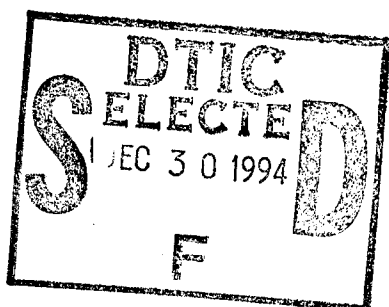# FLOW CONTROL

FINAL TECHNICAL REPORT

Period Covered by This Report: 10/1/92–12/21/94

AVNER FRIEDMAN

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OFFICE OF NAVAL RESEARCH

Grant N00014–93–1–0027

INSTITUTE FOR MATHEMATICS AND ITS APPLICATIONS
514 Vincent Hall
University of Minnesota
Minneapolis, Minnesota 55455

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1. Description of Workshop (Flow Control)

The grant from the Office of Naval Research N00014–93–1–0027 supported the research in Flow Control, part of the IMA 1992–93 program CONTROL THEORY AND ITS APPLICATIONS. Specifically, the grant partially supported the postdocs Ruben Spies and Jean-Francois Collet, who worked in areas related to flow control, and 3 one-month visitors and 7 workshop participants who were in residence at the IMA during fall 1992 and participated in the Period of Concentration on Flow Control (November 16–20, 1992), organized by Max D. Gunzburger.

Majority of the flow control participants were mathematicians involved in the analysis, approximation, and computation of flow control and optimization problems. A small number of engineers were invited and they addressed application issues. The objective of the workshop on Flow Control was to bring together the ever growing community of mathematicians who are addressing these problems by sophisticated numerical and analytical techniques. They used a variety of mathematical tools and the workshop provided them an opportunity for an exchange and comparison of the different approaches. The second objective met by the workshop was to identify some of the important problems, from the point of view of applications, that need to be addressed by mathematicians, including specific flow control and optimization problems of interest to engineers.

2. Comments by the Organizer - Max D. Gunzburger

The following comments appear in the introduction of the IMA volume 68 which contains the proceedings of the Period of Concentration in Flow Control held at the IMA in November, 1992.

The gathering of engineers and mathematicians was especially timely as it coincided with the emergence of the role of mathematics and systematic engineering analysis in flow control and optimization. Since this meeting, this role has significantly expanded to the point where now sophisticated mathematical and computational tools are being increasingly applied to the control and optimization of fluid flows. Thus, these proceedings serve as a valuable record of some important work that has gone on to influence the practical, everyday design of flows. Moreover, they also represent very nearly the state of the art in the formulation, analysis, and computation of flow control problems.

My own article in the proceedings "A prehistory of flow control and optimization" attempts to set the stage for the remaining articles by describing the history of attempts at flow control and optimization and explaining why the time is ripe for the introduction of sophisticated tools from the theory of partial differential equations, from optimization theory, and from computational fluid dynamics into the study of flow control. The remaining articles in the volume show how these tools may be introduced to attack flow control problems. Mathematical issues in optimal control, feedback control, and controllability of fluid

flows are treated in the articles by E. Casas, A. Fursikov and O. Imanuvilov, K. Ito, H. Tran and J. Scroggs, S. Sritharan, S. Stojanovic, T. Svobodny, and R. Temam. Computational studies of algorithms and of particular applications are found in the articles by H. Banks and R. Smith, J. Borggaard, J. Borggaard and J. Burns, J. Brock and W. Ng, J. Burkardt and J. Peterson, Y.-R. Ou, G. Strumulo, and A. Taylor, P. Newman, G. Hou, and H. Jones. Among the applications considered in this volume are acoustics, compressible flows and incompressible flows, chemical vapor deposition, turbulent flows, and flows with shock waves.

I would like to express my sincere thanks to all of the participants in the Period of Concentration, and especially to the speakers and those who contributed to these proceedings. Thanks are also due to the staff of the IMA for their help in the production of these proceedings. Of special note in this regard are Patricia V. Brick, Stephan J. Skogerboe and Kaye Smith. Finally, I would like to acknowledge the hospitality and help extended to me and the other participants by Avner Friedman and Willard Miller, Jr.. Without them, neither the Period of Concentration in Flow Control nor this volume would have been possible.

3. Table of Contents of the IMA Volumes in Mathematics and its Applications #68 Flow Control edited by Max D. Gunzburger.
This Proceeding is scheduled to be released by the publisher, Springer-Verlag in early spring 1995.

4. Manuscript Published in the IMA Preprint Series

1106 John A. Burns and Ruben D. Spies, A numerical study of parameter sensitivities in Landau-Ginzburg models of phase transitions in shape memory alloys

1095 H.O. Fattorini and S.S. Sritharan, Optimal chattering controls for viscous flow

1086 Irena Lasiecka and Mary Ann Horn, Global stabilization of a dynamic von Kármán plate with nonlinear boundary feedback

1151 Irena Lasiecka, Angelo Favini and, Mary Ann Horn, Global existence and uniqueness of regular solutions to the dynamic von Kármán system with nonlinear boundary dissipation

1168 Irena Lasiecka, Angelo Favini, Mary Ann Horn & Daniel Tataru, Global existence, uniqueness and regularity of solutions to a Von Kármán system with nonlinear boundary dissipation

1067 Jean-Pierre Puel, Caroline Fabre, and Enrike Zuazua, Approximate controllability of the semilinear heat equation

1093 Jean-Pierre Puel, Caroline Fabre & Enrique Zuazua, On the density of the range of the semigroup for semilinear heat equations

1054 Ruben D. Spies, A state-space approach to a one-dimensional mathematical model for the dynamics of phase transitions in pseudoelastic materials

1106 Ruben D. Spies and John A. Burns, A numerical study of parameter sensitivities in Landau-Ginzburg models of phase transitions in shape memory alloys

1166 Ruben D. Spies, Local existence and regularity of solutions for a mathematical model of thermomechanical phase transitions in shape memory materials with Landau-Ginzburg free energy

1095 S.S. Sritharan and H.O. Fattorini, Optimal chattering controls for viscous flow

1113 Thomas Svobodny and Srdjan Stojanovic, A free boundary problem for the Stokes equation via nonsmooth analysis

1130 Janos Turi, I. Györi, and F. Hartung, Approximation of functional differential equations with time- and state-dependent delays by equations with piecewise constant arguments

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1131 Janos Turi, I. Györi and, F. Hartung, Stability in delay equations with perturbed time lags

1132 Janos Turi and F. Hartung, On the asymptotic behavior of the solutions of a state-dependent delay equation, IMA Preprint Series # 1132

IMA NEWSLETTER #198

November 1 - November 30, 1992

1992-93 Program
CONTROL THEORY AND ITS APPLICATIONS

NEWS AND NOTES

IMA Period of Concentration:
FLOW CONTROL
November 16 - 20, 1992
Organizer: M. Gunzburger

Historically, flow control problems have been addressed through experimental investigations. Analytic and computational research had been based on drastically simplified flow models. However, recently, a number of mathematicians and other scientists have been addressing flow control problems without invoking such simplifications. There is little doubt that research in flow control will have significant impact on applications.

The ability to control fluid flows is crucial to the design and performance of processes in a wide variety of technological applications. For example, controls can be utilized in order to minimize drag, maximize lift, avoid high temperatures, enhance or deter mixing, delay or accelerate separation, increase mass flow rates, reduce structural vibrations in problems arising in airplane design and performance, in efficient chemical vapor deposition processes, in novel ship and submarine propulsion systems, in various components of chemical and petroleum plants, and in the design of efficient automobile engines and shapes.

Historically, flow control problems have been addressed through experimental investigations. Analytic and computational research had been based on drastically simplified flow models. However, recently, a number of mathematicians and other scientists have been addressing flow control problems without invoking such simplifications. There is little doubt that research in flow control will have significant impact on applications.

The mathematics of flow control involves a wide variety of skills and expertise. Traditional and novel techniques of optimization and the calculus of variations, set in the environment of modern theories for partial differential equations, are used to determine and analyze mathematical models that serve to determine the optimal states and controls. In particular, the great body of work on the Navier-Stokes equations provide a starting point for the analysis of flow control problems. The study of discretization algorithms, such as those based on finite element methods, and of techniques for the solution of the formidable nonlinear system of the discrete equations that result from discretization, also requires novel approaches.

Monday, November 16

Unless otherwise stated, the talks today are in Conference Hall EE/CS 3-180

9:00 am	Registration and coffee	Reception Room EE/CS 3-176
9:30 am	Welcome and Orientation	Conference Hall EE/CS 3-180
9:40 am	Max Gunzburger Virginia Tech	Flow control and optimization: An introduction

Abstract: We give a very unscientific survey of flow control and optimization problems and some of their history. We discuss various approaches for the modeling, analysis, and numerical approximation of such problems and we touch on the role that mathematics can play in future developments in the field.

10:40 am	Coffee Break	Reception Room EE/CS 3-176
11:00 am	A. V. Fursikov Moscow University	On approximate controllability of the Stokes system

Abstract: The problem of approximate controllability of the nonstationary Stokes system in a bounded domain G is investigated in case the density of external forces concentrated in an arbitrary subdomain of the domain G is a control. The approximate controllability takes place in the class of square integrable functions and it does not exist in the class of sufficiently smooth functions. The Burgers equation and semilinear parabolic equations are not approximately controlled with respect to the right-hand-sides concentrated in the subdomain.

2:00 pm	Ralph Jones, III Sverdrup Technology, Inc.	To be announced
3:00 pm		Contributed Talks/Discussion

This session will be organized after the workshop gets underway

4:00 pm	Vincent Hall 502 (The IMA Lounge)	IMA Tea (and more!)

A variety of appetizers and beverages will be served.

Tuesday, November 17

Unless otherwise stated, the talks today are in Conference Hall EE/CS 3-180

9:30 am	John A. Burns Virginia Tech	Optimal control and design of fluid/structure interactions

Abstract: In this paper we discuss several computational issues that arise in optimal control problems for hybrid systems of partial differential equations. These problems are motivated by applications to shape optimization and to optimal control of dynamical systems that arise when fluids and structures interact. We first describe an optimal design problem related to the design of optimal forebodies for the free-jet test facility currently under development at the Arnold Engineering Development Center. This problem is used to illustrate some of the basic ideas. We also discuss a simple feedback control problem with unbounded input and output operators. This model problem is discussed in detail and used to motivate possible practical approaches to more complex fluid flow control problems. Numerical results will be presented to illustrate these ideas.

| 10:30 am | Coffee Break | Reception Room EE/CS 3-176 |

| 11:00 am | Srdjan Stojanovic
University of Cincinnati/IMA | Nonsmooth analysis and shape optimization in
flow problems |

Abstract: Shape optimization (i.e., free boundary problem) for potential and for Stokes flow is considered. The problem is to determine the shape of the boundary for which fluid produces the specified force field on that portion of the boundary. New approach is introduced. The variable domain problem is relaxed so that it becomes a nonsmooth optimization problem on the fixed domain for the somewhat singular state equation. State equation is considered, and the multivalued generalized gradient of the variational functional is studied. The method is constructive.

| 1:30 pm | Arthur C. Taylor III
Old Dominion University | Recent advances in aerodynamic sensitivity
analysis |

Abstract: Recent advances in the development of a systematic methodology for calculating consistent discrete aerodynamic sensitivity derivatives are discussed, where these derivatives are obtained from large-scale

software which numerically solves the multidimensional Euler and Navier-Stokes equations. Special emphasis is placed on solving the large coupled systems of ill-conditioned linear equations which must be solved in accomplishing this task. Subsequent use of these aerodynamic sensitivity derivatives for approximate analysis and for design optimization is discussed and demonstrated. Finally a proposed new strategy for Simultaneous Aerodynamic Analysis and Design Optimization (SAADO) is presented.
Joint work with Gene W. Hou.

| 2:30 pm | Coffee Break | Reception Room EE/CS 3-176 |

| 3:00 pm | L. Steven Hou
Simon Fraser University | Optimal control for some nonlinear P.D.E.s |

Abstract: We present a mathematical framework for the mathematical and numerical analysis of optimal control problems associated with nonlinear equations. In particular we study optimal control problems for the stationary Navier-Stokes equations. We establish optimality systems of equations, and analyze finite dimensional approximations of their solutions. Some numerical results will be demonstrated. Most of the results presented here are joint work with M. Gunzburger and T. Svobodny.

Wednesday, November 18

Unless otherwise stated, the talks today are in Conference Hall EE/CS 3-180

| 9:30 am | Gary S. Strumulo
Ford Motor Company | CFD analysis of and APCVD applicator for thin
film deposition on glass surfaces |

Abstract: Ford Glass R&D is developing several new coatings on glass products such as car windshields and sidelights and architectural glass. These coatings will be deposited by Atmospheric Pressure Chemical Vapor Deposition (APCVD). The vapor will be applied to the glass as it is formed at around 600° C in the molten tin bath by a series of applicators each consisting of a gas feed system and two exhaust manifolds. The glass moves under the applicators at 400 inches per minute and each coated layer is a few hundred angstroms thick.

We've observed a number of problems in applying this technology successfully to produce high quality products. These have stemmed from issues related to exhaust efficiency, temperature gradients, stagnation regions where particulates can form, and a "memory" of how the gas was injected. This latter issue can cause a nonuniformity in the coating across the glass that is dramatically evident by discoloration.

We solved the Navier-Stokes equations numerically both to determine if these problems could be predicted, and to redesign the applicators to help alleviate them. We modified the gas feed system and thermal gradients and observed their effect on the flow near the glass surface.

| 10:30 am | Coffee Break | Reception Room EE/CS 3-176 |

11:00 am   Roger Temam   On the control of turbulence
               Indiana University

Abstract: Our aim in this lecture is to study some problems of control of turbulence. Two cases are considered. In one case the system is governed by the Navier-Stokes equations and we want to minimize turbulence measured by the L^2-norm of the curl vector. Existence of optimal control, necessary optimality conditions and numerical algorithms are presented. In the second case we consider the analogous problem related to the Burgers equations. In this case a different algorithm is presented and has been effectively implemented. Important reduction of drag is observed.

2:00 pm   Yuh-Roung Ou   Computational study of flow control problems
              Virginia Tech   for a rotating cylinder

Abstract: Flow control is a critical issue in the advanced design of aero/hydro-maneuvering vehicles which may provide the real-time effect for important applications, such as highly instantaneous maneuvers for the super-maneuverable aircraft, and optimum design of aerodynamic configurations. This talk presents research on active control of viscous flow around a rotating cylinder. By treating the rotation rate as a control variable in this model, various problems associated with the development of the alternate shedding of vortices and the induced body forces on the cylinder are studied numerically. The numerical results of lift, drag and lift/drag ratio respond to a variety of time-dependent rotation rates will be discussed. Several optimal control problems of maximizing the lift-to-drag ratio are then described. Very precise periodicity of the force evolutions at certain cases are established, and it may provide direct implication of controlling the vortex formation in the cylinder wake. Other issues addressed include the possibility of suppressing vortex shedding by using active control of the rotation rate, and the mathematical formulation of an optimal control problem associated with the rotating cylinder.

Thursday, November 19
Unless otherwise stated, the talks today are in Conference Hall EE/CS 3-180

9:30 am   Kazufumi Ito   Optimal design of chemical vapor deposition
              North Carolina State University reactors

Abstract: Chemical Vapor Deposition (CVD) is a process that uses chemically reacting vapors to deposit a thin solid film. The transport processes in CVD are described by the gas dynamics, i.e. conservation of mass, momentum, energy and mass transfer equations. The objective of our study is to determine an optimal design of the reactor chamber in order to increase purity and uniformity of the deposition layers.

10:30 am   Coffee Break   Reception Room EE/CS 3-176

11:00 am   Eduardo Casas   Some optimal control problems of multistate
               Universidad de Cantabria/IMA   equations appearing in fluid mechanics

Abstract: This talk deals with optimal control problems associated to the Navier-Stokes equations. The state of the system is the velocity of the fluid and the controls are the body forces or the heat flux on the boundary, in this last case the Navier-Stokes equations are coupled with the heat equation. We will consider three-dimensional flows, therefore the state equations are ill-posed in the sense that the relation between the control and the state is multivalued and consequently the derivation of the optimality conditions is not obvious. To overcome this difficulty we introduce an approximate family of optimal control problems governed by well posed differential equations, we obtain the optimality conditions for these problems and then we pass to the limit.

1:30 pm   Thomas P. Svobodny   Hybrid control techniques in hydrodynamics
              Wright State University

Abstract: We investigate the mathematical control theory of some practical engineering problems involving incompressible flow. Specifically, we deal with specifying boundary conditions and controlling separating flow in exterior flows about lifting bodies and interior and exterior flows of electrically conducting liquids. We use as control the boundary velocity and/or the geometric shape of the boundary. Hybrid control means choosing these controls simultaneously in an optimal way.

2:30 pm   Coffee Break   Reception Room EE/CS 3-176

Unless otherwise stated, the talks today are in Conference Hall EE/CS 3-180

9:30 am   S. S. Sritharan   Optimal feedback control of hydrodynamics: A
                 UCLA/NCC OSC   progress report

Abstract: The progress made on the optimal feedback control theory of viscous incompressible flows covering practically important cases such as wind tunnel flow and exterior hydrodynamics will be discussed. Main results are

(1) Existence theory: Ordinary controls as well as Young measure-valued chattering controls.

(2) Pontryagin maximum principle: Using viscosity solution method as well as using Ekeland's variational principle for problems with target constraint.

(3) Dynamic programming: Analysis of the infinite dimensional Hamilton-Jacobi-Bellman equation and the feedback synthesis.

Current ventures include

(1) Optimal Control theory of Combustion.

(2) Optimal control of ergodic properties of turbulent flow using statistical theory of Navier-Stokes equations.

10:30 am   **Coffee Break**   Reception Room EE/CS 3-176

11:00 am   **J. S. Brock**   The formulation of a quasi-analytical
                 Virginia Tech   aerodynamic inverse design method

Abstract: Formulation of the quasi-analytical aerodynamic inverse design method will be presented. This is a new, direct-iterative inverse design method which couples an analysis problem with a design problem in an iterative fashion. The direct-iterative design method begins with an initial geometry and solution, and a target surface profile. The estimate of the new geometry is driven by the difference between the target surface profile and the current, calculated profile. The geometry modifications are obtained with the design portion of the algorithm and an analysis of the new geometry is repeated. The geometry is iteratively modified in this manner until the calculated and target surface profiles are closely matched. The design portion of the new method uses a truncated Taylor series expansion of the discrete residual which describes the governing equations. This provides a linear design problem (linear in the change in solution and geometry) for the non-linear governing equations. This new linearized method causes the iterative nature of the algorithm. That is, all portions of the quasi-analytical design algorithm may utilize the Euler or Navier-Stokes equations in two or three dimensions. Therefore, the design portion or the algorithm is equally valid for subsonic, transonic, and supersonic flow regimes within viscous or inviscid flows. The quasi-analytical differentiation of the governing equations also ensures numerical consistency between analysis and design portions of the algorithm. This new method is applicable for finite difference or finite volume discretizations with either central-difference or upwind flux methods. Along with the formulation of the quasi-analytical inverse design method, results using this new method in a design-like environment will be presented.

2:00 pm   **Antony Jameson**   To be announced
                 Princeton University

CONFIRMED VISITORS: November 16 - 20
Period of Concentration: FLOW CONTROL

Banks, H. Thomas	North Carolina State University	NOV 8 - NOV 19
Borggaard, Jeff	VPI&SU	NOV 15 - NOV 20
Brock, Jerry	Virginia Tech	NOV 18 - NOV 22
Browning, William	Applied Mathematics	NOV 15 - NOV 17
Burkardt, John	VPI&SU	NOV 15 - NOV 20
Burns, John A.	VPI and SU	NOV 12 - NOV 21
Fattorini, Hector O.	UCLA	NOV 8 - NOV 20
Fursikov, A.V.	Moscow University	NOV 16 - NOV 20
Gunzburger, Max D.	VPI & SU	NOV 14 - NOV 20
He, Feiyue	University of Cincinnati	NOV 14 - NOV 21
Hou, Lisheng	Simon Fraser University	NOV 14 - NOV 20
Ito, Kazufumi	North Carolina State University	NOV 8 - NOV 21
Jameson, Antony	Princeton University	NOV 15 - NOV 20
Kneile, Karl	Sverdrup Technology	NOV 15 - NOV 20
Kojima, Fumio	Osaka Institute of Technology	NOV 8 - NOV 20
Kunisch, Karl	TU Graz	NOV 7 - NOV 21
Lasiecka, Irena M.	University of Virginia	NOV 7 - NOV 17
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Wei, Ming	McGill University	NOV 8 - NOV 20