Transition Control of Instability Waves Over a Flexible Surface in the Presence of an Acoustic Field
L. Maestrello and F. Grosveld, NASA-Langley, Hampton, VA
TRANSITION CONTROL OF INSTABILITY WAVES OVER A FLEXIBLE SURFACE IN THE PRESENCE OF AN ACOUSTIC FIELD

L. Maestrello*
NASA Langley Research Center
Hampton, Virginia

F. W. Grosveld*
Lockheed Engineering and Sciences Co.
NASA Langley Research Center
Hampton, Virginia

Abstract

Experimental results are presented which demonstrate the coupling of a laminar boundary layer flow with a typical flexible aircraft panel. It is shown that the boundary layer induces plate oscillations which, in turn, perturb the flow at the same frequencies. This feedback mechanism is an inherent property of laminar boundary layer flow passing over a flexible plate. As a result, the flexibility of the plate becomes a source of early transition. The laminar boundary layer at the leading edge of the plate reacts to small, upstream, unsteady disturbances due to a streamwise pressure gradient. The experiments demonstrate that a nominal sound pressure incident at the leading edge triggers early transition. It is shown that transition can be delayed by activating a heat source at the leading edge of the plate which results in downstream cooling.

Introduction

The coupling of flexible surface oscillations with the boundary layer as a means of controlling skin frictional drag has been investigated since the 1960's by Landahl,1 Kramer,2 Wehmann,3 Gyorffy4 Lauber and Maestrello,5 and by others, both in air and in water. The problem has recently been worked by Breur, Haritonidis, and Landahl.6

In the late 1950's and early 1960's Van Driest and Boison,7 Wisniewski and Jack,8 and Reshotko9 found that the transition Reynolds number increases with a decrease in wall temperature. A transition Reynolds number increasing with cooling is in agreement with the prediction by Lin's linear stability theory for the first mode in compressible flow.10 However, Mack11 shows that cooling does not stabilize the highest inviscid modes. McCroskey12 used localized surface heating at the leading edge of a plate to delay transition at low speeds. Liepmann and Nosenchuck13 used a feedback mechanism to demonstrate the delay of the transition in water. An analysis of this problem by the method of matched asymptotes as a triple deck was reported by Maestrello and Ting.14 Similar studies were conducted experimentally in air by Maestrello15 and by Struminski et al.,16 and numerically in water by Kral.17 Recently the experimental technique has been expanded from delaying transition18 to controlling turbulence over a plate.19 Numerically, transition delay over flat and curved surfaces has been studied and extended to control separated flow over an airfoil.20-22 Research into the problem of viscous drag reduction in boundary layers has been summarized in a 1989 publication edited by Bushnell and Hefner.23

Instability waves leading to the transition process have been observed to be the result of traveling Tollmien-Schlichting waves imposed on the free stream velocity by the vibration of the leading edge of the plate.24,25 This process is not very well understood. In addition, acoustic waves are known to be transformed into Tollmien-Schlichting waves at a rigid leading edge. These receptivity problems, a term suggested by Morkovin,26 have been investigated by Tam,27 Kachanov, Kozlov and Levchenko,28 Goldstein,29 Lawson,30 Bechert,31 Singurson and Roshko,32 Domaradski and Metcalfe,33 Carpenter,34 Yeo and Dowling,35 Kerschen,36 Shapiro,37 Gapanov38 and others. In these studies, the path to transition has been by a single wave interacting with itself causing distortion or interacting with other single waves causing resonances. Comprehensive investigations of different types of excitations that will generate Tollmien-Schlichting waves are needed to understand the practical applications with regard to boundary layer control. One of these is the laminar boundary layer over a flexible plate. A larger number of instability modes are present in a laminar boundary layer over a flexible surface than in a laminar boundary layer over a rigid surface because of the coupling of the panel vibration and the boundary layer. Acoustically induced disturbances from upstream accelerate the laminar boundary layer into transition by forcing the flexible plate to respond with a relatively high amplitude and with a large number of resonance modes. Localized heating at the leading edge alters the growth of the instabilities due to progressive cooling downstream.19,39 As a result, the flow stability is increased by the modifications of the velocity and temperature profiles along the boundary layer. The present work indicates that plate flexibility can induce early transition and shows the combined effects of an incident acoustic wave and surface heating near the leading edge on the boundary layer along a flexible surface.
The purpose of this paper is to report on three related boundary layer experiments with a rigid surface containing a flexible panel. These experiments consider:

1. the instability growth in a laminar boundary layer due to plate vibration;
2. the amplification of instability waves in a laminar boundary layer due to upstream sound; and
3. the delay of transition due to localized upstream surface heating.

**Flow Validation**

The experiments were conducted in an open circuit wind tunnel with a 15 x 15 inch test section and a maximum speed of 120 ft/sec. The 15 x 110 x 1 inch rigid test plate features an elliptical leading edge. The center part of the plate has a section cut out to enable the installation of a 12 x 8 x 0.040 inch flexible aluminum plate with clamped edges. Figure 1. Note that the lower side of the flexible plate is covered by a streamlined rigid surface so that the plate is exposed to the flow only at its upper surface. Flow control is accomplished using a thin, electrically heated nickel-chrome wire embedded in a substrate (space shuttle tile) at the leading edge. The heater wire can be operated in both AC and/or DC modes. A hot wire, a microphone, an accelerometer, and surface temperature sensors were used to measure the response of the flow and the flexible plate and the wall temperature. The hot wire and the accelerometer measurements were conducted at locations A and B as indicated in Figure 1. Location A is at the middle of the centerline 0.2 inches above the plate while location B is on the centerline 3 inches from the end of the plate. The acoustic wave is generated by a loudspeaker placed well ahead of the leading edge. The incident square wave has a fundamental frequency f=286 Hz, corresponding to an oscillating mode of the flexible plate.

The initial experiment concentrates on flow validation over the plate for various Reynolds numbers Re (based on momentum thickness) in terms of the skin friction coefficient C^f and the shape factor H. The results are shown in Figure 2 and comparison with experimental data from references 40 and 41 shows good correlations of C^f and H as function of Re.

**Boundary Layer Experiments**

**Laminar Boundary Layer Over a Flexible Plate**

The unstable behavior of the laminar boundary layer over a flexible surface is maintained by the motion of the surface. This is markedly different from the stable nature of the boundary layer over a rigid surface. The coupling between the plate vibration and the laminar boundary layer enhances the transition process. Shown in Figure 3 are the normalized power spectral densities of the velocity fluctuations u(f), the plate acceleration a(f) and the coherence function γ(f) between the velocity and the acceleration at measurement locations A and B (Figure 1). The Reynolds number and the shape factor have values of Re=756 and H=2.43 indicating a laminar boundary layer. The velocity and the acceleration spectra have similar amplitude versus frequency indicating unique experimental evidence of coupling between the plate vibration and the boundary layer. In a laminar boundary layer, surface vibrations impose broadband velocity fluctuations on the layer with the same spatial and temporal scales as the surface motion. The displacement of the flexible plate, although small, is sufficient to impart a permanent imprint onto the receptive shear layer. Thus, the flexible surface can accelerate the transition process of the laminar boundary layer.

**Transition Induced by an Upstream Acoustic Wave**

The second experiment is to impose an acoustic wave on the upstream mean flow by feeding a square wave (f=286 Hz) into a loudspeaker producing an overall sound pressure level of 106 dB at the leading edge. The spectrum of the wall pressure fluctuations is shown in Figure 4. Discrete spikes are superimposed on the random fluctuations from the wall turbulent boundary layer. The first spike corresponds to the frequency of the square wave input (286 Hz), while the other spikes in the spectrum represent its Fourier components. The boundary layer near the leading edge of the plate is highly receptive to an acoustic wave upstream. The flow and sound couple at the leading edge and, as a result, the transition location moves upstream on the flexible plate resulting in turbulent flow at the measurement locations A and B (Figure 1). The Reynolds number and the shape factor at measurement location A (Figure 1) change to Re=1890, H=1.40 indicating a turbulent state. An incident sound wave with a much higher amplitude (at least twice) is needed to induce early transition at the same location on a rigid plate, indicating that the flexible surface accelerates the transition. Figure 5 shows the normalized power spectral density of the turbulent boundary layer velocity fluctuations and the panel acceleration as well as their incoherence.

Comparing the turbulent flow results, Figure 5, with the laminar flow results in Figure 3, the power spectral density of the velocity fluctuations in the turbulent boundary layer is 2 orders of magnitude...
higher than in the laminar layer. Also, the power spectral density of the plate acceleration increases 3 orders of magnitude with distinct spikes matching the frequencies of excitation. The spectrum of the velocity fluctuations in Figure 5 is smooth, typical for a turbulent boundary layer, while the spectrum of the plate acceleration is not. Note that the coherence function is nearly zero, in contrast with the laminar boundary-layer case which is strongly coherent. One possible explanation is that random phase cancellation take place between the flow and the plate oscillations when there is no time delay. To better understand this discrepancy, further experiments on the correlation function with time delay would be necessary.

The sequence of time histories of the normalized velocity perturbation O(t), from the laminar to turbulent state as a result of the gradual increase in sound pressure level upstream is shown in Figure 6. Distinct flow features in each stage of transition are shown as the transition location moves upstream and passes through the measuring station on the flexible plate.

Transition can be triggered earlier by an acoustic wave of weaker intensity in the presence of a flexible surface than in the presence of a rigid one. The amplitude of oscillation of the laminar boundary layer due to the presence of the flexible surface is an order of magnitude higher than over a rigid surface at an equivalent Reynolds number. The significant increment in oscillation amplitude at the instability frequencies and at the excitation frequencies contributes to accelerated transition and an increase in skin frictional drag.

**Transition Control by Localized Surface Heating**

Control of transition is achieved by localized leading edge surface heating, the configuration of which is illustrated in Figure 1. Due to the favorable pressure gradient at the leading edge, heat released by the surface wire couples with the sublayer producing a temperature gradient with distance. Figure 7 shows the normalized perturbation velocity O(t) as it changes from the turbulent to the laminar state. Distinct features in the time sequences of the perturbations are shown in each stage as the transition shifts downstream past the measurement station. The heat flux through the wire is gradually increased until laminar behavior is established. Figure 8 shows the normalized velocity perturbation power spectral density in the laminar boundary layer after the transition delay, the normalized panel acceleration power spectral density and their mutual coherence. The presence of the upstream acoustic wave is apparent by the distinct peaks in the velocity and acceleration spectra at which frequencies the coherence \( \gamma(f) \) is close or equal to one. The fact that sound from upstream is present in the boundary layer before, during, and after the transition delay, indicates that the thermal gradient along the direction of flow (in the sublayer) is the stabilizing mechanism. Figure 9 shows the rate of decrease of the spatial cooling parameter \( Q = -(T_T / T_e)^2/(P / K_e T_e) \), normalized to the unheated state, \( Q_{ref} \), as function of distance \( x \). \( P \) is the input power to the heater, \( K_e \) is the thermal conductivity, \( T \) and \( T_e \) are the local and free stream total temperatures of the flow. The boundary layer thickness, \( \delta \), skin friction coefficient, \( C_f \), shape factor, \( H \), Reynolds number, \( Re_0 \), the boundary layer momentum thickness, \( \theta \), the power required by the heater, \( P = IE \), and the power reduction, \( D_f U_e \), are shown in the Table for the laminar and turbulent states of the boundary layer. \( I \) is the current, \( E \), the voltage, and \( D_f \) is the skin frictional drag. The amount of input power required to delay transition depends on several factors. The Table shows that the input power to the heater is higher than the power saved by the reduction in skin frictional drag. The power required by an acoustic field to change the transition location is significantly less than the power lost in skin frictional drag. Because of the unstable transition condition, the acoustic power required to trip it as it shifts forward is much less than the power required to reestablish the transition point to its original location by surface heating. No attempt has been made to reduce the power needed by the heating system by improving its efficiency.

At high supersonic speeds, localized aerodynamic heating is a natural phenomenon, which can be utilized to enhance the stability of the boundary layer. The stabilizing effect in the critical layer near the wall is due to the dependence of viscosity on temperature. Viscosity decreases with temperature, thus the dissipation is due to the gradual cooling along the surface in the direction of flow. By stirring up the critical thermal layer, the stabilizing influences quickly diminish. Future experiments are anticipated in which these techniques will be used not only to control transition but also to control turbulence. In summary, the response of a flexible structure is altered by the presence of sound, temperature, pressure gradient, and turbulence.

**Conclusions**

An important source of laminar boundary layer instability has been identified for flow over a flexible plate. The instability is associated with the coupling between the plate vibration and the laminar boundary layer. The perturbations imparted to the laminar layer by the plate vibration are broadband in nature, unlike the leading edge instability waves which are spawned from a single mode. Flow perturbations induced by the plate oscillations develop into unstable Tollmien-Schlichting waves,
which show that the laminar boundary layer is very receptive to small structural vibrations of the surface.

Results are clear evidence that flow-structure-sound interactions cannot be simulated by structure and flow alone or by structure and sound alone but are all inherently coupled, both spatially and temporally.

The experiments demonstrate that the transition over a typical aircraft panel in the presence of an acoustic field can be controlled by localized surface heating at the leading edge, thus reducing the skin friction drag over the panel surface.

The present experiments broaden the field of flow control phenomena beyond instability wave phenomena over a rigid surface. Both sound pressure level and structural vibration were found to be involved in the destabilization of the laminar boundary layer.

References


Fig. 1.- Test configuration of the flexible plate mounted in the rigid model.

Fig. 2.- Experimental validation,
(a) skin friction coefficient
(b) shape factor

Fig. 3.- Coupling between laminar boundary layer and panel vibration,
(a) normalized velocity perturbation
(b) normalized panel acceleration
(c) coherence

Fig. 4.- Power spectral density of the wall pressure fluctuations in front of the leading edge in the presence of upstream sound.
Fig. 6.- Normalized perturbation velocity between laminar and turbulent states as a result of increasing sound pressure level from upstream.

Fig. 7.- Normalized perturbation velocity between turbulent and laminar states as a result of increasing heat supply at the leading edge.
Fig. 8.- Coupling between laminar boundary layer and panel vibration in the presence of the upstream sound,
(a) normalized velocity perturbation
(b) normalized panel acceleration
(c) coherence

TABLE

Mean Flow Parameters, Power Required by the Heater and Power Reduction in the Flow for Different States of the Boundary Layer,

\( U_e = 60 \text{ ft/sec} \)

<table>
<thead>
<tr>
<th>State of the flow</th>
<th>( C_f )</th>
<th>( R_\theta )</th>
<th>( H )</th>
<th>( \theta_e ), in</th>
<th>( \theta_e ), in</th>
<th>( P = \text{IE ft-lb/sec} )</th>
<th>( D_f U_e ), ft-lb/sec</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminar</td>
<td>.00085</td>
<td>756</td>
<td>2.43</td>
<td>0.19</td>
<td>0.025</td>
<td>0</td>
<td>0</td>
<td>Natural state</td>
</tr>
<tr>
<td>Turbulent</td>
<td>.00470</td>
<td>1890</td>
<td>1.42</td>
<td>0.47</td>
<td>0.058</td>
<td>0</td>
<td>0</td>
<td>Turbulent state induced by sound</td>
</tr>
<tr>
<td>Laminar</td>
<td>.00070</td>
<td>790</td>
<td>2.50</td>
<td>0.20</td>
<td>0.023</td>
<td>95</td>
<td>40</td>
<td>Transition delayed by heating</td>
</tr>
</tbody>
</table>