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Experiments on the Automatic Control of Boundary-Layer Transition

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Introduction

THE prospect of substantial savings in fuel costs has led to renewed interest in the subject of laminar flow control.[1,2] In particular, much attention has been devoted recently to the use of suction for the maintenance of laminar flow, since electron-beam drilled titanium sheet can now provide a sufficiently rigid and smooth porous surface through which fluid can be withdrawn. The use of suction itself consumes power, and it is important that the correct suction flow rate be applied for a given flow condition if the total net effective drag of a body is to be minimized. One way to monitor the effect of suction on a boundary layer is to monitor the position of transition. For a given flow condition (mean flow speed, turbulence level, pressure gradient), a desired transition position can be specified that will ensure the minimization of total net effective drag. In this brief Note we demonstrate that it is a simple matter to use measurements of the pressure fluctuations in the transition region of a flat plate boundary layer in order to define the actual position of transition. Furthermore, we demonstrate that the difference between the actual and desired values of transition position can be used to define an "error signal" for use in an automatic control loop that regulates the position of transition about its desired value.

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Experimental Apparatus

The experiments described in this Note were performed in a small wind tunnel having a 0.305- × 0.230-m working section of 2.5 m length, in which a 1.52-m-long plate was positioned. The tunnel allows mean flow velocities up to 22 ms^{-1}, hence, a Reynolds number based on the plate length of $Re_L = 2.2 \times 10^6$, with a turbulence level of 1%. The design of the rig for experimental investigation of boundary-layer suction is based upon the work reported by Reynolds and Saric.[3] The plate is made of a 1.2-m-long × 0.23-m-wide aluminium honeycomb core with 1.2-mm-thick aluminium skins, to which a carefully machined wooden leading edge was bonded, having a ratio of large to small axis of 35:1. Prior to the installation of the suction panel, an experiment consisting of traversing a hot wire probe just above the surface of the plate has shown that transition naturally occurs at $x_t = 0.65$ m downstream of the leading edge for a mean flow speed $U_0 = 20\ ms^{-1}$, and at $x_t = 0.70$ m for $U_0 = 15\ ms^{-1}$. The early onset of transition can be explained by the very high freestream turbulence level.[4] A suction panel was designed to allow suction from 0.46 m down to 0.645 m downstream of the leading edge, which corresponds to the first onset of transition for $U_0 = 20\ ms^{-1}$. This suction panel was made of nine 16-mm (wide in flow direction) individual suction strips, each separated by 4 mm. A laser-drilled titanium sheet with holes of 0.1 mm in diam, randomly spaced by 1 mm, was carefully bonded to the suction panel. The aluminium plate was then drilled and machined in order to receive the suction panel with precision. A sketch of the plate with the suction panel is given in Fig. 1. Outside the wind tunnel, the nine pipes coming out of the suction panel were connected to a manifold, which was in turn connected to a fan. The fan was controlled by a PC via an inverter. Pressure fluctuation measurements were made downstream of the suction panel by using an array of electret microphones mounted flush with the plate surface. The microphone signals were conditioned, then acquired by the PC, which also controls the fan applying the suction. A sketch of all the equipment used is shown in Fig. 2.

Use of Pressure Fluctuations for Transition Control

The signals from the microphones were high-pass filtered above 800 Hz in order to remove the noise from the wind-tunnel fan. The PC illustrated in Fig. 2 enabled the signals to be sampled at a rate of 4 kHz. Some typical time histories are illustrated in Fig. 3. These results show clearly the development of the boundary layer from a laminar state to a

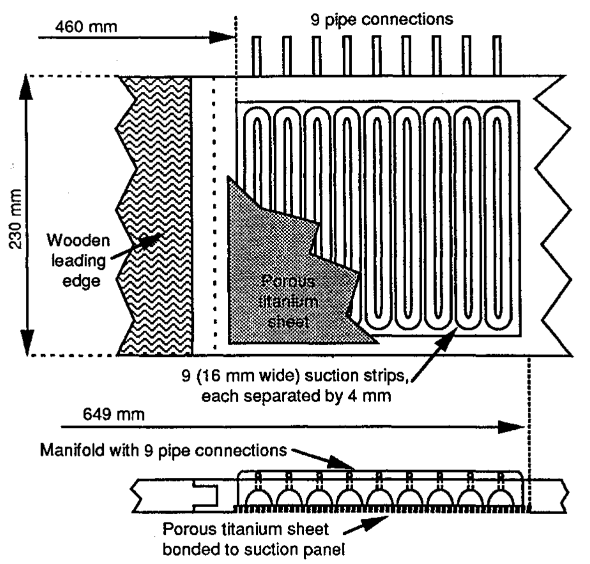

Fig. 1 Sketch of suction panel mounted on the plate.

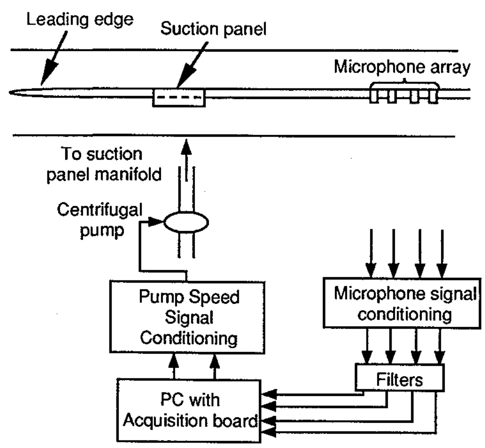

Fig. 2 Sketch of test rig and suction rate control equipment.

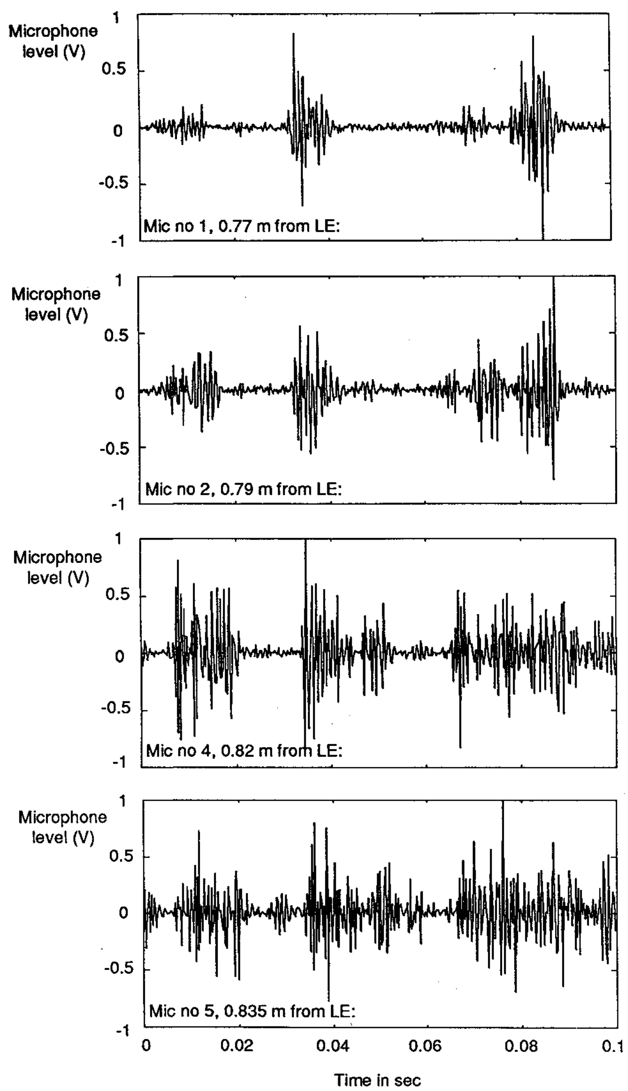

Fig. 3 Pressure fluctuation time histories acquired simultaneously at four microphones in the streamwise direction.

turbulent state downstream of the suction panel. The measurements made in the transition region show the development of turbulent spots, their "intermittency" and size increasing in the streamwise direction until they merge together to form a fully turbulent boundary layer.[5,6] The estimation of the intermittency of the turbulent spots at a given microphone

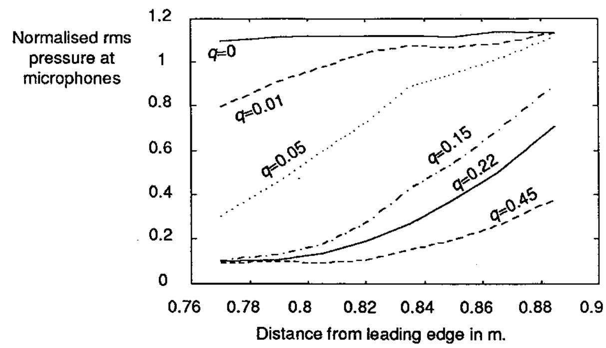

Fig. 4 Pressure fluctuation rms distribution with changing suction, for a mean flow speed $U_0 = 20$ m/s.

position depends on the length of time for which the signal is acquired. It was found that an acquisition time of 10 s could give a good estimate of the rms pressure, whereas an acquisition time of 0.1 s would give up to 48% standard deviation in this estimation. Figure 4 shows the effect of the average suction velocity q (ms^{-1}) normal to the surface of the suction panel on the rms pressure fluctuation measured at the microphones over a 10-s period. The results are normalized on the rms pressure measured in the fully developed turbulent boundary layer, and therefore, typically show a steady increase in value from 0 to 1 as the transition region is traversed in the streamwise direction.

The desired location of transition for a given mean flow speed can therefore be defined by a given distribution of rms pressure, as illustrated in Fig. 5. This shows how each of four microphones in a streamwise array can be attributed with a desired (or reference) value of rms pressure that is associated with the desired location of transition. Assuming that the rms value of the pressure fluctuation at each microphone is evaluated by acquisition of a signal over a period T, then the error signal after the kth acquisition period can be written as

$$e(k) = \sum_{m=1}^{4} [p_r(x_m) - p(x_m, k)] = \sum_{m=1}^{4} p_r(x_m) - \sum_{m=1}^{4} p(x_m, k) \tag{1}$$

where $p_r(x_m)$ is the desired rms value at the mth microphone, and $p(x_m, k)$ is the value measured during the period T. Equation (1) can also be written as

$$e(k) = r - y(k) \tag{2}$$

where r and $y(k)$ are defined by

$$r = \sum_{m=1}^{4} p_r(x_m), \qquad y(k) = \sum_{m=1}^{4} p(x_m, k) \tag{3}$$

Therefore, in terms of the operation of a control system, $y(k)$ can be regarded as the "output" of the plant (boundary layer) to be controlled. In addition, r can be regarded as the "reference" value that we wish the output of the plant to take.

Control Strategy and Experimental Results

The maintenance of the output $y(k)$ about the reference value r is a simple regulator problem,[7,8] and in the experiments described here the use of automatic control is illustrated by using an integral controller.[7] Thus, the error signal $e(k)$ is

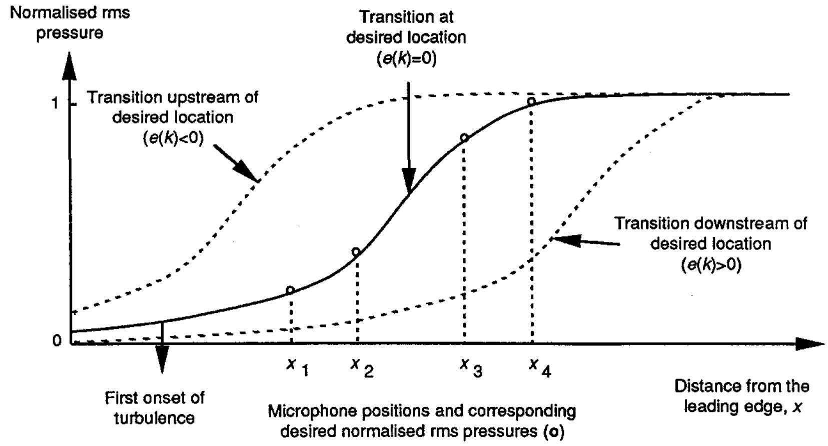

Fig. 5 Monitoring of transition location using four microphones.

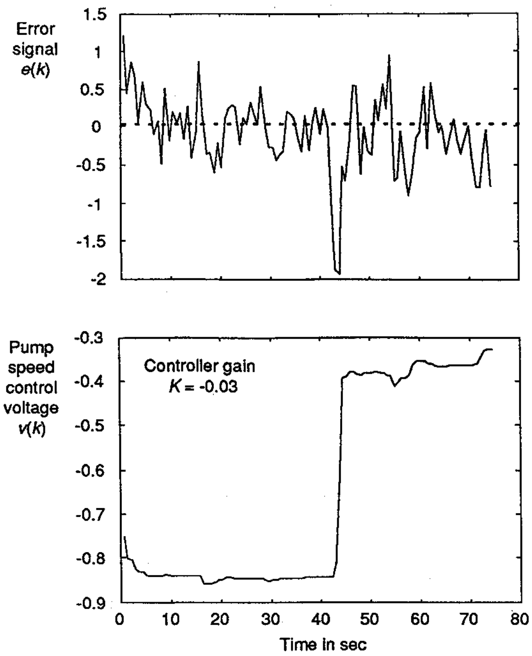

Fig. 6 Controller response to a sudden change in mean flow velocity, from U_0 = 15–20 m/s.

used by a controller that modifies the suction rate to ensure that the error is driven to zero, therefore holding the transition region at the streamwise location prespecified by the desired plant output r. The value of r was in turn defined by specifying the rms pressures required at the microphones placed at the streamwise locations $x_1 = 0.835$ m, $x_2 = 0.85$ m, $x_3 = 0.865$ m, and $x_4 = 0.885$ m, x being measured from the plate leading edge. The value of r was thus given by

$$r = \sum_{m=1}^{4} p_r(x_m) = [0.2 + 0.33 + 0.66 + 0.8] = 2 \quad (4)$$

The "input" $u(k)$ to the plant was defined in terms of the voltage $v(k)$ input by the PC to the pump speed controller at the kth control cycle. Thus, $u(k) = v(k) + c$, where c was a constant chosen such that $u(k)$ was zero when the plant output $y(k)$ had a time-averaged value close to zero. The input $u(k)$ was updated at each iteration of the controller in accordance with the integral control law given by[7]

$$u(k + 1) = u(k) + Ke(k) \quad (5)$$

where K is the controller gain. This form of control was found to be highly successful in regulating the position of transition about its desired value. One remarkable feature of the controller performance was that the acquisition time T used in the evaluation of the rms pressures $p(x_m, k)$ could be reduced to a very low value (0.1 s) without detrimentally affecting the ability of the controller to maintain transition in the desired region. Choosing a low value of T also enabled the controller to have a very rapid response to changes in flow conditions. As an example, Fig. 6 shows the response of the controller to a sudden change in mean flow velocity. Note that the error signal is very "noisy" as a direct result of the short acquisition time used, but that a fast and stable response of the pump speed control voltage is produced. The performance and stability of the control system was examined using conventional discrete time linear control theory,[9] and found to behave in a well-defined and predictable fashion. In particular, the effect of the choice of gain K on the stability of the system were well-predicted by linear theory.

Conclusions

The automatic control of boundary-layer transition has been demonstrated. It has been shown how the pressure fluctuations produced in the transition region can be used to define the position of transition, and in turn define a signal that can be used in an automatic control loop that regulates the position of transition about a desired value.

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