FLOW VISUALIZATION OF HAIRPIN VORTICES IN A MACH 3.0 FLAT-PLATE BOUNDARY LAYER

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Abstract An experimental study has been performed to visualize the coherent structures in a Mach 3 flat-plate boundary layer using the Nano-tracer planar laser scattering technique. The hairpin vortices are identified from the instantaneous structure in the streamwise-wall-normal plane, based on the induced motion of a hairpin model.

INTRODUCTION

The individual hairpin vortex is now widely accepted as a simple coherent structure in wall turbulence, which has been frequently observed in experimental and numerical studies. The hairpin model was first proposed by Theodorsen,[1] and refined later in various studies.[2]-[6] To investigate the hairpin vortices, flow visualization techniques such as hydrogen bubbles in water flows or smoke in air flows have been usually used (see, e.g., Kline and Reynolds,[9] Lu and Smith,[10] Faclo,[11] and Head and Bandyopadhyay[7]). In recent years, particle image velocimetry (PIV) provides a useful tool to identify hairpin structures in wall turbulence (see the work of Adrian et al.[8] for a demonstration). Elsinga et al.[12] applied the tomographic PIV technique to measure the instantaneous three-dimensional velocity distribution in a Mach 2 turbulent boundary layer, which also gave evidence of hairpin vortices aligned in the streamwise direction forming very long zones of low-speed fluid.

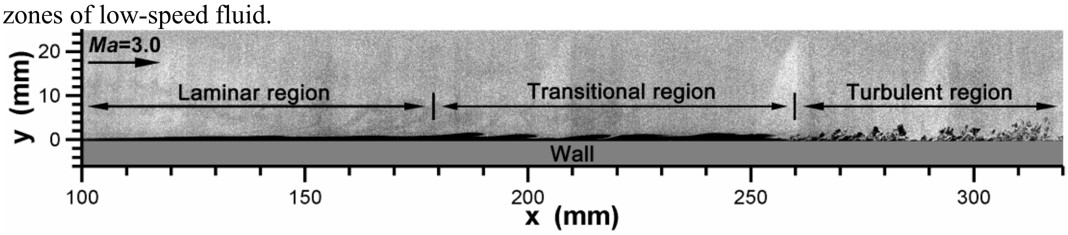

Figure 1. Instantaneous structures of a Mach 3 transitional boundary layer in the *xy*-plane, the flow is from left to right.

An NPLS image of the Mach 3 flat-plate boundary layer is shown in Figure 1. The field of view extends from 100mm to 320mm from the leading edge, and the flow is from left to right. The spatial development of the boundary layer from laminar to turbulent flow can be clear identified, and the large-scale structures occur in the transitional region and then breakdown into smaller-scale structures in the turbulent region.

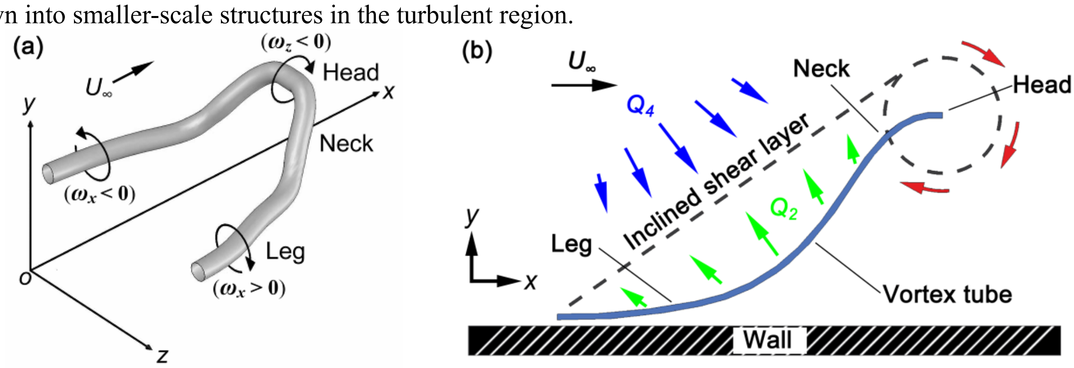

Figure 2. (a) Schematic of an idealized hairpin vortex. (b) Projection of the induced motion of the hairpin vortex in the *xy*-plane.

In order to investigate hairpin vortices in the supersonic boundary layer, we should identify these structures from the NPLS images first. An idealized hairpin vortex is shown in Figure 2(a) schematically, and the projection of the induced motion in the symmetry plane of the hairpin vortex is shown in Figure 2(b). In the symmetry plane, a clockwise rotating spanwise vortex can be observed induced by the hairpin head. Besides, the near-wall fluid is induced by the two legs to move up from the wall, causing the second-quadrant injection (Q_2 events). When this Q_2 flow encounters a fourth quadrant (Q_4) sweep of freestream fluid moving toward the back of the hairpin, the stagnation-point flow occurs forming an inclined shear layer. In the supersonic boundary layer, the inclined shear layer is the interface between the low density (near-wall) fluid and the high density (freestream) fluid. Considering the relationship between the gray value and the gas density mentioned above, the inclined shear layer would be an inclined interface between light and dark regions in the NPLS image. Therefore, an individual hairpin vortex in the NPLS image can be identified from the following features: (i) a clockwise rotating spanwise vortex as the head; (ii) an inclined light/dark interface just upstream and below the spanwise vortex.

EXPERIMENTAL RESULTS

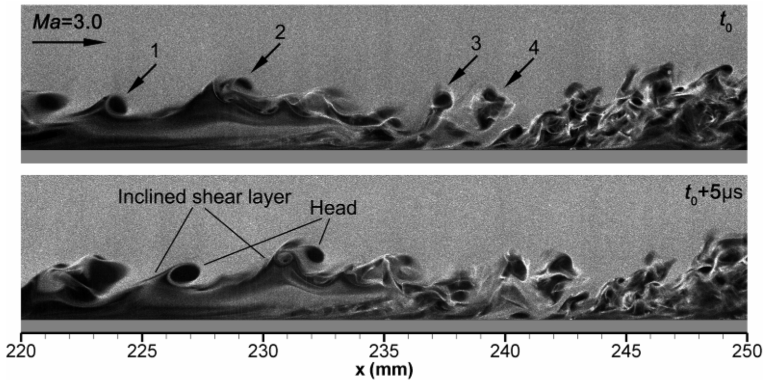

Figure 3. An example of hairpin vortices identified from the NPLS images. The flow is from left to right and the time interval between the two successive NPLS images is 5μs.

Two successive NPLS images in Figure 3 provide convincing evidence for the presence of individual hairpin vortices in the supersonic boundary layer. The field of view is *x*=220-250mm, and the time delay between the two images is 5μs. Compared with the two images, two circular structures labeled 1 and 2 are observed rotating clockwise during the 5μs interval, indicating the spanwise vortices. In addition, an inclined light/dark interface can also be observed below and upstream of each spanwise vortex. The observations coincide with the features mentioned above, and two individual hairpin vortices are identified here. However, more hairpin vortices are believed to exist in Figure 3, such as the structures labeled 3 and 4. It should be noted that the hairpin vortex is a three-dimensional structure, therefore only the hairpin vortices whose symmetry plane just coincides with the laser sheet can be identified using the criteria described above. It is also found that the rotation velocity of each hairpin head is relatively slow compared with their convection velocity, thus increasing the difficulty in the measurement of hairpin vortex signatures in supersonic flows using PIV methods. Nevertheless, the hairpin vortices observed in the Mach 3 boundary layer are similar to that found in incompressible flows.

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