On the propagation of two types of disturbances through a laminar boundary layer subjected to separation and transition

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Separated Boundary Layer Transition (SBLT)

Laminar-turbulent transition of a boundary layer (BL) subjected to adverse pressure gradient (APG) and subsequent separation and re-attachment downstream is studied. The flow over the suction surface of a highly loaded axial compressor blade typically undergoes SBLT under wake impingement. Understanding and controlling the transition process is important to reduce the blade-row losses and to improve the performance range of the compressor stage. In the present work, two different type of disturbances in the form of a loud speaker puff (LSP) and a bar wake (BW) are introduced into the upstream laminar part of an experimentally simulated compressor blade. The nature of the propagation of the two disturbances are then studied with a view to better understand the transition process.

Fig.1 Experimental setup

How do we simulate SBLT experimentally?

The SBLT over a highly loaded compressor blade (Stator 67B, [1]) has been experimentally simulated using a flat plate placed in a wind tunnel test section with contoured top and bottom walls that impose the required pressure field. The LSP is introduced through a surface pressure tapping located at 11% axial chord (C_x) downstream of the plate leading edge (LE). In the case of BW, the wake disturbance is produced from a 12 mm diameter moving bar located $0.6C_x$ upstream of the LE. The bar size and location are chosen such as to produce a wake that is representative of an upstream rotor blade. The strength of the LSP was intended to be such that at the point of introduction its amplitude and temporal range matches that of the wake when it is at the same location. Measurements were conducted along the plate mid-span using pressure tappings, hotwire traversing and PIV data capture at selected chord-wise locations. The plate chord based Reynolds number is 2.1×10^5 and the inlet turbulence intensity is 0.75%. Fig. 1 shows a simplified schematic of the experiment setup.

What did we find?

The non-dimensional pressure distribution realised under no-disturbance (ND) condition over the top surface of the flat plate (solid line) against the Stator-67B target (symbols) is shown in Fig. 2. The dotted lines annotated S and R represent the approximate location of separation ($0.49C_x$) and re-attachment ($0.69C_x$) as due to the bubble. The flow diffusion level is correctly modelled by the flat plate arrangement. Fig. 3 shows hotwire measurements of the velocity profiles at selected chord-wise locations in the vicinity of the separation bubble with the separation and re-attachment points annotated as before. The velocity profiles can be seen to turn from laminar to inflectional immediately upstream of the bubble until the re-attachment point. The dotted line indicates the locus of maximum u_{rms} intensity, which is seen to be very close to the point of inflection. This is similar to that reported in [2]. Contours of the normalised u_{rms} intensity is shown in Fig. 4, where it can be seen that the maximum intensity is measured very close to re-attachment point. This finding is also very similar to that reported by [2]. In Fig.5, ensemble averaged PIV images that are centred around $0.48C_x$ and $0.68C_x$ show the separation and re-attachment regions of the undisturbed (ND) flow field.

The propagation and development of the disturbances, once introduced into the upstream BL is tracked along the line of maximum u_{rms} intensity as measured for the undisturbed case as shown in Fig. 3 and Fig. 4. The resulting ensemble averaged time traces are shown in Fig. 6. Although the LSP disturbance at the source was intended to be of the same amplitude as the wake it is clear from the traces below that it is much weaker compared to the wake prior to the separation point. In both cases, there is evidence of the appearance of a low frequency hump as reported by [2] although this effect seems to be much more pronounced for the wake traces. Note that the upstream LSP traces are scaled up for clarity whereas no such scaling was applied for the BW traces. For the LSP traces, as reported by [2] there is clear evidence of three separate growth regions; (I) low-dispersion, mild growth rate region up until the separation point, (II) a region of exponential growth with increased oscillations followed by (III) a region of non-linear growth close to the re-attachment point. The same can be said about the BW traces except that there was no evidence of multiple oscillations amplified within the wake region. The wake itself is dispersed however, followed by a longer calmed/humped region where any fluctuations are seen suppressed even after flow re-attachment. The above three regions are shown annotated in Fig. 6 and Fig. 7 for each case.

In order to compare the propagation characteristics of the two types of disturbances, their amplitude growth in terms of u_{rms} intensity is presented in semi-log form in Fig. 7 for three disturbance scenarios; ND, LSP and BW. The values plotted are those measured along the maximum u_{rms} intensity line for the undisturbed case. The ND and LSP follow a similar growth pattern with a linear instability region (red lines in Fig. 7) that extends well into the bubble followed by a region of nonlinear growth in the rear part and the re-attachment region. For BW, the linear instability part at the front of the bubble is much shorter and appears 7% C_x earlier than that for the LPS. The higher u_{rms} intensity of the BW in the flow upstream is thought to be due to the velocity deficit associated with the wake.

Fig. 2
Non-dimensional
pressure distribution:
ND

Fig. 3
Boundary Layer
Velocity profiles:
ND

Fig. 4
Contours of normalised
RMS intensity (u_{rms}/U_{fs}):
ND

Fig.5 Ensemble averaged PIV images at $0.48C_x$ (left) and $0.68C_x$ (right), U velocity contours

Fig. 6
Time traces of the two
disturbances as they
propagate in the chord-wise
direction

Fig. 7
Semi-log plot of amplitude
growth of the two
disturbance compared with
the no disturbance case

References

- [1] Schnorenberg, D., G., (1996), Investigation of the effect of Reynolds number on laminar separation bubbles on controlled-diffusion compressor blades in cascade, PhD Thesis, Naval Postgraduate School
- [2] Diwan, S., Ramesh, O. (2009). On the origin of the inflectional instability of a laminar separation bubble. Journal of Fluid Mechanics, 629, 263-298