Behavior of Unstable Disturbances near the Attachment line

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The latest linear theory shows that multiple instabilities co-exist in the region, where the flow becomes unstable at very low Reynolds number compared to that on the attachment line. An experimental investigation has been done focusing boundary-layer instability near the attachment line to clarify the phenomena, especially on which instability devotes to the drop of the critical Reynolds number. These experimental results are compared with the calculations done by the theory.

Keywords : Attachment-line instability, Cross-flow instability, Streamline-curvature instability, 3-D boundary layer

1. Introduction

One of the important subjects in the mechanism of transition phenomena is related to instabilities of the three-dimensional flow developing on swept wings. It is already known that besides the streamline-curvature instability that appears at some distance away from the leading edge, the instability due to crossflow near the leading edge of wing also plays an important role in transition process$^{1,2)}$. According to the recent 3-D theory of linear stability for the attachment-line region developed by Itoh$^{3)}$, the value of the critical Reynolds number experiences sudden drop in the chordwise direction.

Focusing on the instability phenomenon near the attachment-line region, we have two main objectives in the present paper. The first is to determine the local critical Reynolds number of the boundary layer near the attachment line and the second to observe the characteristics of the instability wave itself. These experimental results are compared with the calculations done by Itoh. To accomplish our objectives, a yawed circular cylinder in place of swept wing was used, because of larger attachment-line region. For determining the critical Reynolds number of unstable disturbance, spatial growth of disturbance artificially introduced from a point source on and near the attachment line was investigated.

2. Experiment set up

The experiment was conducted using the Low-Speed Wind Tunnel with a test section of 5.5 m in width, 6.5 m in height and 9 m in length at the National Aerospace Laboratory. A model previously used with a diameter of 0.5 m and length of 3.6 m was set with sweep angles of 70° and 50°. Using a Calibration Wind Tunnel with a test section of 0.55 m in width, 0.65 m in height and 1.5 m in length at NAL also did an experiment with the lowest Reynolds number. The model used for this experiment was also yawed cylinder with a diameter of 0.138 m and length of 0.8 m and sweep-back angle of 50°. For artificial forcing, several small holes with a diameter of 0.5 mm were drilled at several positions from the attachment line to measure the spatial growth, amplitude and phase velocity of traveling waves. The characteristics of instability disturbance were measured by a constant-temperature hot-wire anemometer mounted on the four-axis traversing mechanism.

3. Results

At first, the most amplifying frequency of the disturbance along the attachment line for three different Reynolds number was determined varying forcing frequency of disturbance introduced at the hole. For a free-stream velocity of 20 m/s, which corresponds to R_θ =641, θ being the characteristic length of the attachment-line boundary layer, the most unstable frequency is approximately 610 Hz. This is in good agreement with the result of linear stability theory. Referencing the forcing signal with 610Hz, the amplitude and phase distributions of disturbance developing near the attachment line were conditionally sampled downstream of the hole. Figure 1 depicts the wave fronts of the traveling disturbance, where the numbers in parenthesis denote the values obtained from the linear stability calculations. Surprisingly, good agreement is shown. Although the fronts are highly arced, it was found that its characteristics are representative of T-S wave type as pointed out by theory.

Then, we are going to see about the results obtained from the similar measurements with artificial forcing at the off-attachment line. Forcing at 9° (X=0.05) from the attachment line, the hot-wire scan was repeated in the chordwise direction instead of the spanwise direction, because external streamlines are weakly curved. Figure 2 shows the amplitude and phase distributions at three different spanwise locations with a frequency of ω=0.02 (0.23kHz), which is locally the most unstable at a free-stream velocity of 11m/s (R_θ=486). All amplitudes at every location are measured at the peak position of amplitude profile in the boundary layer. Every distribution consists of two bumps: the large one is due to crossflow (C-F) disturbance and the minor is attributed to streamline-curvature (S-C) instability. It is remarkable that the peak values at three locations are almost invariable, indicating that the C-F mode is neutral in space. Whereas the most amplifying disturbance for S-C mode was applied, C-F mode was found to be dominant under this configuration. It is also worthwhile to note that the C-F traveling wave is confined in the region downstream of the forcing point, although the C-F mode propagates toward the convex side of external streamlines as shown in phase measurements.

In order to determine the critical Reynolds number of off-attachment-line boundary layer farther downstream, the experiments were similarly made at lower Reynolds number. For this purpose, the swept angle was reset at 50° with the same forcing point as before and the free-stream velocity was set at 15m/s. Figure 3 shows amplitude distributions for various frequencies in the chordwise direction. At first, it is seen that all disturbances experience sharp decay as far as X=0.06. After these disturbances cease to decay, they start to grow at certain location in dependence with frequency. The first amplifying component, that is 250Hz, grows from X=0.07, where the local Reynolds number is a value of 358. These growing disturbances investigated here are due to not S-C but C-F instability, although their characteristics are not shown here. It is interesting to point out that the location of X=0.07 under the present experimental condition apparently divides between attachment-line and off-attachment-line regions.

Last, we focus on the area where the critical Reynolds number is supposed to have its minimum value. For this experiment, the Calibration Wind Tunnel was used with a 0.138m circular cylinder model. Artificial disturbance was introduced at $\theta = 20°$. During the experiment, a non-dimensional forcing frequency of $\omega = 0.09$ (0.7kHz) was selected as the most unstable frequency of crossflow mode in accordance with the theoretical prediction. From the measurement, the neutral condition was obtained when the local Reynolds number has its value of 261.

The critical Reynolds number of cross-flow instability, whose most unstable mode is locally neutral in space, is plotted in Figure 4 in comparison with that obtained from the calculation of linear theory[3]. Fairly good agreement between experiment and theory is found, indicating that the critical Reynolds numbers are 560 versus 600 by theory on the attachment line, 486 versus 280 at X=0.06, 358 versus 260 at X=0.07 and 261 versus 200 at X=0.16, respectively. It is clearly shown that the critical Reynolds number is drastically decreased in the chordwise direction.

4. Concluding remarks

The present experiment for the first time revealed the characteristics of instability phenomenon in the vicinity of the attachment line of three-dimensional boundary layer and showed good agreement with the current three-dimensional linear stability theory describing both the attachment-line and the off-attachment-line flows.

References

1) Takagi, S. et al. Proc. 19th ICTAM, Kyoto, 25-31 August, 1996.

2) Takagi, S., Itoh, N. Fluid Dynamics Research **22** (1998) pp. 25-422.

3) Itoh, N. J. Fluid Mech. **317** (1996) pp.129-154.

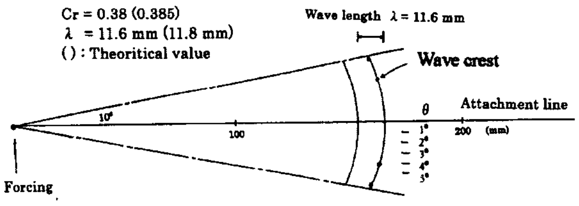

Fig 1. Behavior of unstable disturbance (wave crest)
Q_∞=20m/s, R_θ=641, $\Lambda = 70^0$, f=610Hz

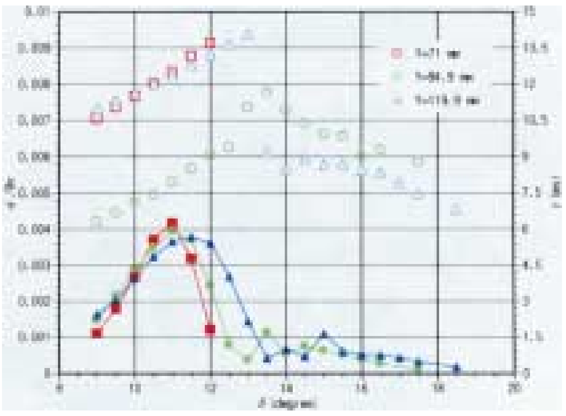

Fig 2. Amplitude and phase distributions along the chordwise direction

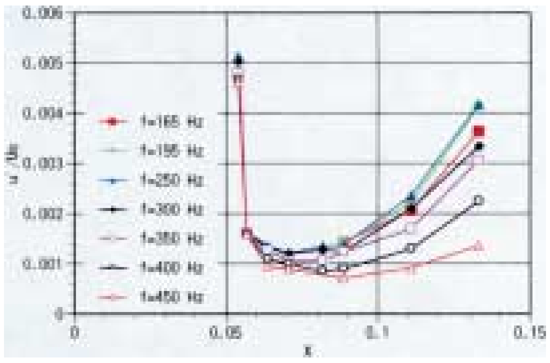

Fig 3. Amplitude peak distributions (at different span locations) along the chordwise direction

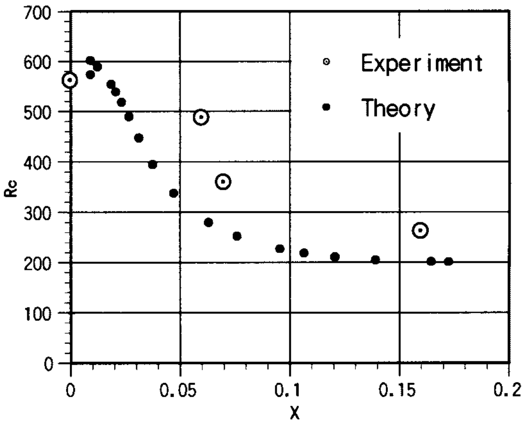

Fig 4. Comparison of the critical Reynolds number Rc between theory and experiment