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With the funding from DURIP grant F 46920-97-1-0812 we purchased a Silicon Graphics Origin 2000 with 12 processors, 2GB memory, and 18GB disk space, as well as flow visualization software and several peripherals, accessories and PC's for pre-and post-processing support. The equipment has been utilized effectively to perform pre- and post-processing tasks for our DOD funded research projects. The multi-processor capability has allowed us to develop and test our Navier-Stokes codes locally and improve their performance before performing production runs at the DOD High-Performance Computing Centers. The high performance multi-processing capability has enabled effective post-processing of the massive time-dependent data sets that are delivered by the simulations on the DOD supercomputers.

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DURIP Grant No. F 49620-97-1-0182

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HIGH PERFORMANCE PRE- AND POST-PROCESSING EQUIPMENT FOR DIRECT NUMERICAL SIMULATIONS (DNS) AND LARGE-EDDY-SIMULATIONS OF TRANSITIONAL AND TURBULENT FLOWS

Final Report

by

Hermann F. Fasel

Abstract

With the funding from DURIP grant F 46920-97-1-0812 we purchased a Silicon Graphics Origin 2000 with 12 processors, 2GB memory, and 18GB disk space, as well as flow visualization software and several peripherals, accessories and PC's for pre-and post-processing support. The equipment has been utilized effectively to perform pre- and post-processing tasks for our DOD funded research projects. The multi-processor capability has allowed us to develop and test our Navier-Stokes codes locally and improve their performance before performing production runs at the DOD High-Performance Computing Centers. The high performance multi-processing capability has enabled effective post-processing of the massive time-dependent data sets that are delivered by the simulations on the DOD supercomputers.

Equipment purchased with funding from DURIP grant F 49620-97-1-0812:

Silicon Graphics Workstations **$273,776.26**

Compute Server
[Origin 2000 by Silicon Graphics Inc.]
Including:
- Origin 2000 Rack
- 2 Insert Modules w/ 3 Node Boards each
- 12 R10000/195MHz CPUs w/ 4MB secondary cache
- 2 GB Memory
- 4.5 GB System Disk
- 2 9GB Ultra SCSI Disks
- Irix 6.4 Operating System
- Installation

Peripherals, Accessories, and Software **$31,425.88**

Color Laserjet Printer
[HP Color Laserjet 5 by Hewlett Packard, Sehi Computer Products, Inc.]
Including: HP Color LaserJet 5 Printer
Postscript SIMM
32 MB Memory
Rear Feed Unit

DLT Tape Drive
[External DLT 7000 Tape Drive by Nordisk Systems, Inc.]

Accessories
[Nordisk, CIC Systems, Electronic City]
Including: Data Cartridges
Printer Supplies
Static Mat and Wrist Strap

Software
[Silicon Graphics, Wolfram Research, Advanced Visual Systems]
Including: Silicon Graphics Varsity Software Licenses
Mathematica
AVS Educational Developers License

Personal Computers **$6,858.64**

Desktop PC
[Dell Dimension XPS by Dell Computer]
Including: Dell Dimension XPS Desktop Computer
Intel Pentium II 400MHz CPU
64MB RAM
8GB System Disk
32x CD ROM Drive
IOMEGA ZIP Drive
33.6/56K Winmodem

Desktop PC
[GP5-166 Desktop by Gateway 2000]
Including: GP5-166 Desktop Computer
Intel Pentium 166 MHz CPU
64 MB RAM
4 GB System Disk
CD-ROM Drive
10/100 Ethernet Card
17" Monitor

Notebook PC

[Solo 2300 SE by Gateway 2000]

Including: Solo 2300 SE Notebook Computer
Intel Pentium 133 MHz CPU
32 MB RAM
2 GB System Disk
Modular CD-ROM Drive
33.6 PCMCIA Fax/Modem
Ethernet Card

TOTAL COST	**$312,060.78**
University of Arizona Cost Sharing	**$67,784.00**
DOD COST	**$244,276.78**

Summaries of Research Projects for which Equipment Was Used

DOD Agency: Air Force Office of Scientific Research
Contract Number: F49620-97-1-0208 (Dr. Mark Glauser)
Title: Control of Separation Using Pulsed Wall Jets: Numerical Investigations Using DNS and LES
Principal Investigator: H. Fasel
Duration: May 1, 1997-December 31, 1999
Amount: $214,279

Wall jets, or wall jet-like, flows are of great technical relevance for numerous 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. (1996) 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 are being investigated in the present research project using Direct Numerical Simulation (DNS) and Large-Eddy Simulation (LES). While use of DNS and LES for flows over actual slotted flaps are the final goal of our research effort, several intermediate steps are taken to explore different aspects of this complex flow geometry. Clearly, for wall jets over actual segmented airfoils, the combined effects of adverse pressure gradient and curvature plays a major role. To isolate the relevant mechanisms, this complex flow geometry is first broken down into simpler modules so that the effect of pressure gradient and curvature can be investigated separately. Both DNS and LES are 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 is employed. For the spatial discretization in the streamwise and the wall-normal directions, fourth-order accurate compact differences are used, while the spanwise direction is treated pseudo-spectrally. For LES of turbulent wall jets, a Smagorinsky-type subgrid-scale turbulence model has been incorporated into the code. More sophisticated subgrid-scale models are currently being implemented. In our LES of transitional and turbulent wall jets, the turbulent flow is periodically forced using a blowing and suction slot in the wall. The effect of the forcing is 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 are generated due to the forcing. While the actual simulations are being performed remotely on DOD supercomputers, analysis and visualization of the massive amount of unsteady flow data can now be performed locally with the help of the acquired equipment.

DOD Agency: Army Research Office
Contract Number: 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-April 30, 2000
Amount: $217,612

A comprehensive effort is being undertaken to investigate transitional and turbulent axisymmetric wakes behind cylindrical bodies aligned with the flow at supersonic speeds. Particular emphasis is 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) are the main investigative tools. The numerical simulations are 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.

For axisymmetric aerodynamic bodies in supersonic flight, the flow field in the wake region has considerable effect on the aerodynamic drag. Even small changes in the flow behavior of the wake may affect the performance of the entire flight vehicle, e.g., missiles, rockets, or projectiles. The effect on the aerodynamic drag is mainly due to the recirculation region that develops in the base region of the body and thus to the low pressure associated with the recirculating flow (base drag). Flight tests with projectiles (U.S. Army 549 projectile) have shown that the base drag may account for up to 35% of the total drag. This suggests that attempts to modify the near-wake flow such that the base pressure would increase could be highly rewarding with respect to drag reduction and, as a consequence, with regard to increasing the performance characteristics of flight vehicles or projectiles.

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 wakes 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, which may be an indication that this behavior might be caused by the presence of large coherent structures. Because of the experimental difficulties, 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. Therefore in the course of this research, we are working on ways to drastically increase the algorithmic efficiency of our Navier-Stokes codes. Toward this end, we are 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 are also performing Large-Eddy Simulations (LES) using subgrid-scale turbulence models. Since our Navier-Stokes equations are highly suited for implementation of subgrid-scale turbulence models, we are able to use essentially identical codes for both the direct and large-eddy simulations. This allows proper fine-tuning of the LES codes (in particular, of the subgrid-scale models) so that they can be applied with greater confidence to the higher Reynolds number calculations. 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 is currently being 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.

DOD Agency: Army Research Office
Contract Number: DAAH04-96-1-0112 (Dr. Thomas Doligalski)
Title: Numerical Investigations of the Control of Separation by Periodic Oscillations: Effects of Compressibility
Principal Investigator: H. Fasel
Duration: May 1, 1996-April 30, 1999
Amount: $130,000

Boundary layer separation is a critical limiting design factor for a wide range of flow devices. For example, separation drastically reduces lift and increases drag of airfoils. It reduces the efficiency of nozzles and turbomachinery. And, in heat transfer, separation can lead to a local hot spot. Any means of delaying the onset of separation would increase the design envelope for a wide variety of engineering applications.

Recent work by Wygnanski et al. (a survey of which can be found in Wygnanski 1997) has shown that introducing disturbances by periodic blowing and suction can delay or even eliminate separation. This active control method is much more efficient than steady blowing, since it creates a net momentum flux with no net mass flux. Also, since it exploits the natural amplification of the control disturbances by the flow, it requires a much smaller net momentum transfer to achieve the same effect. For this reason, it is applicable to a wide variety of cases where steady blowing would be either ineffective or require too high a mass transfer rate.

This research attempts to extend these results to high-subsonic transonic, and supersonic Mach numbers. For this research, we are employing Large-Eddy Simulations (LES) using subgrid-scale turbulence models that are validated by Direct Numerical Simulations (DNS). For non-equilibrium turbulent flows like the present one, traditional eddy-viscosity type turbulence models (such as Smagorinsky-based models) are insufficient. Therefore, in collaboration with C. Speziale (Boston University), we are developing more advanced two-equation non-equilibrium models. These models will initially be used for separation control studies in flat-plate adverse pressure gradient boundary layers, and later in curved wall geometries. The data from the numerical simulations will be analyzed, focusing on understanding the dynamical behavior of the large turbulent structures when active flow control by periodic forcing is employed. The goal is to isolate the essential physical mechanisms that are responsible for the delay of separation.

DOD Agency: Office of Naval Research
Contract Number: N00014-94-1-0095 (Dr. Patrick Purtell)
Title: Effects of Adverse Pressure Gradient and Wall Curvature on the Turbulence Mechanisms in Boundary Layer Flows: Reynolds-Averaged Navier-Stokes Calculations, Large-Eddy Simulations, and Direct Numerical Simulations for the Stratford Ramp / A New Methodology for Numerical Simulations of Complex Turbulent Flows: From DNS to RANS, a Combined Approach
Principal Investigator: H. Fasel
Duration: October 1, 1993-September 30, 1998
Amount: $668,553

The main goal of this research project is to identify and understand the combined effects of strong adverse pressure gradient and strong streamwise curvature on the turbulence mechanisms of turbulent boundary layers at high Reynolds numbers. For these investigations, the so-called Stratford ramp was chosen as a generic flow geometry. For this geometry, both adverse pressure gradient and streamwise curvature act on the turbulent boundary layer in a unique way: the boundary layer is continuously on the verge of separation. This flow geometry is highly suited for our attempts to identify and understand the relevant turbulence mechanisms and, as a consequence, for developing a new methodology for non-equilibrium turbulent boundary layers.

The new methodology is based on employing a new subgrid-scale (SGS) turbulence 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 will 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 an non-traditional Large-Eddy Simulation (LES) (with various degrees of modeled unresolved scales). The new methodology is non-traditional because 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. The results using the new methodology agree very well with comparison calculations. In parallel with developing and testing the new methodology, we carried out Direct Numerical Simulations (DNS) for the Stratford ramp. In addition to standard full blown DNS (no assumptions, no modeling), we developed a simplified DNS model and performed extensive simulations with this model. From this simplified DNS we found that at a low Reynolds number, due to the "natural" generation of instability waves, the flow can sustain a strong adverse pressure gradient for which the steady laminar flow would separate. However, at higher Reynolds number the flow will separate; but, the separation can be suppressed by periodic forcing. The computational effort is being conducted in direct and close collaboration with an experimental effort by I. Wygnanski (The University of Arizona) and a theoretical turbulence modeling effort by C. Speziale (Boston University). In addition, this group effort is linked to the computational effort by T. Huang (David Taylor Model Basin), who will test the improved Reynolds stress models that result from our investigations for Navy relevant geometries.

Summary of How the Acquired Instrumentation Has Enhanced the DOD-Funded Research

The instrumentation has significantly supported our DOD-funded research and, as a consequence, has enabled major progress in DOD-relevant Computational Fluid Dynamics research that would otherwise not have been possible. In particular, with the acquired high-speed compute server (Origin 2000), we were able to close an existing gap that had prevented us from fully utilizing the massive computing power available to us at the DOD High-Performance Computing Centers. As summarized above, we have been and are currently engaged in several DOD-sponsored research projects requiring highly challenging numerical simulations of complex flows that have never been attempted before. We have been numerically simulating transitional and turbulent flow phenomena in a variety of flow geometries, such as wall jets (funded by AFOSR), supersonic wakes (supported by ARO), and boundary layers along flat and curved walls (supported by ONR). In all cases, the flows considered are strongly time dependent and the phenomena to be investigated are highly nonlinear. Flow speeds are from low (incompressible) to high (supersonic).

In all the projects, Direct Numerical Simulations (DNS) and Large-Eddy-Simulations (LES) are carried out with the goal of pushing the relevant Reynolds number to as high a value as currently feasible with available supercomputers. The DNS are based on solving the complete Navier-Stokes equations with no further assumptions other than those made for deriving these equations. The LES require subgrid-scale models. For LES, the grid spacing is such that only the larger scales are resolved directly by the computational grid. Scales smaller than the grid have to be modeled.

In all the projects, the underlying computational model was "spatial". Thus, the structures evolving in the transitional and turbulent flows could develop (grow or decay) not only in time, but also in the spatial (downstream) direction, as is the case in realistic laboratory experiments or in free flight. This spatial model is in contrast to the so-called "temporal" model, for which spatial (downstream) periodicity is assumed and which therefore introduces assumptions that are not realistic for many situations. The temporal model allows for short computational domains and thus considerably reduces the computational demands and, in particular, the size of the data files produced by the numerical simulations. The realistic spatial simulation model, on the other hand, leads to considerably higher computational complexity because of the typically much larger (in the downstream direction) computational domains required and because of the difficulties associated with providing and implementing proper inflow and outflow boundary conditions.

As a consequence of employing the spatial model, considerably more time and effort were necessary for code development. The numerical methods had to be very accurate and efficient for simulations with such large grid sizes to be at all feasible on supercomputers. These efficiency and accuracy requirements, together with the difficulties associated with inflow and outflow conditions, required extensive testing in the development phase of the computer codes. For this reason, adequate pre-processing capabilities have been essential for effective utilization of available supercomputing resources. The high-performance multiprocessor system acquired (Origin 2000) has met our current pre-processing needs. The pre-processing capability of this compute server has enabled us to do all of our pre-processing locally. This has helped to relieve the network and to unclog the supercomputers. After all, supercomputers are best utilized for number crunching, and using it for code development purposes, which can be done more efficiently on considerably less expensive machines, is in fact a waste of supercomputing resources.

In addition, post-processing of the massive amount of data that results from our simulations had been very cumbersome (if possible at all) when carried out remotely at the supercomputing centers. Even attempting it had been wasteful of supercomputing resources. Our post-processing needs have been met more efficiently and cost effectively by the powerful high-performance Origin 2000 in combination with the newly acquired AVS flow-visualization software (purchased with the current DURIP grant) which runs on our graphics workstation (SGI Power Onyx purchased with a previous DURIP grant). The flows that we have been studying are dominated by the generation and evolution of coherent turbulent structures. These three-dimensional, non-periodic structures cover a wide range of spatial and temporal scales. Due to their non-periodic nature, their dynamics cannot be analyzed by means of Fourier transforms. Therefore, detailed investigations of the space-time evolution of the physical flow field have been essential to gaining an understanding of the dynamics and the underlying physics of the turbulent structures. This has important implications for the post-processing of the data generated in our numerical simulations.

Since it is the rapid change of the flow field with time that is important, the most revealing information concerning the dynamical behavior of the flow structures has been obtained by scrutinizing animations of the unsteady data, rather than snapshots of the flow depicting its state at one instant in time. Consequently, our post-processing demands in terms of disk space, CPU time, and computer memory are much greater than for "mainstream" CFD applications, where only a steady-state mean flow is computed and visualized. Typical data sets require approximately 50MB of disk space (and 50MB of memory) per time step, where a meaningful animation of a non-periodic flow requires several hundred time steps. With the powerful Origin 2000, in combination with our SGI Power Onyx, we are now able to generate these animations very quickly.

The typical procedure is to transfer the large data sets (usually several GB) overnight from the DOD supercomputers to our large local disks. Also, for later scrutinization, the data is frequently archived on our newly acquired DLT 7000 tape drive which holds about 30 GB of data. Depending on the animation, portions of the large data sets are then further processed on the Origin 2000, e.g., Fourier transformed to physical space, analyzed using Proper Orthogonal Decomposition (which is extremely memory and CPU-time intensive and is only feasible on the Origin 2000). From these pre-processed data, time-dependent animations are then generated using, for example, the AVS visualization software on our SGI Power Onyx (which can now be dedicated almost exclusively to graphics processing). For generating the time-dependent animation with AVS, at every time step, the data first is read from disk into memory. Then, the data is processed to extract useful information, e.g., to compute level surfaces of flow variables, particle traces, kinetic energy levels, entropy distributions, etc. Finally, the processed data is sent to the graphics processor for display on the screen. This whole process is then repeated for the next time step. Due to the fast disk access and the sophisticated hardware/software, this process takes place interactively, e.g. the angle of view or the displayed surface level can be changed on the fly while the animation is running. Thus, our current post-processing setup allows us to cut the time required to generate a time-dependent animation (including processing on the Origin 2000) from a day to less than an hour and, in some cases, even to several minutes. This tremendous speedup has resulted in a qualitative change in our post-processing: The shorter turn-around time has enabled us to do truly interactive graphics processing of significant data sets.

A great advantage of the acquired Origin 2000 system is that additional processors and memory can be added as our pre- and post-processing demands increase proportionally with the increased computing powers of new supercomputers at the DOD High-Performance Computing Centers. This enables us to solve ever larger CFD problems, pushing advancements in turbulence modeling and turbulence research.