Active control of boundary layer instabilities using MEMs

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The active control of spatially evolving instability waves in the boundary layer of a flat plate is discussed. An open loop control scheme is considered. This type of control requires means of detecting the on-coming wavetrain and driving the downstream exciters to cancel the wave system. The effectiveness of the control turns out to be very dependent on the performance of these devices. The hot-film skin-friction sensors and the oscillating jet exciters are discussed. The overall performance of the control is also affected by the algorithm used to define the signal feeding the cancelling actuators in terms of the sensor signal. A numerical calculation of the flow field resulting from exciters of the type considered enabled the inverse control transfer function to be evaluated. This was then used to synthesize a control system using different spacings of the detectors and actuators. It is shown that a useful amount of control can be obtained when using practical spacings of the detectors and controlling actuators. This is illustrated by applying control to a simulated random disturbance field.

Introduction

On aircraft wings transition from a laminar boundary layer to a turbulent one generally occurs through the amplification of naturally excited instability waves. The wing of an aircraft encounters a free-stream environment that is reasonably clean, but nevertheless it will contain weak acoustic and vorticity fluctuations that can initiate disturbances in the boundary layer, especially when there are small roughness elements or discontinuities in the surface. The 'receptivity' process, that enables these long wavelength external disturbances to excite shorter wavelength instabilities, is still not fully understood. This process results is a broad spectrum of travelling wave instabilities being excited. Some of these will amplify as they propagate downstream until the amplitudes are large enough for the flow to breakdown into turbulence. The resulting turbulent boundary layer has considerably larger skin-friction than that of the laminar flow. Although it is important, in a design sense, to be able to predict the position of the transition and thus estimate the loses or drag, it would be even more beneficial if the transition process could be controlled.

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Research on to the amplification of *passive* control in the form of surface suction has been extensively explored. Suction of small amounts of fluid through the surface can certainly reduce wave amplification and therefore delay the onset of transition to turbulence, but at present this method of control does not appear to be economically viable. On underwater bodies the application of compliant coatings has been considered for the control of boundary layer instabilities, but here again this technique has only limited application and has so far not been implemented. The use of surface temperature to modify the boundary layer stability has also been demonstrated. Heating of underwater bodies can delay the onset of transition and cooling can be used in air to achieve a similar delay, but here again the gains do not appear to be worthwhile when set against the difficulty of implementation. In this paper we discuss some aspects of *active* boundary layer control.

The idea of attempting to interfere *actively* with the laminar/turbulent transition process is not new, but as we now have new tools at our disposal to tackle different aspects of the problem there is a greater chance of achieving a result. Here we describe efforts carried out at Queen Mary College to investigate active control of boundary layer instabilities. This is an on-going project that has not yet been tested in an experiment, but a windtunnel project is being built around the ideas discussed here.

It does not seem possible to use a closed-loop type of control on the spatially evolving instabilities that occur in boundary layers and we therefore chose to use an open-loop cancelling scheme. To do this one needs to know the content of the oncoming wave field so that suitable disturbances can be introduced into the flow at some downstream location to cancel this field. It is vital, therefore, to be able to construct instruments that are capable of adequately measuring the oncoming disturbance, to be able to calculate how the waves continue to evolve downstream and then to be construct an algorithm that prescribes the motion of any downstream actuators used to provide the necessary cancellation. Each of these components of a complete control loop had to be analysed before attempting to build a practical real-time control. It is not even clear how much control can be achieved in an ideal setup with perfectly operating devices. There are some factors that will inevitably prevent the cancellation from exactly annihilating the oncoming wavetrain. For example, the controlling transfer function cannot be causal and any implementation will employ some approximation to the ideal. The hot-film detector will also be contaminated by upstream excitations that arise from the continuous spectrum, whereas the control can, at best, only control the growing eigenmodes. There will also be electronic noise to contend with on the sensor signals. In any practical implementation one has also to take account of the fact that the detectors and actuators are discrete devices that are to be appropriately spaced across the span.

The control scheme that is being designed will be tested in a very low-noise low speed wind tunnel on the boundary layer of a flat plate. The control devices will be mounted in an instrumentation disc 210 mm dia centred at 0.5 m from the leading edge of the plate. The tunnel is capable of running at speeds up to 45 m/s, but generally when very low background noise is required it is better to run at speeds somewhat lower, and therefore 12.5 m/s was chosen for the current project. These physical quantities determine the scaling parameters in the problem. Instability waves have a typical frequency of about 150 Hz and a wavelength of 25 mm.

Sensors

Both pressure sensors and surface mounted hot-film gauges were considered as possible detectors of the instability waves. Suitable small cheap microphones can readily be obtained from the Tandy company. They only require a resistor and a voltage source in order to generate electrical signals. Unfortunately the pressure signatures measured by these transducers are contaminated by the background acoustic pressure fluctuations existing in the tunnel, and these can be particularly troublesome when attempting to detect low-level disturbance waves. Hot-films gauges that respond to skin-friction fluctuations seemed to offer better signal-to-noise ratio, but they do require complex anemometer control electronics to function. Other research groups looking at active control had apparently fabricated satisfactory hot-film arrays using MEMs technology. Ho's[1] group had created the films on thin substrates and evacuated the region beneath the film to reduce heat loss, providing claimed frequency responses up to many kilohertz. British Aerospace had the ability to make such devices and it was thought, therefore, that the development of suitable gauges would only take one or two iterations in mask layout, etc. However apart from the design and fabrication a lot of time was spent learning how to mount the wafers and how to make the electrical connections to the films. The use of conducting glues is not that easy on the scale of small gauge arrays and soldering had to be done with skill that took a while to acquire. British Aerospace also needed to develop their fabrication techniques to produce gauges with the correct resistances and without too much cross-talk between gauges. The initial wafers fabricated with arrays of conventionally shaped gauges showed calibrations with poor sensitivity and even worse frequency response. The response rolled off well below 10 Hz, which seemed absurdly low and was quite unsuitable for our purpose. The question naturally arose as to what we were doing wrong to get such poor results. Our calibration technique used either the skin-friction fluctuations from a turbulent boundary layer, or the flow field generated by an oscillating point source in a laminar flow. The point source produced a known velocity field that was easily measured by a standard hot-wire. Comparison of a profile of velocity fluctuations measured downstream from the source with the computed solution shown in Figure 2 is really very good and indicated how the computed solution could provide a known periodic skin-friction for calibration purpose. Calibrations of the gauges by this method turned out to be quite different from those obtained from purely electrical characteristics of the anemometer system determined by a square-wave test that is so often used to assess performance. Estimates of heat fluxes from the element to the substrate indicated why the performance was so poor compared with the simple surface commercial 'glue-on' gauges produced by Dantec. These gauges, although not suitable for our purpose, did appear to have acceptable frequency response when mounted on a conducting substrate, but had very poor sensitivity. The MEMs type of gauge, with the thin diaphragm substrate, was initially expected to have a somewhat better performance, but the analysis identified the heat flux paths and showed that there were a number of problems in using a thin square diaphragm of the materials being used by BAe.

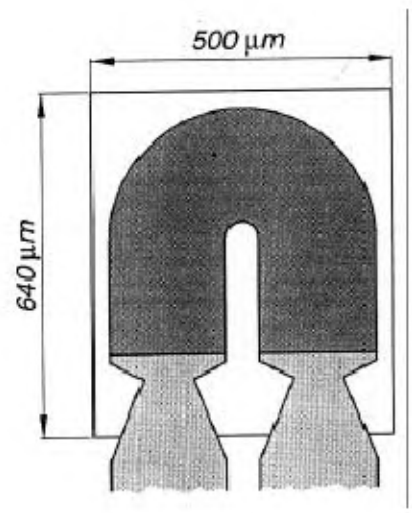

Figure 1. Layout of horseshoe sensor.

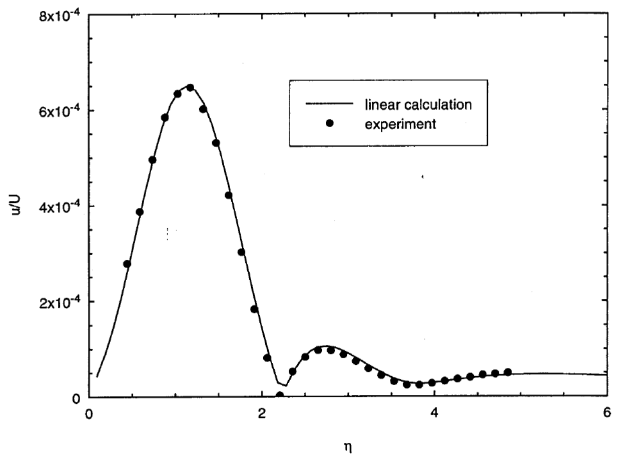

Figure 2. Response to a periodic point source excitation at 160 Hz.

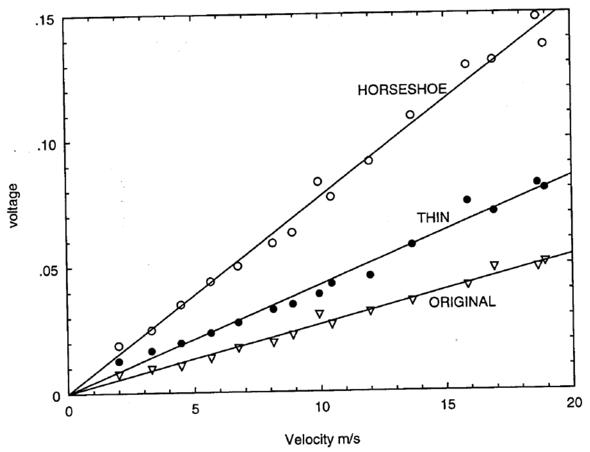

Figure 3. Sensitivities of three hot films.

A surprising amount of heat loss occurred through the gold pads attached to the ends of the film that were used to enable soldered connections to be made. The poor time constant obtained was also associated with the time it took for the thin substrate to reach an equilibrium temperature. Improved designs (see ref. 2) were proposed involving a much larger surface area of active gauge element on the thin substrate. The heat loss to the gold solder pads was also reduced by forming notches at the junction to inhibit conduction. Figure 1 shows the gauge pattern while Figures 3 and 4 show the measured sensitivity and frequency responses respectively for a number of different gauge designs.

Actuators

Actuation of the cancelling disturbances had to be achieved with devices integrated into the boundary wall. The computer codes that had already been developed were used to calculate the flow field around and downstream of localized boundary-value perturbations in the normal and tangential velocity. A simple oscillating jet source can be modelled by an unsteady normal velocity component at a point on the surface, whereas an unsteady bump requires both a normal and a tangential component. It turned out that stronger cancelling signals were more easily generated by the unsteady normal jet-like source and this form of excitation was chosen. MEMs fabrication was considered, so that both sensors and actuators could be produced on the same wafer, but it was more straightforward at this stage to use very cheap and easily obtained miniature earphones. When directly coupled to small driving holes in the plate a Helmholtz response was set up, but this could be damped out by using a long connecting tube of 0.5 mm dia. Figures 5 and 6 show both the predicted behaviour obtained from the modelling together with experimental verification. The final configuration had a reasonable flat frequency response over the range required.

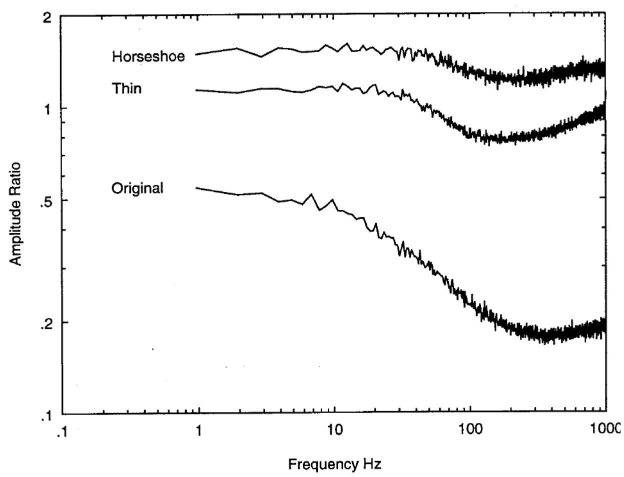

Figure 4. Frequency responses.

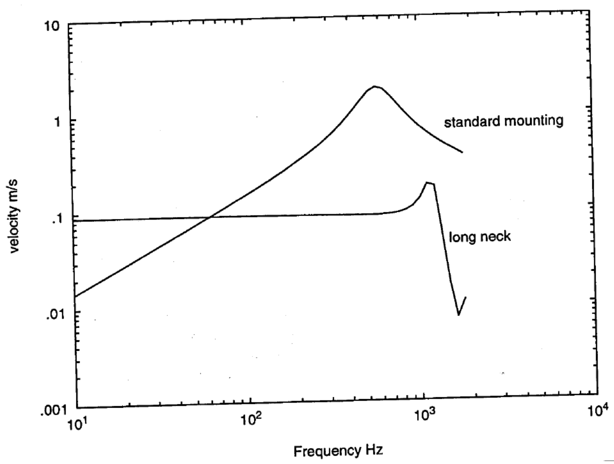

Figure 5. Predicted actuator performance.

Modelling

The open-loop control scheme to be modelled is shown schematically in Figure 7. It was necessary to introduce controlled disturbances at some upstream station to mimic the receptivity process. By creating the upstream disturbances artificially there was complete control of the wave field. Because the free-stream turbulence level in the wind tunnel was low it will also be necessary to consider the introduction of controlled disturbance in the experiment. It was essential to be able to model the whole process of excitation, skin-friction detection by the hot-film gauges and finally that of the creation of the cancelling wavetrain. The computer model would then enable various control algorithms to be explored in order to ascertain what could be achieved in any practical implementation.

The development of codes for calculating the flow field created by unsteady boundary value sources of unsteady jet-type had already been completed and sufficient experiments done to demonstrate the validity of the calculations[3]. Control is only likely to be effective while the disturbances are weak and can be defined by the linearized perturbation equations. As in much of the theoretical treatment of instability waves it was convenient to ignore the fact that the boundary layer slowly develops in thickness with downstream distance. The use of this approximation should only cause errors if solutions are sought at large streamwise distances from the source. The *parallel flow* approximation together with linearization enables the perturbations equations for the fluctuating velocities and vorticities created by the source to separate into a set of ordinary differential equations amenable to solution in Fourier space. The sixth-order set of equations are stiff and some purification of the shooting integration had to be applied to enable uncontaminated solutions to be generated. Integrations of the equations were carried out for a fixed excitation frequency over a range of wave numbers in both streamwise and spanwise directions. The Fourier transforms then provided the solution in physical space. The dominant eigenvalues were extracted from the solution integral. The unstable eigen-solutions were defined as discrete waves while the regular component of the integrand defined the near-field part of the solution. This separation was essential for the control problem as it is only possibly to cancel the eigenmodes.

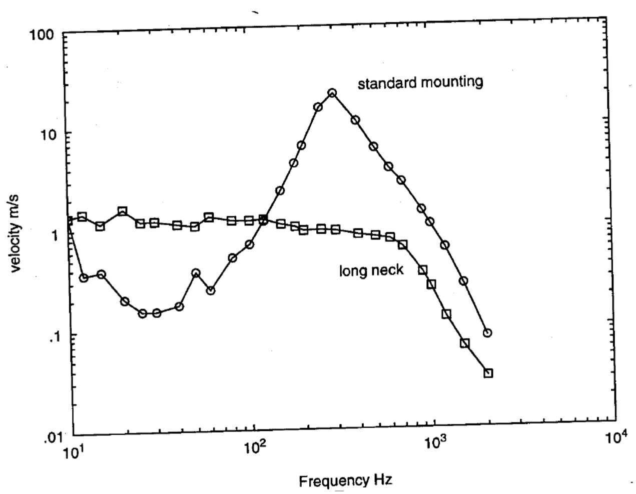

Figure 6. Measured actuator performance.

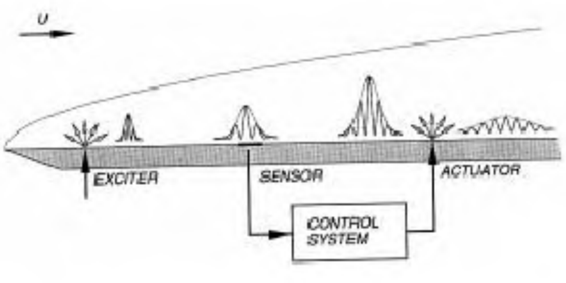

Figure 7. Control set-up.

Two-dimensional control

The computer codes were also used to model two-dimensional excitations, defined by modes with zero spanwise wave number. Preliminary studies of the control problem were carried out for the two-dimensional disturbances and required calculations for 50 frequencies in order to obtain the information for the impulse response. The skin-friction was obtained as two components, the near-field element, arising from the damped modes and the continuous spectrum, and the amplified eigensolutions. The total skin friction from both elements acting on the sensor element could then be evaluated for any given source signal by a convolution with the impulse response. Similarly, the far field, that we wish to cancel, could also be obtained by convolution of the input excitations and the impulse response appropriate to some downstream station where the effectiveness of the control was to be assessed. The driving signal that is required to be fed to the control actuators can be found using the inverse of the impulse response, but based solely on the unstable eigensolutions. There is no mechanism for cancelling the solutions associated with the continuous spectrum and there is no value in trying to cancel eigensolutions that are already damped. Here the relatively small portion of the transfer function that occurs at negative times, and cannot be meaningful when only the hot-film signal in the past is available, was ignored in the implementation. The driving signal was then calculated by a convolution of the sensor signal with that portion of the transfer function shown on Figure 8 that exists for positive delay times. The effectiveness of the control could then be assessed by comparing the original signal at the downstream

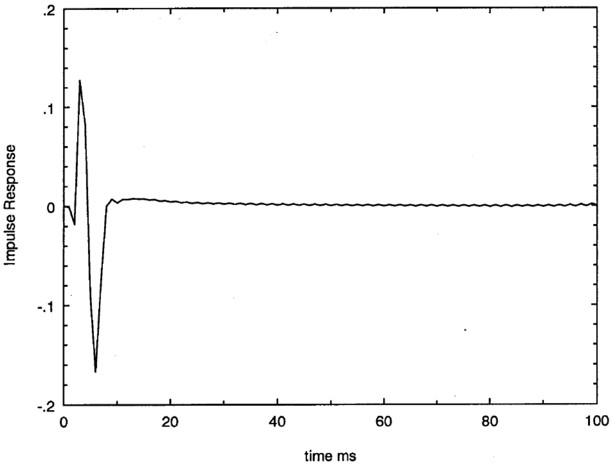

Figure 8. Controller transfer function.

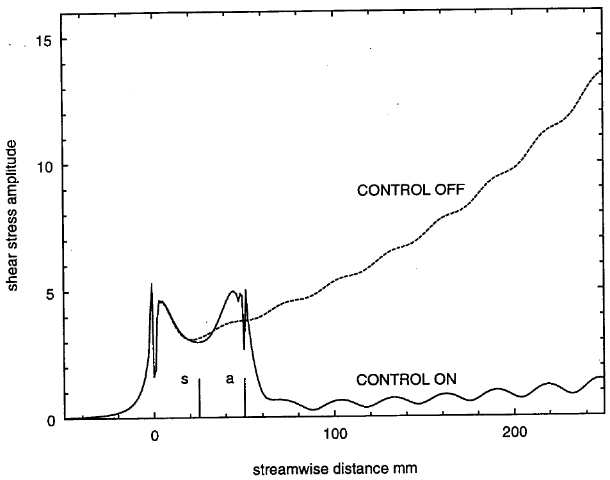

Figure 9. Harmonic excitation at 160 Hz.

location chosen and that generated by the controlling actuators at the same location.

Artificial excitations in the form of regular periodic waves of various frequencies, random excitations covering a broad spectrum and isolated impulses were used to create the disturbances used to represent naturally excited instabilities that were to be controlled. The excitations, containing both the eigensolution and the near field were used to predict the skin-friction fluctuations some 25 mm downstream from the source. The inclusion of the near field is important because in a real situation some of the excitations from natural processes could well have occurred close to the detectors and generated similar disturbances. It was thought desirable to position the actuators as close as possible to the detectors, but there is an up-stream near field from the actuator that dictates a minimum distance of about 25 mm to avoid any feedback to the hot film that could cause the control loop to become unstable. Figure 9 shows the streamwise development of the skin friction for a periodic excitation together with the behaviour when control was applied. Figure 10 shows the outcome for a random excitation with and without control. The control transfer function on Figure 8 consisted of two distinct peaks and it was interesting to find out what would happen if the function was reduced to just two delta functions. The reason for doing this is that if digital control were to be used it would be relatively easy to implement this simple control transfer function. Figure 11 shows the result of applying the control constructed from just two discrete spikes for the case of random excitation. The loss in control is a small price to pay for the advantages to be gained by this form of control transfer function.

Three-dimensional control

It turned out that the computing time required to repeat the two-dimensional exercise for a three-dimensional situation was too long for the computer then available.

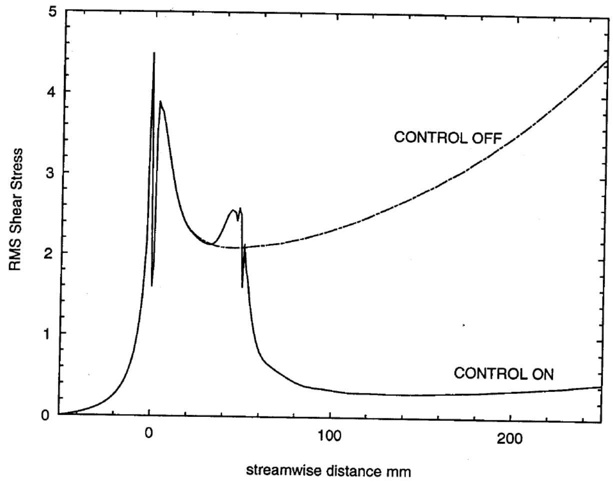

Figure 10. Random excitation.

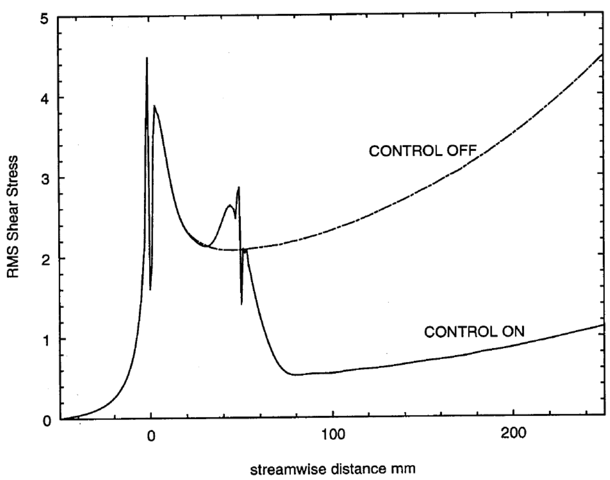

Figure 11. Control using simplified transfer function.

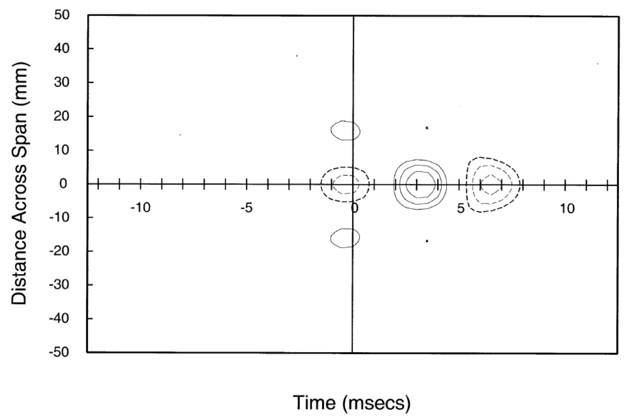

Figure 12. Space-time control transfer function.

A faster machine was acquired and a full three-dimensional impulse response calculated. The source of waves was modelled by a random series of pulsed excitations distributed over a period of time and a spanwise strip of 200 mm placed 75 mm upstream of the hot-film detector array. This distance is larger than that used previously in the two-dimensional case because it was found that the closer distance used previously introduced a rather large and unrealistic near-field component. The resulting skin-friction oscillations were evaluated at the hot-film station and also at 350 mm from the source, the downstream station chosen for monitoring the effectiveness of the cancelling process. Again a 25 mm downstream separation was chosen between the detector and actuator arrays. The control transfer function obtained from the unstable eigenmodes is plotted on Figure 12 as a function of time delay and spanwise separation. The non-causal part that appears at negative time delay is relatively small and must be ignored in the calculations of the signal feeding the control actuators. The random wave field passing over the hot-films was convolved in both the spanwise direction and time with the control transfer function to provide the signal needed to feed the actuators. The result of driving the actuator array with this signal was then evaluated by a further convolution with the full impulse response formed from the damped modes and the continuous part of the spectrum. At the comparator location 350 mm from the source the original solutions and the cancelling field appear to be almost the same, providing excellent cancellation. The degree of success can be judged by the cross correlation of the two solutions. In this case the value of the correlation coefficient, σ, is 0.976. This implies that the mean square of the residual signal after cancellation control is 0.048, or $2(1-\sigma)$, of that from the original source. This cancellation is not perfect because the transfer function has to be treated as causal and the portion linked with the future structure of the waveform has been ignored. In fact this is not necessarily the best way of dealing with causality. In any practical implementation it is also important to consider the influence of transducer spacings across the span as well as the resolution of the sampling times on the correlation coefficient.

The correlation coefficient was determined for a range of different sampling times. It turned out that the correlation maintained roughly the above value until sampling exceeded 2 ms after which the value fell rapidly. Next the spanwise distances of the detectors and actuators were increased. The correlation value above 0.974 was maintained up to a spacing of 10 mm, after which a rapid fall was obtained. The arrangement of 2 ms sampling coupled with 10 mm spanwise transducer spacing is quite a practical one. However the control would still need to have some spanwise cross-coupling so that each actuator control would use the information from neighbouring hot-film detectors as well as the one directly upstream. The degree of cross-coupling will be small because of the shape of the transfer function and it seemed worth seeing what would result from removing the cross-coupling. With this additional constraint the correlation was reduced to 0.953. The transfer function is dominated by peaks along the time axis at 6 and 12 ms. Following the approach used in the two-dimensional study the control transfer function was reduced to delta functions at these locations. The correlation obtained was 0.97, a value approaching that achieved for the full transfer function, but in this case the amplitude levels of the discrete function were optimized.

The randomly excited simulated response of the boundary layer at the comparator station 350 mm downstream from the source line is shown on Figure 13, while the residual pattern remaining after cancellation with the above set-up is drawn on Figure 14.

So far no noise has been added to try to model the electronic noise of the hot-films or the electronics in the control loop. No doubt these factors will influence the result to some extent.

Experimental validation

The experiment will be carried out in two phases, exploiting the fact that a deterministic, and therefore repeatable, excitation can be introduced upstream to simulate natural excitation from the free-stream turbulence and receptivity process. An array of embedded earphones fitted upstream of the control region are to be used to introduce known controlled disturbances of various sorts under computer control. By recording the hot-film signals a number of times for the same excitation pattern one can readily determine the signal-to-noise of the detectors and also obtain a purified noise-free hot-film signal. The control signal to be fed to the actuators can then be computed off-line for any desired control strategy. The experiment will then be repeated

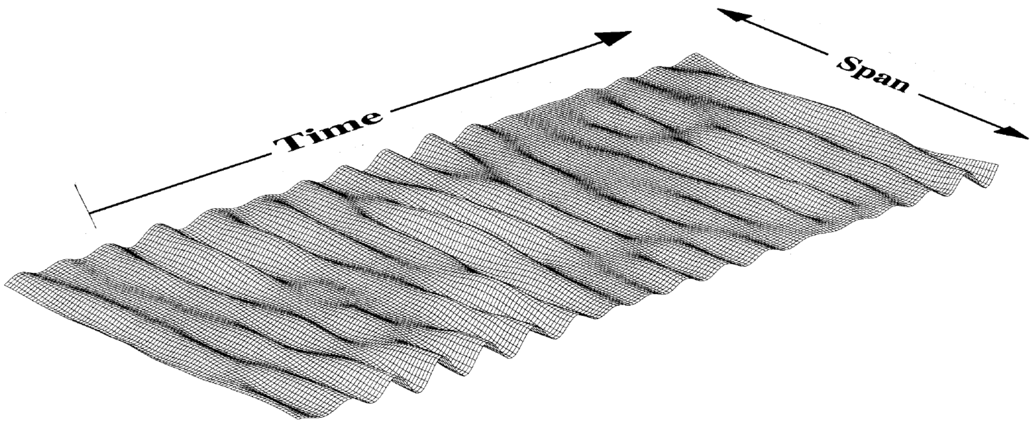

Figure 13. Space-time waveform of random wavefield at the measuring station.

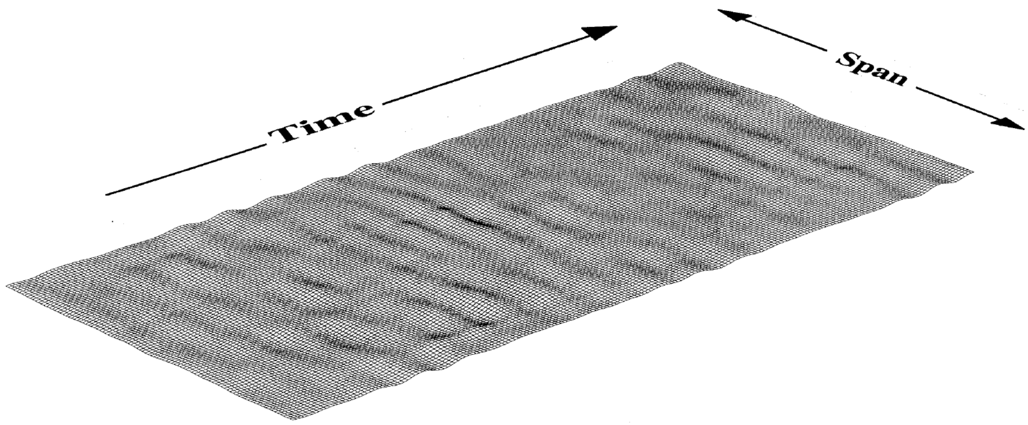

Figure 14. Waveform after cancellation using the simplified control function.

with the same excitation using the computed control signal to drive the cancelling actuators. Off-line processing means that a fast real-time processor is not needed and more complex transfer functions can be explored. At some later stage the chosen control scheme can be constructed in hardware, but this is a much more complex operation.

Concluding remarks

Practical detectors and actuators that can be used in the control of boundary layer stabilities have been developed. Control strategies that use this information have shown to be capable of a high degree of control on three-dimensional random waves. The use of discrete arrays of detectors and actuators with a reasonable spacing of 10 mm makes the implementation possible. This taken together with the greatly simplified control function that only uses delayed and summed information from the detectors directly upstream makes it feasible actively to control instability waves. The experimental validation of this work will be carried out over the next three years with a studentship provided by British Aerospace.

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