Volumetric three-component velocimetry and PIV measurements of laminar separation bubbles on a NACA4412 airfoil

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Measurements of laminar separation bubbles on a NACA4412 airfoil were performed in a water tunnel facility using volumetric three-component velocimetry (V3V) at a Reynolds number of 50,000 and at angles of attack of 4 and 6 degrees. The time-averaged V3V results are analyzed to estimate the locations of separation, onset of transition and reattachment by interpreting the relationships of the different Reynolds normal and shear stresses to these locations. The vortex cores and spanwise vorticity are discussed as well. Additionally, the reattachment region is investigated using time-resolved particle image velocimetry (TR-PIV).

The PIV results are used to validate some flow features obtained by the V3V results, and to uncover details of the instantaneous reattachment of the separated shear layer. The time-averaged results of the V3V show that the backflow in the aft portion of the bubble reaches velocities up to 14% of the freestream velocity. The streamwise Reynolds stress does not provide a reasonable indication of the locations of onset of transition or reattachment. However, the spanwise normal Reynolds stress predicts the location of onset of transition with good agreement with the predicted location based on the e^n method.

The spanwise and wall-normal Reynolds normal stresses suggest the reattachment location. Moreover, the spanwise normal Reynolds stress indicates that three-dimensional disturbances exist in the reattachment region as illustrated by periodic appearance of positive and negative pairs. The growth and periodic behavior of the spanwise Reynolds stresses in the reattachment region and the growth of the wall-normal Reynolds stresses suggest the evolution of three-dimensional disturbances manifesting themselves in three-dimensional vortices.

The time-resolved V3V results show that vortices result from the roll-up of the spanwise vorticity. These vortices induce pairs of positive and negative wall-normal velocity. These pairs bound the vortex cores; however, they have larger diameters than the vortices. The periodic nature of the spanwise vorticity and the presence of spanwise vortices suggest the existence of Kelvin-Helmholtz instabilities in the separated shear layer. The spanwise vorticity and vortices persist up to the trailing edge. The PIV results are in general agreement with the V3V results.

The instantaneous reattachment location obtained from the PIV results is affected by the roll up of the spanwise vorticity and the wall-normal velocity pairs. The PIV results also show that the strong negative wall-normal velocity causes reattachment of the separated shear layer whereas the positive wall-normal velocity "encourages" the reversed flow.

The distance between regions of consecutive strong positive or negative wall-normal velocity is organized and is on average 0.07C. The same distance is found between the vortex cores calculated from the V3V results. Additionally, the wall-normal velocity pairs correspond to regions of high and low streamwise velocity further downstream of reattachment. This observation suggests that the roll-up of vorticity induces strong fluctuations in the streamwise velocity all the way to the trailing edge. These results explain the presence of regions of low streamwise velocity in regions where vortex cores exist as discussed in the literature. Also, the V3V and PIV results show that these footprints of the vortices occur closer to the surface of the airfoil than the vortices themselves.