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Separation bubble characteristics on an axial flow over a cylinder with different noses

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ABSTRACT

Experiments were conducted to study the characteristics of the leading edge separation bubble on an axial cylinder with different nose shapes at different angles of attack and Reynolds numbers. The blunt, conical and hemispherical cylinder noses were examined. The angle of attack α and Reynolds number Re_D, based on cylinder diameter D, were varied from 0° (axial) to 3.5° and from 1.5×10^3 to 4.2×10^4, respectively. The time-mean pressure coefficient (C_p) and fluctuating (rms) pressure coefficient C_p' were measured on the cylinder surface at $x/D = 0.15$, 1.0 and 2.5. The shear layer reattachment length x_R, shear layer transition length x_{Tr}, and bubble height W were determined by particle image velocimetry (PIV) and flow visualization techniques. The x_R, x_{Tr}, and W all shrink substantially with increasing Re_D upto $Re_D = 10^4$. For $Re_D > 10^4$, variations in x_R and W are insignificant but x_{Tr} keeps shrinking. At a given Re_D, x_R and W retreat progressively from the blunt nose to the conical and then to the hemispherical; meanwhile, x_{Tr} is prolonged. Following x_R, W and x_{Tr}, both time-mean pressure coefficient (C_p) and fluctuating (rms) pressure coefficient C_p' in the bubble are highly sensitive to Re_D for $Re_D < 10^4$, but less so for $Re_D > 10^4$. The magnitude of C_p is large near the separation and much smaller around and behind the reattachment. On the other hand, C_p' is small near the separation but large around the reattachment. In the case of the hemispherical nose, the C_p magnitude is smallest of all. The C_p' is highest for the blunt nose but lowest for the hemispherical. An increase in α leads to an elongation of x_R and W and a reduction of x_{Tr} for all three noses.

1. Introduction

Numerous studies have been carried out on the leading edge separation bubble owing to the practical engineering importance, such as on aircraft fuselages, submarines, missiles, road vehicles, underwater vehicles, airfoils etc. When a shear layer separating from a point reattaches, a separation bubble forms. The transitional and reattachment processes induce a large pressure fluctuation in the bubble. In many practical situations, the presence of the separation bubble has a great impact on the performance of devices or systems and results in structural vibration and noise.

Some aspects of flow features around the separation and reattachment on a blunt cylinder in the axial flow have been examined in the literature by Ota (1975), Dong et al. (1997) and Kiya et al. (1991). They found that, for a laminar shear layer ($Re_D < 1.8 \times 10^4$, based on the cylinder diameter D), the shear layer reattachment length decreases rapidly with Re_D increasing. On the other hand, for turbulent shear layer ($Re_D > 1.8 \times 10^4$), the reattachment length is independent of Re_D. Keener (1986) made a comprehensive investigation of the flow around a conical cylinder using Schlieren, vapor-screen, oil-flow, and sublimation flow visualization techniques for attack angle $\alpha = 0$–88° and $Re_D = 0.3 \times 10^6$ to 2.0×10^6, where α is angle between the free-stream flow and the cylinder axis. He found that there is a leading-edge separation bubble on the leeward side of the cylinder at $\alpha < 15°$, and the bubble changes to a primary laminar vortex at $15° < \alpha < 20°$. The point of transition-to-turbulence moves forward when the Re_D is increased. Hsieh (1975,1977a,b) identified three different types of flow separations around a hemispherical cylinder: (i) the boundary layer separation on the hemispherical nose, due to the longitudinal pressure gradient caused by the nose geometry and α, (ii) boundary layer separation around the cylinder body because of the transversal pressure gradient, and (iii) flow separation from the trailing edge (base) of the cylinder. Clainche et al. (2015a,b) for a hemispherical cylinder identified separation bubble and horn vortices (so-called "leeward" vortices) using critical-point theory. The most striking effect of α is the substantial asymmetry of the mean velocity field which may occur even at

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very small α (Bücker and Lueptow, 1998; Heenan and Morrison, 2002). The considerable deviations from axisymmetry are also observed on the wall-pressure fluctuations (Snarski, 2004). The previous researchers focused predominantly on the effects of small α on the fully developed turbulent region, i.e., downstream of the leading edge.

Wall pressure fluctuations in the separation region may generate considerable flow-induced noise/vibration (Patrick, 1987; Imamura et al., 2008). Indeed, the pressure fluctuation in the reattachment region on an axisymmetric body is about ten times higher than that in the fully developed turbulent flow region (Arakeri, 1975). While some studies identified different characteristic frequencies of the large-scale low-frequency ($=0.25U_\infty/x_R$) unsteadiness due to an enlargement and shrinkage of the bubble and also due to a flapping motion of the shear layer near the separation line (e.g., Kiya and Sasaki, 1983; Cherry et al., 1983; Kiya and Sasaki, 1985), some (Ruderich and Fernholz, 1986; Yang and Abdalla, 2009) did not. Obviously, a disparity between the results exists.

The forebody (nose) geometry has a considerable effect on the flow separation and reattachment. The separation point is fixed at the sharp edges of the blunt and conical noses while varying on the hemispherical nose with increasing Reynolds number. Hoang et al. (1997) examined the three-dimensional nature of the separation bubble for a hemispherical cylinder at $\alpha = 0$–$45°$. A separation bubble near the nose wraps around the cylinder for $\alpha = 0°$, the reattachment line forming a ring around the cylinder. With an increase in α, the bubble on the windward side gradually shortens and disappears, and that on the leeward side elongates. The flow on the windward side remained laminar while that on the leeward side transits earlier than that for $\alpha = 0°$. The elongated separation bubble on the leeward side of the cylinder results from the strong adverse pressure gradient due to the incidence angle. The bubble size is highly dependent on Re and α (Hseih, 1977; Hoang et al., 1997). The flow field near the leading edge of a blunt cylinder was examined at some particular Re_D (Reynolds number based on cylinder diameter D) in the literature (e.g., Ota, 1975, $Re_D = 5.6 \times 10^4$; Dong et al., 1997, $Re_D = 2.8 \times 10^3$–1×10^5; Kiya et al., 1991, $Re_D = 2 \times 10^5$; (Higuchi et al., 2005), $Re_D = 10^5$), while Re_D effects on the surface pressure fluctuation in the flow separation region is not yet well understood for not only blunt nose but also conical and hemispherical noses. The cone-nose model has been extensively studied as a model of projectiles or missiles at very high Re_D (subsonic, sonic and supersonic) (e.g., Lamont and Hunt, 1976) and high angles of attack (e.g., Ericsson and Reding, 1992; Lim et al., 2012) where the flow separation and vortex shedding induce a large side force. The incident flow on the cylinder-like submarines, in reality, is always not axial, but may be at a small α. There are some studies on the effect of α on the downstream vortex development for high $\alpha = 35$–$65°$ (Zilliac et al., 1991), separated flow structures for $\alpha = 0$–$30°$ (Hsieh, 1975; Clainche et al., 2016), development of leeward vortices and separation bubble for $\alpha = 0$–$30°$ (Hoang et al., 1999) for the hemisphere-cylinder. The effect of α the leading edge flow, especially how the reattachment position and transition to turbulence are influenced by α is not well understood. In fact, the pressure fluctuation at a point is the integrated effect of the velocity fluctuation, hence giving an overall picture of the flow around the point. The present work focused on the effects of nose shape as well as α on the flow features around the leading edge so as to improve our understanding of the flow separation and reattachment behaviors for such configurations.

The objective of this paper is to examine the surface pressure fluctuation and the behavior of the flow around the leading edge of a circular cylinder with blunt, conical, hemispherical noses, with Re_D ranging from 1.5×10^3 to 4.2×10^4. In particular, apart from the cylinder in axial flow ($\alpha = 0°$), the cylinder with $\alpha = 2.0°$ and $3.5°$ are also studied. Time-mean as well as rms pressure is measured at $x/D = 0.15$, 1.0 and 2.5 (Fig. 1a). Re_D effects are thus discussed at different spatial positions. Furthermore, flow visualization experiment was also conducted to extract the behaviors of shear layer and separation bubble.

2. Experimental details

Experiments were performed in a closed-circuit wind tunnel with

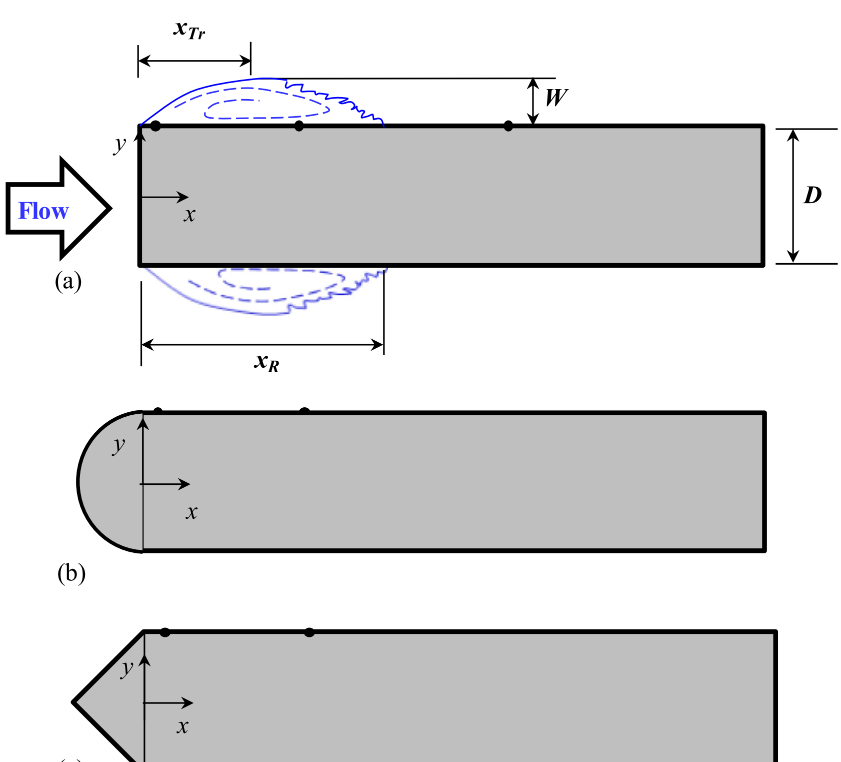

Fig. 1. Sketches of models. (a) Blunt cylinder and definitions of reattachment length x_R, bubble height W and transition length x_{Tr}. (b) Hemispherical-nose cylinder. (c) Cone-nose cylinder. Small solid circles denote the pressure tap positions.

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