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Letter

Response of turbulent fluctuations to the periodic perturbations in a flow over a backward facing step

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ABSTRACT

The flow structures in a separated shear layer actuated by 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 prominent. The size of the peak in the pressure spectra at the forcing frequency ($St_A = f_A H/U$) measured near the separation point ($x/H = 1$) increased linearly with the forcing amplitude (u'/U) suggesting a linear response of the pressure fluctuations to the forcing by 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_A measured at $x/H = 3$ soon saturated when the forcing amplitude became larger than 0.3.

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 [1–5]. 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 0–0.7, the most effective forcing frequencies were close to the vortex shedding frequency of the unforce flow, $St_A = 0.25 - 0.29$. 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 in their study 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 traveling in the shear layer, and X_r reduced as much as 60%. When a 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 the particle image velocimetry (PIV). 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 numerically using the large eddy simulation (LES). 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 current investigation focuses on the distribution of the fluctuating wall pressure under periodic forcing with frequencies of $St_A = 0.04$–0.33, covering the "flapping" frequency and the "shedding" frequency for the separated shear layer [6]. The magnitude in the pressure spectrum at the frequency of St_A for different forcing amplitudes ($u'/U = 0.1$–0.4) were compared to study how the separated flow responded to the actuation. In this letter, the experimental methods are presented in the next section, followed by the results and the concluding remarks.

The investigation was performed in a blown-down wind tunnel shown in Fig. 1. The air flow supplied by a variable speed blower

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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

with a 2.2 kW motor went through a 2 m long diverging section, a large settling chamber (900 mm by 900 mm by 750 mm) and a contraction section with a 9:1 area ratio and a length of 750 mm. The exit of the contraction section is 300 mm by 300 mm. 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 $L = 720$ mm and a width of $W = 300$ mm was attached to the exit of the contraction section. The step was located at $Ls = 300$ mm downstream of the inlet of the test section. The height of the test section was 300 mm initially, and 325 mm downstream of the step. The height of the step was $H = 25$ mm, 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 no top plate in the test section. The free stream turbulence intensity was approximately 0.9%. A free-stream velocity of $U = 5.7$ m/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 $x/H = -1$. The boundary layer thickness was found to be $\delta_{0.99}/H = 0.12$, as shown in Fig. 2.

The fluctuating pressure along the centerline of the wall was measured using 7 Panasonic WM-60B microphones embedded inside the wall sensing the flow through 0.8 mm-diameter, 3 mm-long pinholes. The locations of the pinholes are $x/H = 1$–7 and $z = 0$, with a streamwise distance of H between adjacent microphones. The microphones for these measurements were calibrated externally using a Hongsheng HS6020 piston phone at 1000 Hz with a sound pressure level of 94 dB. The response time of these microphones were checked and was all within ±0.25 ms (or $\tau U/H = \pm 0.06$). The signals from the microphones were recorded using a PC with NI-6014 data acquisition card and a Labview routine. The sampling frequency was 4096 Hz and sampling time was 150 s. More measurement of wall pressure using this technique can be found in Ref. [7]. The static was pressure at $x/H = 1$ was measured using a 1 mm inner diameter pressure tap and a pressure transducer with a resolution of 0.1 Pa. The time-averaged re-attachment location was measured visually using a surface oil flow visualization technique. Silicon oil (Dow Corning fluids) with a normal viscosity of 10 $cSt (1\ cSt = 10^{-6} m^2/s)$ was applied to the wall near the re-attachment location, the location with the largest oil thickness 5 min after applying the oil was taken as the re-attachment location.

The actuator used in this investigation was a 220 mm-diameter 8-ohms loud-speaker mounted under the step forming a 0.22 m × 0.28 m × 0.02 m cavity. Periodic jet flow was produced through a two-dimensional slot with a width of $s = 1$ mm 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° 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 150 W digital amplifier. A single hot-wire probe with a Hanghua CTA-02A constant temperature anemometry system was positioned at the jet exit to measure the rms values of out-flow half of the oscillating jet velocity, u' to characterize the actuator. The sensor in the single-wire probe had a diameter of 5 μm and length of 1.25 mm. The hot wire probes were calibrated at the exit of wind tunnel. The natural frequency of the actuator was approximately 40 Hz, at which the oscillating jet velocity, u', was the largest when sinusoidal signals of various frequencies and a fixed amplitude were applied to the actuator. Four actuation frequencies $f_A = 10$ Hz, 40 Hz, 60 Hz, and 80 Hz 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.

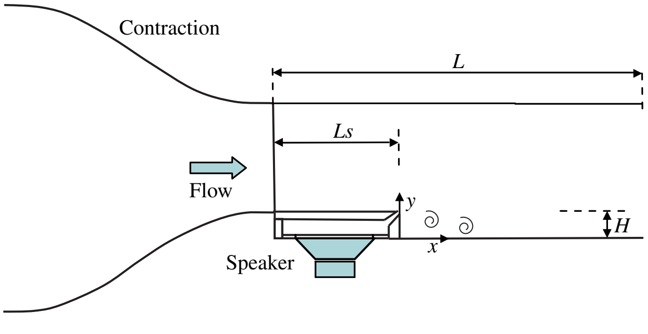

Fig. 1. Schematics of the test rig.

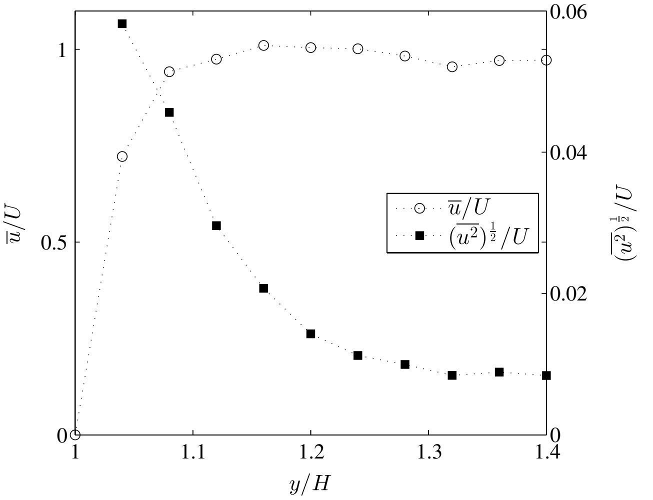

Fig. 2. Distributions of the time-averaged (○) and fluctuating stream-wise (■) velocities measured using a single hot-wire probe at $x/H = -1$.

The time-averaged re-attachment locations for actuation frequencies and amplitudes are shown in Fig. 3. The results reported in Refs. [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. The trends agree with the results reported in Refs. [1,3] though the forcing amplitudes used by Refs. [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. 3(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