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NUMERICAL EXPERIMENTS ON TRANSITION CONTROL IN WALL-BOUNDED SHEAR FLOWS

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Results are presented from a numerical simulation of transition control in plane channel and boundary layer flows. Details of the channel flow control are available in reference 1. The analysis is based on a pseudo-spectral/finite-difference semi-implicit solution procedure (ref. 2) employed to numerically integrate the time-dependent, three-dimensional, incompressible Navier-Stokes equations in a doubly periodic domain. In the channel flow, we find the active periodic suction/blowing method to be effective in controlling strongly three-dimensional disturbances. In the boundary layer, our preliminary analysis indicated that in the early stages, passive control by suction is as effective as active control to suppress instabilities. Our current work is focused on a detailed comparison of active and passive control by suction/blowing in the boundary layer.

GOVERNING EQUATIONS

- CONTINUITY EQUATION

$$\frac{\partial u_i}{\partial x_i} = 0$$

- **MOMENTUM EQUATION**

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = - \frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j}$$

- THERMAL-ENERGY EQUATION

$$\frac{\partial T}{\partial t} + u_i \frac{\partial T}{\partial x_i} = \frac{K}{\rho C_p} \frac{\partial^2 T}{\partial x_j \partial x_j}$$

- CONSTANT PROPERTIES; NO VISCOSITY; TEMPERATURE FIELD UNCOUPLED
- EQUATIONS NONDIMENSIONALIZED BY U_0, h
- FLOW DRIVEN BY A CONSTANT MEAN PRESSURE GRADIENT 2/Re, $Re = U_0 h/\nu$
- CONVECTIVE TERMS PUT INTO A FORM THAT CONSERVES ENERGY AND MOMENTUM

$$\frac{\partial u_i}{\partial t} + u_j \left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right) = - \frac{\partial P^*}{\partial x_i} + \frac{2}{Re} \delta_{i1} + \frac{1}{Re} \frac{\partial^2 u_i}{\partial x_j \partial x_j}$$

$$P^* = P/\rho + \frac{1}{2} u_j u_j$$

SOLUTION PROCEDURE

- SAME TECHNIQUE AS THE VELOCITY FIELD

- Non-dimensionalized with $(T-T_0)/(T_w-T_0)$; h and U_0
- Adams-Bashforth 2-step method for the advective terms
- Crank-Nicholson implicit scheme on the diffusive terms.
- Periodicity along allows x_1 and x_3
    - Two-D Fourier transform in the x_1-x_3 plane
    - The Pseudo spectral method in the x_1, x_3 directions
- Finite differences with variable mesh along the x_2 direction
- Solution in Fourier space as a tridiagonal system
- Back transformed into physical space to obtain temperature field at (n+1)

IMPLEMENTATION OF BOUNDARY CONDITIONS

- No-slip B.C.

  $u_1 = u_2 = u_3 = 0$

  p from x_2-momentum equation
- Suction B.C.
- Flow homogeneous along x_1, x_3
- Incoming mass flow rate must equal to the outgoing mass flow rate

$$\frac{\partial \langle u_2 \rangle}{\partial x_2} = 0$$

$$\langle u_2 \rangle = \text{CONST. or } g(x_1, x_3)$$

- Hence velocity magnitude and direction at one wall must be preserved throughout the flow field to satisfy continuity
- Physically plausible condition is suction-blowing or periodic b. cond.

TRANSITION IN WALL-BOUNDED FLOWS

- 2-D Tollmien-Schlichting waves.
- Formation of streamwise vortices.
- Formation of shear layers away from the wall due to vorticity-induced velocity.
- Secondary instability (kinks and spikes).
- Breakdown into smaller scales, formation of wall shear, hairpin eddies.
- Turbulent spot - horseshoe vortex-turbulence.

MODEL PROBLEMS

* Periodic plane channel flow
* Periodic boundary layer.

COMPUTATIONAL DETAILS

Mesh Resolution : 32 x 51 x 32

Channel flow Reynolds number : $Re = U_o h/\nu = 7500$
U_o : Centerline velocity
h : Channel half-thickness

Boundary layer Reynolds number : $Re = U_e \delta^* /\nu = 1100$
U_e : Free-stream velocity
δ^* : momentum thickness (constant)

Initial Conditions

a. Channel Flow
All velocities per cent of channel centerline velocity.
T_c is the time when control is applied for one time step.

α	β	u_{2D}^{max}	u_{3D}^{max}	T_c
1	1	3	2	20,30,40

b. Boundary Layer
Velocities are per cent of free-stream velocity.

α	β	u_{2D}^{max}	u_{3D}^{max}
$25\delta^*$	$30\delta^*$	0.3	0.1

α : Wave number of the 2D fundamental wave.

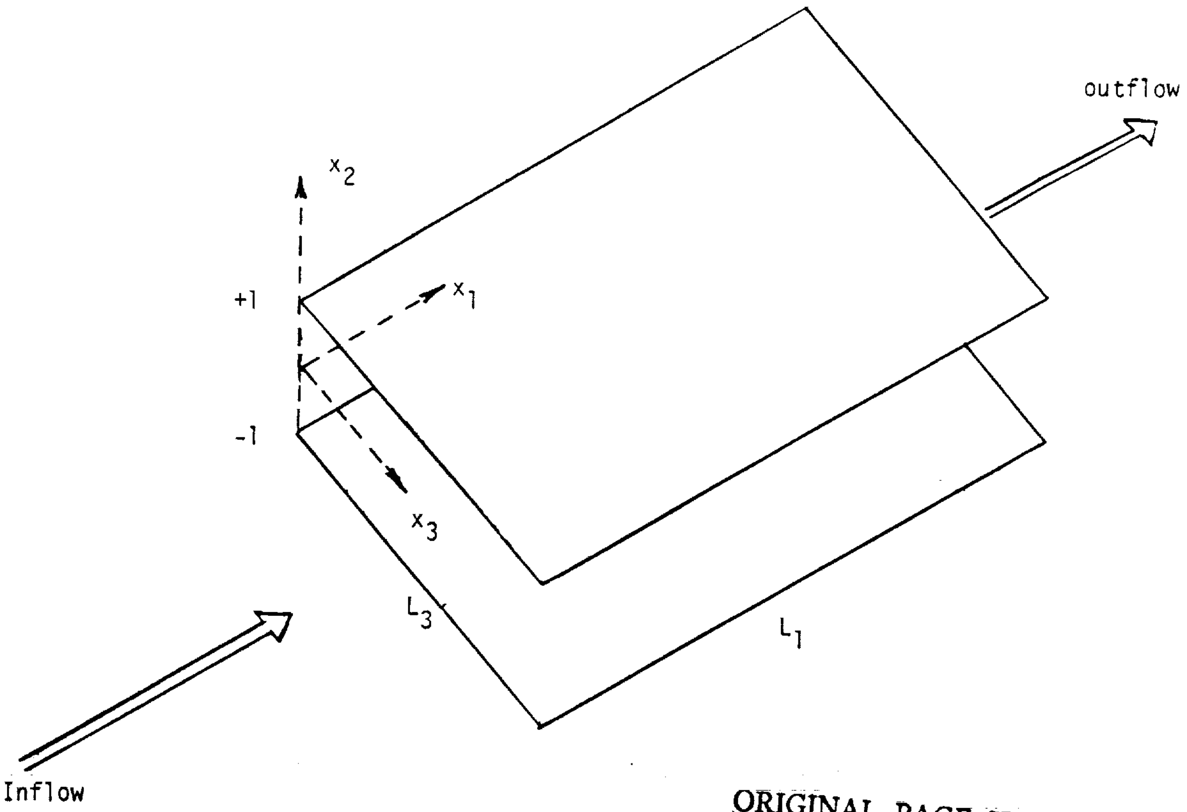
β : Wave number (spanwise) of the oblique wave.

α and β are used to generate the initial conditions from an Orr-Sommerfeld solver.

(u_{2D}^{max}) : Maximum amplitude of the initial 2D wave.

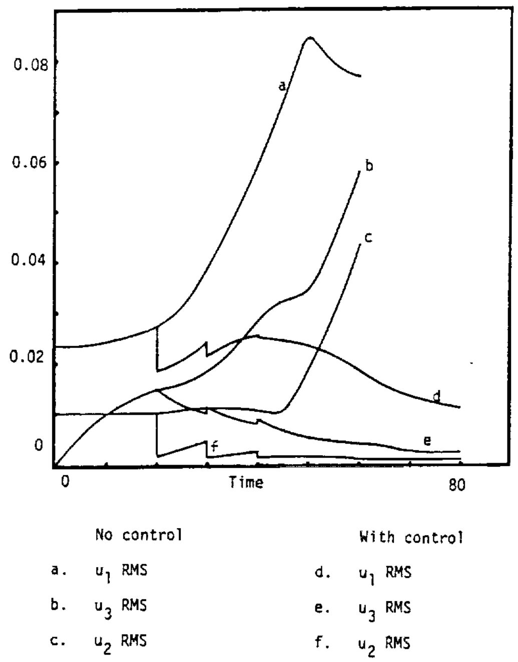
(u_{3D}^{max}) : Maximum amplitude of the initial 3D wave.

Flow geometry, the computational box



MAXIMUM PLANE-AVERAGED RMS VELOCITIES

The temporal development of plane-averaged maximum velocities is presented. These velocities provide comparisons between the controlled flow (three-dimensional control) and no-control cases for the channel flow.



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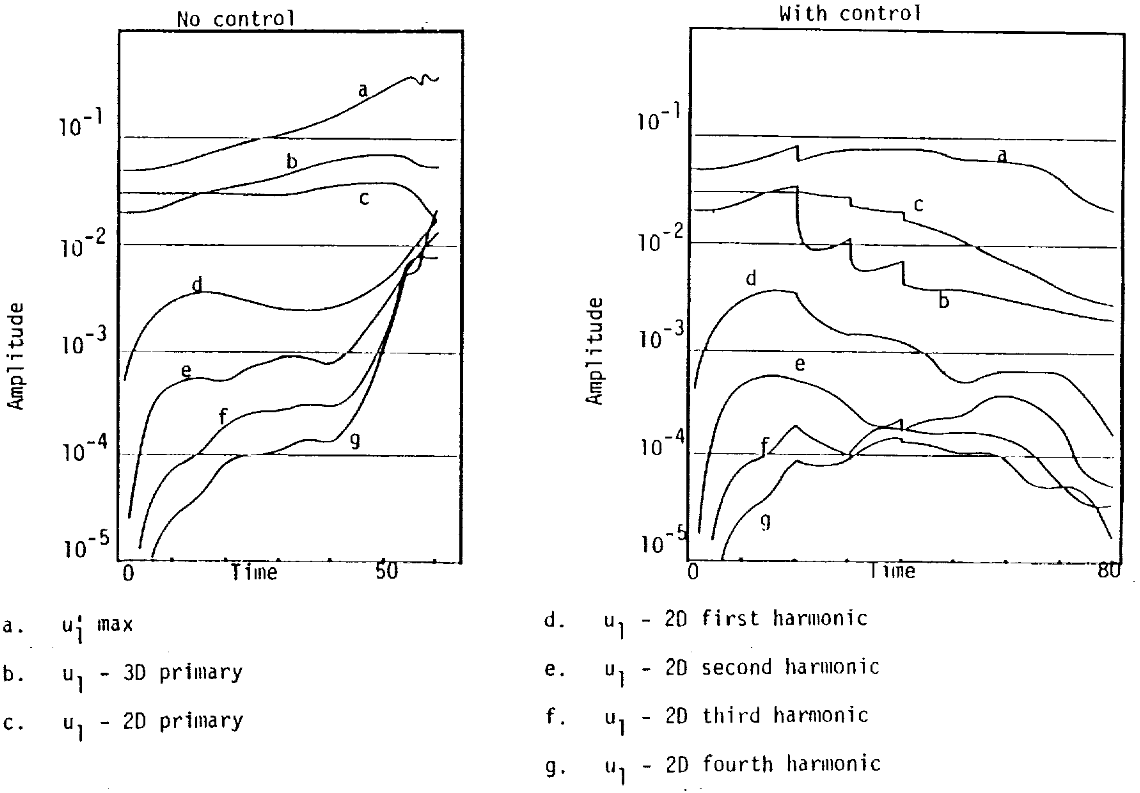
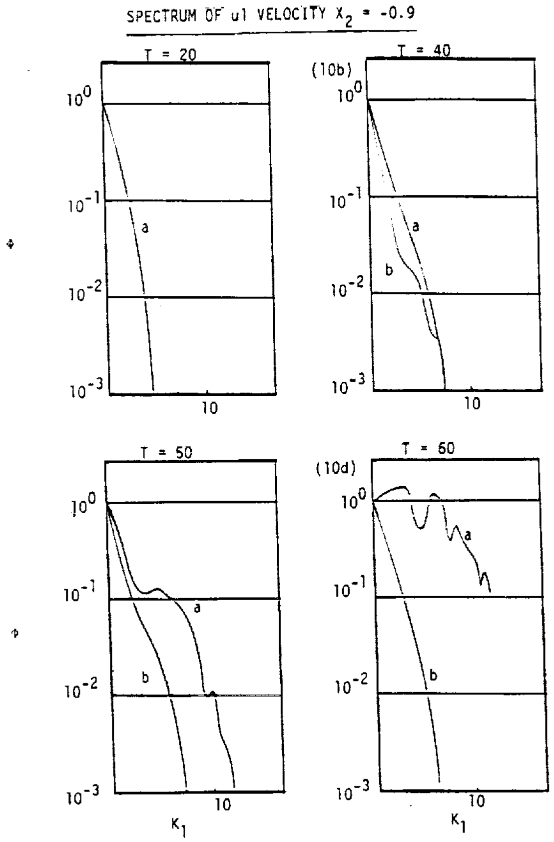
TEMPORAL DEVELOPMENT OF U-COMPONENT FLUCTUATING VELOCITY AND ITS HARMONICS

The evolution of the various Fourier modes indicated that all amplitudes are significantly reduced, and after the third control wave they all decay rapidly.



NORMALIZED ONE-DIMENSIONALIZED WAVE SPECTRUM

In the uncontrolled case we observe that energy transfer to the high wave numbers is indicated by a full spectrum. In the controlled case, this does not occur and energy is concentrated in the low wave numbers preventing the development of higher harmonics.

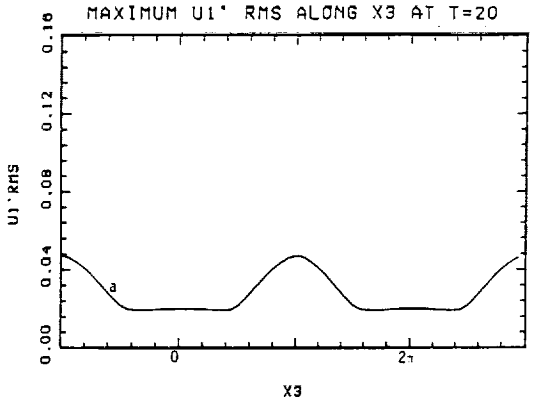


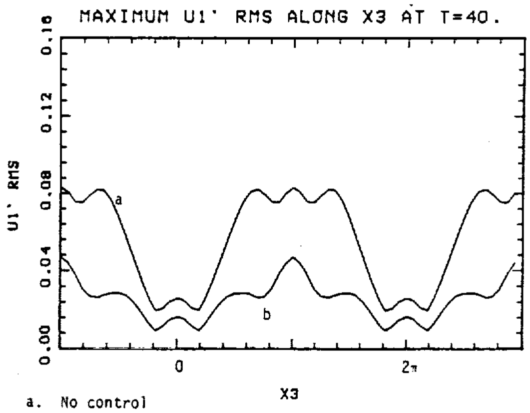
$\Phi = \phi(K_1)/\phi(1)$

a. Without control b. With control

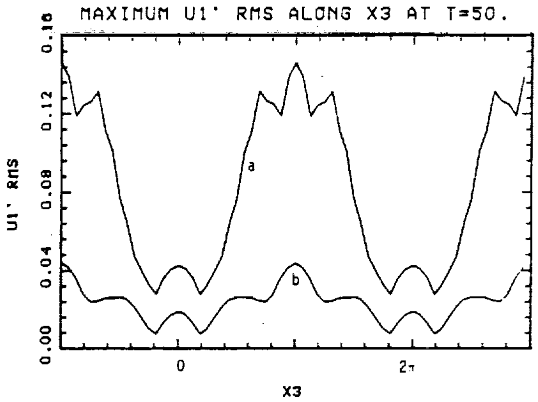
MAXIMUM U-RMS ALONG X_3 (SPANWISE DISTRIBUTION)

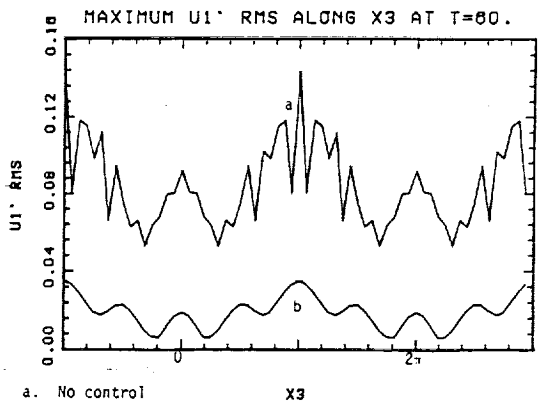
In the uncontrolled flow, peak-valley splitting develops. The control wave does not prevent peak-valley splitting, but reduces the amplitudes. The uncontrolled and controlled distributions remain in phase.


MAXIMUM U1' RMS ALONG X3 AT T=20


MAXIMUM U1' RMS ALONG X3 AT T=40.

a. No control
b. With control

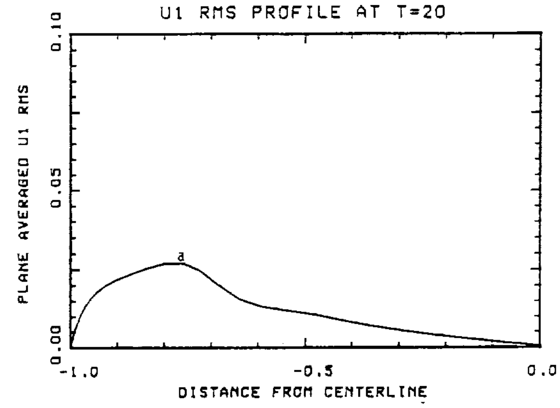

MAXIMUM U1' RMS ALONG X3 AT T=50.


MAXIMUM U1' RMS ALONG X3 AT T=60.

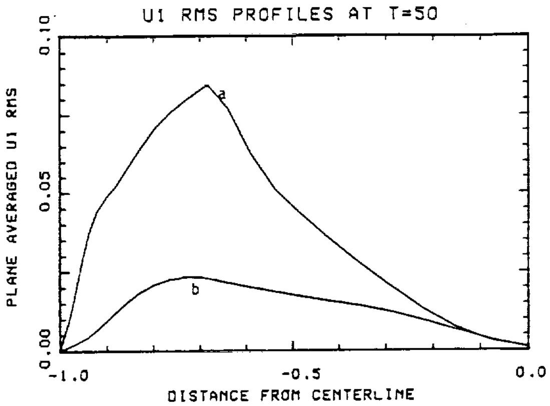
a. No control
b. With control

U-RMS PROFILE

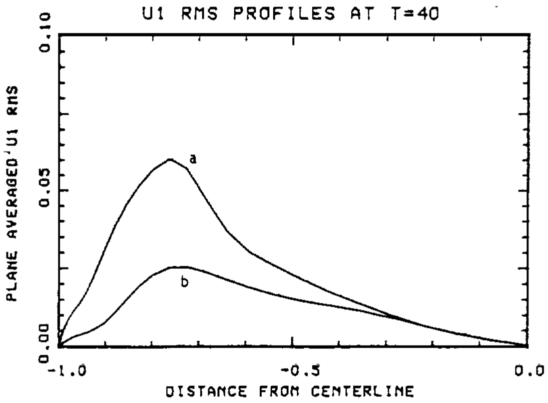
These figures indicate the amplitude reduction in u-rms distributions due to the imposed control waves.



U1 RMS PROFILE AT T=20



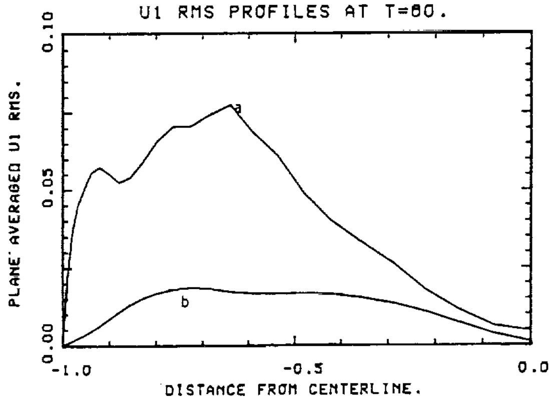
U1 RMS PROFILES AT T=50



U1 RMS PROFILES AT T=40

a. No control

b. With control



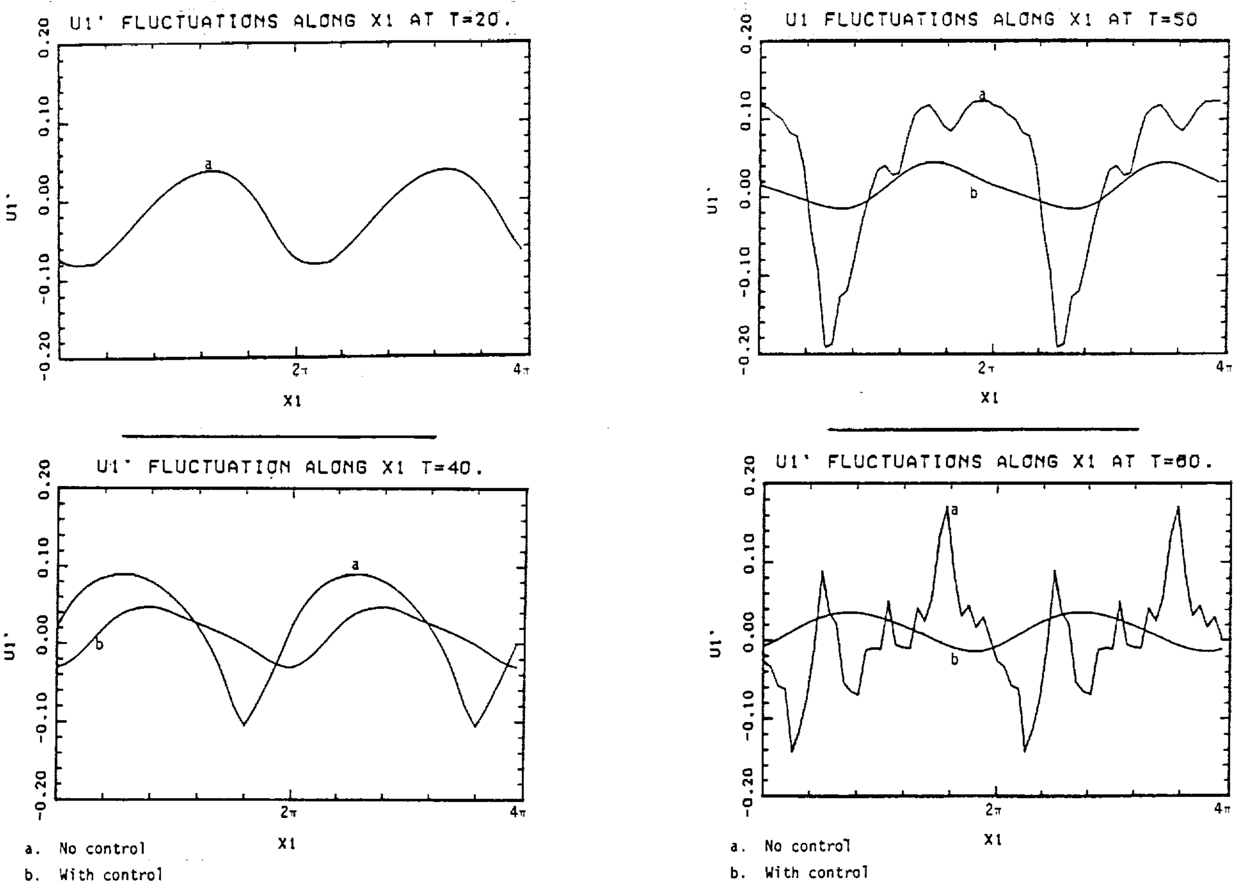
U1 RMS PROFILES AT T=60.

a. No control

b. With control

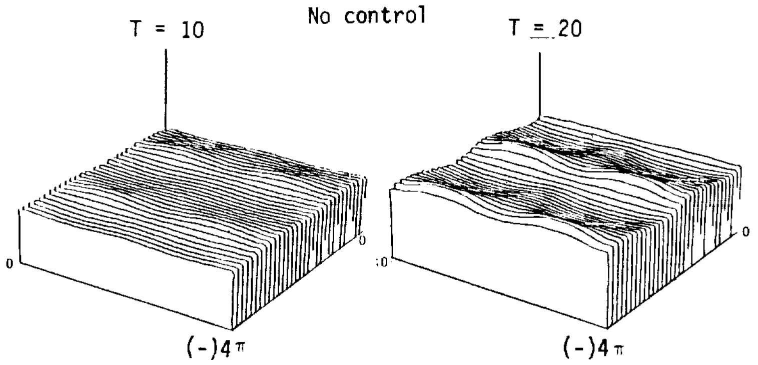
U_1-FLUCTUATIONS ALONG X_1

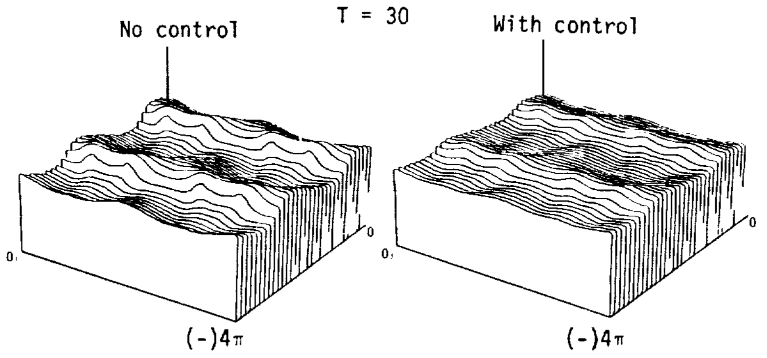
In the uncontrolled case a strong negative spike develops between T = 40 and T = 50. No evidence of spike formation and nonlinear distortions is observed in the uncontrolled case. As T = 60, the controlled distribution is nearly sinusoidal, whereas the uncontrolled case shows a broad frequency content.



SURFACES OF CONSTANT TEMPERATURE

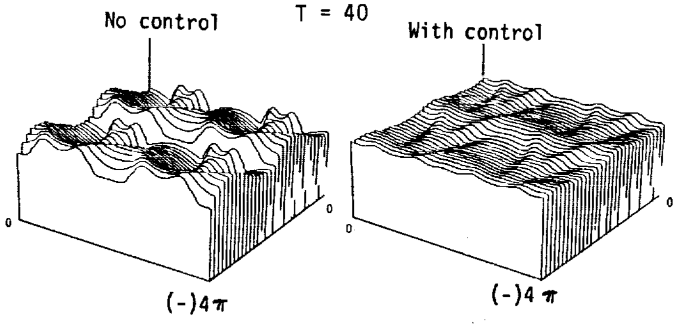
In these figures, three-dimensional representations of the temperature field (treated as a passive scalar) are displayed. The uncontrolled flow displays evidence of strong mixing and a highly convoluted temperature surface, while the controlled flow is relatively uniform and indicates local laminarization.



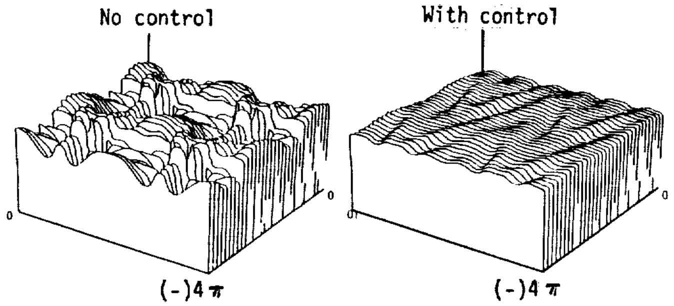


SURFACES OF CONSTANT TEMPERATURE (CONC.)

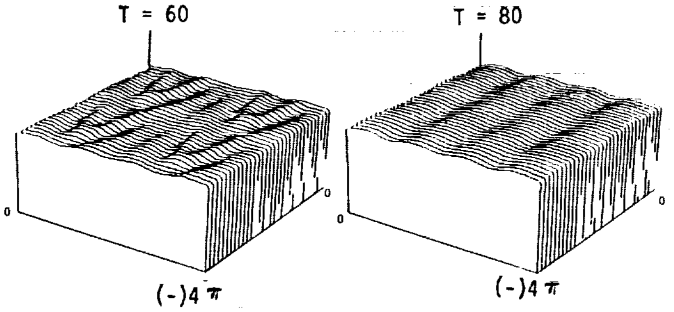
T = 40



T = 50



With control

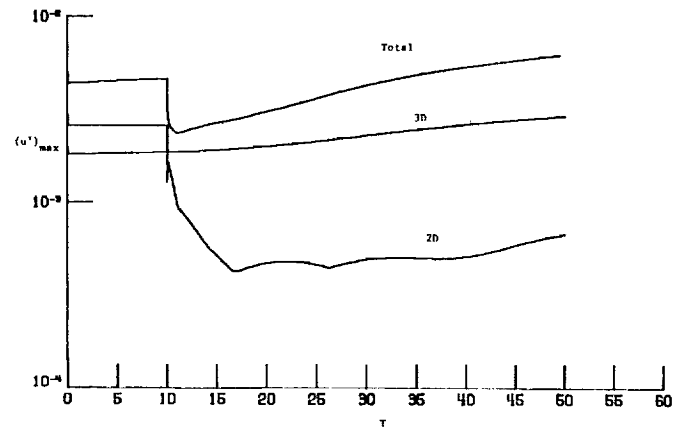


Constant valued temperature surfaces in the computational box between the lower wall and the channel centerline ($\theta = 0.10$).

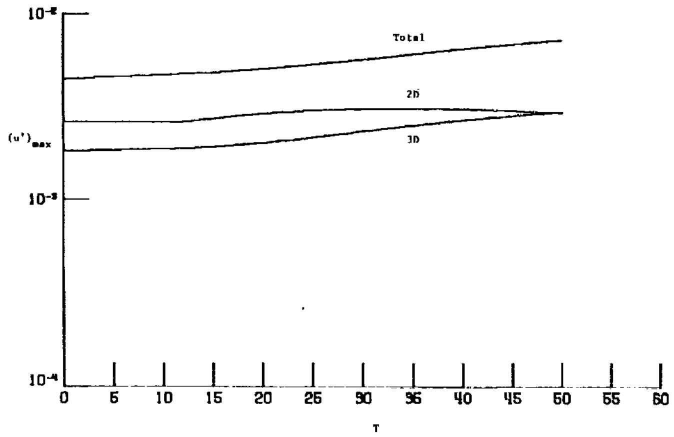
PERIODIC BOUNDARY LAYER

These figures show the time-evolution of the various Fourier components of u-component velocity in response to various control waves.

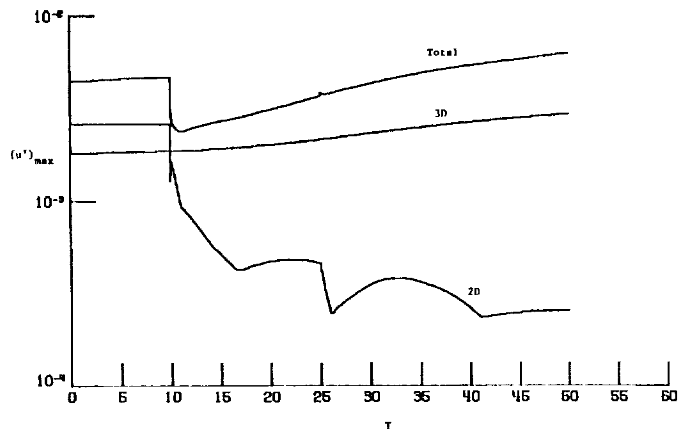
(TS Wave Cancellation (T = 10 - 11))



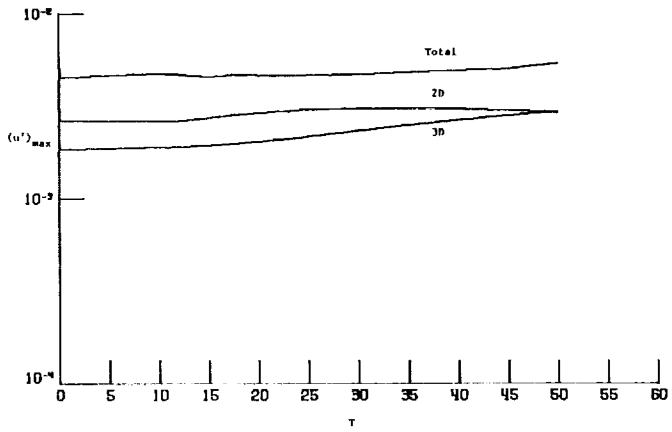
(No Control)



(TS Wave Cancellation (T = 10 - 13, 25 - 26))



(Passive Suction (T = 15 - 22.5))



CONCLUDING REMARKS

- 2D and 3D wave interaction in channel flow.
- Preliminary calculations indicate comparable effects of passive and active control in the periodic boundary layer.
- Passive temperature effective to tag flow dynamics.
- Need for space-evolving numerical experiments.

REFERENCES

1. Biringen, S., Nutt, W. E., and Caruso, M. J., "Numerical experiments on transition control by periodic suction/blowing," AIAA Journal, Vol. 25, 1987, pp. 239-244.
2. Biringen, S., "Final stages of transition in plane channel flow," J. Fluid Mech., Vol. 148, 1984, pp. 413-442.