Active Control of Instabilities in Laminar Boundary-Layer Flow– Part I: An Overview

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Abstract

This paper (the first in a series) focuses on using active-control methods to maintain laminar flow in a region of the flow in which the natural instabilities, if left unattended, lead to turbulent flow. The authors review previous studies that examine wave cancellation (currently the most prominent method) and solve the unsteady, nonlinear Navier-Stokes equations to evaluate this method of controlling instabilities. It is definitively shown that instabilities are controlled by the linear summation of waves (i.e., wave cancellation). Although a mathematically complete method for controlling arbitrary instabilities has been developed (but not yet tested), the review, duplication, and physical explanation of previous studies are important steps for providing an independent verification of those studies, for establishing a framework for subsequent work which will involve automated transition control, and for detailing the phenomena by-which the automated studies can be used to expand knowledge of flow control.

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Introduction

Most studies to date have been restricted to maintaining laminar flow through use of a technique termed "wave cancellation." The wave-cancellation method assumes that a wavelike disturbance can be linearly cancelled by introducing another wave with similar amplitude that is out of phase. The key is to determine the parameters of the downstream wave which counter (cancel) the evolution of the upstream generated wave. Milling (1981) and Liepmann and Nosenchuck (1982a,b) tested the feasibility of this concept in water tunnels with flat plates and a zero pressure gradient. Using two vibrating wires (one in an upstream and one in a downstream location) to generate traveling waves 180^o out of phase, Milling (1981) showed that a wave with a 0.6-percent amplitude could be reduced (cancelled) to a disturbance with a 0.1-percent amplitude and a profile that no longer resembled a wave shape. By using hot strips to generate and control traveling waves, Liepmann and Nosenchuck (1982a,b) obtained wall-shear results that indicate a partial wave cancellation, which led to a 30-percent delay in transition. Liepmann and Nosenchuck (1982b) also noted that the transition to turbulence could be accelerated if the two disturbance generators were in phase; this technique may be useful to force the flow into a turbulent state, for example, to prevent an undesirable flow separation. Finally, Liepmann and Nosenchuck (1982b) showed that a comparable stabilization by steady heating would require a 2000-percent increase in energy over the unstable wave-cancellation technique. In an experimental wind-tunnel facility, Thomas (1983) used electromagnetic generators to study and control traveling waves in a boundary layer on a zero-pressure-gradient flat-plate model. With an optimal choice of phase and amplitude for the second wave, Thomas (1983) showed that a two-dimensional (2D) disturbance with an approximate amplitude of 1 percent was reduced to 0.2 percent through partial wave cancellation, and a transition delay was realized. However, similar to previous experiments, complete relaminarization was not accomplished. Thomas postulated that an interaction between background disturbances and the primary wave lead to increased levels of three dimensionality, which prevents complete relaminarization. Thomas also determined that wave interactions degrade the effectiveness of the cancellation technique and suggested that the control be as close as possible to the primary wave generator to decrease the effect of wave interactions. Based on the study of Liepmann and Nosenchuck (1982a,b), Ladd and Hendricks (1988) employed adaptive heating to control 2D instabilities in a laminar boundary layer on an axisymmetric body (ellipsoid) in a water tunnel. Similar to the above experiments, some degree of wave cancellation was obtained for the 2D instabilities; however, as Ladd and Hendricks noted, the naturally occurring waves on an ellipsoid are highly three dimensional (3D), which makes cancellation much more difficult to achieve. Finally, unlike the previous experiments that used artificially produced Tollmien-Schlichting (TS) waves, Pupator and Saric (1989) and Ladd (1990) examined the cancellation of random disturbances on a flat plate in a wind tunnel and on an axisymmetric body in a water tunnel, respectively. With periodic suction and blowing used as the actuator, both studies showed a reduction in the random disturbance amplitudes.

Various theoretical and computational studies have been aimed at understanding the physics of this wave-cancellation process. The linear asymptotic theory analysis by Maestrello and Ting (1984) indicated that small amounts of local periodic heating can excite disturbances that actively control the TS waves that travel on a flat plate in water. One of the first Navier-Stokes simulations of active control was conducted by Biringen (1984), who used a temporally growing instability formulation in a laminar channel flow. Using suction and blowing as the control, Biringen (1984) observed approximately a 50-percent reduction in the amplitudes of the 2D instabilities and a decrease in the growth of the 3D instabilities; the Reynolds stress that resulted from the control was nearly zero due to the destruction of the streamwise and wall-normal disturbance velocities. Metcalfe et al. (1985) used solutions of the Navier-Stokes equations in the temporally growing instability formulation to study the effect of a moving wall on unstable waves traveling in a laminar flow on a flat plate. By using an energy analysis, they showed that the wall motion causes the Reynolds-stress term to become negative, which implies a feed of energy from the perturbed flow back into the mean flow. In effect, this energy analysis showed how a perturbation to an unstable flow can be stabilizing. However, Metcalfe et al. (1985) pointed out that downstream of the suction and blowing the unstable residual wave began to grow at about the same rate as prior to the control. Bower et al. (1987) and Pal et al. (1991) used the 2D Orr-Sommerfeld equation to study and control instability-wave growth by superposition. They show within the limits of linear stability theory and the parallel-flow assumption that waves (even multifrequency waves) can be cancelled. Laurien and Kleiser (1989) used solutions of the Navier-Stokes equations in the temporally growing instability formulation to study the effects of unsteady suction and blowing on unstable 2D and 3D waves traveling in a parallel laminar flow on a flat plate; Kral and Fasel (1989) used solutions of the Navier-Stokes equations in the spatially growing instability formulation to study the effect of unsteady heating on unstable 2D and 3D waves traveling in a nonparallel laminar flow on a flat plate. The 3D modes are secondary instabilities arising from a threshhold amplitude of the 2D wave. Both studies showed that transition can be delayed (or accelerated) by superposing disturbances out of phase (in phase) with the primary TS wave and that control is only effective if it is applied at an early stage of transition, where the 2D wave is dominant. Finally, Danabasoglu et al. (1991) used solutions of the Navier-Stokes equations in the spatially growing instability formulation to study the effect of unsteady suction and blowing on unstable 2D and 3D waves traveling in a laminar channel flow. Consistent with the previous Navier-Stokes studies, transition was delayed by superposition of out-of-phase control disturbances on the disturbances that were generated upstream. Additionally, a 2D TS wave with an amplitude as large as 3 percent of the channel centerline velocity was suppressed by approximately 85 percent with wave cancellation.

All of the previous active-control studies were undertaken with the *a priori* assumption that wave cancellation was accomplished by the linear superposition (or forcing) of waves with 180^o phase shifts. None of these previous studies were able to achieve complete (or exact) instability removal (wave cancellation) from the flow, except for the linear studies reported in Refs. 11 and 12 which could obtain cancellation because the nonlinear governing equations were reduced to a linear system. The present paper definitively documents the fundamental reason for the reductions in amplitudes of the instabilities in previous experiments and computations by the addition of a control wave, demonstrates why complete wave cancellation was not possible in the previous studies, explains why the wave regains its exponential growth characteristic a small distance downstream of the control wave, and describes why wave cancellation is not possible in the true 3D nonlinear transition case.

Numerical Experiments

These tasks are accomplished by numerical example using a coupled high-order finite-difference/spectral methods direct numerical simulation (DNS) code which solves the full nonlinear, unsteady Navier-Stokes equations. For the present Navier-Stokes computations, the grid has 661 streamwise and 61 wall-normal points. The far-field boundary is located $75\delta_o^*$ from the wall, and the streamwise distance is $308\delta_o^*$ from the inflow. For the time marching, a time-step size of 320 steps per wave period is chosen for the three-stage Runge-Kutta method. Periodic suction and blowing through the wall is used to initiate and control disturbances, where v_f is the initial amplitude and v_w is the control amplitude. A sufficiently refined grid and small enough time step are used to displace the numerical techniques from the flow physics. (This is clearly demonstrated by results in figure 2.)

A small-amplitude disturbance ($v_f = 0.0001$) with a frequency $\omega = 0.0774$ and an inflow Reynolds number $R = 900$ is used for this investigation. A number of simulations were conducted to control the growth of TS waves within the boundary layer. Results from these simulations are shown in Fig. 1, where the TS wave amplitudes are shown with downstream distance. For the range of amplitudes shown, all unsteady control waves lead to significant decreases in amplitudes and growth rates as a result and downstream of the control, which is spatially located just upstream of $R = 1000$. As expected from many previous linear studies and duplicated in Fig. 1, steady blowing is destabilizing, and steady suction is stabilizing. In addition, the steady control cases are included to qualitatively illustrate Liepmann and Nosenchuck's (1982b) hypothesis that steady control requires orders of magnitude more energy than is required for unsteady control to achieve similar control features. The results of Fig. 1 demonstrate that the small amplitudes required for nearly optimal unsteady wave cancellation barely influence the stability of the TS wave with steady suction or blowing.

The wave cancellation by the superposition principle has been assumed to be the reason for the decreased amplitudes and growth rates for the controlled waves. Metcalfe et al. (1985) showed that the moving wall causes a negative Reynolds stress, which implies an energy feed from the unstable flow into the mean flow, which leads to a more stable flow. An examination of the Reynolds stress in light of the above argument may lead to a similiar conclusion for the present results; however, this cause-effect relationship is unlikely with the small-disturbance amplitudes generated by suction and blowing through a solid wall. Three simulations were conducted to ensure that linear superposition of individual instabilities was, in fact, responsible for the results shown in Fig. 1 and in the previous experiments and computations. Figure 2 shows the instantaneous streamwise velocity obtained in one of three ways: by forcing the disturbance with no control (Forcing only); by forcing the suction-and-blowing control with no upstream forcing (Control only); and by upstream disturbance forcing and downstream control forcing, which is the wave-cancellation case (Control). By discretely summing the control-only and forcing-only numerical results, the superposition results are obtained. Shown in Fig. 2, this linear superposed solution is identical to the wave-cancellation simulation. This comparison not only definitively validates the supposition that linear superposition is the reason for the previous experimental and computational results, but it explains the reason for the failure of the simulations to reach an exact cancellation of disturbances. If the waves had a spatial/temporal phase shift of exactly 180^o and the amplitudes were exactly the same quantitative value for each streamwise location, then superposition would lead to a complete wave cancellation. Figure 2 shows that the control wave differs in both amplitude and phase from the initiated instability, where the control has a smaller amplitude than the disturbance. This difference leads to a superposed wave that has a reduced amplitude but retains some semblance of the wave shape and phase. Figure 2 also explains the phase shift of 180^o between the control cases ($v_w = 0.0004$ and $v_w = 0.00088$) which are shown in Fig. 1. For $v_w = 0.0004$, the control amplitude is smaller than the initial disturbance and leads to the qualitatively superposed wave of Fig. 2. As the control amplitude (e.g., $v_w = 0.00088$) exceeds the disturbance amplitude, the resulting superposed wave falls in line with the control phase, which leads to a downstream evolving instability which has a phase shift of approximately 180^o from the original upstream disturbance.

The process of introducing a control wave which exactly matches the phase and amplitude of the initial spatially growing disturbance requires many significant digits of accuracy. This explains why exact wave cancellation was not possible in previous experiments, where such accuracy is not possible. Previous computations could obtain exact cancellation through optimizing the control phase and amplitude to match the initial instability, assuming the initial disturbance had an evolution which could be described by a linear system. This leads us to the final tasks of explaining why the instability regains its exponential growth characteristics in a short distance downstream and why the wave-cancellation technique does not work for the real 3D transition problem.

The above results demonstrate that this process of wave cancellation is very sensitive to amplitude and phase of the control wave. If exact cancellation is not achieved, then the disturbance amplitude is significantly reduced and the semblance of the wave is primarily retained. Within the boundary layer, a redistribution of energy very quickly occurs whereby the dominant mode regains its momentum and begins to exponentially grow as prior to the introduction of the control wave. This process is not limited to the wave-cancellation technique, but occurs with the initiation process of a wave (e.g., vibrating ribbon, etc.).

Finally, the wave-cancellation technique will not work for the real transition problem because the underlying assumption of the technique resides in the ability to linearly superpose instabilities to delay transition for this problem and in general control the flow. The present results document the parameter sensitivities for a small-amplitude disturbance (i.e., the governing equations can be described by a linear system); however, when multiple instabilities are present and have the opportunity to nonlinearly interact, then the required control waves can self-interact and interact with the initial modes. This potential interaction would prohibit any hope for the superposition technique.

Conclusions and Future Directions

The present paper uses direct numerical simulation cases to definitively document that wave cancellation is the fundamental reason for the reductions in amplitudes of the instabilities in previous experiments and computations. It is shown that wave cancellation is very sensitive to the control parameters and usually leads to a downstream evolving wave which has a greatly reduced amplitude but resembles the wave instability. Because the downstream instability retains the wave characteristics, it regains its exponential growth a small distance downstream of the control wave input. Finally, previous studies obtained transition delays only when a 2D control was imposed when three-dimensional instabilities had sufficiently small amplitudes because otherwise the superposition assumption becomes invalid. Hence, wave cancellation is not possible in the true 3D nonlinear transition case.

Much of the transition process involves small-amplitude disturbances and can therefore be described by linear systems. Hence, in a subsequent paper (Part II), the wave-cancellation process will be automated under the linear superposition process such that a controller will be evaluated; it will receive sensor information as input and will provide a signal to control the actuator response as output. The automated scenario for this flow control approach is shown in Fig. 3. (In the present paper only the actuator was used; it will be based on known disturbance information for wave cancellation.) Clearly, this automation could only be successful for small-amplitude non-interacting modes. The final papers (Parts III ad IV) for the flat-plate problem will involve an actuator, a sensor downstream of the actuator, and the coupling of optimal control theory with the Navier-Stokes equations to form a closed-loop feedback system for the control of arbitrary instabilities. For this formal theory, there is no *a priori* assumption of linear wave superposition; therefore, the potential exists for the control of nonlinear instabilities.

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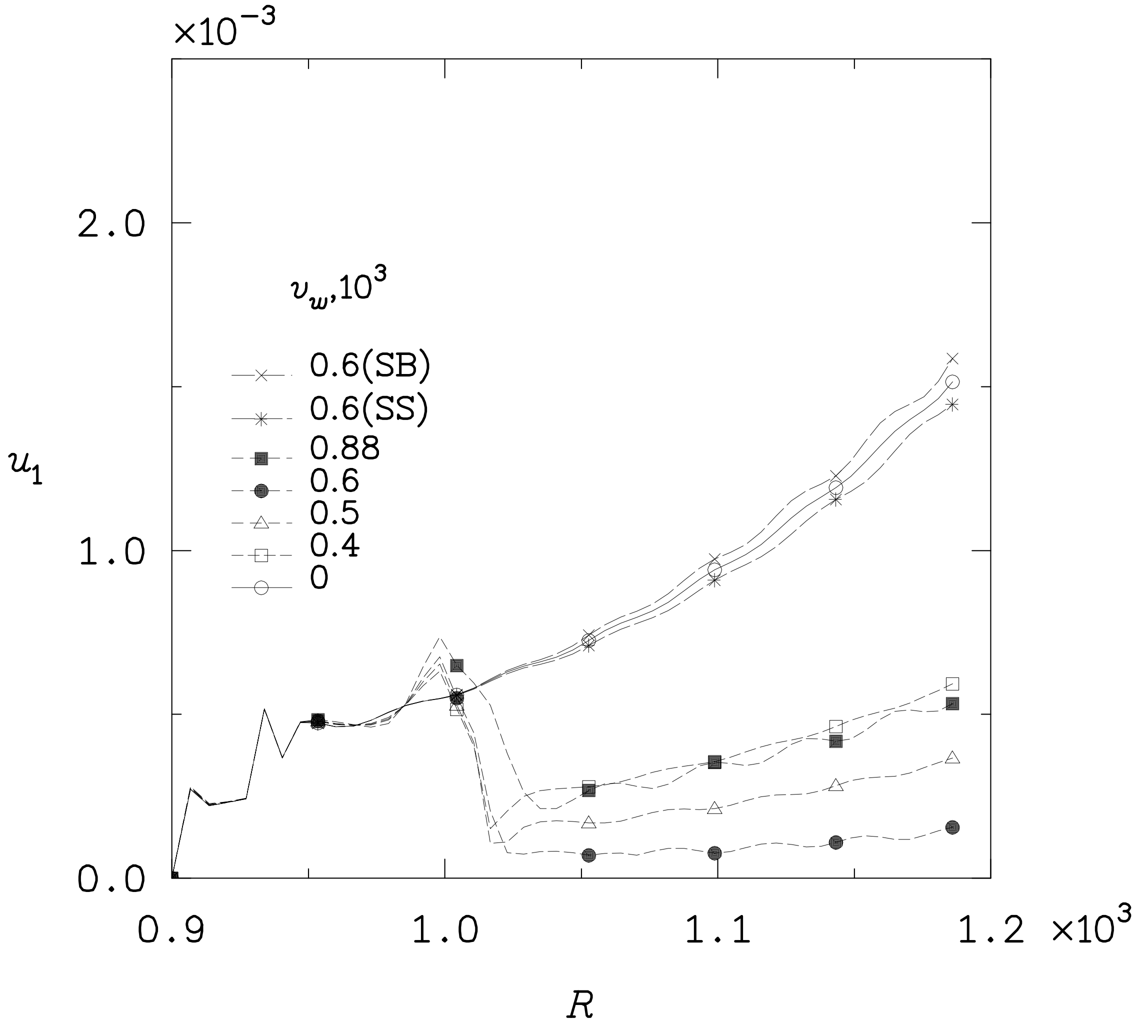

Fig. 1. Active control of Tollmien-Schlichting waves in flat-plate boundary layer. (SB=Steady Blowing, SS=Steady Suction)

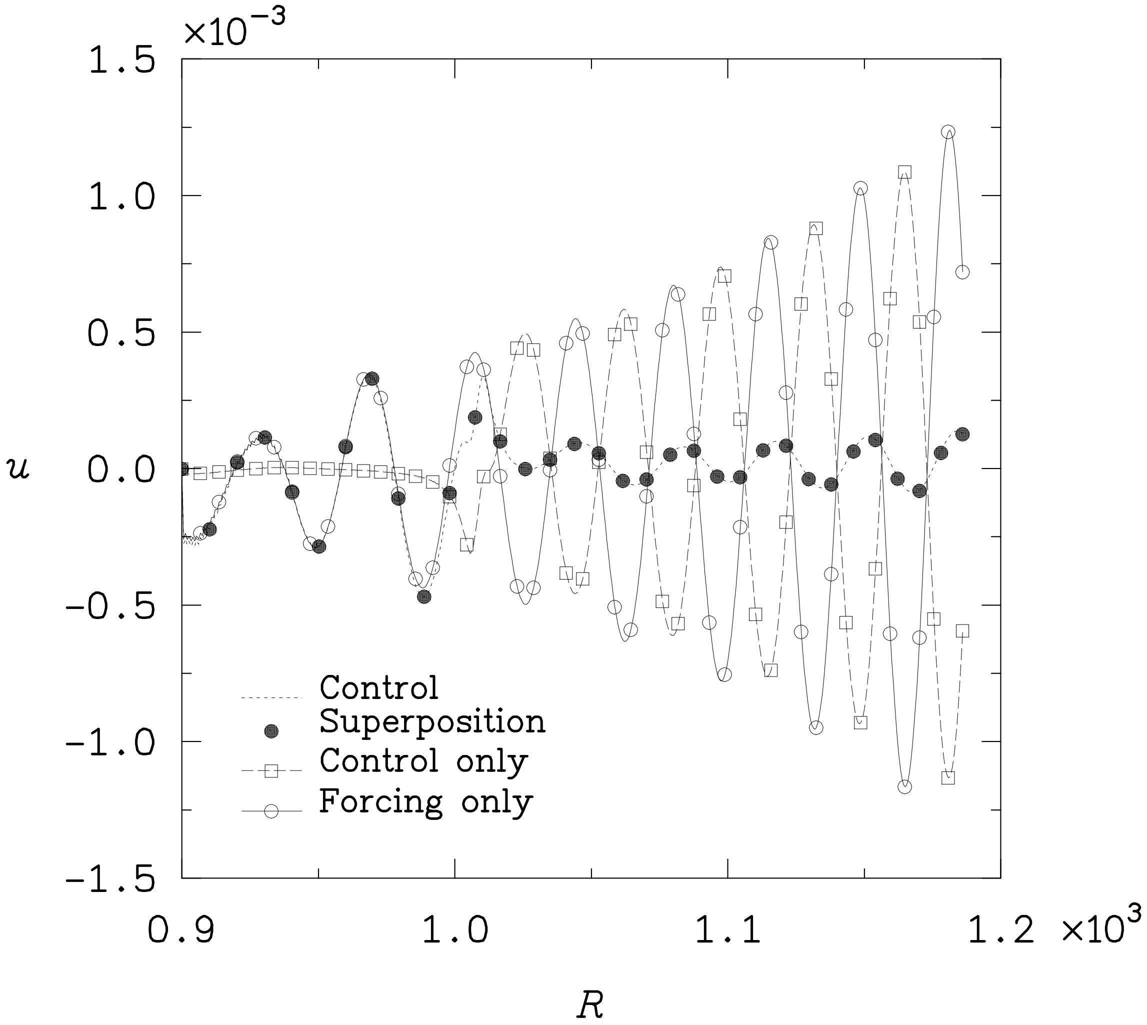

Fig. 2. Verfication of superposition principle.

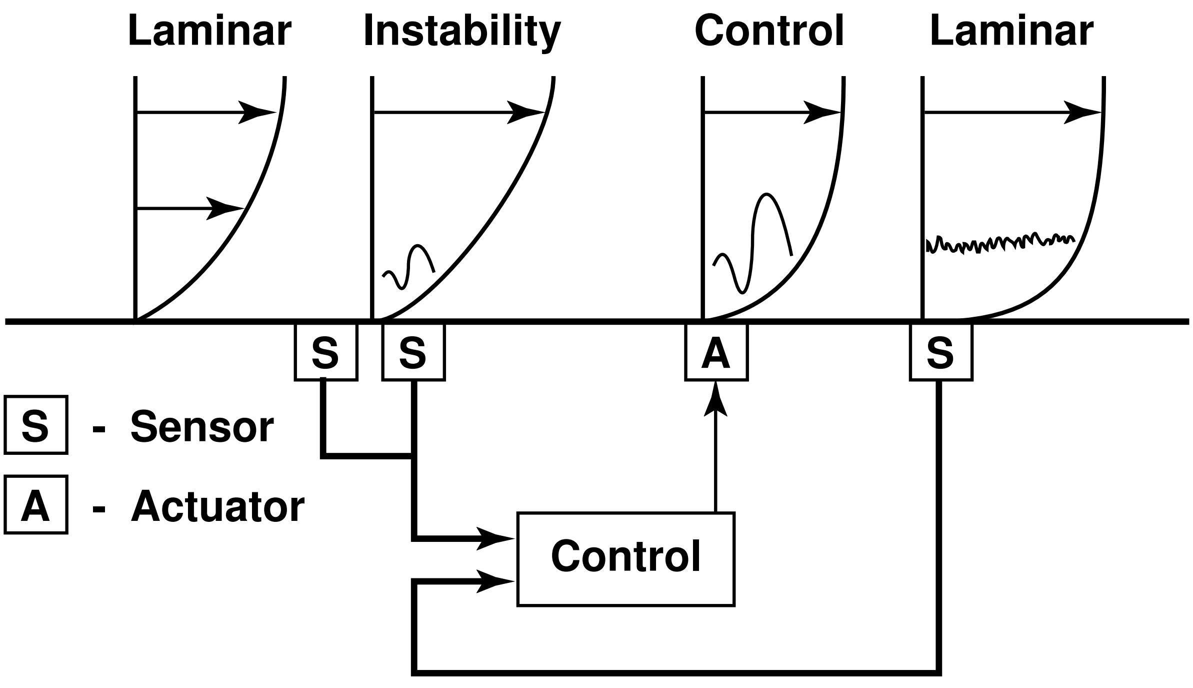

Fig. 3. Schematic of active control with wave cancellation.