Active Control of Laminar Boundary Layer Using Various Wall Motions

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Abstract: In this study, three types of surface motion of wall motion actuators were proposed and used to control the Tollmien-Schlichting (T-S) wave in the laminar boundary layer of a plate. These three types of motion are standing transverse wave (with out-of-plane displacement), traveling transverse wave (with out-of-plane displacement) and standing longitudinal wave (with in-plane displacement). The length of a wall motion actuator was set to 1, 2 or 3 cycles of waveform. Numerical simulation was performed on the generation of T-S wave and its suppression with the three types of surface motion of the wall motion actuator and the dependence of control effect on the amplitude and the phase of the surface motion, and the number of waveform was investigated.

keyword: boundary layer, Tollmien-Schlichting wave control, wall motion actuator.

1 Introduction

Due to its possible future applications in skin friction reduction of transportation vehicles such as high-speed trains, aircraft and ships, boundary layer control has become an active area of research. Various approaches, including passive ones such as those using compliant wall (Gaster, M., (1988)) and riblets (Choi, K. S. (1990)), and active ones such as those using blowing, suction, microbubble (Kato, H. (1999)), wave cancellation (Thomas, S. W. (1983), Milling, R. W. (1982)) and vibrating ribbon (Liepmann, H. W.; Brown G. L.; Nosenchuck, D. M. (1982)), have been proposed by many researchers. Since the skin friction of laminar flow is much smaller than that of turbulent flow, one of reasonable methodology for skin friction reduction is to suppress the transition of the boundary layer from laminar to turbulent.

It has been known that the transition of boundary layer can be attributed to the enhancement of Tollmien-Schlichting (T-S) wave when the background disturbance in the main flow is small. That is, the small background disturbance is enhanced in the form of two-dimensional wave (T-S wave) in the unstable region of the boundary layer and if the magnitude of the wave exceeds 1% of the main flow velocity, it transits to a three-dimensional wave. Further enhancement of three-dimensional wave causes the boundary layer to transit to turbulent. The two-dimensional wave is linear and the unstable region can be calculated from the stability theory (Schlichting, H.; Gersten, K. (2000)). If the enhancement of the T-S wave can be suppressed, the transition of the boundary layer can be controlled.

The authors proposed the concept of wall motion actuator, which can generate the out-of-plane displacement on its surface, for the control of T-S wave. Its effect in the suppression of T-S wave was confirmed by both wind tunnel tests (Han, J. H.; Tani, J.; Qiu, J.; Kohama, Y.; Shindo, Y. (1999)) and numerical simulation (Qiu, J.; Tani, J.; Hayase T.; Suzuki, M. (2002)). In the simulation, a wall motion actuator, which generates a single cycle of standing transverse wave, was used to cancel the T-S wave in the boundary layer. When the amplitude and phase of the wall motion actuator were properly set, the amplitude of T-S wave was reduced by about 90%. In this study, three types of multi-cycle wall motion actuator output: standing transverse wave (with out-of-plane displacement), traveling transverse wave (with out-of-plane displacement) and standing longitudinal wave (with in-plane displacement) were proposed and the dependence of the control effect on the amplitude, phase and number of waveform was investigated in the simulation.

2 Simulation model and method

2.1 Simulation model

The simulation model, shown in Fig. 1, consists of a flat plate, a wall motion actuator embedded on the surface of the plate, and an upper wall. The upper wall is far enough from the plate so that it has no effect on the boundary layer. As air flows from left to right, a boundary layer is formed on the surface of the plate. A tape of 16 mm

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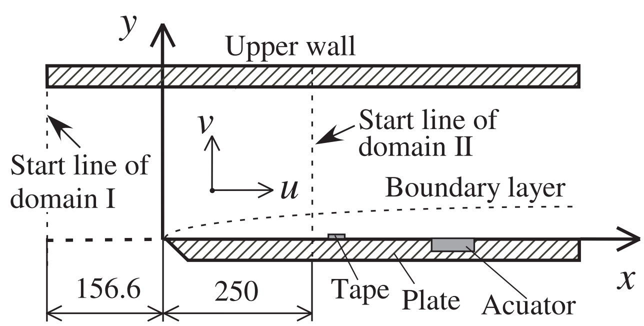

Figure 1 : Computational area

long is installed in the region of 300 mm $< x <$ 316 mm and a disturbance is introduced to boundary layer by the horizontal vibration of the tape, the velocity amplitude of which is 0.01-0.03%U_∞. The disturbance is amplified in the unstable region. The frequency of the tape was set to 104 Hz. From the velocity of the main flow, U_∞=9.9 m/s, and the frequency of the T-S wave, which equals the frequency of the tape vibration, the unstable region of the boundary is estimated to be 257 mm $< x <$ 592 mm, where x is the distance from the leading edge of the plate. Since the phase velocity of the T-S wave is about one third of the mainstream velocity, the wavelength of the T-S wave is λ=32 mm. The wall motion actuator, which generates 1, 2 or 3 cycles of standing or traveling wave with the same wavelength as that of T-S wave, is installed from x=500 mm.

2.2 Simulation Method

The flow was assumed to be two-dimensional, and the two-dimensional Navior-Stokes equation and continuity equation were solved with a SIMPLER-based method (Patankar, S. V. (1980)), more detailed information of which can be founded in reference (Hayase, T. (1999)). In order to save CPU time, only the flow of the area from x=250 mm to x=1394.8 mm (labeled with domain II in Fig. 1) was computed. The inlet boundary condition of domain II was determined from the result of the auxiliary computation of domain I from $x = -156.6$ mm (upstream from the leading edges of the plate) to x= 988.2 mm. The method of discretization for the computational area can be found in (Qiu, J.; Tani, J.; Hayase T.; Suzuki, M. (2002)). The parameters used in the simulation are shown in Tab. 1.

Table 1 : Values of parameters

Velocity of the main flow	9.9 m/s
Position of the actuator l	500 mm
Frequency of T-S wave f	104 Hz
Frequency of actuator f_a	104 Hz
Wave length of T-S wave λ_{TS}	32 mm
Amplitude of plate	0.01%U_∞

2.3 Surface Motion of Wall motion actuator

In order to suppress the T-S wave, three types of surface motion of the wall motion actuator were proposed. The displacement of the three types of surface motion can be expressed in the following forms.

Standing transverse wave (STW):

$$Y = A_a \cos 2\pi f_a (t-\tau) \sin 2\pi \frac{x-l}{\lambda_{TS}} \tag{1}$$

Traveling transverse wave (TTW):

$$Y = A_a \cos 2\pi \left(\frac{t-\tau}{T_{TS}} - \frac{x-l}{\lambda_{TS}} \right) \tag{2}$$

Standing longitudinal wave (SLW):

$$X = A_a \sin \frac{2\pi}{\lambda_{TS}} (x-l) \sin 2\pi f_{TS} (t-\tau) \tag{3}$$

where X and Y are the displacements of the surface motion of the wall motion actuator in x and y directions, respectively, A_a the amplitude of the surface motion, f_{TS} the frequency of the T-S wave, l the distance between the leading edge of the plate and that of the actuator, and τ expresses the phase delay of the wall motion actuator with respect to the tape vibration. In the numerical computation, the velocity of the wall motion actuator surface was calculated and used as its boundary condition.

3 Results and Discussion

3.1 Amplification of T-S Wave

When there is disturbance in the boundary layer, the normalized x-direction velocity U can be expressed as $U = \overline{U} + U'$, where $\overline{U}$ is the average and U' is the fluctuation of U. The root-mean-square of U', denoted by U'_{rms}, is defined as the intensity of turbulence, which can be used to describe the magnitude of T-S wave. Figure 2 shows the amplification of T-S wave at the position of 0.88 mm in the unstable region of the boundary layer when the amplitude of the type is set to $0.01\%U_\infty$, $0.02\%U_\infty$ and $0.03\%U_\infty$, respectively. The value of U'_{rms} is proportional to the amplitude of the tape vibration.

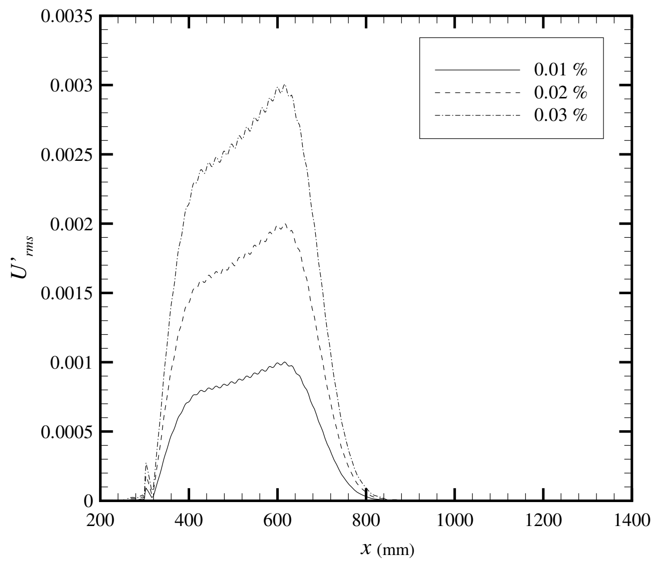

Figure 2 : Amplification of T-S wave

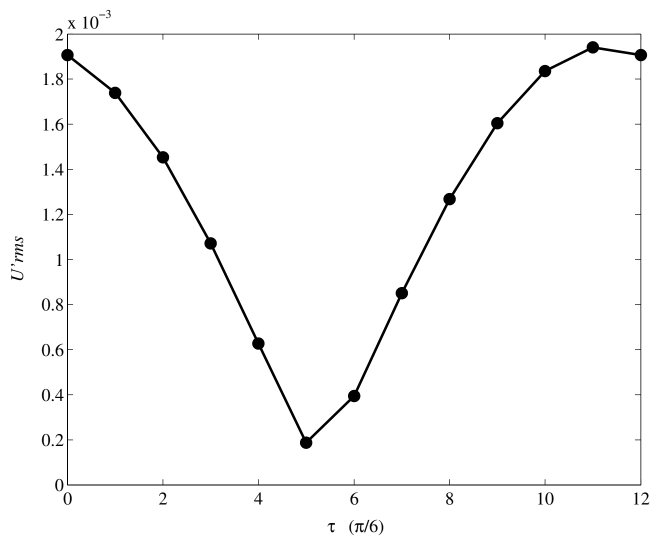

Figure 3 : Influence of STW output phase (n=1)

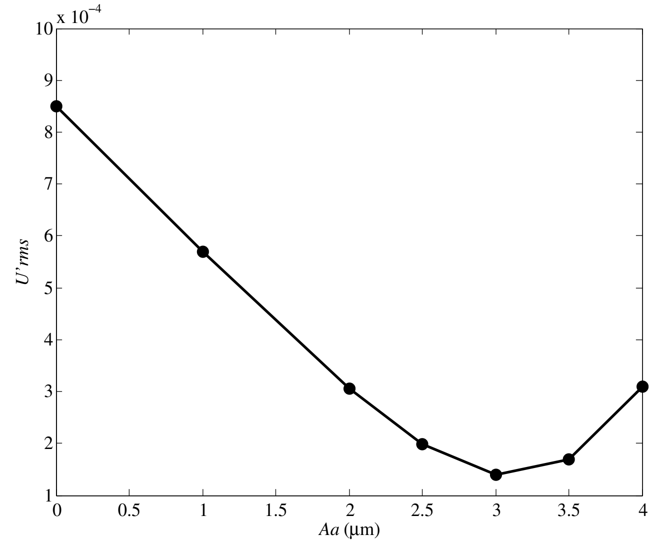

Figure 4 : Influence of STW output amplitude (n=1)

3.2 Control Using Standing Transverse Wave

The influence of the phase and amplitude of standing transverse wave (STW) on the control performance is investigated first. Figure 3 shows the dependence of residual U'_{rms} at x=600 mm and y=0.88 mm on the phase delay of the single-waveform wall motion actuator (n=1) when its amplitude is set to 3.5 μm. Since the uncontrolled U'_{rms} at this position is 8.4×10^{-4}, the surface motion of the wall motion actuator can both suppress and amplify the T-S wave depending on its phase. The optimal phase delay is 5π/12 (τ =0.4 ms).

Figure 4 shows the dependence of residual U'_{rms} at x=562 mm and y=0.88 mm on the surface motion amplitude of the single-waveform wall motion actuator (n=1) when the phase delay of the actuator is set to 5π/12. The optimal amplitude is 3 μm. The above results indicate that the T-S wave can be successfully suppressed by the surface motion of the wall motion actuator if its phase and amplitude are appropriately selected. The distribution of U'_{rms} in the stream direction is shown in Fig. 5 for different amplitude of the wall motion actuator. It can be seen that although U'_{rms} for 3 μm of surface motion amplitude is smaller than that for 3.5 μm of surface motion amplitude immediately behind the rear end of the actuator, U'_{rms} increases much faster behind the actuator in the case of 3 μm of surface motion amplitude.

Figures 6 and 7 show the dependence of the residual in-

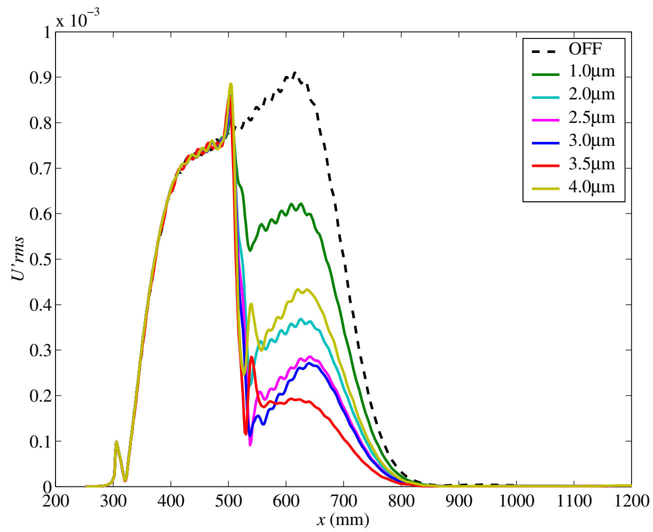

Figure 5 : Distribution of U'_{rms} for different amplitudes of STW

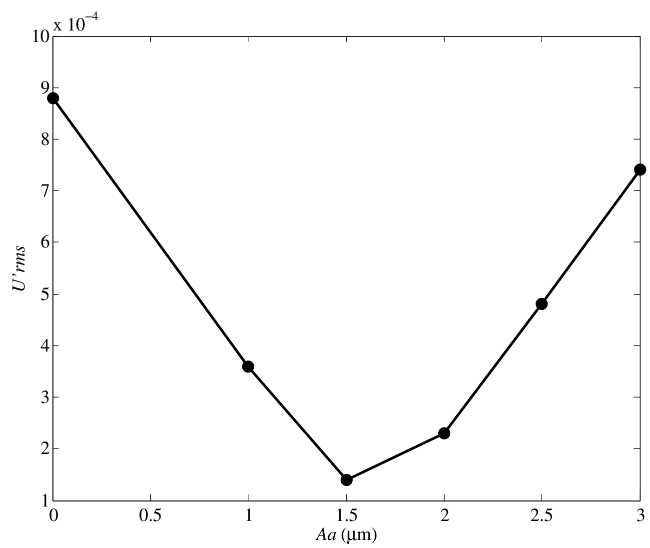

Figure 6 : Influence of STW output amplitude (n=2)

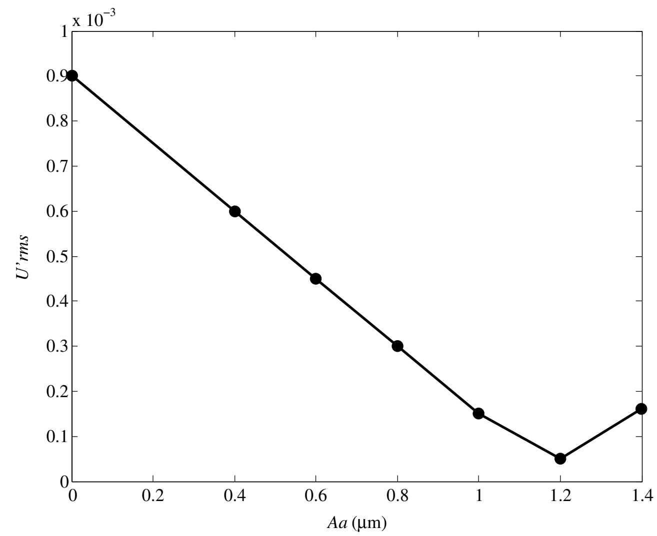

Figure 7 : Influence of STW output amplitude (n=3)

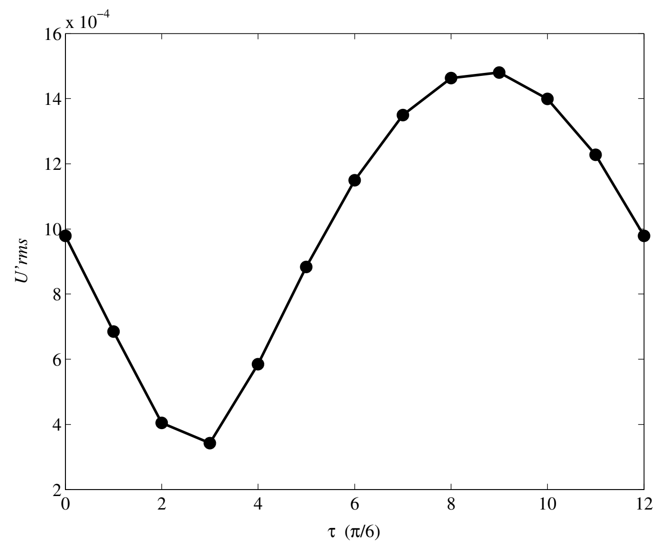

Figure 8 : Influence of TTW output phase (n=1)

tensity of turbulence on the amplitude of the wall motion actuator with two (n=2) or three (n=3) cycles of waveform, where the phase is fixed at 5π/6. The optimal amplitude of two-waveform wall motion actuator is 1.5 μm with a residual U'_{rms} of 1.36×10^{-4} and that of three-waveform wall motion actuator is 1.2 μm with a residual U'_{rms} of 0.5×10^{-4}. As the number of waveform was increased, both the required surface motion amplitude of the actuator and the residual intensity of turbulence decrease.

3.3 *Control Using Traveling Transverse Wave*

The out-of-plane displacement Y of the traveling transverse wave (TTW) on the surface of wall motion actuator is defined in Eq. (2). The dependence of residual intensity of turbulence on the phase of the wall motion actuator with single cycle of waveform (n=1) is shown in Fig. 8, from which it can be concluded that the optimal phase is π/2. Figure 9 shows the stream-direction distribution

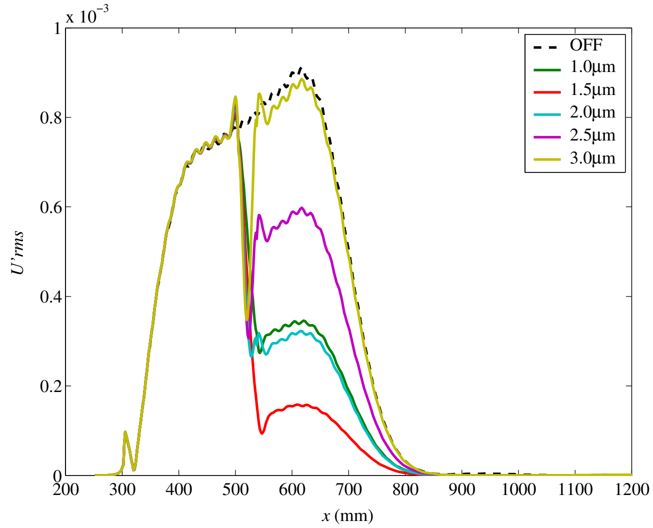

Figure 9 : Influence of STW output amplitude (n=1)

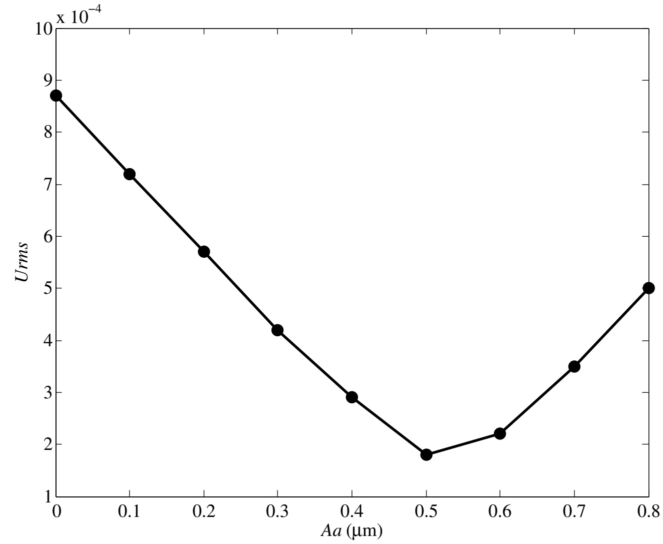

Figure 11 : Influence of TTW output amplitude (n=3)

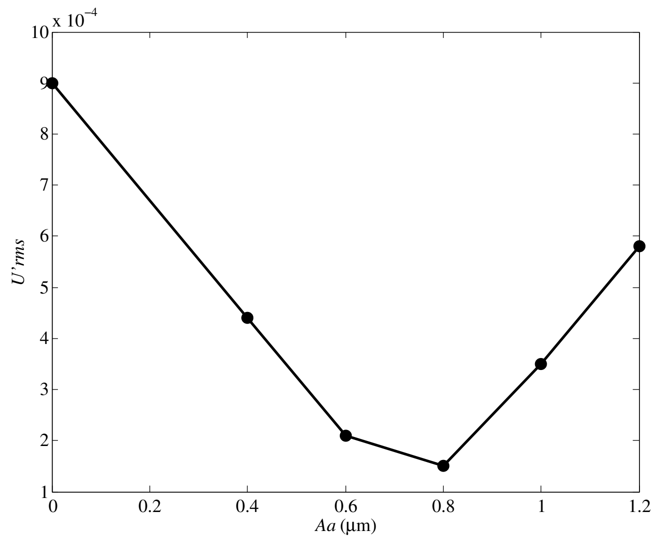

Figure 10 : Influence of TTW output amplitude (n=2)

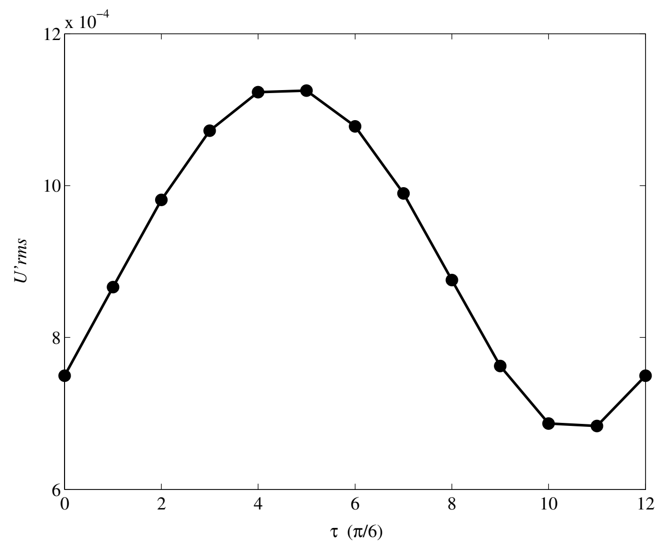

Figure 12 : Influence of SLW output phase (n=1)

of U'_{rms} for difference amplitude of surface motion of the wall motion actuator when its phase is fixed to π/2. It can be seen from Fig. 9 that the optimal surface amplitude of the wall motion actuator is 1.5 μm and the residual U'_{rms} is about 1.4×10^{-4}, 16% of the uncontrolled value, which is smaller than that achieved in the case of the standing transverse wave. This means that a single cycle of traveling transverse wave yield better control effect than single cycle of standing transverse wave.

Figures 10 and 11 show the relationship between the residual intensity of turbulence on the amplitude of the wall motion actuator with two (n=2) or three (n=3) cycles of traveling transverse waveform. The optimal amplitude is 0.8 μm and 0.5 μm, respectively, and the residual U'_{rms} is 1.56×10^{-4} and 1.78×10^{-4}, respectively, for two- and three-waveform wall motion actuators. As the number of waveform increases, the required amplitude of wall motion actuator decreases with the increase of its length, but the residual U'_{rms} conversely increases.

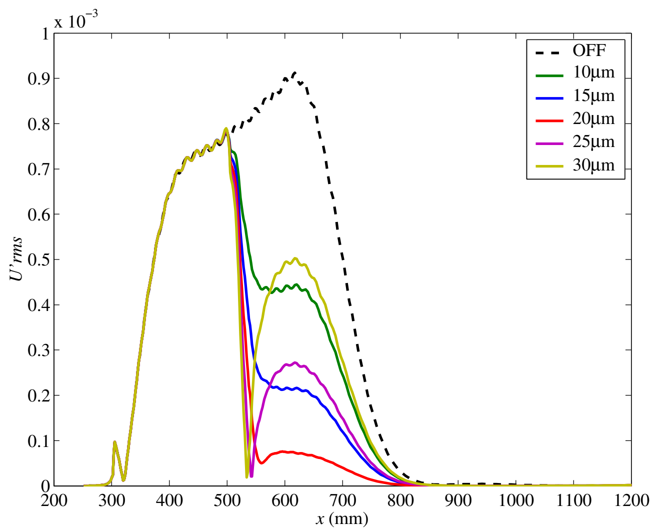

Figure 13 : Influence of SLW output amplitude (n=1)

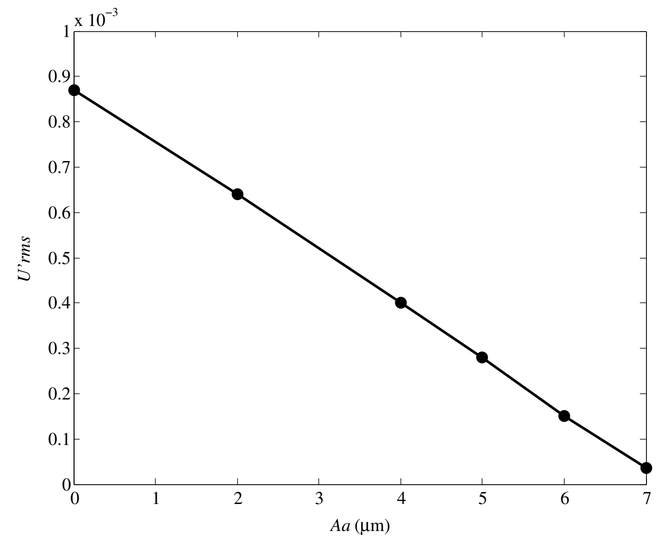

Figure 15 : Influence of SLW output amplitude (n=3)

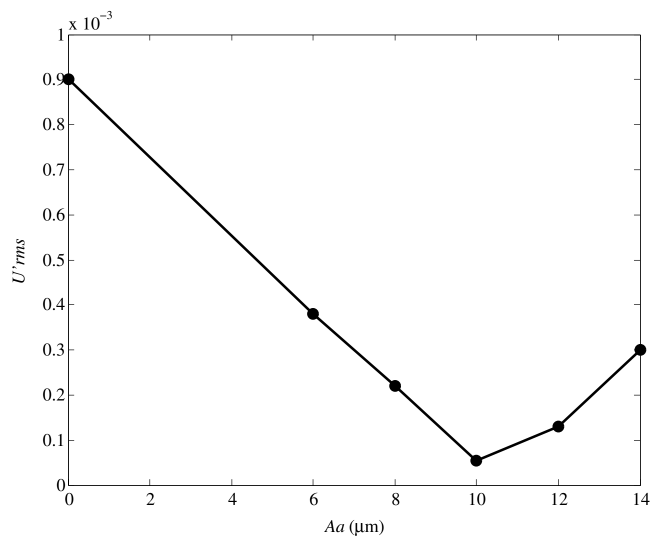

Figure 14 : Influence of SLW output amplitude (n=2)

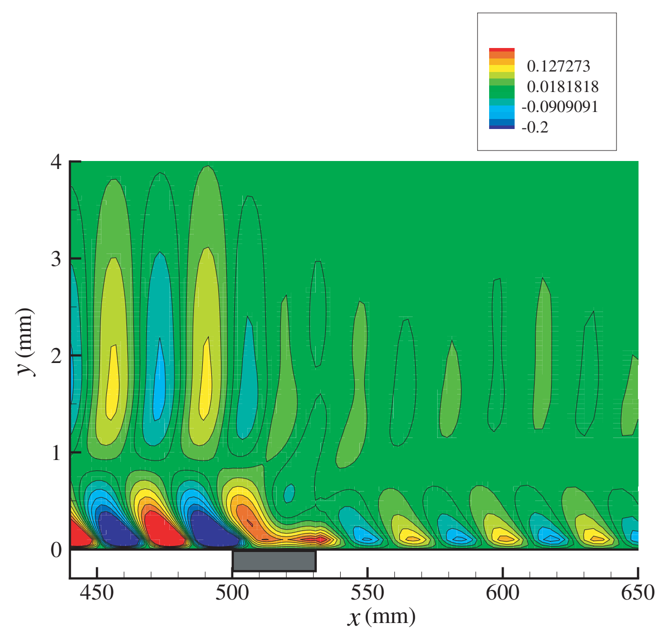

Figure 16 : Influence of STW output at n=1,$\tau = 5\pi/6$, $A_a = 3.5\mu$m

3.4 Control Using Standing Longitudinal Wave

The results of control using standing longitudinal wave (SLW) are shown in Fig. 12-15. Figure 12 indicates that the optimal phase of the single-waveform SLW wall motion actuator (n=1) is 11π/6. The distribution of U'_{rms} in the x direction is shown in Fig. 13 for different amplitude of surface motion when its phase is fixed at 11π/6. It is obvious that the best amplitude is 20 μm. When the amplitude is smaller than 20 μm, the T-S wave can not be sufficiently suppressed. On the other hand, the disturbance is quickly amplified again when the amplitude exceeds 20 μm. For the wall motion actuators with two (n=2) and three (n=3) cycles of waveform, the optimal amplitude is 10 μm and 7 μm respectively and the responding residual U'_{rms} is 0.55×10^{-4} and 0.36×10^{-4} respectively. As the number of waveform in the wall motion actuator increases, both the required amplitude and

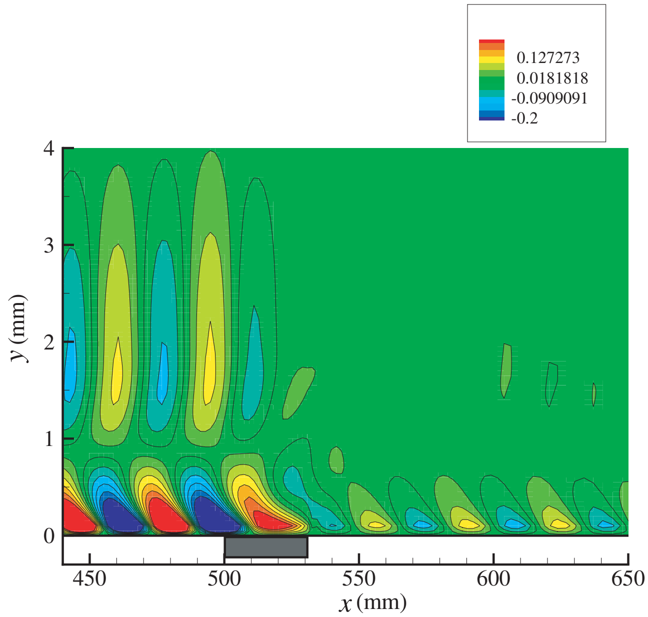

Figure 17 : Influence of TTW output at n=1, $\tau = \pi/2$, $A_a = 1.5\mu$m

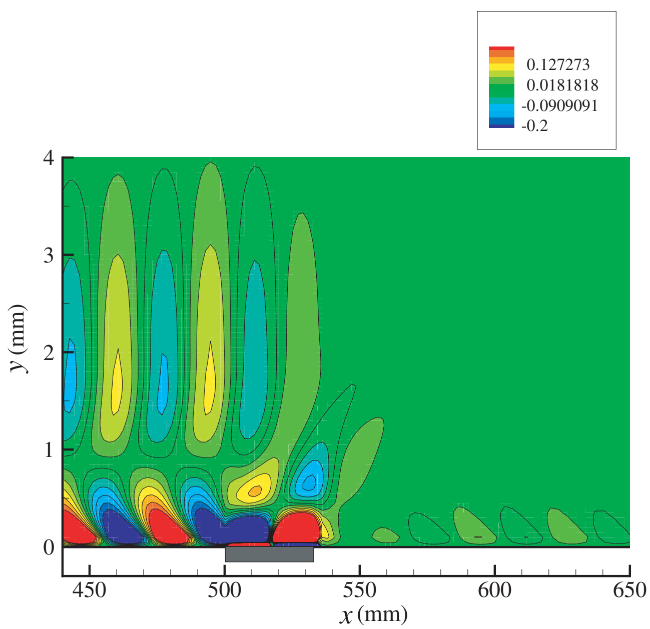

Figure 18 : Influence of SLW output at n=1, $\tau = 11\pi/6$, $A_a = 20\mu$m

the residual U'_{rms} decrease.

3.5 Comparison of Different Surface Motion

Obviously, the different surface motions of the wall motion actuator generate different effects on the fluid in the boundary layer. The STW and TTW wall motion actuators generate out-of-plane displacement, the effect of which is similar to that generated by applying an alternative pressure on the boundary. The effect of the SLW wall motion actuator is to give an alternative tangential shear velocity on the boundary due the no-slip condition. It can also be assumed that the effect of STW and TTW wall motion actuators transmitted by pressure from the boundary to the interior of flow, but the effect of the SLW wall motion actuator is transmitted by viscosity. Hence, the former two are usually more efficient than the later. Figures 16 to 18 show the variation of vorticity around the wall motion actuator. The vorticity distributions of STW and TTW wall motion actuators are similar, but that of the SLW wall motion actuator is very different. This is attributable to their different mechanism of suppression.

The optimal amplitude and control effect of the three type surface motion with 1 to 3 cycles of waveform in the suppression of T-S wave in a boundary are summarized in Tab. 2. All the residual U'_{rms} are sampled at 30 mm behind the rear end of the wall motion actuator and y=0.88 mm. It can be seen that for single-waveform wall motion actuators, the transverse standing wave requires least amplitude. The efficiency of control can be expressed by the inverse of the product of the residual U'_{rms} and required amplitude A_a, that is, e=1/($U'_{rms} \cdot A_a$), since the smaller the residual U'_{rms} and required amplitude A_a are, the larger the value of e is. From the viewpoint of efficiency, TTW wall motion actuator is best among the three in the case of n=1 and 2, but STW is the best in the case of n=3. From the viewpoint of smallest residual U'_{rms}, the three-cycle standing longitudinal wave is the best, but it requires much larger amplitude.

4 Conclusion

Three types of surface motion of wall motion actuators were proposed and their control effect for suppression of T-S wave in laminar boundary layer was investigated by numerical simulation. The numerical results indicate that although all the three types of surface motion can reduce the magnitude of the T-S wave in the boundary layer, their effectiveness depends on the type of surface motion and the length of the actuator. Due to their differ-

Table 2 : Comparison of residual U'_{rms} and the required amplitude A_a

n	STW output	TTW output	SLW output
1	1.80×10^{-4} (21.4%), 3.5μm	1.40×10^{-4} (16.7%), 1.5μm	0.58×10^{-4} (6.9%), 20μm
2	1.36×10^{-4} (15.5%), 1.5μm	1.56×10^{-4} (17.7%), 0.8μm	0.55×10^{-4} (6.25%), 10μm
3	0.50×10^{-4} (5.6%), 1.2μm	1.78×10^{-4} (19.8%), 0.5μm	0.36×10^{-4} (4.0%), 7.0μm

ent mechanism in the reduction of T-S wave, transverse wave is usually more efficient than the longitudinal wave, that is, the former needs less amplitude of surface motion than the later for the same amount of reduction. However, longitudinal wave yields smaller residual T-S wave than the transverse wave does.

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