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Investigation of Self-Sustained Oscillations Along Perforated Surfaces which have Different Hole Sizes

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Abstract. The shear flow of a fully turbulent boundary layer along a perforated plate, which is bounded by a closed cavity on its backside, can give rise to highly coherent, self-sustained oscillations. These oscillations are characterized in terms of velocity fluctuations and quantitative images of the instantaneous and averaged flow structure using a technique of high-image-density particle image velocimetry (PIV). Variations of the effective length L of the perforated plate show nearly invariant values of dimensionless frequency fL/U; in which f is the predominant frequency of oscillation and U is the freestream velocity. In fact, this relationship holds even when the diameter of the hole pattern is altered. Variation of the hole diameter D does, however, strongly influence the amplitude and degree of organization of the self-sustained oscillation. Four different plates were employed, with whole diameters of D = 6.4 mm, 12.7mm, 19.1mm and 25.4mm. The plate was maintained constant thickness at t =11mm for all experiments. The freestream velocity was maintained at a value U = 240 mm/s and the momentum thickness of the turbulent boundary layer was θ =7.5 mm. [The Reynolds number based on θ was Re_θ = 1800.] It is demonstrated that, as the hole diameter becomes larger relative to the inflow boundary layer thickness, the amplitude of the predominant spectral peak is substantially attenuated and, in a limiting case, undetectable.

Keywords: Self-sustained oscillations, Perforated plate, PIV, velocity spectra

Farklı Delik Çaplarına Sahip Gözenekli Levhalar Boyunca Oluşan Serbest Salınımların İncelenmesi

Özet. Kapalı bir kavite üzerine yerleştirilmiş gözenekli bir levha boyunca oluşmuş tam türbülanslı sınır tabaka içerisinde kendiliğinden sürekli salınımlar oluşur. Bu çalışmada parçacık görüntülemeli (PIV) hız ölçme metodu kullanılarak anlık ve ortalama hız değerleri, girdap çizgileri, Reynolds gerilmeleri ve levha boyunca belli bir zaman aralığında ölçülen hız değerleri ile bu salınımlara ait üç boyutlu hız spektrumları verilmiştir. Gözenekli levha boyunca akış yönünde ölçülen basınç değerleri neticesinde hesaplanan boyutsuz frekansın fL/U hemen hemen sabit kaldığı görülmüştür. Burada f salınımın frekansını U da serbest akış hızını ifade etmektedir. Aynı şekilde boyutsuz frekansın gözenek çapının değişmesiyle de sabit olduğu gösterilmiştir. Gözenek çapı D nin değiştirilmesi periyodik salınımlara neden olmakta ve etkili bir şekilde salınımların genliğini etkilemektedir. Dört farklı gözenekli levha delik çapı D = 6.4 mm, 12.7mm, 19.1mm and 25.4mm deneylerde kullanılmıştır. Çalışmada serbest akış hızı U=240 mm olarak alınmış bu hıza karşılık gelen türbülanslı sınır tabaka momentum kalınlığı θ =7.5 mm olarak bulunmuştur. [Momentum kalınlığına bağlı Reynolds Sayısı = 1800 dir.] Gözenkli levhaların kalınlıkları sabit olarak t=11 mm olarak alınmıştır. Sınır tabaka kalınlığına göre gözenek çapı arttırıldığında salınımların genliğinin sönümlendiği ve frekansın belirsiz hale geldiği görülmüştür.

Anahtar Kelimeler: Kendiliğinden oluşan salınımlar, Gözenekli levha, PIV, hız spektraları

1. INTRODUCTION

Flow past a circular perforation, among an array of perforations, usually bounded on the backside by a defined cavity(ies) have been addressed by [1-5]. In this series of studies, the generation of tones was generally attributed to the hydrodynamic instability of the shear layer past a single hole. Related investigations involve those of researcher [6], who experimentally addressed the physics of the unsteadiness past a circular hole, as well as [7-8], who focused on the broadband generation of fluctuations (noise). A still further aspect of this class of investigations is determination of the

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impedance of a perforated plate, with the aid of external excitation, as pursued by [9]. Flow past inclined slats, i.e. louvers, with a cavity on their backside, can give rise to oscillations and noise generation that are analogous to those arising from flow past a perforated plate, as characterized by [10-11]. Furthermore, Zoccola [12] recently investigated the instabilities arising from one to three spanwise obstacles located along the mouth of a resonant cavity.

Flow past a slotted wall bounded by a cavity was investigated experimentally by [13], but the slots were aligned in the streamwise direction. Theoretical and experimental results were compared and good agreement between the theoretical and experimental results was obtained.

If the perforated plate undergoes vibrations, then a number of interesting issues arise. As found by [8], vorticity generation in the apertures of a perforated plate subjected to a grazing flow can lead to dissipation of plate vibrations. In a further theoretical study, Howe [14] determined the sound production arising from both turbulence and vortex shedding. The importance of perforated plates is not limited to low speed applications. Occurrence of high noise levels in transonic wind tunnels is well known, and recent results related to suppression of edge-tone type noise in the systems is described by [15].

Ozalp et al. [16] show that long wavelength hydrodynamic oscillations involve the propagation of coherent concentrations of velocity, vorticity and Reynolds stress correlations along the surface of a perforated plate. Moreover, by observation of a plane of the flow immediately adjacent to the surface of the plate, they showed that such oscillations involved propagation of a well-defined front, i.e., an interface between relatively high and low regions of velocity along the plate surface. This front was reasonably well correlated, in a large-scale sense, along the span of the perforated plate. An experimental investigation was carried out in order to have detailed information on the flow structure around perforated cylinders using high-image density Particle Image Velocimetry technique in shallow water flow by [17].

In this study four different plates were employed, with whole diameters of D = 6.4 mm, 12.4mm, 19.7mm and 25.4mm. The thickness of the plate is maintained constant at t = 11 mm for all experiments. Furthermore, the open area ratio of the plates was maintained constant at 69 %.

2. EXPERIMENTAL SYSTEM AND TECHNIQUES

Techniques of high image velocimetry was employed throughout the investigations. Particle Image Velocimetry (PIV) is a Flow Measurement Technique which can be used to obtain the time dependent full field velocity distributions of single and multi-phase flows. Two-dimensional or three dimensional velocity field distributions can be obtained. The particle image velocimetry (PIV) technique provides, for the first time, a global view of the instantaneous flow field in a quantitative fashion. This allows the user to examine the presence of small flow structures and their influence, obtain vorticity fields quantitatively and, finally, obtain mean, turbulence and stresses globally. These unique capabilities provide a powerful diagnostic tool for solving problems, a unique insight into the nature of flows and the ability to improve the performance of fluid machinery and systems.

Experiments performed in a large-scale water channel, using combination of surface pressure measurement and particle image velocimetry, which yields global representation of the velocity and vorticity fields. The overall aim of this experimental system is to examine instabilities past a fully submerged perforated plate-cavity system, with the option of controlled perturbations of the cavity. This approach allows examination of self-excited instabilities with and without occurrence of simulated cavity resonance. A full boundary layer will be generated along a continuous plate.

The experimental system was mounted within a large-scale water channel as shown in Figure 1. A system of false vertical walls, as well as a suspended horizontal plate at a suitable length with a boundary layer trips at the leading edge to ensure a fully-developed turbulent boundary layer at the leading-corner of the cavity. The overall length L of the perforated plate, which also corresponds to the length L of the bounding cavity. View of the perforated plate is shown in Figure 2. Four different plates are employed, with whole different hole diameters which are given in Figure 2.

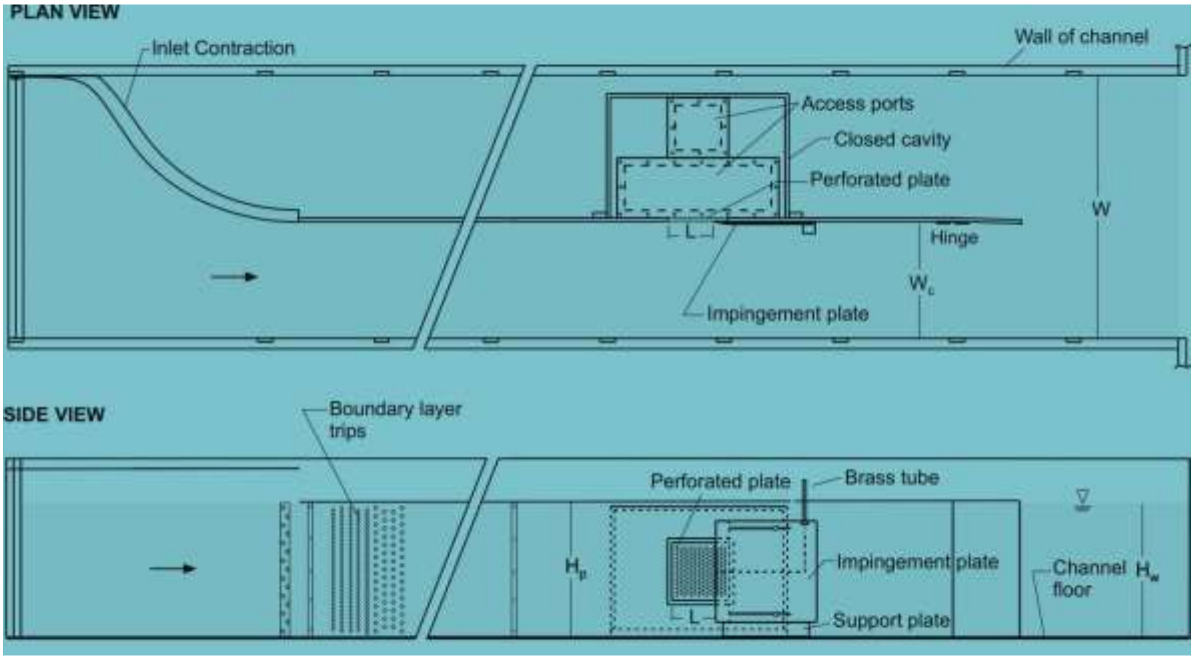
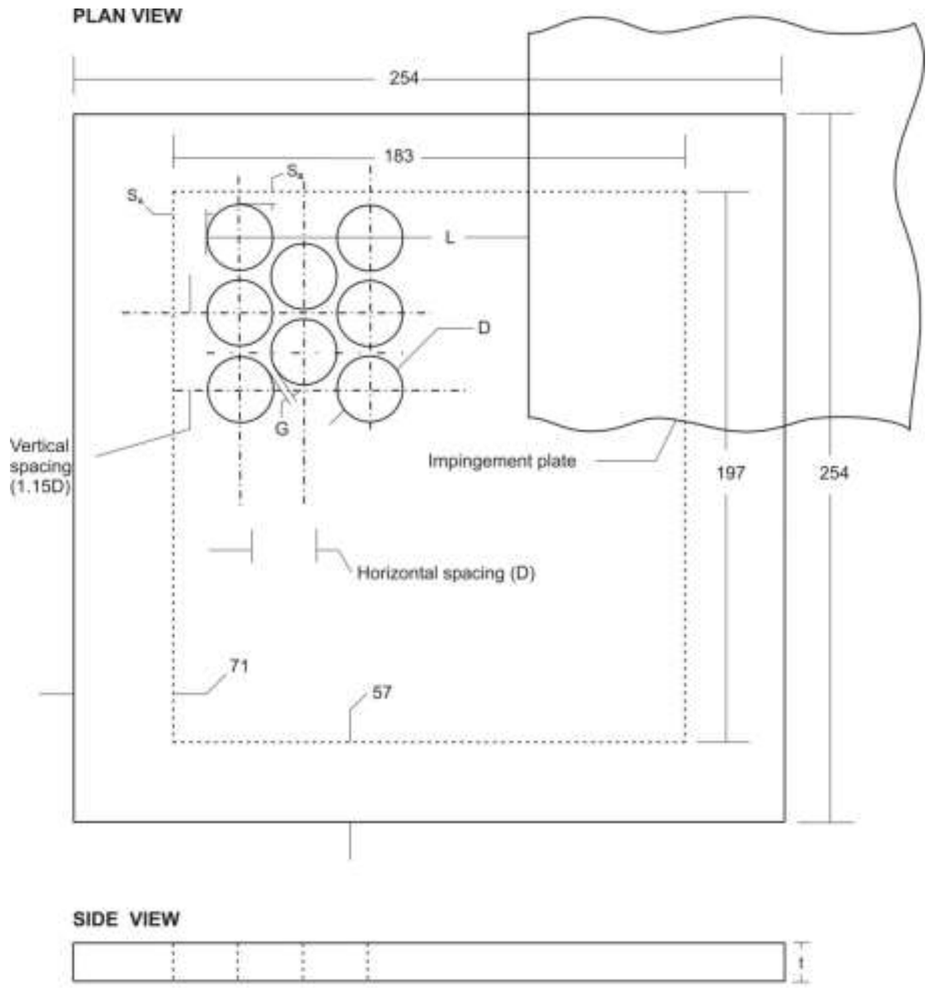


Figure 1. Overview of perforated plate-cavity system in large scale water channel.

Quantitative visualization of the flow patterns was attained using a method of high-image-density particle image velocimetry. Illumination was in the form of a 1mm thick laser sheet which was generated from two Nd:Yag pulsed lasers fitted with a cylindrical–spherical lens system. Each laser of the dual system had a power ratingof 90 mJ. Two orientations of this sheet were employed. This placement of the laser allowed quasi-two-dimensional visualization of the flow structure. Alternately, a horizontal orientation of the laser sheet was used, as indicated in Figure 3. In this case, the sheet was placed close to the surface of the perforated plate, i.e., the distance between the centerline of the laser sheet and the surface of the plate was 1 mm. Using this approach, it is possible to determine the instantaneous spanwise structure of the flow pattern along the perforated plate.



Diameter (D)	Horizontal spacing	Vertical spacing	Gap thickness (G)	Plate Thickness (t)
25.4	25.4	29.2	4	11
19.1	19.1	22	3	11
12.7	12.7	14.6	2	11
6.4	6.4	7.3	1	11

Figure 2. Dimensions of Perforated plates. (All dimensions are in mm.)

A time sequence of series images were acquired at a frequency of fifteen frames per second. This set of instantaneous images could be time-averaged or, by using a selected, coherent event of the instability adjacent to the plate, a phase-average of the flow pattern was acquired. Post-processing involved a combination of instantaneous time-averaged and phase-averaged representations of velocity, vorticity and Reynolds stress. Furthermore, by employing concepts of spectral and cross-spectral analysis of the sequence of PIV images, it was possible to obtain amplitude and phase distributions of the organized fluctuation across the shear flow.

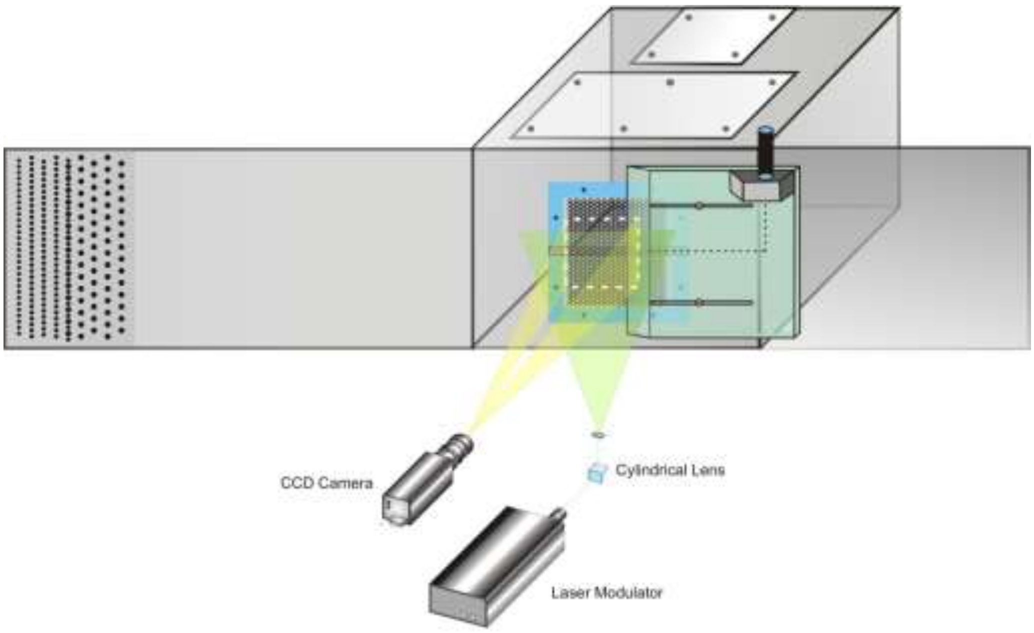


Figure 3. 3D view of cavity and laser orientation

During the pressure analyses experiments pressure signals were subjected to analog filtering and electronic amplifiers. The sampling time was $\Delta t = 0.05$ sec, in order to adequately resolve all the dominant frequencies. Each signal was then transmitted to the A/D board of the host microcomputer, stored in digital form, allowing reconstruction of the time traces, as well as computation of the spectral peaks using an FFT technique. Figure 4. shows the pressure signal lines from transducer to host microcomputer.

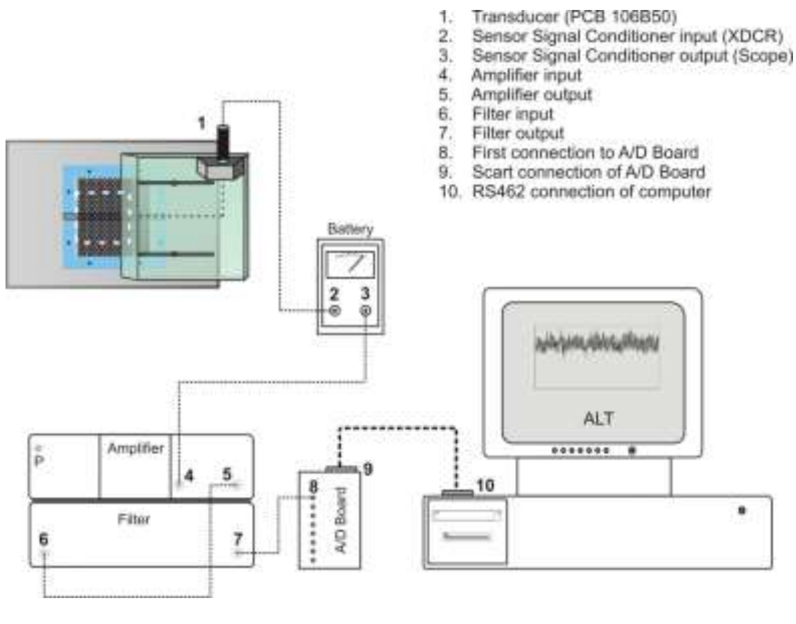


Figure 4. Pressure signal lines from transducer to host microcomputer.

3. RESULTS AND DISCUSSION

In this study self sustained oscillations are characterized in terms of unsteady pressure fluctuations and quantitative images of the instantaneous and averaged flow structure using a technique of high-image-density particle image velocimetry. Variation of the hole diameter D does, however, strongly influence the amplitude and degree of organization of the self-sustained oscillation.Spanwise velocity contours for each perforated plates are shown in Figure 5. It is expected that the coherence of the short-wavelength cavity oscillation will be a function of the perforation geometry.

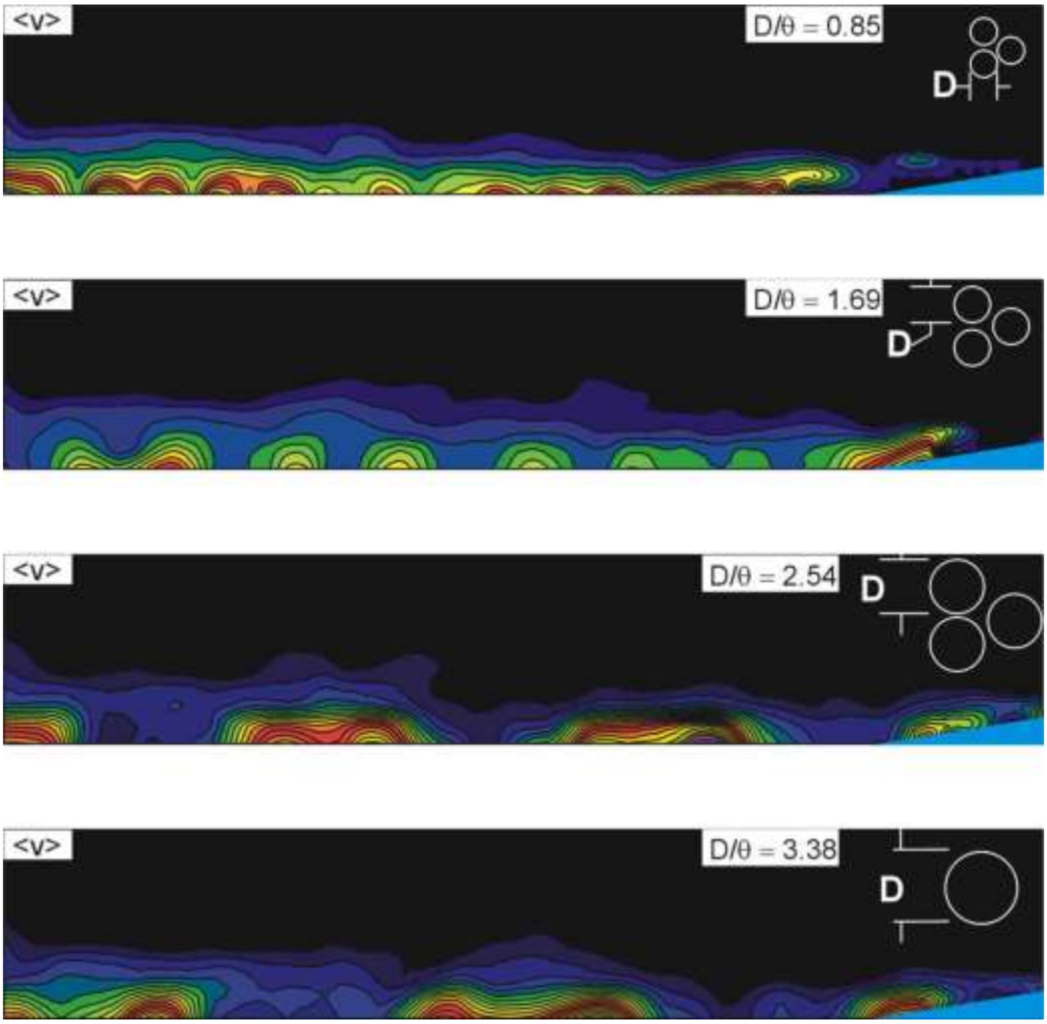


Figure 5. Spanwise velocity contours for each perforated plate

Three dimensional contour plot of streamwise velocity cross spectral density is given in Figure 6. These patterns correspond to the smallest diameter hole D/θ = 0.85. The streamwise location of these patterns corresponds to the region immediately upstream of, and including, the impingement edge. The amplitude of the spectral peak $|S_u(f_0)|$ attains peak values in the region immediately adjacent to the surface of the perforated plate, but contours of relatively high level extend well above the surface of the plate, at a streamwise location immediately upstream of the tip of the impingement edge.

Corresponding patterns of the distribution of the peak amplitude of the spectral component of spanwise velocity component is shown in Figure 7. It shows a highly ordered form, and the region very near the surface of the plate involves a spatially periodic pattern with a wavelength approximately equal to the hole diameter. The highest amplitudes of $|S_v(f_0)|$ occur immediately adjacent to the tip of the impingement edge.

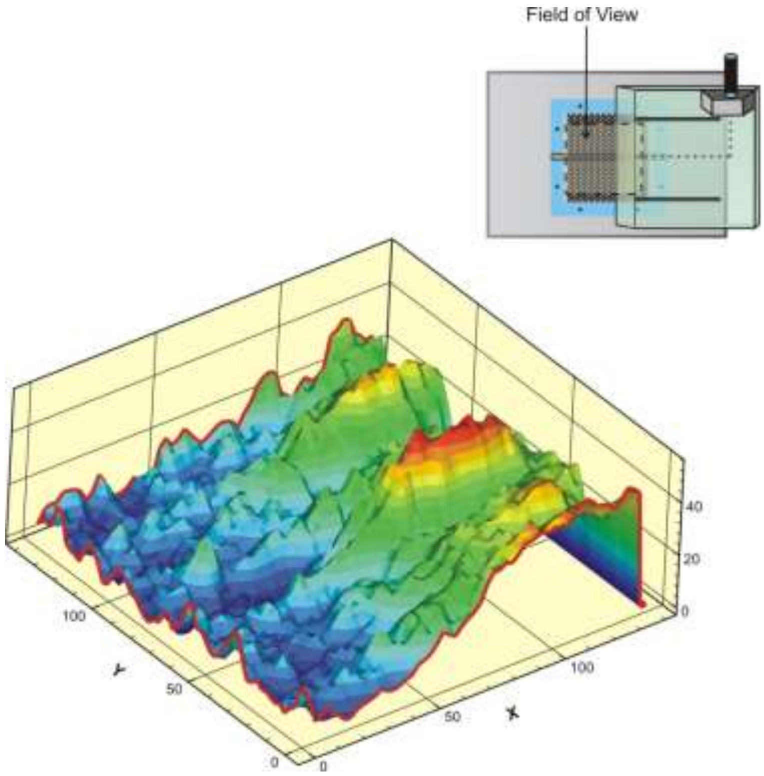


Figure 6. Three dimensional contour plot of cross spectral density S_u for the smallest diameter holes D/θ = 0.85.

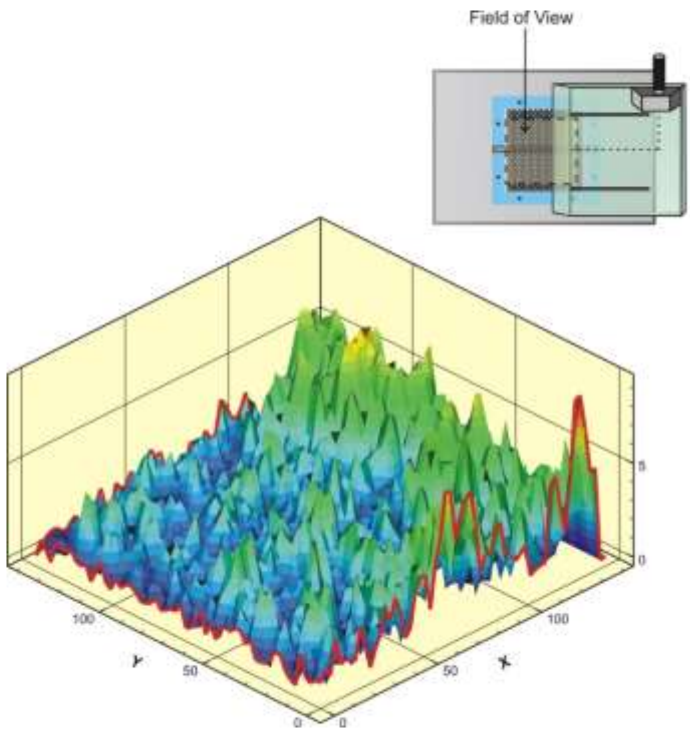


Figure 7. Three dimensional contour plot of cross spectral density S_v for the smallest diameter holes D/θ = 0.85.

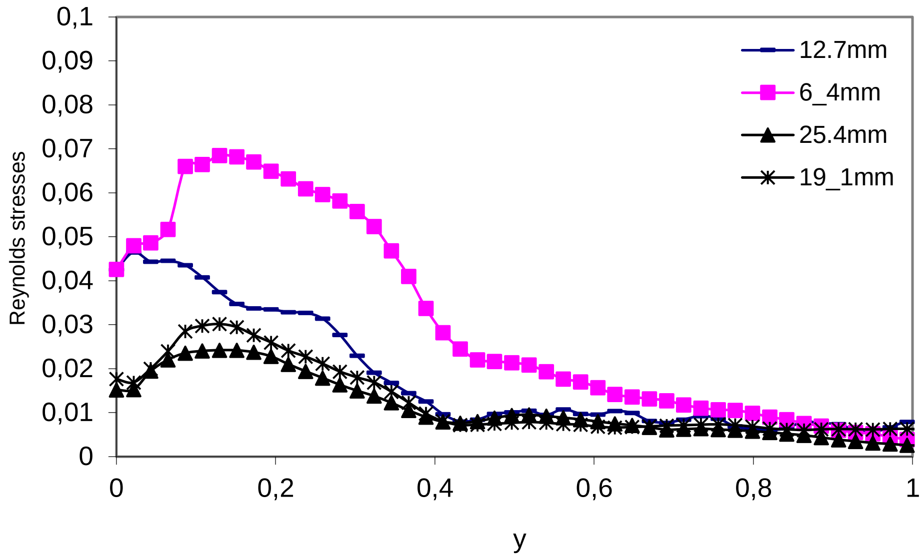


Figure 8. Reynolds stress for each perforated plate along spanwise axis

Figure 8 illustrates velocity correlation for each perforated plate. It can be seen that the maximum of these correlations occur along the 6.4 mm perforated plate and minimum correlations occur along the 25.4 mm. Maksimum Reynolds stresses are occurred near the perforated surface for each perforated plate.

In order to characterize the oscillations through the cavity length pressure signals were acquired at different locations. Pressure records of continuous duration of 102.4 sec., corresponding to, for example 2048 cycles of a fluctuation at 0.05 sampling time, were recorded at various values of impingement length L to momentum thickness θ ratio. Sampling time is Δt = 0.05sec; Nyquist frequency is 10 Hz. These pressure signals are represented in the form of simple time traces and corresponding plots of spectral density. Each of pressure time traces was subjected to a Fast-Fourier transform (FFT) to provide the spectra. Pressure spectra is shown in Figure 9 for the impingement length to momentum thickness ratio is L/θ = 17.75. Figure 9 shows that peak points in the spectra can be defined all perforated plates except the largest hole. These peak points exhibit a decreasing trend with increases in L/θ values. Largest frequency and amplitude of the spectral peak is not detectable for the largest hole perforated plate. It is demonstrated that, as the hole diameter becomes larger relative to the inflow boundary layer thickness, the amplitude of the predominant spectral peak is substantially attenuated and, in a limiting case, undetectable.

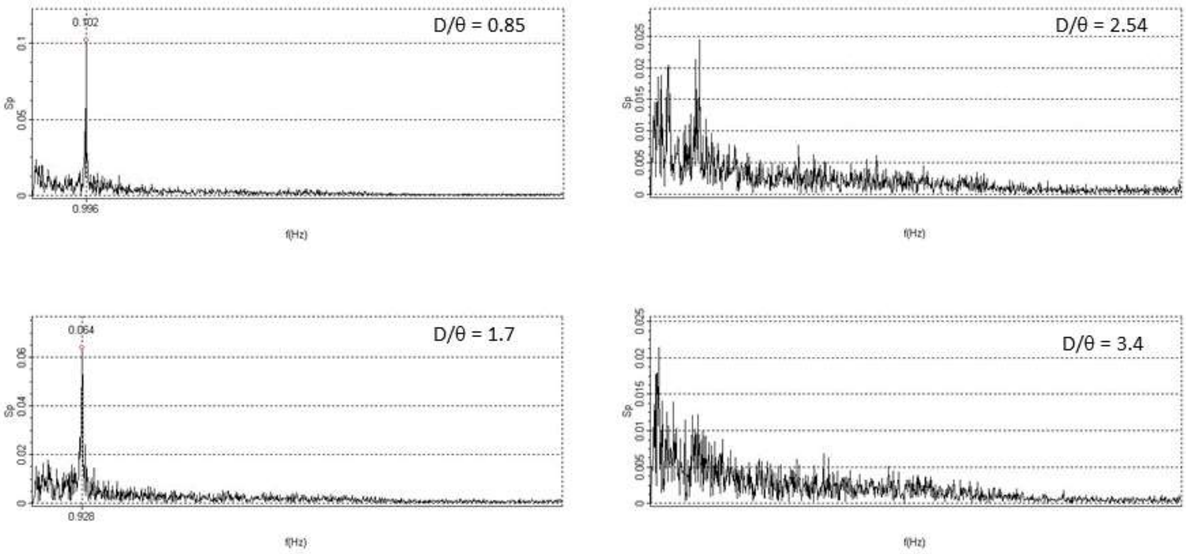


Figure 9. Pressure spectra for each perforated plate. Impingement length to momentum thickness ratio is L/θ = 17.75

4. CONCLUSION

Self-sustained oscillations past a perforated plate is investigated in this study. These oscillations can give rise to highly coherent, Four different plates were employed, with whole diameters of D = 6.4 mm, 12.4mm, 19.7mm and 25.4mm. As the hole diameter is increased the amplitude of the oscillation decreases and the spectral peak becomes ill-defined until, at a value of D/θ~4 Patterns of time-averaged Reynolds stress show that two distinct regions occur. One region is relatively close to the perforated plate and is associated with the interaction between the shear flow and the perforations, and the other region, which is located well above the first, is associated with a classical turbulent boundary layer. For the perforated plate having holes of diameter D/θ~1 which give rise to the most organized and largest amplitude oscillations, the peak amplitude of Reynolds stress occurs very close to the surface of the perforated plate. In contrast, for the largest hole diameter D/θ~4, for which the organized component has an undetectable amplitude, the pattern of Reynolds stress takes on a less ordered form and its peak value is substantially smaller than for the case for which organized oscillations occur.

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