Active Transition Fixing and Control of the Boundary Layer in Air

Lucio Maestrello*
NASA Langley Research Center, Hampton, Virginia

Active transition of flow over an airfoil surface and feedback control by sound is investigated in a wind tunnel. Laminar instability forced by a localized, time-dependent, nonintrusive narrow heating strip causes abrupt changes in velocity to trigger instant transition with a favorable pressure gradient. At zero- and adverse-pressure gradients these changes are only marginal. Feedback control by sound interaction at nearly normal incidence produces significant reduction in velocity perturbation in regions of transition. This reduction is partially at the expense of an increase in background disturbance since it is not possible to restore the flow to its undisturbed state.

Introduction

ACTIVE control on an airfoil leading edge with transition fixing by surface heating and feedback control by sound is investigated in a wind tunnel at the California Institute of Technology (Caltech). The experiment was motivated by the work of Liepmann et al.[1] on the control of laminar boundary-layer instability in a water tunnel. In their experiment, heating strips were used to excite instability waves, and the cancellation of these was obtained with an out-of-phase component.

Liepmann and Nosenchuck,[2] in an extension of their work, used a hot-film surface sensor to measure the fluctuations in the boundary layer, and from this they synthesized a signal to drive the cancellation disturbances. This gave them an active feedback control of transition. In addition, Nosenchuck et al.[3] demonstrated experimentally that active heating is an effective means for transition fixing in air.

A heuristic argument was presented by Liepmann and his colleagues to explain the equivalence between heat flux and the velocity at the wall, since the coupling between the thermal and mechanical effects is provided by the dependence of viscosity on temperature. There is an extra term in the momentum equation for an incompressible boundary layer representing an increment of momentum. The resulting profile becomes fuller near the wall with a thinner displacement thickness, and hence more "favorable." An analysis of this problem by the method of match asymptotics as a "triple deck" is reported by Maestrello and Ting.[4] The analysis confirms that small amounts of active surface heating in water can excite local disturbances, which increase the momentum near the wall and make the velocity profile fuller by reducing the displacement thickness. These effects are considered favorable for delaying the onset of instability and separation.

The effect of boundary-layer stabilization differs between air and water:

$$\frac{\mathrm{d}\mu}{\mathrm{d}T}>0 \quad \text{for air}, \quad \frac{\mathrm{d}\mu}{\mathrm{d}T}<0 \quad \text{for water}$$

The temperature viscosity coupling is stronger for water than air. A small temperature change of 5°C created by a few narrow strips (a total width of 4–8 times the displacement thickness) can effectively excite or control waves in water.[5] For air, instead, the temperature viscosity coupling is much weaker, thus requiring high temperature to impart an equivalent perturbation. The kinematic viscosity ratio between air and water (at ambient temperature) is approximately

$$\frac{\nu_a(T)}{\nu_w(T)} \approx \frac{u_a}{u_w}\left(\frac{r^2}{\ell}\right)^{-1/3} \approx 17$$

expressed in terms of velocity u, Reynolds number ratio $r=Re,_a/Re,_w$ based on L, and heater width $\ell=L_a/L_w$. Similarly, the frequency response between air and water is

$$\frac{f_a}{f_w} \approx \frac{\nu_a(T)}{\nu_w(T)}\left(\frac{r^2}{\ell}\right)^{2/3}$$

and the overheat ratio

$$\frac{\Delta T_a}{\Delta T_w} \approx 11(r)^{1/2}(\ell)^{-1/3}$$

Heating elements in air, therefore, must be capable of substaining much higher temperatures than in water. In addition, the heat flux is given by

$$q_a/q_w \approx \tfrac{1}{2}(r)^{2/3}(\ell)^{-1/3}$$

These considerations suggest that steady-state excitation in air is more difficult to achieve than in water.

The present experiment is conducted in air, and is designed to demonstrate that surface heating can be used to trigger single, small-amplitude disturbances as well as broadband, large full transitional ones. A thin nonintrusive heater strip is heated electrically with frequency ω and the power is proportional to $\cos^2\omega t$. The temperature deviation of the strip is composed of steady and unsteady terms with amplitude and frequency 2ω. By adjusting the frequency and the phase of the wall temperature fluctuations, the induced disturbance in the boundary layer can be controlled, thus the Tollmien-Schlichting (TS) waves can be enhanced or annihilated. Both steady and unsteady oscillation terms contribute to boundary control, but they play different roles. The steady term depends on the sign ΔT for heating or cooling and on $\mathrm{d}\mu/\mathrm{d}T$ for air or

Presented as Paper 85-0564 at the AIAA Shear Flow Control Conference, Boulder, CO, March 12-14, 1985; received April 23, 1985; revision received Dec. 16, 1985.

*Aerospace Technologist; formerly Visiting Associate, Graduate Aeronautical Laboratories, California Institute of Technology. Associate Fellow AIAA.

water, while the unsteady term depends on frequency and phase. We also demonstrate experimentally that large unsteady disturbances in the boundary layer can be controlled by sound interaction with the flow via a feedback mechanism between the heating element and the sound generator. This control reduces drastically the unsteady perturbations in the boundary layer, however, we are unable to recover the original undisturbed state.

Analysis of Flow Excitation by Surface Heating

The analysis must begin with the energy equation, even for an incompressible flow. The problem deals with a sudden change in the thermal boundary condition which, in turn, creates a disturbance field in the boundary layer. Details of the analysis for temperature, velocity, and pressure disturbances to the local surface heating have been presented by Maestrello and Ting[4] using the method of matched asymptotics as a "triple-deck" problem.

The governing equations for $u^2(x,y,t)$, $v^2(x,y,t)$, $T^1(x,y,t)$, and $p^{(3)}(x,t)$, corresponding to velocities, temperature, and pressure are shown below. The superscripts indicate the order of the perturbation in the expansion schemes:

$$\bar{u}_x^{(2)} + \bar{v}_{\bar{y}}^{(4)} = 0 \tag{1}$$

$$\bar{u}_t^{(2)} + \beta\bar{y}\bar{u}_x^{(2)} + \beta\bar{v}^{(4)} = -p_x^{(3)}(x,t) + \bar{\mu}_{\bar{y}\bar{y}}^{(2)} + \Lambda\beta\bar{T}_{\bar{y}}^{(1)} \tag{2}$$

$$\bar{T}_t^{(1)} + \beta\bar{y}\bar{T}_x^{(1)} = (Pr)^{-1}\, T_{\bar{y}\bar{y}}^{(1)} \tag{3}$$

$$p_x^{(3)}(x,t) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{A_\xi(\xi,T)\mathrm{d}\xi}{x-\xi} \tag{4}$$

where Λ is equal to $\mathrm{d}\ell_n\nu/\mathrm{d}\ell_n T$, Pr is the Prandtl number at T_0, and β is the slope of the velocity profile at the wall. For the Blasius profile, $\beta = 0.33206$. Notice the $\Lambda\beta T_y^{(1)}$ dependency of u and T due to the forcing term for $u^{(2)}$, $v^{(4)}$, and $p^{(3)}$. $A\xi(\xi,t)$ is given by Hilbert transforms,[4] and

$$A(x,t) = \beta^{-1}\bar{u}^{(2)}(x, y \to \infty, t)$$

On the heating strip it is assumed that

$$T^{(1)} = (T_w - T_0)/\epsilon T_0 = 1 + \cos\omega t$$

This analysis provides the solution of the velocity and pressure distributions at low nondimensional frequency, $\bar{\omega} \ll 1$. If the frequency is finite, $\bar{\omega} \approx \mathcal{O}(1)$, the full unsteady analysis has to be carried out. In the usual linearized incompressible equations, the unsteady term and the last term in Eq. (2) are absent; the energy equation for temperature is not needed for the solution of the velocity disturbances.

Experimental Apparatus

The experiment was conducted in a wind tunnel at Caltech with a 45×45 cm test section with speeds up to 12 m/s. The model tested was an elliptic airfoil with a 1:1 leading-edge profile, thickness $h = 1.4$ cm, and chord $c = 35$ cm made of plexiglass (Fig. 1). The model was instrumented with pressure taps, a hot-wire anemometer, and a surface microphone. The microphone and hot wire were located 25 cm from the leading edge. The rear portion of the airfoil had an adjustable flap used to position the stagnation point at the leading edge, as well as for varying the pressure gradient. The airfoil spanned the width of the tunnel supported by two lateral straps from above. A loudspeaker placed above the airfoil and mounted on the tunnel wall (Fig. 2) was used to excite the flow.

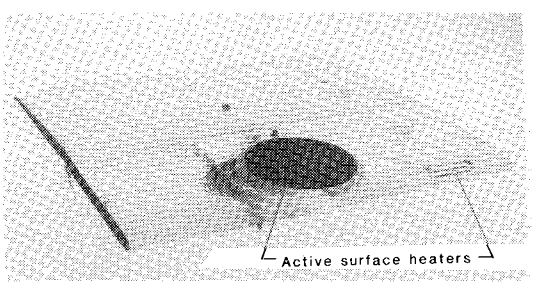

Fig. 1 View of the airfoil.

Experimental Considerations

The wind tunnel used was a reasonably quiet, low turbulence facility; the flow about the airfoil was laminar over 75% of the chord. The experiment was conducted at three different speeds: 4.5, 5, and 12 m/s, corresponding to 1.22, 1.81, and 3.62×10^6 Re/m. The surface pressure measurements were made over 75% of the chord; the data not shown follows reasonably the calculated values except in the vicinity of the stagnation point, Fig. 3.

The active surface heaters were developed at Caltech based on experience gathered at the Aeronautical Laboratories over the past few years. The heaters used in the present experiment were designed based on the same principle. The heaters were mounted on the airfoil, as shown in Fig. 1. The leading-edge heaters were 0.076-cm-thick, 0.125-cm-wide, and 5.08-cm-long Nichrome strips embedded in a ceramic substrate flush with the surface. The resistance varied between 3 and 4 Ω, the frequency response varied from dc to 10,000 cps with an upper temperature limit of 1100°C.

The first set of heaters was mounted over the curvatures of the leading edge (a double strip heater) at $x/c = 0.015$ and behind another double strip at $x/c = 0.03$. These heaters were placed in a region of favorable pressure gradient (the flow accelerates due to the curvature). The coupling between heat flux and the flow was large in this region, thus the flow was highly receptive to outside influence. This is an important region of the flow for external excitation.

The heaters on the circular substrate, Fig. 1, were constructed by vacuum deposition, a uniform layer of palladium over the surface of a high-temperature substrate, on a glass-reinforced epoxy resin board. The palladium was then etched

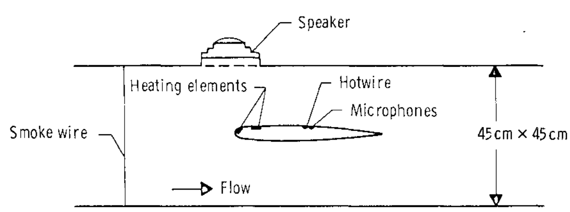

Fig. 2 Test configuration.

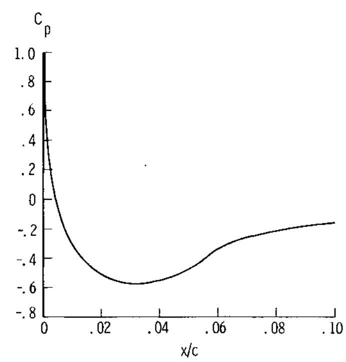

Fig. 3 Pressure distribution about the leading edge: $U_\infty = 12$ m/s; $\alpha = 0$ deg.

by photolithographic technique except for the rectangular-shaped elements shown in the figure. The first strip was located at $x/c = 0.11$, and the last at 0.26 from the leading edge. These heaters were not as durable as the one made by Nichrome strips. The operating temperature of these heaters was less than 300°C limited by the substrate material. Because of the limited temperature, the final experiment was conducted using Nichrome heaters embedded in a ceramic substrate similar to those at the leading edge.

A high-quality power amplifier was used to drive the heaters. A function generator provided the selected frequency to the power amplifier. An equivalent system was used to drive the loudspeaker including a feedback control system.[6] The boundary layer was excited by the surface heater, and the subsequent growth was controlled by sound. Three types of excitations were used in the experiments: single frequency, wave packet, and random. Since the Reynolds numbers were too low to amplify developing disturbances naturally, the wave-packet excitation was selected in most of the test runs for rapid growth.

Results of the Analysis

Numerical results of the pressure variation were obtained for both water and air for steady and quasisteady solution ($\bar{\omega} \ll 1$) induced by a simple heating strip of width $\Delta x = 0.75$. The overheat values for temperature change ΔT, Prandtl number Pr, and Λ are given in Table 1.

The pressure distribution $p^{(3)}$ is plotted in Fig. 4 for water with $\Delta T = 10$°C and air with $\Delta T = 10$ and 100°C with distance x. ΔT is the temperature of the heating strip above the plate temperature. For $x < 0$, the pressure distribution decreased slightly below zero for water and then increased drastically over the heating strip reaching a maximum at the end of the strip, and decreased drastically downstream. For air, the effect was opposite to that of the water. Heating in water stabilized, while in air it destabilized since $d\mu/dT$ is less than zero for water and greater than zero for air. In addition, for an equal temperature of $\Delta T = 10$°C, the resulting pressure variation for air was approximately one-tenth that of the water, indicating that heating in air needs ten times the water temperature for an equivalent pressure amplitude (of opposite sign). The results can be extended to multiple strips; in Ref. 4, Maestrello and Ting show that in water two strips can be used more effectively for control or for amplification. The contribution from the steady-quasisteady terms depends on the size of ΔT and $(d\mu/dT)$, while the unsteady terms depend on the frequency and phases relative to Tollmien-Schlichting waves and can be used either to cancel or enhance the incoming disturbance.

Table 1 Overheat values for temperatures change, Prandtl number, and Λ

	ΔT, °C	Pr	$\Lambda = (T/\nu)\,(d\nu/dT)$
Water	10	9.5	−0.72
Air	10	0.72	1.535
	100	0.72	16.52

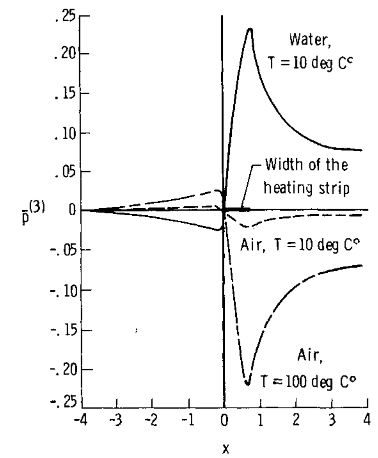

Fig. 4 Wall pressure variations due to a single heating strip in water and air.

Results of the Experiment

Flow Visualization

Flow visualization about the leading edge using smoke wire at a speed of 12 m/s is shown in Figs. 5a and 5b, at 6 m/s in Fig. 5c, and at 4.5 m/s in Fig. 5d. The flow is laminar; in Fig. 5a, is is unexcited, while in all of the other figures the flow is excited by sound at frequency of 300 cps at the same acoustic pressure level (Fig. 2). As the speed decreases (Figs. 5b to 5d) the wavelength decreases, the phase is preserved across the test section, and the flow maintains a uniform profile ahead of the leading edge. During the initial part of the experiment the appearance of waviness in the smokeline was surprising. The explanation was not immediately known. It is now clear, however, that the origin was due to the vibration of the smoke wire in the primary mode when excited by sound. Smoke visualization was used to determine the type of flow that exists in the presence of sound in the vicinity of the active heater elements as well as at the leading edge.

Acoustic Excitation

The objective of the first part of the experiment was to determine the response of the flow to sound, and the last part to use sound as a means of controlling the flow. The outcome was to provide information on the coupling, which in turn was used to develop the control mechanism either by phase or by broadband interaction. Three types of acoustic interactions were investigated: pure tone, wave packet, and random noise. The response was measured with a hot wire (H.W.) and microphone (M) together with the response of the unexcited boundary layer, Fig. 6. A remarkably clear, distinct response of the hot wire and microphone to the excitation field is shown, indicating that the laminar flow was weakly coupled to sound in many regions of the flow except at the leading edge as seen in the next section.

Active Transition Fixing

Results of the velocity perturbation (H.W.) from the excitation of a wave packet by surface heating heater output (H.O.) in a laminar boundary layer in regions of adverse, favorable, and zero pressure gradients at speeds of 4.5 and 12 m/s are shown in Figs. 7, 8, and 9, respectively. In the regions of favorable pressure gradients, (Figs. 7 and 8), due to the curvature of the leading edge, the flow stretches and becomes mostly receptive to outside influence. As a result of the surface

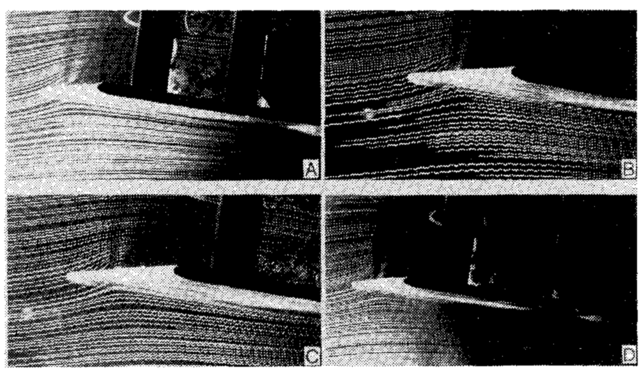

Fig. 5 Flow about the leading edge. a) unexcited; b–d) excited by sound, $f = 300$ cps.

heating at $x/c = 0.015$, the flow easily couples (Figs. 7b and 7c) and the hot-wire output distinctively shows a burst of vorticity in each packet. Even at reduced input power to the heater from 3.5 to 2.5 A the burst of vorticity still has significant amplitude. Figure 7a shows the unperturbed state for comparison. At a higher speed of $U = 12$ m/s (Fig. 8), a significant increase in perturbation can be seen. A comparison is again made with the unperturbed state at the same speed.

The wave pattern response at 12 m/s no longer follows successively the trigger of the regular occurrence of the packet signal input, but rather a definite explosive independent random pattern typical of the laminar turbulent transition.

A collection of results suggests that active heating can perhaps be efficiently used for transition fixing for an airfoil.

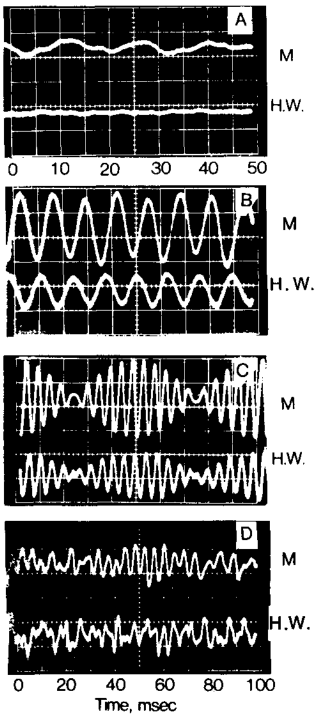

Fig. 6 Amplification caused by sound. a) no sound, b) pure tone, c) wave packet, d) random noise.

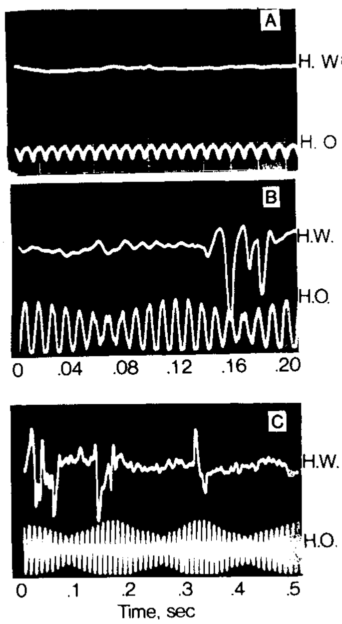

Fig. 7 Velocity perturbation amplitude caused by heating: a) unexcited; b) and c) excited. $U_\infty = 4.5$ m/s; $x/c = 0.015$.

The elements are nonintrusive in addition to being amplitude- and frequency-sensitive. Thus, this type of device is favored over a passive one. Prior to this experiment at Caltech, Nosenchuck et al.[3] experimentally demonstrated active transition fixing over a body of revolution in air and indicated the advantage over the passive intrusive types. These two experiments demonstrated the practicality of triggering transition in air in regions of favorable pressure gradient, an effective region to locate laminar-turbulent transition.

To illustrate the behavior in the region of the zero-pressure gradient, the velocity perturbations caused by surface heating at $x/c = 0.11$ and 0.26 is shown in Fig. 9. It is clear that smaller changes occur; the response of the hot wire is no longer as sensitive as in the region of favorable gradients. This experiment indicates that the sign of the pressure gradient determines the degree of flow receptivity. The signature of the hot-wire output differs markedly from the early burst, the frequency response increases and the amplitude decreases (Figs. 9a and 9b). For these reasons, the flow is excited by the heater with a variety of input signals over a broad range of frequency (see, for example, the heater input of Fig. 9b). In order to improve the signal-to-noise ratio, heated input was increased by 30%, which caused an increase in background disturbances. In conclusion, these results show that it is indeed much harder to excite a disturbance in flow regions where the pressure gradient is zero.

Boundary-Layer Control by Sound

The effectiveness of the boundary-layer control by sound interaction was determined in a flow region where the amplitude was no longer small; the flow was transitional

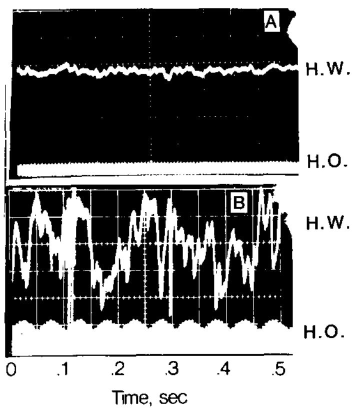

Fig. 8 Velocity perturbation amplitude caused by heating: a) unexcited; b) excited. $U_\infty = 12$ m/s; $x/c = 0.015$.

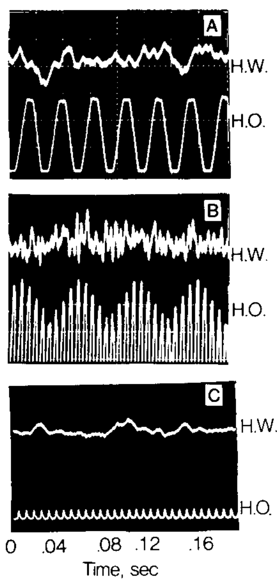

Fig. 9 Velocity perturbation amplitude caused by heating: a) at $x/c = 0.11$, b) at $x/c = 0.26$, and c) excited.

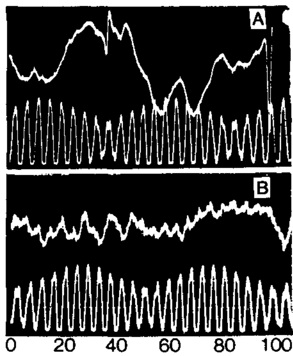

Fig. 10 Velocity perturbation amplitude a) caused by heating and b) controlled by sound. $U_\infty = 4.5$ m/s; $x/c = 0.015$.

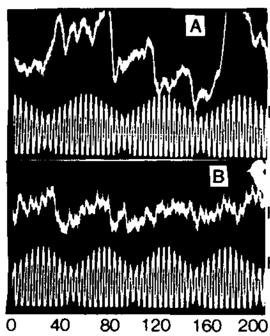

Fig. 11 Velocity perturbation amplitude a) caused by heating and b) controlled by sound. $U_\infty = 12$ m/s; $x/c = 0.015$.

caused by an abrupt change in surface heating. Comparison between the control and the uncontrolled state is shown in Figs. 10 and 11 at two different speeds. It is evident that a dramatic amplitude reduction was achieved. Similar reduction was also noticed with different input, since the experiments were conducted with wave-packet, pure-tone, and random signatures showing in all three cases a broad yet lower frequency control.

The output signature of the hot wire after control was no longer comparable to its uncontrolled state. At the control output the amplitude of the lower frequencies was reduced drastically at the expense of an increase in background disturbance dominated by the higher frequencies; thus, it was clear that it would not be possible to completely return the flow to its undisturbed state. The experiment can be enlarged by considering the full scattering problem; one must keep in mind, however, that we are dealing with a full coupled field with a gradient in the flow. One can match the two frequencies, which describe the packet of the heater to that of the speaker output, and determine the response over a variety of wavelengths that do not match. In actuality, this is the experimental setting.

Resuts observed thus far are encouraging, in fact, by matching frequencies and amplitude in a feedback loop between heater and speaker outputs, within a narrow adjustable delay window, changes in amplitude are observed including the lock-in-into a self-control cycle. Several causes prevent us from utilizing the full feedback circuitry; some are control-related, others are facility-related. It is necessary, therefore, to find a feedback rule for applying cooling, heating, or sound such that the stresses in the flow are minimized; a challenging problem in a boundary controlled by a distributed-parameter system. Other efforts require a test section with acoustically absorbing sidewalls over a broad range of frequencies.

Concluding Remarks

In the region of the favorable pressure gradient, the flow is highly receptive to surface heating and one can easily trigger small- or large-amplitude disturbances as well as impart "instant" transition. This is an important region of the flow, and could be utilized to trigger transition to "augment" airfoil maximum lift.

Interaction of sound at near-normal incident with transitional flow reduces the amplitude "significantly." This is an effective way to control the amplitude of transition. The method is most effective when the frequencies of the disturbance in the flow match those of the acoustic interaction.

The flow in the region of zero-pressure gradient, which is a large region of the flow, is indeed "weakly coupled" to sound. Theoretically one needs to incorporate the effect of pressure gradient on receptivity, a helpful addition for attaining new guidelines for future experiments.

Acknowledgments

Research for this paper was conducted at the Graduate Aeronautical Laboratory under the NASA Langley Floyd L. Thompson Fellowship. Thanks to Professor Anatol Roshko for his advice and for the opportunity to use his facility, and to the Aeronautical Laboratory shop personnel for the construction of the hardware components. The author gratefully acknowledges Professor Hans Liepmann, Mr. Steve Taylor, and Mr. Harry Robey for their support and advice. Thanks to Mr. Cecil Stephens for the expert craftsmanship in the construction of the active transducers, and to Dr. Paresh Parikh for computational support.

References

[1]Liepmann, H. W., Brown, G. L., and Nosenchuck, D. M., "Control of Laminar-Instability Waves Using a New Technique," *Journal of Fluid Mechanics,* Vol. 118, 1982, pp. 187-200.

[2]Liepmann, H. W. and Nosenchuck, D. M., "Active Control of Laminar-Turbulent Transition," *Journal of Fluid Mechanics,* Vol. 118, 1982, pp. 201-204.

[3]Nosenchuck, D. M., Bettes, W. H., and Liepmann, H. W., "Active Transition Fixing," private communication, 1983.

[4]Maestrello, L. and Ting, L., "Analysis of Active Control by Surface Heating," *AIAA Journal,* Vol. 23, July 1985, pp. 1038-1045.

[5]Nosenchuck, D. M., "Active and Passive Control of Boundary Layer Transition," Ph.D. Thesis, California Institute of Technology, Pasadena, 1982.

[6]Lyons, J. L., *Optimal Control of Systems Governed by Partial Differential Equations,* Springer-Verlag, 1971.