On the modality of velocity histograms in the plane of symmetry of a wing-body juncture

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Abstract The presence of a region of multi-modal velocity histograms in the plane of symmetry of a wing-body juncture have been reported. This region not only contains bi-modal histograms but also tri-modal distributions. LDV measurements supplemented by detailed analysis of the flow-visualization results has been used to propose that the reason for this behavior is the dynamic character of the juncture-vortex system and not turbulent intermittency as reported earlier.

1 Introduction

Skew-induced secondary flow and an adverse pressure gradient due to the presence of a wing causes the on-coming boundary layer to separate and roll-up into a complicated vortical system in the juncture of a wing-body. A simplified model of this flow, commonly referred to as the juncture-vortex (or horseshoe-vortex) system, is shown in Fig. 1. Various researchers have observed different types of Reynolds number dependent patterns of this system (Baker 1979, 1980). These observations pertain to the number of vortices present and whether the system is steady or unsteady and the nature of unsteadiness (Thomas 1987). A detailed discussion of these observations is given by Khan (1994).

Bi-modality of the velocity histograms in certain regions of the wing-body juncture flow was first reported by Devenport and Simpson (1987) based on laser Doppler velocimetry (LDV) measurements. They attributed this bi-modality to the unsteady character of the juncture-vortex system and noted that such bi-modality was possible only if the fixed measurement location was experiencing two velocity states of the fluid in a given period of time. Based on the bi-modal nature of the velocity histograms they proposed a model with 'zero-flow' and 'no-flow' modes. The model simply stated assumes that for 70–80% of the time the backflow near the wall continues upstream as a 'jet' and for the remaining time it reseparates forming a 'weak secondary re-circulation'. Devenport and Simpson have explained this phenomenon by suggesting that the backflow might consist of rotational fluid from region of the boundary layer with low momentum and irrotational fluid from the freestream with high momentum. They explain their conjecture by noting that due to low momentum the rotational fluid moves out from the nose-region under the action of the cross-stream pressure gradients which stretch the spanwise vorticity and also results in the formation of a smaller recirculation zone. This has been depicted by them as calculated velocity vectors for the zero-flow mode. However, the irrotational fluid in their opinion has to form a 'jet to preserve its irrotationality'.

2 Description of facilities and test conditions

Measurements were made in the TAMU 0.9 m × 1.2 m wind tunnel. The wing-body juncture was simulated by a modified NACA 0020 wing with a 3:2 elliptic leading-edge mounted on the tunnel floor. The modified airfoil had maximum thickness t_{max} of 122 mm and a chord of 518 mm. The effective aspect ratio of the test model was 10. A typical setup and coordinate system is shown in Fig. 1. The boundary layer on the floor was artificially tripped to ensure that the approach boundary layer was turbulent. In the empty test section the boundary layer thickness δ was measured to be 43 mm at the location where the wing leading edge was later positioned. At the same location the momentum thickness Reynolds number was 4950 and the Reynolds number based on maximum thickness of the wing was 95,000. The six beams Aerometrics Inc LDV system used in this study had a FFT processor and a 40 MHz Bragg-cell frequency shifting to discriminate reverse flow. Measurements were made in the back-scatter mode with an on-axis measurements of the third component. Simultaneous measurements of the three velocity components (data-coincidence) was made possible by acceptance of data only when a validated Doppler burst met a specified overlap on all three channels. Extensive flow-visualization tests of wing-body juncture flow in the TAMU 0.6 m × 0.9 m water tunnel utilized a variety of techniques like hydrogen-bubbles, laser induced fluorescence and a combination of vertical and horizontal laser light-sheets. A NEC TI23A CCD camera was used to record the flow visualization results on a Toshiba VCR. The data was later digitally post processed with the help of Motion Analysis Inc. Expert Vision system.

3 Results and discussion

The flow visualization tests in the water tunnel provided a detailed overall physical insight into the phenomenon and confirmed the existence of a multi-vortex system in the juncture region. This system remained steady for Reynolds numbers
based on maximum thickness of the wing of up to 2000. Beyond this range of Reynolds number the vortex system began to oscillate to-and-fro. For Reynolds number greater than 3500, the system transitioned to a third state in which a vortex continued to move towards the wing, became highly stretched, and after splitting near the leading edge into two legs convected downstream; the process then repeated itself. This behavior of the juncture vortex was similar to that reported by Thomas (1987). More details of flow visualization tests and calculation of vortex trajectory and Strouhal number can be found in Khan et al. (1993).

A multi-vortex system was also inferred from detailed three-component LDV measurements. Figure 2 shows the measured non-dimensionalized normal (V) and streamwise (U) mean

Fig. 1. Description of juncture flow system

Fig. 2. Mean velocities of juncture vortex system

Fig. 3. Velocity histograms in the plane of symmetry (streamwise measurements)