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Effects of micro-perturbations on the asymmetric vortices over a blunt-nose slender body at a high angle of attack

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ABSTRACT

Asymmetric vortices over its blunt-nose slender body are generated when a missile flies at high angles of attack (AoA, up to 40–50°) to attain high manoeuvrability. The pattern of the asymmetric vortices changes randomly, due to uncertainties in manufacturing and surrounding conditions, thus resulting in unexpected side-forces (in both magnitude and direction). In order to control the behaviour of the asymmetric vortices, a micro-perturbation is introduced and attached on the nose of the slender body at a high AoA $\alpha = 50°$. The micro-perturbation is a hemispherical protrusion with a radius of $r = 0.0015 - 0.015D$, where D is the diameter of the blunt-nose slender body. Experimental tests and numerical simulations are conducted to investigate disturbed flows over the blunt-nose slender body at a Reynolds number $Re_D = 1.54 \times 10^5$, based on oncoming free-stream velocity and D. The side-forces, pressure distributions and vortical structures are measured using force balance, pressure scanning and particle-image velocimetry (PIV), respectively. Three-dimensional numerical simulations are conducted, with the shear-stress transport (SST) $k - \omega$ turbulence model employed. It is found that the randomness features of the asymmetric vortices pattern were inhibited in the presence of the tiny perturbation. The pattern of asymmetric vortices and the corresponding side-forces are manageable and highly dependent on the location and the size of the perturbation. The associated pressure distributions and flow separation are discussed in detail.

1. Introduction

In order to realize tactical advantages in missions, a missile is required to possess high manoeuvrability, which is usually achieved through flight at high angles of attack (AoA). However, uncertain separation flows, which are featured by asymmetric vortices, occur over the blunt-nose slender body of a missile flying at high AoA [1]. The pattern of the asymmetric vortices is highly random, owing to the uncertainties in manufacturing and surrounding conditions [2]. Consequently, unexpected side-forces and yawing moments are generated, the latter being largely greater than that by the rudder of a missile [3], which may change the desired track of a missile and even cause mission failure. So, it is practically significant to control the pattern of the asymmetric vortices over the blunt-nose slender body.

The asymmetric vortices over the slender body with either a pointed nose or a blunt nose, in the absence of an artificial perturbation, have been extensively investigated, in order to uncover the flow physics underlying the phenomena. The asymmetric flow over the slender bodies at high AoA was observed in wind tunnel experiments [4–6]. That is, the magnitude and direction of the side-force acting on the slender body varied with the rolling of the test model, though which was nominally axisymmetric about its axis. In other words, there was dependence of the side-force magnitude and direction on the roll angle of the test model. Pick [7] is the first researcher to study the asymmetric vortices generated over a pointed-nose slender body at high AoA. The random occurrence of the flow pattern was ascribed to the micro asymmetries and geometrical imperfections near the nose. Keener [8] also noted that the pattern of asymmetric vortices was mainly affected by the pointed nose, instead of the afterbody.

Extensive investigations have been conducted, with attempts to change the asymmetric flow into symmetric. The asymmetry of the vortical structures over the blunt-nose slender body can be suppressed or even inhibited through disturbances from extra artificial devices attached on the nose or forebody. These methods include nose blunting [8–10], strakes over the forebody [11,12], booms on the nose [13], blowing/suction issued at the nose [14], as well as boundary-layer trips over the nose surface [15]. These techniques

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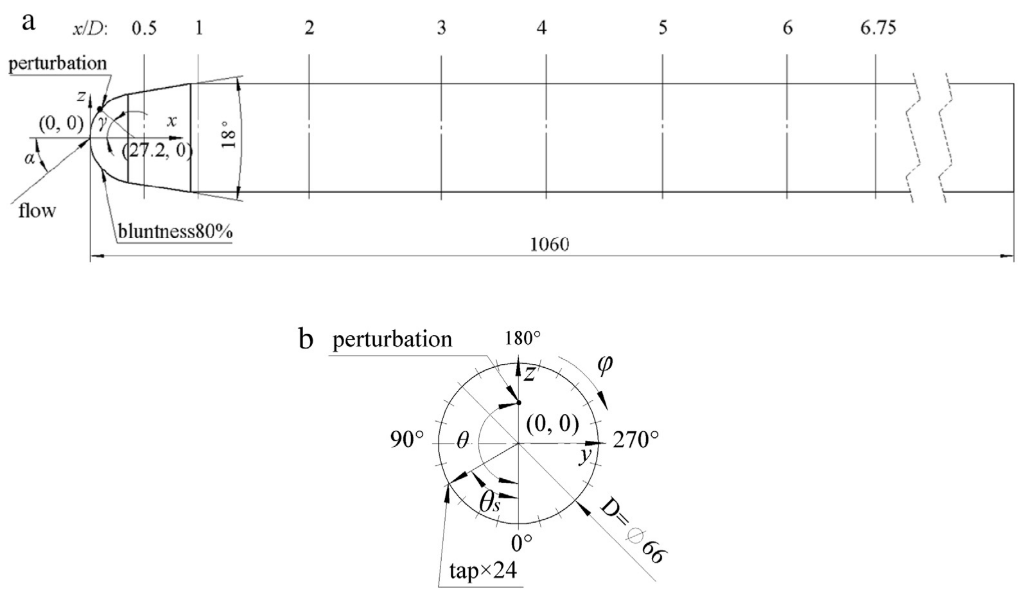

Fig. 1. Schematics showing the test model of a blunt-slender body, together with symbol designations. (a) Side view; (b) end view. Units of length scale are in mm.

have achieved limited success and need to be demonstrated in a wide range of flow parameters.

Alternatively, some investigations have been focused on the passive and/or active approaches to eliminating the randomness nature of the asymmetric vortices occurrence, aiming at manipulating the flow pattern and thus the side-forces and moments. A cylindrical bead (1.6 mm high and 3.2 mm wide) attached on the blunt-nose was used by Moskovitz [16] to disturb the vortical flows. The randomness occurrence of the vortices pattern was inhibited due to the presence of the perturbation. As such, the side-force measured was determinate and highly repeatable. Similar observations were made by Lopera [17] and Sirangu (2012) using a strake (3 mm high and 5 mm long) attached on the blunt-nose. These devices have relatively large physical sizes, and local flow separation was induced, which is unexpected. On the other hand, a perturbation with simple geometry and small size is desirable, given that the uncertainty of the asymmetric vortices can be eliminated by the micro perturbation. A tiny particle, which size is only 0.2 mm in diameter, was used to disturb the asymmetric vortices over a pointed-nose slender body at high AoA [18]. The micro perturbation was placed on the tip of the pointed-nose slender body. It is found that the vortices pattern was quite manageable in the presence of the micro perturbation [18–20]. However, to the best of our knowledge, no studies have been conducted to investigate the effects of the micro perturbation on the asymmetric vortices over the blunt-nose slender body, where the size of the perturbation is so small compared to the large nose of the slender body.

This work is focused on the effects of the micro perturbation on the vortical structures over the blunt-nose slender body at a high AoA $\alpha = 50°$. A tiny hemisphere attached on the nose of the slender body is taken as the micro perturbation. Wind tunnel tests and numerical simulations are conducted at a Reynolds number $Re_D = 1.54 \times 10^5$. The flow structures and forces are examined in detail. The test model and approaches are described in Section 2. Results are presented and discussed in Section 3. This work is concluded in Section 4.

2. Test model and approaches

2.1. Test model

Fig. 1 presents the schematics of the test model of a blunt-nose slender body, together with the symbol designations. The test model is composed of three parts, i.e., the blunt nose, the cylindrical slender afterbody, and the conical part connecting the former two. The cylindrical slender afterbody has a diameter $D =$ 66 mm and the full length is 1060 mm ($= 16.0606D$). The blunt nose, which is a part of a ball with a radius of 27.2 mm ($= 0.4121D$), has a bluntness of 80%, which is defined by the ratio between the nose diameter and the afterbody diameter. The conical part has a length of 38.21 mm ($= 0.5789D$) and an apex angle of 18°. The coordinate system is defined at the tip of the blunt nose (i.e., the origin), with x-direction along the symmetric axis of the slender body, and y- and z-directions as the horizontal and vertical axes, respectively, in the normal plane to the slender body axis (Fig. 1). The blunt-nose slender body has an angle of attack (AoA) α, which is the incident angle of the oncoming flow to the x-direction. The roll angle of the blunt-nose slender body is designated by φ. A tiny hemisphere with a radius $r(= 0.0015 - 0.015D)$ is taken as the micro perturbation in the present study. It is attached on the nose surface and its location is determined by the following two angles, the meridian and circumferential angles γ and θ, respectively. γ is the angle between the x-axis and the nose radius corresponding to the perturbation location (Fig. 1a), and θ is the angle between the z-axis and the sectional radius corresponding to the perturbation location (Fig. 1b).

A test model with pressure taps is used in the pressure measurements. As illustrated in Fig. 1, there are a total of eight tapping stations, each having 24 equally-spaced taps along the circumference. The pressure tap has a diameter of 1 mm. The tap location is indicated by the angle θ_s between the negative z-axis and the sectional radius corresponding to the pressure tap.

2.2. Wind tunnel tests

Experiments are conducted in a low-speed open-circuit wind tunnel with a 2.5 m-long square test section of 1.5 m ×1.5 m. This tunnel has a maximum velocity of 60 m/s, with a freestream turbulence intensity ≤ 0.08%. As shown in Fig. 2, the test model of the blunt-nose slender body is sting-mounted on a support mechanism attached with an apparatus for the change of AoA. The oncoming freestream is $V_\infty = 35$ m/s in all the following tests, corresponding to a Reynolds number $Re_D = 1.54 \times 10^5$, based D and V_∞.