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Supersonic flow over rounded contour bumps with vortex generators or passive longitudinal jets

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ABSTRACT

An experimental study has been conducted to investigate the flow characteristics over two rounded contour bumps. Vane-type vortex generators or longitudinal aligned passive by-pass jets were implemented in attempt to achieve wake flow control in rounded contour bumps. According to the results collected from the surface oil flow visualisation experiments, it was observed that the use of both the vane-type vortex generators and the longitudinally aligned passive by-pass jet could reduce the size of the spanwise vortices in the bump valley. In addition, a pair of streamwise horseshoe vortices was observed downstream of the bump crest of the contour bump that equipped with the vane-type vortex generators. From the data collected in the particle image velocimetry measurements, it was found that the use of both the vane-type vortex generators and the longitudinally aligned passive by-pass jet could not reduce the size of the wake region but they could reduce its strength. It is deduced that the two streamwise horseshoe vortices generated by the vane-type vortex generators enhance flow mixing which results in reducing the strength of the wake region. In contrast, blowing passive by-pass jet in the bump valley increases the local flow velocity in order to reduce the strength of the wake region.

1. Introduction

Flow characteristics over rounded contour bumps have been extensively investigated in both subsonic and supersonic freestream in the last two decades [1–8] because of their potential applications in achieving wave drag reduction in both transonic aircraft wings [9–13] and Diverterness Supersonic Inlets (DSI) [14,15]. In the flow physics of rounded contour bumps, the experimental studies conducted by Byun [1] and Byun et al. [2] were two earliest investigations in the flow characteristics over a range of three-dimensional rounded contour bumps in subsonic freestream. The authors in these studies observed that large-scale vortical structures are presented downstream of the bump crest due to the occurrence of flow separation at the leeward side of the bump. In addition, spanwise, counter-rotating vortices are formed in the valley of the rounded contour bumps resulting from flow separation. The authors concluded that the length-to-width and length-to-apex height ratios of the bump determine the number, size and shape of the spanwise vortices that present at the leeward side of a rounded contour bump.

Yakeno et al. [3] and Iaccarino et al. [4] considered the flow physics over two-dimensional rounded contour bumps in subsonic laminar and turbulent flow, respectively. The authors in [3,4] confirmed the conclusions drawn by Byun [1] and Byun et al. [2] that the appearance of flow separation at the leeward side of the bump leads to the formation of large-scale three-dimensional vortical structures downstream of the bump crest. Moreover, the authors indicated that the flow Reynolds number determines the size and shape of the vortical structures that formed. Long and wide vortical structures are presented when the rounded contour bumps are subjected to laminar flow. In contrast, the vortical structures those shown in turbulent flow are generally shorter and narrower. Svensson [15] investigated numerically the problem of subsonic flow over a number of three-dimensional rounded contour bumps with various length-to-width and length-to-apex height ratios. The author confirmed the formation of large-scale three-dimensional vortical structures and the spanwise counter-rotating vortices at the leeward side of the bump as concluded in [1–4]. In addition, the author observed that for a given length-to-width ratio of a rounded contour bump, in subsonic flow, increasing the freestream Mach number increases the sizes of both the wake region and the spanwise vortices that present at the leeward side of the bump. This further indicates that the size and shape of the flow features that formed are flow Reynolds number dependent.

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In supersonic flow, Lo [5], Lo and Kontis [6,7] and Svensson [15] studied the flow characteristics over three-dimensional rounded contour bumps. In the numerical study conducted by Svensoon [15], the author concluded that the large-scale three-dimensional vortical structures and the spanwise counter-rotating vortices that present in subsonic flow also appear in supersonic freestream. Interestingly, the author found that for a rounded contour bump with a given length-to-width ratio, the sizes of the three-dimensional vortical structures and the spanwise vortices reduce with increasing the freestream Mach number. This finding was later confirmed in the experimental study conducted by Lo [5] using a three-dimensional rounded contour bump subjected to both Mach 1.3 and 1.9 supersonic freestream. The author in [5] confirmed that larger wake region and spanwise counter-rotating vortices are formed at the leeward side of the bump in Mach 1.3 freestream than those shown in Mach 1.9 freestream.

Since flow separation is observed downstream of the bump crest of rounded contour bumps which leads to the formation of the wake region at the leeward side of the bumps; wake flow control in subsonic and supersonic freestream using various flow control strategies have been investigated in several studies [5–7,16,17]. Recently, Chen et al. [16,17] investigated the effects of passive jet in achieving wake flow control over a stationary circular cylinder in a subsonic freestream. The authors concluded that compared to the baseline circular cylinder, blowing passive-by-pass jet at the leeward side could effectively reduce drag encountered by the circular cylinder. In addition, the passive blowing jet reduces the turbulence kinetic energy levels along the wake region with passive jet blowing implemented at the leeward side of the circular cylinder.

Lo and Kontis [6] recently investigated the functions of transverse passive by-pass jet and active blowing jet in achieving wake flow control in a three-dimensional rounded contour bump in Mach 1.3 freestream. The authors in [6] found that the use of transverse passive by-pass jet could reduce neither the size nor the strength of the wake region. It was observed that the blowing transverse passive by-pass jet could only exert effects immediately behind the jet orifices that situated in the bump valley. However, the result shown in [6] suggested that the blowing transverse passive by-pass jet could reduce the size and strength of the spanwise vortices that formed in the bump valley by hindering the formation of the spanwise vortices around the centre portion of the bump. In contrast, the blowing active jet with total pressure of 2 and 4 bar in the bump valley could effectively reduce both the size and strength of the wake region at the leeward size of the bump in Mach 1.3 freestream. The authors in [6] indicated that the active blowing jet deflected the shear layer downwards so that reattachment of the separated flow downstream of the bump crest is accelerated. In addition, the active blowing jet in the bump valley also increases the momentum of the flow in the wake region so that the strength of the wake vortex is significantly reduced. This wake flow control effect is particularly promising when the jet total pressure is 2 bar. Moreover, the blowing jet also increases the local pressure level around the centre portion of the bump valley and hence, only small and diffuse spanwise vortices are formed in the bump valley. Similar effects provided by the active blowing jet in achieving wake flow control in three-dimensional rounded contour bumps also observed in Mach 1.9 freestream as concluded by Lo et al. [7]. However, the size and structure of the spanwise vortices that present in the bump valley in Mach 1.9 freestream are considerably different from those shown in Mach 1.3 freestream.

The present experimental study serves as the second part of an earlier study conducted by Lo and Kontis [6] in order to investigate the functions of vane-type vortex generators and longitudinally aligned passive by-pass jet in achieving wake flow control in three-dimensional rounded contour bumps in Mach 1.3 freestream. Vortex generators have been proven to be able to achieve flow separation control in transonic and supersonic freestream [18–22]. It is unclear that whether the same flow control strategy in achieving wake flow control can be achieved in three-dimensional rounded contour bumps. Similarly, it is also unclear that whether flow control in rounded contour bumps could be obtained by blowing longitudinally aligned passive by-pass jet in the bump valley as observed in [16,17] using a stationary circular cylinder. Surface oil flow visualisation, high-speed Schlieren photography and time-averaged two-component Particle Image Velocimetry (PIV) measurements were used for flow diagnostics. The data collected from the present study could improve our understanding in using vane-type vortex generators and passive by-pass jet in achieving wake flow control in three-dimensional rounded contour bumps.

2. Experimental setup

2.1. Supersonic wind tunnel

All experiments in the present study were conducted using an intermittent in-draft supersonic wind tunnel. A systematic diagram and a snapshot of the actual wind tunnel used are shown in Fig. 1a and b, respectively. Detailed information of the supersonic wind tunnel used could be found in [5–8] and only a brief description is provided here. The required Mach 1.3 free-stream was generated by expanding the incoming airflow through a convergent-divergent nozzle situated upstream of the wind tunnel test section. The contour bump model was mounted 82.5 mm downstream of the beginning of the wind tunnel test section. Optical access to the wind tunnel test section was achieved through the two quartz-made side windows and the ceiling mounted quartz window. The wind tunnel has a stable run-time of 6 s. Under the same initial conditions, the variation of the freestream Mach number (M_∞) is $M_\infty = 1.3 \pm 0.1$ [6,8] which is corresponding to the freestream velocity $U_\infty = 373 \pm 37\ \text{ms}^{-1}$. The inlet of the supersonic wind tunnel is subjected to atmospheric pressure and temperature. Static pressure (P) and temperature (T) in the test section during wind tunnel operation are P = 35.84 kPa and T = 203.79 K. The flow Reynolds number per unit length (Re/L) is $Re/L = 12.11 \times 10^6$ [6].

The boundary layer profile of the incoming flow 5 mm upstream of the front of the contour bump model was measured using a pitot rig and the detailed methodology of measurement could be found in [6]. At that location, the boundary layer thickness based on 99% of the freestream velocity (δ_{99}) is 14.9 mm. The corresponding displacement (δ^*) and momentum thickness (θ) of the boundary layer are $\delta^* = 4.54$ mm and $\theta = 2.57$ mm. This yields a shape factor (H), defined as the ratio between δ^* and θ, of H = 1.77. Since the contour bump model was completely submerged in the boundary layer; the contour bump was subjected to both subsonic and supersonic incoming flow. The subsonic flow region appears in between $0 < y < 7.6$ mm and the supersonic flow region exists in anywhere within the flow field where $y > 7.6$ mm [6].

2.2. Rounded contour bumps

Two rounded, three-dimensional contour bump models, known as the VG bump and the longitudinal jet bump were used in the present experimental study. These two contour bump models have the same general geometry as shown in Fig. 2a (adopted from [6]) but incorporated with different passive flow control devices. The dimensions of these two bump models are 75 mm (length) × 50 mm (width) × 10 mm (apex height). It should be noted that contour bumps with identical general geometry also employed in