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A Computational Environment for Design of Aerospace Systems

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THE AIR FORCE
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for the period

1 March 1999 - 28 February 2000

by

John A. Burns, Director
Air Force Center for Optimal Design and Control

Wright House / West Campus Drive
Virginia Polytechnic Institute & State University
Blacksburg, VA 24061- 0531

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13. ABSTRACT *(Maximum 200 words)*

This report contains a summary and highlights of the work funded by the Air Force under AFOSR Grant F49620-99-1-0121, titled " A Computational Environment for Design of Aerospace Systems". This effort, funded under the Defense University Research Instrumentation Program (DURIP), was conducted by the Center for Optimal Design and Control (**CODAC**), at Virginia Tech during the period 1 March 1999 – 28 February 2000.

The objective of the grant was to enhance the computational facilities we have assembled for a sensitivity-based design environment. In recent years researchers at **CODAC** have developed mathematical foundations and a computational framework for the rapid calculation of design-sensitivities for aerospace applications. Implementation requires approximate solution of certain linear partial differential equation. In aerodynamic applications, for example, these solutions describe in linear approximation how the flow will change with a given change in a (geometric) design parameter. We have acquired an SGI Origin 2000 computer with 32 processors and two SGI Octane workstations to provide the computational platform for these calculations.

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Chapter 1

Introduction

This grant was awarded under the Defense University Research Instrumentation Program (DURIP) and has provided support for equipment to enhance the capabilities of the **PRET- CODAC** researchers to develop and utilize tools that will facilitate engineering design. We have greatly enhanced the power of our main computational platform for use in the development of of distributed-parameter control design tools as well as in the development of interactive design tools for aero–propulsion systems.

The Air Force Center for Optimal Design And Control (**CODAC**), established in 1993, addresses a number of technological thrusts related to these key components. **CODAC** researchers have made significant progress in these areas and our industrial partners: AeroSoft, BEAM Technologies, Boeing Defense and Space Group, give us a proven team of scientists and engineers from small high-tech firms and major aerospace companies. The research group at Virginia Tech has been at the forefront of the development of sensitivity methods for optimal design, with applications to shape optimization for fluid flow management. AeroSoft provides expertise in computational methods for optimization and for simulation of fluid dynamics.

CODAC is funded by the Air Force Office of Scientific Research through the Air Force Program for Research Excellence and Transition (*PRET*) under (Grant AFOSR–49620–96–1–0329). Dr. John A. Burns, Hatcher Professor of Mathematics at VPI & SU, is the Director of **CODAC** and principal investigator on the project. Lt. Col. R. Canfield, AFOSR/NM is the technical monitor. **CODAC** is located within the Interdisciplinary Center for Applied Mathematics (**ICAM**) at Virginia Tech. Dr. Terry L. Herdman, Professor of Mathematics at VPI & SU, is the Director of **ICAM**.

Research conducted at **CODAC** has wide applicability and promises considerable payoff in aerospace design applications. In order to provide focus for the research and to expedite its transition to industrial use, the *Center* has developed research partnerships with the following groups:

- Boeing Defense and Space Group (BDSG), Seattle, WA

  E.L. Roetman, J. Lee and W. Herling

  Tools for 3DOpt Design Environment

- AeroSoft Inc., Blacksburg, VA

  A. G. Godfrey, W. M. Eppard and W. McGrory

  Sensitivity Calculation of Body-Rate Stability Derivatives

  Sensitivity Tools for COIL Laser Design

- BEAM Technologies, Ithaca, NY

  G. Berkooz

  Sensitivity Enhancements in the PDESolve$^{\mathrm{TM}}$ Environment

- Air Vehicles Directorate, (AFRL/VA), Wright-Patterson AFB, OH

  S. Banda

  Feedback Control of Fluid Flows

One major theme of the research program integrates scientific and computational tools developed at AeroSoft, BEAM Technologies and Boeing with new sensitivity techniques and optimization algorithms developed at Virginia Tech. This aspect of the project has produced a computational framework and related computer tools that engineers can use to efficiently model, design and optimize aerospace systems. AeroSoft has released a version of its aerodynamic sensitivity software package $\mathcal{SENSE}$ (A Sensitivity Ensemble for the Navier-Stokes Equations). We are currently working with the developers at AeroSoft and researchers at AFRL/DEC (Dr. T. Madden) to develop procedures for coupling the chemically reacting flow sensitivity code $\mathcal{SENSE}$ with an analysis/sensitivity code for the laser cavity to produce a coupled analysis/sensitivity code for COIL lasers. The laser-power device for the Airborne Laser Labortatory will be provided by a COIL device.

A second major theme of the program focuses on development of computational tools for sensor-actuator placement and for feedback control of distributed-parameter systems. This research is important for the development of actively controlled low-drag airfoils for advanced transport applications and is the key driver for the equipment being requested here. We are currently exploring the possibilities for joint research in this area with Dr. S. Banda of AFRL/VA, Wright-Patterson AFB, OH.

1.1 Educational Component

The Interdisciplinary Center for Applied Mathematics (**ICAM**) was formed in August 1987 to to promote and facilitate interdisciplinary research and education in applied mathematics at Virginia Polytechnic Institute and State University. The goal of **ICAM** is to enhance the historical links among mathematics, engineering and the sciences. Core participants in **ICAM** are committed to providing interdisciplinary research experience for both graduate and undergraduate students. The equipment purchased under this grant is available for use by qualified students in their research and in their formal studies.

Chapter 2

Status and Highlights

2.1 Equipment Purchased

The principal equipment purchased under the grant were an SGI Origin 2000 expansion unit with 16 R10000 processors (250MHz) and an SGI Origin200 Slave Server. Along with the University cost-sharing we were able to purchase

- SGI Origin 2000 upgrade unit with 16 R10000 processors (250 MHz) and 2 GB of memory
- Cray Cross-Link cables
- Additional disk-drives (45 GB)
- SGI Origin200 Slave Server with with two R12000 (300 MHz) processors, two replacement R12000 processors for exisitng SGI Origin 200, and related software

This equipment has been integrated into the **ICAM** computer network.

2.2 Current Computing Facilities

ICAM houses a heterogeneous Unix system with file-sharing under a Network File System (NFS). The Unix system currently consists of the following components:

1. Our (new) file server is four processor SGI Origin200, with 4GB internal memory. An external cabinet houses approximately 50GB of disk space through a SCSI connection.
2. Our graphics workstations include a Silicon Graphics Onyx2 with Infinite Reality graphics and four R10000 processors, and four single-processor (three R10000, one R12000) Octane workstations. In addition we have an SGI IRIS 4D/310 graphics workstations (R4000) and an SGI-Indigo2 workstation (R8000).
3. Our main computational platform is the (newly) enhanced SGI Origin 2000 with 32 R10000 processors and 20GB of memory (`origin.icam.vt.edu`). This machine, which operates in the range of 20 GF, supports interactive use and batch use under the Network Queuing System (NQS). The machine can be dedicated to a single-user for particularly challenging computations.
4. Additionally, we support a dual-processor DEC AlphaServer 2100 with 512MB of memory, and a DEC Alpha 3000/600 computer with 256MB of memory.

5. The system is connected via an Asynchronous Transfer Mode network (ATM - OC3, 155 Mb/s) and by switched-Ethernet.
6. In addition to the dedicated monitor/keyboard for each platform, the computers can be accessed via the switched-Ethernet. The *Center* currently has six Pentium III–based personal computers (two in faculty offices and four for public use) and four (4) Power-Mac machines (two in faculty offices).

Chapter 3

Accomplishments

Advances in computational arts - analysis, software and hardware - have greatly enhanced the process of analyzing proposed design concepts. Such advances have occurred in virtually all engineering disciplines but especially in those related to advanced aerospace systems. While such analysis tools are important, an even bigger payoff awaits the development of advanced tools for design synthesis. The equipment purchased under this grant has enhanced our abilities to do fundamental research on the development of interactive design tools. In the following we briefly describe some recent work on feedback control design procedures and algorithms for control of distributed-parameter systems.

3.1 Controller reduction for PDE systems

In recent years much research has been focused in the area of active feedback control for physical systems descrbed by PDEs. However, an important area in which much work remains is that of *low order* controller design for such problems. When distributed parameter control techniques are applied to partial differential equation (PDE) models (e.g., Navier-Stokes, Euler equations), the controller is also modeled by a PDE and approximations must take place. One technique is to apply a high-order numerical approximation scheme, resulting in a large order controller. An approach to obtaining low order controllers is to use a low-order approximation to the PDE model (or another low order model), and then to apply standard controller designs. Although this is frequently done in practice, it necessitates a robust controller to stabilize the system in the presence of large uncertainty, or unmodeled dynamics. Moreover, it was shown in our earlier work that reduced models which satisfactorily predict uncontrolled system dynamics can lead to highly erroneous results for control design.

An alternative approach is one which has been used extensively for control design in the context of PDE systems [1, 2, 3, 4, 7, 8]. This technique involves design of a controller for the PDE system which is reduced by projection onto or approximation by low-order bases. Various low-order basis formulations have been explored in the above references, including standard finite elements, bases which preserve specific stability radii, and bases formed by the proper orthogonal decomposition (POD). A benefit of this approach which has been found in all of these investigations is the design of closed-loop systems which have both good performance and robustness properties.

This framework requires large scale computations. In particular, the first step is computation of a high order numerical approximation of a compensator based control design. An integral representation of the feedback control operator can be written in which the kernels, called functional gains in this context, give insight into controller reduction and sensor placement. Once obtained, a low order basis is formed to represent them in an optimal way.

We have computed such controller designs for simple one-dimensional PDE problems, and for the 2-D heat equation. Computation of gains for the latter on a 20 x 20 grid took over 2 hours on a single processor Octane -(R10000, 250 MHz) and on a 30 x 30 grid took over 3 days. To apply our framework to more complicated problems, more computing capability was necessary. Here, we show results of computations for control of a thermal convection loop.

A thermal convection loop consists of a viscous fluid contained in a circular pipe standing in a vertical plane as shown in Figure 1. Experiments show that when the difference in temperature between the top and the bottom of the loop is large enough, the fluid exhibits unstable motion which may also be chaotic (see [6, 9, 10]).

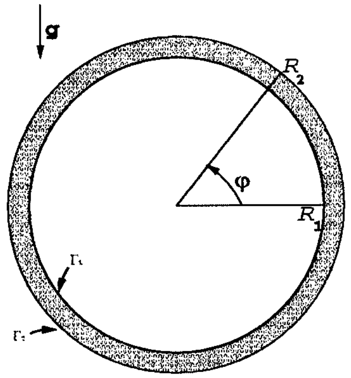

Figure 3.1: Depiction of the thermal convection loop.

We consider the problem of boundary control for this two-dimensional thermal fluid flow problem as in [5]. We assume that one can apply a temperature (boundary) control at the outer wall and measure the flux at the inner wall. The interior radius of the loop is denoted by R_1 and the exterior radius by R_2. The radial position of a fluid particle is denoted by $r \in [R_1, R_2]$ and the angular position, denoted by φ, is measured counterclockwise from the horizontal position. We restrict ourselves to the case of a thin pipe where the width of the pipe is small as compared with the interior radius, i.e., $R_2 - R_1 << R_1$. In this case, the fluid may be considered as flowing in a straight pipe of width $R_2 - R_1$ so that the velocity depends only on the radial coordinate. Moreover, we assume that the fluid flow has circular streamlines so that each fluid particle flows at a fixed distance from the center of the pipe.

Figure (3.2) shows the functional gain for velocity, and (3.3) shows samples of four functional gains for temperature. Notice, there is one funcitional gain for velocity and one temperature at each controller location φ. Thus, since the functional gain for velocity depends on r only, these plots can be shown on the same plot, that in Figure (3.2). In contrast, each functional gain for temperature depends on both r and φ, so they must be considered for each controller location individually.

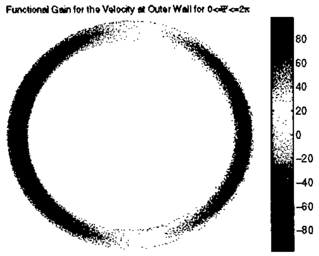

Figure 3.2: Functional gain for velocity.

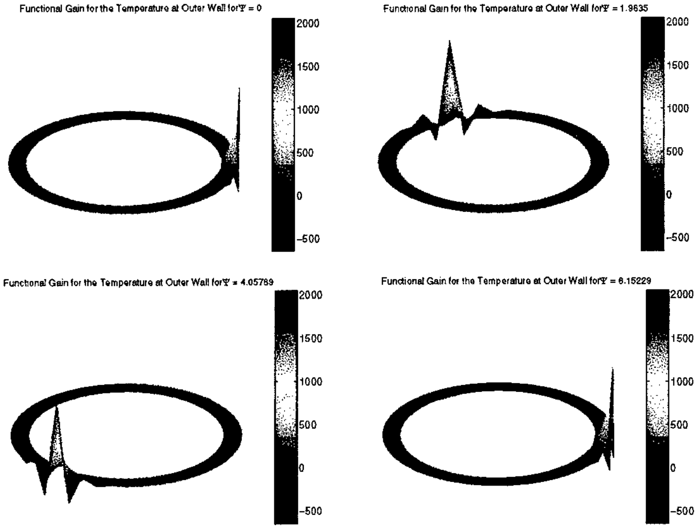

Figure 3.3: Four sample functional gains for temperature.

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