TRANSITIONAL BUBBLE IN PERIODIC FLOW PHASE SHIFT

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One particular characteristic observed in unsteady shear layers is the phase shift relative to the main flow. In attached boundary layers this will have an effect both on the instantaneous skin friction and heat transfer. In separation bubbles the contribution to the drag is dominated by the pressure distribution. However, the most significant effect appears to be the phase shift on the transition process. Unsteady transition behaviour may determine the bursting of the bubble resulting in an unrecoverable full separation.

An early analysis of the phase shift was performed by Stokes for the incompressible boundary layer of an oscillating wall and an oscillating main flow. An amplitude overshoot within the shear layer as well as a phase shift were observed that can be attributed to the realtively slow diffusion of viscous stresses compared to the fast change of pressure.

Experiments in a low speed facility with the boundary layer of a flat plate were evaluated in respect to phase shift. A pressure distribution similar to that on the suction surface of a turbomachinery aerofoil was superimposed generating a typical transitional separation bubble. A periodically unsteady mainflow in the suction type wind tunnel was introduced via a rotating flap downstream of the test section. The experiments covered a range of the three similarity parameters of momentum-loss-thickness Reynolds-number of 92 to 226 and Strouhal-number (reduced frequency) of 0.0001 to 0.0004 at the separation point, and an amplitude range up to 19 %. The free stream turbulence level was less than 1%

Upstream of the separation point the phase shift in the laminar boundary layer does not appear to be affected significantly bei either of the three parameters. The trend perpendicular to the wall is similar to the Stokes analysis. The problem scales well with the wave velocity introduced by Stokes, however, the lag of the main flow near the wall is less than indicated analytically. The separation point comes closest to the Stokes analysis but the phase is still 20 degrees lower at the wall.

The behaviour in the bubble is somewhat different. For comparison purposes with the Stokes data the origin of the y-coordinate was shifted to the point of zero velocity at the reversing flow. Far from the wall and close to the wall the phase appears to follow the general trend of the Stokes-model. In between, however, a phase lag in the shear layer is observed which is increasing with the growth of the bubble and the displacement thickness downstream. Within the separation, in the deadwater zone, the phase lags by about 180 degrees.

The most pronounced phase shift is observed at the transtion and reattachment regions. The phase lag upstream, half way through the laminar shear layer (x/L = 0.43), being only about 45 degrees, a dramatic change to about 280 degrees can be seen in the transitional region. After reattachment, in the full developed turbulent boundary layer downstream, the phase shift is very low. This phenomenon is caused by the initiation of transition which is not only affected by the the diffusion of shear stresses but predominantly by the stability characteristics. Stability response to unsteadiness is obviously very much stronger than that of the viscous effects. Accordingly the behaviour of the flow will depend considerably on the Strouhal-number and the amplitude of the free stream.

Summerizing the phase shift characteristics, it is observed that:

- transition is very sensitive to main flow unsteadiness;
- the phase shift upstream of the separation point is very similar to the analytical results for the oscillating Stokes-flow;
- there is a very pronounced time lag of the transitional region resulting in an out of phase oscillation of reattachement and the dead water zone,
- generating positive shear stress at the wall over large portions of the cycle.

Another phenomemon was observed for low Reynolds numbers. The instability of the separated shear layer generates large vortical structures which are released downstream at the end of the separation bubble. They are very similar to those observed in laminar steady flow experiments and CFD calculations, however, in the unsteady case they are locked to the frequency of the external flow. This vortex shedding occured well within the lower range of turbomachinery Reynolds numbers, but with the low turbulence levels of the experiment.