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Attenuation of Shockwave-induced Flow Separation over a Double Ramp Using Herringbone Riblets at $M_\infty=5$

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In this paper, the effect of herringbone riblets as a means of suppressing shockwave-induced flow separation is investigated. A spanwise array of ribleted strips is applied behind the leading edge of a double ramp model placed in a Mach 5 freestream. High-speed schlieren technique is used to examine the shockwave pattern and the state of the boundary layer developing along the surface of the model. Both pressure-sensitive paints and temperature-sensitive paints are employed to assess the impact of riblets on the interaction between the shockwave and the boundary layer. The results from this experiment show that herringbone riblets are capable of suppressing shock-induced flow separation and hence improving pressure recovery. Furthermore, it is also revealed that these micro-scale riblets induce large-scale streamwise vortical structures within the boundary layer similar to those observed in incompressible flows. It is believed that these vortices promote momentum transfer within the boundary layer hence providing the dominant mechanism for suppressing flow separation.

I. Introduction

Shockwave-boundary layer interaction is a flow phenomenon that vehicles flying at transonic and supersonic speed must face with. A variety of flow control methods have been explored, both active and passive, in order to mitigate the adverse effect of such an interaction. Porous surfaces[1], contour bumps[2] and vortex generators[3] are typical examples of passive control methods, whereas boundary layer bleeding[4] is a typical example of active control methods. Comprehensive reviews of such work can be found in[5-7].

Among the various flow control methods which have been explored, passive flow control devices such as contour bumps and micro-vortex generators have attracted a lot of research attention due to their simplicity in installation and effectiveness. These devices typically have a height greater than a fraction of the boundary layer thickness. Contrast to the great success of these passive control devices, especially micro-vortex generators, on controlling shock-induced separation in transonic flows[8, 9], their control effectiveness is found to be reduced substantially in supersonic flows[10-13] because only localized variations in the extent of flow separation were observed and no investigation has reported entirely reattached flow[3]. A possible reason given by Panaras[14] is that the counter-rotating vortex pair produced by micro-vortex generators decays more rapidly in a supersonic flow than in a subsonic flow making it less effective. Furthermore, they also produce an appreciable amount of parasitic drag since a sizeable protrusion height into the local boundary layer is required to deliver a sufficient control effect. Therefore, other passive flow control methods, which are capable of delaying flow separation in supersonic flows while introducing as little amount of unwanted drag as possible, are still being sought.

Herringbone riblets are a type of directional surface roughness which is inspired by the surface pattern on bird secondary flight feathers, see Fig. 1. Despite their micro-scale size, these riblets are very effective in inducing large-scale streamwise counter-rotating vortices, which moderate the properties of a boundary layer[15]. Chen et al[16] showed that by covering the inner surface of a circular pipe with herringbone riblets a 17% reduction in turbulent friction drag can be obtained. Liu et al[17] demonstrated that herringbone riblets fixed on the suction surfaces of highly loaded diffuser blades can bring about a substantial reduction in the pressure losses and an increase in flow turning angle in a linear cascade. In the latter case, it is believed that the streamwise counter-rotating vortices generated by these riblets are responsible for suppressing the flow separation occurring on the suction surfaces. Based on the existing experiments reported in the literature, herringbone riblets could provide an attractive passive flow control method potentially suitable for controlling shockwave-induced flow separation.

In this paper, the results from the first experimental assessment of the effectiveness of herringbone riblets in attenuating flow separation in a supersonic flow are reported. In this experiment, a spanwise array of herringbone riblets strips is applied to the forward section of a double ramp placed in a Mach 5 flow. The double ramp geometry is a generic model that used for the aerodynamic and thermal design of control surfaces on atmospheric re-entry vehicles[18]. High-speed schlieren technique is used to examine the shockwave structure and the state of the boundary layer developing along the surface of the model fitted with riblets of different depths. The pressure-sensitive paints (PSP) technique is utilized to examine the impact of these riblets on the

size of flow separation zone on the model. The temperature-sensitive paint (TSP) technique is employed to provide qualitative information about the structures produced by the riblets and their interaction with the surface flow. The effects of riblets with the same depths but different orientations are also examined with an attempt to confirm the mechanism responsible for the flow control effect observed in the experiments.

Fig. 1 Bird secondary flight feathers[19]

II. Experimental setup

A. The wind tunnel facility

Our experiments were conducted in the High-Speed Supersonic Tunnel (HSST) at the Manchester University. It is a blowdown wind tunnel that utilizes dried, heated, and filtered air as the working gas and it is capable of a maximum run time of 8 seconds. The Mach 5 jet nozzle has an exit diameter of 152mm and it is enclosed in a test section measuring 325mm×325mm×900mm (width × height× length). To enable optical access, the test section is fitted with a 195mm-diameter quartz window on each side and two 110mm-diameter windows on the ceiling. The total pressure in the test section can be varied between 4 to 8.2 bars with less than 2% variations over different runs and the total temperature can be raised from 375K to 600K to prevent liquefaction. As such, the unit Reynolds number can be varied from 3.91 to $17.1 \times 10^6 \text{m}^{-1}$ at Mach 5. The temporal variations of the total pressure and total temperature during a typical run are shown in Fig. 2.

Fig. 2 Total temperature and total pressure during the run

B. Wind tunnel models and herringbone riblets

The geometry of the double ramp model used in this experiment is similar to that tested by Yang[20, 21]. It has a spanwise length of 35mm. The model as shown in Fig. 3 consists of three sections with different surface slopes: the first section has a surface length of 50mm and a ramp angle of 12° ; the second section has a surface length of 35mm and a ramp angle of 22° ; the third section is 40mm in length with its top surface aligned parallelly to the incoming flow. For the PSP tests, in order to minimize the temperature variation across the model surface the model is made of aluminum. For the TSP experiments, in order to capture the thermal footprints of any flow features within the boundary layer the model is made of Acrylonitrile butadiene styrene (ABS plastic). To measure the surface pressure, nine 1mm-diameter pressure tappings were made on the model for PSP tests. These holes were connected to pressure sensors through hypodermic and flexible tubing.

All the tests were performed at a total temperature of 85° and total pressure of 7.4bar, yielding a Reynolds number of 8.0×10^5 based on the length of the first ramp. The thickness of the laminar boundary layer can be estimated using the semi-empirical formula given by Van Driest [22]:

$$\frac{\delta}{x} Re_x^{1/2} \approx C_w^{1/2} [5.0 + (0.2 + 0.9 \frac{T_w}{T_{aw}})(\gamma - 1)M^2] \quad [1]$$

where δ stands for the boundary layer thickness at location x , which is the streamwise distance from the leading edge, T_w is the wall temperature, T_{aw} is the adiabatic wall condition, Re_x is the Reynolds number based on x , M is the Mach number, γ is the heat capacity ratio, and C_w is the Chapman-Rubesin parameter at the wall:

$$C_w = \frac{\rho_w \mu_w}{\rho_e \mu_e} \approx \left(\frac{T_w}{T_e} \right)^{-1/3} \quad [2]$$

in which ρ and μ stands for the density and viscosity respectively, the subscript e indicates the condition of the undisturbed flow. The local boundary layer thickness at the end of the strips which are 20mm long is estimated to be $\delta=0.41$ mm.

C. PSP measurements

The PSP method, which is based on the mechanism of oxygen quenching, is utilized to measure the surface pressure distribution on the model. Detailed descriptions about their working principles can be found in [23, 24]. Despite its extensive application at transonic tests, PSP has been less widely used in supersonic or even hypersonic conditions due to its sensitivity to temperature [25]. In the present experiment, several attempts have been made to minimize the temperature effects during the tests: firstly, the total temperature was set to a low value (85°, just above the temperature that keeps the flow from liquefaction) to mitigate the model surface heating; secondly, the model was made of heat-conducting material to reduce the temperature variations across the surface.

Fig. 4 A schematic of the PSP measurements

In order to perform the PSP experiment, an optical system was set up above the wind tunnel test section as shown in Fig. 4. The coating used in the present study is a kind of single-luminophore PSP and it was purchased from ISSI (product ID: Uni-FIB). A matte white primer (20 μ m thick) was firstly sprayed onto the models to increase reflection and the PSP was then applied to the model surface. The coating was illuminated with a UV light source with 390 nm wavelength. A PCO 1600 monochrome camera with a 24-mm focal-length $f/1.4$ lens were utilized to record the emission from the coating. The cutoff wavelength of the long-pass filter fitted on the lens was 610nm. Reference images were first acquired when the model was kept at a constant pressure in the test section and the wind-on images were then taken under the same illumination conditions. The pressure at the ports seen in Fig. 3 at the reference and the wind-on conditions were measured by nine Honeywell SDX05D4 differential pressure sensors (0.35 bar range, 0.2%FSL accuracy) with reference to a pressure of 0.2 bar provided by a PACE 5000 pressure controller (0-2bar range, 0.0033%FSL accuracy).

After taking the ratio of the reference image to the wind-on image, the intensity at the pressure tappings was calculated using inward interpolation. With the *in situ* pressure measurements, the intensity ratio can be related to pressure using a second order polynomial:

$$\frac{P}{P_{ref}} = A + B \left(\frac{I_{ref}}{I} \right) + C \left(\frac{I_{ref}}{I} \right)^2 \quad [3]$$

in which P and I stand for the pressure and image intensity for wind-on condition, the subscripts ref represents the values at reference condition and A , B and C are the calibration coefficients. The calibrations of PSP were conducted individually for different cases considering the reference pressure varies from case to case. An example of the calibration curve for the baseline case is given in Fig. 5, the three coefficients A , B and C in this

case are equal to -3.2248, 2.4178 and 1.7842 respectively. As can be seen, the calibration curve fits the pressure tapping measurements well with an overall deviation of only 0.19%.

Fig. 5 PSP calibration curve for the baseline case

According to Liu[23] the uncertainty in the PSP measurement caused by the camera shot noise can be estimated by the following formula:

$$\frac{\Delta P_{\min}}{P} = \frac{1}{\sqrt{n_{pe_ref}}} \times \left(1 + \frac{A \times P_{ref}}{B \times P}\right) \times \left(1 + A + B \frac{P}{P_{ref}}\right)^{1/2} \quad [4]$$

where $\sqrt{n_{pe_ref}}$ is the full-well capacity of the camera CCD which was set as 40,000 counts during tests. With the calibration constants A and B obtained from the *in situ* calibration, the uncertainty of the PSP is estimated to have a range of 10 to 180Pa depending on the local pressure. Specifically, in the separation region where the pressure is around 7000Pa, the PSP measurement uncertainty is about 100Pa (1.4%). The temperature variation across the model surface during the run was found to be less than 2°C using an IR camera and according to its official specification this PSP has a temperature sensitivity of 0.4% per °C. Taking these two factors into consideration, the accuracy of our PSP measurement is estimated to be 3%.

D. Heat transfer measurements

The TSP (ISSI product ID: UNT-12) was applied for temperature measurements in the same manner as PSP except that a plastic model was used for TSP application to increase the surface thermal deposit and a 520nm long pass filter was fitted to the lens due to its different emission spectra. Unlike the *in situ* calibration conducted for PSP, TSP calibrations were performed *a priori* before each run under the same optical conditions as in the experiments, by heating the model in the wind tunnel and allowing it to cool naturally whilst the emission intensity of the coating and surface temperature were simultaneously recorded. By relating the image intensity to the corresponding temperature measured by a K-type thermocouple, a calibration curve can be obtained as shown in Fig. 6:

Fig. 6 TSP calibration curve for all cases

Once the temperature history is obtained from TSP images with the aid of the calibration curve, the rate of heat flux at the surface can be evaluated by assuming one-dimensional semi-infinite heat conduction[26]:

$$q(t) = \frac{2\sqrt{\rho ck}}{\sqrt{\pi}} \left[\sum_{i=1}^n \frac{T(t_i) - T(t_{i-1})}{\sqrt{t_n - t_i} + \sqrt{t_n - t_{i-1}}} \right] \quad [5]$$

where ρ is the density, c is the heat capacity and k is the thermal conductivity of the ABS plastic. The Stanton number C_H can then be found:

$$C_H = \frac{q}{c_p \rho_e u_e (T_{aw} - T_w)} \quad [6]$$

The adiabatic wall temperature is

$$T_{aw} = \gamma^* (T_0 - T_e) + T_e \quad [7]$$

where C_p is the heat capacity at constant pressure, ρ_e , u_e and T_e are the density, velocity and temperature at the boundary layer edge which can be assumed to be equal to their corresponding free stream values, γ^* is the recovery factor which is assumed to be constant and is given by

$$\gamma^* = \sqrt{\text{Pr}} \quad [8]$$

The Prandtl number Pr is 0.715 for air.

It should be noted that the accuracy of Stanton number obtained with this method is affected by a number of uncertainties. Firstly, the *a priori* calibration curve in Fig. 6 was applied to all cases for temperature calculation and it did not account for the change of the illumination due to model movements between tests. Secondly, although a relatively high-sampling rate of temperature reading will be desirable to ensure the accuracy of the Stanton number deduced from the surface temperature history, due to the limitation of the camera, the maximum frame rate used for recording the TSP images can only be set as 10Hz in this experiment. Thirdly, a recovery factor for laminar boundary layers is assumed in estimating T_{aw} and this assumption will be less appropriate when the boundary layer is transitional or even turbulent. Nevertheless, despite the relatively high level of uncertainties in the absolute values of the Stanton number obtained from this experiment, TSP can still be used as a valid qualitative tool in identifying regions of low and high heat transfer rate caused by distinct flow features in the boundary layer.

III. Results and discussion

A. The baseline case

A Z-type Toepler schlieren system was firstly used to visualize the shockwave system. The schlieren images were acquired with a Phantom V1611 high-speed camera at a frame rate of 5000Hz with an exposure time of 1 μ s. A Newport 1000W arc lamp was used as the light source and the knife edge was positioned vertically with a 50% cut-off. The instantaneous schlieren image of the baseline case and a schematic of the shock waves are shown in Fig. 7. After the first shock C_1 generated by the first ramp, the flow Mach number is reduced to M_1 . The flow structures become very complicated as the flow approaches the corner junction of the two ramps due to the viscous effect in the boundary layer. Due to the sudden change of the geometry at the corner, the boundary layer separates from the wall, resulting in a separation shock C_2 . When the boundary layer reattaches to the second ramp-up section, a reattachment shock C_3 is generated. The outline of shock C_2 is much less well defined compared to that of C_1 and C_3 because on one hand the protuberance to the flow from the separation bubble is very weak and on the other hand the intensity of the separation shock is not uniform across the span due to the 3D effects.

Apart from the shockwave patterns, the structures in the boundary layer can also be visualized in the schlieren images. It appears that the boundary layer remains to be laminar until after the reattachment point on the second ramp surface where coherent structures can be observed inside the boundary layer. Since the minimum exposure time of the Phantom V1611 camera (1 μ s) is not short enough to freeze the flow structures within the boundary layer, the location of transition can only be estimated roughly and in the baseline case it is around at $x=62\text{mm}$.

To estimate the intensity of the separation shock C_2 , we can assume that the separation bubble has a wedge shape with the three vertices v_1 , v_2 and v_3 of the 'wedge' being defined by the surface contour corner and the intersection point of C_2 , C_3 with the edge of the boundary layer respectively. As such, the flow deflection angle over the 'wedge' with regards to the freestream flow φ_2 and the shock angle θ_2 can be estimated with the help of schlieren image. With the combination of the flow direction of the two ramps φ_1 and φ_3 , the shock angles of C_1 and C_3 can be obtained according to Rankine-Hugoniot equations. Following this, the Mach number and pressure after shock C_1 , C_2 and C_3 can all be resolved as: $M_1=3.81$, $M_2=3.76$ and $M_3=3.14$, and the theoretical pressure ratio to the free stream pressure after the three shocks are $p_1=3.8$, $p_2=3.98$ and $p_3=8.97$, respectively.

Fig. 7 Shock wave system of the baseline case

Fig. 8 and 9 show the prespective view of the contour of pressure and Stanton number on the model surface for the baseline case. To remove image distortion caused by the inclined viewing angle of the camera, perspective transformation was first performed on the three ramp surfaces individually to map the corresponding image segment to its physical dimension before they are combined to form the 2D or 3D contours for final presentation. On the first ramp section, the region of a relatively high pressure with a curved upstream border before the corner is believed to be related to the separation zone as will be discussed later (Fig. 8). Due to the flow spillage from the top surface to the two sides of the model, the local Mach number approaching the corner is higher in the centre. As a result, the forefront of the this area extends further upstream in the centre than on the sides. The Stanton number remains alomost constant at a relatively low value until very close to the corner between the first and the second ramp (Fig. 9).

Fig. 8 3D pressure mapping of the baseline case

Fig. 9 3D Stanton number mapping of the baseline case

On the second ramp surface, the pressure appears to be much higher due to the compression of the shock C_3 . Nevertheless the higher pressure area does not emanate right at the corner hinge. There is still a small band after the corner where the pressure remains at the same level as in the separation region indicating that the

reattachment does not occur till a small distance after the corner. This is consistent with the occurrence of peaks of the Stanton number slightly downstream of the corner. The streaky structures observed in the heat flux mapping on the second ramp-up section are produced by Goertler-like vortices caused by the centrifugal instability which has been reported and studied in detail by other researchers[27, 28]. After the expansion waves originating from the shoulder of the model, both of the pressure and Stanton number plummet back down to a level even lower than that on the first ramp.

The streamwise distributions of surface pressure and Stanton number can be used to investigate the flow development along the ramp surface. In order to obtain a smoother profile and remove the end effect, such distributions are obtained by averaging the pressure and Stanton number distribution respectively across a spanwise width of 11mm over which the middle ribleted strip is located. Note that in Fig. 10, the abscissa in the plot is defined using the distance from the leading edge along the model surface, instead of the streamwise distance in the flow direction.

Fig. 10 Streamwise distributions of surface pressure and Stanton number in the baseline case. The vertical dash lines indicate the location of the end of the first and second ramp, respectively.

In order to compare the control effects among different cases, the streamwise length of the separation zone needs to be obtained. It will be desirable to extract such information from velocity measurements or surface oil flow visualization. However, due to the experimental constraints it is not possible to extract reliable results on the separation and reattachment location using either velocity or oil flow data in our experiment. Firstly, under the flow condition considered here, the boundary layer is extremely thin (less than 1mm) and as such the zone of laser light reflection from the model surface is comparable to the thickness of the boundary layer making a reliable PIV measurement essentially impossible. Secondly, to examine the flow separation zone using the oil flow visualization technique, the oil has to be applied before the corner hinge and after the end of the riblets. However, due to the slope of the first ramp the oil film tends to flow down and into the riblets, making the results invalid. Thirdly, according to the free-interaction theory proposed by Chapman[29], for a 2D shockwave-induced flow separation associated with a pressure plateau the separation point can be determined as the point where a fraction of the pressure value on the plateau is reached. However due to the finite spanwise width of our model, the flow is essentially 3D and the pressure plateau is absent. Hence, this rules out the possibility of determining the separation point using the free-interaction theory too.

Therefore, in our experiment we developed a method to extract the approximate size of the separation zone from the pressure and the Stanton number distribution to aid the comparison among different cases. In order to differentiate the flow zone identified using this method from the actual separation zone, we call it the ‘interaction zone’ instead: a zone where a strong interaction between the shockwave and the boundary layer takes place. Here, the start of the ‘interaction zone’ (P_1 in Fig. 10) coincides with the footprint of the separation shock located upstream of the separation point, while the end point of the ‘interaction zone’ (P_2 in Fig. 10) coincides with the footprint of the reattachment shock located downstream of the reattachment point. Due to the way in which the ‘interaction zone’ is defined, it is longer than the separation length. Nevertheless, its length is closely correlated to the actual length of the separation zone because the locations of the separation shock and the reattachment shock are dictated by the size of the separation bubble.

From Fig. 10, one can see that P_1 is located roughly 10mm before the corner hinge and P_2 is located 6mm after the corner hinge, giving rise to an ‘interaction zone’ with a streamwise length of 16mm for the baseline case. The ‘interaction length’ defined by this approach will be subsequently used for cases with riblets to evaluate their effectiveness on flow separation control.

B. The effect of herringbone riblets

The schlieren images of the shockwave system for Cases 1 to 4 are shown in Fig. 11. Shocks C_1 , C_3 and the expansion waves at the shoulder of the model can be observed clearly with identical inclination angles in all

four cases. The wave at the trailing edge of the control device in Case 2-4 is caused by the finite thickness of the strip ($110\mu\text{m}$). It is composed of a fan of expansion waves and a very weak shock as can be judged from the two-color pattern of it: a relatively brighter line followed by a relatively darker line. The appearance of the separation shockwave near the beginning of the second ramp, on the other hand, varies from case to case. Compared to the baseline case without control (Case 1), the strength and location of the separation shock remains almost unchanged by the smooth strips without riblets (Case 2). However, the shock is significantly weakened with the strips with riblets of $39\mu\text{m}$ in depth (Case 3) and it disappears when the depth of riblets is increased to $78\mu\text{m}$ (Case 4).

Fig. 11 Schlieren images for Case 1 to 4

Fig. 12 shows the surface pressure contours for Case 1-4 and the ‘interaction zone’ associated with separation strength can be compared intuitively among cases as indicated by the light blue area around the corner. It is also in this zone that the pressure recovers from a low value on the first ramp to a higher level on the second ramp. Even though it is not the same as the separation zone, its size gives a good indication about the separation strength. It can be seen that, in comparison to the baseline case (Case 1), the streamwise extent of the ‘interaction zone’ is reduced with the use of riblets $39\mu\text{m}$ in depth (Case 3). If the depth of riblets is increased to $78\mu\text{m}$, the streamwise length of it is reduced further (Case 4). Nevertheless, the smooth strips without riblets (Case 2) appear to result in a reduced ‘interaction length’ too, indicating that strips with an arrow headed leading edge and a finite thickness can be beneficial to separation attenuation. However, the fact that the amount of reduction is less than in the cases with ribleted strips implies the added benefit of riblets. Overall, the changes in the streamwise length of the ‘interaction zone’ revealed using PSP is consistent with the weakening and disappearance of the separation shock observed in the corresponding schlieren images in Fig. 11.

In Case 2 to 4, the shape of the ‘interaction zone’ appears like a pair of “swimming goggles”. The spanwise locations, where the streamwise extent of the ‘interaction zone’ narrows down, appear to coincide with the locations of vertices of the three strips on each model. This indicates that the deduction of ‘interaction zone’ extent is likely to be related to the flow features generated locally by the strips. With a closer examination of the

surface pressure contours in the region directly downstream of the strips, one can see three faint streamwise streaks in light blue emitting behind the central line of the ribleted strips especially in case 4. However these streaks decay very fast and can only be identified immediately downstream of the riblets.

The footprints of flow features which produce the aforementioned faint streamwise streaks can be revealed more clearly in the surface contours of the Stanton number shown in Fig. 13 due to the use of a less heat conductive material for making the model. One thing worth noticing is that the convergence of the Stanton number doesn't reach the same level as the pressure in Fig. 12, that is because the TSP coating applied to the model surface is not as smooth as the PSP coating and this leads to a higher level of noise in the temperature distribution which is subsequently integrated in time to calculate the heat flux.

In Case 1, the distribution of Stanton number on the first ramp section appears to be quite uniform except for the presence of a faint streak on the right hand side of the model which is caused by a small dent at its leading edge. In Case 3 and 4 streamwise streaks trailing behind the central lines of each ribleted strip can be observed. It is known from the existing studies in incompressible flows that each herringbone riblet strip generates counter-rotating streamwise vortex pairs which create a common flow down on its plane of symmetry[16]. The presence of these streaks associated with high heat flux directly downstream of the central plane of each herringbone riblet strip seems to provide compelling evidence to support the existence of counter-rotating streamwise vortex pairs in the present experiment. Although these streaks expand in width as they propagate downstream, they persist within the boundary layer until the corner hinge. It is very likely that these vortices bring higher momentum flow from the main stream into the boundary layer and hence reenergize the boundary layer leading to a reduced separation region compared to the baseline case. Based on our results, the riblets with a depth of $78\mu\text{m}$ depth create stronger vortices than the riblets with a depth of $39\mu\text{m}$ depth resulting in a smaller separation region.

Fig. 12 Surface pressure contours for Case 1 to 4

Fig. 13 Contours of Stanton number for Case 1 to 4

To further verify the existence of counter-rotating vortical structure, the spanwise pressure and heat flux distributions at two streamwise locations; one at $L=22\text{mm}$ which is located immediately downstream of the end of the strips, another one at $L=32\text{mm}$, are extracted and shown in Fig. 14. Due to the flow spillage effects on the sides of the model, the pressure on the model surface decreases from mid-plane to the two sides. With no strips fitted on the model (Case 1), the pressure profile remains relatively smooth across the whole span at both streamwise locations. Due to the expansion waves produced by the trailing edge of the strips, the surface pressure is lower in Case 2 to 4. Although the level of pressure fluctuations is similar at $L=22\text{mm}$ in both Case 2 and 3, the presence of local pressure spikes in Case 4 at the centreline of each strip is obvious. Nevertheless, these pressure peaks disappear at $L=32\text{mm}$, indicating a decay of these structures.

The presence of local events is captured more clearly by the heat flux profile across the span. Immediately downstream of the strips at $L=22\text{mm}$, the Stanton number stays at around 0.0015 in Case 1 and Case 2 whereas its peak values escalate to 0.0045 and 0.007 in Case 3 and Case 4, respectively. While the magnitude of Stanton number in Case 4 reduces quickly down to around 0.004 at $L=32\text{mm}$, it remains at a similar level in Case 3. Furthermore, it is noticed that the peaks in the Stanton number downstream of each ribleted strip occur in pairs confirming the streamwise structures which produce these peaks are formed in pairs. Further downstream at $L=32\text{mm}$, not only the peaks become broader but also the gap between the twin peaks increases indicating a gradual dissipation of the initial structures. Apart from that, the valley of the ‘peak pairs’ also moves outwards from the strip center plane. Hence the spanwise movement of the vortex pairs is composed of two components: the diverging due to the ‘guidance effects’ of the riblets channels and the lateral moving due to the 3D spillage effects. The diverging affects the three vortex pairs equally while the lateral moving affects the further outboard vortex more. As a result the two further outboard vortexes are displaced most from the centerline and a significant variation in the spanwise extent of the streaks from the central can be observed in Fig. 13.

Fig. 14 Spanwise pressure and Stanton number distribution at different streamwise locations. The three vertical dashed lines in each plot indicate the locations of the centreline of the ribleted strips

In Case 2 which has strips with zero riblet depth, streamwise streaks with high heat flux do appear but in a less regular manner. Having an arrow headed leading edge and a finite thickness, these strips will potentially

induce streamwise vortices too. However, these vortices are expected to be less well organized and weaker than the streamwise vortices produced by the ribleted strips. A schematic diagram illustrating the counter-rotating vortex pair is given in Fig. 15.

In Fig. 16, the streamwise pressure and Stanton number distributions averaged across a spanwise width of 11mm, over which the middle ribleted strip is located, are presented to aid a comparison among different cases in a more quantitative manner. On the first ramp, the surface pressure in all the cases with the strips is slightly lower than in the baseline case because the expansion waves at the end of the strips cause the surface pressure to reduce by a small amount (Fig. 16(a)). It can be seen that the location of the starting point of the ‘interaction zone’, at which the surface pressure begins to rise considerably, moves progressively upstream as the depth of riblets increases from 0 to 39 μ m then to 78 μ m, indicating in a more rapid pressure recovery. This point is found to be at $L = 43, 45$ and 47 mm in Case 2 to 4 respectively, much further downstream than that in the baseline case ($L=40$ mm). As seen in Fig. 16(b), the magnitude of Stanton number in the cases with strips appears to be higher than in the baseline case. This is because the vortices produced by the strips and riblets intensify the local heat transfer. It can be deduced from Fig. 16(b) that the ending point of the ‘interaction zone’ is approximately located at $L = 56, 54, 52$ and 51 mm respectively in these four cases. Combining the location of start of ‘interaction zone’ from the pressure distribution and the location of the end of ‘interaction zone’ determined from the Stanton Number distribution respectively, the average ‘interaction length’ is estimated to be 16, 9, 7 and 4mm for Case 1 to Case 4.

Fig. 15 Vortices generated by the ribleted strips

Fig. 16 Streamwise distributions of surface pressure and Stanton number averaged across the spanwise width equivalent to one wavelength for Case 1 to 4. The vertical dash lines indicate the location of the end of the first and second ramp, respectively.

In Fig. 13, the periodical striations observed on the second ramp in Case 1 and Case 2 are suspected to be produced by Goertler vortices. These periodical striations become weaker in Case 3 and almost disappear completely in Case 4. A plausible explanation is given here. As the separated shear layer over a separation bubble passes through shock C_2 and C_3 located before and after the corner hinge, it becomes curved leading to Goertler instability and formation of Goertler vortices[30]. When the ribbled strips are applied, the separation line and the reattachment line become very close to each other. As such, the separated shear layer diminishes resulting in the Goertler vortices becoming much weaker in Case 3 and disappearing completely in Case 4. The disappearance of the Goertler vortices mitigates the local surface heating downstream of shock C_3 , therefore the average heat flux on the second ramp with riblets is much lower than in the baseline case (see Fig. 16(b)).

C. The flow control mechanism

From the results presented in the previous section, it can be seen that the ribbled strips are capable of suppressing the shock-induced flow separation over the corner before the second ramp, and the separation attenuation observed is linked to the vortices generated by these strips. In this section, the associated mechanism will be examined further.

In the present experiment, the height of ribbled strips is $110\mu\text{m}$ and the riblet depth is comparable to the local laminar boundary layer thickness. Therefore the strips of finite thickness and/or the riblets could trigger boundary layer laminar to turbulent flow transition. It is understandable that since a turbulent boundary layer has a fuller velocity profile it is more resilient to the adverse pressure gradient caused by a shockwave. The question is if the attenuation of flow separation observed in the present experiment is primarily caused by tripping of the boundary layer by the riblets or by the streamwise vortex pairs induced by herringbone riblets.

To answer the above question, the instantaneous schlieren images shown in Fig. 11 are examined again since they can provide some qualitative indication of the state of the boundary layer. If inclined striations of turbulent structures are observed within the boundary layer, the boundary layer should be turbulent. Otherwise, the boundary layer is most likely laminar. Based on this criteria, one can see that the boundary layer remains laminar even after the reattachment point till $x=60\text{mm}$ in Case 1 (Fig. 11(a)). On the other hand, when the strips are applied to the model, the transition point moves progressively upstream as the depth of riblets increases from zero to $78\mu\text{m}$. Nevertheless, the boundary layer appears to remain laminar before the first corner in Case 1, 2 and 3. Therefore at least for Case 3, boundary layer tripping may be excluded as the main mechanism.

To further access the likelihood of riblets as the boundary layer tripping devices, we decided to undertake another set of experiments with riblets aligned in different orientations. All the parameters of the riblets except the inclined angle are kept the same. Two more cases are hence added: in Case 5 the riblets are orientated in the streamwise direction and in Case 6 the riblets are orientated in the spanwise direction.

Fig. 17 Contours of surface pressure in Case 5, 6 and 4

In Fig. 18, the contours of surface pressure in Case 5 and Case 6 are compared to those in Case 4. As shown in Fig. 17(a), in Case 5 the size of the ‘interaction zone’ appears to be unaffected since it has almost the same shape and size as that in the baseline case (Fig. 12 (a)). In Case 6 (Fig. 17(b)), although the length of the ‘interaction zone’ is reduced, its control effect is similar to that in Case 2 (Fig. 12 (b)) and smaller than that in Case 4. Furthermore, the contours of Stanton number (Fig. 18(a)) reveal that in Case 5 only weak streamwise streaks are observed on the first ramp. Though the wave number of the Goertler vortices on the second ramp remains unaffected, they appear to be intensified in term of magnitude compared to case 1. However the reason behind this requires further investigation and is beyond the scope of the current study. In Case 6, only some

weak turbulent wedge-like features are observed on the first ramp (Fig.18(b)). Therefore, despite having the same riblet height, neither Case 5 nor Case 6 delivers a control effect which matches that of Case 4.

Based on the instantaneous schlieren images and the results from this additional experiment, we conclude that it is the streamwise vortex pairs induced by the herringbone riblets that provide the main mechanism for the reduction of shock-induced flow separation that we observed in Case 3 and Case 4.

Fig.18 Contours of Stanton number in Case 5, 6 and 4

IV. Conclusions

In this paper, the effect of herringbone riblets as a means of suppressing shockwave-induced flow separation is investigated. A spanwise array of ribleted strips is applied behind the leading edge of a double ramp model placed in a Mach 5 freestream. High-speed schlieren technique is used to examine the shockwave pattern and the state of the boundary layer developing along the surface of the model. Both pressure-sensitive paints and temperature-sensitive paints are employed to assess the impact of riblets on the interaction between the shockwave and the boundary layer. The results from this experiment show that herringbone riblets are capable of suppressing shock-induced flow separation and hence improving pressure recovery. Furthermore, it is also revealed that these micro-scale riblets induce large-scale streamwise vortical structures within the boundary layer similar to those observed in incompressible flows. It is believed that these vortices promote momentum transfer within the boundary layer hence providing the dominant mechanism for suppressing flow separation.

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