

# REPORT DOCUMENTATION PAGE

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6. AUTHOR(S) Hermann F. Fasel				
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13. ABSTRACT <p>High-performance graphics processing equipment consisting of a Silicon Graphics Origin 3400, 2 Silicon Graphics Octane SSEs, and other peripherals was purchased with funding from DURIP Grant No. DAAD19-00-1-0116. This equipment significantly enhanced our research projects funded by DOD. For these research projects, Direct Numerical Simulations and Large-Eddy Simulations were employed to investigate complex transitional and turbulent flows for a wide range of applications and flow speeds, both subsonic and supersonic. Examples are: supersonic axisymmetric base flows (ARO), actuators for active flow control (AFOSR), control of separation using wall jets (AFOSR), and longitudinal vortices in turbulent boundary layers subjected to wall curvature and strong adverse pressure gradients (ONR). A common objective of these research projects was the physical understanding of the time-dependent dynamical behavior of the dominant turbulent structures. This understanding is essential for successful implementation of active flow control for DOD-relevant applications.</p> <p>The numerical simulations generate vast amounts of data that have to be post-processed in order to extract the essential physical mechanisms that govern the dynamical behavior of the large coherent structures. Turbulent flows characteristically exhibit a complicated time-space behavior, which is due to the dynamics of large coherent structures with a strongly non-periodic time behavior. In order to analyze this complicated spatio-temporal behavior, the flow-field data from the numerical simulations have to be visualized by <i>rapid, interactive, time-dependent, graphics processing</i>. The acquired graphics processing equipment with its flexible, scalable architecture enabled us to perform such interactive visualizations. The requested equipment filled a critical need for fully utilizing the computing power provided by DOD computers and thus for effectively carrying out the proposed research of our DOD grants.</p>				
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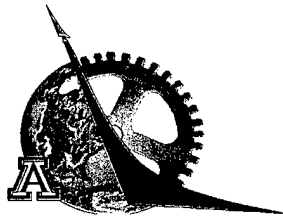
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**Final Report**  
**DURIP Grant No. DAAD19-00-1-0116**

**INTERACTIVE VISUALIZATION OF HIGHLY TIME-DEPENDENT DATA  
FROM NUMERICAL SIMULATIONS OF  
TRANSITIONAL AND TURBULENT SUPERSONIC FLOWS**

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**1. Equipment Purchased with Funding from DURIP Grant No. DAAD19-00-1-0116**

***Silicon Graphics Workstations*** **\$319,892**

Computer Server  
SGI Origin 3400 rack  
15 400MHz R12000 CPUs with 8MB secondary cache  
4GB memory  
18GB system disk  
6 36GB Fibre Channel disks  
7 72GB Fibre Channel disks  
RAID controller  
Irix 6.5 operating system  
Installation  
External FWD SCSI controller

2 Graphics Workstations  
Octane SSE  
2 250MHz R10000 CPUs with 1MB secondary cache  
256MB memory  
9GB system disk  
21-inch monitor  
1 Octane video option  
Irix 6.5 operating system

***Other Equipment***

1 Dell PC	\$2,100
1 Sony digital camcorder	\$1,935
2 Dell monitors	\$1,980
1 CD burner	\$210
Cables, connectors, etc.	\$860

***Total Cost*** **\$326,977**

***University of Arizona Share*** **\$109,977**

***DOD Share*** **\$217,000**

## 2. Summaries of Research Projects for Which Equipment was Used

The computer acquired from the DURIP grant considerably enhanced the quality and depth of all of our research projects that were funded by DOD by enabling considerably improved utilization of the high-performance computing resources available at DOD Supercomputer Centers. The research projects that were funded by DOD are summarized below.

### 2.1 Army Research Office

*Contract No.: DAAG55-97-1-0128 (Dr. Thomas Doligalski)*

*Title: Passive and Active Control of Supersonic Axisymmetric Base Flows: Numerical Investigations Using Direct Numerical Simulations and Large-Eddy Simulations*

*Principal Investigator: H. Fasel*

*Duration: May 1, 1997-September 30, 2001*

*Amount: \$281,857*

A comprehensive effort was undertaken to investigate transitional and turbulent axisymmetric wakes behind cylindrical bodies aligned with the flow at supersonic speeds. Particular emphasis was on identifying and understanding the dynamical behavior of the large-scale vortical structures that control the flow behavior in a supersonic wake. Direct Numerical Simulations (DNS) and Large-Eddy Simulations (LES) were the main investigative tools. The numerical simulations were supported and complemented by a theoretical effort based on stability theory analysis and Proper Orthogonal Decomposition (POD) techniques, which are applied to the numerically generated data.

It is well known that, for subsonic (incompressible) wakes, the dynamics of the large (coherent) structures play a dominant role in the local and global behavior of the flow. This evidence was found from both experimental investigations and numerical simulations (including ours) and was confirmed by theoretical studies. For supersonic speeds, on the other hand, very little is yet known about the dynamical behavior of turbulent flows. This is true for supersonic flows in general and for axisymmetric flows in particular. Thus, the question arises, "Do large structures play a similarly important role for supersonic separated flows and, in particular, for supersonic axisymmetric wakes?" The answer to this question is of fundamental relevance for applying flow control. There are few experimental investigations that have focused on this issue. However, when looking at flow visualization pictures of supersonic wake flows, distinct patterns with large-scale structures can be observed. For supersonic axisymmetric wakes, the mean flow structure of the near-wake region is characterized by the axisymmetric shear layer originating at the sharp corners of the blunt base.

Supersonic axisymmetric wakes are extremely difficult to investigate experimentally. Wind tunnel interference and interference from model support strongly affect the mean flow behavior. Therefore, numerical simulations represent a new alternative for investigating the complicated unsteady flow phenomena in the supersonic wake. Direct numerical simulations using the complete Navier-Stokes equations are restricted to somewhat low-to-moderate Reynolds numbers because of the rapidly increasing demands on computing power as the Reynolds number increases. In the course of this research, we were working on ways to drastically increase the algorithmic efficiency of our Navier-Stokes codes. Toward this end, we were also incorporating the use of massively parallel computers. With our own smaller-scale parallel computing capacity, we have found that our basic codes require relatively little overhead costs when run on parallel machines. Because of the Reynolds number limitations on direct simulations, we were also performing Large-Eddy Simulations (LES) using subgrid-scale turbulent models. However, even with current LES models, reproducing the large Reynolds numbers seen in experiments requires a massive computational effort. For this reason, a new LES methodology was

implemented. It will allow the simulations to be pushed to considerably larger Reynolds numbers than traditional LES, and thus closer to the flow conditions seen in experiments, while at the same time capturing the large (coherent) structures that in all likelihood have a central importance to the flow and are not captured with a Reynolds-averaged simulation.

## 2.2 Air Force Office of Scientific Research

*Contract No.: F49620-96-1-0015 (Dr. Steven Walker)*

*Title: The Effectiveness of Actuators Used in Active Flow Control: Numerical Simulations, Analysis, and Experiments*

*Principal Investigators: H. Fasel, M. Gaster, I. Wygnanski*

*Duration: October 1, 1998-September 30, 2001*

*Amount: \$391,286*

Various schemes that employ actuators to modify fluid flows in some way are currently being developed to enable overall performance measures to be controlled and thus improved. In particular, significant research is being carried out using periodic injection of momentum (suction and blowing) to control separation. Actuators can take various forms, but their design is generally constrained by the manufacturing process. It would seem that the details of actuator construction and the way that the actuators control the flow field have so far largely been ignored. We are performing a detailed investigation of the mechanics of disturbance excitation by various surface-mounted actuators in order to understand the excitation process. Only after the process is understood will it be possible to design devices effectively for specific applications in real three-dimensional flows. In this research project, we will utilize a number of already-available tools that have been developed by us and are at our disposal to study how small surface devices generate disturbances in boundary layers. The plan is to attack the problem by a blend of the three basic tools: numerical simulation, analysis, and experiment. For synergism, it is essential to carry out these tasks simultaneously. Our analytical/calculation methods based on the linearized equations of motion have already produced some insight into the mechanics of flow excitation. Results obtained for very simple actuators have been verified by experiment. The scheme is relatively fast and therefore inexpensive; typical calculations can be performed on a small desktop machine in a few hours. However, further code development is required to enable the method to take into account some degree of nonlinearity and to cater to the boundary layer growth. Direct Numerical Simulations (DNS) based on the complete Navier-Stokes equations will be used to obtain definitive data sets for certain key situations. This will allow validation of the analytical calculation methods. DNS codes already exist for this work and have been used to provide flow field calculations for a single slot and circular suction holes. Experimental measurements of the flow fields created by different devices will also be made for a range of geometries in order to verify the predictions of the numerical simulations. We believe that the three-pronged attack—using theory, simulations, and experiments—will provide the necessary insight required to design efficient actuator systems for active flow control.

*Contract No.: F49620-97-1-0208 (Dr. Tom Beutner)*

*Title: Control of Separation Using Pulsed Wall Jets: Numerical Investigations Using DNS and LES*

*Principal Investigator: H. Fasel*

*Duration: May 1, 1997-December 10, 1999*

*Amount: \$14,279*

Wall jets or wall jet-like flows are of great technical relevance for aerospace applications. Wall jets can be used as efficient means of controlling external and internal boundary layers. For external applications, they are used, for example, for boundary layer control on airfoils. Experiments by Wygnanski et al. (private communication) have demonstrated the effectiveness of pulsed wall jets to control separation for

flows over single-element or segmented airfoils. For gaining insight into the fundamental mechanisms responsible for the often striking effect of periodic forcing on wall jets, forced transitional and turbulent wall jets were investigated in this research project using Direct Numerical Simulations (DNS) and Large-Eddy Simulation (LES). While use of DNS and LES for flows over actual slotted flaps were the final goal of our research effort, several intermediate steps were taken to explore different aspects of this complex flow geometry. Clearly, for wall jets over actual segmented airfoils, the combined effects of the adverse pressure gradient and curvature plays a major role. To isolate the relevant mechanisms, this complex flow geometry was first broken down into simpler modules so that the effect of pressure gradient and curvature could be investigated separately. Both DNS and LES were performed using a three-dimensional Navier-Stokes code based on an incompressible vorticity-velocity formulation. For the time integration, a fourth-order Runge-Kutta method was employed. For the spatial discretization in the streamwise and the wall-normal directions, fourth-order accurate compact differences were used while the spanwise direction was treated pseudo-spectrally. For LES of turbulent wall jets, a Smagorinsky-type subgrid-scale turbulence has been incorporated into the code. More sophisticated subgrid-scale models were implemented, also. The effect of the forcing was investigated by analyzing the time-dependent flow data using statistical methods, Fourier decomposition in time, and flow visualization including tracking of the large coherent structures that were generated due to the forcing.

### **2.3 Office of Naval Research**

*Contract No.: N00014-99-1-0885 (Dr. Patrick L. Purtell)*

*Title: Longitudinal Vortices in Turbulent Boundary Layers Subjected to Wall Curvature and Strong Adverse Pressure Gradients: Numerical Investigations Using LES and DNS*

*Principal Investigator: H. Fasel*

*Duration: June 14, 1999-June 13, 2001*

*Amount: \$269,892*

The main goal of this research project was to numerically investigate longitudinal vortices in turbulent boundary layers that are subjected to strong wall curvature (both convex and concave) and strong adverse pressure gradients. Special emphasis was on uncovering the fundamental mechanisms responsible for the generation of longitudinal vortices and their dynamical interaction with the other dominant coherent structures that arise from the presence of a wall and strong adverse pressure gradients. This understanding is essential for future implementation of separation control techniques for practical flows when longitudinal vortices are inherently present, or when forced longitudinal vortices are employed for separation control (i.e., on demand vortex generators). Furthermore, the investigations shed light on the turbulence generation mechanism for boundary layers with curvature and pressure gradient when longitudinal vortices are present.

The investigations were carried out using DNS, LES, and unsteady RANS. Toward this end, a new methodology that we developed with funding from a previous ONR grant for simulating turbulent flow was employed. The new methodology is based on employing a new subgrid-scale (SGS) turbulent model for time-dependent turbulent simulations, where the resolved scales are computed by solving the Navier-Stokes equations and the unresolved scales are modeled by the new turbulence model. The simulations approach an unsteady Reynolds-Averaged Navier-Stokes (RANS) calculation when the grid resolution is decreased (and/or Reynolds number is increased) and consistently approach a Direct Numerical Simulation (DNS) when the grid resolution is increased (and/or Reynolds number is decreased). In between these limits, we have a non-traditional Large-Eddy Simulation (LES) (with various degrees of modeling of the unresolved scales). The new methodology is non-traditional in the sense that the SGS model is far superior to models used in traditional LES, including the so-called dynamic model, which have significant shortcomings as they are based on the Smagorinsky model and are thus not really

applicable to complex geometries. Preliminary results using the new methodology agreed very well with comparison calculations.

In parallel with developing and testing the new methodology, we also carried out Direct Numerical Simulations (DNS) for the Stratford ramp flow. In addition to standard full-blown DNS (no assumptions, no modeling), we developed a simplified DNS model and performed extensive simulations with this model. At a low Reynolds number, due to the "natural" generation of instability waves, the flow could sustain a strong adverse pressure gradient for which the steady laminar flow would separate. At higher Reynolds number, the flow would separate; however, the separation could be suppressed by periodic forcing.



### **3. Summary of How Proposed Instrument Enhanced DOD-Funded Research**

High-performance graphics equipment consisting of a Silicon Graphics Origin 3400, two Silicon Graphics Octane SSE workstations, and other peripheral equipment were purchased with funding from DURIP Grant No. DAAD19-00-1-0116. With this equipment, we have available a state-of-the-art graphics post-processing environment that is commensurate with the computing power of the supercomputers at the DOD High-Performance Computer Centers where our numerical simulations are performed.

The new equipment significantly enhanced all of our research projects funded by DOD (ARO, AFOSR, and ONR). The common tools used in these projects were Direct Numerical Simulations (DNS) and Large-Eddy Simulations (LES), which were employed to investigate complex transitional and turbulent flows for a wide range of applications and flow speeds, both subsonic and supersonic. Examples as stated in section 2 are wakes behind axisymmetric projectiles at high subsonic and supersonic speeds (ARO, DAAG55-97-1-0128), active flow control (AFOSR, F49620-96-1-0015), wall jets (as relevant for separation control) with and without an external stream (AFOSR, F49620-97-1-0208), and longitudinal vortices in high Reynolds number turbulent boundary layer subjected to wall curvature and strong adverse pressure gradients (ONR, N00014-99-1-0885). The common objective of these research projects was a physical understanding of the time-dependent, dynamical behavior of the large (coherent) structures that contain most of the turbulent kinetic energy. This understanding is essential for eventual implementation of active flow control for DOD-relevant applications.

Because of the massive requirements in computing power, the numerical simulations—including the ones required for the active flow control investigations—can only be performed on high-performance computers, such as those of the DOD High-Performance Computing Centers. Therefore, we were remotely accessing the high-performance computers at various DOD centers. In order to be able to efficiently use the DOD high-performance computing resources, graphics post-processing tasks have to be performed locally. Prior to the equipment obtained from this DURIP grant, our graphics post-processing capability was totally inadequate for efficient use of the remote DOD computers due to the considerable increase in computing power of the DOD high-performance computers in recent years.