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Feedback Control of Instability Waves in a Transitional Flat-Plate Boundary Layer

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Abstract : A semi-automatic and active control of T-S waves and oblique waves in a transitional flat plate boundary layer is carried out in a wind-tunnel experiment and a numerical simulation. An array of piezo-ceramic actuators attached on a surface is used to generate counter waves that cancel the incoming instability waves. The actuator's operating amplitudes and phases are successively updated using the velocity fluctuations monitored downstream by a rake of hotwires. Experimental results show that the system is effective in weakening these waves when their inclination angles are less than 15 degrees. However, the system encountered difficulty in controlling the waves of large inclination angles. In the numerical simulation, it is shown that the control can be accomplished much easier. The numerical results show that controllability of the large inclination angle waves can be improved by shortening the spanwise length each actuator piece. The danger of pursuing this kind of research solely by a numerical simulation is pointed out.

Keywords : Transitional Boundary Layer, T-S Wave, Oblique Wave, Active Control, Feedback.

1. Introduction

Stability of a boundary layer and its transition mechanism have been widely studied in the past. It is because the transition not only causes a large increase in the aerodynamic drag, but also leads to a significant change in the flow properties such as the heat transfer from the surface. In recent years, strong attention has been paid toward the active control of the laminar-turbulent transition process in a boundary layer. The Tollmien-Schlichting (T-S) type transition, which is the standard transition process in a low-noise environment, starts with an exponential growth of two-dimensional Tollmien-Schlichting (T-S) waves. When the amplitude of T-S waves becomes larger than a certain threshold, a pair of oblique waves starts to develop. The overlapping of these two types of waves leads to the onset of a localized turbulence near the wall. It is expected that the boundary layer transition can be delayed by suppressing the growth of these instability waves.

Liepmann et al. (1982) successfully suppressed the T-S waves by generating counter waves using periodically heated surface elements of thin nichrome film. Elofsson (1998) excited the oblique wave by periodic blowing and suction from a slit on a flat-plate. Sturzebecher and Nitche (2002) succeed to delay the transition using a slot system, which is an all-in-one device including actuators and sensors. In our past studies (Sakai et al., 2003; Fukunishi et al., 2005), it was shown that small and thin piezo-ceramic (PZT) actuators attached to the surface were effective in controlling the flow. In the present study, a semi-automatic and active control of T-S waves and oblique waves in a transitional flat-plate boundary layer is carried out in a wind-tunnel experiment and a numerical simulation, using PZT actuators as the flow controlling device. The purpose of the numerical research is to find a way to improve the feedback algorithm for the control, and to check the effect of the spanwise length of each actuator toward the controlling efficiency.

2. Experimental Setup and Numerical Scheme

2.1 Flat Plate and Actuators

The experiment is conducted in the low turbulence wind tunnel of the Institute of Fluid Science, Tohoku University. The experimental setup is shown in Fig. 1. A smooth flat plate made of an aluminum alloy, which is 3,200 mm long, 1,000 mm wide and 10 mm thick, is mounted vertically in the middle of the test-section. The plate is carefully installed parallel to the flow, so that the variation of pressure coefficient along the surface is less than 0.01 %. In order to lower the receptivity at the joint between the leading edge and the flat-plate section, a modified elliptic leading edge is used. Its shape is a 36:1 ellipse with a modification at the joint to the flat-plate in order to eliminate the curvature discontinuity at the ellipse/flat-plate junction. The target waves are introduced into the boundary layer by a combination of roughness elements of 100 μm thick (Scotch tapes) attached on the surface and an acoustic forcing at the frequency of $f = 77.8$ Hz by a loud speaker located upstream of the settling chamber (Kobayashi et al., 1994). The inclination angle θ of the target waves can be changed by changing the angles of the roughness elements. The axes x, y, and z are in the streamwise, wall-normal, and spanwise directions, respectively. The wall-normal coordinate is normalized as $\eta = y\sqrt{U_\infty/(\nu x)}$, where U_∞ is freestream velocity and ν is kinematic viscosity.

As shown in Fig. 2, the actuators used in the experiment are made of PZT pieces, where each piece is 0.3 mm thick, 20 mm and 80 mm long in the spanwise and streamwise directions, respectively. In order to obtain a large controlling effect, the streamwise size of the actuator should be long, and it is better to keep the spanwise size of the actuator as small as possible. The difficulty in handling the actuator will increase when the spanwise size of the actuator is reduced. There are fewer restrictions for the streamwise length of the actuator. The PZT actuators are aligned side by side along the spanwise direction. The downstream tip of the actuator moves less than 2 μm in the streamwise direction. Because our preliminary experiments revealed that a slight difference in the tilt angle of each actuator could lead to a large difference in the amplitude of the introduced velocity fluctuations, an additional insulator is inserted between the actuators and the insulator attached to the surface so that the upper surfaces of all actuators will be leveled. Both the upstream and downstream ends of the actuators are sloped to prevent separations and high-receptivities at the edges. The velocity measurement is carried out by a standard single hot-wire probe and its signal is digitized at the rate of 5 kHz. The freestream velocity is 14.0 m/s and the velocity fluctuation within the freestream is 0.07 %. The Reynolds number Re_x at the actuators' location, $x = 1{,}000$ mm, is 9.9×10^5. The thickness of each actuator including the insulators is approximately 0.6 mm, which is 13 % of the boundary layer thickness at the location. The presence of the actuator shifts the boundary layer away from the wall for an amount nearly equivalent to the thickness of the actuators. However, the boundary layer returns to a regular Blasius-profile 300 mm downstream of the actuators.

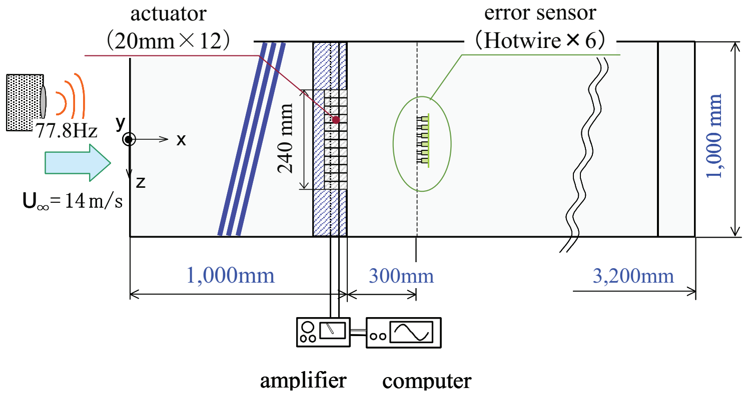
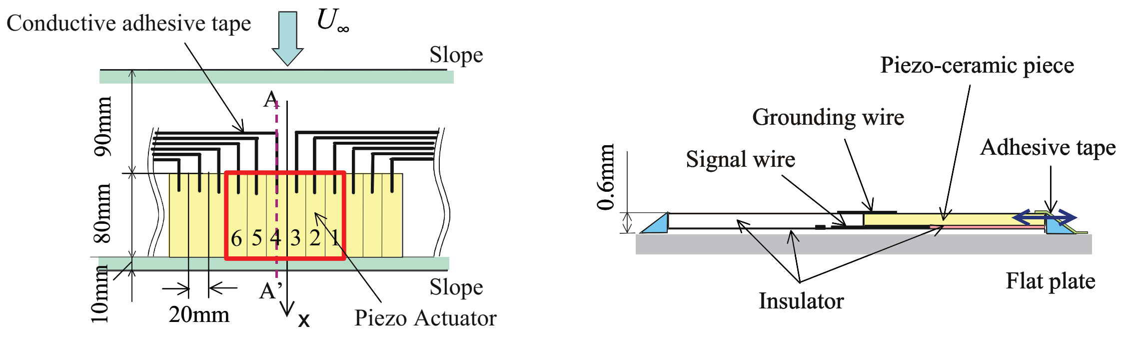


Fig. 1. Experimental setup.



(a) Plane view (b) A-A' cross section view

Fig. 2. Piezo-ceramic actuators.

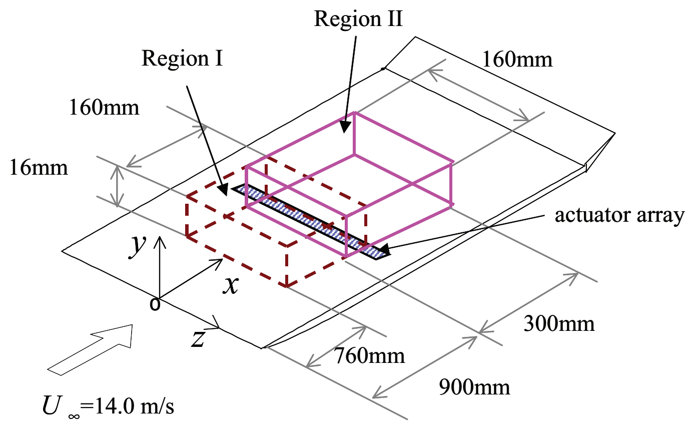


Fig. 3. Computational regions.

2.2 Feedback Control

For the control, six middle pieces among the twelve pieces of the actuator array are used to save time for the tuning of the actuators. The effect of control is checked by a rake of hotwire sensors, 2 mm away from the wall. The location corresponds to the height where the amplitude of the velocity fluctuation of the target waves has its peak. Each sensor is placed straight downstream of the center of an activated actuator. First, an attempt to adjust the movements of all the actuators at the same time using the information obtained by the downstream sensors was carried out, which turned out unsuccessful. So, the adjustment is made to the movement of only one actuator at a time. The target waves are monitored for one second by the downstream sensors. The adjustment of the amplitude and phase of the movement of each actuator is based on the information obtained by the sensor directly downstream. However, because the wave generated by a single actuator spreads in the spanwise direction as the waves travels downstream (Sakai et al., 2003), an adjustment of an actuator can influence several sensors downstream. So, eliminating the waves at the sensor locations on both spanwise ends had to be cast aside. Also in this study, each adjustment is limited to 5 % of the previous value for smoother control. One cycle of the adjustment process takes less than a second and the adjustments are carried out at the same interval. This adjustment process is repeated until the waves are damped to a level lower than a certain criterion. The same controlling protocol is used for the T-S waves and the oblique waves.

2.3 Numerical Simulation

Three-dimensional incompressible Navier-Stokes equations are computed by a finite difference method. A third-order upwind (Kawamura-Kuwahara) scheme (Kawamura and Kuwahara, 1984) is used for the convection terms. The flow conditions are the same as the experiment. Computations on two different regions are carried out, which are shown in Fig. 3: the upstream region for generating the target waves (Region I) and the downstream region for the active wave-cancellation trial (Region

II). In the Region I computation, a Blasius profile is given as the inflow condition. The results of the Region I computation for one forcing period in *yz* plane at $x = 900$ mm are repeatedly used as the inflow condition when Region II is computed. The computations of the two regions are not bilaterally coupled. The second order derivatives at the outlet and outside boundaries are fixed to zero. On the wall, the non-slip condition is used except at the actuators' surfaces. The motions of the actuators are simulated by imposing a sinusoidal velocity fluctuation at the actuator surfaces. In this simulation, once the phase is detected, it is fixed for the rest of the control, and only the amplitude is repeatedly adjusted and updated, because that gives better results.

3. Results and Discussion

3.1 Wind-Tunnel Experiment

First, the active control of two-dimensional T-S waves is carried out. Figure 4 shows the variation of the RMS value of the streamwise velocity fluctuation component $u'_{\mathrm{rms}}/U_\infty$ for the middle four sensor channels 2 to 5. The velocity fluctuation becomes weaker at all sensor locations after 54 adjustments, however the amplitudes of the waves do not monotonously decrease as the adjustment advances. Figure 5 presents the RMS profiles of the streamwise velocity fluctuation components u'/U_∞, measured 350 mm downstream from the actuator array. The peak at $\eta = 1.0$ is lowered to 62% of the non-controlled case.

The effect of the control against the velocity fluctuation waves that are inclined 15 degrees is shown in Fig. 6. It can be found that the control effect is uneven until the number of feedback control reaches approximately 35. Before that, a large imbalance between the fluctuating amplitudes exists between the channels; even if an amplitude of one channel becomes smaller the others do not.

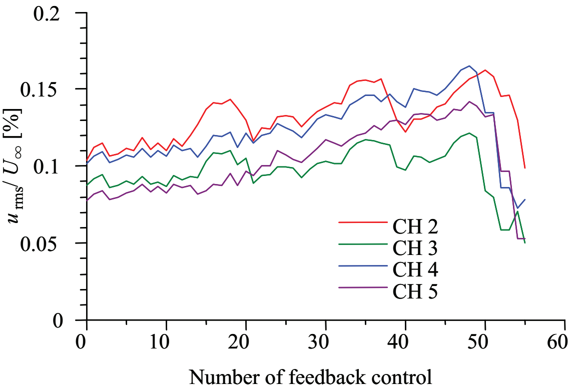


Fig. 4. Control effect on velocity fluctuation waves (T-S waves).

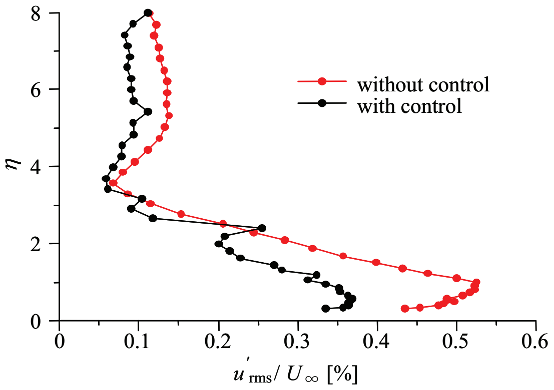


Fig. 5. RMS profile of *u'* at $x = 1{,}350$ mm and $z = 0$ mm (T-S waves).

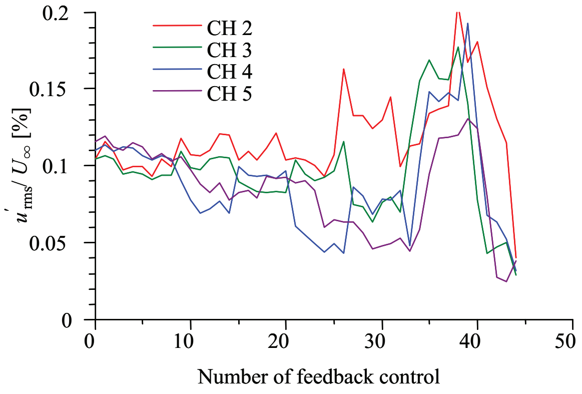


Fig. 6. Control effect on velocity fluctuation waves (oblique waves, θ = 15°).

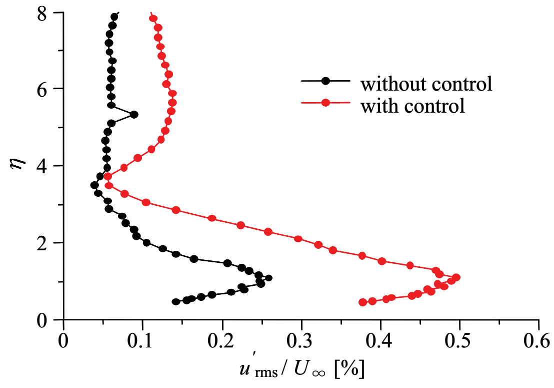


Fig. 7. RMS profile of *u'* at $x = 1{,}350$ mm and $z = 0$ mm (oblique waves, θ = 15°).

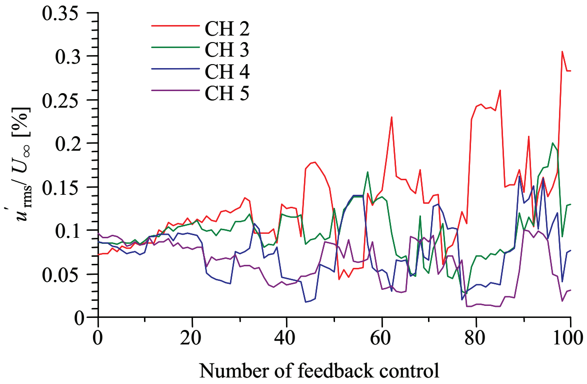


Fig. 8. Control effect on velocity fluctuation waves (oblique waves, θ = 30°).

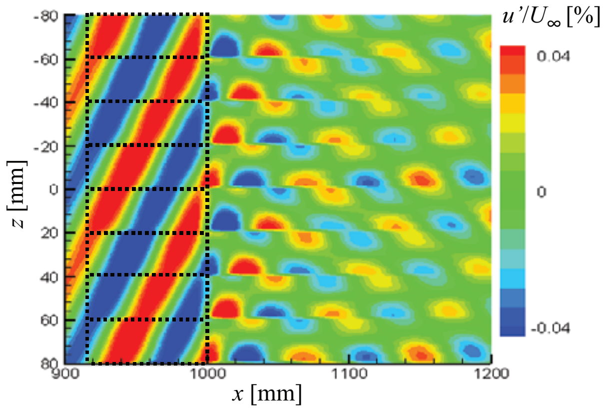


Fig. 9. Contour map of u' at η = 1.0 and L_a = 20 mm (oblique waves, θ = 30°).

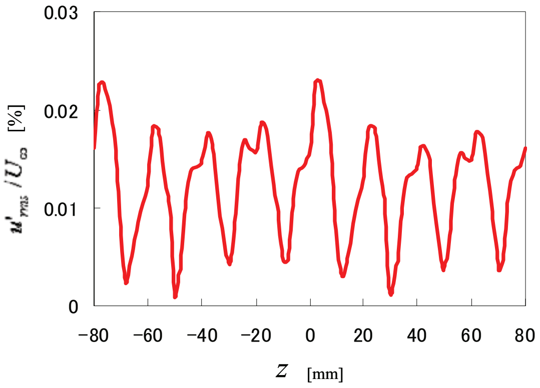


Fig. 10. RMS profile of u' at x = 1,120 mm and η = 1.0 (oblique waves, θ = 30°).

As shown in Fig. 7, the peak in the fluctuation observed around η = 1.5 decreases to nearly one half after 44 adjustments.

However, when the same method was applied against the oblique waves of a larger inclination angle, 30 degrees, the current control system could not suppress the waves. Figure 8 shows the results for the oblique waves with 30 degrees. It is shown that the unevenness between the channels does not decrease, but rather increase continuously instead.

3.2 Numerical Simulation

In order to find the hint for an improved control, numerical simulations are carried out. Figure 9 shows the numerical results for the wave-suppressing attempts against the θ = 30° oblique waves. In the figure, the η = 1.0 plane, where the RMS of velocity fluctuation $u'_{\rm rms}$ becomes maximum, is shown. Although the strong and periodical pattern of velocity fluctuation weakens in the region downstream of the actuators, some fluctuations still can be found. Figure 10 shows the RMS profile of $u'_{\rm rms}$ along the spanwise direction. As shown in the figure, the target velocity fluctuations are well suppressed at the center of each actuator, z = ±10, ±30, ±50, ±70, while the large fluctuations remain on the boundaries between the actuators at z = 0, ±10, ±30, ±50, ±80. This spanwise unevenness of the control effect can be speculated to arise from the spanwise resolution of counter waves, because the waves generated by the piezo-ceramic actuators have a step-like shape in the spanwise direction and are not smooth and continuous.

Figure 11 shows the results when the spanwise length L_a of each actuator is shortened to half and twice as many actuator pieces are used for the control. By comparing Fig. 9 (L_a = 20 mm) and Fig. 11 (L_a = 10 mm), it can be found that shortening the spanwise length of each actuator L_a is effective in

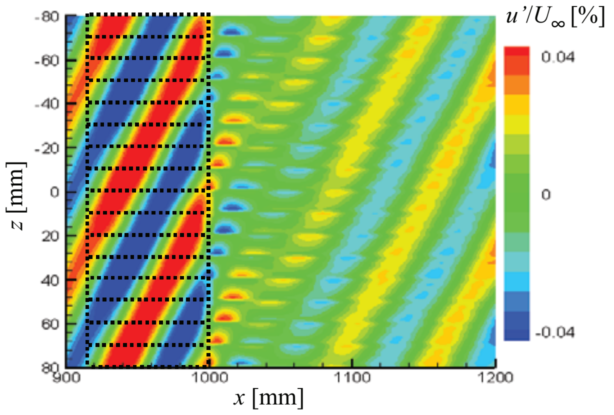


Fig. 11. Contour map of u' at η = 1.0 and L_a = 10 mm (oblique waves, θ = 30°).

reducing the velocity fluctuation that remains after the control. Compared at the x = 1,200 mm location, when L_a = 10 mm, the spanwise-averaged value of u'_{rms} is 32% of the non-controlled case, which is not so different from the L_a = 20 mm case that is 28 % of the non-controlled case. However, there is a major difference in how the u'_{rms} values change depending on the spanwise locations. The spanwise differences of the u'_{rms} values for the L_a = 10 mm case is only one-seventh of those for the L_a = 20 mm case. Consequently, it can be concluded that; improved controlling effect can be expected by using a larger number of actuator pieces and shortening the spanwise length of each actuator. However, manufacturing the controlling device by assembling a large number of smaller pieces with precision will be extremely difficult in practice.

3.3 Discussion

Comparing the experimental results and the numerical ones, it is obvious that a large discrepancy between them exists. In most cases, the numerical simulations show better controllability compared to the experiments. For the case of this research, the geometrical configurations of the actuator pieces are ideal in the numerical simulations, while it is not so in the experiment, and the flow dealt here is very sensitive to the small imperfectness of the controlling device. During the experiment, when the precision of the controlling device was not sufficiently good, especially when the top surfaces of the neighboring actuator pieces were not leveled, a development of a longitudinal vortex, which had strong influence to the flow field, was observed. It should be pointed out that in such flows, where small imperfectness of the surface may result in a major difference in the outcome, pursuing the research solely by numerical simulation could be very dangerous.

4. Conclusions

A feedback control of transitional flat-plate boundary layer was attempted in a wind-tunnel experiment and a numerical simulation. It was shown from the experiment that the system was capable of weakening the two-dimensional T-S waves and the oblique waves of smaller angles. However, it was found that the system was not effective against oblique waves of a large inclination angle. In the numerical simulation, the flow control was found to be much easier. It was shown that the difficulty in controlling oblique waves of large inclination angle could be relieved by decreasing the spanwise length of each actuator. The danger of pursuing this kind of research solely by the numerical simulation was also pointed out.

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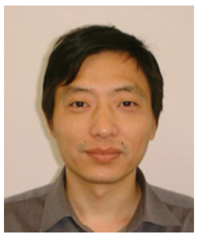

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