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Technical Notes

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Self-Sustained Oscillations past Perforated and Slotted Plates: Effect of Plate Thickness

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I. Introduction

A. Previous Related Investigations

GENERATION of highly coherent oscillations caused by grazing flow past a cavity, in the absence of a perforated or slotted plate, has been the subject of a variety of investigations in recent decades. The conditions for the onset of oscillation, characterization of the dimensionless frequency and amplitude, and techniques for control are addressed in the works of DeMetz and Farabee,[1] Knisely and Rockwell,[2] Blake,[3] Gharib and Roshko,[4] Burroughs and Stinebring,[5] Howe,[6,7] Rockwell,[8] Ziada,[9] Zoccola and Farabee,[10] Kuo and Huang,[11] and Rowley et al.,[12] and Cattafesta et al.[13]

When a perforated or slotted plate is placed along the cavity opening, it is also possible to generate highly coherent oscillations caused by coupling between 1) the shear-layer instability along an individual orifice or gap opening and 2) a resonant mode of a cavity(ies) on the backside of the plate. This category of studies includes the works of Howe,[7] Kirby and Cummings,[14] Dickey et al.,[15] and Jing et al.[16] for a perforated plate and Bruggemann et al.[17] and Looijmans and Bruggeman[18] for a plate with louvers (inclined slats).

More recently, it has been demonstrated that, in absence of coupling with a resonant acoustic mode of the cavity, it is possible to generate highly coherent oscillations that scale on the length L of the perforated or slotted plate, rather than an individual hole or slot. These investigations include Celik and Rockwell[19,20] and Ozalp et al.,[21] and Sever and Rockwell.[22] In the event that this type of purely hydrodynamic instability couples with an acoustic resonant mode of the cavity, then the concept of lock-on is prevalent, and sharply coherent oscillations are attainable. Ekmekci and Rockwell[23] investigated this concept using a free-surface simulation, and Zoccola[24,25] has characterized resonant coupled instabilities caused by flow past a variety of slotted-plate configurations.

The focus of the present investigation is on purely hydrodynamic oscillations past perforated and slotted plates, with emphasis on the effects of plate thickness, heretofore uninvestigated.

B. Unresolved Issues

From the foregoing investigations, it is known that highly coherent, self-sustained oscillations can occur for grazing flow past both perforated and slotted plates. The following aspects, however, have remained unclarified:

1) The effects of plate thickness on the spectral content of the pressure fluctuations at the trailing edge of the plate, for both perforated and slotted plates, have not been addressed. Pressure fluctuations at this critical location are indicative of the strength and coherence of the self-sustained oscillation throughout the flowfield. Moreover, the possibility of an optimal thickness of a perforated or slotted plate that yields the largest amplitude oscillations has not been defined in dimensionless form.

2) It has been established that the appropriate length scale for characterizing the oscillations is the overall length L of the plate. Unknown, however, is the relation between the dimensionless frequency of oscillation and the dimensionless thickness of the perforated or slotted plate, while accounting for variations of the plate length L. Moreover, the possible equivalence of oscillation characteristics because of flow past a slotted plate and a perforated plate, in terms of dimensionless frequency of oscillation, has not been explored.

3) Self-sustained oscillations past perforated or slotted plates can have a substantial influence on the time-averaged patterns of the flow, particularly on the back side of the plate. The degree to which such time-averaged representations can provide an index of the strength of the oscillation, as a function of plate thickness, has not been pursued for either perforated or slotted plates.

The present investigation employs pressure measurements in conjunction with flow imaging to address these unclarified points.

II. Experimental System and Techniques

Full details of the experimental arrangements and approaches are given in the works of Celik and Rockwell[19] and Sever and Rockwell,[22] which focused on other aspects of grazing flow past perforated and slotted plates. Essential features of these experiments are described in the following. For both of the foregoing experimental systems, the perforated or slotted plate was backed by a cavity having a relatively large volume. The cavity walls, as well as the plate, were sufficiently thick to preclude elasticity effects at the low flow speeds of interest herein. Furthermore, the acoustic wavelength corresponding to the frequencies of oscillation was orders of magnitude larger than the length scale of the bounding cavity, thereby ensuring that acoustic resonant effects are absent.

For the perforated plate experiments, the length L of the plate was maintained constant at 140 mm; for the slotted plate experiments $L = 142$ mm. For both experiments, the inflow boundary layer was turbulent and had values of momentum thickness $\theta_0 = 1.45$ and 2.02 mm for the perforated and slotted plates, respectively. The values of freestream velocity U are 283 and 400 mm/s for the perforated and slotted plate configurations.

The open area ratio of the perforated and slotted plates was respectively 69 and 63%; it was maintained constant for all values of plate thickness. The values of hole diameter D in the perforated plate were constant at $D = 6.35$ mm, and, correspondingly, for the slotted plate, the slot width G was constant at $G = 6.35$ mm. For the perforated plate, the thickness t of the plate varied from 1.5 to 44 mm, giving dimensionless values of $t/D = 0.23$ to 6.88. For the slotted plate, t varied from 1.6 to 38.1 mm, yielding $t/G = 0.25$ to 6.

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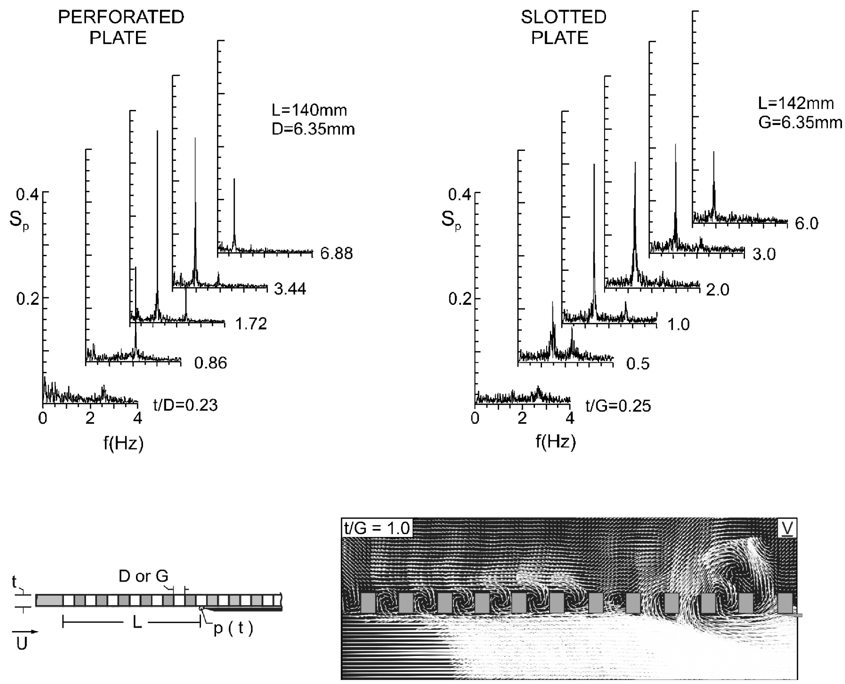

Fig. 1 Comparison of spectra S_p (*f*) of pressure fluctuations at trailing edge of perforated plate and slotted plates, for various values of plate thicknesses *t/D* and *t/G*. Also shown is an image of the instantaneous velocity field corresponding to highly coherent self-sustained oscillation past the slotted plate.

Pressure measurements were made at the effective trailing end of the plate, which corresponded to the tip of a sharp-edged impingement plate, as indicated in the inset of Fig. 1. The unsteady pressure signals were subjected to fast-Fourier-transform analysis to yield spectra, which provided guidance on the overall coherence and strength of the oscillation along the perforated or slotted plate.

To determine quantitative patterns of the flow structure, a technique of high-image-density particle image velocimetry was employed. Twelve-micron metallic-coated particles were illuminated with a double-pulsed laser sheet. Images of the particle patterns were recorded on a charge-coupled-device camera having an array of 1024×1024 pixels. The effective window size employed for interrogation was 16×16 pixels, yielding between 4784 and 7200 velocity vectors.

III. Results

A. Spectra of Pressure Fluctuations

Figure 1 shows spectra of pressure fluctuations, measured at the effective trailing edge of the impingement plate, as indicated in the schematic. In addition, as a reference for the physical structure of the flow, an instantaneous image of the velocity vectors is provided for the case of an oscillation because of flow past a slotted plate. This oscillation occurs at a value of dimensionless thickness that yields large oscillation amplitude.

The left set of spectra corresponds to the case of the perforated plate, and the right set to the slotted plate. For the perforated plate, the smallest thickness $t/D = 0.23$ shows a discernible peak, and the amplitude of the peak successively increases at $t/D = 0.86$ and 1.72, followed by decreases at $t/D = 3.44$ and 6.88. For the slotted plate, a barely detectable peak is evident for the thinnest plate $t/G = 0.25$. Increases of plate thickness to $t/G = 1.0$ yields the largest amplitude response. Further increases of t/G show progressively smaller amplitudes.

Considering together the sets of spectra of Fig. 1, it is evident that an optimum dimensionless thickness t/D or t/G exists for which the oscillation amplitude is largest. Furthermore, sufficiently thin or thick plates yield relatively small, or even ill-defined, amplitudes.

B. Dimensionless Frequencies of Oscillation

Figure 2 compares the dimensionless frequency fL/U with the dimensionless length L/D (or L/G) for a range of dimensionless

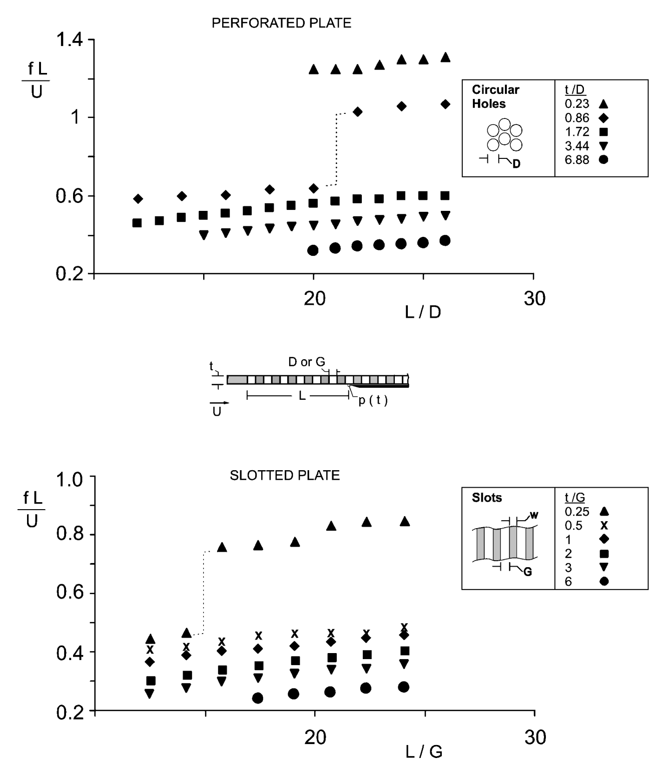

Fig. 2 Comparison of dimensionless frequency of oscillation *fL/U* vs dimensionless plate length *L/G* for various values of thickness of perforated plate *t/D* and slotted plate *t/G*.

plate thicknesses t/D (or t/G). For both the perforated and slotted plate, the value of fL/U is minimal for the thickest plate. As the value of plate thickness t/D (or t/G) decreases, the value of fL/U increases, and, when the thickness becomes sufficiently small, the value of fL/U jumps to the second mode (stage) of oscillation. At this jump, the value approximately doubles. Note that, for the perforated plate configuration, the oscillation exists in the higher mode (stage) for the thinnest plate, $t/D = 0.23$. Furthermore, note the expanded scale of fL/U for the case of the slotted plate. Values

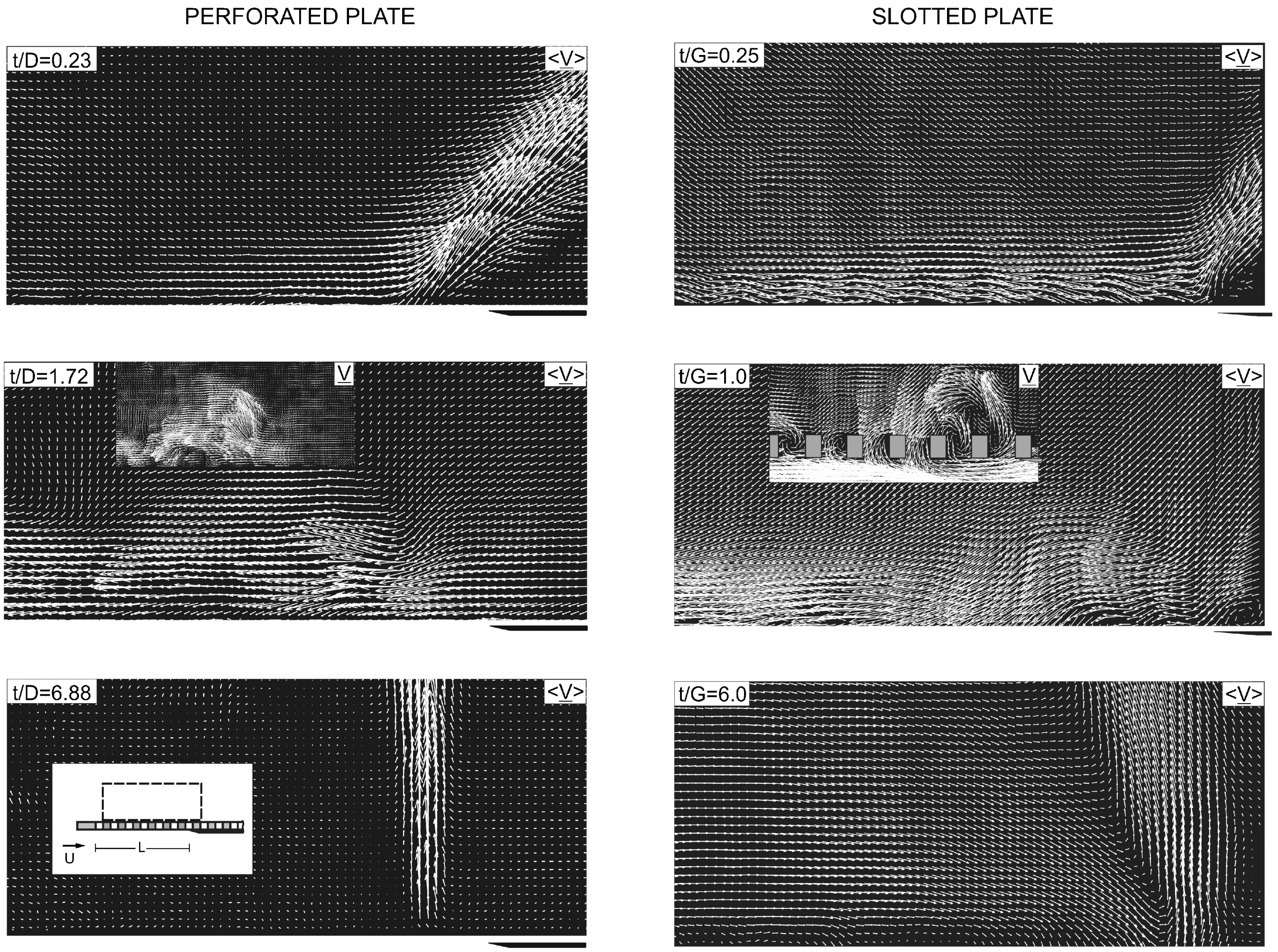

Fig. 3 Patterns of time-averaged velocity as a function of dimensionless thickness *t/D* of perforate plate and *t/G* of slotted plate. Also shown in the insets are patterns of instantaneous velocity $\underline{V}$, representative of a highly coherent oscillation.

of fL/U are less sensitive to variations of dimensionless thickness t/G than variations of fL/U with t/D for the case of the perforated plate.

C. Time-Averaged Flow Patterns

The time-averaged flow patterns can provide an indication of the existence and degree of coherence of the oscillation, especially on the backside of the plate, as indicated in Fig. 3. Consider, first, the plate thickness $t/D = 1.72$ for the case of the perforated plate and $t/G = 1.0$ for the slotted plate. Referring to Fig. 2, these cases correspond to attainment of the optimal, or maximum, amplitude of oscillation, as defined by the pressure spectra. Remarkably, both patterns show well-defined counterflow, that is, an upstream-oriented flow along the entire extent of the backside of the plate. As suggested by the instantaneous image of Fig. 1, this counterflow is associated with the instantaneous, upstream-oriented jet-like patterns along the backside of the plate, which are associated with pulsating flow through each of the slots or, equivalently, each of the holes in the perforated plate. In contrast, when the plate is sufficiently thin, corresponding to $t/D = 0.23$ for the perforated plate and $t/G = 0.25$ for the slotted plate, an inclined, steady jet emanates from the last set of holes, or the last slot in the plate. This pattern corresponds to a nearly undetectable oscillation, as shown in the corresponding spectra of Fig. 1. At the other extreme, when the perforated plate is sufficiently thick, at $t/D = 6.88$ or the slotted plate is sufficiently thick at $t/G = 6.0$, a steady, vertically oriented jet originates from the trailing end of the plate. The perforated and slotted plates therefore exhibit remarkably similar averaged patterns at equivalent values of dimensionless thickness.

IV. Conclusions

The effect of plate thickness on self-sustained oscillations past perforated and slotted plates, hereto time unexplored, has been addressed herein. The consequence of variations of thickness is remarkably similar for both classes of plates. The key findings are summarized in the following:

Pressure spectra indicate that the amplitude of oscillation reaches its peak value at an optimum dimensionless thickness of the plate. Either an increase or decrease in dimensionless thickness from this optimal value results in a decrease of oscillation amplitude. For sufficiently thin plates, the amplitude is barely detectable.

The dimensionless frequency of oscillation is smallest for the largest value of plate thickness. Successive decreases in thickness from this value yield substantial increases in dimensionless frequency, and, when the plate becomes sufficiently thin, oscillations occur in a higher order mode (stage). These trends are valid over a wide range of dimensionless length of both the perforated and slotted plates.

Time-averaged flow patterns can be used as an index of the amplitude of oscillation. When the oscillation has its highest amplitude, a well-defined counterflow persists on the back side of the plate; this pattern occurs for the cases of both perforated and slotted plates. On the other hand, when the amplitude of oscillation becomes sufficiently small, corresponding to a relatively thick or thin plate, such counterflow does not occur; rather, well-defined steady jets are formed in the trailing-end region of the plate. Again, these features are consistent for both perforated and slotted plates.

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