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An experimental investigation of the control of natural laminar instability waves on an axisymmetric body was conducted in the NOSC high speed water tunnel. The body used was a 9:1 ellipsoid of revolution, 50mm in diameter at the midsection. Control perturbations were introduced into the boundary layer through a suction/blowing slot of 0.075mm width at 130mm from the nose. Hot film sensors before and after the slot were used to measure the passage and attenuation of the instability waves. A very simple invert and delay control loop was used to control a speaker embedded in the suction/blowing slot. At a freestream velocity of 8.67m/sec, and approximately 50 percent reduction in the RMS fluctuations of the instability waves was achieved after control. At this velocity the frequency of the instability waves was about 1kHz. The experimental run conditions corresponded to Reynolds numbers, at the slot location, of 1.24 million and 1520 based on axial location and boundary layer displacement thickness respectively.			
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CONTROL OF NATURAL LAMINAR INSTABILITY WAVES ON AN AXISYMMETRIC BODY

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ABSTRACT

An experimental investigation of the control of "natural" laminar instability waves on an axisymmetric body was conducted in the NOSC high speed water tunnel. The body used was a 9:1 ellipsoid of revolution, 50mm in diameter at the mid-section. Control perturbations were introduced into the boundary layer through a suction/blowing slot of 0.075mm width at 130mm from the nose. Hot film sensors before and after the slot were used to measure the passage and attenuation of the instability waves. A very simple invert and delay control loop was used to control a speaker embedded in the suction/blowing slot. At a freestream velocity of 8.67m/sec, an approximately 50 percent reduction in the RMS fluctuations of the instability waves was achieved after control. At this velocity the frequency of the instability waves was about 1kHz. The experimental run conditions corresponded to Reynolds numbers, at the slot location, of 1.24 million and 1520 based on axial location and boundary layer displacement thickness respectively.

NOMENCLATURE

c	TS wave velocity
L	model length (450mm)
Pr	Prandtl number
Re_δ^*	$U_\infty \delta^* / \nu$
Re_s	$U_s \delta / \nu$
r	model radius
s	surface distance
T_∞	freestream temperature
t	time
U_∞	freestream velocity
U_e	boundary layer edge velocity
u'	fluctuating axial velocity component
v_o	wall motion velocity
x	axial distance from model nose
α_i	wave number imaginary part
β	Hartree pressure gradient parameter
ΔT	wall temperature - freestream temperature
δ^*	boundary layer displacement thickness
ν	kinematic viscosity
μ	viscosity
τ	wall shear stress
ξ	heater width
ω	rotational frequency

INTRODUCTION

The response of a two dimensional laminar boundary layer instability (so called Tollmein-Schlichting or TS waves) to wave superposition has been the subject of several recent investigations. Leipmann, Brown and Nosenchuck¹ demonstrated the generation of artificial TS waves on a flat plate using periodic pulsing of heaters embedded in a flat plate in water. Later, Leipmann and Nosenchuck² used this technique to actively attenuate the "naturally" occurring TS waves, and increase the length of laminar flow on the flat plate. Gedney³ used plate vibration to attenuate sound produced artificial TS waves. Thomas⁴ used two vibrating ribbons on a flat plate in air. By varying the phase and amplitude of the downstream ribbon, the TS waves were attenuated. However, Thomas points out that, due to the formation of three dimensional disturbances, the flow could not be returned to a totally quiescent state. Milling⁵ performed a similar operation with vibrating ribbons in a water channel. Ladd and Hendricks⁶ used thin film heating elements on a 9:1 ellipsoid of revolution to create and then cancel TS waves using a least mean square type of algorithm. In yet another experiment Maestrello⁷ used sound to control the TS waves produced with heating strips on a flat plate (in air). With the exception of Leipmann and Nosenchuck², all these experiments used artificially produced TS waves. Conceptually, the theory of linear superposition is simple, however many questions are yet to be resolved. One is whether the superposition of two dimensional waves will excite three dimensional instabilities. Biringen, Nut and Caruso⁸ reported a numerical study which showed that significant reductions in amplitudes of two and three dimensional finite amplitude disturbances can be obtained by application of two dimensional periodic suction and blowing in plane channel flow. In this case no excitation of three dimensional modes was indicated. Bower et. al.⁹ did a similar numerical study in a developing channel flow.

Ultimately, the goal of this research is to increase the length of laminar boundary layer flow over that which would occur "naturally". In the case of wind or water tunnel experiments, natural TS waves is a somewhat subjective term, in that the generation of TS waves is linked to the turbulence level (and often other factors) of the experimental facility. In the facility of Leipmann et. al., the natural TS waves occurred at a remarkably regular frequency, phase and amplitude. This allowed the use of a feedforward loop for control of these TS waves. The essence of a feedforward loop is that the control system must be able to predict the future state of the system from past events. In Leipmann and Nosenchuck², the sensing shear stress sensor was well downstream of the heating element. The theory of small disturbances, (e.g. the solution of the Orr-Sommerfeld equation) can

predict the range of frequencies and the rate at which disturbances will be amplified, however there is nothing to suggest that only one frequency should appear. The fundamental problem in using wave superposition in the attenuation of "natural" TS waves, is that usually the exact frequency, phase or amplitude can not be predicted ahead of time. This present study addresses that problem.

EXPERIMENTAL APPARATUS

The facility used for this experiment was the NOSC high speed water tunnel. This water tunnel has a 305mm circular open jet, where velocities up to 15m/sec are possible. Turbulence level (u'/U_∞) is a respectable 0.16 percent through out the speed range.

Figure 1 shows the 9:1 fineness ratio ellipsoid of revolution used in this present experiment. The body of the model was made out of Noryl® plastic and was mounted to a stainless steel sting. The diameter of the midsection was 50mm. The ellipsoid maintained a true elliptical outline until an axial distance of 397mm (x), at which point constant slope was maintained to intercept the sting diameter of 25.4mm. The significant dimension of this body (L) is somewhat arbitrarily taken to be 450mm, the untruncated ellipsoid length. Figure 2 shows the calculated and measured edge velocity ratio of the model. Velocity measurements were taken with a Laser Doppler Velocimeter. The model was mostly contained in the open jet region of the tunnel

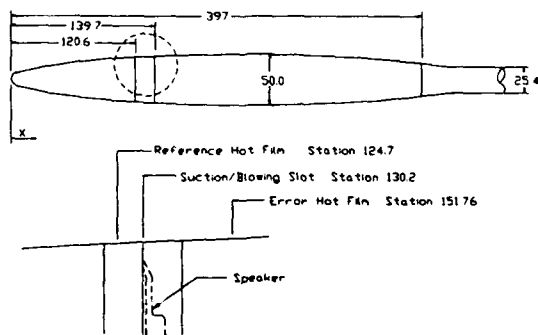


Fig. 1 Ellipsoid model (insert shows location of suction/blowing slot and hot films). Dimensions in millimeters.

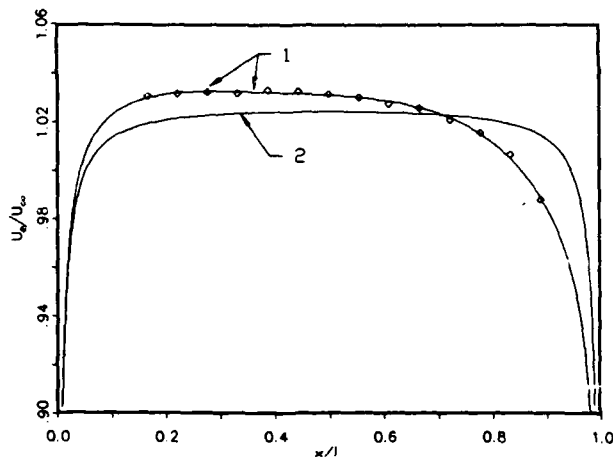


Fig. 2 Theoretical and experimental edge velocity ratio for 9:1 ellipsoid of revolution. 1-Experimental points and curve fit. 2-Theoretical curve.

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and wall effects are apparently small. The velocity (and pressure) distribution of this model is very flat. This model is essentially the axisymmetric equivalent of a flat plate. Previous experiments with identically shaped models have shown transition Reynolds numbers of about 2.8 million, which agrees well with the measured 0.16 percent turbulence level of the tunnel.

EARLY EXPERIMENTS

In the first experiments of Ladd and Hendricks⁶, vapor deposited gold heating elements, were used to create artificial TS waves on the forward portion of a 9:1 ellipsoid. A second heater was used to cancel the TS wave, within a few wavelengths of creation. Essentially total cancellation was achieved. The shear stress probe (flush mounted hot film) used to measure the success of superposition was located well aft of the heaters. This allowed easy measurement of the TS waves due to the large amount of flow induced amplification occurring from the heater to the sensor. Since the wave producing heater was pulsed at constant frequency and amplitude, it was only necessary for the controller of the second heater to learn the correct phase and amplitude information. The velocities used in this experiment were such that naturally occurring TS waves did not interfere with the experiment.

Later experiments showed that naturally occurring TS waves could be induced on this model by increasing the tunnel velocity. Figure 3 is an example of the output of a flush

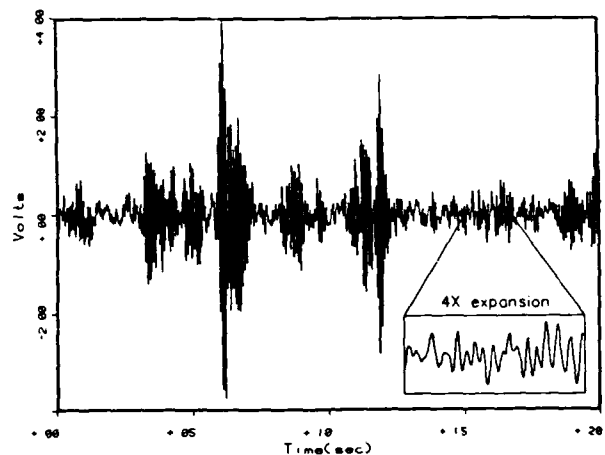


Fig. 3 Hot film output $x=123.8$ mm, $U_\infty=8.67$ m/sec, $T_\infty=26.0^\circ$ C, filtered 200Hz-2kHz, gain=100x $Re_\tau=1511$.

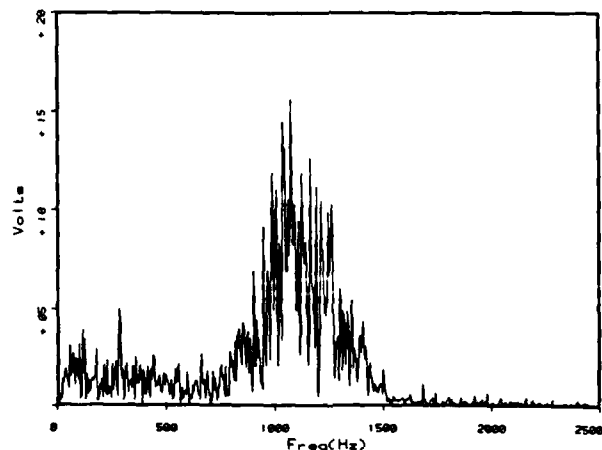


Fig. 4 Frequency amplitude spectrum of data of figure 3.

mounted hot film sensor and Figure 4 is an example of a typical frequency spectrum. These TS waves are very different from the almost pure tone TS waves of Leipmann and Nosenchuck². Note that the "natural" TS waves occur in wave packets of apparently random phase and frequency. In the first experiment it was found that even with constant amplitude forcing of the foremost heater, the artificial TS waves produced would appear at the shear stress sensor with varying amplitude.

A limited investigation into the cause of the wave packeting behavior (using only the existing hot film data) showed a correlation between the low frequency fluctuations of shear stress and the presence or absence of a wave packet. In this case, low frequency is defined as bandpass filtered between 2 and 200 Hz and high frequency is bandpass filtered from 200 to 5000 Hz. In most cases, the most unstable TS wave frequency was in the neighborhood of 1000 Hz, depending on tunnel speed and water temperature. When the low frequency portion of the shear stress was increasing (i.e. $d\tau/dt > 0$) this usually indicated the presence of a wave packet. Likewise, when $d\tau/dt < 0$, this usually indicated an absence of a wave packet. The addition of more hot film sensors on this model at the same axial location of $x=152\text{mm}$, at azimuthal angles of 90 and 180 degrees, showed that the wave packets were not correlated between the top, bottom and (port) side of the model. Additionally, the low frequency variations of shear stress were not correlated between each other as would occur if the model were vibrating. It is unclear whether the wave packet itself causes the low frequency shear stress variation, or low frequency freestream turbulence causes small scale pressure variations, which causes a wave packet to amplify. The latter explanation seems more likely to this author.

The lack of correlation of wave packet data around the circumference of the model could be related to the relative size of TS wavelength to model radius. The experiment of Kegelmann and Mueller¹⁰ showed smoke visualizations on an axisymmetric body with highly uniform TS waves around the circumference of the body. In that experiment it appears that the TS wavelength is on the order of 20 percent of model radius. In this present experiment, the approximate wavelength is about 10 percent of model radius (at $x=130\text{mm}$, $r=22.6\text{mm}$). Other differences between the Kegelmann and Mueller experiment and the present work, are the turbulence level of the tunnels (0.10 percent and 0.16 percent respectively) and the sharp pressure gradient variations of Kegelmann and Mueller's projectile shaped model.

Figure 5 is the calculated spatial stability for a laminar boundary layer at Hartree $\beta=0$, taken from Wazzan, Okamura and Smith¹¹. Also plotted on figure 5 are the center, maximum and minimum dimensionless frequencies of the spectrum of a hot film located at $x=125\text{mm}$. The change in Reynolds number was produced by changing the velocity of the tunnel. The center frequencies fall close to the upper branch of the stability curve, in complete agreement with stability theory. At frequencies higher than the center frequency, the TS waves are being damped, eventually to be of no concern. Frequencies lower than the center frequency are still in the process of being amplified, yet to reach overall peak amplification. The center frequency has reached its peak amplification and is about ready to be damped (e.g. zero amplification rate, the upper branch of the stability curve). This simple result is a direct consequence of the very flat pressure distribution on the 9:1 ellipsoid shape. That is, the stability curve for all boundary layer stations is little changed from that of figure 5. For this model, the center frequency of a TS wave spectrum, can be predicted merely by following the upper branch of the stability curve for Hartree $\beta=0$.

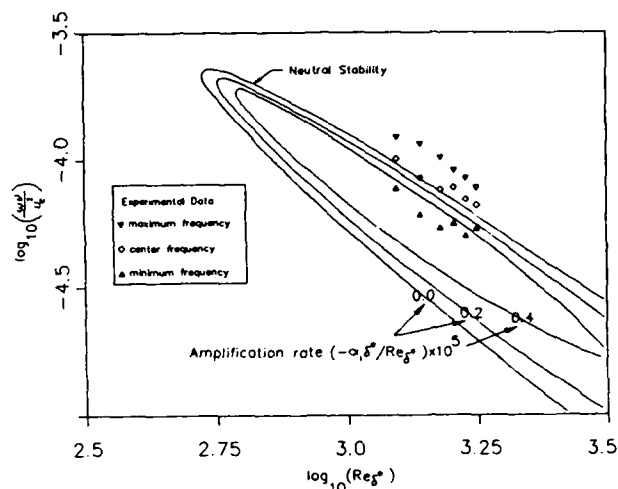


Fig. 5 Spatial stability diagram, Hartree $\beta=0$.

PRESENT EXPERIMENT

To tackle the problem of the ambient random type TS waves that occurred this experiment, a new model was designed. This model placed the TS wave control actuator at a location well downstream from the nose. This allowed an ambient TS wave to amplify enough such that a shear stress sensor could reasonably be expected to sense the presence of a TS wave before arriving at the actuator. Due to a lack of hardware, no attempt was made to address the problem of the circumferential variation of the TS waves on this body. The present results pertain to only one circumferential location (usually the top or 0 degree location). Eventually, the problem of what happens around the rest of the body, particularly in the form of three dimensional interactions, must be addressed. However that question is beyond the scope of this experiment.

The goal of an actuator design, for this experiment, was to be able to produce a perturbation of one percent of freestream velocity at a frequency of 1000Hz. Using a simple analogy between heating and wall suction/blowing (for instance see Leipmann, Brown and Nosenchuck), it can be found that

$$\frac{v_o}{U_e} \approx -0.548 \text{Pr}^{1/4} (\text{Re}_s)^{-1/4} \left(\frac{s}{\xi}\right)^{1/4} \frac{d\mu}{dT} \frac{\Delta T}{\mu} \quad (1)$$

where U_e is edge velocity, v_o is wall vertical motion, Pr is Prandtl number, Re_s is Reynolds number based on surface distance, s is surface distance from nose, ξ is heater width, μ is viscosity and ΔT is wall overheat. To arrive at eq(1), the assumption must be made that the thermal boundary layer thickness is small compared with the boundary layer thickness. For the conditions of this experiment eq(1) implied an overheat ΔT of 70°C, a formidable but not impossible task.

A new model was fabricated with a ceramic insert from $x=120.6$ to $x=139.7\text{mm}$. On this insert a gold platinum heater 0.5mm wide was vapor deposited at an x location of 130.2mm from the nose. To achieve a thermal frequency response of 1000Hz, the thickness of the heater was only 600nm. The heater was lacquer covered (1.0μm thickness) to protect it from the water. Unfortunately, the survivability of this very thin heater was such that no useful data could be obtained before the heater failed (open circuit).

A new insert was fabricated for this model using a totally different design. A small commercially available acoustic speaker was obtained with a 21.6mm stainless steel diaphragm. This speaker fit conveniently inside the model perpendicular to the model axis (see Fig. 1). The function of the speaker was to change the volume of a small cavity inside the model, to produce suction/blowing through a circumferential slot. The slot width was about 0.075mm, and was continuous around the model, except for four small areas blocked by the tie rods between the forward and aft insert sections. All measurements were taken at locations 45 degrees to these blocked areas. The axial location of the suction/blowing slot was 130mm. Also installed was a flush mounted hot film sensor at axial location of 125mm (just before the slot) and another sensor directly downstream at an axial location of 152mm. The hot film sensors had active areas of 0.2mm by 0.7mm, with the long dimension oriented perpendicular to the flow. Physical constraints of model construction limited the choice of possible sensor locations. It should be mentioned again that although the slot would produce a suction/blowing perturbation around the circumference of the model, this experiment could only be concerned with one azimuthal location.

First experiments driving the speaker with a wave packet like waveform from a function generator, produced gratifyingly large shear perturbations on the downstream hot film sensor. The

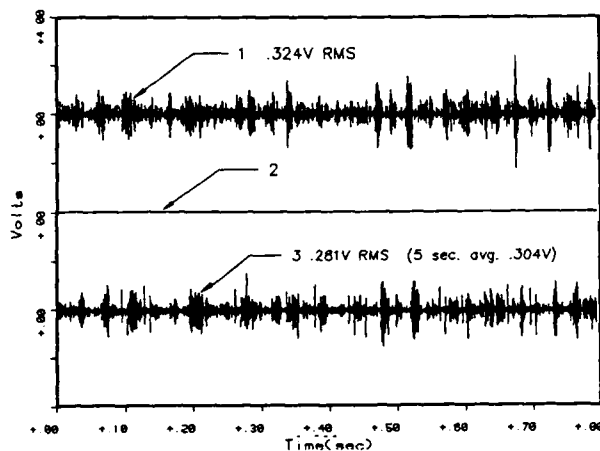


Fig. 6 TS waves, no control $U_\infty=8.67\text{m/sec}$, $T_\infty=24.1^\circ\text{C}$. Trace 1- hot film voltage $x=123.8\text{mm}$, gain=100x, filtered 500Hz-2kHz, $Re_\rho=1479$. Trace 2- control voltage. Trace 3- hot film voltage $x=151.6\text{mm}$, gain =10x, $Re_\rho=1658$.

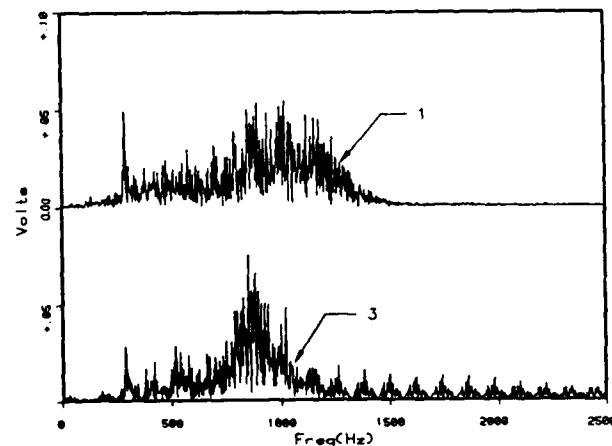


Fig. 7 Frequency amplitude spectrum of traces 1 and 3 figure 6.

efficiency of this actuator was much greater than the thin film heater. In this case efficiency is defined as (perturbation size)/(power input). Interestingly, it was found that the time delay between a control signal to the actuator and the corresponding perturbation at the aft hot film probe, was much greater than would be expected from just the phase speed of a TS wave between these two points. Some of this delay can be explained by the combined delay of several analog filters and amplifiers in series. Also, the control voltage represents a command force (i.e. acceleration) to the speaker diaphragm. A TS wave is a velocity perturbation, so one would expect a $\pi/2$ phase lag (at least) between control voltage and perturbation.

The first trace of figure 6 shows a typical hot film trace from the the forward hot film sensor (after filtering). The third trace shows the shear stress at the aft hot film. A cross correlation between trace 1 and trace 3, shows a time delay of 7.8ms. For the flow conditions of figure 6, this corresponds to a phase speed (c/U_∞) of 0.39. Also note that the relative amplification between trace 1 and trace 3 is about 10 times, and that trace 3 is not one hundred percent similar to trace 1. This illustrates the evolving nature of TS waves on this body.

An extremely simple (minded) control system was devised for this system. The control signal applied to the actuator slot, was a time delayed image of the signal arriving at the forward shear sensor (labeled reference signal in figure 10). The gain

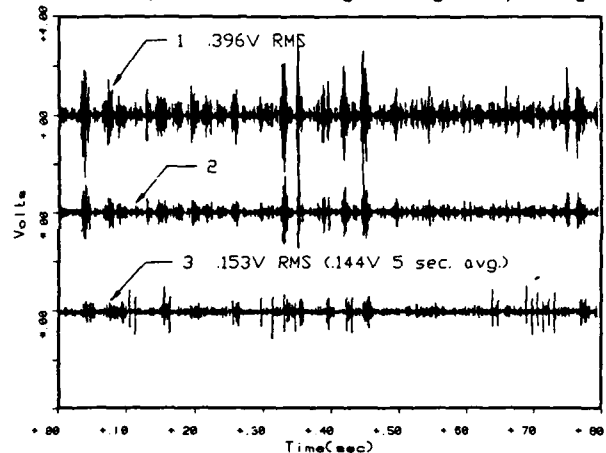


Fig. 8 TS waves with control, same conditions as in figure 6.

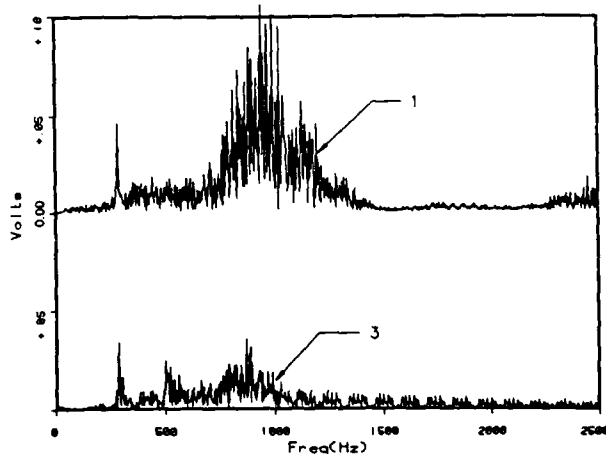


Fig. 9 Frequency amplitude spectrum of traces 1 and 3 figure 8.

(multiplying factor) and time delay are initially unknown. The gain is a function of TS wave amplification, power amplifier gain, mechanical coupling etc. of the speaker/slot system. The time delay is a function of flow speed, TS wave phase speed and any other mechanical or electrical time delays in the feedback system. The function of the controller is to adjust the variables of time delay and gain factor such that a minimum signal (RMS) appears at the downstream hot film. A hybrid digital/analog controller system was developed to perform these functions. Figure 10 is a block diagram of this system. The digital portion of the system implemented the time delay loop and the binary search algorithm for the time delay and gain. Since the TS wave frequencies were high (approximately 1kHz), requiring a digital sample rate of greater than 3kHz, the functions of gain multiplying and RMS calculation were performed using analog circuit elements. The simple optimization algorithm used an initial guess for time delay and initial gain and time delay increments. A binary search was then performed for the optimum time delay and gain. The search increments were normalized to the RMS voltage of the second sensor (i.e. smaller RMS, smaller step sizes). The time delay loop was implemented using a variable sample rate clock and array element index. This type of control system has been called an "invert and delay" type of control.

Figures 6 and 8 show the action of this control system on TS waves at a freestream velocity of 8.67m/sec. Figure 6 is the forward and aft shear stress signals with no control. Figure 8 is the same conditions after control. For the particular sample records shown, the ratio of the fore shear stress RMS to the aft shear stress has been reduced about 55 percent with control. Using a five second running average, the RMS voltage has been reduced about 53 percent after control. Figures 7 and 9 show the Fourier amplitude spectrum of the before and after control conditions. As would be expected, the center frequency of Fig. 9, trace 3 spectrum has moved to a lower frequency after control. The stability chart of figure 5, shows that only the low boundary layer frequencies should be amplified after the actuator.

CONCLUSIONS

Figure 8 shows that random "natural" TS waves can be controlled, to some extent, using a suction/blowing slot and a simple control algorithm. The suction/blowing slot appears to be a powerful method of introducing perturbations into a laminar boundary layer. The implementation of the invert and delay algorithm used in the present study is in no way optimum, but was only a first attempt at control. In particular, the hardware used in this existing experiment suffered from marginal comput-

ing speed and limited clock resolution (only a small finite number of time delays were possible). Use of improved hardware, using dedicated digital signal processing chips is planned for future experiments.

Additionally, a much smarter control algorithm is possible. The evolution of a TS wave between the reference (forward) sensor and the suction/blowing has a transfer function that can be calculated or approximated. In the present experiment, this transfer function is approximated with a single time delay and gain. In reality, time delay (phase speed) and gain (amplification) is a function of TS wave frequency. With present digital signal processing techniques, there is no reason that this transfer function could not be included into the control loop.

ACKNOWLEDGEMENTS

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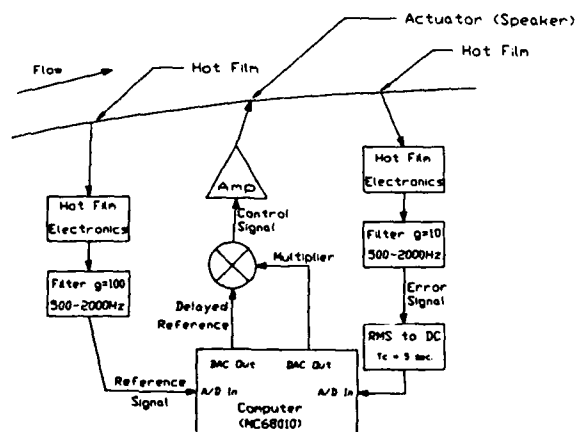


Fig. 10 Block diagram for "invert and delay" control loop.