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Flow control around a circular cylinder with swinging thin plates

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Flow around a 2D circular cylinder with attached swinging thin splitter plates is numerically investigated. The ratio of the plates' length to the cylinder diameter is 1 ($\frac{L}{D} = 1$) where L is the Plates' length and D is the cylinder diameter. The plates are attached at ±55 degrees (trigonometric angle) downstream and are forced to oscillate at different ratios of the natural vortex shedding frequencies with magnitudes of $FR = 0.75, 1, 1.25, 1.5$ and 2. The oscillation amplitude "α" as the other main variable ranges from 10 to 18 degrees. Two-dimensional simulations are carried out at the Reynolds number 100, and then extended to higher Reynolds number of 200. The results show that in certain configurations, an in-phase vortex-shedding pattern is dominant and the oscillatory nature of the lift force completely vanishes. Different flow patterns are observed and classified as well. The effects of the splitter plates' oscillation on the lift and drag forces, flow patterns and vortex shedding frequencies are also discussed to develop a link between different flow patterns and the acting lift force on the cylinder.

1. Introduction

For decades, vortex dominated flows have been the subject of study for engineers and researchers interested in vortex shedding phenomenon. When a fluid flows over a non-streamlined body like a circular cylinder, two symmetrically placed attached eddies take form on the body. This condition becomes unstable if the flow is perturbed or the Reynolds number exceeds 47, then eddies will begin to shed from the body with a harmonic pattern. The development of instabilities results in an unsteady separation equivalent to an oscillating force on the body. If the Reynolds number is low enough (47–400), the laminar vortex shedding known as Karman vortex shedding occurs. These oscillatory vortices arise many challenges in engineering ranging from tall and off-shore structures to tube bundle heat exchangers. Hence, in order to prevent structural damage or maximizing system efficiency, it is mandatory to study and control the behavior of the flow in these situations (Anderson, 2010; Eckert, 2007).

The majority of the past research papers on the flow passing bluff bodies were conducted using a two-dimensional circular cylinder. As noted by Roshko (1993) the circular cylinder is, by far, the "quintessential" bluff body. Experiments and researches done by Roshko (1954b), Miller and Williamson (1994); Williamson (1989, 1996); Williamson and Roshko (1990); Williamson and Govardhan (2004), Rockwell (1987) and Kovasznay (1949) underlie further investigations of bluff body wake and vortex shedding.

Braza et al. (1986) numerically simulated the wake behind a circular cylinder at Reynolds numbers 100, 200, and 1000 and reported the flow data. In another Numerical research, Park et al. (1998) simulated vortex shedding of a two-dimensional

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Nomenclature

A	Harmonic function amplitude
C_l	Lift coefficient
C_l'	Fluctuating Lift coefficient (RMS)
C_d	Mean Drag coefficient
D	Cylinder diameter (m)
F	Total acting force on control volume (N)
f	Frequency (Hz)
f_s	Dimensionless frequency
FR	Frequency ratio
FFT	Fast Fourier Transfer
L	Splitter plate's length (m)
L/D	Ratio of splitter plate's length to cylinder diameter
p	Pressure ($\mathrm{N\,m^{-2}}$)
PIV	Particle image velocimetry
Re	Reynolds Number
S	Control surface Area ($\mathrm{m^2}$)
S_t	Strouhal Number
t	Time (s)
t^*	Non-dimensional time
u	Flow velocity vector ($\mathrm{m\,s^{-1}}$)
V	Volume ($\mathrm{m^3}$)
y	Harmonic function
α	Plates oscillation amplitude (deg)
ρ	Fluid density ($\mathrm{kg\,m^{-3}}$)
τ	Characteristic time (s)
ω	Angular velocity ($\mathrm{rad\,s^{-1}}$)

circular cylinder at Reynolds numbers up to 160 and reported the monitored Strouhal number and drag coefficient. Homescu et al. (2002) used numerical methods to suppress laminar vortex shedding by means of angular velocity (cylinder rotation). They found an empirical logarithmic law relating the regularization coefficient to the Reynolds number. In an experimental investigation, Kunze and Brücker (2012) employed flexible self-adaptive hairy-flaps to control the separation and used PIV method to monitor the flow dynamics and hair motions. The results of their experiments conducted at $5000 < Re < 31\,000$ showed that hairy flaps alter the natural vortex separation cycle in such a way that the vortices do not shed in a zig-zag like arrangement as in the classical von-Karman vortex street, but in line in a row with the cylinder wake axis.

Using a wake splitter plate is considered a passive method, which has been widely used to suppress or control the vortex shedding frequency. The Length of the splitter plate has a considerable effect on the Strouhal number (S_t) and drag coefficient (C_D). Experimental studies conducted by Roshko (1954b) showed that using a splitter plate with the length of five times of cylinder diameters long behind a circular cylinder results in complete suppression of vortex shedding and increase in the base pressure. In his research, Gerrardt (1966) investigated the effect of splitter plate length on the vortex shedding frequency from cylinder. He showed that the minimum Strouhal number occurs when the length of splitter plate is equal to the cylinder diameter and further increment of the plate length causes rise in the Strouhal number again. Shukla et al. (2009) studied the effects of a rigid splitter plate hinged at the base of the cylinder. They found that the splitter plate length to cylinder diameter (L/D) ratio is crucial in determining the character and magnitude of the oscillations. They conclude that for small splitter plate to cylinder diameter ratio the oscillations appear to be nearly periodic with tip amplitudes of about 0.45D nearly independent of L/D. However the non-dimensional frequency (Strouhal Number) continuously vary with L/D from $fD/U \approx 0.2$ at $L/D = 1$ to $fD/U \approx 0.1$ at $L/D = 3$.

Rockwell and Unal (1988) conducted their experiments on circular cylinder with an attached splitter plate at Reynolds numbers ranging from 140 to 1600. They observed two separate flow patterns, i.e. pre-vortex formation and post-vortex formation regimes characterized by the absence and presence of large-scale vortices upstream of the plate's tip, respectively. They found that moving the plate from one regime to another will affect the unsteady pressure force drastically.

Bao and Tao (2013) numerically studied the effects of two stationary splitter plates symmetrically attached at the rear surface of the cylinder. The plates are fixed parallel to flow and the ratio of plates length to cylinder diameter is 0.3. They concluded that In comparison to the use of a single splitter plate, the dual plates cause increased drag reduction and stronger wake suppression at relatively shorter plate lengths. It is shown that the attachment angle has a crucial effect on the control efficiency, and the most effective range associated with the maximum drag reduction is between 40°≤ θ_f ≤ 50°.

In a numerical study, Kwon and Choi (1996) investigated the vortex shedding behind a circular cylinder and its control using a splitter plate at Reynolds numbers ranging from 80 to 160. They noticed that in the range of $Re \leq 100$, the Strouhal