Sādhanā Vol. 32, Parts 1 & 2, February–April 2007, pp. 111–122. © Printed in India

On wake response to asymmetric blowing in spurts from a blunt trailing edge

S D SHARMA and R R PANT

Department of Aerospace Engineering, Indian Institute of Technology–Bombay, Mumbai 400 076
e-mail: sd.sharma@iitb.ac.in

Abstract. In the present investigation, a technique has experimentally been evolved with the aim to control the unsteady wake dominated by periodic vortex-shedding. The technique uses pulsating surface blowing that is applied asymmetrically just before separation from the blunt trailing edge of a thick aerofoil model. Thus, momentum is injected in spurts in only one of the two separated shear layers. The control parameters are the mass flow rate and the forcing frequency of the pulsating blowing. The technique is particularly effective in suppressing the vortex-shedding when the blowing is moderate and the forcing frequency is twice the natural vortex-shedding frequency. As a consequence of injecting momentum in spurts, there is a significant saving in mass flow required to achieve a condition of the momentumless wake. In spite of the initial conditions being strongly asymmetric, the flow pattern in the wake was observed to quickly assume a remarkable symmetry.

Keywords. Momentumless wake; coherent structures; unsteady momentum injection; control of periodic wake; vortex-shedding suppression; drag reduction.

1. Introduction

Wake of a two-dimensional bluff body is characterized by the interaction of two separated shear layers, formation of large-scale vortices with oppositely signed vorticity and their alternate shedding, resulting in significant energy dissipation and periodic fluctuations in the flow. Associated engineering problems like high drag due to momentum deficit, flow-induced vibration and generation of noise continue to attract the attention of researchers and pose newer challenges to develop more effective control techniques for suppression of the wake oscillations. It was noted very early by Wood (1964, 1967) and Bearman (1967) that compensation of momentum deficit in the wake by blowing from the blunt base has favourable effects in terms of reduction of both drag and wake oscillation. This active flow control technique was later studied in detail by Cimbala & Park (1990) through systematic experiments to produce momentumless wake and wake with positive momentum by means of steady blowing through a narrow slit in the middle of the model base. Subsequently, Park & Cimbala (1991) investigated the effect of slit configuration for blowing, on the development of the momentumless wake. It was observed that the initial conditions have strong influence which could persist even in the far-wake region. For example, the growth pattern for a momentumless wake produced by blowing from dual slits, symmetrically positioned about the base centre, was found to be strikingly different in comparison to when a single asymmetrically positioned slit was used to produce the momentumless wake.

Using tiny pulsing jets as a control technique with zero net mass addition, Williams & Amato (1989) have demonstrated that the naturally unsteady wake of a circular cylinder could be stabilized by unsteady forcing, appropriately applied in certain combination of amplitude and frequency. The quantity of outflow and inflow in creating the pulsing jets was kept equal in order to satisfy the conservation of mass. However, as a consequence of the nonlinear nature of the streaming process, a positive momentum was injected into the wake. It was further shown by Williams *et al* (1992) that the symmetric mode of periodic forcing, when applied selectively in the boundary layer before separation, was most effective in suppressing the Karman vortex street. Contrastingly, asymmetric forcing (180° out-of-phase) was found ineffective in controlling the sinuous behaviour of the wake. Success of the control method seemed to hinge around the coupling between two unsteady flows – jets and wake. Recently, Henning & King (2005) employed a technique of acoustic excitation using loudspeakers to force the wake of a plane blunt base through thin slots provided at both the trailing edges. In the forcing of the wake, amplitude, frequency and phase difference between the actuation from the two slots could be varied in a controlled manner. When actuation was applied symmetrically in-phase from both the slots, about 10% drag reduction along with effective suppression of the vortex-shedding was obtained for actuating frequency, in a small range of about 0·4 to 0·7 times the natural frequency of vortex-shedding. This gain turned into a loss for further increase in the actuating frequency matching with the natural frequency of vortex-shedding and beyond up to 1·6 times. The actuation became effective only beyond a certain minimum threshold value of forcing amplitude. Further, optimization of the technique improved the performance and made this threshold value effective when only one of the slots was actuated out of phase with respect to the other non-actuated slot at the frequency of vortex-shedding. Thus, a significant gain could be reaped for 50% saving in the actuation energy.

Gerrard's (1966) explanation for the mechanism of vortex formation in the region close behind a plane bluff body makes it sufficiently clear that interaction between the two inherently unstable separated shear layers, springing from the opposite ends of a blunt base, is essential for occurrence of periodic vortex-shedding. Inferring from this that even if one of the shear layers is interfered with, it would affect the process of interaction, in their experiments on control of wake flow behind a blunt trailing edge aerofoil, Sahoo (1996), Sharma & Sahoo (1998), and Pedgaonkar (1999) successfully achieved a complete suppression of the Karman vortex street when surface blowing was steadily applied just before the separation from the trailing edge to only one of the separated shear layers. Interestingly, the vortex-shedding was similarly inhibited when Sahoo (1996) and Sharma & Sahoo (1998) applied suction with varying strength, instead of blowing, only at one of the trailing edges just before the separation of boundary layer. Thus, the wake was forced asymmetrically and there was no forcing frequency used. Surprisingly, in spite of highly asymmetric initial conditions, the resultant wake was found to quickly assume an appreciable symmetry within about 5 base heights when the forcing was with blowing. However, the asymmetry generated due to the forcing with suction appeared to persist further downstream.

In the present investigation, in order to save energy, we have introduced forcing frequency as one of the control parameters and studied the effects of forcing amplitude (blowing) and frequency on the dynamics of a plane wake while still maintaining the asymmetry in the application of the control technique.

2. Experimental setup

The experiments were performed in a low-turbulence wind tunnel with the test section 305 mm in height and 229 mm in width. The test model used was an aerofoil with 30 mm thick blunt-trailing edge and 150 mm long chord. The front two-thirds of the model formed a semi-elliptic forebody followed by a parallel-sided rearbody. The model was constructed out of Perspex with glossy finish and was hollow with openings in the sides and a narrow slit for tangential surface blowing over the last 1 mm all along one of the trailing edges. The model was mounted at zero incidence, spanning the tunnel sidewalls such that the slit for the surface blowing was oriented on the upper side. Details of the test model and arrangement for blowing with spanwise uniformity are described in Sahoo (1996).

Figure 1 depicts a schematic of the experimental setup used in the present study. A 5-micron tungsten hot-wire probe in conjunction with a constant temperature anemometer (CTA) bridge was used for the measurements in the wake flow. A PC-based data acquisition system (DAS) comprising a Dynalog PCL-208 high performance A/D card was used for acquiring and storing the data. A compressor with a storage tank was used as a source for blowing. The blowing rate was regulated by a control valve and monitored by a flowmeter. The blowing was rendered pulsating by means of a solenoid valve that was introduced between the control valve and the flowmeter and was actuated through a function generator.

Figure 2 shows plots of two signals simultaneously acquired from the function generator and the hot wire behind the slit, when moderate blowing was employed without the wind tunnel being on. A square wave with frequency 1 Hz was chosen as the actuating signal with its crest width being 20% of the full cycle. The hot-wire signal appears to mimic the function generator signal with a slight lag, which is indicative of proper functioning of the

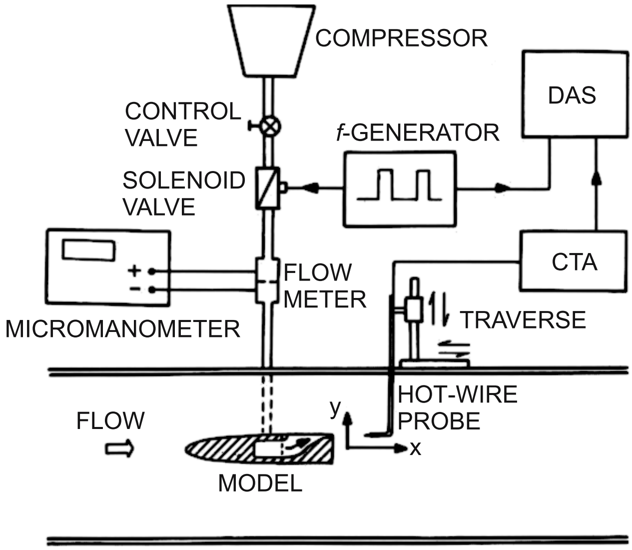

Figure 1. Schematic of experimental setup.

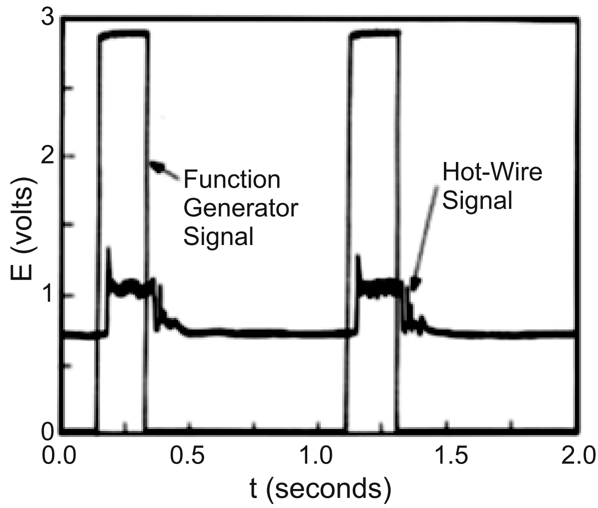

Figure 2. Signals from the function generator and hot-wire exhibit responsiveness of solenoid valve.

solenoid valve. The lag between the two signals was expected depending on the distance of the hot wire from the model base and the rate of blowing. The frequency response of the solenoid valve was found to reach saturation due to inertia when the frequency of the actuating signal from the function generator was increased beyond 22 Hz. Therefore it was decided to limit the maximum forcing frequency to 20 Hz. However, throughout this frequency range, the crest width was maintained as one-fifth of the full cycle, thereby making the blowing rate (flow quantity per unit time) independent of the forcing frequency. A similar setup was used for flow visualization experiments using colour dye injection in a water tunnel, except that instead of the compressor a water pump was used for the blowing purpose, and the flowmeter along with the pressure sensors was of lower range. Further details are given by Pant (2000).

3. Test conditions and procedure

The control parameters used are the blowing rate and the forcing frequency. These are presented in non-dimensional form as the blowing coefficient, C_q, and the frequency ratio, F, and defined respectively as $(q)/(UA_b)$ and f/f_o. Here q is the blowing rate, U is the freestream velocity, A_b is the model base area, f is the forcing frequency and f_o is the natural (unforced) vortex-shedding frequency. Constrain of the forcing frequency in the present investigation restricted the freestream velocity in obtaining the frequency ratios $F < 1$ and $F > 1$. From our previous experience on this model, the forcing frequencies of 16 and 20 Hz were selected and accordingly, the experiments were carried out at two different flow velocities of 4·1 and 1·1 m/s which gave values of Reynolds number, based on the model base height, of 7800 and 2100 respectively. The water tunnel flow visualization tests were performed at a velocity of about 25 mm/s which corresponded to a Reynolds number of about 750.

The wake spectra were obtained by positioning the hot-wire probe at a point ($x/h = 4$, $y/h = 1$) downstream of the vortex formation region near the wake edge by fast Fourier transformation (FFT) of the fluctuating part of the hot-wire signal. The data were acquired at the rate of 2000 samples per second and a total of 7000 samples were registered for carrying out the FFT. Distribution of the mean velocity and turbulence across the wake was obtained at two streamwise locations ($x/h = 2$ and 5) by traversing the hot-wire probe in the transverse plane. A technique of conditional sampling was employed following Sahoo (1996) and the cyclic actuating signal of the function generator was used as a reference signal to obtain the phase averaged velocity. Each cycle of the actuating signal was divided into six phases. The data were acquired at each location for 4 seconds at a sampling rate of 1600 samples per second.

4. Results and discussion

It has been established through numerous experiments by various researchers that a spectrum of velocity fluctuations obtained at the wake edge of a two-dimensional bluff body contains only one single peak corresponding to the vortex-shedding frequency. However, the spectrum obtained at the wake axis contains two peaks – one at the vortex-shedding frequency and the other at twice this frequency, because in the wake centre the sensor is equally responsive to the vortices shedding from both sides of the body. The control technique is expected to be effective when the forcing is applied just when the vortex is about to form and shed. Thus, if vortices in both the rows are to be interfered with, forcing with twice the vortex-shedding frequency is required.

Figure 3 shows wake spectral plots at two different flow velocities. $C_q = 0$ corresponds to the natural wake without any forcing (blowing). The spectral peak corresponding to the vortex-shedding at a frequency of 45 Hz for the freestream velocity of 4·1 m/s is seen to shift proportionately to 11 Hz at the reduced flow velocity of 1·1 m/s. For the case when forcing frequency is less than the natural vortex-shedding frequency ($F = 0{\cdot}36$), the moderate blowing of $C_q = 0{\cdot}075$ alters the vortex-shedding frequency to a lower value of 34 Hz and the interaction generates two other spectral peaks of difference at 18 Hz ($= 34 - 16$) and sum at 50 Hz ($= 34 + 16$). As the blowing amplitude is further increased to $C_q = 0{\cdot}1$, the wake energy is seen to be contained mainly in the spectral peak at the forcing frequency and in its harmonics which are prominent up to the fifth multiple. The forcing at $F < 1$ does not seem to suppress the vortex-shedding as is evident later from flow visualization pictures. So it is believed that the vortex-shedding frequency shifts to 32 Hz which coincides with the first harmonic of the forcing frequency. Further, it is to be noted that an enhancement in blowing from $C_q = 0{\cdot}075$ to $C_q = 0{\cdot}1$ has resulted in a spectacular change in the wake spectrum with significantly enhanced spectral peaks that suggest strong interaction between the forcing flow and the wake flow, causing transfer of energy from the mean flow. When the forcing frequency is greater than the vortex-shedding frequency ($F = 1{\cdot}82$), the moderate blowing shifts the vortex-shedding from 11 Hz to 10 Hz with reduced peak amplitude and there the first harmonic appears, which coincides with the forcing frequency, while the second harmonic is at 30 Hz. With further increase in the blowing ($C_q = 0{\cdot}1$), suppression of the vortex-shedding is evident and the only spectral peaks that exist are at the forcing frequency of 20 Hz and its first harmonic at 40 Hz.

Figure 4 shows a comparison of the wake profiles obtained at two different freestream velocities for unforced wakes in the present experiments. What is inferred is that the wake characteristics, in terms of the mean velocity and turbulence distribution, have not changed to warrant any considerable effect of Reynolds number within the measurement range.

Figure 5 shows that when forced with moderate blowing, $C_q = 0{\cdot}075$, the velocity defect diminishes quickly and then disappears. Though the forcing frequency does not seem to result in any discernible change in the velocity profile far from the base region, $x/h = 5$,

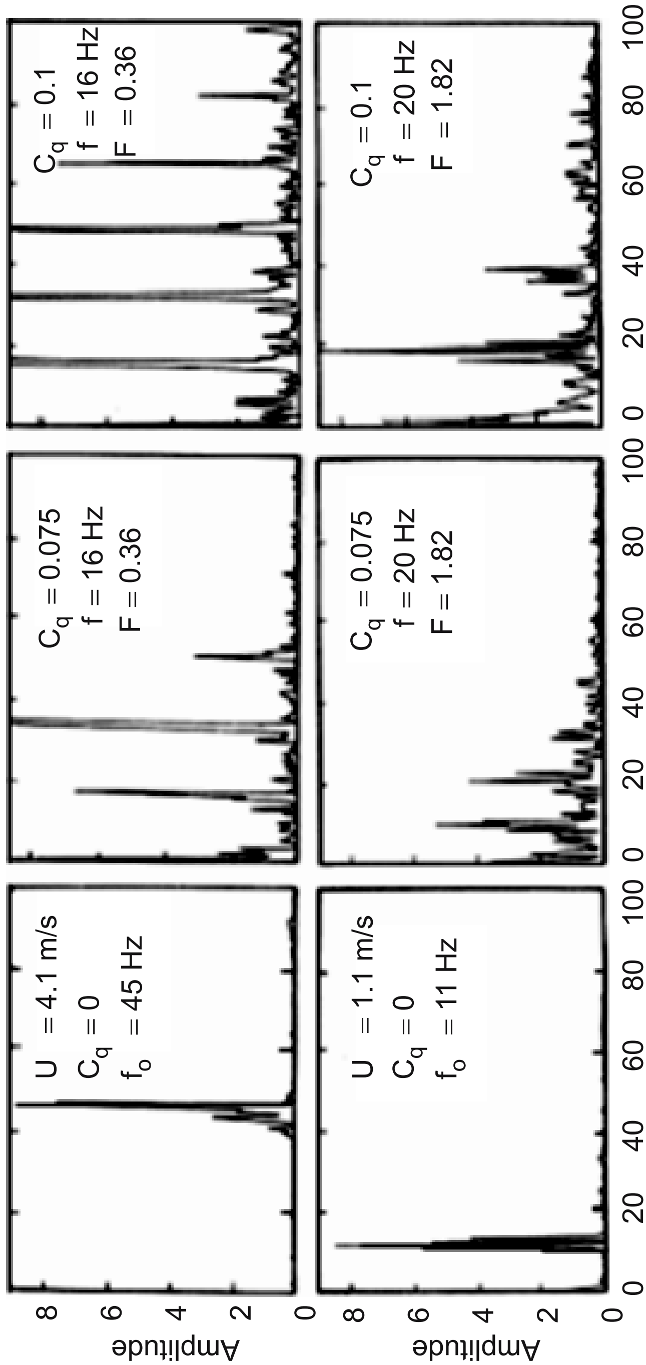

Figure 3. Frequency spectra showing effects of pulsating momentum injection on the wake flow.

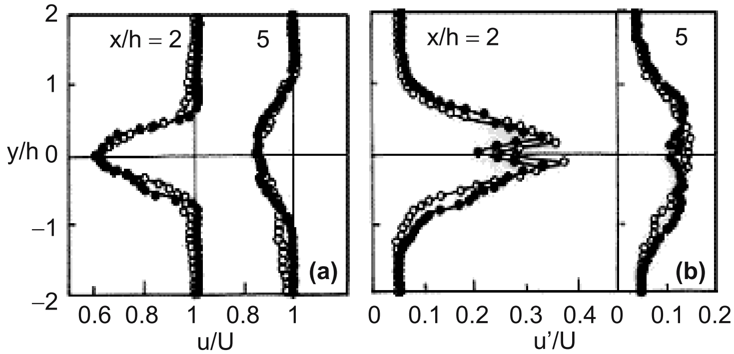

Figure 4. Unforced wake profiles: **(a)** mean velocity and **(b)** turbulence. (○ : $U = 4{\cdot}1$ m/s, • : $U = 1{\cdot}1$ m/s).

it influences the region in the close vicinity. For example, velocity profile at $x/h = 2$ gains higher momentum with $F = 1{\cdot}82$ in the centre with appreciable symmetry. The forcing also seems to enhance the mixing.

Figure 6 represents the case of complete suppression of the vortex-shedding when the wake is forced at $F = 1{\cdot}82$ with increased blowing, $C_q = 0{\cdot}1$. The mean velocity profiles suggest that the forcing affects the near-wake area through strong entrainment of the flow from the regions outside the separated shear layers where velocities are reduced as seen at $x/h = 2$. However, velocity in the centre increases to about 160% of the freestream velocity. The profile rapidly flattens out at $x/h = 5$ apparently with no wake defect signifying intense mixing, which is further substantiated by the turbulence profiles that show significant increase in the levels compared to unforced wake. For asymmetric blowing, the symmetry of the profiles is incredible. For the purpose of comparison, the results for steady blowing from the previous work by Sharma & Sahoo (1998) on the same model are shown in figure 7. In this case, the net mass blown is effectively greater by 6·45 times due to continuous blowing at the higher value of C_q. However, the maximum rise in the velocity registered at $x/h = 2$ is only up to 120% of the freestream against 160% as seen in figure 6. Also, the mixing does not seem to be effectively promoted with steady blowing.

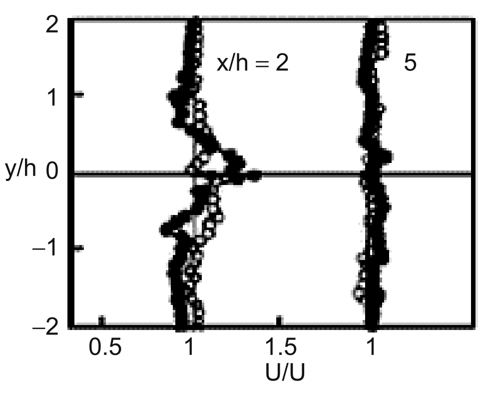

Figure 5. Wake profiles with $C_q = 0{\cdot}075$ forced at $F = 0{\cdot}36$(○) and $F = 1{\cdot}82$(•).

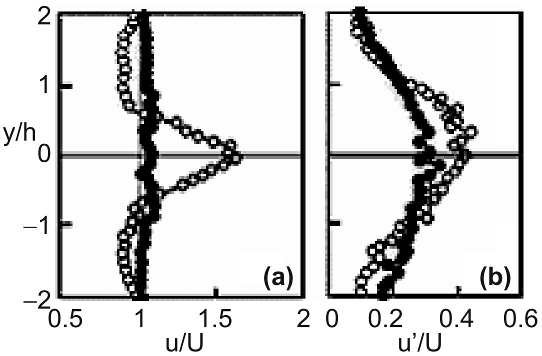

Figure 6. Wake profiles: **(a)** mean velocity and **(b)** turbulence with $C_q = 0{\cdot}1$ forced at $F = 1{\cdot}8(\circ : x/h = 2, \bullet : x/h = 5)$.

The ensemble-average velocity profiles shown in figures 8 and 9 give details of how wake dynamics changes from one phase to another over a complete cycle of two forcing frequencies with $C_q = 0{\cdot}075$. The time gap and velocity change between the two consecutive phases indicate that the wake is more violent due to forcing at $F = 0{\cdot}36$ compared to that at $F = 1{\cdot}82$. For example, calculations revealed an acceleration of about 230 m/s^2 from phase 3 to 4 at $x/h = 2$ and 160 m/s^2 from phase 4 to 5 at $x/h = 5$ in figure 8. Whereas, in figure 9 it was about 50 m/s^2 from phases 1 to 2 and 5 to 6 at $x/h = 2$; however, further downstream at $x/h = 5$ the changes appear to be insignificant. As seen in figure 10, increasing the blowing coefficient to $C_q = 0{\cdot}1$, which resulted in a complete suppression of the vortex-shedding at $F = 1{\cdot}82$ (figure 3), appears to pump the energy in the base region ($x/h = 2$), wherein the velocity in the middle reaches up to 200% of the freestream velocity. It is seen in figure 2 that opening and closing of the solenoid valve gives rise to transient spikes in the forcing which may be injecting additional momentum. The wake flow quickly attains a somewhat uniform state at $x/h = 5$. We believe this is because of the strong strain field promoting the mixing. The turbulence profiles in figure 11 support this view with overall high levels. These profiles apparently follow no particular phase-related trend.

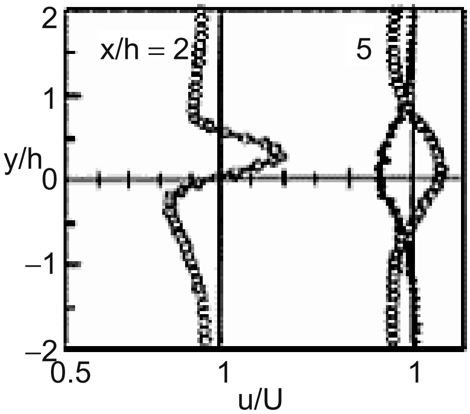

Figure 7. Mean velocity profiles with steady blowing $C_q = 0{\cdot}129(\circ)$ and $C_q = 0(\bullet)$ from Sharma & Sahoo (1998).

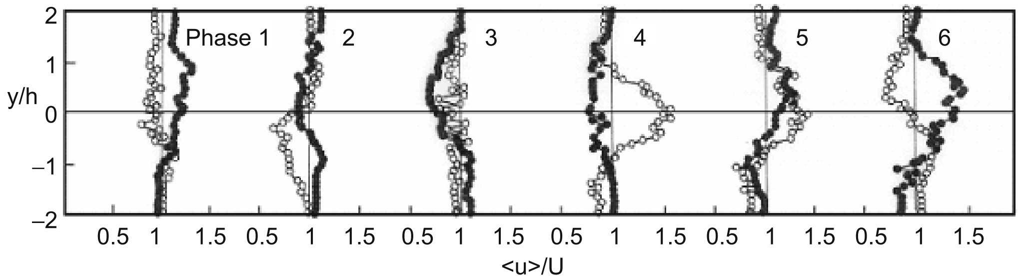

Figure 8. Ensemble-average velocity profiles for $C_q = 0{\cdot}075$ and $F = 0{\cdot}36$ ($\circ$: $x/h = 2$, $\bullet$: $x/h = 5$).

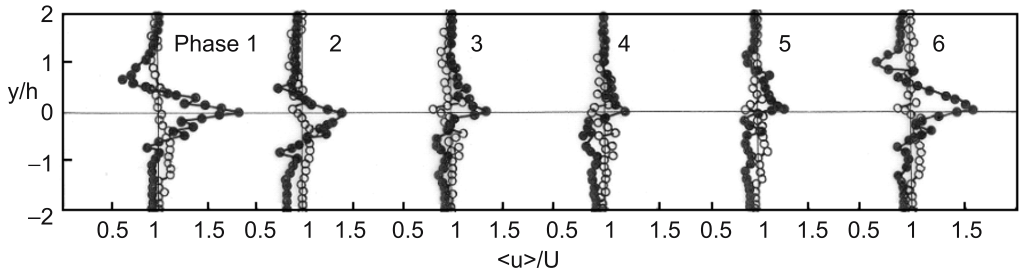

Figure 9. Ensemble-average velocity profiles for $C_q = 0{\cdot}075$ and $F = 1{\cdot}82$ ($\circ$: $x/h = 2$, $\bullet$: $x/h = 5$).

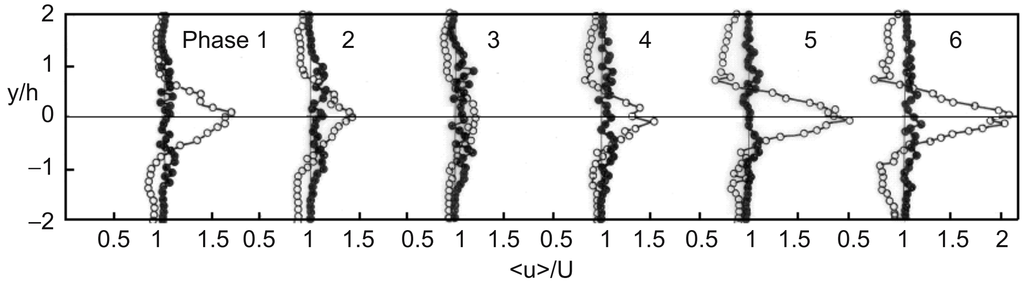

Figure 10. Ensemble-average velocity profiles for $C_q = 0{\cdot}1$ and $F = 1{\cdot}82$ ($\circ$: $x/h = 2$, $\bullet$: $x/h = 5$).

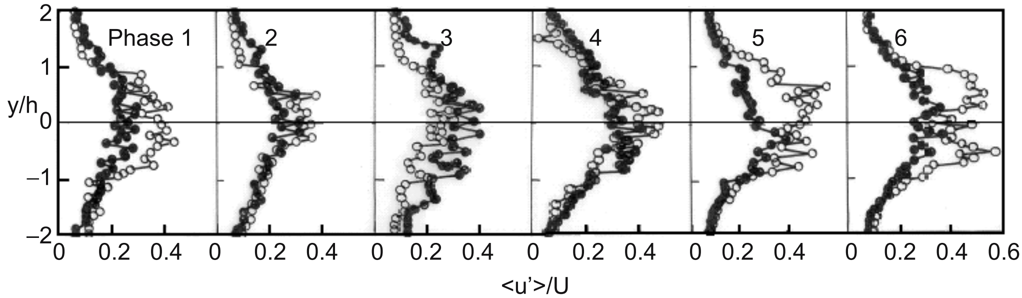

Figure 11. Phasewise turbulence profiles for $C_q = 0{\cdot}1$ and $F = 1{\cdot}82$($\circ$: $x/h = 2$, $\bullet$: $x/h = 5$).

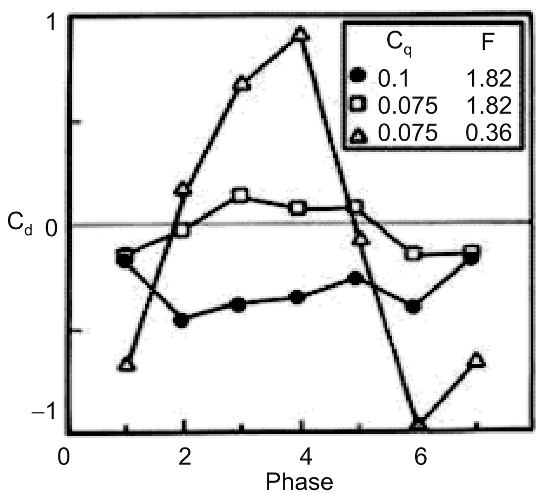

Figure 12. Phasewise variation of drag coefficient.

The coefficient of drag, C_d, was estimated from the momentum calculation from the ensemble-average velocity profiles at $x/h = 5$ with the assumption of negligible pressure gradient at that location. The phasewise variation of C_d for three different forcing conditions is shown in figure 12. The area under the curve would give the net drag value. Forcing the wake with the same amplitude but at different frequencies produces different effects. From the figure it turns out that the momentum when injected with $C_q = 0{\cdot}075$ at $F = 0{\cdot}36$, yields the net $C_d = 0{\cdot}0025$ which changes to $-0{\cdot}08$ at $F = 1{\cdot}82$. Although the vortex-shedding was not fully suppressed for these conditions as can be inferred from figure 3, the wake surprisingly becomes momentumless thus reflecting the effectiveness of the present technique. In the case of unforced (natural) wake, $C_d = 0{\cdot}4$ was calculated. The main feature of the figure is the negative C_d at all the phases for $C_q = 0{\cdot}1$ and $F = 1{\cdot}82$ yielding the net $C_d = -0{\cdot}359$ which is nothing but a thrust. Owing to the peculiar manner of forcing the wake with mass injection for only a fifth of the cycle, the blowing is effectively equivalent to $C_q = 0{\cdot}02$ for a steady blowing case.

Figure 13 shows pictures of flow visualization which exhibit the effect of forcing parameters on the wake. Well-defined Karman vortex street characterizes the unforced wake in (a). Increasing strength of the steady blowing weakens the alternate vortex formation (b, c) and finally stops it (d, e). Low forcing may interfere but does not inhibit the vortex-shedding (f, g). Moderate to high forcing effectively suppresses the vortex-shedding at $F = 2(j, p)$ but not at $F = 0{\cdot}4(h, n)$ and as the frequency increases further, vortices start to form again (k, m, q). However, further increase in the forcing amplitude may again make it effective in suppressing the vortex-shedding (r).

5. Concluding remarks

Momentum injection in short spurts in just one of the separated shear layers is not only a novel technique but also extremely effective in suppressing the vortex-shedding. The effectiveness of the technique depends on certain combinations of the strength and frequency of blowing, and has shown great promise in producing momentumless or even *thrust yielding* wakes with significant saving on the blowing mass.

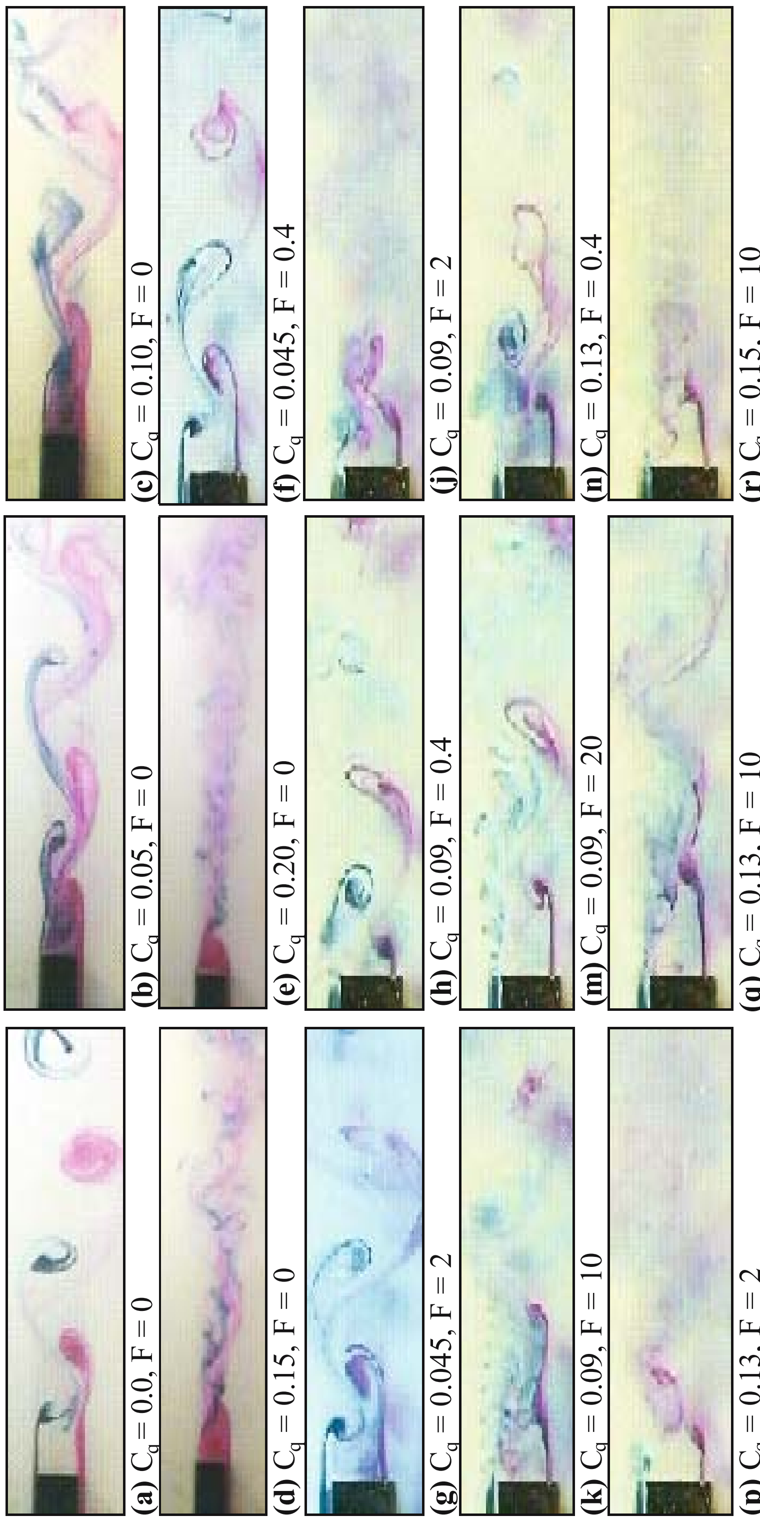

Figure 13. Wake flow visualization showing effect of steady **(b–e)** and pulsating **(f-q)** blowing from the top edge.

List of symbols

A_b model base area;
C_d drag coefficient;
C_q blowing coefficient;
f forcing frequency;
f_o vortex-shedding frequency;
F frequency ratio;
h model base height;
q blowing rate;
U freestream velocity;
x longitudinal axis;
y transverse axis.

References

Bearman P W 1967 The effect of base bleed on the flow behind a two dimensional model with blunt trailing edge. *Aero Q.* 18: 207–224

Cimbala J M, Park W J 1990 An experimental investigation of turbulent structure in a two-dimensional momentumless wake. *J. Fluid Mech.* 213: 479–509

Gerrard J H 1966 The mechanism of formation region of vortices behind bluff bodies. *J. Fluid Mech.* 25: 401–413

Henning L, King R 2005 Drag reduction by closed-loop control of a separated flow over a bluff body with a blunt trailing edge. *Proceedings of the 44th IEEE Conf. on Decision and Control, and European Control Conference (CDC-ECC'05)*, Seville, Spain, pp 494–499

Pant R R 2000 *Effect of pulsating momentum injection on the wake of a blunt trailing edge*. M Tech dissertation, Indian Institute of Technology – Bombay, Mumbai

Pedgaonkar S V 1999 Effect of momentum injection on wake behind plane blunt base. M Tech dissertation, Indian Institute of Technolgy – Bombay, Mumbai

Sahoo R K 1996 *Plane base flow structures of a blunt trailing edge with boundary layer control*. Ph D thesis, Indian Institute of Technolgy – Bombay, Mumbai

Sharma S D, Sahoo R K 1998 Control of the periodic wake behind a plane blunt base. In *Fluid mechanics and its applications, 53, Proceedings of IUTAM Symposium on Mechanics of Passive and Active Flow Control* (eds) G E A Meier and P R Viswanath (Dordrecht/Boston/London: Kluwer Academic) pp 267–272

Williams D R, Amato C W 1989 Unsteady pulsing of cylinder wakes. In *Lecture Notes in Engineering, 46 - Frontiers in experimental fluid mechanics* (ed.) M Gad-el-Hak (Berlin: Springer-Verlag) pp 337–364

Williams D R, Mansy H, Amato C W 1992 The response and symmetry properties of a cylinder wake subjected to localized surface excitation. *J. Fluid Mech.* 234: 71–96.