NASA-CR-172,575

NASA Contractor Report 172575

ICASE REPORT NO. 85-23

NASA-CR-172575
19850017445

ICASE

NUMERICAL SIMULATION OF BOUNDARY LAYER
EXCITATION BY SURFACE HEATING/COOLING

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Contract Nos. NAS1-16394, NAS1-17070, and NAS1-17130

March 1985

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Operated by the Universities Space Research Association

National Aeronautics and
Space Administration

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Abstract

This paper is a numerical study of the concept of active control of growing disturbances in an unstable compressible flow by using time periodic, localized surface heating. The simulations are calculated by a fourth-order accurate solution of the compressible, laminar Navier-Stokes equations. Fourth-order accuracy is particularly important for this problem because the solution must be computed over many wavelengths. The numerical results demonstrate the growth of an initially small fluctuation into the nonlinear regime where a local breakdown into smaller scale disturbances can be observed. It is shown that periodic surface heating over a small strip can reduce the level of the fluctuation provided that the phase of the heating current is properly chosen.

Research for the fourth author was supported by the National Aeronautics and Space Administration under NASA Contract Nos. NAS1-16394, NAS1-17070, and NAS1-17130 while he was in residence at the ICASE, NASA Langley Research Center, Hampton, VA 23665.

Partial support was provided for the first author under NAS1-17070 and for the third author under NASA Contract No. NAS1-17252.

Introduction

Transition in a boundary layer arises from the spatial growth and nonlinear saturation of instability waves. A method of controlling or delaying transition is to introduce localized surface disturbances which can interfere with and reduce the level of the propagating disturbances. This concept was introduced by Liepmann, et al. [1], [2]. They demonstrated that the introduction, in water, of localized, periodic temperature disturbances of appropriate phase could either enhance or reduce, depending on the phase, the overall level of fluctuations for a significant distance downstream. In addition, by measuring the fluctuating disturbance in the boundary layer upstream of the controlling surface, they were able to synthesize a signal to drive the cancellation disturbance at the controlling surface. This provided for active feedback control. An analysis by Maestrello and Ting [3] provided a theoretical justification for this method. The use of localized heating strips provides a control mechanism with a significantly lower expenditure of energy than that for passive control; for example, a steady heating of the entire surface.

Nosenchuk, et al.* have demonstrated that localized surface heating can be used to trip the boundary layer and accelerate transition in air. Maestrello [4] has shown that localized surface heating in air can be used to trigger instantaneous transition. In addition, he showed that by using feedback control to drive an acoustic disturbance, a significant reduction in the level of the disturbances could be obtained. Thomas [5] demonstrated that

*Nosenchuck, D. M., Bettes, W. H., and Liepmann, H. W., "Active Transition Fixing," private communication, 1983.

a vibrating ribbon could be used to generate an unstable wave. In addition, he showed that by using a second ribbon downstream to generate an out of phase disturbance, the level of the disturbance could be reduced.

At the present time, we are not aware of any experiments that have shown reduction in the level of a growing disturbance, in air, by using only localized surface heating. The use of localized heating to introduce an out of phase disturbance is considerably more delicate in air than in water. There are several reasons for this. First, much larger temperature disturbances are required to change the viscosity by an equivalent amount in air than in water [4]. In addition, in air $d\mu/dT > 0$ which is destabilizing while in water $d\mu/dT < 0$. Finally, in a compressible flow a temperature disturbance affects the pressure gradients via the equation of state in a manner that is difficult to analyze.

Localized surface heating has obvious attractions as a mechanism for active flow control for reasons of simplicity and efficiency. The primary objective of this paper is to demonstrate by numerical solutions of the compressible Navier-Stokes equations that time periodic localized surface heating can be an effective technique to reduce the level of growing disturbances in air at flow velocities for which compressibility effects can be expected to be noticeable.

The simulations are based on solving the two-dimensional, compressible, Navier-Stokes equations using a fourth-order accurate finite difference scheme. It is our experience that a higher-order accurate scheme is necessary in order to compute the solutions appropriate to this problem. In Section 2 we describe the model. In Section 3 we discuss numerical results and in Section 4 we present conclusions.

In summary, our results demonstrate that localized temperature disturbances can be an effective technique to reduce the level of growing disturbances in the boundary layer. A localized disturbance over a strip a quarter of a wavelength in width can reduce the level of the fluctuations. Other techniques such as localized vibration, e.g., a vibrating ribbon, also offer potential. The greatest deficiency in the present program is the restriction to two-dimensional disturbances. In two dimensions the development of instabilities and the transition to nonlinear behavior is very different than in three dimensions. We are currently developing a three-dimensional version of the code and will report results from that study at a later time.

Computational Model

We consider the full Navier-Stokes equations written in conservation form

$$W_t + F_x + G_y = 0. \tag{2.1}$$

Here W is the vector $(\rho, \rho U, \rho V, E)$, ρ is the density, U and V are the x and y components of velocity and E is total internal energy. The forms of the flux functions F and G are standard and will not be reproduced here for brevity. All viscous terms are retained.

The computational domain is the rectangle shown in Figure 1. A steady solution is computed given an inflow boundary layer profile [6]. Unsteady solutions are generated by modifying the inflow data by adding to the mean, a perturbation of the form

$$\varepsilon \; \mathrm{Re}\{F(y)e^{i\omega t}\}. \tag{2.2}$$

Here ε is the amplitude of the disturbance, and ω is a frequency for which there is a spatially unstable eigenfunction $F(y)$ for the inflow profile. The eigenfunction is obtained from the corresponding Orr-Sommerfeld equation for the inflow profile (assuming for simplicity incompressible flow). For an inflow Mach number of 0.4, which we use in all of our calculations, we have found that during the initial stage of growth the behavior of the solution is well predicted by neglecting compressibility. Compressibility becomes more important as the disturbance grows and temperature and density fluctuations become large. The code is written in conservation form and so can handle any Mach number including transonic problems with shock development.

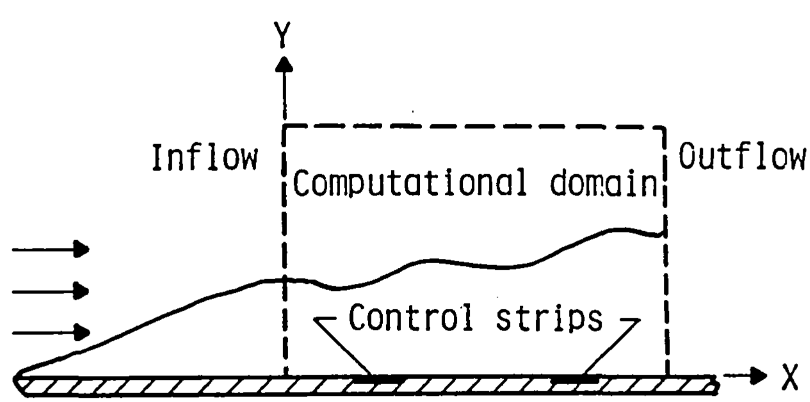

Figure 1. Schematic of computational domain.

The resolution requirements for this problem are severe. The disturbance must be followed over a relatively large number of wavelengths and it is necessary to prevent an accumulation of phase errors. Thus, the problem shares the difficulties of both fluid dynamics and wave propagation. In addition, smaller scale structures, requiring still more resolution, will be generated by nonlinear interactions. It is our experience that approximately ten points per wavelength (in the x direction) are necessary to give acceptable results. In addition, more resolution in the boundary layer (e.g., 50 points or more) is required than for steady flows. This density of grid points is necessary to resolve the wave propagation and the Orr-Sommerfeld eigenfunction normal to the plate. These requirements are greatly reduced by using the fourth-order scheme. The advantages of higher-order methods for the numerical computation of waves have been well documented [7], [8] and it is well known that numerical errors in approximating the convective terms of (2.1) can cause a numerical dissipation which reduces the effective Reynolds number in viscous regions. For this reason, we use a scheme which is a simple modification of the second-order MacCormack scheme that is fourth-order accurate on both the inviscid terms and on the viscous terms [9].

For the one-dimensional equation

$$W_t + F_x = 0$$

we have

$$\overline{W}_i^{n+1} = W_i^n - \frac{\Delta t}{6\Delta x}\left[7\left(F_{i+1}^n - F_i^n\right) - \left(F_{i+2}^n - F_{i+1}^n\right)\right]$$

$$W_i^{n+1} = \frac{1}{2}\left[\overline{W}_i^{n+1} + W_i^n - \frac{\Delta t}{6\Delta x} \cdot \left\{7\left(\overline{F}_i^{n+1} - \overline{F}_{i-1}^{n+1}\right) - \left(\overline{F}_{i-1}^{n+1} - \overline{F}_{i-2}^{n+1}\right)\right\}\right] . \qquad (2.3)$$

The scheme (2.3) becomes fourth-order when it is alternated with a symmetric variant. It has a greatly reduced truncation error compared with the second-order MacCormack scheme. Our experience has been that fourth-order accuracy is necessary to efficiently compute the class of problems considered here. Operator splitting is used so that the two-dimensional system (2.1) is solved by successive applications of one-dimensional solution operators of the form (2.3). The computer program has been fully vectorized on the CDC VPS32 at NASA Langley Research Center and has been validated by comparing with known steady state solutions and by comparing, in the linear regime, the growth rates obtained from imposing unstable disturbances on a mean flow with those obtained from linear theory.

We now describe the boundary conditions. At the inflow we impose an unsteady disturbance on the three incoming characteristic variables based on linearizing and neglecting the y derivatives and viscous terms. The outgoing characteristic is extrapolated from the interior. At the plate, we assume a no-slip condition and specify the temperature. Active control is simulated by locally modifying the temperature boundary condition. Pressure is obtained from the normal momentum equation.

Both the outflow and upper boundaries are subsonic boundaries and one boundary condition must be imposed. We impose the incoming characteristic variable (based on the one-dimensional theory) as having zero fluctuation and extrapolate the outgoing characteristics from the interior. The characteristic condition is not exact for this problem but we have not observed any reflections provided the observation points are taken sufficiently far from the boundaries.

Results

In this section we describe numerical results obtained from the code. This section will be divided into two parts. In the first part we present results for uncontrolled spatial disturbances evolving into a nonlinearly distorted fluctuation. In the second part the effect of active control procedures will be demonstrated.

The basic model is described in Figure 1. The mean flow is a boundary layer. The free stream Mach number is 0.4 and the unit Reynolds number is 3.0×10^5. The computational domain is chosen so that at inflow $Re_{\delta*}$ (Reynolds number based on displacement thickness) is 998 and at outflow $Re_{\delta*}$ is 1730. This distance corresponds to approximately $200\delta_I$ where δ_I is the boundary layer thickness at the inflow. A fluctuating disturbance is introduced at inflow with non-dimensional frequency $F = (\frac{2\pi f \nu}{U_\infty^2})$ of $.8 \times 10^4$. (Here f is the frequency, ν the kinematic viscosity and U_∞ the free stream velocity.) It is known that this frequency is linearly unstable for the $Re_{\delta*}$ used at the inflow. A typical grid size for the calculations is 251×66 parallel and normal to the plate respectively. We have used an exponential stretching in the normal direction. To obtain a more accurate solution for regions where nonlinear distortion is evident, a larger grid of 313×80 has also been used. The computational domain in the vertical direction extended over three boundary layer thicknesses. In practice, the mean profile was computed with a considerably coarser grid and interpolated to the fine grid. The program was then run for a short time with the fine grid in order to smooth out any interpolation errors.

Uncontrolled Results

In Figure 2 spatial growth rates are shown for two different amplitudes of the inflow disturbance and compared with those obtained from linear incompressible theory*. The growth rates are obtained from computing the RMS $\left(\sqrt{\overline{(\rho u - (\rho u)_{mean})^2}}\right)$ at different y locations and integrating the results with respect to y.

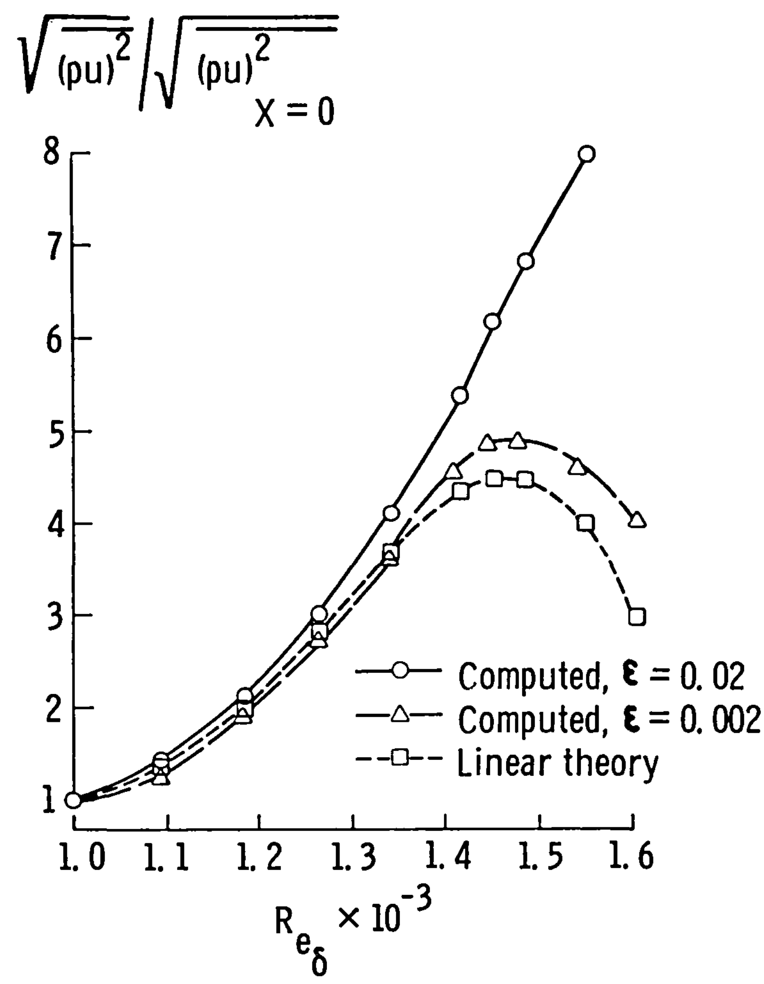

Figure 2. Comparison of amplitude growth with linear theory.

*Dagenhart, R., private communication, 1983.

The results in Figure 2 indicate good agreement with linear theory for small initial disturbance (i.e., peak disturbance of 0.2% of freestream). In particular, the regions of growth and decay follow the linear theory predictions. For larger disturbances (i.e., 2% of freestream), nonlinear effects become important and the solution shows a definite departure from the linear theory.

Based on the wavelength of the disturbance at the inflow, the computational domain extended over approximately 20 wavelengths during which the disturbance grew by a factor of approximately 10. The results of Figure 2 were also validated by mesh refinement. A resolution of approximately 10 points per wavelength (at inflow; the wavelength gets smaller downstream) was required to give acceptable results. This is due to the fourth-order accuracy of the algorithm. In regions where nonlinear distortion was evident, more resolution was required to simulate the smaller scales. Approximately 30 points in the boundary layer (based on δ_I) were required to resolve the fluctuating disturbance. The second-order scheme with comparable grids consistently predicted either decay or greatly reduced growth rates.

In Figure 3 we plot $\left(\sqrt{\overline{((\rho u) - (\rho u)_{mean})^2}}\right)$ as a function of $\eta = (y/x)\sqrt{Re_x}$ for several different downstream locations. These profiles are similar to those obtained by Murdock for incompressible flows [10]. It is apparent that the basic shape of the inflow profile (i.e., the Orr-Sommerfeld solution) is maintained as the disturbance grows. Most of the nonlinear distortion was observed near the wall and near the point where the disturbance changed sign. We believe that this is because the derivatives of disturbances (in y) are changing most rapidly at these locations.

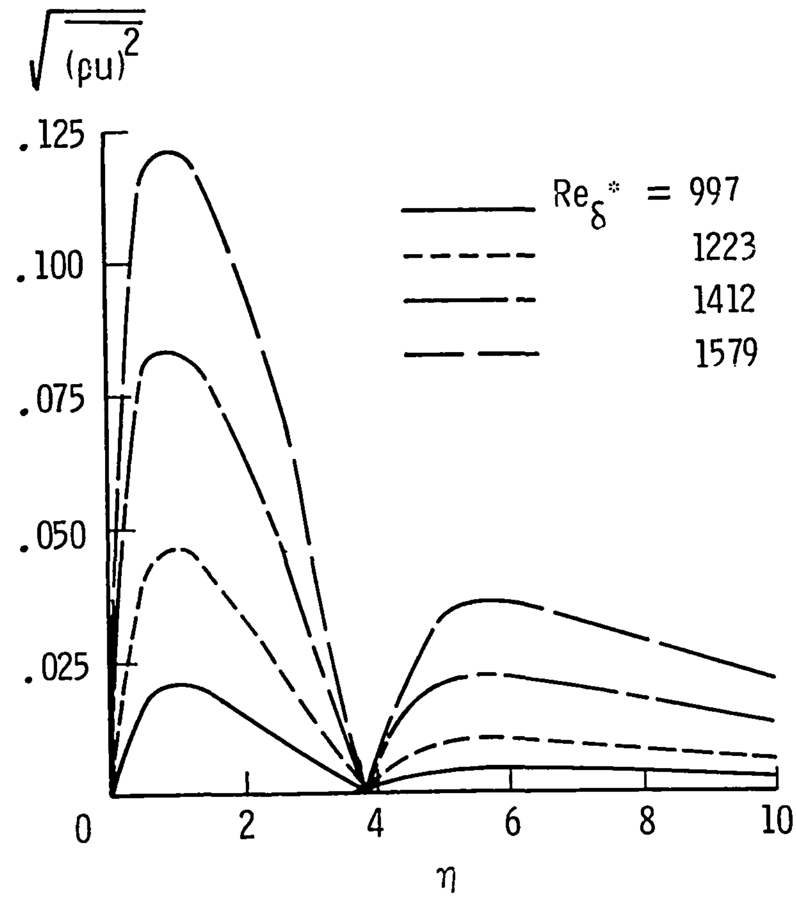

Figure 3. Growth of RMS amplitude vs. $\eta\left(= \frac{y}{x}\sqrt{Re_x}\right)$.

To examine the evolution of the disturbance we plot in Figure 4 $\rho u(t)$ as a function of (non-dimensional) time for a fixed y location ($y = 0.0115\ \delta_I$). In Figures 5a and 5b we plot $\rho u(t)$ against t for several different y locations for $Re_{\delta^*} = 1412$ and $Re_{\delta^*} = 1579$. It is apparent from these figures that a significant laminar growth has occurred between Re_{δ^*} of 1412 and Re_{δ^*} of 1579. In addition at the second station, $\rho u(t)$ at $y/\delta = 0.066$ becomes negative for part of the cycle indicating a cylical separation and reattachment of flow on the plate. This phenomenon is further clarified in Figure 6 where the instantaneous velocity profile is plotted at the two extrema of a time cycle close to the wall.

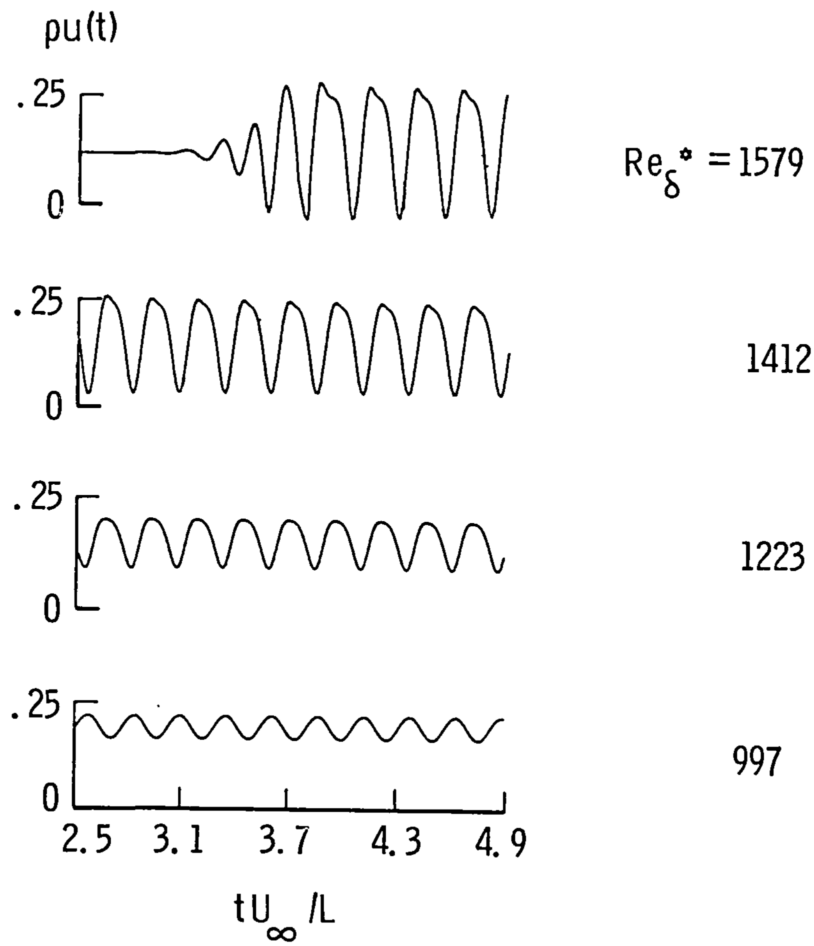

Figure 4. Growth of $\rho u(t)$ **vs. time for** $y = 0.0115\ \delta_I$**.**

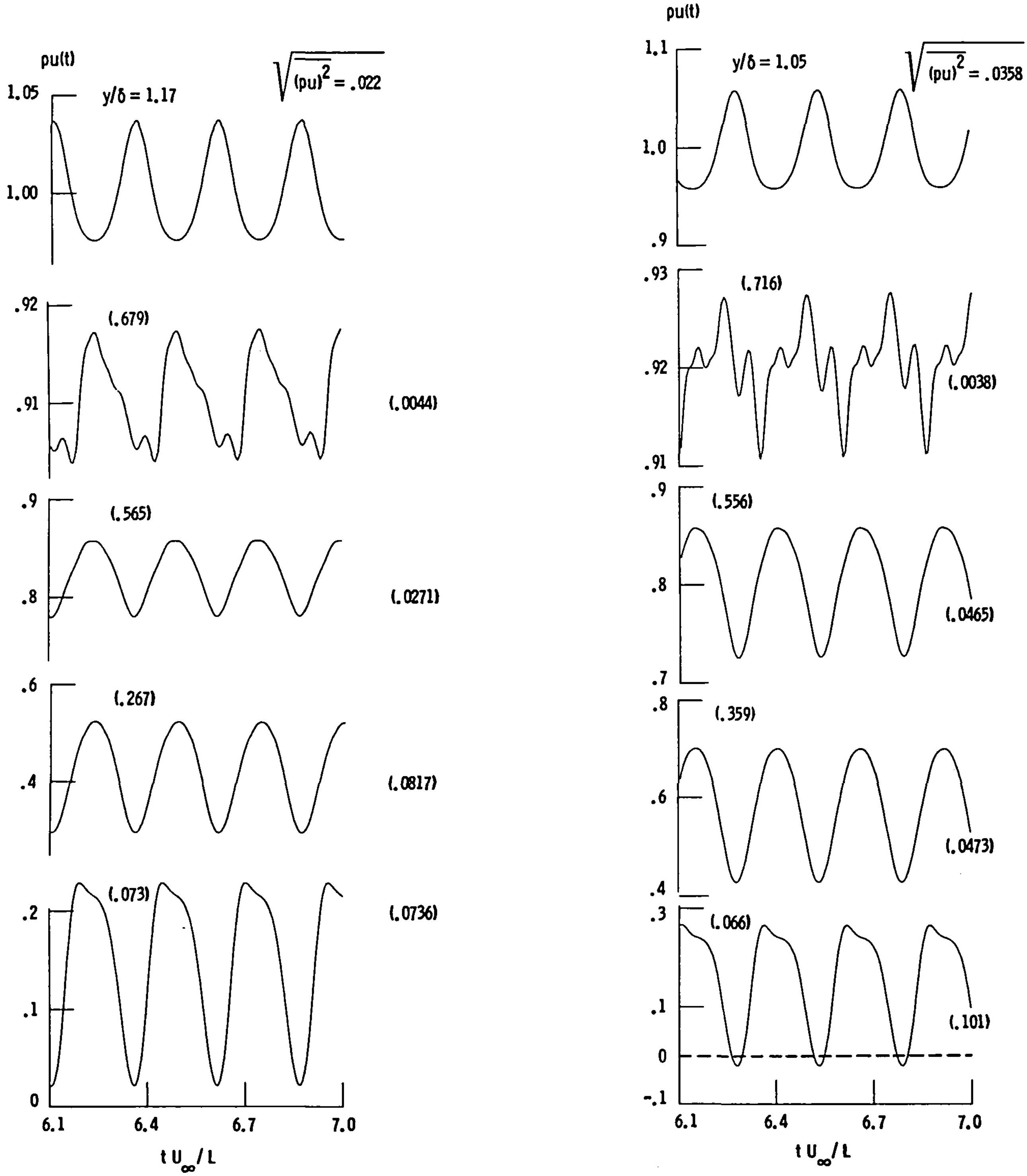

Figure 5. Instantaneous $\rho u(t)$ across the boundary layer at (a) $Re_{\delta*} = 1412$, (b) $Re_{\delta*} = 1579$, L = 1.

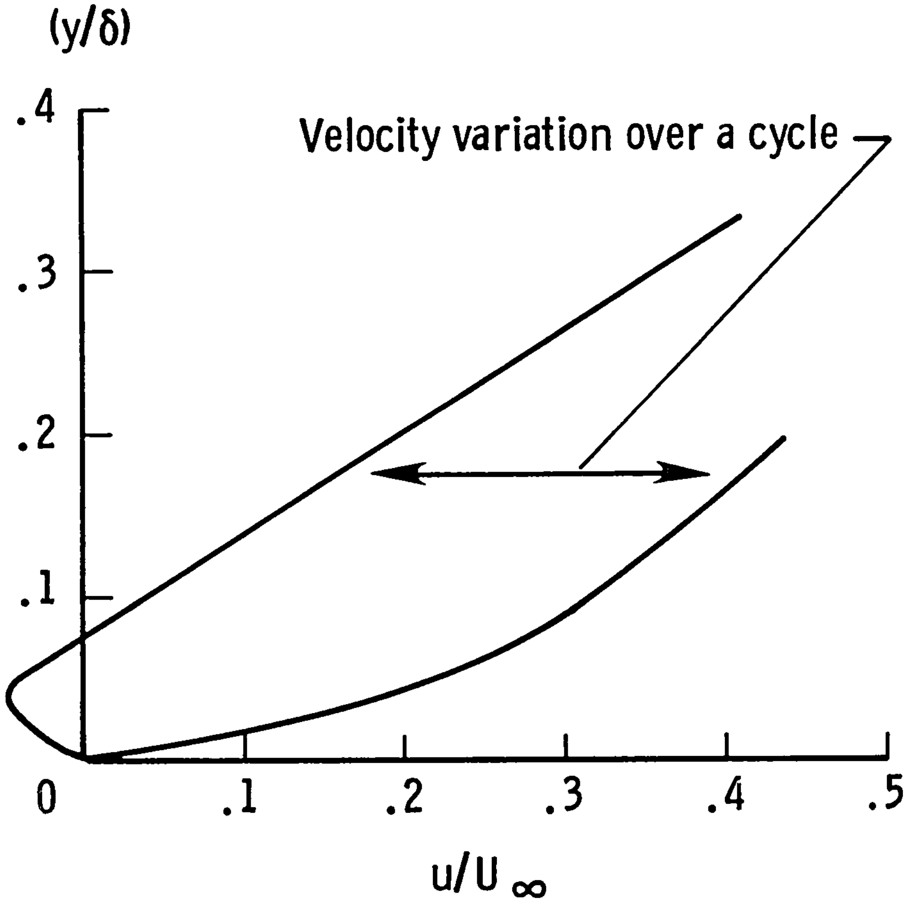

Fig. 6. Velocity profile at the extreme of a time cycle at $Re_{\delta*} = 1547$.

The developing flow, with an initial peak disturbance of 2% of the freestream has grown so large that close to the wall the flow separates and reattaches cyclically. By reducing the amplitude of inflow disturbances (but large enough to exhibit nonlinear effects) the laminar separation occurs further downstream. If three-dimensional effects are accounted for, the lateral spreading will limit the maximum growth of the disturbance, thus preventing the laminar separation.

Control Results

The effect of the active control was investigated at two stations with the control strip located at $Re_{\delta*}$ of 1263 and 1547. Surface heating and cooling was accomplished by modifying the temperature boundary condition over a small strip on the plate. The formula was

$$\frac{T}{T_{ref}} = \frac{T_w}{T_{ref}} \pm \left(\alpha + \beta \sin(\omega t + \phi)\right)^2, \tag{3.1}$$

with the plus sign for heating and the minus sign for cooling. In (3.1) T_w is the temperature of the wall (520^o R) and T_{ref} is the reference temperature. The functional form of (3.1) models a D.C. current (α) and an A.C. current (β) with phase ϕ.

In Figure 7 the growth rates are compared with the uncontrolled case for a control strip located at $Re_{\delta*} = 1263$. The width of the strip b is $b/\delta* = 3.98$ where $\delta*$ is the local displacement thickness. This corresponds to a width of approximately 20% of the wavelength of the disturbance at the inflow.

In Figure 7 the parameters for the heated case were $\alpha = 1$, $\beta = 4$, $\phi = 180^o$, corresponding to a peak temperature of about 1650^o R. For the cooled case the parameters were $\alpha = 1$, $\beta = 1.7$, $\phi = 0^o$, with a peak temperature of about 190^o R. In the heating case the temperature corresponds to roughly three times the unheated wall temperature which is close to the temperature obtained in reference 4 using a tungsten wire. In the cooled case the parameters are chosen so that the temperature will stay in the range where Sutherland's law is valid for the viscosity as a function of the temperature. Such a periodic cooling is not attainable by experimental techniques available at the present time. There were no numerical instabilities due to the large temperature perturbation but the heating forced a reduction in the allowed time-step.

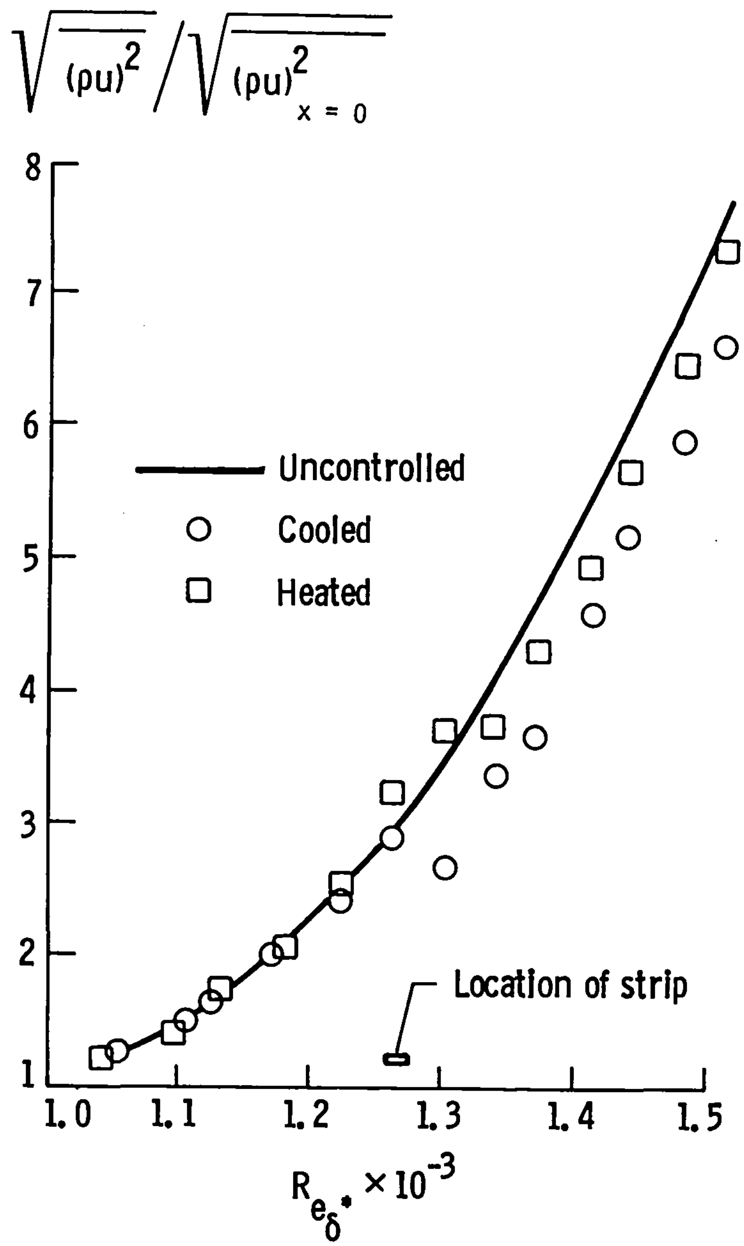

Figure 7. Effect of control on RMS amplitude growth with control strip at $Re_{\delta*} = 1263$, $b/\delta* = 3.98$.

The results in Figure 7 demonstrate that by an appropriate choice of phase, a reduction in the level of the fluctuating disturbance can be obtained just by surface heating. The maximum reduction in the growth rate is approximately 6% for heating and 12% for cooling. The phase depends on the position of the control strip.

In Figures 8a and 8b we plot $\rho u(t)$ as a function of non-dimensional time tU_∞/L comparing heated and uncontrolled fluctuations (Figure 8a) and the cooled and uncontrolled fluctuations (Figure 8b). The graphs are shown at an x location slightly downstream of the heating strip where maximum reduction occurs and the RMS values of the fluctuations are shown in each case. The figures show a reduction in amplitude in both cases with a slight phase change introduced by the heating. In both cases the control appears to have only a slight effect on the structure of the waveform. The numerical simulation establishes the feasibility of reducing the amplitude of the fluctuations by heating and cooling. This is not the best control that can be achieved. The amount of control that is possible depends on the parameters used for the control and on the number and location of the strips. We have not systemically tried the possibilities.

The effect of control at the second station ($Re_{\delta*} = 1547$) is expected to be different from that of the first station because of the cyclical separation and reattachment of the flow (Figure 6). This flow reversal causes the temperature to be partly convected upstream and so effective phase control is lost. In the downstream direction, although control is achieved for both heating and cooling, it is significantly reduced. This occurs because effective phase control is lost for a portion of the time cycle in the layers close to the wall (Figure 9).

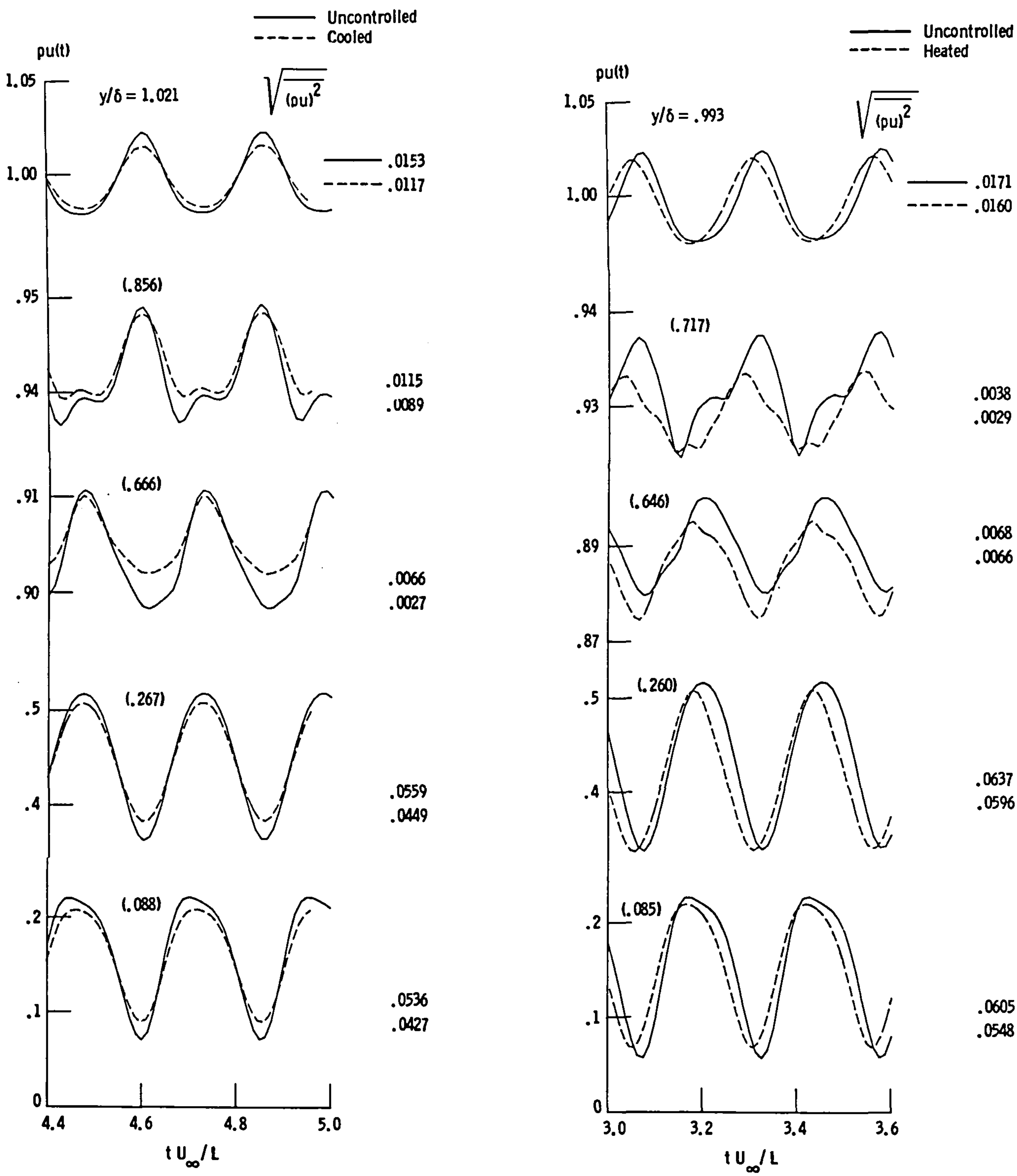

Figure 8. Comparison of $\rho u(t)$ between controlled and uncontrolled cases, (a) cooled with $Re_{\delta*} = 1320$, (b) heated with $Re_{\delta*} = 1340$.

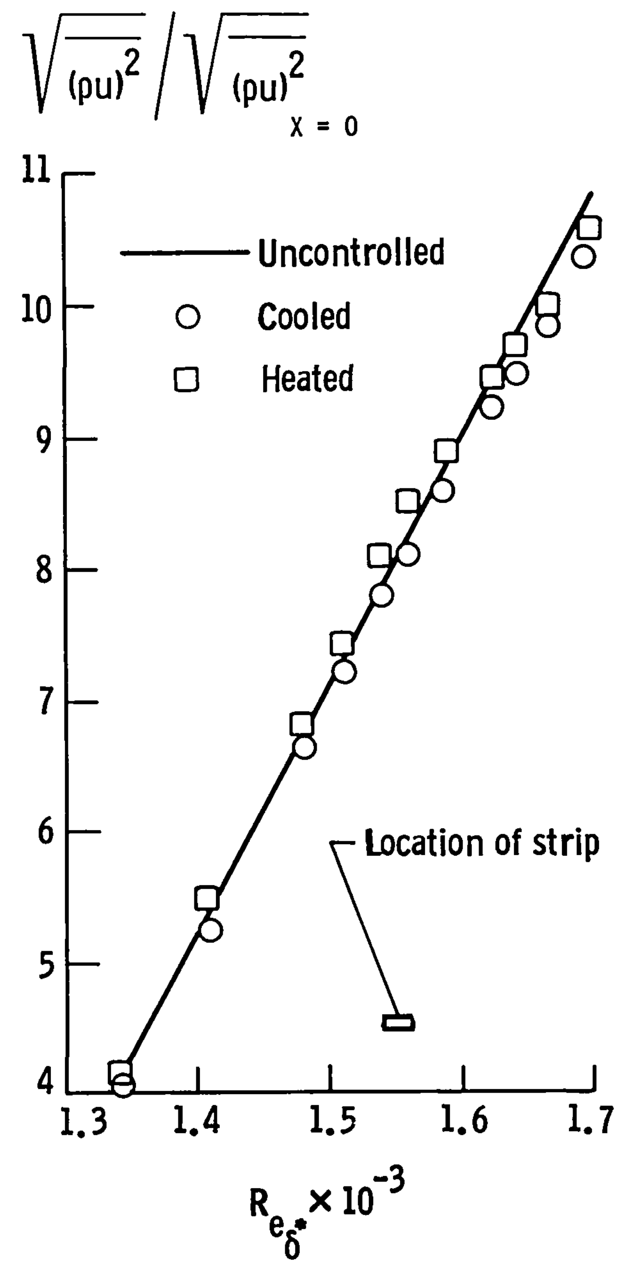

Figure 9. **Effect of control on RMS amplitude growth, with control strip at** $Re_{\delta*} = 1547$, $b/\delta* = 1.6$.

Conclusion

The concept of localized, periodic, surface heating to control growing disturbances in a subsonic flow has been simulated numerically. It was found that by appropriate adjustment of the phase of the controlling disturbances, the level of the fluctuation can be reduced provided that the disturbances are quasi-periodic and not too large. A more pronounced effect can be obtained by cooling although this technique is practical at the present time for steady state and very low frequency only.

This work shows the mechanism of the active control. Larger reductions in amplitude can be obtained by using multiple control strips with proper phase relationships. The results show that the increased growth causes separation with distance. This is due to the large inflow disturbance level. The control in this region is much less effective because of the loss of phase control near the wall.

The limitation in this model is the restriction to two-dimensional flow, since three-dimensional effects become important further downstream. This may prevent the kind of separation and reattachment experienced at the second station which we observed.

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1. Report No. NASA CR-172575 ICASE Report No. 85-23	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle NUMERICAL SIMULATION OF BOUNDARY LAYER EXCITATION BY SURFACE HEATING/COOLING		5. Report Date March 1985 6. Performing Organization Code
7. Author(s) A. Bayliss, L. Maestrello, P. Parikh, and Eli Turkel		8. Performing Organization Report No. 85-23
9. Performing Organization Name and Address Institute for Computer Applications in Science and Engineering Mail Stop 132C, NASA Langley Research Center Hampton, VA 23665		10. Work Unit No. 11. Contract or Grant No. NAS1-16394, NAS1-17070, and NAS1-17130
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Contractor Report 14. Sponsoring Agency Code 505-31-83-01
15. Supplementary Notes Langley Technical Monitor: J. C. South, Jr. Final Report		Submitted to AIAA J.

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This paper is a numerical study of the concept of active control of growing disturbances in an unstable compressible flow by using time periodic, localized surface heating. The simulations are calculated by a fourth-order accurate solution of the compressible, laminar Navier-Stokes equations. Fourth-order accuracy is particularly important for this problem because the solution must be computed over many wavelengths. The numerical results demonstrate the growth of an initially small fluctuation into the nonlinear regime where a local breakdown into smaller scale disturbances can be observed. It is shown that periodic surface heating over a small strip can reduce the level of the fluctuation provided that the phase of the heating current is properly chosen.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
flow control, active control by heating, fourth-order Navier-Stokes solution	34 - Fluid Mechanics 64 - Numerical Analysis Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	23	A02

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NASA-Langley, 1985