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CONTROL OF BOUNDARY-LAYER INSTABILITIES BY ACTIVE MEANS

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ABSTRACT: The control of boundary-layer instability waves is considered. A wave-cancelling scheme that employs arrays of detectors coupled through a digital filtering control unit to an array of actuators has been modelled. The two-dimensional process has been analysed for a number of different forms of on-coming waves and appears to be very satisfactory. Current work examines the more important problem of fully three-dimensional disturbances. The analysis is more complex, but is in the process of being evaluated. The basic building block defined by an isolated wavepacket has been determined, and this will be used to study more general on-coming wavetrains. The experimental work will be carried out on three-dimensional disturbances. The appropriate transfer function has been calculated and will be programed into the hardware digital filtering unit. The experimental work on this problem is currently being carried out.

I. INTRODUCTION

Over the last hundred years or so, great advances have been made in our understanding of boundary layers and how they develop. This has had important implications in many engineering applications that involve fluid flows. The design of efficient wings, for example, could only have been accomplished with some understanding of factors that control the state of the boundary layer. Apart from the need to avoid any gross separations, it was also important to be able to determine the skin friction. Skin-friction drag on an aerofoil cannot be estimated without some knowledge of the location of transition from a laminar state to a turbulent one. This has been, and still remains, a very difficult task that has involved an on-going worldwide research programme on flow instability.

With all the knowledge gained on flow instabilities that lead to transition, it now seems just possible actively to control the process so as to inhibit wave development and so delay transition onset. If this can be done so that the transition front is moved downstream, then worthwhile drag savings can be obtained. The current impetus for this type of research has come about because very small actuators and detectors can, in principle, be manufactured using technologies developed for microchip production. The current research programme at Queen Mary & Westfield College was started in order to investigate the possibility of controlling linear instability waves before they develop in a nonlinear manner and break down into turbulence. British Aerospace has some abilities in the construction of MEMs (Micro Electronic Mechanisms).

II. APPROACH

Consider the flow in the boundary layer of a flat plate in an on-coming stream containing turbulence. The free-stream background noise will excite instabilities in the boundary layer that, if unchecked, will amplify as they propagate downstream and develop into turbulence. The proposed scheme for the control of these waves is to excite an appropriate cancelling wavefield. The disturbances are detected at some station and the required excitations are then fed to actuators, positioned downstream of the sensors, that generate instability waves of opposite sign to those from the upstream source. In order to design a scheme for doing this, we need to be able model each phase of the process. This requires a method for calculating the skin-friction pattern generated by the motion of an actuator. We also need to know the characteristics of the skin-friction sensor.

2.1 Sensors

It was necessary to be able to detect and measure the on-coming travelling waves by some non-intrusive instrument. Surface pressure sensors can be used, but the signals are generally contaminated to a considerable degree by extraneous pressure fluctuations in the wind tunnel. In this work, hot-film sensors were chosen as they had been shown by Ho [1] to be useful in this context and could readily be fabricated on wafers as arrays. But the original versions of these hot-film arrays had neither the frequency response nor the sensitivity required. If purely electrical frequency response of the anemometer system is carried out, it appears that the roll-off occurs at roughly 20 kHz, but this gives a false view of the true response to skin-friction oscillations. Because a numerical code [2] for calculating the unsteady flow field behind an actuator existed, it was possible to predict the skin-friction oscillations downstream. When this information was used in the calibrations, it was found that the roll-off started at 10 Hz [3]!

A great deal of effort was expended trying to understand why the performance was so poor. It appears that the heat was being transferred to the substrate through the electrical soldering pads, as well as by conduction along the insulating film. These two factors reduced the performance considerably. Modified versions were constructed that had most of the thin insulating substrate covered by metallic film. The soldering pads were also modified by creating a neck before the connection zone.

These changes increased the sensitivity by a factor of around 8 and the frequency response to about 300 Hz. Although these new gauges were not ideal, as the signal-to-noise ratio was still high, they were used because of a lack of time for further development. The final sensor array contained hot-film elements made from 0.5-micron titanium film, 400 microns long by 50 wide, on a polyimide diaphragm 20 microns thick covering an area of about 660 microns square. Connections were made using gold tracks through the polyimide to pads on the back of the wafer. Sensors were placed on the wafer at a 5-mm spacing. For our purpose, only one spanwise array was required, but it turned out that a full two-dimensional pattern of sensors cost no more to manufacture. This gave some flexibility in selecting the best row of gauges.

2.2 Actuators

There are a number of ways to create disturbances in the flow, but the simplest one to implement is the normal velocity point-source. Excitation through an unsteady surface bump is also possible, but our experiments and analytical studies suggest that this does not drive the flow as effectively as the unsteady jet configuration that can be driven by a simple buried earphone that connects to the surface of the plate via a small hole of 0.5 mm dia.

2.3 Analytical Model

In order to model the processes involved in the control problem, it was necessary to be able to calculate the flow field created by an unsteady-jet-type of exciter. By treating the problem as a linear one in a purely parallel mean boundary-layer flow, it was possible to obtain the solution in terms of Fourier transforms in wavenumber space from a set of O.D.E.'s. The functions can readily be evaluated for one excitation frequency and the solution obtained on a computer of low power in a few hours. A velocity/vorticity formulation using six variables was used. Three equations were integrated by Runge-Kutta, using a filtering scheme to remove the divergent root. These were then combined at the wall to satisfy the prescribed boundary condition. The whole flow field, as well as the skin-friction pattern, was then predicted for the chosen excitation frequency. By repeating this computation for a range of frequencies, it was possible to generate the impulse response. It was convenient for the control work to split the flow response into a near-field component and an asymptotic element related to the singularities in the transform integrals. The near-field part is formed by the continuous spectrum and the decaying eigenmodes, while the asymptotic element is formed from the residues of the singularities in the transform integrals.

The results from this calculation scheme have been compared with experimental measurements made in a Blasius boundary layer that formed on a flat plate [2]. The agreement between the calculated and measured streamwise velocity perturbation turned out to be very good when the amplitudes of the disturbance were kept within the linear range. The skin-friction predictions were then used for calibrating the hot films.

III. CONTROL

The simulation, whether for two or three-dimensional disturbances, involved the introduction of controlled disturbances of some form at a location upstream of the detectors. The numerical code was used to calculate the resulting skin-friction fluctuations at the location of the hot-films. This part of the calculation used the full response consisting of both the near field and asymptote. The inverse transfer function between an exciter and the surface-friction pattern was computed for the asymptotic modes only. This function was then convolved with the hot-film signal to create the control signal that was designed to cancel the on-coming wavetrain far downstream. The cancelling signal was used to drive the control actuators at some downstream location. The response wavetrain also used the full transfer function, as this was appropriate to the experiment.

The effectiveness of this cancellation could then be assessed by comparing the response created with the downstream form of the original disturbance that was introduced upstream of the control device. The inverse transfer function was not entirely causal and the non-causal part had to be ignored. This feature was more significant in three dimensions that in two dimensions.

The effectiveness of this control depended to some extent on how much of the wavetrain arose from the damped modes and the continuum, as this part of the motion could not be eliminated by the control function that was based only on the eigensolutions. This presented some difficulty because it was not obvious whether or not to classify neutral or very slightly damped solutions as part of the asymptotic form or of the near-field, and this influenced the calculation of the inverse transfer function used in the control.

Control was assessed for the two-dimensional wavetrains using the computed inverse transfer function. A single frequency source, an impulsive excitation, and broadband noise were used as test signals. Very good control was achieved in all cases. Reasonable results were obtained even when the time series used for the convolution was simplified to just two discrete spikes. The simplification was introduced to see what penalties would be introduced by this rather crude form of digital processing. But the more important case of three-dimensional waves has proven more difficult. The computations are still in progress, but it is expected that some results will be available by the time of the conference.

IV. EXPERIMENTAL SETUP

The experiments are being carried out in the 0.9-m-square low-turbulence wind tunnel at Queen Mary & Westfield College. The tunnel is a conventional closed-return type with a modest contraction of about 7:1. There are numerous screens, a fine honeycomb, and a very long settling chamber to reduce the free-stream turbulence to below 0.01% within a band between 4 Hz and 4 kHz. The tunnel was fitted with a computer-controlled three-dimensional probe traverse, controlled wind speed, and data-acquisition system. Experiments were carried out on a flat plate mounted centrally in the working section. The test wafer was mounted in a 200-mm disc insert in the plate. An array of small earphones were fitted some 25 mm upstream of the first row of sensors to simulate the effect of excitation from the free stream. Another row of small exciters was positioned on the wafer 25 mm downstream of the sensors to provide the control excitations. The hot-films are being driven by Dantec 55M01 anemometers. The signals, after some signal conditioning, were fed to the digital control unit. Eight channels are simultaneously sampled, processed, and used to control 4 actuators. The control unit could only handle this number of channels, and it will be necessary to construct more control units if a larger area is to be controlled.

V. RESULTS

The experimental phase of the project is currently in progress and it is expected that some preliminary measurements will be available by the time of the Congress.

VI. DISCUSSION AND CONCLUSIONS

A cancelling control scheme for three-dimensional instability waves has been investigated by modelling the process. So far only the simplest excitation of a wavepacket has been simulated, but this can be used to model more general types of on-coming disturbance. The hot-film sensors have been developed to provide an adequate frequency response and sensitivity for this work, although further effort directed to improving the signal-to-noise ratio would be worthwhile. The control circuitry to detect and process the hot-film signals in order to produce the cancelling excitation has been constructed and tested out of the wind tunnel. The wind-tunnel testing is in progress.

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