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WAVE PHENOMENA IN A HIGH REYNOLDS NUMBER
COMPRESSIBLE BOUNDARY LAYER

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WAVE PHENOMENA IN A HIGH

REYNOLDS NUMBER COMPRESSIBLE BOUNDARY LAYER

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ABSTRACT

Growth of unstable disturbances in a high Reynolds number compressible boundary layer is numerically simulated. Localized periodic surface heating and cooling as a means of active control of these disturbances is studied. It is shown that compressibility in itself stabilizes the flow but at a lower Mach number, significant nonlinear distortions are produced. Phase cancellation is shown to be an effective mechanism for active boundary layer control.

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Introduction

This paper is a numerical study of the behavior of spatially unstable waves in a high Reynolds number, compressible boundary layer. The numerical simulations are conducted by solving the laminar, two-dimensional, compressible Navier-Stokes equations over a flat plate with a fluctuating disturbance generated at the inflow. The primary objectives of this work are to study the nonlinear growth and distortion of the unstable waves and also to study techniques for the active control of these disturbances by time-periodic surface heating and cooling. The results presented here are an extension of the results presented in [1], [2].

An extensive experimental investigation of the evolution of linearly unstable waves in a boundary layer is described in [3]. The numerical simulations closely parallel the conditions of this experiment except for the Mach number of the mean flow which is considerably higher than in the experiment. The authors in [3] investigated the initial stage of the development of the disturbance, in particular the growth of the higher harmonics. It was shown that in this region three-dimensional effects were not important. Our results are in qualitative agreement with these experimental observations. Murdock [4] studied the growth of spatially unstable disturbances in an incompressible flow. The results presented here are similar to those obtained in [4]. However, our results are obtained for a much smaller initial disturbance level and bring out some additional features of the wave development. Furthermore, we account for compressibility effects.

The active control of unstable waves by surface heating was introduced in [5] and [6] for disturbances in water. The idea is to introduce a temperature disturbance by surface heating which is out of phase with the propagating disturbance. The growth of the unstable wave is reduced because the two waves cancel. In [5] and [6] a feedback control mechanism was used to generate the control signal. A feedback mechanism is needed since by an appropriate choice of phase the signals can be made to amplify rather than cancel. In the experiments of Maestrello [7], instantaneous transition in air was achieved by localized surface heating.

The use of active control techniques which attempt to modify the unstable wave, rather than the basic mean flow, offers considerable promise as an efficient method of delaying transition. It was shown in [8] that this technique should be considerably more difficult to apply in air than in water. There are three reasons for this. First, steady heating tends to destabilize the mean flow. Second, a much larger temperature disturbance is required to generate an equivalent change in the viscosity. Finally, there is the possibility that temperature disturbances can be transformed into acoustic disturbances, thereby losing effective phase control. Nevertheless, the numerical simulations presented in [2] and in the present paper demonstrate that this technique is feasible.

In Section 2 we discuss the numerical model. The major feature of the numerical scheme is the use of fourth-order accurate finite differences for the inviscid terms of the Navier-Stokes equations. It is well known (see, for example, [9], [10]) that fourth-order accuracy is essential in preventing numerical dispersion and dissipation from significantly degrading the accuracy of wave propagation problems. Fourth-order accuracy is even more essential for the present problem, in order to prevent numerical errors on the inviscid terms, which act as an additional source of viscosity, from lowering the effective Reynolds number of the mean flow and hence, incorrectly stabilizing the flow.

In Section 3 we present numerical results. The section is divided into two parts. In the first part the nonlinear evolution of the uncontrolled wave is described and compared with experimental observations. In the second part the simulation of localized time-periodic surface heating and cooling is discussed. Generally, the active control would be expected to be most effective in the linear regime before nonlinear growth and distortion becomes significant. When nonlinear effects predominate then periodic control is no longer possible as harmonics develop and the waves will not have a well-defined phase. One needs to develop control techniques which account for random amplitudes and phases. In Section 4 we discuss our conclusions.

2. Numerical Model

In this section we describe the numerical model. An extensive discussion of the model is presented in [1]. The discussion here will be brief and the reader is referred to [1] for further details.

The laminar, compressible Navier-Stokes equations can be written in the form

$$w_t = F_x + G_y. \tag{2.1}$$

Here, w is the vector $(\rho, \rho u, \rho v, E)^T$, ρ is the density, u and v are the x and y velocity components respectively, and E is the total energy. The functional forms of the functions F and G are standard and will be omitted for brevity.

The computational domain is the rectangle shown in figure 1. First, a basic steady flow, in this case a spreading boundary layer, is computed. Then an unsteady disturbance is specified at inflow and the development of the disturbance as it propagates through the steady flow is simulated by solving the system (2.1). Since the disturbance must be followed over a large number of wavelengths, it is essential to use a higher order accurate scheme. We therefore use a scheme which is second-order accurate in time and fourth-order accurate in space.

For the one-dimensional equation

$$W_t + F_x = 0,$$

we have

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

$$W_i^{n+1} = \frac{1}{2}\left(\overline{W}_i^{n+1} + W_i^n - \frac{\Delta t}{6\Delta x}\left\{7\left(\overline{F}_i^{n+1} - \overline{F}_{i-1}^{n+1}\right) - \left(\overline{F}_{i-1}^{n+1} - \overline{F}_{i-2}^{n+1}\right)\right\}\right) . \qquad (2.2)$$

The scheme (2.2) becomes fourth-order when $F = F(u)$ if it is alternated with a symmetric variant in which there are backward differences in the predictor and forward differences in the corrector. 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 (2.2). This scheme is fourth-order accurate on the inviscid terms. The scheme is fourth-order on the viscous terms for a constant viscosity but is only second-order accurate on the viscous terms when the viscosity is spatially dependent. For this problem, due to the high Reynolds number, the primary source of error is due to the inviscid terms and the scheme is very accurate. A sixth-order, in space, algorithm is presented in [2].

A detailed description of the boundary conditions is given in [1]. Radiation conditions are used at the outflow and upper boundaries. At the inflow we must specify three boundary conditions. These are the three incoming characteristic variables based on linearizing the function F in (2.1) and ignoring variations in the y direction. Let Q denote an incoming variable. We specify Q at inflow by

$$Q = Q_{steady} + \varepsilon\, e^{i\omega t}\, Q_{OS}(y)$$

where Q_{steady} is the steady state solution, and $Q_{OS}(y)$ is obtained from the linearized Orr-Sommerfeld equation (linearized about the inflow steady profile) for the (unstable) frequency ω. The Orr-Sommerfeld solutions were obtained from a program developed by J. R. Dagenhart at NASA Langley Research Center. This program neglects compressibility effects. Thus, there exists a discrepancy when comparing with linear theory at large flow velocities. However, for an inflow Mach number of 0.4 close agreement with linear theory is obtained.

3. Numerical Results

In this section we present numerical results for the model described in Section 2. The section is divided into two parts. Part A is concerned with wave propagation through the mean flow without external active control. In Part B the effect of active surface heating and cooling is discussed.

A. Uncontrolled Wave Propagation

We first consider a boundary layer with a free stream Mach number of 0.4. 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 990 and at outflow $Re_{\delta*}$ is 1730. Based on the inflow profile, the nondimensional frequency $F = (2\pi f\nu/U_\infty^2)$ of $.8 \times 10^{-4}$ is unstable. (Here f is the frequency in Hertz, ν the kinematic viscosity and U_∞ the free stream velocity.)

In figure 2 we plot the growth rates of the unstable disturbance as a function of $Re_{\delta*}$. The growth rates are computed by computing the RMS of $\rho u(t,y)$, integrating the result in y and normalizing by the value at inflow. The results in figure 2 are plotted for two different values of ε (amplitude of the inflow perturbation) and compared with results obtained from linear (incompressible) stability theory.

It is apparent that for small ε, the growth rates are very close to those predicted by linear theory. Differences can be attributed to nonparallel and possibly compressibility effects. In particular, the solution decays at roughly the same position as predicted by linear theory. For larger values of ε, the solution does not decay and exhibits a nonlinear growth. This behavior is similar to that observed by Thomas [11] using a vibrating ribbon in air.

In order to analyze the solution as a function of y we plot in figure 3 the RMS of ρu as a function of y at four different x locations. The results in figure 3 are obtained with $\varepsilon = 0.02$. In this case the profiles follow the basic shape of the inflow Tollmein-Schlichting profile. However, the amplitude increases as the disturbance grows downstream. The shape of

Tollmein-Schlichting profile is preserved even though the solution is exhibiting a growth which is not predicted by linear theory (which, in fact, predicts decay for $Re_{\delta*} > 1500$).

In figure 4 the amplitude of the fundamental (F_1) and the first harmonic (F_2) are plotted as a function of y/δ where δ is the local boundary layer thickness for $Re_{\delta*} = 1579$. The data is normalized so that the peak of the fundamental is 1.0. It can be seen that the amplitude of the first harmonic has grown to roughly 30% of the peak of the fundamental. It is also apparent that the harmonic has maximum near the wall and thus the nonlinearity is most pronounced there. This is in agreement with the experimental measurements of [3]. In figure 5 we reproduce a figure from [3] illustrating the experimental fluctuation level.

The experimental data clearly shows a much larger degree of nonlinearity than the computations. However, the flow velocity in [3] is much less than the present computation. The value of $Re_{\delta*}$ can not be determined from the information presented in [3]. The computation does not produce a double peak for the fundamental although there is some indication of a double peak for the harmonic.

It is apparent from both figures that nonlinearity is expected to be most noticeable in the solution near the wall and near the turning point where the fluctuation goes through zero. This can also be seen in figure 6 where ρu is plotted as a function of nondimensional time at several y locations for $Re_{\delta*} = 1579$. We observe that at this location the disturbance has grown so large that there is a cylic separation and reattachment near the wall.

The compressibility effects for this case are not large. In order to examine the effect of compressibility we compare in figure 7 the growth of the disturbance for free stream Mach numbers 0.4 and 0.7. The data is taken so that Re_{δ^*} at inflow is 998.0 in both cases. The parameter ε is also the same in both cases. Both inflow Tollmien-Schlichting profiles are taken from an incompressible program and would therefore be expected to be slightly less accurate for $M = 0.7$.

The results demonstrate a very strong stabilizing effect due to increasing compressibility. In fact the $M = 0.7$ decays downstream following the stability curve while the $M = 0.4$ case does not decay due to nonlinear effects. Examination of the solution indicates that there is much less nonlinearity in the $M = 0.7$ case.

B. Active Control by Surface Heating and Cooling

We next consider the effect of active surface heating and cooling. All results are obtained for the $M = 0.4$ case described previously. The surface heating and cooling is effected by imposing a boundary condition of the form

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

where the $+$ sign is for heating and the $-$ sign is for cooling. T_w is the temperature at the wall (520^oR) and T_{ref} is a reference temperature. The form of (3.1) is chosen to model a combination of a DC current and an AC current. No attempt was made to optimize the coefficients α and β, however, the effect of varying the phase ϕ was studied.

It is well known that static heating is destabilizing in air and static cooling is stabilizing. The numerical results with $\alpha >> \beta$ confirm this. In order to demonstrate the effect of phase we plot the growth rates in figure 8 for cooling with different values of ϕ and in figure 9 for heating. In all cases the control strip extends over roughly 20% of a wavelength and is centered at $Re_{\delta*} = 1263$.

It is apparent from figures 8 and 9 that the response is very sensitive to the phase. In particular, cooling can destabilize with an appropriate choice of phase and heating can stabilize. These results clearly indicate that phase cancellation can be a viable mechanism for the control of unstable disturbances. By appropriate choice of phase the active heating and cooling can have effects exactly opposite from the static case.

In figures 10 and 11 we examine time traces for $\rho u(t)$ at different y locations. The traces are all taken at $x = 1.0$ ft., significantly downstream of the heating (or cooling) strip which was placed at 0.6 ft. The figures show that the residual effects of the active heating and cooling are an amplitude and phase change in the propagating wave. Very little distortion in the wave form is introduced by the active heating and cooling.

4. Conclusions

The behavior of unstable disturbances in a high Reynolds number flow can be effectively computed provided a fourth-order accurate finite difference scheme is used. The results show that significant nonlinear distortion is produced which is in qualitative agreement with experiment.

It is shown via a full Navier-Stokes solution that increasing compressibility can significantly stabilize the flow over a flat plate. In addition, it is shown that the mechanism of phase cancellation is a viable mechanism for the control of growing disturbances. The authors are currently extending these results to flows over curved surfaces thus accounting for non-zero pressure gradients.

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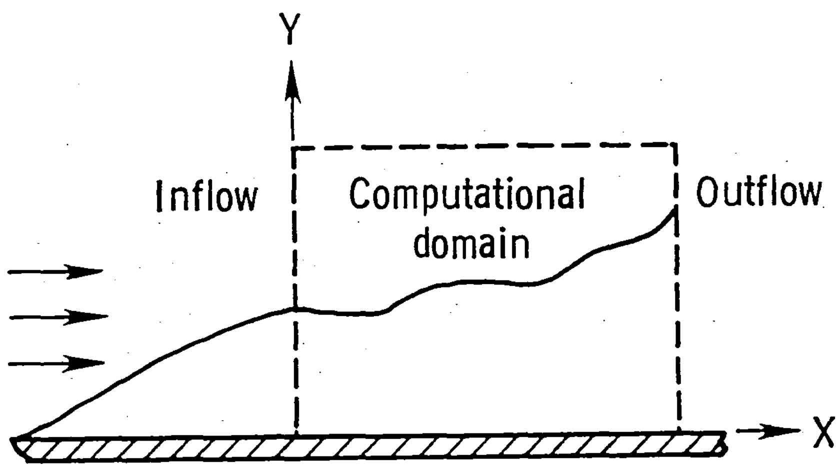

Figure 1. Schematic of computational domain.

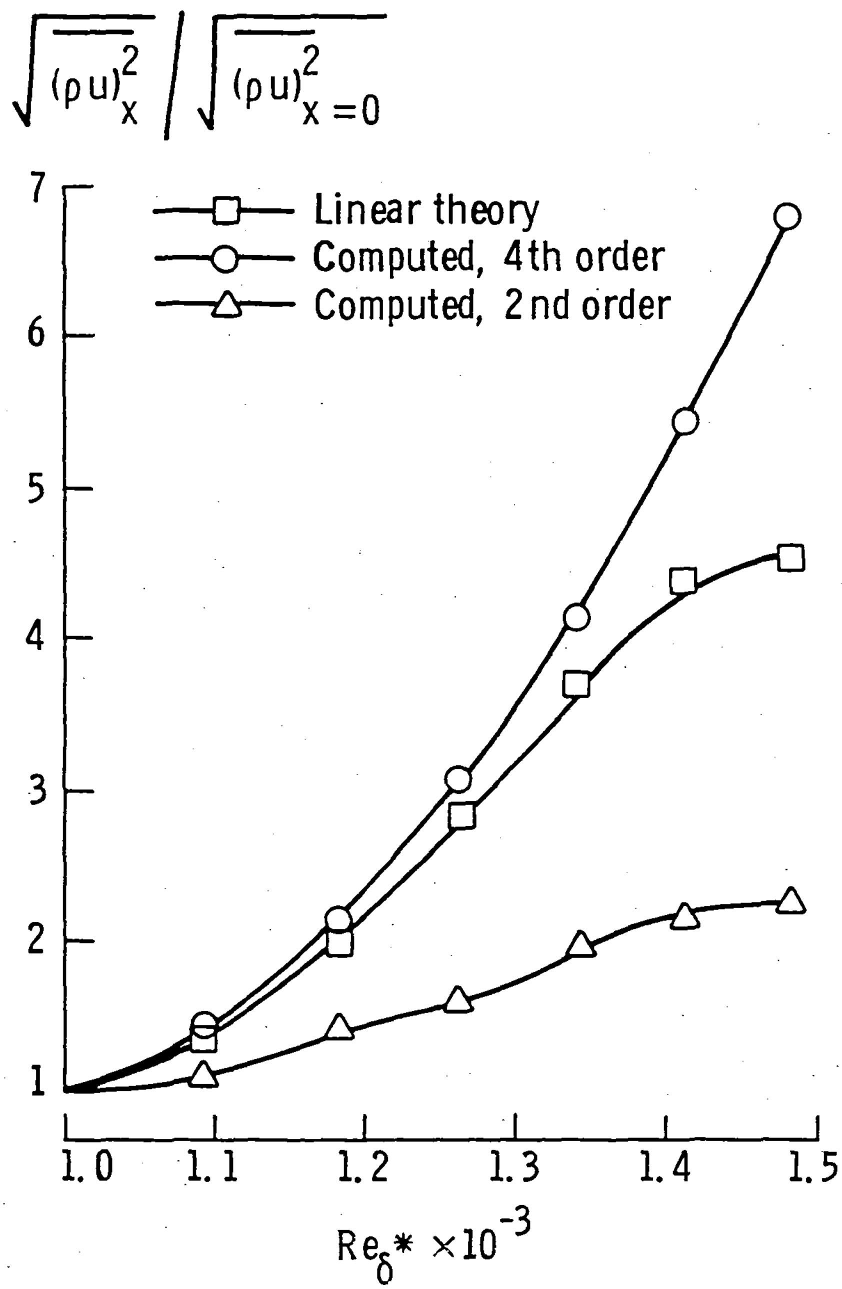

Figure 2. Comparison of amplitude growth with linear theory.

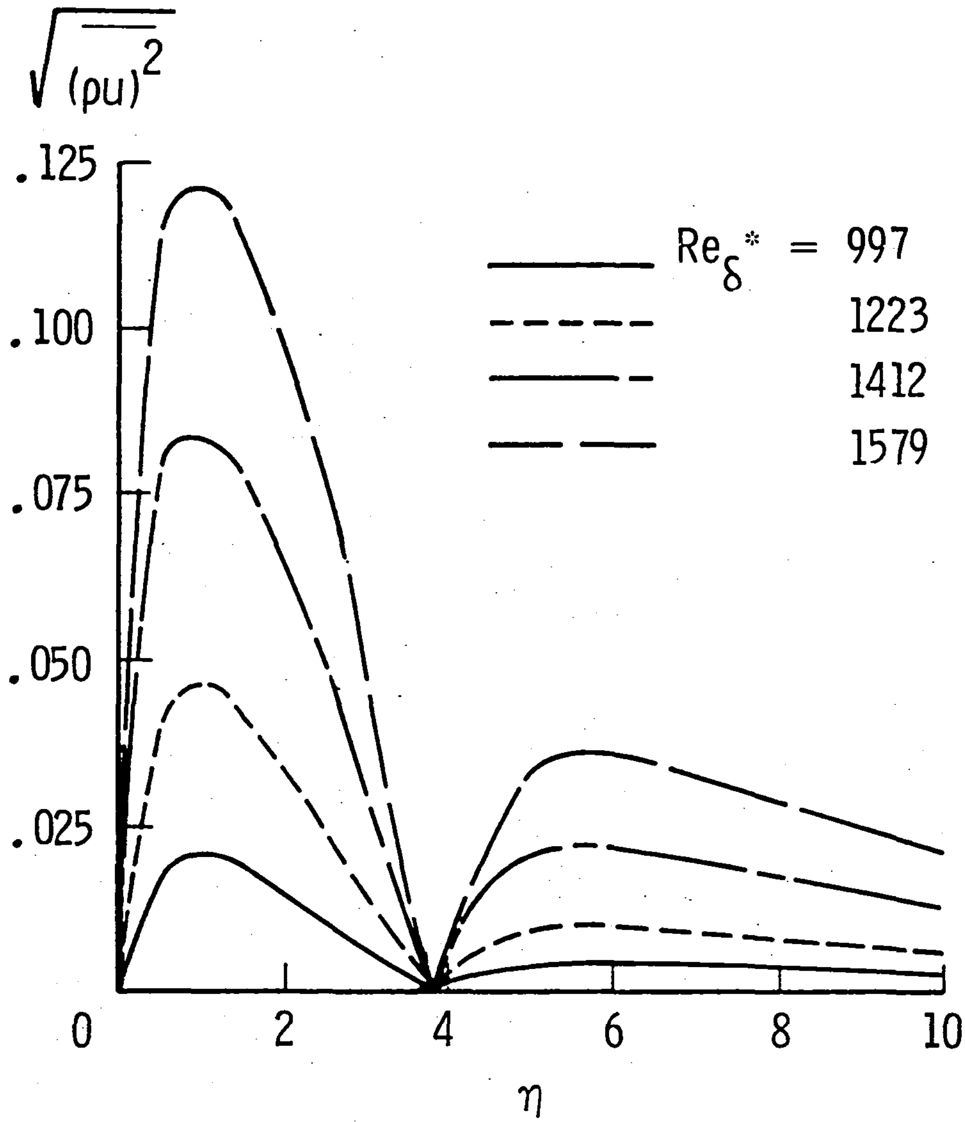

Figure 3. RMS ρu versus y at different x locations.

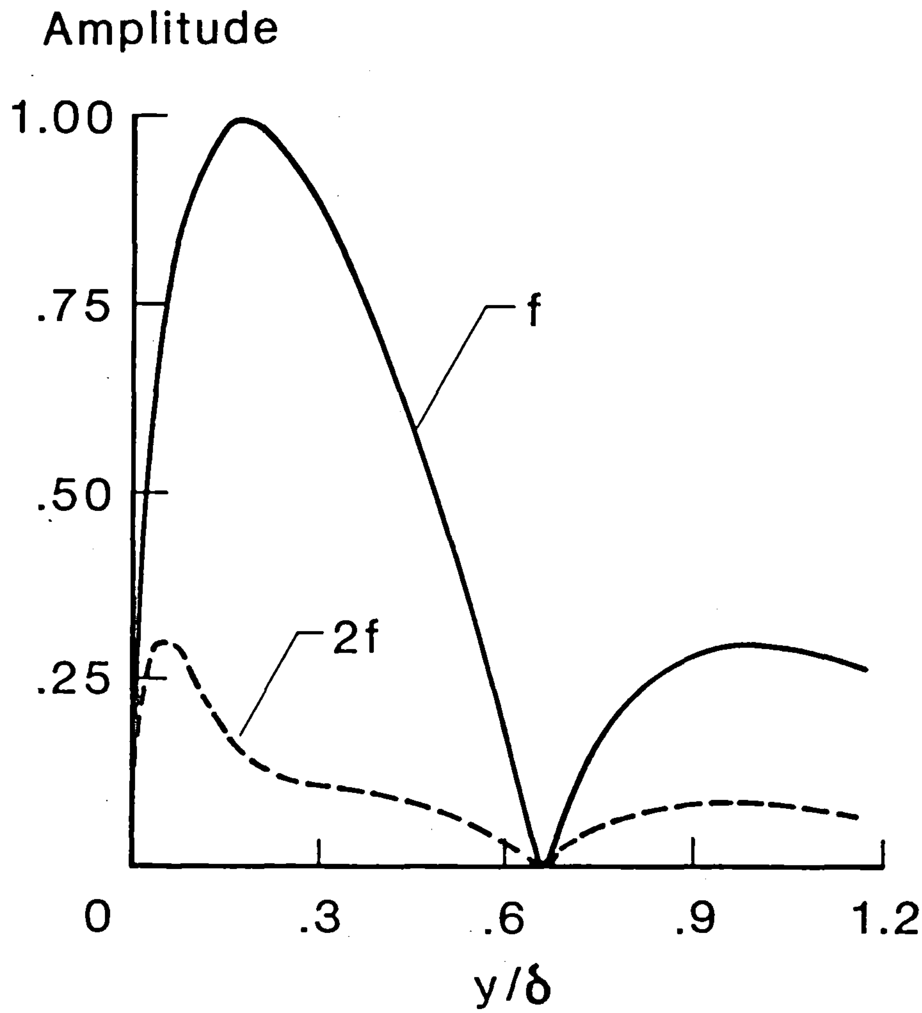

Figure 4. F_1 and F_2 versus y/δ at $Re_{\delta*} = 1579$.

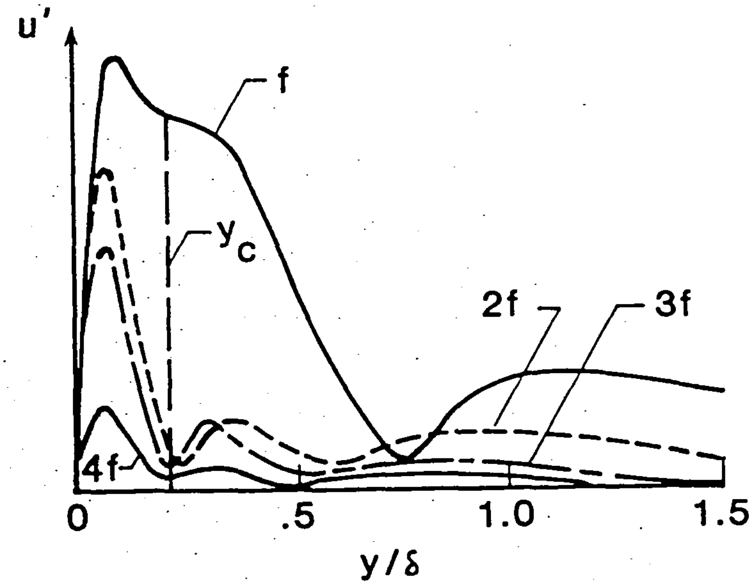

Figure 5. Experimental analysis of harmonic content of fluctuating disturbance (from [3]).

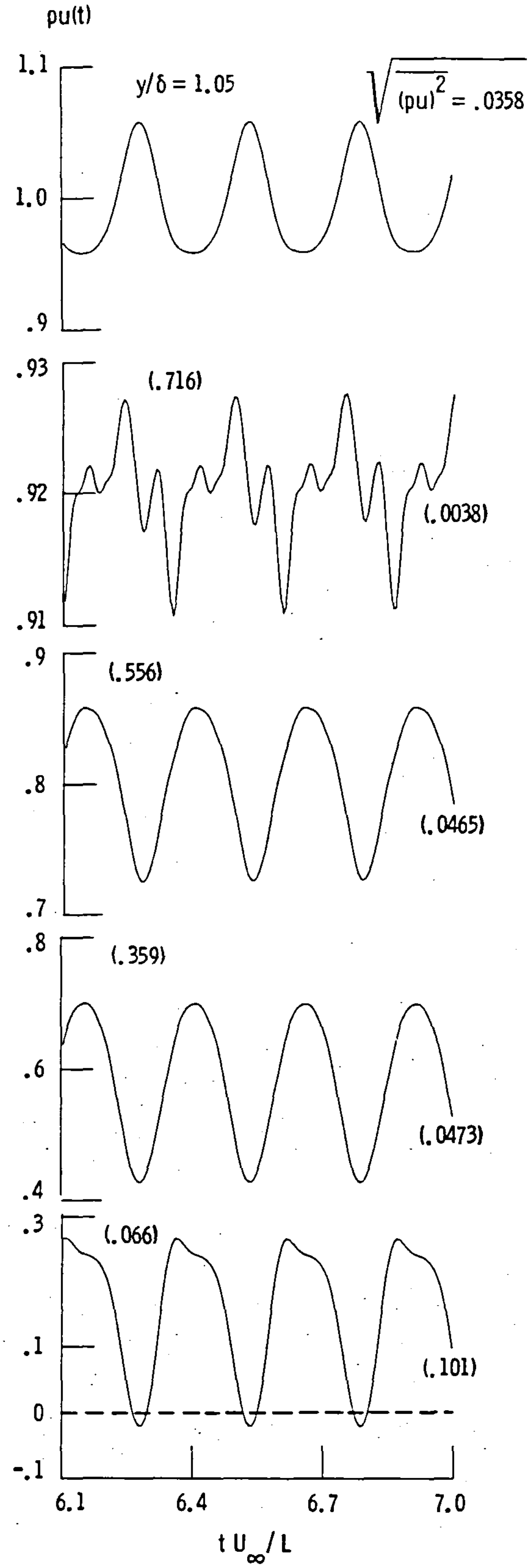

Figure 6. ρu versus t for selected values of y; $Re_{\delta*} = 1579$.

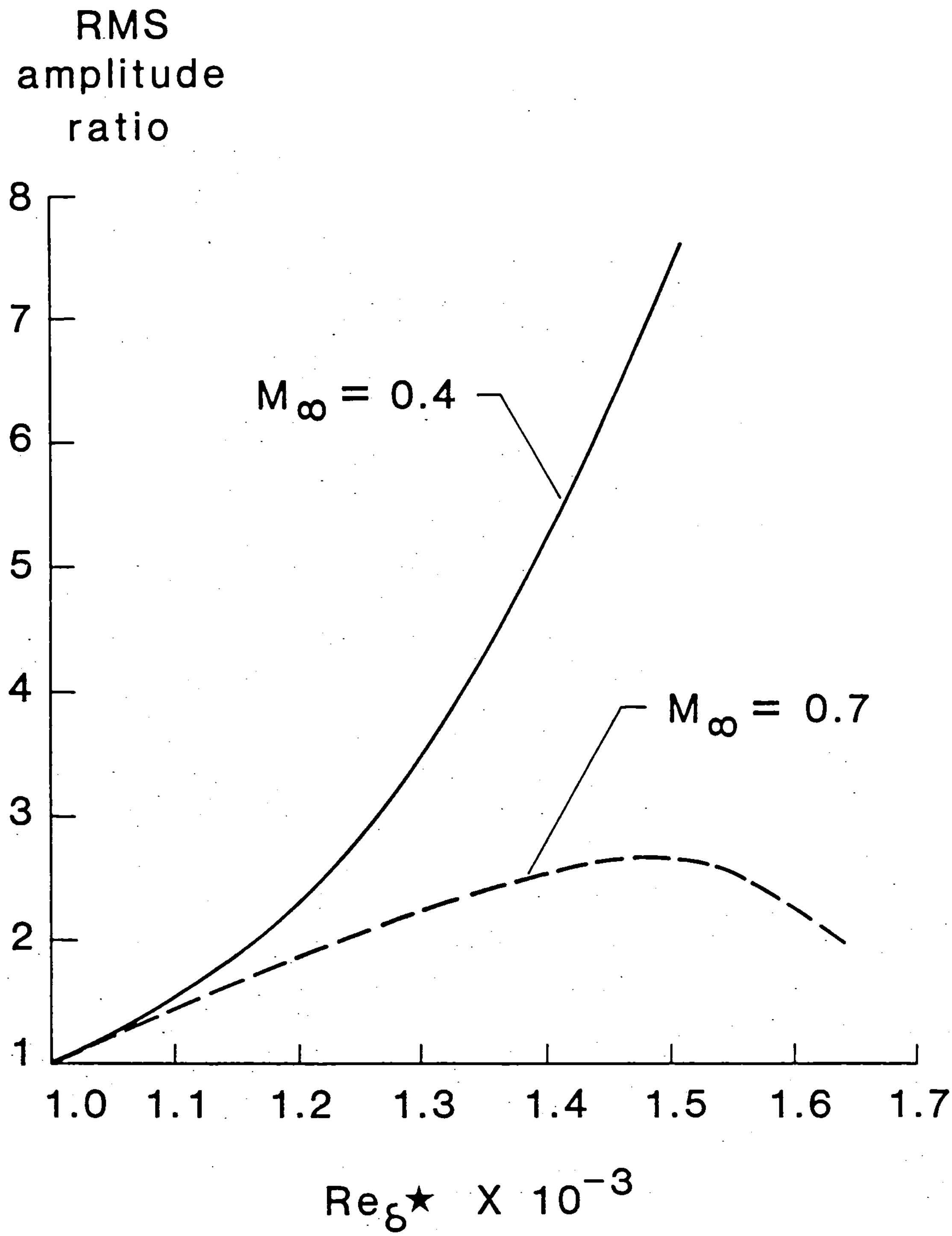

Figure 7. Growth rates for M = 0.7 and M = 0.4.

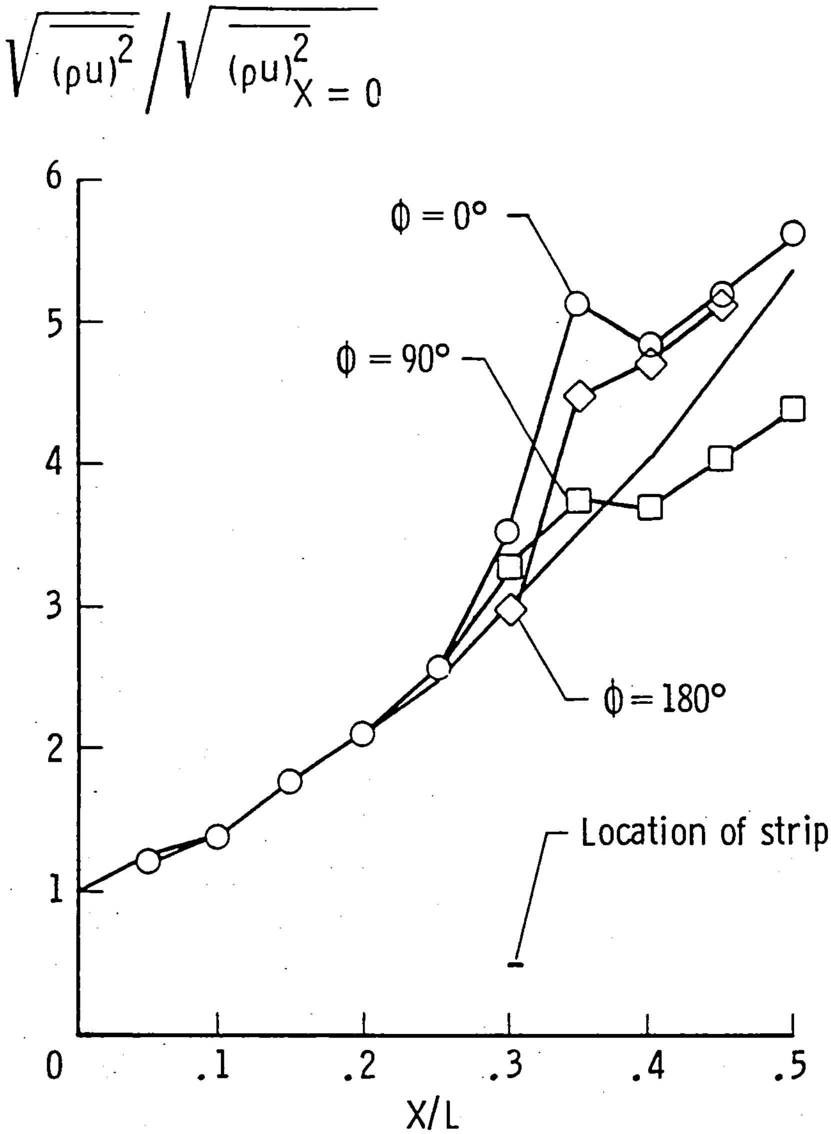

Figure 8. Effect of phase - cooling.

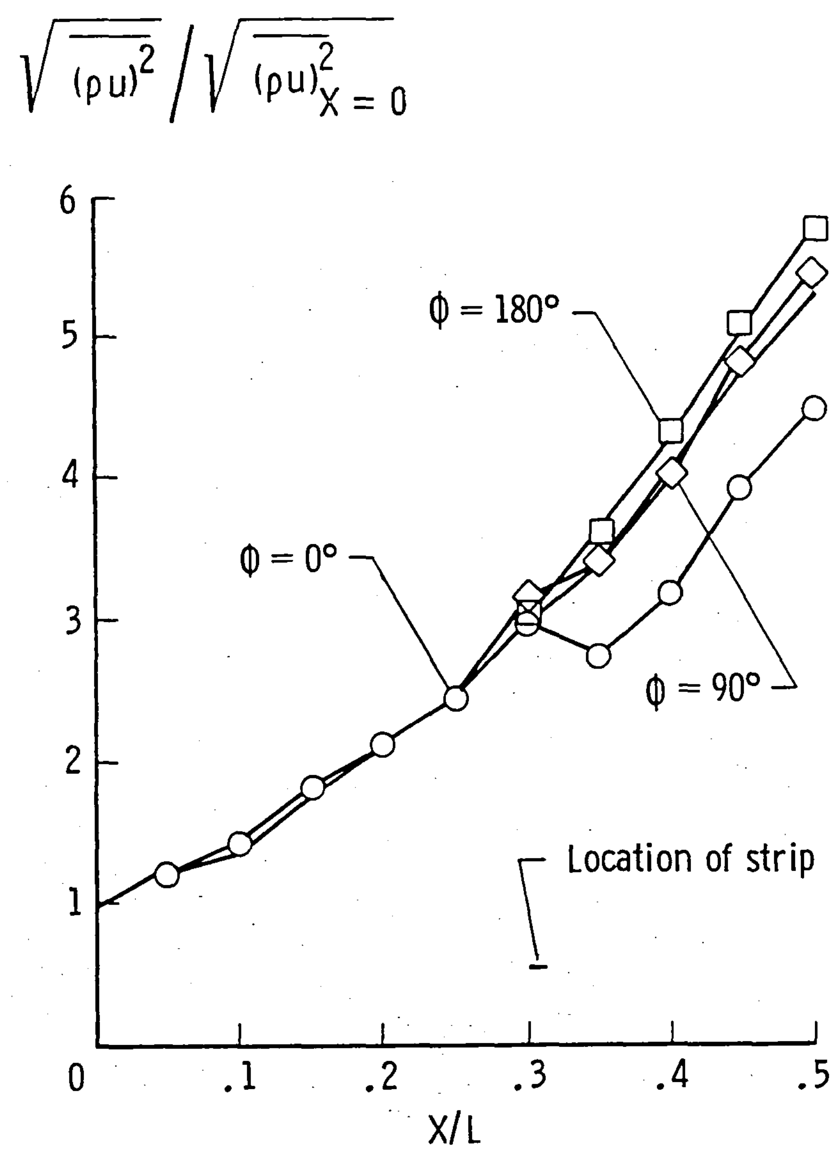

Figure 9. Effect of phase - heating.

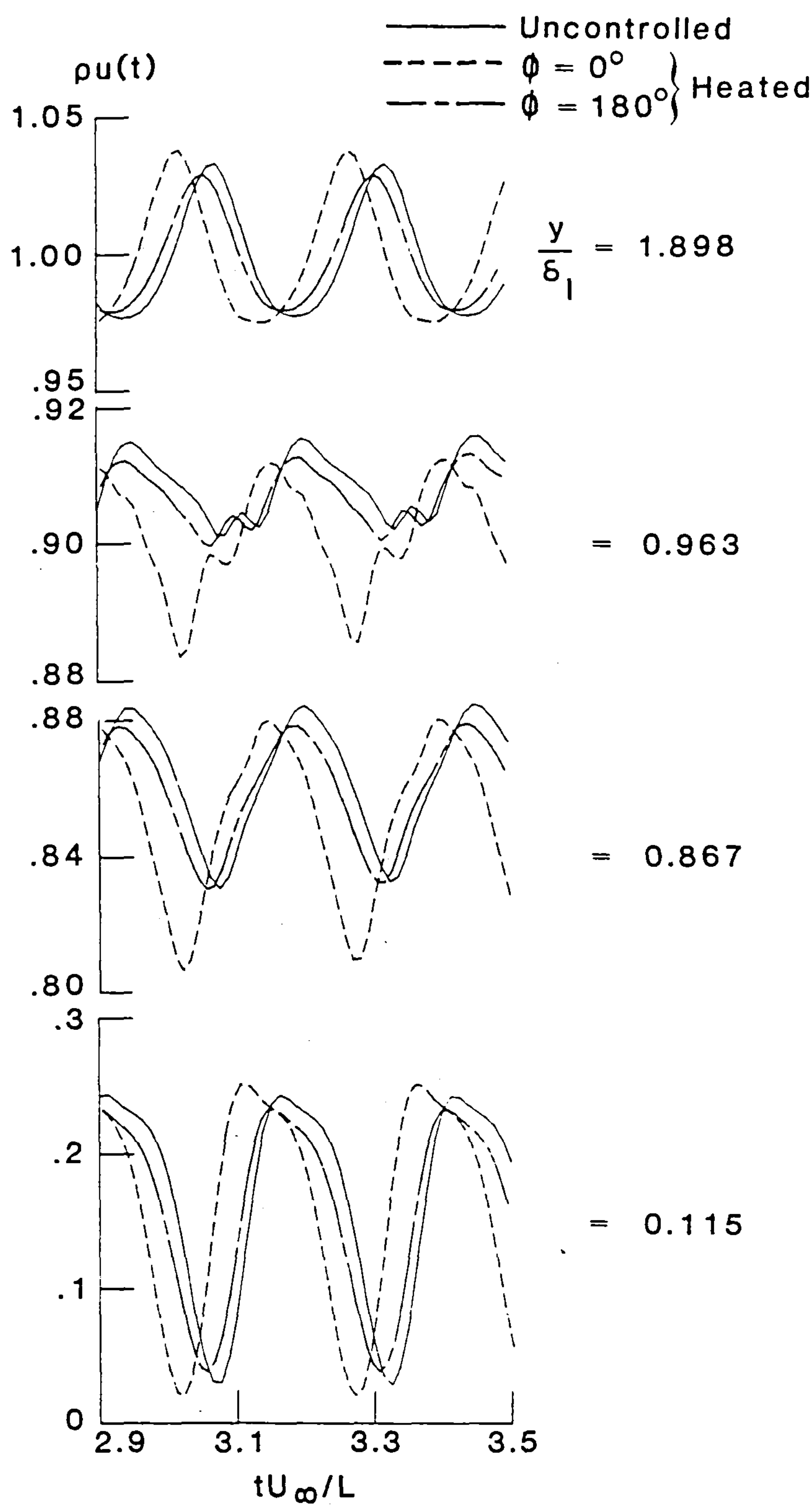

Figure 10. ρu versus t for different phases at x = 1.0 ft; heating at x = 0.6 ft.

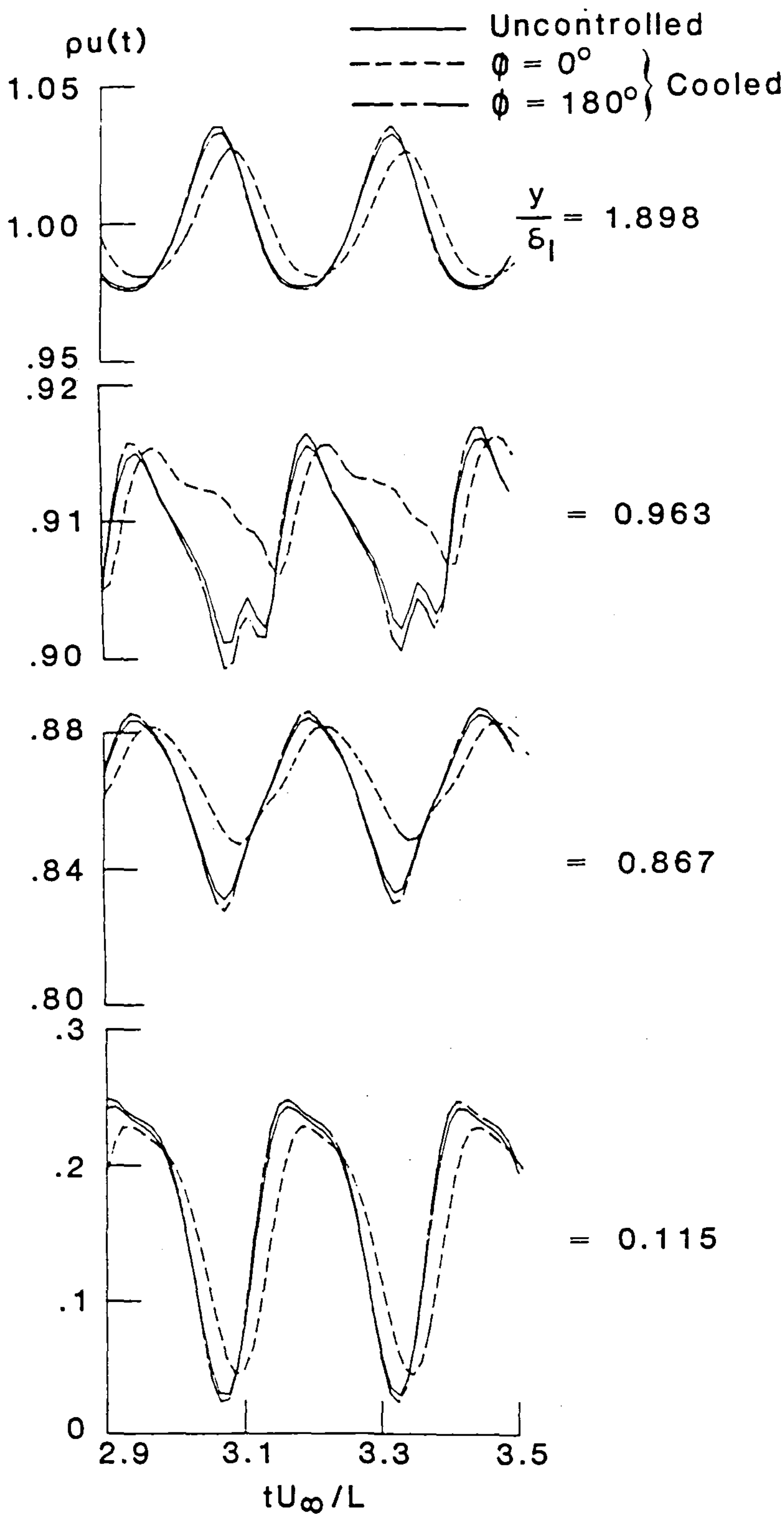

Figure 11. ρu versus t for different phases at $x = 1.0$ ft; cooling at $x = 0.6$ ft.

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16. Abstract

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