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Experimental investigation of vortex shedding from a plate : effect of external velocity perturbation

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Abstract

Vortex shedding behind a plate with a square trailing edge was investigated in a water tunnel. Both the case where the shedding occurs naturally and the case where the shedding is "forced" by an applied transverse velocity field were studied. The perturbation velocity at the trailing edge of the plate was calibrated by accurately measuring the velocity at this point using laser doppler anemometry.

The spanwise cross-correlation of the fluctuating velocity was determined based on velocity measurements taken at two different spanwise separations; hot film sensors were used to measure the velocities. It was found that high spanwise correlation of the vortex shedding could be induced by applying a low level perturbation at the natural shedding frequency. It was found that there was a threshold below which the vortex shedding was not well correlated.

To prove that the correlations were due to an ordering of the vortices as they were shed, rather than being mainly due to the perturbation field, validation tests were conducted.

The phenomenon was also studied by flow visualization using hydrogen bubbles illuminated by a laser. In natural shedding, spanwise waviness of the vortices could be seen clearly in the cross–stream view. This explains the limited spanwise correlation length for this case. On the application of a low–level perturbation this waviness disappeared, corresponding to the high degree of spanwise correlation measured by the hot films.

NOMENCLATURE

A'	root mean square of displacement of the oscillating wall (mm)
C	ratio of disturbance velocity to the oscillating wall velocity
D	thickness of the plate (mm)
f	forcing frequency (Hz)
f_v	Strouhal vortex frequency (Hz)
R	cross-correlation of two hot-film signals
R_{max}	peak of the cross-correlation

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Re	Reynolds number based on plate thickness & U_0
U_0	free stream velocity (m/s)
u'	longitudinal root mean square of forcing velocity (mm/s)
u'_0	RMS velocity due to random movement of the tracers without forcing (mm/s)
u'_t	threshold of perturbation velocity (mm/s)
ΔZ	spanwise separation distance (mm)

INTRODUCTION

Vortex shedding from a bluff body has been investigated for many decades due to its important role in understanding fundamental fluid dynamics and its close link to a wide range of industrial applications. Vortex induced acoustic resonance is known to be the source of the noise generation in heat exchangers and fans. An aeroacoustic feedback mechanism is often associated with such a resonance. The resonant oscillations can be sustained in a number of ways. One known mechanism is associated with the impingement of a free shear layer, as reviewed by Rockwell and Naudascher [7]. The mechanism involves a disturbance propagating upstream from the impingement region to the receptive area of the shear layer near separation, causing self-sustaining oscillations.

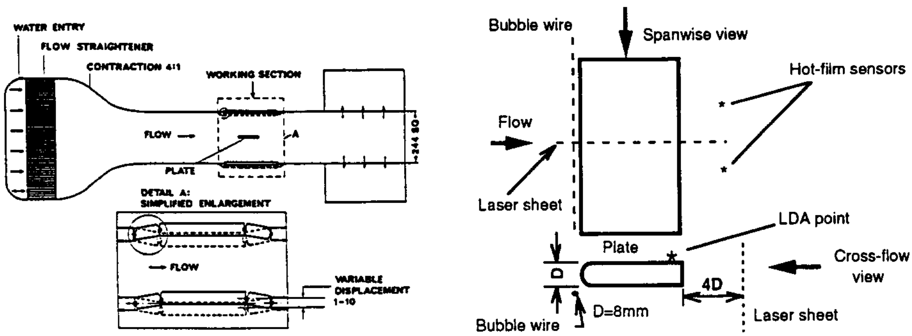
Ho and Nosseir [2] studied self-sustained flow oscillation when a high speed jet impinges on a vertical plate. The aeroacoustic resonance occurs when sound reflected from the plate effectively excites the shear layer of the jet at the nozzle exit.

Welsh et al. [9] examined the fluid dynamics of the flow-excited acoustic resonance process of a plate in a duct. They demonstrated a resonant mechanism whereby a transverse acoustic mode excited by a vortex street behind a plate fed back to lock the vortex shedding process, resulting in a self-sustaining oscillation. The model they developed to describe this process has three key elements: (1) an acoustic source (vortex street), (2) a feedback of the sound on the development of the vortex street, and (3) a damping process whereby the acoustic energy was transferred out of the duct. While the emission of the sound by the vortical motion of the fluid flow has been elucidated by Howe's [5] theory, the process whereby the sound influences the vortical motion is not well understood. Further investigation is needed based the works of Welsh et al. [9]. This is the primary motivation of the present work.

Hourigan et al. [3] used a numerical method to simulate the vortex shedding induced by a longitudinal acoustic resonance of a duct containing two sets of baffles. They demonstrated that the velocity perturbation due to sound field feeds back and synchronizes the vortex shedding from the upstream baffle. They also showed the condition whereby acoustic resonance can be sustained.

Blevins [1] studied the effect of an imposed sound field on the fluid mechanics of vortex shedding. He demonstrated that under natural shedding when no sound field is imposed, the shedding frequency wandered 1-2 % about the mean value. When a sound field greater than 130 dB is applied, the frequency wander is eliminated and shedding becomes well correlated along the cylinder span. He showed that it is not the sound pressure but rather the acoustic particle velocity which influences vortex shedding.

In this paper, we present some experimental results carried out in a water tunnel. A



(a) (b)

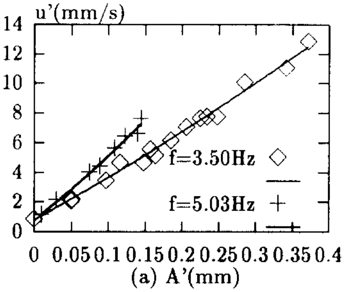
Figure 1. Experimental set-up. (a) Schematic of return circuit water tunnel showing the oscillating side walls of the working section; (b) Test model and measurement points.

plate with a square trailing edge and semi-circular leading edge was used as a test model. An external transverse oscillating velocity field was applied analogous to the acoustic β-mode in a duct (Parker [6]). The threshold of the perturbation velocity above which vortex shedding is found to become well correlated along the span was determined. Flow visualization was also carried out.

WATER TUNNEL FACILITIES AND INSTRUMENTATION

The water tunnel has a square working section 244 by 244 mm, a maximum velocity in the working section of 400 mm/s, and was specially designed and built to have a pair of flexible walls in the test section. Thus, the walls can be oscillated in the cross flow direction imposing a perturbation velocity field analogous to that produced by the acoustic transverse mode in a duct near a body located in the working section. A schematic of the water tunnel is shown in Figure 1 (a). Details of the water tunnel have been described by Welsh et al. [8]. The second and third harmonics of the perturbation velocity spectrum of the oscillating walls are 25 and 15.5 dB below the fundamental frequency respectively. The free stream velocity profile is uniform within 0.5% outside the wall boundary layer in the test section. The longitudinal turbulence intensity is typically 0.1%. A schematic of the test plate is shown in Figure 1 (b). It has a semi-circular leading edge and square trailing edge, a thickness of 8 mm and chord length 40 mm. The Reynolds number based on the plate thickness was 600.

In the flow visualization tests, hydrogen bubbles generated by a nicrome wire cathode were used as seeding particles. The bubble wire was located near the leading edge of the plate, as shown in Figure 1 (b). The light from a 4W Argon-Ion continuous laser was spread into a thin sheet to illuminate the near wake region behind the plate. Photographs were recorded through a "Megaplus" CCD camera controlled by a personal computer. Pulsation of the laser light was achieved using an acoustic-optic modulator (AOM) unit and synchronized to the camera through the computer; "IMPRO-II" image processing



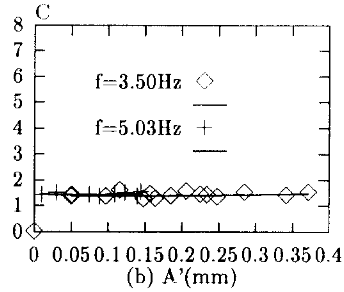


Figure 2. Calibration of the perturbation velocity at the trailing edge of the plate, (a) variation of u' with amplitude of the oscillating wall, (b) variation of C with amplitude of the oscillating wall.

software was used to enhance the digital pictures.

A TSI Laser Doppler Anemometry (LDA) operating in back scatter was used to calibrate the perturbation velocity intensity near the trailing edge of the plate at zero free steam velocity. Seeding for the LDA was achieved using the hydrogen bubbles. Frequency shift was applied during the measurement. The typical data rate was approximately 1000 points/sec. The calibration point was located 2 mm upstream of the trailing edge and 1 mm from the surface of the plate, as shown in Figure 1 (b).

Two TSI hot-film sensors were placed 30 mm downstream of the trailing edge of the plate. The hot-film sensors are 1 mm in length and 4μ m in diameter. Data acquisition and processing was controlled by a personal computer. The typical sampling rate was 80Hz. Every realization had 60×512 data points, equivalent to 800 cycles of the vortex shedding.

RESULTS

Calibration of the perturbation velocity at the trailing edge of the plate

The sensitive region of vortex shedding flow is near the separation point, where flow instability initiates. The root mean square of the perturbation velocity u', as measured by the LDA, was normalized by the velocity of the oscillating wall: $C = (u' - u'_0)/(2\pi f A')$, where f is the forcing frequency. Two frequencies were used in the calibration: $f = 3.5$ and $5.03Hz$, A' is the root mean square of the forcing amplitude of the oscillating wall. u'_0 was due to random movement of the tracers when no forcing was applied, and was measured when no forcing was used. C is found to be a constant ($C \approx 1.43$). Since the perturbation level was very low, the forcing is expected to be linear. The results are presented in Figures 2 (a),(b).

Spanwise cross-correlation measurement

At a free stream velocity of $U_0 = 0.071m/s$, the nominal vortex shedding frequency was 2.05Hz. Two hot-film sensors separated by 6D and 9D spanwise were used to simultaneously measure the longitudinal fluctuating velocity induced by the vortex shedding. The perturbations were forced at the nominal Strouhal vortex shedding frequency of 2.05Hz. The spanwise velocity cross-correlations for increasing perturbation levels are shown in Figures 3 (a)-(d), where R is the normalized cross-correlations. The cross-correlations were obtained from the two hot-film velocity oscillation signals by the digital FFT method.

Curve 1 in Figures 3 (a),(b),(c),(d) shows that as the forcing level is increased, the spanwise correlation also increases. Curve 2 in Figures 3 (b),(c),(d) shows the results of a validation test used to verify that the increased correlation is due to a change in flow rather than due to forced perturbation, as described later. For the spanwise separation $\Delta Z = 6D$, the peak correlation at zero forcing level was approximately 0.45. When a forcing at $u' = 0.25mm/s$ was imposed, the correlation peak reached 0.65. As u' was further increased, the correlation saturated at approximately 0.90.

The forcing level was very low and even the maximum level was still an order of magnitude lower than that of the fluctuating velocity induced by the natural vortex shedding. For the maximum forcing level, $u' = 0.8mm/s$, or $\approx 1.2\%$ of the free stream velocity. In order to verify that the measured spanwise cross-correlation was indeed due to the vortex shedding signals instead of the applied perturbation velocity field, a validation test was carried out each time the spanwise correlation was recorded. In the validation test, the free stream velocity was adjusted to 0.110 m/s. The natural shedding frequency shifted to $f = 3.18Hz$ while the forcing conditions were left unchanged. The spanwise correlation was immediately lost therefore illustrating that the spanwise cross-correlations measured were indeed due to the vortex shedding, instead of the perturbation field itself. If the spanwise correlation was that of the perturbation velocity field no change of the correlation should occur, since the forcing condition was not changed.

The same procedure was repeated for spanwise separation $\Delta Z = 9D$. For brevity only the peak values R_{max} are shown in Figure 4.

Threshold of the forcing

The peak cross-correlation for two spanwise separations is shown in Figure 4 as a function of the forcing level. This data shows that the peak cross-correlation for the two separations are of similar value within experimental uncertainty as the forcing level increases. Therefore, a threshold for the forcing level can be defined above which the vortex shedding is well-correlated along the span of the plate. This threshold is approximately $u'_T \approx 0.25mm/s$ ($u'_T/U_0 \approx 0.35\%$).

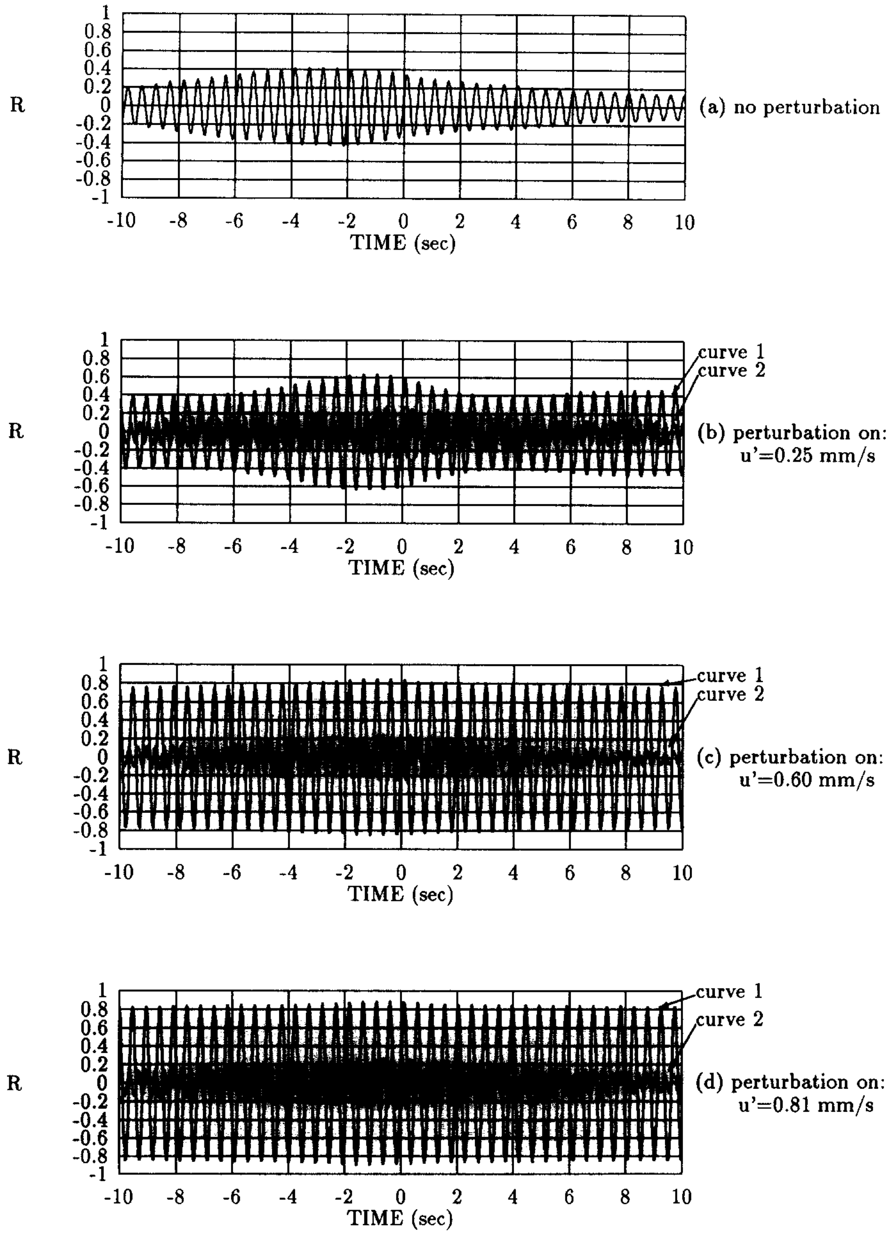


Figure 3. Cross-correlation: $\Delta Z = 6D$, forcing frequency $f = 2.05Hz$. Curve 1: $U_0 = 0.071m/s$, shedding frequency $f_v = 2.05Hz$; curve 2: validation test, $U_0 = 0.110m/s$, $f_v = 3.18Hz$.

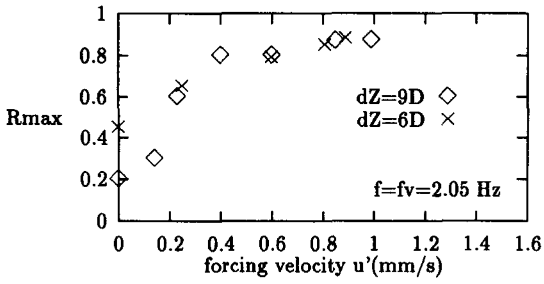


Figure 4. Peak correlation variation vs forcing level; $U_0 = 0.071m/s$.

Flow visualization experiments

Typical results are shown in Figures 5 (a),(b). Compared with those at the natural condition, the shed vortices in forced flow appear more concentrated and regular. It was also observed that the vortex formation length during forcing was shortened. This observation is in agreement with the findings of Griffin and Ramberg [4].

Cross-stream views are provided in Figures 6 (a),(b) for natural and forced shedding. In the unforced condition a waviness in the visualized hydrogen bubble sheet cut by the laser light can be seen. The bubbles were released from a vertical wire parallel to the plate upstream of the wake, as shown in Figure 1(b). This waviness suggests a phase shift exists in the vortex shedding along the span of the plate. When a perturbation above the threshold was applied at the vortex shedding frequency the waviness was eliminated.

DISCUSSION

The influence of sound on the development of vortices is part of the feedback loop behind many fluid induced acoustic resonances. An understanding of the effect of sound on the fluid process is therefore essential in improving our knowledge about the aeroacoustic phenomenon. The results presented in this paper demonstrated the effects of the external velocity perturbation field on the vortex street development. The perturbation field simulated the acoustic particle velocities produced by the aeroacoustic resonant β-mode in a duct (Parker [6]). The simulation of acoustic particle velocity field is considered to be important, because the vortex street is sensitive to acoustic velocity rather than pressure. [1]

A development in three dimensionality of the vortical structures in the near wake region behind a bluff body in cross flow is implied in the rapid decay of the spanwise cross-correlation. For instance, the present results suggest that the correlation drops from 0.45 at $\Delta Z = 6D$ to 0.25 at $\Delta Z = 9D$ for natural shedding. The decay of the correlation is due to two main factors: one is associated with the phase jitter of the Strouhal vortex shedding. As a result of this jitter, there is a random phase shift between the vortices along the span. The phase shift was demonstrated in our cross-flow visualization. The

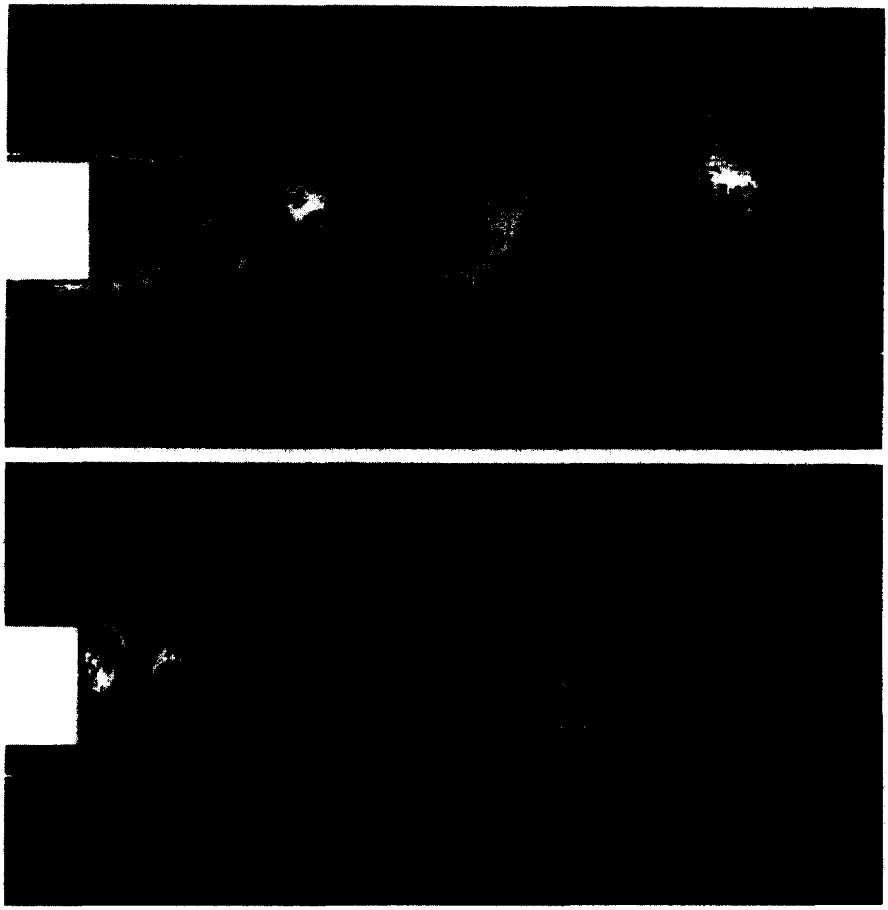


Figure 5. Spanwise view of the vortex shedding behind a plate, $U_0 = 70mm/s, Re$ $600, f_v = 2.05Hz$. (a)unforced, (b) forced at $f = 2.05Hz, u'/U_0 \approx 1\%$.

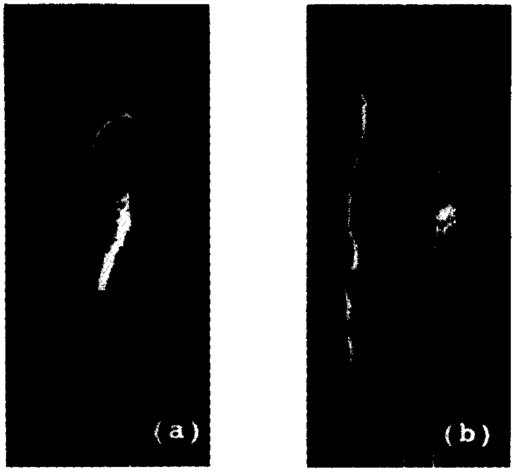


Figure 6. Cross-flow view. The conditions are same as figure 5.

other factor can be attributed to the random incoherent velocity fluctuation, caused for example by the formation of streamwise vortices. When a two dimensional transverse velocity perturbation field is applied in the near wake region at the vortex shedding frequency, the phase shift is eliminated. Vortices are shed in phase along the span of the plate, resulting in higher correlation. This was also confirmed by the elimination of the waviness of the vortices, as shown in the cross flow visualization pictures (Figures 6 (a), (b)).

An estimation of the threshold over which vortices become correlated along the span is of particular importance in theoretical modeling of the feedback phenomenon, (see for example the work of Hourigan et al. [3]). When the forcing of the fed back sound is above the threshold, the vortices are fully correlated resulting in fluid acoustic resonance.

CONCLUSION

Spanwise correlation of the vortex shedding from a plate is sensitive to low level transverse perturbation. A threshold of the forcing velocity was determined through experiments above which the vortices shed in phase along the span of the plate. The study illustrates the mechanism through which the sound field influences the vortex shedding process in a fluid acoustic feedback loop.

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