. This concept and related ones, addressed in the works of Abrahams (1989), Howe (1980) and Howe (1997c), are currently being assessed to provide guidance for further investigations of the physics of the instability described herein.

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