EFFECTS OF SURFACE CORRUGATION ON BOUNDARY LAYER INSTABILITY

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Summary Effects of small amplitude surface corrugation on the growth of Tollmien-Schlichting (T-S) waves were examined experimentally in a boundary layer with zero-pressure-gradient. Two- and three-dimensional corrugations with wavelength of the same order as that of T-S wave were considered. The results show that two-dimensional surface corrugation destabilized the boundary layer significantly, while the three-dimensional corrugated wall was almost the same as that in the smooth wall case.

INTRODUCTION

It is known that surface roughness has significant effects on boundary layer transition when roughness height is above a certain critical value. In past literatures(1), the critical roughness height above which roughness elements can affect on the transition of Blasius boundary layer is often cited to be 25 in terms of the roughness Reynolds number Re_k. When the roughness height is so small that the roughness little modifies the boundary layer profiles, however, its role in the transition process has not fully been understood except for isolated roughness. Isolated roughness of small height generally plays a role in the receptivity process where any departure from surface smoothness can excite T-S waves in cooperation with free-stream disturbances and acoustic noise. In the case of distributed roughness of our interest, Corke et al(2) compared amplification of T-S waves in zero-pressure gradient boundary layers on the smooth wall and on the rough wall (with sandpaper roughness) under a natural disturbance condition experimentally. They showed that T-S waves grew more rapidly on the rough wall than on the smooth wall in spite of no appreciable difference in the velocity profile across the boundary layer between both the cases but could not clarify whether the faster growth of T-S waves was caused by increase of receptivity due to roughness or destabilization effect of roughness or both. This problem still remains open even now.

Recently our knowledge on the effect of distributed roughness has been improved in part. Floryan(3) analyzed the stability of two-dimensional channel flow with two-dimensional surface corrugation (sinusoidal surface geometry). It was found that in the case of channel flow the two-dimensional corrugation, even for very small height of Re_k much less than 25 when the corrugation amplitude is used as roughness height, destabilized the flow to T-S waves, and the results were supported by the corresponding experiments by Asai and Floryan(4). However, distributed roughness generally consists of three-dimensional distribution of roughness elements. In connection with actual distributed roughness, it is important to further clarify how the effect of three-dimensional corrugation on the flow instability is different from the two-dimensional one. In the present study, effects of two- dimensional and three-dimensional surface corrugations of small amplitude on the growth of T-S waves are examined experimentally.

EXPERIMENTAL SETUP AND PROCEDURE

The whole experiment was conducted in a low turbulence wind tunnel of open jet type, with a test section of $400\times400mm^2$ in cross section. The boundary layer plate is1195mm long and consists of brass plate of 5mm thick and 300mm long with a sharp leading edge, followed by Plexiglas plate of 20mm thick and 895 mm long. The Plexiglas flat plate can be replaced with a plate with 2D or 3D corrugation. The vibrating ribbon was stretched in the spanwise direction at a streamwise location 190mm downstream from the leading edge. The freestream velocity U_∞ was fixed at 6m/s and free-stream turbulence was about 0.1% at the leading-edge location. Downstream of the vibration ribbon location, the streamwise variation of external flow remains within 0.2% of U_∞.

The 2D surface corrugation is given as $y_w = A_w\sin(\alpha_w x)$ where the wavelength $2\pi/\alpha_w$ is 32mm and the corrugation amplitude A_w is 0.21mm. The 3D surface corrugation which has the same amplitude and streamwise wavelength as those of 2D corrugation is given as $y_w = A_w\sin(\alpha_w x)\sin(\beta_w z)$ with $\beta_w = \alpha_w$. The corrugated walls extend downstream from x = 320mm, as shown in Fig. 1. The Reynolds number based on the displacement thickness δ^*, defined as $Re^* = U_\infty\delta/^*\nu$, was 560 at the vibrating ribbon location (x =190mm) for U_∞ = 6m/s. The ratio of the corrugation amplitude to the displacement thickness A_w/δ^* changes from 12.6% to 8.4% over the distance x = 310-824mm where Re^* varied from 670 to 1005.

RESULTS AND DISCUSSION

We measured y-distributions of streamwise velocity U at various streamwise locations carefully and confirmed that the Blasius boundary layer under zero pressure gradient was developed with good accuracy. When the vibrating ribbon was

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driven, almost two-dimensional T-S waves were developed downstream. Streamwise development of T-S waves was found to agree with the theoretical prediction from the Orr-Sommerfeld stability equation almost completely. Then we examined streamwise growth of T-S waves in the boundary layer on the 2D and 3D corrugated wall. The upstream part of the plate (up to x=300mm) is the same as that of the smooth-plate model. Surface transition from the smooth wall to the corrugated wall at and around x=320mm was smoothed out in such a way that the average y-position of the corrugated wall was unchanged with the upstream smooth wall part. Figs. 2(a) to (c) illustrate the streamwise development of T-S waves excited at $F = 1.5\times10^{-4}$ and 1.9×10^{-4}, respectively by comparing with the corresponding results for the smooth-wall case. Here the amplitudes of T-S waves are sufficiently below the threshold for the onset of the secondary instability in all the cases. The comparisons show that the 2D surface corrugation enhanced the amplification of T-S waves significantly even when the corrugation amplitude A_w is only of the order of $0.1\delta^*$ or about 10 in terms of roughness Reynolds number $Re_k = kU_k/\nu$ where A_w is used as k and U_k is the Blasius flow velocity at $y=A_w$. The destabilizing effect of small-amplitude 2D corrugation is the same as observed in the study on the instability of plane channel flow [3, 4]. On the other hand, growth of T-S waves on the 3D corrugation is almost the same as on the smooth wall. Thus, the destabilizing effect of the 3D corrugation is quite different from that of the 2D corrugation.

CONCLUSIONS

A distinct difference was found in the destabilizing effect between two- and three-dimensional surface corrugations. Two-dimensional corrugation destabilized the boundary layer significantly as shown theoretically and experimentally for plane channel flows[2,3], while the amplification of T-S waves on the three-dimensional corrugated wall was almost the same as that in the smooth wall case, at least for the small corrugation amplitude sufficiently below the often-cited critical height. Dependency of the instability on the corrugation amplitude of 3D surface corrugation is under investigation.

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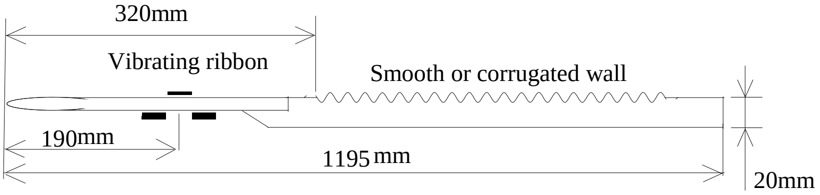

Fig. 1. Boundary-layer plate.

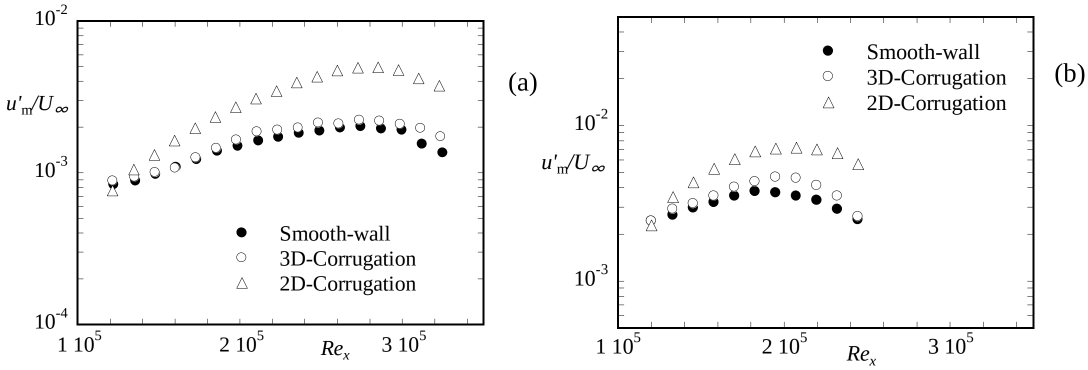

Fig. 2. Comparison of development of TS-waves at U_∞=6m/s. Excited at (a) F $(=2\pi f_0\nu/U_\infty^2) = 1.5\times10^{-4}$, (b) $F = 1.9\times10^{-4}$.