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REAL-TIME ADAPTIVE CONTROL OF MIXING IN A PLANE SHEAR LAYER

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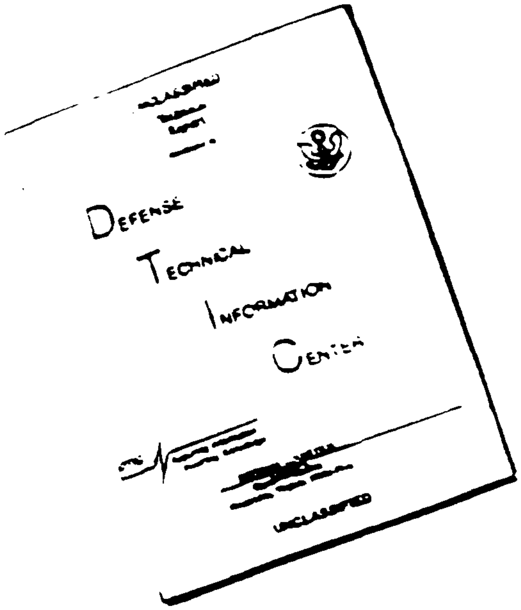

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FINAL REPORT

AFOSR GRANT 89-0343

Real-Time Adaptive Control of Mixing in a Plane Shear Layer

April 1, 1989 – May 31, 1991

J.S. Gibson

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1 Introduction

This research project has focussed on two classes problems in active control of fluid flows. In the first class of problems, active control is uses to enhance and stabilize mixing of two fluids. This portion of the research was based on an experiment at the University of Arizona. The experiment is funded under a separate grant from AFOSR. The second research problem is to use active control to regulate the wake produced by flow past a cylinder and to regulate the lift and drag on the cylinder.

2 Control of Fluid Mixing in a Plane Shear Layer

This segment of the research was performed in conjunction with Professor Ari Glezer at the University of Arizona (now at Georgia Tech) and Professor Arne Pearlstein at the University of Illinois. The research was based on an experiment at the University of Arizona in Tucson.

The experimental facility is a closed-return water tunnel in which two streams of water mix after passing a splitter plate. Before mixing, the two streams have different velocities and temperatures. The objective of the experiment is to enhance mixing using active control.

A detailed description of this project is given in [1] [1]. Numerical results for adaptive identification and control of a simulation motivated by the experiment are given in [2]. More results on adaptive identification and control of the simulation model are given in Chapter 7 of S.-B. Jiang's PhD dissertation, "Unwindowed Multichannel Lattice Filters and Application in Adaptive Identification and Control," UCLA, 1992.

Here, we summarize the modeling, analysis, and controller design for the fluid-mixing research. The control actuator is an array of heaters on one side of the splitter plate. These heaters have high bandwidth and fast response time, so that they respond accurately to a wide range of control commands. The sensor used is a rake of cold wires that can be positioned anywhere in the flow downstream of the splitter plate. The level of mixing a given position in the flow can be inferred

[1] Numbers in brackets refer to the papers included in the Appendix of this report.

from the temperature distribution measured by the rake of cold wires. That the mixing can be increased by forcing the flow with various time-dependent heating profiles has been demonstrated experimentally. The objective of the research is to use feedback control to enhance the mixing optimally and consistently for a range of operating conditions.

The basic mechanism of the mixing in the experiment is the roll up of large vortices in the mixing layer. Inside the vortices, hot and cold fluid is wrapped in layers that eventually break up to produce mixed fluid. These vortices begin small about five inches past the splitter plate and then grow in diameter as they move downstream. The heaters on the splitter plate vary the viscosity of the colder fluid, thereby altering the dynamics of the interface between the cold and hot fluid and the roll up of the vortices.

Much of the first year of the research was spent analyzing input/output data for many different kinds of open-loop forcing and different sensor locations in an effort to formulate a meaningful and workable feedback control problem whose solution would enhance our control over the fluid mixing.

Because the dynamics of the process is so complicated and nonlinear, we decided that it would be futile to try to design a feedback controller based on an explicit model of the flow field; i.e., the Navier-Stokes equations and the boundary conditions associated with the two interacting streams of fluid, the splitter plate, the heater array, and the shear layer (or vorticity sheet) between the two streams. Rather, our approach is adaptive control. We look for a measurable output that can be correlated with mixing and design a controller that identifies adaptively an input/output relationship between the inputs from the heaters and this output. Once the input/output relationship is identified, the controller computes a feedback control law designed to manipulate the output in a desired way.

We studied two basic approaches for feedback control. The approach considered first was to feedback the temperature profile from a location in the turbulent region at a distance x_1 downstream of the splitter plate (see Figure 1 in the paper by Gibson, Glezer, and Pearlstein in the Appendix). Such a temperature profile gives a direct indication of the level of mixing. Unfortunately, analysis of the mechanics of the flow field and time-series analysis of experimental results have shown that the large vortices in this region cause the input/output relationship between the heaters and the temperature distribution at such a location to be so nonlinear and nonsmooth that it is not useful for feedback control.

Our second approach for feedback control was to use the cross-stream position $y(t)$ of the Kelvin-Helmholtz shear layer (KH layer) at a fixed location x_2 downstream of the splitter plate (see Figure 1 in the paper by Gibson, Glezer, and Pearlstein). This shear layer is very thin (< 1mm) for $0 < x < 5$in and oscillates in the y direction. The unforced response of the KH layer is a stable limit cycle. The objective of feedback control in the mixing problem is to increase the amplitude and perhaps the frequency of the limit cycle. Enhancing the action of the KH layer enhances mixing by increasing downstream turbulence.

The prospects of using an adaptive controller to drive the motion of the KH layer in a desired fashion are being investigated currently by simulations with a model developed by S.-B. Jiang, a UCLA graduate research assistant working on this project. The purpose of this model is to represent the main characteristics of the cross-stream motion of the KH layer at a fixed downstream position. Although research is still under way to put the model on a more rigorous fluid mechanics basis, the model exhibits the most prominent experimentally observed characteristic of the cross-stream motion of the shear layer: a nonsymmetric limit cycle. The lack of symmetry of the shear layer results from the different free-stream velocities of the hot and cold fluids. The model is the functional differential equation

$$\ddot{y}(t) + c_0|\dot{y}(t)|\dot{y}(t) + f(y(t) - u(t)) \cdot (y(t-\tau) - u(t-\tau)) = 0,$$

$$f(z) = \frac{c_1 v_1^2}{1 + e^{-c_2 z}} + \frac{c_1 v_2^2}{1 + e^{c_2 z}},$$

where $y(t)$ is the cross-stream position of the KH layer at a fixed position x, $u(t)$ is the vector of commands to the heaters, τ is a time delay, v_1 and v_2 are the free-stream velocities, and c_0, c_1 and c_2 are constants. An adaptive controller based on a lattice filter for adaptive plant identification has been applied to this model in simulation. The simulations in the CDC paper by Jiang, Gibson, Pearlstein, and Glezer and in Jiang's dissertation show that the adaptive controller can be used either to eliminate the limit cycle or to increase the amplitude of the limit cycle as wished. While eliminating limit cycles is desirable in many flow control problems, the amplitude of the limit cycle should be increased to enhance mixing of the hot and cold flow in the experiment in this project.

3 Control of Flow Past a Cylinder

The objective of this part of the research is to stabilize certain features of the flow field around a cylinder. The research is based on simulation using a vortex method supplied by Professor Christopher Anderson of the UCLA Department of Mathematics. A description of this research and preliminary results are given in [3].

Vortex methods simulate the large-scale features of a flow field by using significantly lower-order computation than more common finite difference methods. Therefore, vortex methods allow control-system designers many more simulations than would otherwise be possible for complex flows.

As in the experimental problem, the main controllers developed are adaptive. The control action in the initial simulations is rotation of the cylinder, but the methods being developed should apply equally to problems in which the control action is rotation of a portion of the boundary, cross-stream motion of the cylinder or suck and blow action.

The nominal flow field is a symmetric flow about a nonrotating cylinder, which is unstable. The stable unforced flow is a limit cycle produced by von Karman vortices shedding alternately from the top and the bottom of the cylinder. This vortex shedding produces an oscillating wake and oscillating lift and drag forces. The control objective is to use adaptive feedback control to eliminate oscillations of the wake and eliminate oscillations in lift and drag.

An adaptive controller was designed and applied to the vortex blob simulation illustrated in Figures 1–3 in [3]. The controller takes a filtered version of the lift coefficient generated by the simulation as the output of the plant and commands the angular velocity of the cylinder. At the relatively low resolutions used for simulating the control problem on long time intervals, the vortex blob method generates a very noisy lift coefficient. This is why we filtered the lift coefficient to obtain the output to be controlled.

Figure 4 in [3] compares the controlled and uncontrolled output. The output (filtered lift) is plotted versus sampling times of the digital adaptive controller. The controller uses the first 50 steps (sampling times) for preliminary estimation of an input-output model of the plant. During this period, a small random input is used to excite the flow (this is a common practice in adaptive control), producing the slight difference between controlled and uncontrolled response during the first 50 steps. After 50 steps, the adaptive feedback controller is engaged. Because the feedback control significantly alters the vortex shedding, the control gains based on input-output model identified with the small random input produce two spikes in the response at about 60 steps. While these spikes are not what the controller was designed to produce, they do excite the closed-loop system sufficiently for a better input-output model to be identified by the adaptive controller. After this, the closed-loop response is better than the open-loop response in the sense that the oscillation in the filtered lift reduced significantly.

The results in [3] are preliminary. They motivated a current AFOSR-sponsored project at UCLA for joint research on computational fluid dynamics and fluid flow control, C.R. Anderson and J.S. Gibson, Principal Investigators.

APPENDIX

[1] J.S. Gibson, A. Glezer, and A.J. Pearlstein, "Real-time Feedback Control of Mixing in a Plane Shear Layer," presented at the AFOSR Workshop on Turbulence, Columbus, Ohio, April 1–3, 1991.

[2] S.-B. Jiang, J.S. Gibson, A.J. Pearlstein, and A. Glezer, "Adaptive Control of a Functional Differential Equation Exhibiting Some Features of the Vortex Sheet in a Plane Shear Layer," 31st IEEE Conference on Decision and Control, Tucson, Az, December 1992.

[3] C.R. Anderson and J.S. Gibson, "Vortex Methods and Adaptive Control for Bluff-Body Flows," presented at the AFOSR Workshop on Turbulence, Columbus, Ohio, April 1–3, 1991.

REAL-TIME FEEDBACK CONTROL OF MIXING IN A PLANE SHEAR LAYER

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1. Overview

This work is concerned with the development and implementation of feedback control systems for the enhancement and regulation of mixing in a plane shear layer and is supported by AFOSR Grants 89-0343, 89-0465, and 90-0156 at UCLA, Arizona, and Illinois, respectively.

Our work focuses on a plane shear layer in which, far upstream of the flow partition, the high- and low-speed streams have uniform, steady temperatures differing by ΔT. Downstream of the flow partition, we sense and control the temperature distribution. Because we study mixing of a passive scalar in a nonreacting flow, we are able to conduct the experimental part of this project in a closed-return water facility. Furthermore, the theoretical fluid mechanics effort can be restricted to analysis of a nonisothermal, nonreacting incompressible flow.

2. Physical Basis

Any feedback control system is comprised of three elements in addition to the plant: actuators, sensors, and a controller. The concept underlying our choice of actuators is rooted in several experimental facts. First, in a plane shear layer, the onset of the mixing transition is associated with and accelerated by the presence of three-dimensionality and streamwise vorticity in the flow. Second, the degree of mixing achieved at any streamwise location downstream of the mixing transition is strongly dependent on the relative amounts of low- and high-speed fluid that have been entrained into the large, nominally spanwise vortices up to that point. Third, the degree of entrainment can be significantly manipulated by two-dimensional forcing.

Given these facts, we have chosen as actuators surface film heaters flush-mounted on the high-speed side of the flow partition (see Figure 1). The heaters are arranged in a mosaic consisting of four spanwise-uniform elements upstream of a 32-element spanwise row. Each of the 36 elements is wired to a DC amplifier and can be separately driven by the laboratory computer. Since the viscosity of water varies significantly with temperature, these heaters can be used to excite Tollmien-Schlichting (T-S) waves in the boundary layer on the high-speed side. Between the heaters and the end of the flow partition, these waves amplify or decay according to an essentially linear mechanism. The bandwidth of frequencies which is amplified depends on the Re_x at the location of the heaters.

The spanwise-uniform heaters provide the control authority for influencing the nominally two-dimensional roll-up and entrainment in the shear layer. The 32-element spanwise nonuniform array provides the capability to introduce a high degree of three-dimensionality into the flow.

To date, we have implemented two different sensor configurations. The first consists of a cross-stream array of 31 cold wires placed downstream of the flow partition. These sensors and their associated electronics allow for measurement of cross-stream temperature distributions with a frequency response of about 1 kHz and a resolution of 0.03°C. In the second sensor configuration, a shadowgraph of the interface between the low- and high-speed streams is projected onto an x-y plane. A small photodetector, with an active area characterized by a length smaller than the width of the thermal interface at $y = 0$, $x = 3.8$ cm, is placed in the plane of the shadowgraph image at that point, which is upstream of the first roll-up of primary (spanwise) vortices. The signal, which is zero when the measurement station doesn't lie within the nonzero width of the interface and is essentially constant otherwise, allows the passage of the thermal interface to be sensed with high precision.

3. Status

In what follows, we summarize accomplishments to date and plans for future work in the areas of experimental fluid mechanics, theoretical fluid mechanics, and control systems.

3.1. Experimental Fluid Mechanics

The experimental work is conducted in a two-stream closed-return water shear layer facility. The facility and ancillary equipment are described in detail by Nygaard and Glezer (1991). The use of nonreactive flow requires a substitute for product distribution measurements from which local reaction rates (and hence mixing of the two streams for diffusion-limited reactions) are customarily inferred. In the present experiments mixing is estimated using a thermal analog in which the two streams, having slightly different upstream temperatures, mix downstream of the flow partition. An upstream temperature difference (up to 5°C) is maintained by heating the low-speed stream upstream of the test section and by cooling the mixed fluid downstream of the test section in such a way that the net heat addition is zero. The temperature difference between the two streams is maintained within 0.05°C using a personal computer to run a dedicated controller which continuously monitors the water temperature at a number of stations throughout the shear layer facility.

In what follows we briefly describe open-loop experiments in which the cold-wire rake is used to study the effectiveness of time-harmonic excitation, as well as closed-loop experiments in which output from the photodetector is fed back to the heaters and the cold wires are used to study temperature distributions farther downstream.

The degree of mixing between the two streams without external excitation and with open-loop harmonic excitation is studied using the probability density function (pdf) of cross-stream temperature distributions $p(T,y)$ with 2-mm cross-stream resolution at a number of streamwise stations. The free-stream velocities are $U_2 = 42$ cm/sec and $U_1 = 13$ cm/sec, and their respective temperatures are $T_L = 25°C$, and $T_H = 27.8°C$. Figures 2(a-c), 3(a-c), and 4(a-c) show contour plots of $p(T,y)$ measured at $X = Rx\nu_i/U_c = 1.45$, 2.18, and 2.90, respectively, where $R = (U_2-U_1)/(U_2+U_1)$, $U_c = (U_1+U_2)/2$, and $\nu_i = 8$ Hz is near the most unstable frequency downstream of the flow partition. The pdf distribution at a fixed y-elevation is shown to the right of each contour plot. When the flow is unforced, the cross-stream distributions of $p(T,y)$ demonstrate that although the amount of mixed fluid at a temperature $T_L < T < T_H$ increases somewhat with x, unmixed fluid at either T_L or T_H can be found at virtually any y-elevation within the mixing layer at the three streamwise positions considered here. Even when the flow is excited with a spanwise-uniform time-harmonic wavetrain (ν_f = 8 Hz), cross-stream distributions p(T,y) do not appear to vary substantially for $T_L < T < T_H$ compared to the unforced case. We note, however, that when the flow is harmonically excited, $p(y;T = T_H)$ decreases faster with y within the mixing layer at X = 1.45 and 2.18 than in the unforced case. This means that harmonic excitation results in a reduction in the mean fraction of unmixed low-speed (hot) fluid within the mixing layer, and suggests that entrainment of low-speed fluid can be modified.

A significant change in the cross-stream distribution of p(T,y) occurs when the time-harmonic excitation waveform is spanwise-nonuniform [Figures 4(a-c)]. The amplitude of the excitation waveform is spanwise-periodic with wavelength λ_z = 2.5 cm. This form of excitation leads to the appearance of spanwise-periodic nominally-streamwise counter-rotating vortex pairs in the "braids" region between adjacent primary (spanwise) vortices. Nygaard and Glezer (1991) showed that appearance of the streamwise vortices is accompanied by enhancement of small-scale motion and the spatial modification of its distribution within the primary vortices. They suggested that these small-scale motions may lead to mixing enhancement and the premature onset of mixing transition. The present measurements clearly demonstrate that spanwise nonuniform excitation leads to a significant increase in the mixing between the two streams. In fact, Figure 4c shows that at y = -0.9 cm, virtually all of the fluid from both streams is mixed.

In the plane shear layer, mixing is accomplished by nominally two-dimensional entrainment of irrotational fluid from both streams by the spanwise vortices, and three-dimensional motion induced by the streamwise vortices. Previous experiments have demonstrated that these vortical structures can be effectively manipulated by open-loop excitation at the flow partition. Of particular note are the experiments of Roberts and Roshko (1985) in a chemically-reacting plane shear layer. These authors reported that time-harmonic, spanwise-uniform excitation can significantly reduce mixing and correspondingly alter the amount of reaction product downstream of the mixing transition. These findings suggest that entrainment and hence mixing in a plane shear layer can be controlled by spanwise manipulation of the primary vortices, which have their origin in an instability of the thin vorticity layer downstream of the flow partition. Feedback control of the motion of this layer is our first step towards the implementation of closed-loop control of mixing.

The vorticity layer downstream of the flow partition is sensed using the photodetector described in §2. The signal is low-pass filtered and time delayed (using the laboratory computer) before it is fed back to the upstream spanwise-uniform surface heater. The interface elevation $y_{\Delta T}(t;x)$ is measured at x = 5.0 cm (upstream of the first rollup of the primary vortices) using the cold-wire rake. The free-stream velocities are 36 and 12 cm/sec.

Power spectra of $y_{\Delta T}$ are shown in Figures 5(a-d). The spectrum of the unforced interface (Figure 5a) shows a number of peaks in addition to the most unstable frequency (5.5 Hz) and its higher harmonics. In Figure 5b the layer is harmonically forced at 5.5 Hz and the interface spectrum is dominated by the forcing frequency and its higher harmonics. Figures 5c-d are obtained with feedback from the photodetector with two different delays. In Figure 5c the delay (t_1^D) results in large spectral peaks at the most unstable frequency and its higher harmonics, but unlike the case of open-loop excitation (Figure 5b) these spectral peaks have developed significant sidebands. Finally, for a different delay ($t_2^D = t_1^D$+50 msec) the magnitudes of the spectral peaks at the sideband frequencies are substantially higher and they are comparable to the spectral peaks at the most unstable frequency and its higher harmonics. We expect that the apparent differences in the dynamics of the interface motion (or the motion of the vortex sheet), as depicted by the power spectra of Figures 5, will result in significant changes in the evolution of the ensuing spanwise vortices and hence in the entrainment of fluid from both streams.

Figures 6(a-d) show cross-stream distributions of p(T,y) measured at X = 1.75 (upstream of mixing transition), which correspond to the power spectra of $y_{\Delta T}$ in Figures 5(a-d). The unforced flow (Figure 6a) shows the presence of unmixed low-speed (hot) fluid near the high-speed edge of the shear layer. When the flow is harmonically forced, there is a significant diminution in the fraction of low-speed (hot) fluid within the mixing layer, indicating that entrainment from the low-speed side is significantly reduced. This is consistent with the observations of Roberts and Roshko (1985), because in a chemically reacting shear layer a reduction in the concentration of one of the species may result in reduction in reaction product. Figures 6(c-d) correspond to feedback of the interface motion with delays t_1^D and t_2^D, respectively. It is remarkable that at delay t_2^D the concentration of low-speed fluid within the mixing layer is significantly increased. This clearly indicates that feedback control of the motion of the temperature interface can be a powerful means of controlling the nominally 2-D entrainment by the spanwise vortices (at least from the low-speed side) and hence effectively controlling mixing downstream of the mixing transition.

3.2 Theoretical Fluid Mechanics

The theoretical work performed as part of this project is initially concerned with the problem of developing a low-order ordinary differential equation (ODE) model of the flow, using the proper orthogonal decomposition to effect a Galerkin projection of the Navier-Stokes equations onto a finite-dimensionless basis. This requires two- or three-dimensional basis functions, which in turn require two- or three-dimensional velocity data, preferably simultaneous and full-field. The generation of a low-order ODE model will in turn be extremely useful in the development and implementation of real-time feedback control of mixing in the plane shear layer and other flows.

We have set as our first task the problem of development of a technique for obtaining full-field velocity data without making full-field measurements of the velocity vector. Indeed, the technique upon which we have settled requires no velocity measurements whatsoever.

The possibility of obtaining full-field velocity information in a shear flow without needing full-field velocity data does not seem to have been recognized previously. The method under development is restricted to incompressible flows, and requires full-field measurements of one passive scalar for two-dimensional flows or two passive scalars for three-dimensional flows. The following centers on the two-dimensional case. The extension to three dimensions is straightforward, and will be discussed briefly.

The basic idea is to realize that in a nonisothermal two-dimensional flow in which compressibie heating and viscous dissipation heating are negligible, the equations for conservation of mass and energy involve three unknowns (temperature and two velocity components). If full-field measurements of one of these unknowns are available, then one is left with the problem of solving two equations in two unknowns. (Measurements of another passive scalar can be used if temperature measurements aren't available.) Full-field temperature and concentration data in many flows are readily accessible using a variety of optical techniques.

If full-field measurements of temperature are available, then the two remaining unknowns are u(x,y,t) and v(x,y,t), the x- and y-components of the velocity. We note that u and v appear only linearly in the energy equation, in the convective terms on the left-hand side. In the continuity equation, u and v also appear only linearly, in the form of their x- and y-derivatives, respectively. Hence, we have two linear equations for u and v, one of which is strictly algebraic, and the other of which involves only one first derivative of each dependent variable with respect to a single coordinate. The approach chosen in this work involves solving the energy equation for one of the velocity components (say, u) as a function of the other (say, v), substituting the result into the continuity equation, and solving the resulting first-order partial differential equation for the remaining variable (v). Sufficient boundary data are available on v by making use of the no-slip boundary condition on the flow partition.

For a three-dimensional flow, there are three unknown velocity components, so that three equations are necessary for their joint determination. The logical extension from the two-dimensional case is to use the continuity equation, along with equations for the transport of two passive scalars (temperature and the concentration of some species, say, A). Alternatively, one could make use of measurements of two species, A and B. We note that data from chemically reacting species (or the product(s) of chemical reactions) can be used provided that the kinetics of their disappearance and formation are known and do not depend on the concentrations of unmeasured species or on temperature (if that variable is not measured).

In principle, this method works for any incompressible nonisothermal flow provided that full-field instantaneous data for the temperature (or two passive scalars in the three-dimensional case) are available with sufficient spatial and temporal precision to permit accurate calculation of its first and second x- and y-derivatives (including the mixed derivative) and time derivative. Our next objectives will be to investigate the effects of finite sampling rate and limited spatial resolution on the accuracy of the velocity field determined by this procedure, as well as to investigate the computational complexity of the procedure, with an eye towards its implementation in the laboratory. After that, the method will be implemented in the laboratory, beginning with temperature data from two-dimensional flows.

3.3 Control Systems

Much of the first year of research was spent analyzing input/output data obtained from many experiments using open-loop heater inputs with different temporal and spatial waveforms, with data taken at various streamwise sensor locations. The goal of this part of the research was to identify input/output models and define a meaningful and tractable feedback control problem, whose solution would enhance our control over the fluid mixing.

Because the dynamics of the process is so complicated and nonlinear, we have decided that it would be futile to try to design a feedback controller based on an explicit model of the flow field; i.e., the Navier-Stokes, energy, and continuity equations and boundary conditions associated with the two interacting streams of fluid, the flow partition, the heater array, and the shear layer (or vorticity sheet) between the two streams. Rather, our approach is adaptive control. We look for a measurable output that can be correlated with mixing, and design a controller that identifies adaptively an input/output relationship between the inputs from the heaters and this output. Once the input/output relationship is identified, the controller computes a feedback control law designed to manipulate the output in a desired way.

Two basic approaches have been studied for feedback control. The approach considered first is to feed back the temperature profile from a location in the turbulent region at a distance x_1 downstream of the flow partition. Such a temperature profile gives a direct indication of the level of mixing. Unfortunately, analysis of the mechanics of the flow field and time-series analysis of experimental results have shown that the large vortices in this region cause the input/output relationship between the heaters and the temperature distribution at such a location to be so nonlinear and nonsmooth that it is not useful for feedback control.

The approach now being pursued for feedback control is to use the cross-stream position y(t) of the Kelvin-Helmholtz shear layer (KH layer) at a fixed location x_2 downstream of the flow partition ($x_2 < x_1$). This shear layer is very thin (< 3 mm) for $0 < x < 5$ cm and oscillates in the y direction. The unforced response of the KH layer is approximately a limit cycle. The objective of the feedback control in the mixing problem is to increase the amplitude and perhaps the frequency of the limit cycle. Enhancing the action of the KH layer enhances mixing by increasing downstream turbulence.

The prospects of using an adaptive controller to drive the motion of the KH layer in a desired fashion are being investigated currently by simulations with a model developed recently by S.-B. Jiang, a UCLA graduate research assistant working on this project. The principal characteristcs of this nonlinear model are that it contains an explicit delay and that its solutions exhibit asymmetric limit cycle behavior. Thus, it qualitatively incorporates the main features of the cross-stream motion of the KH layer at a fixed downstream position. The lack of symmetry of the shear layer results from the different free-stream velocities of the hot and cold fluids. The model is the functional differential equation

$$\ddot{y}(t) + c_0 |\dot{y}(t)| \dot{y}(t) + f[y(t) - u(t)][y(t - \tau) - u(t - \tau)] = 0$$

$$f(z) = \frac{c_1 U_1^2}{1 + e^{-c_2 z}} + \frac{c_1 U_2^2}{1 + e^{c_2 z}}$$

where y(t) is the cross-stream position of the KH layer at a fixed position x, u(t) is the vector of commands to the heaters, τ is a time delay, U_1 and U_2 are the free-stream velocities, and c_0, c_1 and c_2 are constants. An adaptive controller based on a lattice filter for adaptive plant identification has been applied to this model. The results show that the adaptive controller can be used either to eliminate the limit cycle or to increase the amplitude of the limit cycle as desired. While eliminating limit cycle-like behavior is desirable in many flow control problems, the amplitude of the oscillations should be increased to enhance mixing of hot and cold fluids in our laboratory experiments.

The next step in implementing the adaptive controller in the laboratory experiment is to improve the resulution in measuring the position of the KH layer. The resolution of the current method produces the equivalent of measurement noise with time-varying nonzero mean. Such noise makes high-authority control very difficult, and both hardware and software solutions to this problem are being pursued. The most promising hardware solution appears to be an optical measurement of the position of the KH layer, an early version of which has been implemented recently in the facility. The software solution involves new adaptive filtering methods to estimate the true position of the KH layer.

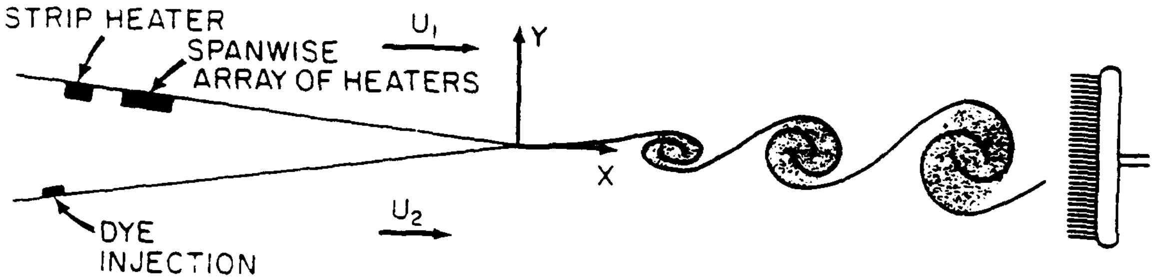


Figure 1.

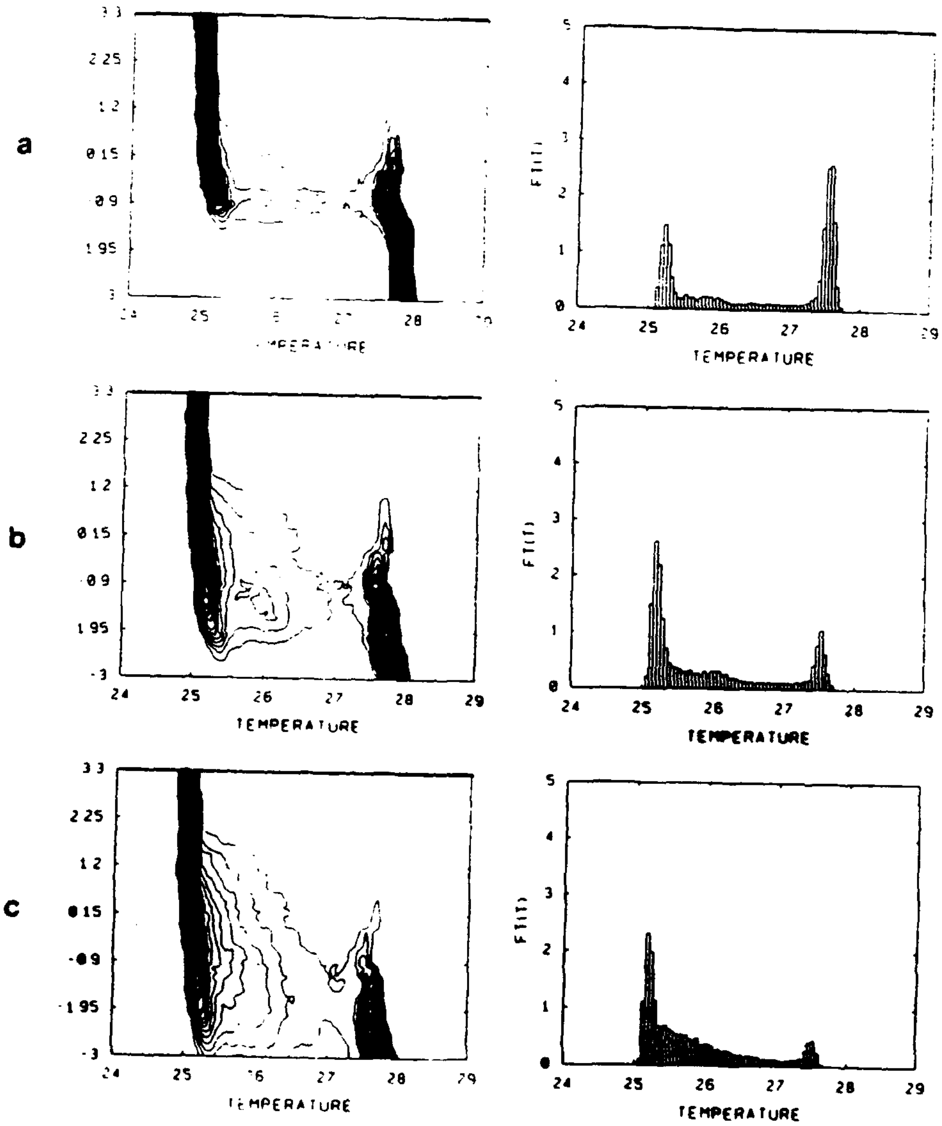


Figure 2.

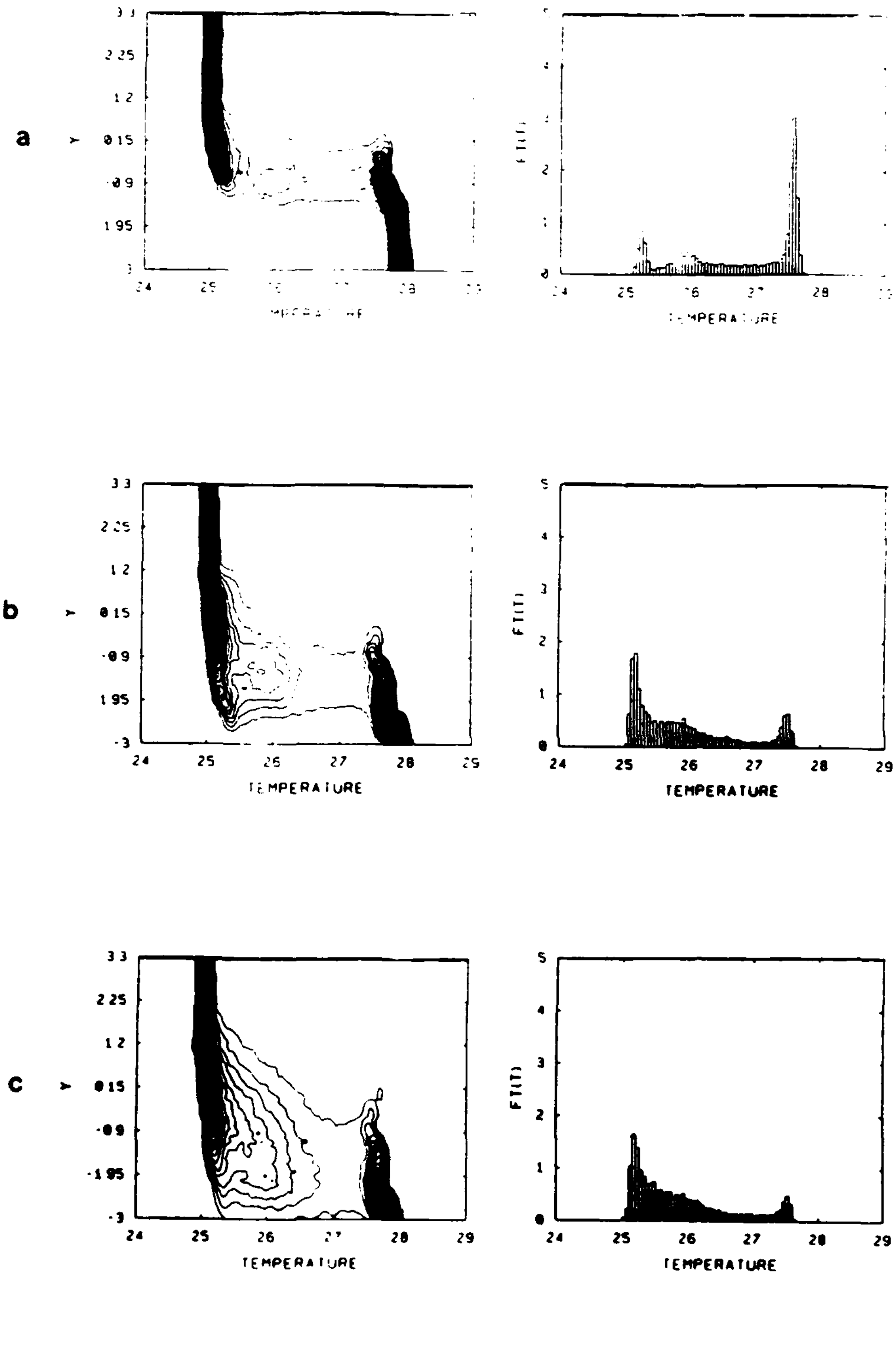
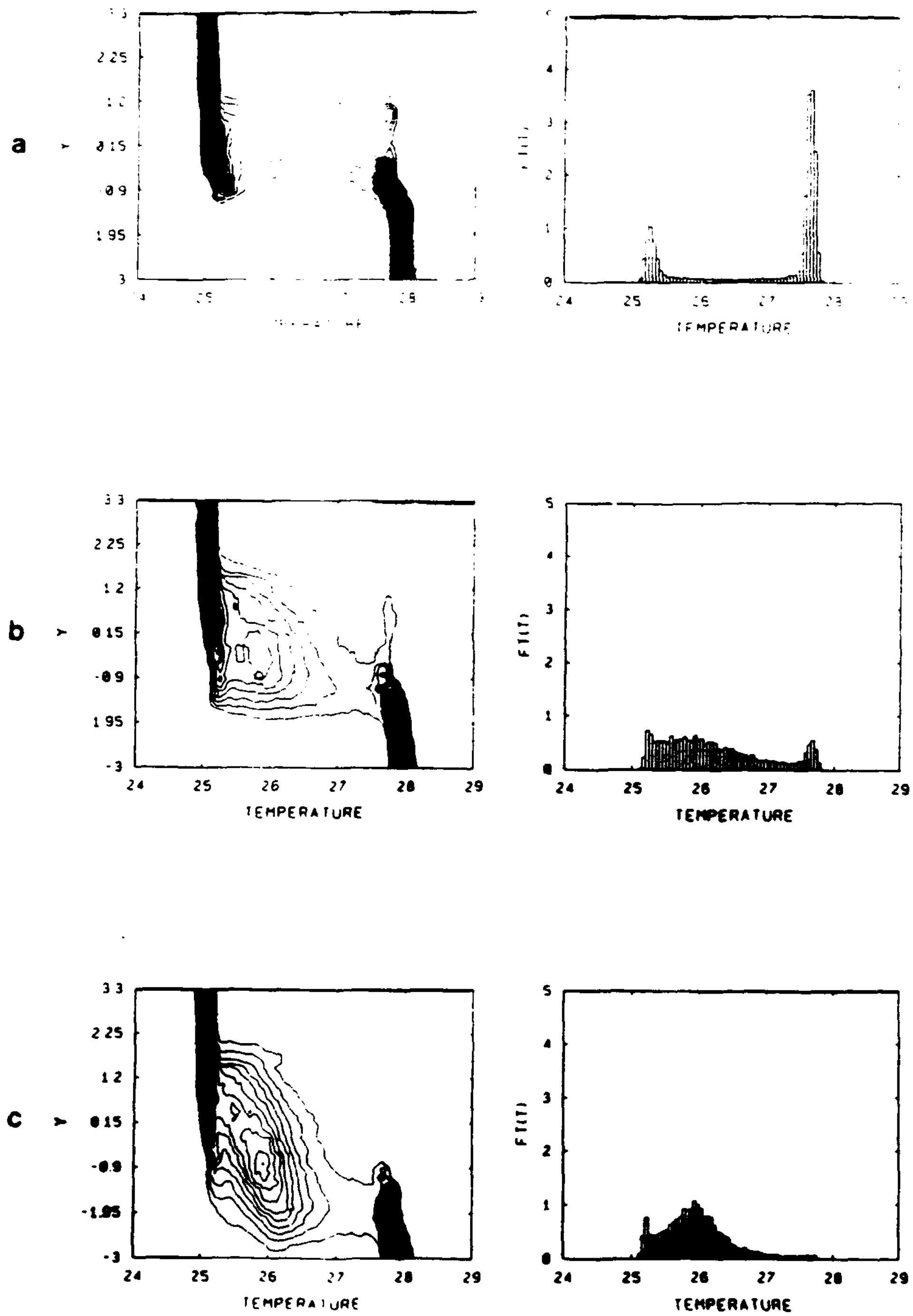


Figure 3.


a
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F(T)
TEMPERATURE
24
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Figure 4.

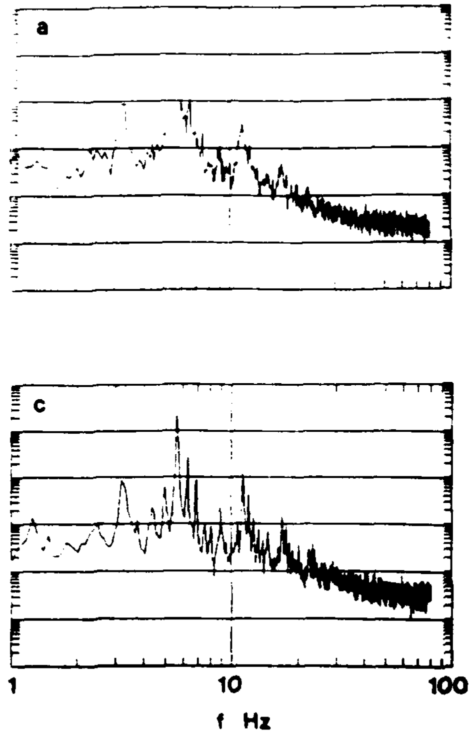

Figure 5.

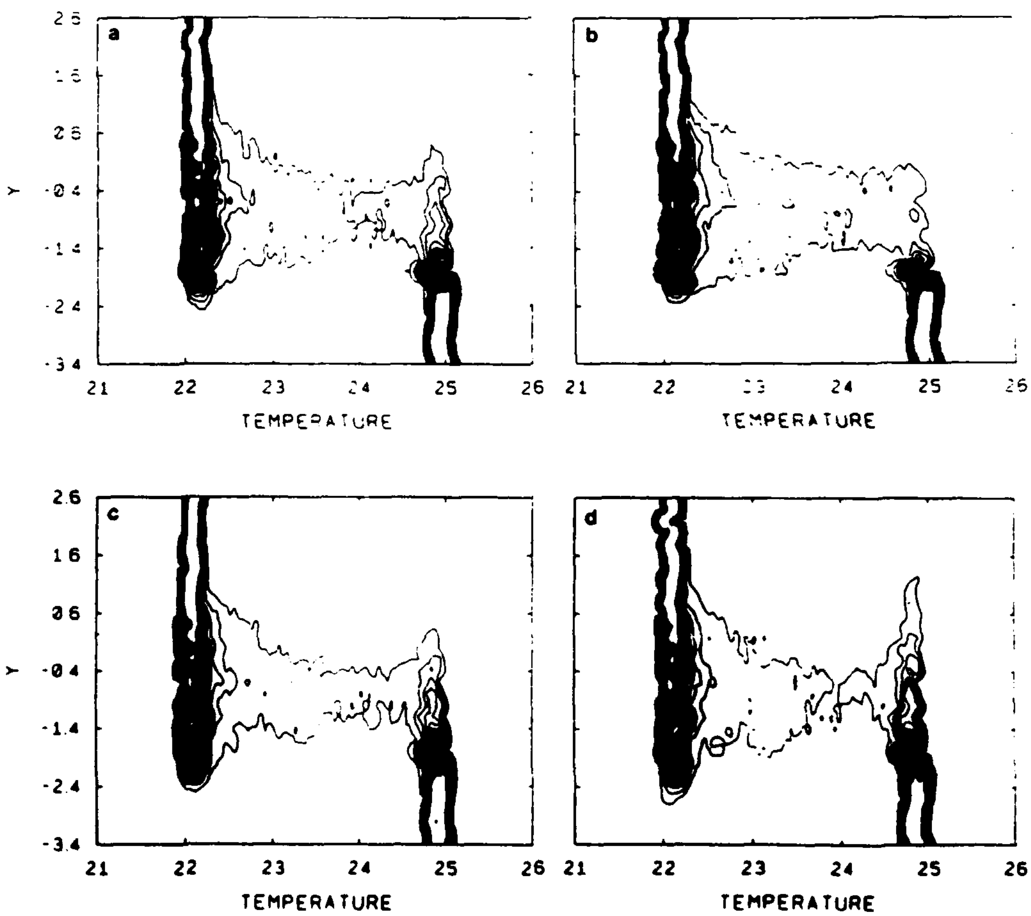

Figure 6.

Adaptive Control of a Functional Differential Equation Exhibiting Some Features of the Vortex Sheet in a Plane Shear Layer. *

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Abstract

Experiment shows that the mixing of two fluids in a plane shear layer can be affected by time-dependent heating of one side of the flow partition. In this paper, we describe the development of an adaptive LQG controller for a functional differential equation whose solutions display some of the characteristics of the motion of the Kelvin-Helmholtz layer separating the two streams.

1 Introduction

This paper focusses on the use of adaptive control to enhance thermal mixing of two streams in a plane shear layer. The experimental facility motivating the paper is a closed-return water tunnel in which two streams of water mix after passing a splitter plate. The experiment is shown schematically in Figure 1. Before mixing, the two streams have different velocities and temperatures. Experimental results demonstrate that forcing the flow with various time-periodic inputs to the heaters can affect mixing [1]. The objective of the current and future research is to use active feedback control to enhance mixing.

This paper proposes an adaptive controller based on an input-output model with parameters to be identified on-line. An adaptive controller has yet to be implemented in the experiment. This paper illustrates adaptive control of a nonlinear delay differential equation whose solutions exhibit qualitative characteristics similar to the main characteristics of the motion of the Kelvin-Helmholtz layer between the two fluids in the experiment.

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2 The Experiment and the Model Control Problem

Since the flow is three-dimensional and highly nonlinear, design of a feedback controller based on an explicit model of the flow (i.e., the Navier-Stokes equations, an energy equation, and the appropriate thermal boundary conditions on the splitter plate, through which the control input enters the problem) would be exceedingly difficult. Thus, we have chosen to pursue the design of an adaptive controller for this flow, based on measurement of the Kelvin-Helmholtz layer separating the two streams.

The mixing that occurs in a plane shear layer can be thought of as a two-stage process. In the first stage, fluid from the two isothermal free streams is entrained into the mixing layer. In the flow of interest, the characteristic length scales are too large for any significant thermal mixing to occur, however, until the onset of turbulence occurs farther downstream. There, mixed fluid (i.e., fluid with a temperature intermediate between the temperatures of the two free streams) is produced by the thermal conduction that occurs on the small length scales characteristic of the ensuing turbulent flow. The streamwise location of the onset of this mixing transition can in turn be affected by the introduction of three-dimensionality into the flow, using spanwise nonuniform control inputs to the heaters on the splitter plate.

The nominally two-dimensional motion of the K-H layer is clearly related to the entrainment of unmixed fluid from the free streams into the mixing layer. Thus, our approach is to try to increase the rate of entrainment. This has the effect of mixing more fluid.

The prospects of using an adaptive controller to drive the motion of the K-H layer are being investigated by simulations using a functional differential equation whose solutions exhibit some of the important characteristics of the cross-stream motion of the K-H later at a given streamwise location. Specifically, the motion of an unforced K-H later is approximately periodic in time. At a given streamwise location, the motion of the interface separating hot and cold fluid closely approximates an asymmetric limit cycle.

The simulation model is the functional differential equation

$$\ddot{y}(t) + c_0|\dot{y}(t)|\dot{y}(t) + f(y(t) - u(t)) \cdot (y(t-\tau) - u(t-\tau)) = 0, \tag{1}$$

$$f(z) = \frac{c_1 v_1^2}{1+e^{-c_2 z}} + \frac{c_1 v_2^2}{1+e^{c_2 z}}, \tag{2}$$

where $y(t)$ corresponds to the cross-stream position of the K-H layer at a fixed position x, $u(t)$ represents the control inputs, τ is a time delay, v_1 and v_2 represent the free-stream velocities, and c_0, c_1 and c_2 are constants. The parameters can be adjusted to fit the amplitude and frequency of the experimental K-H layer motion. In this research, the coefficients are $c_0 = 0.1$, $c_1 = 0.1$, $v_1 = 1$, $v_2 = 3$, $c_2 = 0.1$, $\tau = 1.5$.

3 Adaptive Identification and Control

The controller is based on the auto-regressive moving-average (ARMA) model

$$y(t) = \sum_{i=1}^{n} a_i(t)y(t-i) + \sum_{i=1}^{n} b_i(t)u(t-i). \tag{3}$$

The coefficients $a_i(t)$ and $b_i(t)$ are estimated adaptively by an recursive least squares (RLS) lattice filter [2]. At each sampling time t, the lattice filter computes parameter estimates $\bar{a}_i(t)$ and $\bar{b}_i(t)$ $(i = 1, \ldots n)$. Of course, for no order n will the ARMA model fit the input/output data exactly. The effectiveness of the controller proposed in this paper depends on how closely the ARMA model approximates the true nonlinear, infinite-dimensional input-output map of the plant.

If the input-output data did satisfy (3) exactly for some time-varying coefficients $\bar{a}_i(t)$ and $\bar{b}_i(t)$, then the RLS estimations of the parameters would be given by the following equations (for $i = 1, \ldots n$):

$$\bar{a}_i(t) = \frac{\sum_{\tau=0}^{t} a_i(\tau)\lambda^{t-\tau} y^2(\tau - i)}{\sum_{\tau=0}^{t} \lambda^{t-\tau} y^2(\tau - i)} \tag{4}$$

and

$$\bar{b}_i(t) = \frac{\sum_{\tau=0}^{t} b_i(\tau)\lambda^{t-\tau} u^2(\tau - i)}{\sum_{\tau=0}^{t} \lambda^{t-\tau} u^2(\tau - i)}. \tag{5}$$

In other words, the parameter estimates would be weighted time-averages of the time-varying parameters. If the system has periodic ARMA parameters, the estimates in (4) and (5) converge to the region bounded by the extreme values of the periodic parameters.

In this paper, the objective of the controller is to reduce the amplitude of the limit cycle to zero, using minimum control effort. This objective is represented by the performance index

$$J_c(t) = \sum_{\tau=t}^{\infty} [Qy^2(\tau) + Ru^2(\tau)], \tag{6}$$

where Q and R are weightings. At each sampling time t, the coefficients in the ARMA model are assumed to be constant and equal to the current estimates, and an LQG compensator is designed to minimize $J_c(t)$.

4 Simulation Results

The simulation model in (1) was integrated numerically with a finite difference scheme with a time step of 0.1. The length of the sampling interval for the lattice filter and the control law was 0.5. The same adaptive controller used here has been used when the delay differential equation in (1) was integrated numerically with the AVE scheme, in which the history interval of length $\tau = 1.5$ was divided into 5 and 10 subintervals. In those cases, the adaptive controller produced results very similar to those presented here.

In the adaptive LQG controller, we took $Q/R = 1$, and in the lattice filter, we used the forgetting factor $\lambda = 0.99$. Perhaps surprisingly, since the plant model is infinite-dimensional, a second-order adaptive controller ($n = 2$) performed well, as the results in Figures 2 and 3 show.

In each simulation, we excited the plant with a small-amplitude white-noise sequence for 50 steps before closing the control loop. During this 50-step learning period, the lattice obtained initial estimates of the parameters. The adaptive controller was engaged from step 51 throughout the remainder of the 1000-step simulation.

Figures 4 and 5 and show that, while the lattice filter converges to almost constant estimates of the AR parameters during the learning period, the estimates of the MA parameters obtained during the learning period are poor. These erroneous MA parameters appear to cause the incorrect control action when the feedback control law is engaged initially at step 51. However the controller quickly recovers and eliminates the limit-cycle of this system within 600 steps. Also, once the control input becomes smoother and nearly periodic, the estimates of the MA paremeters become relatively smooth and eventually converge.

During the learning period. the dominant response is the stable limit cycle. For this reason, the AR coefficients, which represent the correlation between the output and its history, are affected much less by the noisy input than the MA coefficients, which represent the correlation between output and the input history.

We also simulated the case in which there is actuator noise unknown to the controller. We used a Gaussian white noise sequence with variance 1 for this actuator noise. As Figure 6 shows, the controller reduces the amplitude of the output by about 2/3. It is unlikely that any controller could drive the output to zero in the presence of actuator noise. The estimates of the AR parameters in this case are similar to those in the case of no actuator noise, but, as might be expected, the estimates of the MA parameters are altered significantly.

5 Conclusions

This paper demonstrates adaptive control of a nonlinear delay differential system motivated by the problem of controlling the shear layer between two streams of different velocities. The delay differential equation was developed to exhibit certain important features of the experimental flow, particularly, a stable open-loop limit cycle. An adaptive lattice filter is used to identify a digital input-output model on which the feedback control law is based.

References

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[2] S.-B. Jiang, J. S. Gibson, and J. J. Hollkamp. Adaptive Identification of a Flexible Structure by a New Multichannel Lattice Filter. In *American Control Conference*, Chicago, June 1992.

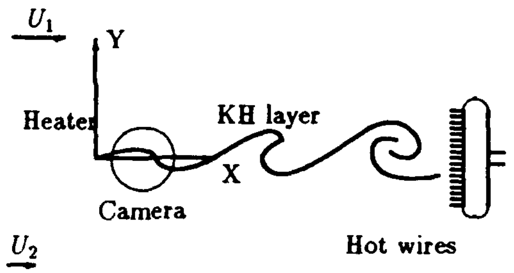

Figure 1: Experiment Configuration

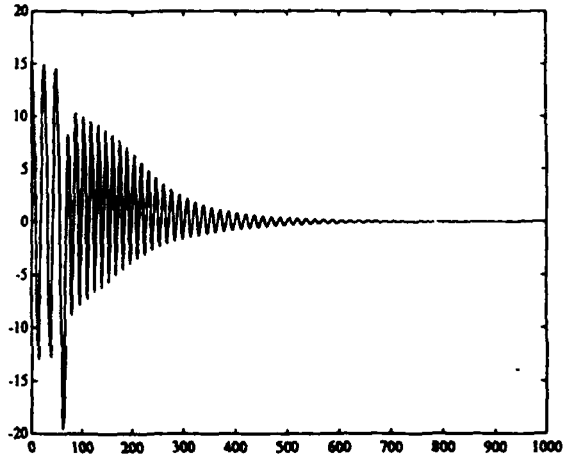

Figure 2: Controlled Output for No Noise

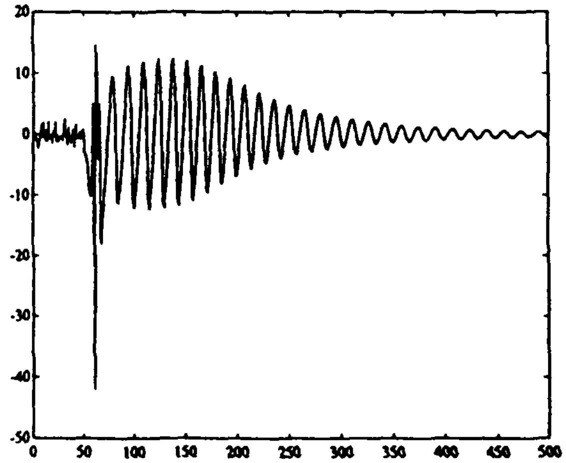

Figure 3: Control Input for No Noise

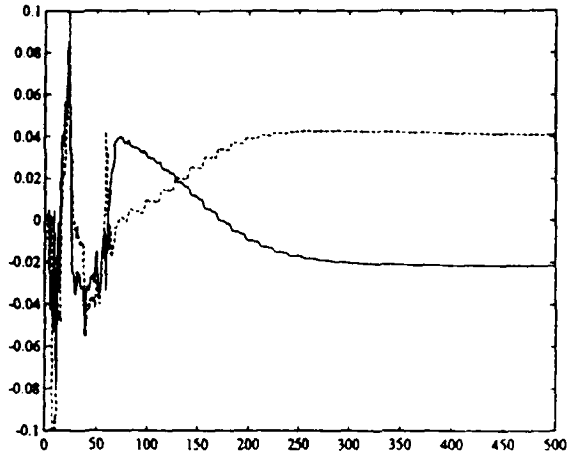

Figure 4: Identified MA Coefficients

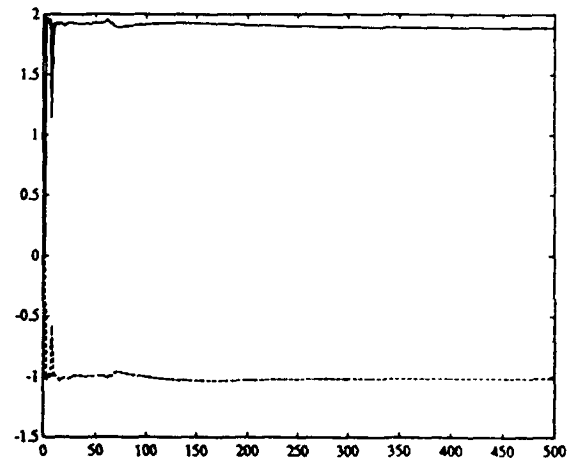

Figure 5: Identified AR Coefficients

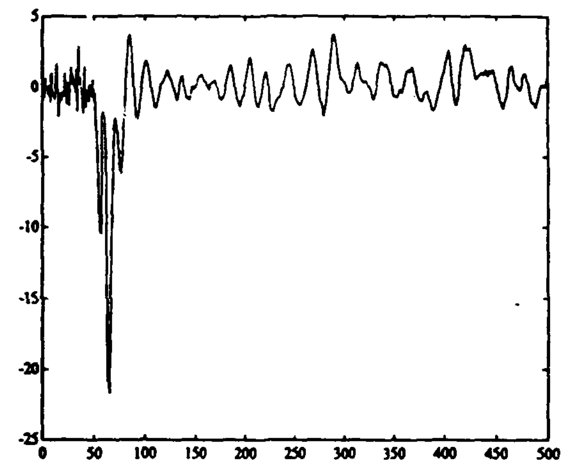

Figure 7: Control Input for Input Noise

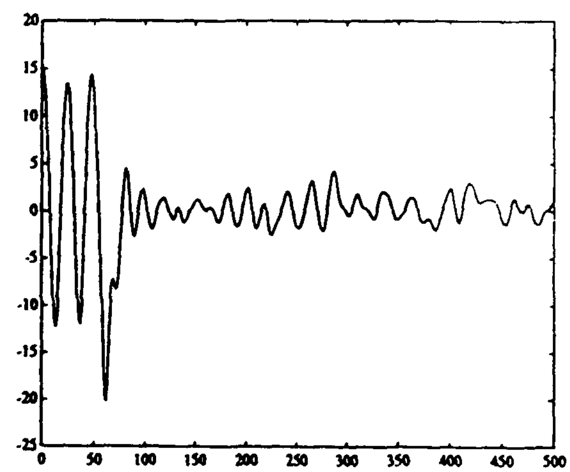

Figure 6: Controlled Output for Input Noise

Vortex Methods and Adaptive Control for Bluff-Body Flows

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1 Introduction

This is a joint research project which involves the concurrent development of adaptive controllers for high Reynolds number fluid flows and the development of efficient numerical simulations which can provide computational models upon which the controllers are designed and tested. We are using both vortex blob and finite difference methods but are emphasizing the vortex blob method because of its ability to simulate the large-scale features of the flow with relatively few computational elements. The flow problem we are focusing on is the control of the oscillations of lift and drag which are induced on a circular cylinder by its wake. The nominal flow field is a symmetric flow about a nonrotating cylinder, which is unstable. The stable unforced flow appears to be a limit cycle produced by the wake dynamics of the vorticity shed by the cylinder. The control action in our current simulations is the rotation of the cylinder, but the methods being developed should apply equally to problems in which the control action is the rotation of a portion of the boundary, cross-stream motion of the cylinder, or blowing and suction.

Beyond this adaptive regulator problem, work is planned on a second adaptive control problem to increase lift and reduce drag while maintaining a stable flow. This second problem will be formulated as an adaptive tracking problem in which the adaptive controller forces the lift, for example, to track a desired function of time that is greater than the nominal lift.

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†Supported by AFOSR Grant 890343.

2 Numerical Methods

We divide up the use of numerical simulations in the design of active flow controllers into two components. The first component is the design phase in which a great number of computational experiments are carried out and a particular control strategy is decided upon. The second component consists of testing the efficacy of the final control systems using fully resolved simulations. The great differences in the requirements of the numerical simulations when they are used in these different phases of investigations have led us to develop different numerical methods for each phase. We are developing a numerical method based on vortex blobs to provide us with a simulation for the first phase of the active control investigation and are developing an efficient fourth order finite difference solution procedure to be used in the second phase.

For two dimensional problems in which vortex shedding and wake formation are the most prominent features, vortex blob methods have shown an ability to provide solutions which exhibit the characteristic features (fluctuating lift, vortex street formation etc.) when only a small number of computational elements are used (on the order of 1000 particles). This observation has led us to consider a vortex blob method to provide us with a simulation which would model vortex shedding from a circular cylinder at high Reynolds number. The vortex method can also be easily modified to model blowing or suction control actions or active deformation of portions of the surface of the cylinder, another attractive feature of the technique. Sample results are given in Figs. 1–3. In Fig. 1 we show the form component of the lift coefficient as a function of time. In Figs. 2 and 3, we give the blob vorticity distribution and streak-line particle locations at time $t = 80$. The run time for the simulations presented in Figs. 1–3 are about 5 hours on a Sun Sparcstation 1, or 4 hours on an Intel 486-based PC. Our current simulation exhibits the main features of the fluid flow problem, and we are now using this model as a basis for control design.

The restriction that our simulation use a limited number of computational particles has led to difficulties in creating a useful vortex method simulation. The primary source of our difficulties stems from the fact that the phenomenon which we are trying to capture depends on the boundary vorticity dynamics. This is very complex, as can be seen in Fig. 4, in which we give the contours of the vorticity distribution near the cylinder shortly after startup. (These were obtained with our finite difference solver.) With the number of computational elements which we are willing to use, it is completely clear that these dynamics are not being well resolved. The challenge has been (and continues to be) the proper way to design the simulation so that the errors committed in the representation of these boundary layer dynamics do not adversely affect the general features of the flow which we are trying to capture. At this time we believe that we have modeled to some extent the effect of such boundary dynamics, but we are actively working on refining our model of vortex shedding.

The numerical method which we are working on to be used in the second phase of controller development is a fourth order finite difference solver (in both space and time). Sample results of the vorticity distribution for Reynolds number 5000 are given in Figs. 4 and 5. These results represent fully converged solutions. These finite difference simulations are capable of resolving the the vorticity dynamics near the boundary of the cylinder for short times. For larger times—the regime in which we are particularly interested—we intend to combine, via a domain decomposition approach, the current finite difference solver with another method (perhaps another finite difference method or a particle scheme). We are also extending the method, using conformal mapping, so that it can handle objects other than circular cylinders.

3 Adaptive Control

The adaptive controller proposed here is designed to identify a local linearization of the nonlinear dynamics that describe the relationship between an input such as the rotation of the cylinder and an output such as lift coefficient. Similar controllers have proved successful for control of other highly nonlinear systems, including systems with limit cycles with features similar to those in fluid flows. An important feature of the controller proposed here is that the lattice filters proposed for adaptive identification allow the order of the controller to vary as well as the gains.

We assume that we have a measurement vector y that is sampled at times $t = 0, 1, 2, \ldots$, and that the control vector u is constant on each sampling interval. Throughout this discussion, t denotes sampling times and takes integer values. In the current applications, y is the lift coefficient and u the angular velocity of the cylinder. (Both y and u are scalars in this case.)

The controller is based on the autoregressive-moving average (ARMA) model

$$y(t) + \sum_{i=1}^{n} A_i(t) y(t-i) = \sum_{i=1}^{n} B_i(t) u(t-i),$$

with the time-varying coefficients $A_i(t)$ and $B_i(t)$ estimated adaptively by a least-squares lattice filter. One important advantage of the lattice filter is that it is recursive in order as well as in time, so that the order n of the ARMA model can be varied adaptively to adjust to varying plant characteristics. We assume that the matrices $A_i(t)$ and $B_i(t)$ vary slowly enough for the parameter estimates and control law to adapt to the changing plant dynamics. This assumption appears valid for the current application because the sampling rate is much faster than the frequency of the oscillation of the lift coefficient, as Fig. 1 illustrates.

The adaptive control law is designed to minimize approximately the performance index

$$J(t) = \sum_{t'=t}^{\infty} [|y - y_*|^2 + u^T R u](t')$$

where y_* is a desired output and R is a positive definite symmetric matrix. The control law has the form

$$u(t) = -\sum_{i=1}^{n} [K_{0i}(t) u(t-i) + K_{1i}(t) y(t-i)] + \varepsilon(t)$$

where $K_{0i}(t)$ and $K_{1i}(t)$ are control gains and $\varepsilon(t)$ is a linear function of the desired output sequence $y_*(t)$.

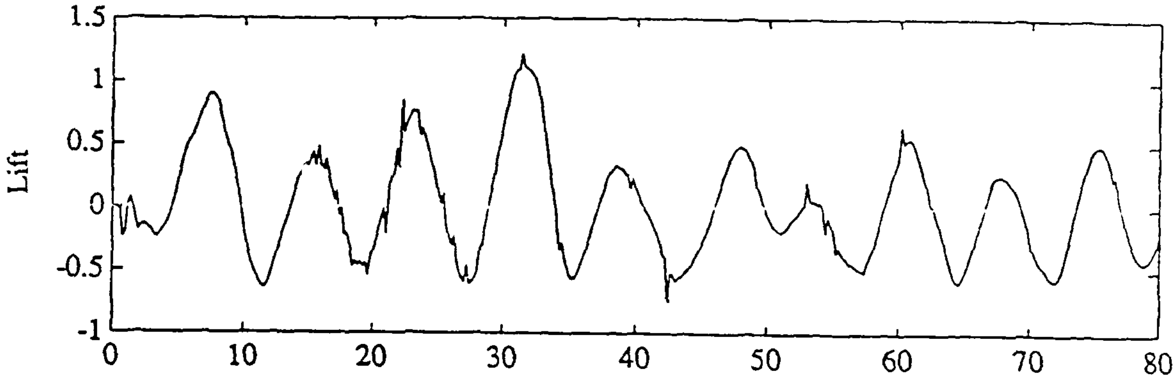

Figure 1: Lift vs. time for a vortex blob simulation with 975 particles

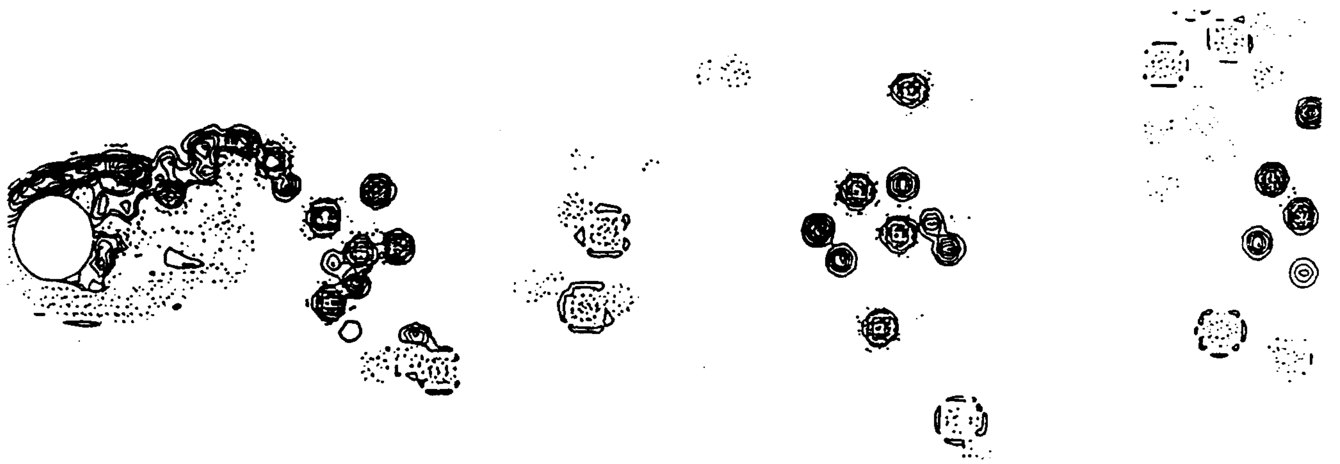

Figure 2: Blob vorticity distribution at time $t = 80$

Figure 3: Streak-line particle locations at time $t = 80$

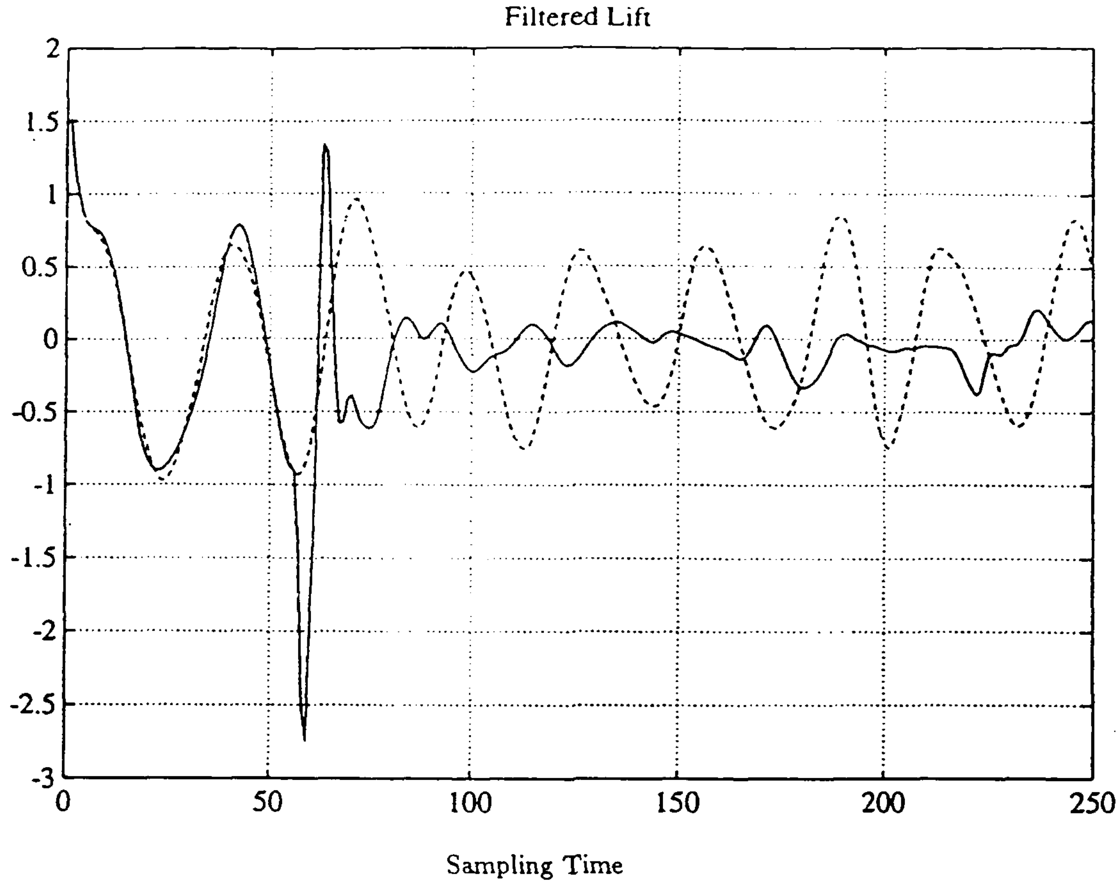

Figure 4: Filtered Lift from Flow Past a Rotating Cylinder
Controlled Response (Solid Curve)
Uncontrolled Response (Dashed Curve)

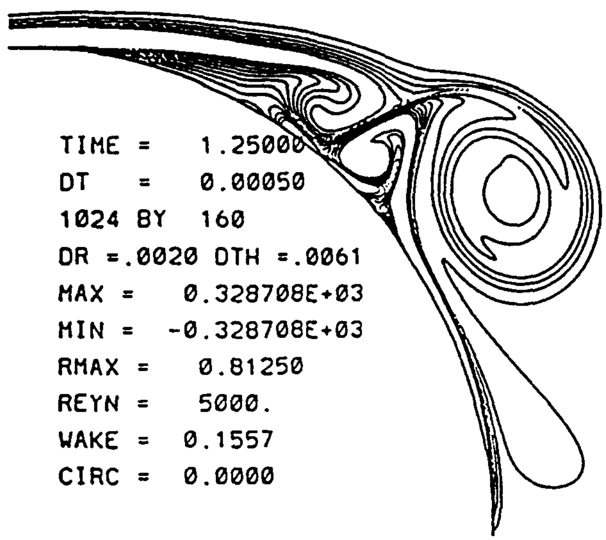

Figure 5: Vorticity distribution from a fourth order finite difference method. Both positive and negative contours are shown as solid lines.

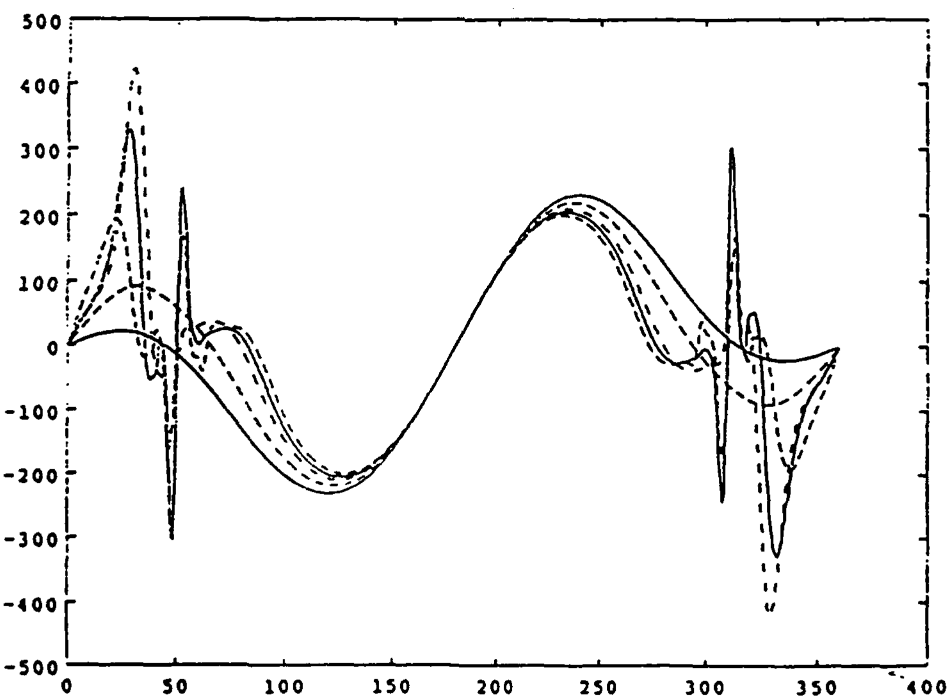

Figure 6: Surface vorticity distribution as a function of time. Individual curves represent vorticity distribution at increments of $\delta t = .25$.