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Effect of the periodic perturbations on the wall pressure downstream of a backward facing step

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Abstract

The flow structures in a separated shear layer actuated using a synthetic jet actuator were studied using experimental methods. When forced at a frequency much lower than the natural shedding frequency ($fH/U = 0.042$ or $fX_r/U = 0.24$), the vertical flapping motion of the shear layer downstream of the separation point became very prominent. The peak of the pressure spectra at the forcing frequency measured near the separation point ($x/H = 1$) increased linearly with the forcing amplitude (u') suggesting a linear response of the pressure fluctuations to the forcing of the synthetic jet. The linear response did not hold for the pressure fluctuations away from the jet exit as the magnitude of the peak for $St = St_A$ measured at $x/H = 3$ soon saturated when the forcing amplitude (u'/U) became larger than 0.25.

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Keywords: Active flow control; synthetic jet; backward facing step

Nomenclature

C_P	static wall pressure coefficient, $P/(0.5\rho U^2)$
$C_{p'}$	root-mean-square value of the wall pressure coefficient, $p'/(0.5\rho U^2)$
f_A	forcing frequency, Hz
F_{pp}	power spectrum of wall pressure, Pa^2/Hz
H	height of the step, m
Re_H	Reynolds number based on the step height, UH/ν
St_A	Strouhal number for the forcing frequency, $f_A H/U$
u'	root-mean-square value of the exit velocity for the synthetic jet, m/s
U	free-stream velocity, m/s
x, y, z	Spatial coordinates, m
X_r	Time-averaged re-attachment length, m

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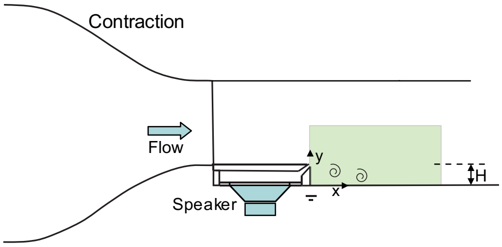

Fig. 1. Schematics of the test rig

1. Introduction

There is great amount of interest in the flow over a backward facing step where the separated flow re-attached to the wall forming a well-defined separation region. Efforts were made to alleviate the surface pressure fluctuations using active methods. Periodically perturbing the shear layer at the separation location using a zero-net-mass-flux (synthetic jet) actuator was found to be effective[1,3,5]. Chun and Shun [1] studied the effect of the periodic perturbation at the separation location on the size of the re-circulation bubble (X_r) for flow with a Reynolds numbers (Re_H) of 13000-33000 using a zero-net-mass-flux actuator. They found X_r decreased when the non-dimensional actuation frequency $St_A = f_A H/U$ varied between $0 \sim 0.7$, the most effective forcing frequencies was close to the vortex shedding frequency of the unforce flow, $St_A = 0.25$ to 0.29. The static pressure inside of the re-circulation region also decreased significantly when X_r decreased. Chun and Shun [2] also studied the evolution of the structures over a backward facing step under periodic forcing using flow visualization technique. The Reynolds number was 1200. The visualization revealed that the flow structures in the shear layer locked in with the periodic actuation when St_A was 0.47. The structures grew in size while travelling in the shear layer, X_r reduced as much as 60%. When high actuation frequency, $St_A = 0.82$. was used, the growth of the structures were small comparing with the low-frequency forcing case and X_r was similar to that for the un-forced flow. Yoshioka et al. [3,4] studied the flow over a backward facing step under periodic actuation using Particle Image Velocimetry. The Reynolds number (Re_H) was approximately 3700. They found the most effective forcing frequency in reducing X_r was $St_A = 0.19$. The Reynolds shear stresses in the shear layer near the re-attachment was the largest under forcing with this optimum frequency. They also found the propagation velocity of the structures over the re-attachment region was $U_c \approx 0.3U$ Dejoan and Leschziner [5] studied the flow over a backward facing step under periodic actuation at a frequency (St_A) of 0.2 using Large Eddy Simulation. They found X_r reduced nearly 30% when Re_H was 3700. The propagation velocity of the structures over the re-attachment region was $U_c \approx 0.4U$. Previous investigations focused on the changes in re-attachment length and the static pressure inside of the re-circulation region. The most effective forcing frequency (f_A) in reducing the reattachment length was found to be close the natural shedding frequency $f_A H/U = 0.25$ to 0.29. The current investigation focused on the distribution of the fluctuating wall pressure under periodic forcing with frequencies of $f_A H/U = 0.04$ to 0.33. Different amplitudes of the periodic forcing velocity ($u'/U = 0.1$ to 0.4) were compared to illustrate how the separated flow responded to the actuation.

2. Experimental methods

The investigation was performed in a blown-down wind tunnel shown in Fig. 1. The air flow supplied by a variable speed blower with a 2.2kW motor went through a 2m long diverging section, a large settling chamber (900mm by 900mm by 750mm) and a contraction section with a 9:1 area ratio and a length of 750mm. The exit of the contraction section is 300mm by 300mm. There was a perforated plate with opening ratio of 50% at the end of the diverging section to condition the flow before it entered the settling chamber. Plexiglas test section with a length of $L = 7200mm$ and a width of $W = 300mm$ was attached to the exit of the contraction section. The step was located at 300mm downstream of the inlet of the test section. The height of the test section was 300mm initially, and 325mm downstream of the step. The height of the step was $H = 25mm$, thus the aspect ratio of the step was 12, that was large enough to ensure a two dimensional flow in the central part of the test section near the mean re-attachment point. There was

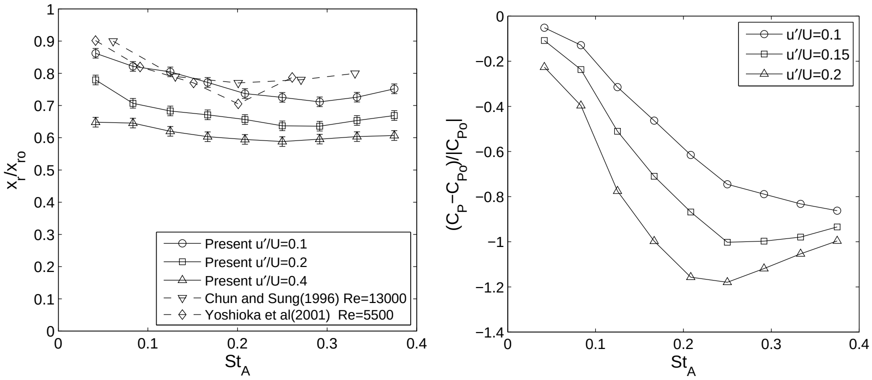

Fig. 2. Time-averaged (a) re-attachment locations for $u'/U = \circ\ 0.1$, $\triangle\ 0.2$ and $\times\ 0.4$ and (b) static wall pressure coefficients at $x/H = 1$ for $u'/U = \circ\ 0.1$, $\Box\ 0.15$ and $\triangle\ 0.2$. Results by $\Box$ Chun and Shun [1] and ∇ Yoshioka et al. [3] were also shown for comparisons.

no top plate in the test section. The free stream turbulence intensity was approximately 1.9%. A free-stream velocity of $5.7m/s$ was used, the corresponding Re_H is 9100. A single hot-wire probe was used to measure the profile of the in-coming velocity at $x/H = -0.5$. The boundary layer thickness was found to be $\delta_{0.99}/H = 0.12$.

The fluctuating pressure along the centerline of the wall was measured using 8 Panasonic WM-60B microphones embedded inside the wall sensing the flow through a 0.8mm-diameter, 3mm-long pinhole. The microphones for these measurements were calibrated externally using a Hongsheng HS6020 piston phone at 1000Hz with a sound pressure level of 94dB. The response time of these microphones were checked and was all within ±0.25ms (or $\tau U/H = \pm 0.06$). More measurement of wall pressure using this technique can be found in [8].

The actuator used in this investigation was a 220mm-diameter 8-ohms loud-speaker mounted under the step forming a $0.22m * 0.28m * 0.02m$ cavity. Periodic jet flow was produced through a two-dimensional slot with a width of $s = 1mm$ on top of the cavity. The jet was issued at the edge of the step ($x/H = 0$, $y/H = 1.0$) and oriented 45^o to the free stream velocity. The speaker was driven by harmonic signals with different frequencies and amplitudes generated using a Texas Instruments TMS320C6713 Digital Signal Processor (DSP) board and amplified using a 150W digital amplifier. A single hot-wire probes with a Hanghua CTA-02A constant temperature anemometry system was positioned at 1 slot width downstream of the jet exit to characterize the actuator. The sensor in the single-wire probe had a diameter of 5μm and length of 1.25mm. The hot wire probes were calibrated at the exit of wind tunnel. The velocity probe was located at 3mm downstream of the jet exit. The natural frequency of the actuator was found by applying sinusoidal signals of various frequencies and a fixed amplitude to the actuator and examining the rms values of out-flow half of the oscillating jet velocity, u'. The natural frequency was found to be approximately 40Hz where u' was the largest among all the forcing frequencies. Sinusoidal signals of different frequencies and amplitudes were then applied to the actuator. The oscillatory jet velocity was recorded using a PC with NI-6014 data acquisition card and a Labview routine. Four actuation frequencies $f_A = 10Hz$, $40Hz$, $60Hz$ and $80Hz$ were examined here, corresponding to non-dimensional frequencies of $St_A = 0.042$, 0.167, 0.250 and 0.333, respectively. Three actuation amplitudes $u'/U = 0.1$, 0.2 and 0.4 were studied for each actuation frequency.

3. Results and Discussion

The time-averaged re-attachment locations for actuation frequencies and amplitudes are shown in Fig. 2. The results reported in [1,3] were also shown for comparisons. When the actuation amplitude was $u'/U = 0.1$, X_r decreased when the actuation frequency increased from $St_A = 0.04$ and reaching a minimum at $St_A \approx 0.25 - 0.3$, in agreement with the results reported in [1,3], though the forcing amplitudes used by [1,3] might be different. X_r then decreased when u'/U was increased. The time-averaged size of the re-circulation bubble was shortened for as much as 40% when $u'/U = 0.4$ and $St_A = 0.25$. The time-averaged static pressure at $x/H_j = 1$ for different actuation frequencies and amplitudes are shown in Fig. 2 (b). The changes in the static pressure at $x/H_j = 1$ were closely related to the changes in the time-averaged re-attachment point. The static pressure near the base of the step became more negative

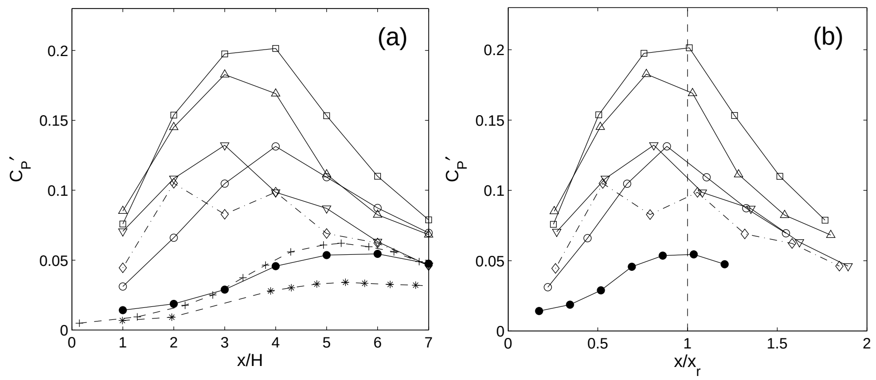

Fig. 3. Distributions of the fluctuating pressure coefficients for • un-actuated flow and flow actuated with a frequency of St_A = ○ 0.042 □ 0.125 △ 0.250 ∇ 0.333 and a forcing amplitude of u'/U =0.2. The results for un-actuated flow by + [6] ∗ [7] were also shown for comparisons.

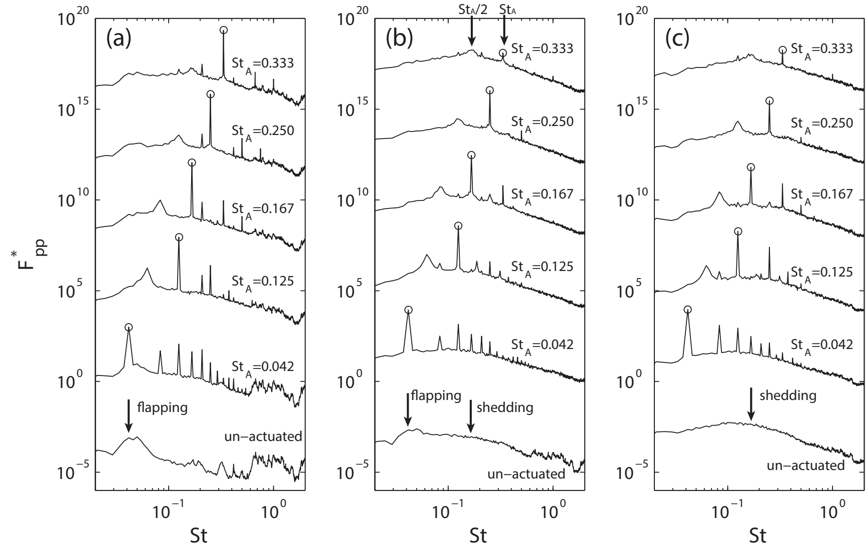

Fig. 4. Non-dimensional power spectra of fluctuating wall pressure measured at x/H = (a) 1, (b) 3 and (c) 5 for a forcing amplitude of u'/U =0.2.

when X_r became small. This is expected as the curvature in the streamline of the attaching flow became large when the size of the re-circulation bubble decreased.

The fluctuating wall pressure coefficient for un-actuated flow and flows forced using a forcing amplitude of u'/U of 0.2 and different forcing frequencies are shown in Fig. 3. The results for un-actuated flow agree with those measured by Heenan and Morrison[6] and Driver et al.[7]. There was a peak in the fluctuating wall pressure at x/H = 5 to 6, that was slightly upstream of the time-averaged re-attachment location. C_p' increased significantly and the location of the peak in C_p' moved upstream to x/H = 3-4 when the flow was forced, particularly at a frequency St_A of 0.125, where the size of the peak was approximately four times of that for the un-forced flow. The location of the peak shifted further upstream and the size of the peak decreased when the forcing frequency further increased.

The normalized pressure spectra ($F^*_{pp} = F_{pp}(H/U)/(0.5\rho U^2)^2$) measured at x/H = 1, 3 and 5 for different forcing frequencies and a forcing amplitude of u'/U = 0.2 are shown in Fig. 4. The un-forced case were also shown. The spectra were offset for 4 decades for clarity. The peak at the forcing frequency ($St = St_A$) was marked using a circle. The spectra at x/H = 1 and 3 for the un-forced flow showed a low frequency peak St ≈0.04, the maximum in the spectrum at x/H = 5 indicated the shedding frequency of the shear layer structures was approximately St ≈0.17. When the flow was forced at the flapping frequency St_A = 0.042, a strong peak emerged in the spectra at this frequency, the magnitudes of the peak were much larger than the peaks without forcing. When the flow was forced

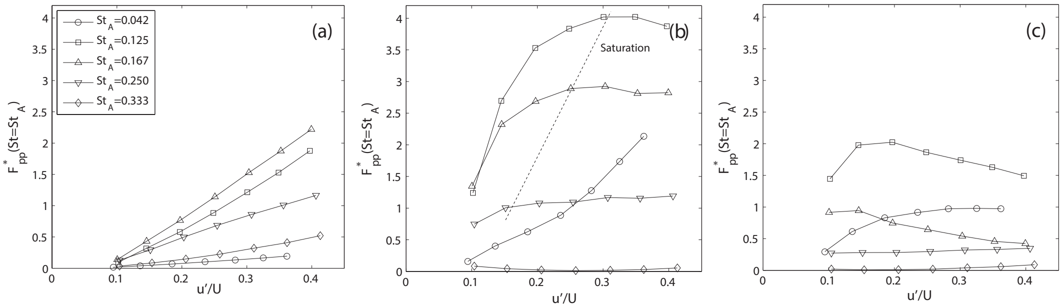

Fig. 5. Magnitude of spectra at the forcing frequency $F^*_{pp}(St = St_A)$ at x/H = (a) 1, (b) 3 and (c) 5

at a higher frequency $St_A \geq 0.125$, peaks at the forcing frequency also emerged in the spectra, a sub-harmonic also emerged. The size of the peak at the sub-harmonic frequency relative to the peak at the forcing frequency increased when the forcing frequency increased. At $x/H = 3$ and $St_A = 0.333$, the peak at $St_A/2$ was larger than the peak at St_A, suggesting the reaction of the flow to the forcing was much larger near the shedding frequency, when the forcing frequency was twice of the shedding frequency.

The magnitude of the peak at the frequency of St_A at $x/H = 1$, 3 and 5 are shown in Fig. 5. The changes of magnitude of the peaks varied for different forcing frequencies, and the changes were different at different stream-wise locations. At $x/H = 1$, the size of the peak at St_A increased with the forcing amplitude for all the forcing frequencies examined here. At $x/H = 3$, the size of the peak saturated for forcing amplitude $u'/U \geq 0.3$ for forcing frequency of $0.125 \leq St_A \leq 0.167$, the sizes of the peaks do not increased with the forcing amplitude. The saturation amplitudes further decreased at $x/H = 5$, the size of the peak reached to a maximum and then decreased in size when the forcing amplitude further increased. The decrease in the size of the peak was caused by the fact that the re-attachment location occurred at a location $x/H < 4.0$ when the forcing amplitude was large enough.

4. Conclusions

The flow structures in a separated shear layer actuated using a synthetic jet actuator were studied using experimental methods. When forced at a frequency much lower than the natural shedding frequency ($fH/U = 0.042$ or $fX_r/U = 0.24$), the vertical flapping motion of the shear layer downstream of the separation point became very prominent. The peak of the pressure spectra at the forcing frequency measured near the separation point ($x/H = 1$) increased linearly with the forcing amplitude (u') suggesting a linear response of the pressure fluctuations to the forcing of the synthetic jet. The linear response did not hold for the pressure fluctuations away from the jet exit as the magnitude of the peak for $St = St_A$ measured at $x/H = 3$ soon saturated when the forcing amplitude (u'/U) became larger than 0.25.

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References

[1] Chun, K B, Sung, H J. (1996) Control of turbulent separated flow over a backward-facing step by local forcing. Experiments in Fluids 21: 417-426

[2] Chun, K B, Sung, H J.(1998) Visualisation of a locally-forced separated flow over a backward-facing step. Experiments in Fluids 25:133-142

[3] Yoshioka, S, Obi, S, Masuda, S.(2001) Turbulence statistics of periodically perturbed separated flow over a backward-facing step.International Journal of Heat and Fluid Flow 22:393-401

[4] Yoshioka, S, Obi, S, Masuda, S.(2001) Organized vortex motion in periodically perturbed turbulent separated flow over a backward-facing step. International Jourlnal of Heat and Fluid Flow 22:301-307

[5] Dejoan A, Leschziner M A.(2004) Large eddy simulation of periodically perturbed separated flow over a backward-facing step.International Journal of Heat and Fluid Flow 25:581-592

[6] Heenan A, Morrison J (1998) Passive control of pressure fluctuations generated by separated flow. AIAA J 36:1014-1022.

[7] Driver D, Seegmiller H, Marvin J (1987) Time-dependent behavior of a reattaching shear layer. AIAA J 25:914-919.

[8] Hudy L, Naguib A, Humphreys W (2007) Stochastic estimation of a separated-flow field using wall-pressure-array measurements. Phys Fluids 19:024103.