FLOW OVER A SQUARE CYLINDER WITH AN ATTACHED CAMBERED FLEXIBLE WAKE SPLITTER

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Abstract

Particle Image Velocimetry (PIV) study is performed to analyse the effects of flow over a cambered flexible wake splitter attached to the lee side of a square cylinder at an intermediate Reynolds number (Re_D = 600, where D is the blocking width of the cylinder). The study shows that the cambered flexible wake splitter (length, L = 8D) undergoes vortex induced, asymmetric low amplitude flapping due to which near wake becomes slightly asymmetric. The flexible film increases the centre line celerity in the wake by transferring momentum to the fluid downstream and reduces the wake width due to less entrainment of free stream fluid. Wake splitters beyond a particular length, interact with the primary vortices and shed secondary vortices on either side of the wake splitter due to Coanda effect. In the present study, shedding of asymmetric secondary vortices is observed which owes to the increased pressure in the lower wake envelope due to asymmetric flapping of the cambered splitter. The study indicates towards the positive lift generation due to asymmetric flapping of the cambered film.

Keywords: Cambered Flexible wake splitter, fluid structure interaction, PIV, Square Cylinder

1 Introduction

Fluid structure interaction has intrigued aerodynamicists and scientists since past few decades because of its practical importance to many fields of engineering like buildings, bridges, chimneys and also to understand the unsteady aerodynamics involved in the flight of natural fliers and swimmers. Rigid splitter plate attached to the base of bluff bodies has been extensively studied in the literature and established as a low drag solution. It also, suppresses the vortex shedding phenomenon of the bluff body as shown in a recent experimental study [1]. Few numerical and experimental studies have also been carried out to characterize the flow using an attached flexible wake splitters. The unsteady pressure variations in the wake of a bluff body excites a limit cycle oscillations in the flexible foil [2]. Drag reduction of a D section cylinder is achieved by placing a wavy foil downstream in a numerical study [2]. Another numerical study showed that vortex shedding frequency of a bluff body varies non-monotonically with respect to the length of the flexible plate [3]. The study also showed that the oscillation frequency of the flexible plate is function of wake frequency as well as natural frequency of the plate and high flexibility increases the drag and lift forces of the bluff body. Another numerical study states that long flexible filament with low flexibility improves the flow control over a cylinder better than rigid wake splitters [4]. An experimental study for a flow over a circular cylinder attached with a flexible splitter plate showed transitions in the dynamic behaviour of the plate as its length is varied [5]. The splitter plate undergoes a shift from periodic to aperiodic oscillations as the length of the plate is varied from L/D =3 to L/D = 4, where D is the diameter of the cylinder and with further increase in the splitter plate length, the periodic oscillations are restored. The study also presented the effect of bending stiffness of the flexible splitter plate. In an experimental study it is shown that the flow characteristics of an oscillating circular cylinder significantly change with the increase in the length of the flexible tail particularly in between L/D = 3 & 4 [6]. The vortex shedding pattern changes from 2S_Karman mode at L/D = 2 to 2P mode at L/D = 3 and at L/D = 4 to 2S_reverse Karman vortex mode. An interesting numerical study of a hinged flapping filament attached to lee side of a circular cylinder experienced asymmetric flapping of the filament of short lengths which enhance the lift characteristics of the bluff body [7]. The lock-in between the vortex shedding frequency and the filament’s Eigen frequency is suggested to be the reason behind this unprompted symmetry breaking. Recent studies have also shown the possibility of attached flexible wake splitter as
energy harvesters [8], [9].

Present study evaluates the effect of asymmetric oscillations of the cambered flexible wake splitter on the flow over a bluff body which has not been experimentally investigated yet. Moreover, the effective stiffness (Π) of the present cambered flexible wake splitter (Π = 1.71) falls well in the range of chord-wise effective stiffness of few insects like bees and hawkmoths (0.19 ≤ Π ≤ 3.0) [6]. Equation (1) shows the expression for effective stiffness of the cambered flexible wake splitter,

\[ Π = \frac{Eh^3}{12 \rho_f (1 - \nu^2) U^2 L} \]

Where, E stands for elastic modulus, h stands for thickness, \( \rho_f \) stands for density of the fluid, U is the free stream velocity, \( \nu \) is Poisson’s ratio and L is the length of the flexible wake splitter. Also, the present wind tunnel experiments gives the similar structure to fluid density ratio (\( \rho = 2.0 \times 10^3 \)) as in the case of insect flight. As the insect wing behaves as a bluff body during down stroke on an inclined stroke plane [10], the present study can also be helpful in explaining the reason behind camber of natural fliers.

2 Methodology

The PIV experiments have been performed for a flow over a square cylinder attached with a cambered flexible wake splitter, which is fixed vertically in the test section of a sub-sonic wind tunnel having contraction ratio of 9:1. The test section of the wind tunnel has cross-section of 0.3 x 0.2 m and is 3.6 m long. Material of the test section is acrylic, to keep it optically accessible for PIV measurements. The Reynolds number based on the cylinder blockage width ‘D’ is 600. The free-stream turbulence intensity of the flow in the wind tunnel is less than 0.1 %. The blockage width (D) of the cylinder is 10 mm. The material of the cylinder is aluminium and that of the cambered flexible wake splitter is polyester. The thickness of the wake splitter is approximately 0.01D (100 µm). Aspect ratio of the cylinder is (l/D) = 20 and blockage to flow is nearly 3 %. Figure 1 shows the schematic arrangement of the attached cambered flexible wake splitter (plan view). Related nomenclature and the two co-ordinate systems used in the study has also been shown i.e. absolute coordinate system OXY (origin located at the centre of the cylinder) & relative coordinate system O’X’Y’ (origin at trailing edge of the splitter).

![Figure 1: Plan view of square cylinder attached with the cambered flexible wake splitter](image)

In Table 1, the material properties of the cambered flexible wake splitter are shown which have been measured by an instrumented nanoindentation setup (Hysitron, TI950 Triboindenter, Hysitron Inc, USA) at Metallurgical and Materials Engineering Department of IIT Roorkee.

2.1 Details of PIV Experiment

The PIV system consists a laser head and laser source, a CCD camera (2048 x 2048 pixels), a synchronizer, a frame grabber and a high-speed computer. The camera has a field of view 152.8 x 152.8 mm with 70 mm manual lens. The photographic view of the experimental setup is shown in figure 2. The frame straddling time is kept minimum as 200 ns. The pulse separation time between two frames ‘Δt’ is kept 100 µs and 500 realisations have been taken to obtain time-averaged flow field. Recursive Nyquist criteria has been used for cross-correlation between two frames of images with minimum interrogation window size of 24 x 24 pixels² and overlap of 50 % is applied. Total of 169 x 169 vectors are obtained after analysis with spatial resolution of 0.9041 mm. Atomized olive oil particles have been used as tracer particles. The overall uncertainty in the mean velocity is estimated to be less than ± 2.2 % of the averaged mean stream-wise velocity at 95 % confidence level. The long cambered flexible wake splitter is chosen for the study of non-dimensional length (L/D) of 8. The schematic close view of the arrangement of
attached cambered flexible wake splitter has been shown in figure 3. The cylinder with an attached cambered flexible wake splitter is kept vertical in test section so that the deflections of the splitter are purely flow induced. Figure 4 shows the initial deflection of the cambered flexible wake splitter in quiescent air which is nearly 0.25D from the wake centre line (measured using ImageJ software). CTA (constant temperature anemometer) system has also been used for a limited study of Strouhal number for the bare cylinder. Total of 2000 velocity samples are taken at a sampling rate of 1 KHz using a single wire probe (55P11). Fast Fourier transform (FFT) is done on the samples to obtain the power spectrum. The peak in the power spectrum represents the wake frequency (f). Normalized wake frequency (fD/U) is the Strouhal number for the bare cylinder at Re number under consideration.

Table 1: Mechanical properties of the cambered flexible wake splitter

<table>
<thead>
<tr>
<th>Material (thickness ‘h’)</th>
<th>Elastic Modulus (GPa)</th>
<th>Hardness (GPa)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester (0.02D)</td>
<td>8.57 ± 0.23</td>
<td>0.84 ± 0.043</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Figure 2: Photographic view of the experimental arrangement

Figure 3: The schematic close view of the test section
3 Results and discussion

An experimental study has been performed for a flow over a square cylinder with an attached cambered flexible wake splitter using PIV. Figure 5 (a) shows time-averaged non-dimensional stream-wise velocity ($u/U$) for bare cylinder case, a symmetric wake envelope can be seen in the contour. Figure 5 (b) shows time-averaged non-dimensional stream-wise velocity ($u/U$) for an attached cambered flexible wake splitter case. Asymmetry in the near wake and also near the trailing edge of the wake splitter can be noticed which is due to asymmetric oscillation of the cambered flexible wake splitter. Increased celerity in the upper half of the wake in figure 5(b) and enlarged roll up of primary vortex, indicates the reduced pressure above the cambered flexible wake splitter. A reduction in the wake width can also be noticed in the wake splitter case which owes to the reduction in the free stream entrainment as the wake splitter transfers momentum to the fluid downstream trailing edge. Figure 6(a) shows the non-dimensional transverse velocity ($v/U$) for bare cylinder case and figure 6(b) shows the same for cambered wake splitter. An increase in the transverse velocity can be seen in the cambered flexible wake splitter case owing to the strains brought by the wake splitter oscillations. Near wake asymmetry can be seen above the wake splitter due to asymmetric oscillations of the cambered flexible wake splitter.

Figure 7(a) shows the time-averaged span-wise vorticity ($\omega_z D/U$) for bare cylinder and figure 7(b) shows the same for the wake splitter case. The contour in figure 7(b) shows asymmetric vortex structures on the either side of the wake splitter. Moreover,shedding of secondary vortices on either side of the wake splitter can also be noticed. If it would be the case of symmetric flapping of the wake splitter then symmetric secondary vortex shedding on the either side of the wake splitter would be experienced due to Coanda effect. The vortex interaction with the trailing edge of the wake splitter generates the Coanda effect due to which, after interaction with the trailing edge the vortices get deflected towards the low pressure region (which is the base of the cylinder in this case). Counter clock-wise secondary vortices shed to the upper side of the cambered flexible wake splitter are stronger than the clock-wise secondary vortex shed on the bottom side. This confirms the difference in the pressure in base regions parted by the wake splitter as upper region of low pressure and lower region of comparatively higher pressure which owes to the cambered shape of the wake splitter. Similar results can also be seen in stream traces shown in figure 8(b). Figure 8(a) shows the streamlines for bare cylinder case. A symmetric vortex structure can be noticed but in figure 8(b) an asymmetric vortex cores can be seen on either side of the wake splitter. The upper vortex core being broad in size shows presence of less pressure above the wake splitter in comparison to lower side.

Figure 9 shows the power spectral density for the bare cylinder at Re = 600, The Strouhal number is found to be 0.13, which matches well with the literature for same Reynolds number [11], [12]. The X and Y location of the measurement has been mentioned in the figure. Figure 10 shows the instantaneous span-wise vorticity plot superimposed with velocity vectors for the cambered flexible wake splitter case. The asymmetric shedding of secondary vortices can be seen along with the deflected flexible wake splitter. Figure 11 (a) represents the time-averaged stream-wise velocity profile at six different stream-wise locations across the wake of the cylinder with attached flexible wake splitter. The Six stream-wise locations are namely, $X' = -2D$, $-1D$, $0D$, $1D$, $2D$ and $3D$. The plot has a frame of reference at trailing edge (relative coordinate system, $O'X'Y'$).
Figure 5: Time-averaged stream-wise velocity \((u/U)\) of (a) flow over the bare cylinder and (b) flow over the cylinder with an attached cambered flexible wake splitter.

Figure 6: Time-averaged transverse velocity \((v/U)\) of (a) flow over the Bare Cylinder and (b) flow over the cylinder with an attached cambered flexible wake splitter.

Figure 7: Time-averaged span-wise vorticity \((\omega_z D/U)\) of (a) flow over the Bare Cylinder and (b) flow over the cylinder with an attached cambered flexible wake splitter.
Figure 8: Time-averaged stream traces of (a) flow over the Bare Cylinder and (b) flow over the cylinder with an attached cambered flexible wake splitter.

Figure 9: The power spectrum of bare cylinder at Re = 600.

Figure 10: Instantaneous span-wise vorticity ($\omega_z D/U$) superimposed with velocity vectors for flow over the Cylinder with an attached cambered flexible wake splitter.
Asymmetric velocity profile can be seen for two upstream positions and at the trailing edge of the wake splitter ($X = -2D$, $-1D$ and $0D$, respectively) whereas, the downstream velocity profiles seem to be symmetric. Also, an increase in the celerity in the wake centre-line velocity can be noticed in the downstream velocity profiles. The sudden increase in the stream-wise velocity in the upstream velocity profiles due to reduced flow reversal because of increased pressure near the wake splitter. This asymmetric behaviour of the flow can be attributed with asymmetric flapping of the cambered flexible wake splitter. Figure 11(b) shows the time-averaged non-dimensional transverse velocity profiles across the wake of the cylinder attached with the flexible cambered wake splitter. The velocity profiles at same six stream-wise locations have been shown as for figure 11(a). There is a hike in the vertical velocity at the upstream location reason of which is same as for the hike in stream-wise velocity. This sudden hike in stream-wise and transverse velocity near the wake splitter in the lower region shows that the wake splitter adds to the momentum of the wake splitter so the flow gets accelerated thus the u velocity contours shown in figure 5(b) are asymmetric near the trailing edge of the wake splitter.

4 Conclusion

An experimental investigation was carried out for the flow over a bluff body attached with a cambered flexible wake splitter. The study shows that the cambered flexible wake splitter stimulates asymmetric oscillations, induced by the vortex shedding over the square cylinder. As a result the wake envelop above and below becomes slightly asymmetric due to pressure difference created by cambered flexible wake splitter. The results suggest that the cambered flexible wake splitter generates a positive lift on the upper side. Hence, the study shows that camber in the insect wings generates an additional lift during down-stroke in an inclined stroke-plane. A further study is needed to optimize the camber angle with a direct aerodynamic force measurements for the case.

References


