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Effects of aspect ratio and orientation on the wake characteristics of low Reynolds number flow over a triangular prism

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ABSTRACT

The wake characteristics of unconfined flows over triangular prisms of different aspect ratios have been numerically analysed in the present work. For this purpose, a fixed Cartesian-grid based numerical technique that involves the porous medium approach to mimic the effect of solid blockage has been utilised. Correspondingly, laminar flow simulations ranging from the sub-critical regime (before the onset of vortex shedding) to the super-critical regime have been considered here within the limits of two-dimensionality. In the sub-critical regime, correlations relating the wake bubble length with Reynolds number (Re) have been proposed for various aspect ratios. Also, the effects of aspect ratio and Reynolds Number on the drag force coefficient (C_D) have been characterised for two different geometrical orientations of the prism (base or apex facing the flow). Subsequently, the critical Reynolds number at the onset of vortex shedding has been predicted for each of the aspect ratio considered, by an extrapolation procedure. The unsteady flow characteristics of the super-critical regime are finally highlighted for different aspect ratios and triangular orientations considered in the study.

1. Introduction

In the event of flow around bluff bodies, the persistent non-linear fluid structure interactions result in the manifestation of diverse flow behaviour occurring at different ranges of parameters and structural configurations. Generally, these flows are characterised by the presence of a low-pressure wake region (pocket of recirculating low momentum fluid behind the bluff body) that determines the overall flow dynamics. At lower values of Reynolds number (Re), this wake region is stably enclosed between the separated streamlines of the free stream. However, with the increase in Re, the wake bubble undergoes a stream-wise elongation due to viscous stresses and becomes vulnerable to the shear layer instabilities acting on its interface with the free stream. Finally at a critical value of Re, the wake breaks up and starts to shed eddies that form the von Karman vortex street. As a consequence of these events, the bluff body is subjected to fluctuating drag and lift forces and a corresponding momentum defect is introduced into the fluid stream. This initial transition has further supplements at higher Re where the route to turbulence is attained via various modes of shear layer and boundary layer modifications.

Various classical reviews have well elucidated the critical features exhibited by the wake of circular cylinders (Zdravkovich, 1990, 1997; Williamson, 1989, 1996; Thompson et al., 2001; Sumner, 2010). These features include the

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Nomenclature

AR	aspect ratio
C	computational constant
C_D	drag coefficient
C_L	lift coefficient
D	base of triangular prism
F	volume fraction; hydrodynamic force
h	height of triangle
H	height of the computational domain
k	ratio of dimensionless wake bubble length to Re
L	length
n	normal
p'	pressure correction
q	computational constant
Re	Reynolds number ($\rho u_\infty D/\mu$)
$\vec{S}$	momentum sink
t^*	non-dimensional time (tU/D)
u	horizontal velocity component
v	vertical velocity component
x	horizontal coordinate
y	vertical coordinate

Greek

Γ	control volume
ζ	grid density
λ	porosity
μ	dynamic viscosity
ρ	fluid density
σ	stress
Ω	computational domain

Subscripts

bp	base pressure
cr	critical
D	drag
f	fluid
L	lift
max	maximum
r	recirculation
rms	root mean square
s	solid
∞	free-stream

Superscripts

ij	cell index
n	present time step

diverse modes of vortex shedding, laminar to turbulent transition, presence of intermittent oblique eddies and their resultant effects on the base pressure coefficient (C_{bp}), etc. Although some of the above effects are also observed for bodies of other cross-sections, each of them is abundant with its own unique flow characteristics. In many cases, the flow separation points in the rear region of the bluff body act as sources of disparities in the downstream flow behaviour. Specifically, for circular cylinders, the points of flow separation strongly depend on the value of Re. On the other hand, for square cylinders, the flow separation normally takes place at its corners. Despite this, a strong relationship between the force coefficients and Re is observed for these cases, more specifically for bluff rectangular cylinders (Davis and Moore, 1982). Similar interesting but distinct features are also exhibited in the case of triangular cylinders. Here, at higher Re and increased bluffness, the fluctuating force coefficients are mainly dominated by the form drag over the skin friction drag. This happens even though the flow separation points are always located at the corners of the base (for both the cases of base and apex facing the approach flow). Additional distinctions are also evident from the fact that critical Re is lower for triangular cylinders (De and Dalal, 2006; Zielinska and Wesfreid, 1995) as compared to that of an equivalent square cylinder (Kelkar and Patankar, 1992).

Even though the existing research publications rigorously bring out various distinctions of flow over circular and square cylinders, the scenario with respect to triangular cylinders (Zeitoun et al., 2011; Srikanth et al., 2010; De and Dalal, 2006, 2007) seems to be less explored. Precisely for the latter systems, the analysis of flow behaviour has often been restricted to equilateral triangles where linear relationship persists (De and Dalal, 2006) between the dimensionless wake bubble length (L_r) and Re in the sub-critical regime (before the onset of vortex shedding). Akin to the case of square cylinders, no secondary bifurcations have been observed within the range of Re between 80 and 200. Also, the global modes in the wake region are characterised by the occurrence of a definite maximum in the amplitude at a particular wake location (Zielinska and Wesfreid, 1995). This maximum amplitude is a function of Re near the critical range and has been suitably exploited by Zielinska and Wesfreid (1995) for the accurate evaluation of critical Re.

Although, many of the above features of triangular cylinder are also observed for other cross-sections like circle and square, its actual uniqueness is revealed when there is a change in its aspect ratio or orientation. For instance, Bao et al. (2010) have observed that for an inclination of 0° (where base of the triangle faces the approach flow), the shed vortices combine to form a bigger eddy whose characteristics are different from those behind an equivalent circular cylinder. At other inclinations, the asymmetry of the cylinder with respect to the approaching flow has its notable influence on the mean forces (Iungo and Buresti, 2009). Particularly at 90° inclination angle (where the base of the triangle is parallel to the approaching flow), the system depicts a flat plate behaviour on one side and a sharp edge behaviour on the other (Srigrarom and Koh, 2008). The implications of aspect ratio effects on the triangular systems are evident from the work of Abbassi et al. (2001) where