Suppression of T-S Wave Using Wall Motion Actuator*

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In this study, numerical simulation was performed with the SIMPLER method on the amplification of Tollmien-Schlichting (T-S) wave in the boundary layer over a flat plate and its suppression with a wall motion actuator. The T-S wave was induced by the interaction between sound wave introduced by a speaker and a protuberance on the surface of the plate, and amplified in the unstable region of the boundary layer. The vertical vibration of a wall motion actuator was used to control the T-S wave. The influence of the amplitude and phase of actuator vibration on the control effectiveness was investigated in the simulation. The results show that the T-S wave can be effectively suppressed by the motion of the actuator surface if the phase and amplitude of the actuator are appropriately adjusted.

Key Words: Tollmien-Schlichting Wave, Wall Motion Actuator, Active Control, Boundary Layer

1. Introduction

The friction drag acting on an object in a flow field is significantly dependent on the state of boundary layer: laminar or turbulent. Laminar boundary layer control is a method for the reduction of friction drag by suppressing the transition of boundary layer and sustaining laminar boundary layer as long as possible, since the friction drag of a laminar boundary layer is much smaller than that of a turbulent boundary layer⁽¹⁾⁻⁽⁵⁾. When the turbulence in the main stream is very small, the amplification of Tollmien-Schlichting (T-S) wave in the unstable region of the boundary layer is the main cause for the transition of the boundary layer from laminar to turbulent.

In the previous research, the authors designed and made a wall motion actuator consisting of a layer of magnetic fluid, an elastic membrane and nine electromagnets for T-S wave control⁽⁶⁾. Wind tunnel test was performed on the control of T-S wave in the boundary layer over a plate with the developed actuator and the experimental setup as shown in Fig. 1. A tape of 0.7 mm high and 16 mm wide was attached on the surface of the plate at the position of 300 mm from the

leading edge of the plate. The T-S wave is induced by the two-dimensional disturbance generated by the interaction of the tape and the sound wave from the speaker on the upper wall of the wind tunnel. The magnetic fluid layer in the actuator is 3 mm thick and is covered by an elastic membrane. When AC current is applied to the coils, alternative magnetic force is generated in the magnetic fluid and the elastic membrane is driven up and down at twice the frequency of the electric current. The vertical motion of the actuator surface is used to control the T-S wave in the boundary layer.

Fig.1 Experimental setup

In this study, numerical simulation was performed on the amplification of T-S wave in the boundary layer over the plate and the mechanism of suppression due to the motion of the actuator surface. Since the effectiveness of

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control is dependent upon the amplitude and phase of vibration of the actuator surface, it is important to clarify these relationships for the future design of wall motion actuators with high performance.

2. Model and Computational Method

2.1 Computational area and grids

In order to compute the amplification and suppression of T-S wave in the boundary layer efficiently, the whole computational area was divided into two domains as shown in Fig. 2. The front domain starts at 156.6 mm upstream from the leading edge of the plate and the rear domain starts at 200 mm downstream from the leading edge. The rear domain shown in Fig. 3 is the main one, in which the tape and actuator are located and the amplification and suppression of T-S wave occur. The front domain was used for the auxiliary computation of the inlet boundary conditions of the rear domain. The length of both the front and rear domains is 1,144.8 mm in the stream direction and their height is 139 mm.

Both the front and rear regions were meshed with a grid of 305 points in x direction by 314 points in y direction. The coordinates of the grid points are defined in the following equations.

In x direction:

$$i \leq n_x \quad x(i) = x(i-1) + \Delta x \quad (1)$$

$$i > n_x \quad x(i) = x(i-1) + \left(1 + \frac{\alpha_x(i-n_x)}{100}\right) \Delta x \quad (2)$$

In y direction:

$$j \leq n_y \quad y(j) = y(j-1) + \Delta y \quad (3)$$

$$j > n_y \quad y(j) = y(j-1) + \left(1 + \frac{\alpha_y(j-n_y)}{100}\right) \Delta y \quad (4)$$

where i and j are the node number in the x and y directions, respectively. The parameters n_x , n_y , α_x , α_y , Δx , Δy are defined in Table 1. The flow in this region is supposed to be two-dimensional and incompressible, and the Navier-Stokes equations and the equation of continuity were solved using the SIMPLER-based method⁽⁷⁾, more detailed information of which can be found in reference⁽⁸⁾.

Table 1 Parameters for grids

	Total No. of node	$\Delta x, \Delta y$ (mm)	n_x, n_y	α_x, α_y
x direction	305	1.80	190	0.05
y direction	314	0.05	90	0.10

2.2 Modeling of sound wave and actuator

The disturbance used to induce the T-S wave was generated by the interaction of the sound wave from a speaker on the upper wall of the wind tunnel and the tape in the experiment. Based on the experimental result, the effect of sound wave is equivalent to 0.01–0.02% fluctuation of the mainstream velocity. The fluctuation of the mainstream velocity does not cause any affect on the main flow, but cause affect in the boundary layer. The affect of the fluctuating mainstream velocity in the boundary layer over a static plate is equivalent to the affect of the opposite-phase vibration of the plate with constant velocity of main flow. Hence, in the simulation the plate was given a small vibration in the stream direction but the mainstream velocity was assumed to be constant. The amplitude of the plate vibration was supposed to be 0.01% of the mainstream velocity U_∞ (≈ 9.9 m/s), and its frequency to be the same as that of the sound wave.

The actuator used in the experiment generated 4 or 5 cycles of standing wave when in-phase alternative currents were applied to even or odd numbered coils⁽¹⁾. In the simulation, the actuator was supposed to generate one cycle of standing wave, the displacement of which satisfies the following equation:

Table 2 Values of parameters

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_∞

Fig. 2 Computational area

Fig. 3 Rear domain

$$y = A_a \sin 2\pi \frac{x-l}{\lambda_{TS}} \sin 2\pi f_a (t-\tau) \quad (5)$$

where A_a is the amplitude of the actuator, λ_{TS} is wave length of T-S wave, l is the distance between the leading edge of the actuator and the leading edge of the plate, f_a is the frequency of the actuator, and τ is the time delay of the actuator vibration with respect to the vibration of the plate (phase delay is $\phi=2\pi f_a \tau$). The values of the parameters used in the simulation are shown in Table 2.

2.3 Boundary conditions

No-slip condition was used for the upper and lower solid boundaries of the front domain and symmetrical condition was used to the lower non-solid boundary upstream from the leading edge of the plate. Velocity conditions of $u=U_\infty$ and $v=0$ were used for the inlet boundary and free stream condition was used for the outlet boundary. As stated above, the front domain was only used in the auxiliary computation of the boundary conditions for the rear domain. The velocities u and v at $x=250$ obtained from the results of the front domain were used as the inlet boundary conditions of the rear domain. No-slip condition was used for the upper and lower boundary and free stream condition was used for the outlet boundary of the rear domain.

3. Evolution of T-S Wave

The flow field of the front domain was computed first and the distribution of u and v at the cross-section of $x=250$ mm was used as the inlet boundary condition of the rear domain. The velocities u and v are non-dimensionalized with respect to $U_\infty=9.9$ m/s, that is, $U=u/U_\infty$, $V=v/U_\infty$. The non-dimensional velocities U and V , which obey the Blasius distribution, are shown in Fig. 4.

When the plate is given a horizontal vibration, a disturbance is induced in the boundary layer by the interaction of the edge of the tape and the fluid. From the neural stability curve and the conditions of the flow and sound wave, it can be obtained that the unstable region is $257 \text{ mm} < x < 592 \text{ mm}$. Since the tape is located inside the unstable region, the disturbance induced by the tape is amplified in the form of T-S wave when it propagates downstream. Figure 5 shows the fluctuation of U , V and P at four points with $x=533.5$ mm, 569.5 mm, 610.4 mm, and 683.3 mm and $y=0.98$ mm. The vibration of the plate was started at $t=0$ ms. The larger the coordinate x of the point is, the later the T-S wave is observed due to downstream propagation. The propagating speed of the T-S wave can also be calculated from these results. The first three points are

located inside the unstable region and the amplitude of fluctuation is amplified in the downstream direction. However, since the forth point is located in the stable region in which the T-S wave decays, the amplitude of fluctuation at this point is smaller than that at the upstream neighboring point.

When the fluctuation of the main flow velocity is denoted by U' , the root-mean-square of U' , denoted by U'_{rms} , is defined as the intensity of turbulence as follows:

$$U'_{rms} = \sqrt{(U')^2} \quad (1)$$

The vertical distributions of the intensity of turbulence U'_{rms} at four cross-sections are shown in Fig. 6. The non-dimensional coordinate η in the vertical direction is defined as $\eta = y\sqrt{U_\infty/\nu x}$. The intensity of turbulence reaches its maximum at around $\eta = 1.0$ and minimum at around $\eta = 3.5$. From the time history of velocity fluctuation, it can also be seen that the phases of U' below and above $\eta = 3.5$ are opposite.

The estimated propagation speed of the T-S is about

(a) Velocity U

(b) Velocity V

Fig. 4 Vertical distribution of velocity at $x=250.0$ mm

(a) Time variation of U (b) Time variation of V (c) Time variation of P Fig. 5 Variation of U , V , P with time

3.3 m/s, one third of the mainstream velocity. The results agree with characteristics of T-S wave. From Fig. 6, it can also be seen that the intensity of turbulence

Fig. 6 Distribution of U'_{rms}

Fig. 7 Amplification of T-S wave

increases ahead of $x = 610.4$ mm, but decreases behind that point. This result also agrees with the theoretical results of the unstable region.

The horizontal distribution of the intensity of turbulence at $y=0.88$ mm is shown in Fig. 7 for different amplitudes of the plate vibration (0.01%, 0.02% and 0.03% of the main flow velocity). For all the three amplitudes of the plate vibration, the intensity of turbulence reaches the maximum at $x=616.1$ mm. It can be seen that the maximum value of intensity U'_{rms} is 0.001 for 0.01% amplitude, 0.002 for 0.02% amplitude and 0.003 for 0.03% amplitude, that is, the intensity of turbulence is in direct proportion to the amplitude of the plate vibration.

4. Suppression of T-S Wave

In this section, suppression of T-S wave using the motion of the actuator surface is investigated. As shown in Table 2, the actuator is located between $x=500$ mm and $x=532$ mm. It was also supposed that the frequency of the actuator vibration equals the frequency of T-S

Fig. 8 Influence of actuator phase

Fig. 9 Influence of actuator amplitude

wave (104 Hz) and the shape of actuator surface is always a full cycle of standing sine wave.

First, the variation of the intensity of turbulence was investigated when the phase delay of the actuator motion with respect to plate vibration is changed from 0 to 2π (or time delay from 0 to 9.6 ms), but the amplitude of the actuator is fixed to 0.0035 mm. Figure 8 shows the simulation result of turbulence intensity U'_{rms} at $x=616.1$ mm and $y=0.88$ mm. The horizontal dotted line is the intensity of turbulence in uncontrolled state. The intensity of turbulence was reduced for the time delay between 2.3 ms and 5.5 ms (or the phase delay between $10\pi/21$ and $24\pi/21$), but it was amplified for the other phases. When the phase delay is $5\pi/6$ (or 4 ms), the best control effect is achieved.

Next, the variation of the intensity of turbulence was investigated when the phase delay was fixed to $5\pi/6$, but the amplitude of the actuator was changed from 0.002 mm to 0.005 mm. The result of intensity at the same point is shown in Fig. 9. The intensity of turbulence is a function of the amplitude of the actuator and reaches minimum at the amplitude of 0.0035 mm.

Figure 10 shows the time history of U at four points

(a) Phase delay $5\pi/6$ (b) Phase delay $11\pi/6$ Fig. 10 Variation of U with time

Fig. 11 Suppression of T-S wave

with $x=533.5$ mm, 569.5 mm, 610.4 mm, and 683.3 mm and $y=0.88$ mm for two different phases of actuator motion. The amplitude of actuator is 0.0035 mm and the phase delay is $5\pi/6$ for Fig. 10(a) and $11\pi/6$ for Fig.

(a) $\tau=4.0$ ms, $A_a=0.0035$ mm (b) $\tau=8.8$ ms, $A_a=0.0035$ mm

Fig. 12 Influence of actuation on vorticity

10(b). The amplitude of T-S wave was reduced for the phase delay of $5\pi/6$, but it was amplified for the phase delay of $11\pi/6$ after the actuator was turned on. It can also be observed from the figure that the affect of the actuator was delayed in the downstream direction because of the time needed for the propagation of T-S wave.

Figure 11 shows the distribution of the intensity of turbulence in the x direction at the height of $y=0.98$ when the actuator is driven at the two different phases. The distribution of the intensity without control is also shown in the same figure for comparison. The intensity is reduced by about 90% due to the motion of the actuator when the phase delay is $5\pi/6$, but the intensity is almost doubled when the phase delay is $11\pi/6$. In the case of $5\pi/6$ phase delay, the intensity increases again, though slightly, in the unstable region behind the actuator. Since the unstable region is very short under the flow conditions used in the study, the T-S wave decays immediately outside the unstable region and no

further control is required. For certain flow conditions, the unstable region can be very long and the T-S wave can be amplified to relatively large amplitude again behind the actuator. In these cases, it is necessary to use multiple actuators aligned in the surface of the plate to consecutively control the T-S wave in the stream direction.

Figure 12 shows the vorticity in the flow field when the actuator is driven at the phase delays of $5\pi/6$ ($\tau=4$ ms) and $11\pi/6$ ($\tau=8.8$ ms), respectively. It can be clearly seen that the vorticity is reduced for the phase delays of $5\pi/6$ but intensified for the phase delays $11\pi/6$. These results are in agreement with the suppression and amplification of the T-S wave.

5. Conclusion

Simulation was carried out on the amplification of T-S wave in the boundary layer over a plate and the suppression process with a wall motion actuator. The following results were obtained from the simulation:

- (1) The amplification of T-S wave behind a vibrating protuberance was computed, and the fluctuation of velocity and the distribution of the intensity of turbulence were obtained.
- (2) The suppression of T-S wave with the vibration of actuator surface is computed. The influence of the actuator phase and amplitude on the distribution of the intensity of turbulence was clarified by the simulation results.

6. References

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