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Langley Research Center
Hampton, Virginia 23665-5225

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INTRODUCTION

The Institute for Computer Applications in Science and Engineering (ICASE) is operated at the Langley Research Center (LaRC) of NASA by the Universities Space Research Association (USRA) under a contract with the Center. USRA is a nonprofit consortium of major U. S. colleges and universities.

The Institute conducts unclassified basic research in applied mathematics, numerical analysis, fluid mechanics, and computer science in order to extend and improve problem-solving capabilities in science and engineering, particularly in the areas of aeronautics and space research.

ICASE has a small permanent staff. Research is conducted primarily by visiting scientists from universities and industry who have resident appointments for limited periods of time as well as by visiting and resident consultants. Members of NASA's research staff may also be residents at ICASE for limited periods.

The major categories of the current ICASE research program are:

- Applied and numerical mathematics, including numerical analysis and algorithm development;

- Theoretical and computational research in fluid mechanics in selected areas of interest to LaRC, including fluid dynamics, acoustics and combustion;

- Experimental research in transition and turbulence and aerodynamics involving LaRC facilities and scientists;

- Computer science.

ICASE reports are considered to be primarily preprints of manuscripts that have been submitted to appropriate research journals or that are to appear in conference proceedings. A list of these reports for the period April 1, 1992 through September 30, 1992 is given in the Reports and Abstracts section which follows a brief description of the research in progress.

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RESEARCH IN PROGRESS

APPLIED AND NUMERICAL MATHEMATICS

Saul Abarbanel

The results obtained so far in studying stable boundary conditions for higher order schemes (compact or otherwise) have now been summarized in ICASE Report No. 92-71 (coauthored with Mark Carpenter (Fluid Mechanics Division – Theoretical Flow Physics Branch, NASA LaRC)and David Gottlieb) and have also been accepted for publication in the Journal of Computational Physics. The next step is to apply the new theoretical treatment to compact sixth order accurate schemes. A graduate student (I. Chertock) will explore the possibilities of extending the analysis to multi-dimensional hyperbolic systems.

The work done in collaboration with doctoral student Jeff Danowitz on non-reflecting boundary conditions for compressible viscous flow past two-dimensional finite bodies is now being extended to the regime of higher Reynolds numbers (Re $> 100,000$).

Remi Abgrall

During the past few years, Harten and his coauthors have started to derive a new class of numerical schemes, the Essentially Non-Oscillatory Schemes (ENO), in order to cure one of the main weakness of Total Variation Diminishing (TVD) schemes, namely their lack of precision, especially near extrema. The idea is to work with a reconstruction technique that may be as precise as wished, at least formally, and to use in a Monotone Upwind Scheme for Conservation Laws (MUSCL) type way.

Some attempts have been made to extend these ideas to multidimensional flows on regular structured meshes, but very few attempts have been made on unstructured meshes.

The aim of our work is to adapt the ENO ideas to truly unstructured meshes. To do that, we have started by deriving (last year) an essentially nonoscillatory reconstruction method. We first analyzed its properties (regularity of the approximation, efficient and stable procedure to compute it). We also proposed a technique to find the minimal set of stencil necessary to reconstruct a piece-wise smooth function, and show examples for third and fourth order approximation. This method is then adapted to the Euler equation for the third order reconstruction. We present some preliminary results on classical problems (2-D shock tubes, backward facing step, vortex flow), that clearly indicate improvements of the solution.

Shapour Azarm

In collaboration with J. Sobieski, Head of Interdisciplinary Research Office, we began in mid August our research work on "optimization-based-design of multiobjective nonhierarchic engineering systems". Optimization-based design of today's engineering systems has become increasingly complex and costly due to their (i) multidisciplinary nature, (ii) different noncommensurable design objectives, (iii) cross-disciplinary couplings (often nonhierarchic) in between the subsystems, and (iv) large number of variables and constraints in the optimization formulation. Our focus here will be on a solution approach of systems in which the analysis and optimization are performed separately. We plan to use the *global sensitivity analysis* and some size-reduction measures to obtain the optimum solution of such nonhierarchically decomposed systems.

Kurt Bryan

Work has continued with W. P. Winfree of the Nondestructive Sciences Evaluation Branch, LaRC, on the problem of recovery estimates of defects (voids) in materials using thermal imaging methods. The voids are modeled as regions which block heat flow. The forward thermal conduction problem was formulated using the method of boundary integral equations and a method for solving the inverse problem was proposed and programmed. Actual thermal data has now been taken and we were able to successfully detect and locate voids using this approach. These experimental and computational results were presented at the Review of Progress in Quantitative Nondestructive Evaluation Conference in San Diego in July. Much of the data remains to be analyzed, particularly with regard to the resolution of the technique in detecting voids of various sizes and depths.

We have also begun work on using thermal methods for obtaining information about interfacial corrosion and oxidation in composite materials. We are interested in composites made of silicon nitride and reinforced with silicon carbide fibers. In these materials, corrosion can occur in a thin carbon interface between the fibers and surrounding material. Previous research suggests that this corrosion can be detected with thermal methods. We are currently formulating the problem and modeling the degree of interface corrosion as a thermal "contact" resistance. The goal is to recover an estimate of this resistance using nondestructive thermal methods. Also, since even a modestly sized sample may contain many of these microscopic fibers, and since we are interested primarily in the macroscopic behavior of the sample (an average level of corrosion) we are investigating homogenization techniques for simplifying the mathematical model of the sample.

Work has also continued with Michael Vogelius of Rutgers University on the problem of detecting cracks in electrical conductors. Previous research lead to the development of

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an algorithm for locating multiple cracks in a conductor by means of voltage and current flux measurements on the boundary of the conductor. The algorithm adaptively changes the applied current flux patterns to obtain maximal sensitivity for the measurements. Numerical experiments were quite successful. Valdis Liepa of the Radiation Laboratory at the University of Michigan, Ann Arbor has constructed an actual device for taking such measurements and he, in collaboration with Michael Vogelius and Fadil Santosa of the University of Delaware, has demonstrated that such a technique works in practice for the location of a single crack. We now hope to use the apparatus to collect experimental data to test the algorithm on multiple and/or curved crack inverse problems. We have also begun to investigate whether the techniques used in the crack location algorithm may be applicable to eddy-current imaging, a common method for locating near-surface cracks in conductors. The first step will be a careful mathematical formulation of the problem.

Wai Sun Don

Building upon the previous successes in applying spectral methods to shock wave simulation, research is initiated in studying both the two and three dimensional supersonic air-hydrogen jet interaction using Chebyshev collocation methods. This study involves nine chemical species and eighteen chemical reactions, coupled with the conservation of mass, momentum and energy and forms a set of partial differential equations governing both the fluid dynamics and chemical reaction process. The ultimate goal of this research is to study the physics of the chemical combustion process in an air-breath supersonic scram jet engine. Working with Dr. Philip Drummond at LaRC, we are studying the chemical mixing process which is very important for efficient combustion under the supersonic environments. Preliminary numerical results of the two dimensional shock-hydrogen jet interaction with four species and single reaction $H_2 + 2O_2 <=> 2H_2O$ are very encouraging.

Collaborating with Dr. Jones, Dr. Rudy at Langley and Prof. Gottlieb and Prof. Abarbanel, along with graduate student Eric Voth, we looked into the effect that a heated cylinder had on the Karman vortex street. We find numerically that as the cylinder temperature rose, the shedding frequency (Strouhal number) was reduced. A report related to this finding is currently in preparation.

Daniele Funaro

My field of research is the approximation of boundary value problems by spectral methods. In particular, I develope the convergence analysis for discretizations using orthogonal polynomials of differential equations, with a concern to those equations related to fluid

dynamics models. Recently, I am working on the approximation of advection-diffusion equations by collocation on a special grid, depending on the differential operator, which gives better numerical results and suggests a fast way to solve the corresponding linear system. During my stay at ICASE, I have been involved in discussions with other researchers of the group working on spectral method, and I had the chance to get new ideas to refine the method and extend it to other problems.

David Gottlieb

Work is currently advancing on two fronts. The first is time stability for high order compact difference schemes and is joint work with M. Carpenter (Fluid Mechanics Division, NASA LaRC) and S. Abarbanel. On this topic, we have continued to study the time stability of compact schemes. We have also suggested a new way of imposing inflow boundary conditions (SAT - for Simultaneous Approximation Term). In this way the boundary condition is imposed via adding terms to the equations not only at the boundaries. This method yields time stability for systems provided that the scalar case is time stable and admits a decreasing energy norm. Using this method we have constructed a fourth order compact scheme that is stable and time stable for systems of hyperbolic equations. The research is focused now on finding a time stable six order compact scheme.

The second topic of research involves the interactions of shock waves and hydrogen jets. Here we are carrying out a numerical simulation of shock induced vortical flows. This had been proposed by Marble (1990) as a mechanism of achieving more efficient mixing in a supersonic combustion ramjet. The simulation is done by numerically solving the full N-S equations with the use of spectral shock capturing techniques. The research focuses now on finding an optimal configuration of four jets in order that optimal mixing will be achieved.

Amiram Harten

In collaboration with Itai Yad-Shalom (Tel-Aviv University) we have developed a class of multiresolution algorithms for fast application of structured dense matrices to arbitrary vectors. This class of algorithms includes the fast wavelet transform of Beylkin, Coifman and Rokhlin as well as the multilevel matrix multiplication of Brandt and Lubrecht. In designing these algorithms we first apply data compression techniques to the matrix and then show how to compute the desired matrix-vector multiplication from the compressed form of the matrix. The data compression techniques that can be used in this class of algorithms are very general and are subject only to two requirements: the discretization is done by convolution with a weight function that satisfies a dilation relation and the reconstruction of the function from its discrete values is conservative.

We point out that the algorithm corresponding to discretization by cell-averages and polynomial reconstruction seems to be a particularly suitable for the iterative solution of integral equations with integrably singular kernels, and prove stability of the resulting algorithm.

Daniel Inman

Modern finite elements methods (FEMs) enable the precise modeling of mass and stiffness properties. These models allow the accurate determination of natural frequencies and mode shapes. However, adequate methods for modeling highly damped and highly frequency dependent structures did not exist until recently. The most commonly used method, Modal Strain Energy, does not correctly predict complex mode shapes since it is based on the assumption that the mode shapes of a structure are real, i.e., that the differential equations of motion decouple. Recently, many techniques have been developed which allow the modeling of frequency dependent damping properties of materials in a finite element compatible form. Two of these methods, the Golla-Hughes-McTavish method and the Lesieutre-Mingori method, model the frequency dependent effects by adding coordinates to the the existing system thus maintaining the linearity of the model. The third model, proposed by Bagley and Torvik, is based on the Fractional Calculus method and requires fewer empirical parameters to model the frequency dependence at the expense of linearity of the governing equations. This work examines the Modal Strain Energy, Golla-Hughes-McTavish and Bagley and Torvik models and compares them to determine the plausibility of using them for modeling viscoelastic damping in large structures for the purpose of performing active control.

Smadar Karni

Attempting to compute mixing fluids via a multicomponent Euler model in conservation form gives rise to oscillations and other bothersome computational inaccuracies near material interfaces. These can be shown to be a consequence of the simple wave model of the conservative system, more specifically, its inability to maintain constant pressure across contact surfaces. The result is generation of spurious pressure fluctuations which subsequently contaminate the flow field. This can be cured by using a primitive (nonconservative) model, using density, velocity and pressure. The primitive description offers simple wave models better suited for propagating fronts computations, and produces oscillation free material interfaces. High order viscous correction terms are used to handle conservation errors. The resulting primitive algorithm is conservative to the order of the numerical approximation. One and two dimensional experiments of multicomponents fluid flows are promising. First steps towards incorporating this new technique into a sophisticated adaptive mesh refine-

ment program have (in collaboration with J.J. Quirk of ICASE), to enable looking at front propagating problems in combustion and in bubble dynamics.

Fumio Kojima

In collaboration with H.T. Banks and W.P. Winfree (Nondestructive Measurement Science Br., LaRC), work is continuing on the development of computer aided software for nondestructive testings by thermal tomography techniques. Major efforts during this period were focused on an artificial neural network approach that imitates intelligent behavior of human experts in nondestructive evaluations. The idea of a neural network classification was adapted to thermal testing of materials. Due to the large volume of inspection data that needs to be categorized, classification procedures in nondestructive testings are a time-consuming and tedious tasks even for a trained person. Research is aimed at producing a neural network classification system that would perform the task at the level of human expert. The pattern classification rule is specified by adjusting weight values for the network connection. The backpropagation learning for a multi-layer feed-forward neural network is applied to the pattern classification. A new backpropagation algorithm was proposed using the trust region method and successfully tested for the disbond detection in thermal testing of materials. Results in all test cases have shown that the method proposed is clearly superior in overall performance to the conventional backpropagation algorithm based on the method of steepest descent.

David Kopriva

Research continues on the development and application of spectral methods for the solution of inviscid and viscous compressible flows. The emphasis this year has been on the development and implementation of a multidomain method for viscous flows. The single domain method cannot easily solve viscous flows in complicated or large geometries. The problem is that a global mapping must be used to map the computational region to a rectangle and a large number of grid points must be used to resolve boundary layers. This results in a very stiff problem to be solved. A multidomain approach allows for local resolution of boundary layers and leads to a globally less stiff approximation. A method for the interface conditions between subdomains, based on a penalty proportional to the jump in the first derivatives, has been developed. Stability for Legendre approximations can be proved. Tests have been done on linear one- and two-dimensional parabolic systems. The method has been applied to the boundary-layer flow over a flat plate and to the hypersonic flow over a two-dimensional or axisymmetric blunt body. The blunt body multidomain code is now being tested.

Catherine Mavriplis

Adaptive spectral element methods are being developed for the efficient solution of partial differential equations. Specifically, h-refinement, p-refinement and moving meshes have been implemented for some model problems. Error estimators serve as refinement criteria and nonconforming spectral discretizations allow local refinement without wasting resources. Sharp gradients are well resolved and tracked by the adaptive method. Furthermore, singularities are isolated by small low order elements, locally limiting the discretization error. Moving meshes appear to be difficult to implement. Simple prescribed motion of the mesh is recommended, if needed. Otherwise, simple h- and p-refinement and coarsening should serve as the main refinement choices. The techniques developed are applicable to the solution of any partial differential equation. Applications to complex fluid dynamics simulations are underway. The full incompressible Navier-Stokes equations are solved for fairly complex geometries. The adaptive method greatly increases the flexibility and efficiency of spectral-type methods in general, thereby broadening the realm of applications.

Concurrently, in collaboration with John Van Rosendale, the geometric flexibility of the method was increased by developing tensor product algorithms for triangular spectral elements. Triangles provide greater geometric flexibility than quadrilaterals and are also better conditioned and more accurate than quadrilateral elements in complex geometries. However, the lack of efficient tensor product algorithms for triangles has inhibited their use. We showed that, through a sequence of polynomial transformations on each element, one can construct fast tensor product algorithms for triangular elements. The resulting curvilinear triangular elements can be used in conjunction with the traditional curvilinear quadrilaterals, yielding a general and flexible high order method for complex geometries in two dimensions. Rectilinear triangular elements are currently implemented in a 2D Poisson solver. We plan to implement them in a 2D incompressible Navier Stokes code, where they will also be useful for adaptivity.

Dimitri Mavriplis

Work is continuing on the use of unstructured meshes for solving computational fluid dynamics problems in both two and three dimensions.

A new unstructured grid generation strategy has been developed and implemented in two dimensions. The method consists of an advancing front type algorithm for placing new grid points while employing the Delaunay triangulation criterion for forming new triangles with the new points. The advantages of such an approach are increased efficiency and robustness over other unstructured grid generation methods. This algorithm is currently being implemented in three dimensions.

A previously developed three dimensional unstructured multigrid Euler solver has been bench-marked on the CRAY-YMP-C90 machine using 1, 2, 4, 8, and 16 processors. A computational rate of 3.2 Gflops was achieved using all 16 processors of the machine. The same case has been run on the Intel Delta distributed memory machine, using 512 processors, resulting in a computational rate of about 1.5 Gflops. These results are to be presented at the Supercomputing '92 meeting, to be held in Minneapolis, Minnesota, in November 1992.

Future research in parallel computations will be extended to include operations such as unstructured mesh generation, parallel partitioning, and the use of adaptive meshing strategies.

Ijaz Parpia

Unlike classical upwind methods, in which much of the wave physics is determined by the computational grid, "genuinely multidimensional" schemes rely on a grid-independent local wave decomposition of the flowfield. Several numerical studies have shown that low-order implementations of the grid-independent approach give remarkably high resolution of discontinuous regions. A more realistic evaluation, based on side-by-side comparisons of grid-independent wave decomposition methods with high-order grid-aligned schemes shows clearly the need for grid-independent schemes with improved accuracy.

A preliminary effort has been made in this direction. A high-order extension of a first-order finite-volume scheme for unstructured grids [I.H. Parpia and D.J. Michalek, "A nearly-monotone genuinely multidimensional scheme for the Euler equations," AIAA Paper 92-0325, Reno, NV, January 1992] has been implemented. In the first-order method, the data is node-centered, and the flowfield gradient data is locally reconstructed on a triangle. The accuracy of the scheme is enhanced using corrections based on a second reconstruction of the gradient over a larger support. The effect of the corrections is to modify the dissipation terms in the first-order numerical flux formula so that the dissipation vanishes exactly if the solution varies linearly over the support of the reconstruction.

James Quirk

Building upon our experience of simulating shock wave phenomena using an adaptive mesh algorithm, work was started on developing a numerical tool for performing detailed simulations of detonation flows. Preliminary work showed that modern Godunov-type schemes contain subtle flaws that are readily exposed by some of the complex flow behaviour exhibited by detonation phenomena. A simple strategy has been developed whereby a preferred Riemann solver may be combined with one or more auxiliary Riemann solvers so as to produce

a scheme that is sufficiently robust for detonation simulations. This work has been written up and will appear as an ICASE report. Using the so-called reactive Euler equations, successful simulations have been performed for detonation cell phenomena and galloping instabilities. Given the simplified nature of the reaction modelling, these simulations can only provide qualitative information. Our future efforts will concentrate on improving the reaction modelling in order that reliable quantitative information may also be obtained.

Philip Roe

During my visit this year I concentrated mainly on advancing the techniques of multi-dimensional upwinding. All existing methods, including those of dimension-by-dimension upwinding, can be considered as adding numerical dissipation to stabilise wave motions that are detected in the data. Any method that detects waves when they are not really there is probably adding dissipation without cause. Only in one dimension is the dissipation guaranteed to be the minimum required. An example of unnecessary dissipation occurs with all existing methods near stagnation points, where compression in one directed balanced by expansion in another introduces dissipation in both directions. The new idea is separate the gradients observed within a flow element into those that can be explained as due to steady nonuniform flow, and those that cannot. Wave decompositions and dissipation are only to be applied to the latter. I am presently conducting numerical experiments to verify the theory.

A second topic is that of devising numerical schemes for essentially linear problems such as Maxwells equations or the acoustic equations that are required to be solved for short waves in large three-dimensional domains. Even for truly linear problems, the cost of a 3D simulation using singularity methods is proportional to N^6, where N is the number of mesh points needed to resolve one wavelength. CFD methods reduce this to N^4, but conventional methods require $N \simeq 20$. Spectral and compact methods have problems with irregular geometries. A little studied class of multilevel schemes that combine upwinding and leapfrog methods promise very low dispersion and dissipation errors with $N \simeq 6$.

Chi-Wang Shu

Jointly with Dr. H. Atkins (Fluid Mechanics Division, NASA LaRC) and Dr. J. Casper (Vigyan, Inc.), we have been performing comparisons of finite volume and finite difference high order ENO (Essentially Non-Oscillatory) schemes. Test cases include two dimensional steady and unsteady channel flows, Riemann problems with different angles, shocks running through smooth and non-smooth non-uniform meshes, etc. We have paid special attention to high order boundary conditions both for a solid wall and for inflow-outflow. Accuracy is studied for smooth grids as well as for grids containing singularities.

Jointly with Dr. G. Erlebacher and Dr. Y. Hussaini, we have been continuing the numerical investigation of shock interaction with a vortex. A computer program is written for predicting the post shock flow perturbations based on linear theory. We plan to perform direct numerical simulation using high order ENO method to compare with linear theory and to explore any non-linear effects.

Jointly with Dr. S. Sarkar, we have been implementing ENO method into the 3D direct simulation of compressible turbulence in a shear flow. Simple accuracy tests have been performed. After a careful resolution and cost study, we plan to perform simulations to compare and to supplement results obtained by spectral and compact methods.

Ralph Smith

In collaboration with H.T. Banks (North Carolina State University), work is continuing on the development of theoretical and numerical techniques for the estimation of physical parameters and control of noise in structural acoustics problems. The unwanted interior noise in these problems is being generated by the vibrations of an elastic structure which in turn are due to an exterior noise field.

The 3-D model under consideration consists of a cylindrical interior acoustic cavity which is enclosed by a flexible boundary (a shell or cylindrical hard wall). The acoustic response is modeled by a 3-D acoustic wave equation while elasticity equations are used to approximate the structural dynamics. The two are coupled through force and momentum conditions. Control is implemented via piezoceramic patches which are bonded to the elastic boundary of the cavity, and through applied voltages, can be excited so as produce bending moments and/or extensional forces. In this way, we can take advantage of the natural "feedback" loop which is due to the coupling of the structural vibrations and the acoustic fields. Because the incorporation of the feedback control is through actuators covering only sections of the boundary, the resulting system contains an unbounded input term.

The modeling system of PDE's can then be written as a first-order abstract Cauchy equation which provides a form which is conducive to the application of infinite dimensional LQR state space theory. This form is also advantageous when developing approximation techniques both for the control problem and for the problem of estimating physical parameters through data fitting techniques.

The validity of this model has been tested numerically in the simplified case consisting of a 2-D cavity with a flexible beam at one end. Numerical parameter estimation and control simulations have been run, and tests have shown that substantial reductions in acoustic pressure can be realized with physically realistic controlling voltages into the patches, even in the model involving nonlinear coupling terms.

As a prelude to the 3-D control and parameter estimation problems, detailed piezoceramic patch/structure interaction models, which take into account the curvature of the underlying substructure, have been developed. These models have then been combined with the acoustic and underlying elasticity equations to form a model for the fully coupled 3-D system. Current efforts are being directed toward the development of accurate, efficient and stable algorithms for discretizing the resulting system of PDE's. In conjunction with these efforts, work is continuing on extending the control and parameter estimation techniques that were developed for the 2-D problem to the 3-D geometries of interest. The validity of the models and control techniques will then be tested against experimental data being obtained by H.C. Lester and R.J. Silcox (Acoustics Division, LaRC).

N. Sundarajan

The main work carried out during my stay at ICASE was to investigate the newly evolving area of Artificial Neural Networks for application in the areas of Control of Flexible Structures, Active Control of Flexible Wing Aircraft and also for use in Robotic Control. I had number of discussions with the groups of NASA scientists working in these areas and identified the approaches to be followed. The main approach will be the use of multilayer feedforward neural networks and use of backpropagation algorithm for the learning scheme. Other networks like recurrent networks will also be investigated. The following groups were involved in the discussions:

Spacecraft Controls Branch: Dr.Price, Dr.S.M.Joshi and Dr. Pamadi and others working in optimisation area.

Aeroservoelasticity Branch: Dr.Vivek Mukopadhyay, Sherry Tiffany and others working in the area of testing of active control of flexible wing.

Apart from these groups, scientists working at ICASE were involve in discussions.

Since the time of stay was short we could only map the approach to be followed in these areas. We also agreed that we will continue working in these areas independently and compare our results, problems etc. after a year.

In order to appraise the NASA scientists in the broad area of Neural Networks, an intensive 3 hour course on "Introduction to Neural networks" was conducted by me on 19 June 92 and also a seminar on "Evaluation of Adaptive Control Scheme Using Neural Networks" was given at ICASE on 5 June 92. For both the seminar and the short course the response was quite encouraging. Some of the results of using neural networks for control scheme were presented by me in these seminars.

Shlomo Ta'asan

The development of efficient multigrid solvers for constraint optimization problems governed by partial differential equations has continued with research in two directions. The first, which is well developed by now, deals with problems in which the parameter space on which optimization is performed is of finite dimension in the differential formulation of the problem. The methods use relaxation for the parameter space in a multilevel way. Parameters that have a non-smooth effect on the solution are relaxed on fine levels while those of smooth effect are solved for on coarse grids only. The methods use adjoint variables to define a descent direction for the minimization problem. The other direction focuses on problems in which the optimization is over an infinite dimensional parameter space (in the differential level). The same type of ideas for the treatment of the different scales in the problems is being used here. Experiments with some model problems involving elliptic partial differential equations as the constraint equations have been performed demonstrating that the full optimization problem can be solved with a computational cost which is only a few times more than that of solving the PDE alone.

The above ideas have been applied in aerodynamics design problems where airfoils are to be calculated so as to meet certain design requirements, for example, to give pressure distribution in some flow conditions which are closest to a given pressure distribution. The present model for the flow is the transonic full potential equation with a body fitted grid. The shape of the airfoil in these calculations is being expressed in terms of a finite number of given shape functions with amplitudes to be found by the design process. Currently, subsonic design problems are being investigated. The goal is to obtain a solution of the optimization problem in a computational cost which is just a few times (2-3) that of the flow solver. Preliminary results show the possibility of getting this efficiency for general problems. This work is jointly done with M. D. Salas (Fluid Dynamics Division, LaRC) and G. Kuruvila (Vigyan, Inc.).

New multigrid solvers for inviscid flow problems are being developed in which the convergence rates are to be like that of the full potential equation. These convergence rates have been predicted by Fourier analysis. These solvers employ relaxation methods of the Gauss-Seidel type with a proper modification to handle systems of partial differential equations. At present we focus on the incompressible and compressible inviscid case working with body fitted grids in two dimension, using MAC discretization schemes. With non-conservative discretization the method developed yield optimal convergence rates for exterior as well as interior (nozzle) problems. Currently the focus is on extending it to conservative discretization enabling the future implementation of the method to transonic flow problems governed by the Euler equations.

Another field of study is the efficient treatment of time dependent problems for long integration times. Usually the grids needed for such problems are much finer than that needed for spatial resolution. A method for efficiently calculating the time evolution using mainly coarse grids (depending on the spatial resolution only), has been developed. Coarse grids use extra source terms to correct their evolution process making it arbitrarily close to the fine grid solution. These source terms are shown to satisfy some equations in general, and are being solved for on the coarse grid together with the main solution. The method referred to as Large Discretization Step (LDS) method yields extremely efficient evolution processes. Experiments with hyperbolic equation with periodic boundary conditions have demonstrated typical efficiencies to be expected. Extensions to general boundary conditions and nonlinear case is the next development stage.

Hillel Talezer

The semidiscrete formulation of time-dependent P.D.E's is a large set of O.D.E's which can be written in the general linear case as $\frac{d}{dt}U - GU = S$, where U and S are the unknown and source vectors, respectively. For stiff problems, a standard explicit scheme (e.g. Runge-Kutta), which is based on Taylor expansion considerations, suffers from severe time-step restriction. In the linear case, the Taylor expansion is equivalent to an approximation based on interpolating the exponential function where all the interpolating points are zero or close to the origin. A new algorithm has been developed where the interpolating points, used for polynomial approximation of the evolution operator, depend on the operator G itself and on the vectors upon which it is operating. Using this adaptive approach one can get a very efficient time marching algorithm (A by-product of the present research is an extremely fast algorithm for solving nonsymmetric set of linear equations).

Implementing the algorithm for nonlinear problems is the subject of a future research.

Eli Turkel

Work continued on introducing chemistry into the two dimensional central difference multi-stage scheme. The chemistry model allows for a general number of reactions and also allows for a general equation of state without introducing extra species. The same programming will also allow for introducing multi-equation turbulence models and having these models strongly coupled to the fluid equations and included in the multigrid acceleration. Preliminary calculations for a mixing shear layer are being carried out.

Together with R.C. Swanson we are making a a detailed study of the central difference scheme for high Reynolds number laminar flow over a flat plate. In this case the artificial viscosity can strongly affect the accuracy of the code. With individual eigenvalue scaling of

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the dissipation and matrix viscosity we are able to achieve results that are comparable to those achieved by an upwind scheme. Convergence is adversely affected by this reduction of the dissipation levels and we are investigating ways of improving the convergence to the steady state.

A rational Runge-Kutta scheme has been implemented into the central difference code and comparisons are being made with the explicit Runge-Kutta presently used. For a large range of Mach numbers the rational scheme is about twice as fast as the explicit scheme. For hypersonic flow it is necessary to use different parameters in order to achieve rapid convergence. Ways of automating this procedure are being investigated.

A review paper was completed on preconditioning methods for the inviscid and viscous fluid dynamics equations. This review compared matrix preconditioners of Merkle, Turkel and Van Leer. This technique was then generalized to consider differential preconditioners such as residual smoothing.

Bram van Leer

A local preconditioning method previously developed for the Euler equations is being extended to the Navier-Stokes equations. When using variables that symmetrize the matrix coefficients of the linearized Navier-Stokes equations (Abarbanel and Gottlieb, 1980), the Euler-based preconditioning remains symmetric. Its effect on the Fourier footprint of the discretized Navier-Stokes residual, though, is not satisfactory: for low enough values of the cell Reynolds-number the clustering of eigenvalues achieved for Euler residuals is lost. Research efforts are focussed on modifying the non-zero matrix elements so as to include the influence of $Re_{\Delta y}$, and adding more non-zero elements.

A start was made with the development of genuinely multi-dimensional limiters for Euler and Navier-Stokes computations on unstructured triangular meshes; collaborators are J. L. Thomas and W. K. Anderson (both in CMB). It is assumed that the code is based on the projection-evolution technique also known as the MUSCL approach; this research focuses on the projection step, viz. on obtaining a non-oscillatory interpolant of the discrete values. The gradient needed to reconstruct a linear distribution in a finite volume of the dual mesh is nominally obtained by a least-squares fit to the data; the direction of this gradient is adopted, but its modulus may be reduced in order to avoid over- and undershoots. The parameters p_k serving as input to the limiting factor $\phi(p_1, .., p_N)$ are chosen to be $(u_k - u_0)/\vec{r}_k \cdot \nabla u$, where $\vec{r}_k$ is the position vector of nodal point k with regard to the central point 0. By recasting one-dimensional limiters into this form it is hoped that multi-dimensional formulas will follow by analogy.

John Van Rosendale

In the past six months, work has continued on robust parallel multigrid algorithms. The focus has been on multigrid algorithms based on multiple semicoarsened grids, a class of algorithms first investigated by Wim Mulder. In collaboration with Naomi Naik of Columbia University, a V-cycle proof of the fast convergence of one such algorithm was recently obtained in the difficult case of non-constant coefficients. Also, in collaboration with Joe Dendy, one version of this algorithm was implemented and tested on the Los Alamos CM-2.

At the moment, the MSG (multiple semicoarsened grid) algorithms implemented on the CM-2 are not as fast as the best line-relaxation based multigrid algorithms. This is partly due to the highly tuned cyclic reduction tridiagonal solvers available on the CM-2, but also points to the need for a better understanding of MSG. While MSG is faster per multigrid cycle, the most parallel version of MSG has a poorer convergence rate than line-relaxation based multigrid algorithms If this relatively poorer convergence rate can be fixed, MSG would be substantially faster than existing robust parallel multigrid algorithms on massively parallel architectures.

Another direction of research on these multigrid algorithms is underway in collaboration with Rolf Radespiel and Cord Rossow of DLR. DLR, the German analog of NASA, is developing a Navier Stokes code for hypersonic flows in cooperation with NASA LaRC. MSG multigrid algorithms have the potential to overcome the slow convergence of Navier Stokes solvers caused by the highly stretched grids needed to resolve turbulent boundary layers. In some cases, cell aspect ratios has high as 20,000 to 1 occur, resulting in very slow convergence.

During a recent visit to DLR, and a subsequent visit of Cord Rossow to NASA Langley, a version of MSG was implemented and tested in a 3d Navier Stokes code for hypersonic flow. The code used was a block structured upwind code, developed by DLR in collaboration with NASA LaRC. The MSG algorithm used was found to be more robust, but the cost of the many coarse grids needed in 3D makes it less efficient than standard multigrid for simple ramp flows. We expect to test this algorithm on more difficult blunt body problems in coming months, in which more severe grid stretching occurs. In problems with severe grid stretching, the new algorithm should be superior to current methods, though this remains to be demonstrated.

FLUID MECHANICS

S. Balachandar

We have initiated an investigation of the stability of corner flow that develops at the intersection of two perpendicular semi-infinite flat plates. First, the mean flow for this problem was computed using a spectral ADI (alternating-direction-implicit) technique and asymptotic boundary conditions were used at the outer boundaries. The asymptotic boundary conditions were extended to include instances of wall suction and blowing, and corresponding mean flows were obtained. As the second step, an inviscid instability of this flow was conducted. Here the three components of mean flow varies along the two wall normal directions and therefore the resulting eigenvalue problem from the linear stability analysis is computationally demanding both in terms of memory and CPU time requirements. Symmetry about the corner bisector present in this problem is exploited to reduce this computational demand. Inviscid instability analysis indicates the presence of growing disturbance modes arising from the inflectional nature of the streamwise velocity profile along the corner bisector. The inviscid analysis is currently being extended to include finite Reynolds number effects. Preliminary results suggest the importance of viscous effects and the critical-layer on the overall stability of this flow.

Andrew Bassom

Over the period spent at ICASE work proceeded on a number of fronts. The primary aim of the study was to extend the findings concerning the nonlinear stability properties of high wavenumber Görtler vortices within three dimensional boundary layer flows (jointly with Dr. S.R. Otto). Previous investigations had revealed that according to a classical weakly nonlinear theory, vortices within a suitable slightly three dimensional boundary layer are supercritically stable whilst calculations by Denier & Hall (ICASE Rep. 91-86) have shown that in a two dimensional boundary layer nonlinear, vortices tend to be unstable and, in certain circumstances, they can suffer a finite distance breakdown as they progress downstream. Our calculations were designed so as to explain and quantify the contrasting destabilising role of nonlinearity and the stabilising effect of crossflow upon strongly nonlinear Görtler modes. We shall report on our results in due course.

Meanwhile work also continued on vortex-wave interaction phenomena within time dependent boundary layer flows (joint work with Prof. P. Hall). Earlier investigations by us have concentrated on the evolution of vortex/wave pairings within channels and we have extended the study to consider more realistic boundary layer situations.

Alvin Bayliss

Together with L. Maestrello (ACOD - Structural Acoustics Branch, NASA LaRC) and A. Frendi (Analytical Mechanics Association, Inc., NASA LaRC), we consider the problem of computing the radiation from an acoustically excited flexible surface clamped between two rigid surfaces. The problem is solved by coupling the nonlinear Euler equations describing the near and far field radiation to an equation for the evolution of the flexible surface. The pressure difference across the surface acts as a source term.

We consider excitation by an acoustic plane wave at a near resonant frequency and study the behavior as the strength of the acoustic excitation is increased. At present we have found transitions from linear sinusoidal responses to nonlinear responses (characterized by the appearance of subharmonics) and finally transitions to possibly chaotic responses. The results show that the effect of coupling tends to reduce the panel response for a given source strength. An ICASE report has been prepared describing these results. Extensions to three dimensions are currently being implemented.

Stanley Berger

The sensitivity of the onset and the location of vortex breakdowns in concentrated vortex cores, and the pronounced tendency of the breakdowns to migrate upstream have been characteristic observations of experimental investigations; they have also been features of numerical simulations and led to questions about the validity of these simulations. This behavior seems to be inconsistent with the strong time-like axial evolution of the flow, as expressed explicitly, for example, by the quasi-cylindrical approximate equations for this flow. An order-of-magnitude analysis of the equations of motion near breakdown leads to a modified set of governing equations; analysis of which demonstrates that the interplay between radial inertial, pressure, and viscous forces gives an elliptic character to these concentrated swirling flows. Analytical, asymptotic, and numerical solutions of a simplified non-linear equation have been obtained; these qualitatively exhibit the features of vortex onset and location noted above.

Fabio Bertolotti

The $xPSE$ transition analysis tool-kit has been developed and tested. The tool-kit performs PSE based analysis of user-specified flows. The parabolized stability equations, boundary conditions, and mean flow are described by the user through subroutines which are then linked with the $xPSE$ library. The description of the equations is very concise, typically requiring 10 to 30 lines of code. Any number of dependent variables is allowed. The numerical formulation uses a multi-domain spectral method in the direction perpendicular to

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the free stream, and the number of polynomials within each domain, as well as the number of domains, is specified by the user. Provisions are made for variable fluid properties, (user specified) as well as geometric properties, such as curvature, suction, etc. Once the flow and equations are specified, the user has at his/her disposal the *xPSE* executable, as well as a number of pre and post processors, including *xLOC* for tracing single eigenvalues, *xPROF* for visualizing profiles, *xAMP* for plotting growth rates and amplitudes, and *xP3D* for translating the results into *Plot3D* and *FAST* format.

The *xPSE* code can perform nonlinear analysis; calculations with up to 120 harmonics have been made. Nonlinear boundary conditions are employed in an ongoing receptivity study. The stability of the far wake is been studied in cooperation with T. Corke, IIT, while that of the supersonic jet is been studied in cooperation with A. Cain, at McDonnell-Douglas.

Nicholas Blackaby

The main area of research has been the study of the effect of cross–flow on longitudinal–vortex–type instabilities in boundary–layer flows. This has been done in collaboration with Meelan Choudhari (HTC, Nasa Langley). The two classes of flows considered were (i) flows over locally curved walls i.e. Taylor–Gortler instabilities, and (ii) flows over heated and cooled walls i.e. buoyancy–driven instabilities. Asymptotic methods based on large Reynolds and Grashof and/or Gortler numbers yield eigenvalue problems governing the flows' stability which must be solved numerically. We have found that the most unstable mode for a 2D boundary-layer flow over a heated plate is very quickly stabilised by the additional of a small component of cross-flow. This suggests that in physical flows, in regions where the Grashof number is large, the observed instabilities will be inviscid in nature. The description of the nonlinear evolution of such inviscid instabilities has been considered. The general problem would appear to require a numerical solution of the full 'Euler–type' nonlinear governing equations. However, analytical progress is possible by appealing to the recent theories of Goldstein for shear flows—this is the subject of on going research with Andrew Dando and Philip Hall (Manchester University).

Gregory A. Blaisdell

The pressure strain correlation for Reynolds stress modeling of compressible flows was investigated using data from direct numerical simulations of compressible homogeneous turbulent shear flow. The pressure field was split into "incompressible" and "compressible" parts based on a Poisson equation similar to that used in incompressible flows. This decomposition of the pressure was used by Sarkar in the modeling the pressure-dilatation correlation, and in the current work we sought to use a similar approach for the pressure strain terms. It

was found that the normal components of the compressible part of the pressure strain tensor oscillate and have little net contribution to the rate of change of the Reynolds stresses. Therefore, only the incompressible part of the pressure strain term needs to be considered for the normal Reynolds stresses. However, the off-diagonal component of the compressible pressure strain tensor exhibits a secular growth that has a significant net contribution to the rate of change of the Reynolds shear stress and, therefore, must be included in a pressure strain model.

In order to gain a better understanding of the decomposed pressure fields, various analysis tools were developed to calculate single point statistics, two-point correlations, spectra and co-spectra of the decomposed pressure and the dilatation. A preliminary analysis using these tools shows that the pressure-dilatation correlation is a large scale phenomenon.

Future plans include a more thorough analysis of the flow fields and formulation of pressure strain models for compressible flows. The current results have been included in an abstract submitted to the Symposium on Transitional and Turbulent Compressible Flows — the 1993 ASME Fluids Engineering Conference.

Thomas J. Bridges

Work/research at ICASE during my visit involved application of dynamical systems theory to the study of spatial bifurcations in shear flows. The motivating question is how, why and when shear flows undergo wavelength doubling, bifurcation to spatially quasiperiodic states and bifurcation to spatially complicated – and chaotic – states. The current research focuses on spatial bifurcations in parallel shear flows with a thumb neutral curve; in particular, the low-amplitude quasi-periodic interaction of a 2D wave with a 3D *detuned* wave is considered. Experiments and numerical simulation have shown that detuned wave interaction provides an alternate route to transition. A semi-analytic theory has been developed for this interaction using spatial centre-manifold theory and normal form transformations. Secondary spatial bifurcations have also been studied: a question of interest is whether there is a symmetry-breaking bifurcation in channel flow that brings in the odd-modes in the transition process or whether the transition process consists of flow that is even about the channel centerline.

John Buckmaster

A number of diffusion flame studies are underway which we concerned with structure and stability. One motivation stems from experimental observations of G. Pellett at NASA Langley Research Center. In counterflows of air and hydrogen he observes holes in the flame for certain flow rates. The closure and opening of these holes with varying flow rate

exhibits hysterisis. An attempt is being made to understand this phenomenon. A related problem is that of diffusion flame stability, an issue that has received much less attention than the stability of premixed flames. A systematic study of diffusion flame stability has been initiated.

William O. Criminale

General means for investigating initial-value problems in nonparallel shear flows has been developed. Critical issues center around vorticity, completeness of any initial disturbance, continuous as well as discrete spectra, and early transient versus asymptotic dynamics. The solution method leads to results that are closed form solutions and fully three-dimensional. Finally, viscous as well as inviscid dynamics are possible. Within this general framework, specific attention has been directed at understanding the evolution of perturbations in an arbitrary three-dimensional incompressible stagnation flow. Other prototypical flows will be considered in due course.

Ayodeji Demuren

Research activity in this period centered around the development of numerical techniques suitable for computations of complex 3D flows with second-moment closure models. It has been possible to utilize full Reynolds stress models in computations of complex flows with little difficulty, and minimal additional cost by a splitting of the source terms. Several topical Reynolds stress models have been applied to jets, wakes, mixing layers and plane channel flows to test their performance in simple inhomogeneous base flows. Application to complex 3D flows such as jets in crossflow and flow in circular to rectangular transition duct is progressing. Multigrid acceleration is essential in this case. Von Neumann stability analysis and local mode analysis are being utilized to improve the performance and reliability of the multigrid method.

James P. Denier

During my time at ICASE, work continued in a number of directions. Work was begun into the evolution of nonlinear Görtler vortices in the heated boundary layer flow over heated flat plate. This work aims to extend the linear calculations of Hall & Morris (ICASE Rep. 91-44) to the nonlinear regime. The emphasis of this work has been on the most unstable Görtler mode, found by Hall & Morris, which is confined to a thin viscous sublayer adjacent to the wall surface. This work has demonstrated that the nonlinear vortex motion provides an efficient method for the convection/diffusion of heat throughout this thin layer. Results

suggest that these modes will be susceptible to both Rayleigh and Taylor–Goldstein waves for all values of the Prandtl number. Work into this problem is in progress.

Other work currently underway is the fully nonlinear development of Taylor–Görtler vortices in the Rayleigh layer generated on a cylinder which has been "spun up" from rest. This work involves extending the results of Hall & Lakin (1988) to a time–dependent Rayleigh layer. The effect of a flow along the cylinder on the stability characteristics of the problem will also be discussed. Results from this joint investigation with S. R. Otto and A. P. Bassom (Univ. of Exeter, UK) will be reported in the near future.

Manhar Dhanak

The linear stability of the blending layer between the boundary layer in a 90° streamwise corner and a Blasius boundary layer away from the corner was investigated during the summer of 1992. The steady flow due to Rubin (1966) for the blending layer was taken as the basic flow. The equations governing small perturbation of this basic flow, considered to be locally parallel, are given by Lakin and Hussaini (1984). In the present work, it is shown that the magnitude of the cross flow in the boundary layer is too small to be a contributory factor in the observed early transition in the blending layer. However, the influence of the outer boundary conditions associated with modes of disturbances which are anti-symmetric about the bisector line are shown to have a profound effect on the stability of the flow. As a result, the critical Reynolds number associated with a spanwise location is significantly reduced as the corner is approached, being $Re_{cr} = 3600$ for spanwise distance of $z = 1.2\delta$ from the corner compared with $Re_{cr} = 3.6 \times 10^5$ for $z = 4\delta$ where δ is the thickness of a Blasius boundary layer. At $Re = 3.6 \times 10^5$, the maximum growth rate at the former location is approximately six times greater than that at the latter; the wave vector corresponding to the maximum growth rate at the two locations makes an angle of 44° and 5° to the streamwise direction. The effect of application of boundary layer suction on these results is being considered next.

Peter Duck

Work has been undertaken to study the interaction between a shock wave attached to a wedge and small amplitude, unsteady, freestream disturbances. The upstream disturbances may take on the form of acoustic waves, vorticity waves or entropy waves (or indeed a combination of all three, using superposition). These waves then generate disturbances behind the shock of all three classes, an aspect that was investigated in some detail. The motivation here is to investigate possible mechanisms for boundary layer receptivity, caused through the amplification and modification of freestream turbulence.

This study then led naturally to the consideration of the stability of attached shock waves in general. Further, the effect of the modified disturbances on the boundary layer on the wedge surface was computed. This work was joint with Drs. Lasseigne and Hussaini.

Other work has been involved with the study of flow along a corner, of general angle, together with its inviscid stability. The basic flow is determined from the simultaneous computation of three coupled, nonlinear, boundary layer type equations (essentially one for each of the three velocity components). This work was joint with Dr. M. Dhanak.

Finally, work has been carried out to study the inviscid stability of the 'Trailing-line vortex' in the compressible regime. This turns out to have properties, which, although at low Mach numbers are similar to features observed in the incompressible regime, as the freestream Mach number increases, the stability of the basic flow differs drastically, and new modes of instability are possible. Results have been obtained using a variety of numerical methods; because of the many modes of instability that exist (many of which are in close proximity of each other) global methods are best suited to this problem. Results have also been obtained using asymptotic techniques, and these compare very favorably with the computed results.

Gordon Erlebacher

A three-dimensional code capable of performing direct numerical simulations of compressible isotropic turbulence has been ported from the Cray class of computers to the Touchstone Delta computer at Caltech. Based on the solution of periodic tridiagonal equations, the code achieves a peak performance just shy of 3 Gflops on all 512 nodes. Several simulations on 256^3 and 384^3 have led to databases which will later be analyzed to extract the small-scale features of the flows. Turbulence with and without shocks was generated. The algorithmic features of the code have been presented at several conferences.

Work on the stability of cones in the supersonic regime is slow and is in progress. The crucial part of the work is the check of the results against those of a flat plate in a rational manner. The ultimate objective of this project is to develop a consistent formulation for the stability problem on cones in the hypersonic regime, both at zero and at finite angles of attack.

Work is still in progress with Shu (Brown University) on the interaction of a shock with an impinging longitudinal vortex. This work has relevance for the stability of aircraft. Linear theory has been used to predict the shape of the incoming vortex downstream of the shock. Conditions under which breakdown occurs are being investigated. Currently, cross-checking between simulation and theory is underway.

Work with Biringen at Colorado State University on the linear stability of compressible Couette flow has led to a paper in the Physics of Fluids.

Michael Gaster

During the Summer of 1992 an experiment was carried out in the low-turbulence wind tunnel of the Engineering Department, University of Cambridge, on very low frequency boundary layer disturbances. A theoretical treatment of two-dimensional perturbations to the boundary layer equations had previously been carried out by Grosch and Jackson. The experimental measurements were made on the three dimensional disturbances induced in the boundary layer of a flat plate by a vibrating membrane disc embedded in the plate. The data was processed and all necessary plots were produced whilst at ICASE.

A theory for boundary value excitations of the type used in the experiment was developed for a parallel flow model of the boundary layer. A two-dimensional solution for this Orr-Sommerfeld based approach has been found. The linearised equations are elliptic and the solution provides meaningful predictions in the neighbourhood of the source, both upstream and downstream, but it will not provide useful results far downstream. On the other hand, the solutions of the boundary layer equations that are parabolic in character cannot predict the flow upstream, but will furnish sensible solutions far downstream. The two approaches are therefore complementary.

A two-dimensional wind tunnel experiment is planned for direct comparison with these two analytical approaches. A Navier-Stokes solution is also to be attempted.

Extensions of the analytical techniques to cover fully three-dimensional disturbances are being pursued.

James Geer

The problem of determining the acoustic field in an inviscid, isentropic fluid generated by a solid body whose surface executes prescribed vibrations has been formulated and solved as a multiple scales perturbation problem, using the Mach number M based on the maximum surface velocity as the perturbation parameter. Following the idea of multiple scales, new "slow" spacial scales have been introduced. These scales are defined as the usual physical spacial scale multiplied by powers of M. The governing nonlinear differential equations have lead to a sequence of linear problems for the perturbation coefficient functions. It has been shown that the higher order perturbation functions obtained in this manner will dominate the lower order solutions unless their dependence on the slow spacial scales is chosen in a certain manner. In particular, it has been shown that the perturbation functions must satisfy

an equation similar to Burgers' equation, with a slow spacial scale playing the role of the time-like variable. The method is being illustrated by a simple one-dimensional example, as well as by three different cases of a vibrating sphere. The results are being compared with solutions obtained by purely numerical methods and show excellent qualitative agreement. Several insights provided by the perturbation approach are being discussed.

Several variations of a hybrid perturbation/variational technique, which have been under development for some time, are being applied to a variety of different problem areas. In particular, the technique is being used to compute semi-analytical, semi-numerical approximations to the resonant frequencies for Hamiltonian or Lagrangian systems of nonlinear ordinary or partial differential equations. In the context of this problem, a variety of different formulations of the technique are being compared to determine the relative merits of each approach. The technique is also being applied to several classes of elliptic boundary value problems with irregularly shaped domains. The basic idea here is first to use some simple homotopy ideas to embed the problem of interest in a family of problems, which can be analyzed using standard perturbation techniques. Then, the perturbation solutions are "improved" using a variety of Galerkin type approximations.

A three-step hybrid analysis technique, which successively uses the regular perturbation expansion method, the Pade' expansion method, and then a type of Galerkin approximation, is also being developed and studied. It is being applied to several model problems which develop boundary layers as a certain parameter becomes large. In particular, the technique appears to simulate these boundary layers by producing approximate solutions with singularities which lie just outside the domain of interest. Based on some preliminary results, the technique appears to provide good approximations to the solution, even when the perturbation and Pade' approximations fail to do so.

Another new technique (temporarily called the "flexible singularity expansion technique") is being developed to determine a family of approximate solutions, based on a small parameter e, to certain classes of exterior boundary value problems. These solutions are expressed in terms of singular solutions to the governing differential equation for which the singularities lie outside the region of interest. In general, the exact type, location, and strength of these "flexible" singularities are determined by the governing equation and shape of the domain of the problem. More specifically, the various parameters associated with these new singularities are determined by requiring that the "flexible singularity solution" agree with the perturbation solution to the problem to within a prescribed order in e as e30. The technique is being applied to several classes of problems involving nonlinear PDE's and to problems which are geometrically nonlinear.

Chet Grosch

Major effort has been devoted to understanding the structure, and the effect on stability, of a number of reduced reaction mechanisms for reacting free shear layers and the effect on the growth rate of these flows of the "convective Mach number". To date, all of the studies of the structure and stability of reacting free shear layers have used the simplest possible model of the combustion, namely that of a single step, irreversible reaction. It is known that this is a somewhat poor representation of the chemistry. In particular, this simple model does not allow for flame quenching which is known to be a function of the strain rate. A number of two and three step reversible reactions have been examined and are being incorporated into the structure and stability calculations. A review of the experimental results on the growth of compressible mixing layers was also undertaken. This was to collect all available data of measured growth rates as a function of the convective Mach number for incorporation in the review paper for the ICASE Combustion Workshop. It was concluded that there is no single "convection speed" for the large scale structures and that the convective Mach number based on the existence of such a speed is not a reliable correlation parameter for the experimental results.

Philip Hall

Work continued on vortex wave interaction problems in highly curved boundary layers. In particular the initial stages of Rayleigh wave-vortex interactions were considered. The effect of heating on boundary layer transition was investigated, in particular the effect of streamwise vortices on short scale secondary'instabilities was carried out. The effect of crossflows, real gas effects and large amplitude vortices on Rayleigh waves in hypersonic boundary layers was investigated. Vortex-wave interactions in hypersonic boundary layers were investigated.

Tom Jackson

Work focuses on different aspects of flame/vortex interactions, a fundamental problem for the understanding of small scale structures in turbulent combustion. Particular aspects under consideration include compressibility effects and thermal expansion. A combination of asymptotics and numerics will be used to reduce the complex problems to a model problems, thus isolating key physical effects for analysis. This work is in collaboration with M. Macaraeg (Fluid Machanics Division, LaRC) and M.Y. Hussaini.

In addition, work is continuing on the stability of both reacting and nonreacting gases in a stagnation point flow. For nonreacting flows, an initial value approach is undertaken to

investigate the effect of transients on the evolution of the solution. This work is in collaboration with W. Criminale (University of Washington). For reacting flows, disturbances are expressed as an infinite series. When the series is truncated at some large N, a finite number of boundary value systems result for the determination of the growth rate and the flame shape that depends on N, on the cross stream wavenumber and on all the relevant physio-chemical parameters. Work has been completed for the planar geometry and is currently being extended to axisymmetric geometry. This work is in collaboration with M. Matalon (Northwestern University).

Ashwani Kapila

Research is continuing on unsteady processes (especially ignition) in combustion systems. Analytical progress has been made on the evolution of fine-scale compressive disturbances in reactive atmospheres, which, under certain conditions, can lead to the development of strongly accelerating shocks and even detonations. Work on ignition in multi-phase systems has also been initiated.

D. Glen Lasseigne

Research involving a number of topics has been pursued. The response of the flow field behind a nonreacting shock wave supported by a wedge to general disturbances upstream of the shock has been investigated in detail. Non-linear aspects of the above interaction are currently being reviewed. New ways of quantifying the results applicable to the receptivity problem as well as to the problem of enhanced mixing have been developed. We are also investigating the interaction of freestream disturbances taking into account the shock structure.

Jennifer Levin

In collaboration with L. Maestrello (ACOD - Structural Acoustics Branch, NASA LaRC), A. Frendi (Analytical Mechanics Association, Inc.), and A. Bayliss, we began a numerical study of the structural response of, and the resulting radiation from, a flexible surface excited by jet noise. The numerical method couples the nonlinear Euler equations describing both the jet flow field and the radiation field with a solver for the nonlinear plate equation describing the vibration of the flexible surface. The pressure difference across the panel provides a source term for the panel equation, while the output of the panel equation provides a boundary condition for the Euler equations. Computations are obtained using a fourth order accurate Euler solver. The Euler computation includes the jet exiting from the nozzle and

the resulting acoustic field. Boundary conditions to avoid reflections at artificial boundaries are implemented as well as boundary conditions at the nozzle exit. Preliminary results have been obtained and the activity is still ongoing.

Geoffrey Lilley

I have collaborated with S. Sarkar and Dr. Jay Hardin of the Acoustics Division (LaRC), with the aim of exploiting the recent developments in computer power, and the successful growth in computational fluid dynamics, to improve our understanding in the mechanisms of noise generation, propagation and radiation from the exhausts of a turbojet engine at high subsonic speeds.

I have examined current work on the simulation of the turbulent structure of the spatially growing mixing region as well as the temporally growing mixing region, and have re-examined the recent work I completed in collaboration with Professor Philip Morris of Penn State (1990) using the wave theory of turbulence, as well as an approximate theory for estimating the changes in the mean vorticity thickness with changes in velocity and density ratio, as well as Mach number.

I have also made an in-depth study of the early work of Proudman (1952) on the noise radiated from isotropic turbulence and have made a reappraisal of his results and conclusions. This aeroacoustic flow problem has been studied numerically using DNS by Sarkar (1992) and hence, justifies a detailed comparison with the results of Proudman. Such comparisons are currently being investigated.

Stephen Otto

In the work of Denier & Hall (ICASE Report No. 91-86) the nonlinear development of high wavenumber vortices is discussed. It is found that as the vortices evolve downstream the wall shear decreases until separation occurs. In a current study with J. P. Denier (University of New South Wales, Australia) the secondary instability of this inflectional profile is considered and it is contended that prior to the separation the inviscid waves will cause the system to breakdown. This calculation will also be affected for the problem where the flow is slightly three dimensional; this case is of interest as the crossflow has a stabilising effect on the linear vortex system.

Also of current interest is the effect of crossflow on the linear stability of vortices occurring within a boundary layer that results as a cylinder undergoes spin–up (this work is with A. P. Bassom (University of Exeter, UK)). It is known that a high wavenumber vortex occupies a thin layer in the neighbourhood of the cylinder (this is the position at which

the Rayleigh criterion is most violated). As the flow along the length of the cylinder is increased, the normal extent of the vortex decreases and the Görtler number at which the vortex becomes unstable increases; this implies that the flow is stabilised by the imposition of the crossflow. Eventually the crossflow drives the vortex to be confined to the viscous layer and in realistic situations this would imply that the crossflow will ultimately eliminate the Görtler instability.

Work is continuing with P. Hall (University of Manchester, UK) concerning the interaction of Görtler vortices and Rayleigh waves. The effect of a pressure gradient is being considered on the nonlinear development of high wavenumber vortices on a curved plate. The effect of compressibility is also being investigated. In this problem, suitable pressure gradients and Mach numbers imply that the underlying basic states contain inflection points and thus may support inviscid Rayleigh waves. The size of the waves may be such that although they remain linear themselves they have a leading order effect on the basic flow. There is also some interaction with C. L. Streett (Theoretical Flow Physics Branch, LaRC) to investigate this phenomena with a linearised Navier–Stokes equations methodology, where selected nonlinear terms are retained that represent the vortex-wave interactions.

It is well known that as a Görtler vortex evolves downstream its structure may be determined by a high wavenumber calculation. In this regime it is known that the vortex boundaries are susceptible to wavy modes out of phase with the vortex state. This is similar to the wavy modes observed in the Taylor problem. Currently a study is being made to consider the nonlinear fate of these modes, and this extends the previous linear and weakly nonlinear work.

Demetrious Papageorgiou

We have been considering stability characteristics of three-dimensional flows. In particular circular jets are of interest with a wide range of applications. In many situations a high-speed jet of uniform axial velocity flows into another medium which may be at rest or have constant vorticity, for example. The presence of the outer fluid induces velocity jumps (in an inviscid model where the flow is a weak solution of the Euler equations) in both the axial and azimuthal directions, and so a three-dimensional Kelvin Helmholtz instability is present. Nonlinearly these equations are ill-posed (short wave instabilities dominate) and we have used two different physical regularizations: (i) surface tension and (ii) finite thickness vorticity layers. Presently we are analyzing the linear stability characteristics of these flows with particular emphasis on absolute/convective instabilities. Long wave nonlinear theories have also been developed for surface tension regularized incompressible jets. These ideas will be extended to compressible jets also.

Ugo Piomelli

In work performed jointly with Sutanu Sarkar, a theoretical investigation of the spectral properties of the dynamic subgrid-scale eddy viscosity model [Germano et al., Phys. Fluids A, vol. 3, 1760 (1991)] is being carried out. Using incompressible and compressible isotropic turbulence databases, we are trying to estimate how local filtering affects the model predictions, and to come up with methods to avoid the ill-conditioning that occurs when the denominator of the expression used to yield the model coefficient becomes very small. The possibility of explicit calculation of the subgrid-scale energy have also been investigated.

Helen Reed

The receptivity to freestream sound and vorticity of the laminar boundary layer over a semi-infinite flat plate with different leading edges is simulated numerically. The incompressible flow past the flat plate is computed by solving the full Navier-Stokes equations in general curvilinear coordinates. Spatial and temporal growth of the T-S wave in the boundary layer, due to the introduction of perturbations on the upstream and/or farfield boundary, is studied. This work was/is being done in collaboration with Nay Lin, Thomas Buter, David Fuciarelli, and William Saric (Arizona State University).

The effect of including wall and streamline curvature terms in swept-wing boundary-layer stability calculations is studied. The linear disturbance equations are cast on a fixed, body-intrinsic coordinate system. Those nonparallel terms which contribute mainly to streamline curvature are retained. Convex wall curvature has a stabilizing effect, while streamline curvature is destabilizing. This work was done in collaboration with Ray-Sing Lin and Media Petraglia (Arizona State University).

Sutanu Sarkar

In the past six months, we have been engaged in three projects. The first one has been the computation of sound radiated from bounded, isotropic turbulence. A hybrid DNS approach has been developed; it combines the accurate simulation of the aerodynamic turbulence with an integral representation of the far-field acoustics. The second project, in collaboration with A.O. Demuren, evaluates the performance of the new generation of Reynolds stress models in plane free shear layers: the mixing layer, the wake and the jet. The third project revisits the DNS of compressible, homogeneous shear. Based on linear analysis, it is found that there is a parameter - the gradient Mach number - whose increase leads to a decrease in the transient growth rate of initial perturbations. Furthermore, it is found that an increase in gradient Mach number leads to a decrease in the asymptotic growth rate of the turbulent kinetic energy in the full non-linear simulations.

Peter Schmid

In work done in collaboration with Dan Henningson, transient energy density growth of spatially evolving disturbances in subcritical plane Poiseuille flow has been considered. The concept of ε-pseudo-eigenvalues (introduced by N. Trefethen) has been used in conjunction with an expansion in the spatial eigenfunctions of the linearized, incompressible Navier-Stokes equations to quantify transient flow phenomena. Large growth in energy density has been observed and parameter studies revealed that the maximum amplification of initial energy density occurred for disturbances with vanishing frequency. Transient growth is due to the non-orthogonality of the eigenfunctions which in turn is a result of the non-normality of the linearized Navier-Stokes operator. Disturbances that exploit this linear growth mechanism in an optimal way have been determined and their spatial evolution has been computed. These studies are meant as the theoretical foundation for future spatial direct numerical simulations of the breakdown of two oblique waves.

Studies on the eigenvalue sensitivity for hydrodynamic stability operators has been brought to completion as a joint effort with M. Khorrami and M. Malik (High Technology Corporation). A variety of linear stability operators (including swirling flow and compressible Blasius flow) have been investigated for their non-normality and their potential for transient, non-modal growth. The results of these studies have been summarized in form of an ICASE report.

John Shebalin

An examination of compressible turbulent phenomena through direct numerical simulation of Navier-Stokes flows has been initiated. The phenomena include 3-D high Mach number isotropic compressible turbulence and 2-D shock–turbulence interactions in both chemically inactive and reacting gasses. The numerical approach is based on a pseudo-spectral logarithmic variable method, which entails solving for $\ln \rho$, $\mathbf{u}$, and $\ln T$, rather than ρ, $\mathbf{u}$, and T. This prevents the positive-definite quantities density (ρ) and temperature (T) from inadvertently acquiring non-positive values on the numerical grid. Another important feature of the numerical approach is the use of non-zero bulk viscosity to realistically model polytomic gas flows, a feature which also helps to stabilize the numerical method.

Charles Speziale

Research was conducted with R. Abid (High Technology Corporation, LaRC) that establishes a direct theoretical connection between homogeneous turbulent shear flow in equilibrium and the log-layer of turbulent channel flow. It was shown that if a second-order closure model yields good equilibrium values for homogeneous shear flow it will also yield

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good results for the log-layer of turbulent channel flow provided that the Rotta constant is not too far removed from one. Most of the commonly used second-order closures introduce an ad hoc wall reflection term to mask deficient predictions for the log-layer that result from either a miscalibration of homogeneous shear flow or from the use of a Rotta constant that is too large. This has impeded progress in the application of second-order closures to the wall-bounded turbulent flows of technological interest.

A systematic study of algebraic stress models of turbulence was conducted in collaboration with T.B. Gatski (Fluid Mechanics Division, LaRC). It was demonstrated that the traditional algebraic stress models – which relate the Reynolds stresses to the mean velocity gradients through implicit algebraic equations obtained from a local equilibrium hypothesis – can be solved explicitly. This leads to explicit algebraic stress models where the Reynolds stress tensor is a nonlinear function of the mean velocity gradients. A general expression, valid for three-dimensional turbulent flows in non-inertial frames, was derived for a hierarchy of second-order closures. For large strain rates, these models can become singular – a feature that explains why traditional algebraic stress models have failed. This problem can now be overcome by a regularization technique based on a Padé approximation.

A fairly comprehensive review of turbulent secondary flows in circular pipes and non-circular ducts has been conducted with R.M.C. So (Arizona State University) and B.A. Younis (City University). Secondary flows arising from normal Reynolds stress differences, curvature and a system rotation were considered in an effort to categorize the underlying physical mechanisms. Illustrative calculations using two-equation models and second-order closures were provided.

Siva Thangam

The application of a number of turbulence models for the prediction of massively turbulent separated flows was conducted from both experimental and computational point of view. The first and the second phases of this collaborative effort (involving C.G. Speziale and M.Y. Hussaini of ICASE, and S.O. Kjelgaard of Experimental Methods Branch) were completed in 1991 and dealt with the evaluation of two-equation Reynolds stress closure models and large-eddy simulation based on a second-order accurate finite-volume algorithm. The major findings included the accurate prediction of the dominant features of the flow field, namely the size of the separation bubble, the mean velocity profiles, and the wall pressure variation.

The third and the final phase of this work was started during the current period and focusses on (i) the development of accurate experimental data base for both the high Reynolds number and the low Reynolds number regimes in channels of different step-to-channel height

ratio, and (ii) the validation of a selected group of two-equation and full Reynolds stress closure turbulence models. To this effect, the existing rearward-facing step facility was completely redesigned by S.O. Kjelgaard by increasing the lengths of the inlet section upstream of the step and the flow development region downstream of the step. The new tunnel is equipped with a three-component particle laser velocimetry system mounted on a specially-designed three-dimensional traverse. The system allows for the accurate measurement of all components of the mean velocity and turbulent stresses in all three-directions. The first group of experimental investigations in the high Reynolds number regime (at a Reynolds number of 50000 based on the step height and inlet mean velocity) was completed by S.O. Kjelgaard during this period for the 1:2 step-to-channel height ratio case. Computational investigations based on a second-order accurate finite-volume algorithm using the two-equation Reynolds stress closure schemes with isotropic and anisotropic eddy-viscosities were also completed. Excellent agreement between the computational and experimental results was present for the mean flow quantities. In addition, the computed values of turbulence stresses were in good agreement with the experimental results. During this phase additional experimental investigations covering a wider range of parameters are planned along with the development and validation of Reynolds-stress closure models.

Lu Ting

In collaboration with Drs. L. Maestrello and A. Frendi of NASA LaRC we study *the accuracy of the on surface condition in structural acoustic interaction.* This is a model problem to study the transmission of exterior incident waves through an airframe into the interior. Experiments using the same model are being conducted at NASA.

In the scattering of an incident wave by a flexible panel, the panel oscillation is governed by the partial differential equation for a vibrating plate while the loading, the pressure difference across the plate, depends on the reflected and transmitted waves. These waves are solutions of wave equation in half space above and below the panel subject to the far field radiation condition. We express the loading as a double integral involving the history of the panel oscillation. The interaction is then governed by a system of integro-differential equations in time t and two spatial variables. A computational code for this system of equations are being constructed with the help of K. Wlodarski in the ICASE summer student program. The numerical solutions will be referred to as the *exact* ones. When the double integral for the loading is replaced by its first order and second order approximations of Miksis and Ting, we have the first order and second order on surface conditions respectively. Earlier studies of the interaction of acoustic waves with a membrane showed that the second order correction is needed when the incident wave is nearly in resonance with a natural frequency

of the panel. Numerical solutions of the acoustic/panel interaction using these approximate on surface conditions is being constructed and compared with the *exact* solutions to establish the accuracy of these on surface conditions.

Nick Verhaagen

The visit to ICASE was used to help initiate a cooperative research program between ICASE, NASA LaRC, TUD and possible other research institutes. The program is meant to generate experimental and numerical data on the interaction process of vortices over double-delta wings. This data will help the further development of wing platforms applied for future high-speed aircraft.

As preparation for future cooperative experimental research, I have familiarized myself with the various visualization and flowfield measuring techniques in use at the Basic Aerodynamics Research Tunnel of the Experimental Methods Branch. In addition, I have worked with scientists of the Computational Aerodynamics Branch in order to generate incompressible Navier-Stokes solutions for the flow over a double-delta wing. These solutions will guide experimental tests that will be carried out in the frame of the cooperative research program in the course of 1993.

To gain information on advanced measurement and computational techniques for vortical flows under development at other institutes, visits were paid to laboratories at Penn State University, NAWC and the University of Michigan.

Bassom Younis

My efforts at ICASE were focused on three separate areas:

1. To assess the performance of a complete Reynolds-stress-transport model of turbulence in separated (steady and unsteady) flows.

The model used was a variant of the LRR model, used in conjunction with wall functions. The test cases considered included vortex shedding from cylinders (square and circular) and steady separation from a semi-circular cylinder. The objective was to see whether the adoption of a higher-order closure can resolve some of the difficulties experienced with mean-field closures such as the k-epsilon model. Fine grid- and time-step resolutions were attempted to minimize numerical diffusion errors. It was found that the model still predicts separation from a circular cylinder to occur downstream of measurements although the results were in marked improvement over the k-epsilon model. For vortex shedding, the model succeeded in capturing the correct amplitude and frequency of oscillations but there were some unsatisfactory features arising mainly from the model used to account for wall reflections.

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2. To see whether some new ideas and proposals in turbulence modelling succeed in resolving the long-standing 'plane jet/round jet' anomaly.

I worked closely with Charles Speziale on testing several newly published (and some yet unpublished) turbulence model adaptations for a wide range of free shear layers, focusing in particular on the plane and axisymmetric jets in stagnant surroundings. The aim was to determine whether any of the models succeeds in resolving the problem that has plagued turbulence models for the last 30 years, namely that all predict the spreading rate of the round jet to be greater than that of the plane jet, contrary to experiments. Some of the models tested were fairly complicated (e.g. Reynolds-stress models with variable coefficients), others were of the k-epsilon variety with input from RNG. None succeeded entirely although some predicted the two spreading rates to be equal.

3. To carry out detailed verification of the SSG (Speziale, Sarkar & Gatski) model for two-dimensional shear flows.

This was perhaps the most interesting and productive part of the visit. Again working closely with Speziale, we applied the SSG to a wide range of wall and free shear flows to assess its performance within the context of a complete Reynolds-stress closure.

The flows considered included: Channel flow, equilibrium wall jets (in adverse pressure gradients), flat-plate boundary layers, plane and round jets, plane wakes and plane mixing layers. The most significant result was the confirmation that the model does indeed reproduce the mean-flow and turbulent details of wall-bounded flows WITHOUT the use of the troublesome model for wall-reflections effects. Moreover, and in most cases, the model was in better accord with measurements than any other practical Reynolds-stress closure. The implications of this part of the work obvious: dispensation with the wall-reflections model removes the principal obstacle to the use of Reynolds-stress-transport models in complex geometries, especially those involving sharp surface discontinuities.

We also tested the SSG model for the case of flow in a channel rotated about its spanwise axis. This is an interesting flow because the turbulence is very sensitive to the body force set up by rotation and many turbulence models fail to capture this without ad-hoc modifications. The SSG model succeeded in reproducing the measured amplification/suppression of turbulence due to rotation (again without using a wall-reflections model) and some of the results appear in ICASE Report 92-57.

Yousef Zurigat

During the period of June 16 to September 15, 1992, a joint research work was conducted on compressible and incompressible boundary layer stability. Two problems were investigated:

The first problem investigated jointly with Dr. J.A. Masad (High Technology Corporation, Hampton, VA) was on supersonic and hypersonic first-mode instability under the influence of pressure gradient. Results are presented in an ICASE report under preparation. A paper entitled "The influence of wall shaping on the first-mode of instability in compressible boundary layers" was submitted to the 1993 Symposium on Transitional and Turbulent Compressible Flows, ASME Fluids Engineering Conference, Washington, DC, June 20-23, 1993.

The second problem investigated jointly with Dr. M. Malik (High Technology Corporation, Hampton, VA) was on incompressible Görtler instability over swept wings. In particular, the effect of crossflow on Görtler instability was studied. A paper entitled "Effect of crossflow on Görtler instability" is being written and will be submitted to TCFD.

Experimental Research

Anwar Ahmed

Listed below are my tasks and responsibilities during my stay at NASA Langley Research Center:

1. Development of Software for turbulence measurements in LTPT

As a part of this assignment I helped develop hot wire data acquisition software for use in the LTPT. The objective of this exercise was to measure and map the turbulence and by two point correlation isolate the acoustic field from the turbulence field. Tests were scheduled for the late August and September. This data has yet to be processed.

2. Control of flow separation on a McDonald Douglas airfoil

Sub-scale vortex generators were used to control separation on the flap. The results were very encouraging. However the results are proprietary.

3. Flow field measurements of a multi-element airfoil at high Reynolds numbers in LTPT

As a part of these tests boundary layer profiles were measured at several locations on the airfoil and flap. The skin friction measured with the help of three different methods namely the Preston tubes, modified Preston tubes (Bertelrud calibration) and a laser interferometer. At present data analyses is in progress at NASA Langley. Additional data will be transferred to Texas A & M for further analysis. The pressure distributions and the skin friction data will be used to calibrate and validate a Navier Stokes Code developed at ICASE.

4. Upgrading of 2-component traversing system in a 2ft X 3ft wind tunnel.

The old traversing system which used optical encoders for position was replaced by an Aerotech stepper motor traversing system and controller. The two axis system was mechanically configured for the 2ft X 3ft wind tunnel and was extensively used for the tests later.

5. Measurement of auto and cross correlations in 2ft X 3ft wind tunnel.

As a precursor to boundary layer receptivity experiments both longitudinal and transverse two points auto and cross correlation measurements were made in the wind tunnel with two hot wire sensors. The goal was to detect any long wavelength standing waves in the test section. Additional goal was to isolate acoustics from turbulence and a check of flow quality. The data has yet to be transferred to Texas A & M University for further analysis.

6. Modification and use of a laser interferometer for skin friction measurement.

A new laser interferometer was built for use in the LTPT. The device met is design objectives was used in the LTPT in conjunction with the high Reynolds number flow field measurements of an airfoil.

7. Design of a low speed water tunnel for PIV measurements.

Based on my experience with the water tunnel at TAMU, I was requested to design a low cost water tunnel for Particle Image Velocity measurements. The tunnel was designed for optical access and test section momentum thickness Reynolds number of 1500. Currently work is in progress.

Thomas Corke

During this six month period we have continued research on problems on instability and transition to turbulence in three principle flow areas: in three-dimensional boundary layers over a rotating disk, in boundary layers over a 7° half-angle cone at supersonic and hypersonic velocities, and in the far-wake region of two-dimensional bluff bodies. The broad objective of this work is to provide a close framework between computational and physical experiments, with an emphasis for the latter of providing as complete as possible documentation and control of initial and background conditions.

In the past six months we have begun assembly of a rotating disk setup at IIT which is comparable to that at LaRC. The setup uses a rotating air bearing on which removable disk surfaces are placed. The design allows complete interchangeability of disks between the setup at IIT and LaRC. We expect to complete the setup by the end of October, 1992. For this we are machining two disk surfaces made from cast aluminum plates. These are ground and lapped to produce a highly flat (within 0.0038mm) and polished surface. One of the disks will be used to study the effect of passive surface imperfections such as single

and multiple (distributed) roughness. The second plate will be further machined in order to insert an azimuthal array of 22 high-strength permanent (Neodymium-Iron-Boron) magnets into the plate and flush with the surface. This plate will be used to introduce stationary and travelling disturbances at the surface. We expect to bring an instrumented disk to use in the LaRC facility for the upcoming ICASE Workshop in the Summer, 1993.

For the second area of research, in the past six months we have been designing all aspects of the model that will be used in the Mach 3.5 Pilot "quiet" Tunnel. In addition we have been refining the technique for introducing controlled disturbances using surface mounted electric glow discharge actuators. The model is designed to fit completely within the "quiet" zone of the Mach 3.5 axisymmetric nozzle. Its length is 35.6cm. The actuator array will be located 3.8cm downstream of the leading point of the model. This will place it just upstream of Branch I for our operating conditions, based on calculations provided by Dr. Craig Streett and his colleagues at ICASE and LaRC. Because of the lack of any access to the model in the tunnel nozzle, the mechanism for traversing velocity sensors will be located just downstream of the base of the model on the support sting. We have been working on the design of this component as well during this period. The traversing mechanism will be fully motorized and capable of traversing hot-wire sensors in all three space dimensions while the tunnel is operating.

In the past six months we have also been working towards validating a computational model for the 3-D spatial nonparallel nonlinear instability analysis for the far wake region based on a Parabolized Stability Equation (PSE) formulation. The model was developed by Dr. Fabio Bertolotti at ICASE. This is the first application of PSE in a flowfield other than in a boundary layer. The far-wake is an especially good candidate for this approach because the instability modes are wholly convective and, as a result of the weak mean shear, they are slow evolving. The experimental analog comes from Corke, Krull and Ghassemi [2]. At this stage the qualitative comparisons look very good. In particular the computational results show the characteristic asymmetry in the 3-D subharmonic mode amplitude distribution across the wake centerline that was predicted by a temporal secondary instability analysis and observed in our experiment. We also compared the streamwise development of all of the important (energy containing) modes that are directly input or result from nonlinear interactions.

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[2]Corke, T. C., Krull, J. and Ghassemi, M. 1992. *J. Fluid Mech.*, *239*, pp 99-132.

Chelakara S. Subramanian

The work reported here is a part of ongoing research on three-dimensional turbulent boundary layer structures carried out by the Experimental Flow Physics Branch (EFPB) at LaRC. The Branch coordinators are Drs. S.K. Robinson, J.T. Kegelman and Mr. B.S. Lazos. This study aims to investigate the characteristics of a boundary layer formed as a result of secondary flow induced by a rotating disc in a fully developed turbulent boundary layer. The information from this study is important for developing better turbulence models to predict flows such as those on swept wings.

A rotating disc in an otherwise quiescent fluid induces axial secondary flow normal to the disc to replenish the mass of radial outflow caused by centrifugal forces (Schlichting, 1979). In this case, the overall fluid motion is controlled by the interaction of viscous, pressure gradient and centrifugal forces. The viscosity of the fluid causes a boundary layer to form on the disc, the thickness of which is roughly proportional to $\sqrt{(v/\omega)}$, where v is the kinematic viscosity and ω is the angular speed of rotation on the disc. The tangential velocity is the only non-zero velocity component of the flow at the surface of the disc. Outside the disc boundary layer all the velocity components decay to zero. However, the dynamics of the flow on the disc will be different when an external two-dimensional boundary layer flow is superimposed on the rotating boundary layer. To understand this flow's dynamics, the present experiment is performed in the 50.96 cm $\times$ 71.34 cm $\times$ 4.57 m open circuit wind tunnel on a 4.57 m long flat plate with a 10.19 cm diameter disc, the center of which is located 3.66 m downstream of the plate's leading edge. The disc is driven by a variable speed DC motor. For validating the flow quality and experimental techniques, the following baseline checks are used. The cross-stream dynamic pressure distributions at four streamwise stations indicate a satisfactory flow uniformity within the middle of the 38.2 cm $\times$ 50.96 cm area of the test section. The measured freestream turbulence intensity is found to be less than 0.08 percent. This value, however, increased to 0.15 percent with the introduction of the flat (splitter) plate in the tunnel. The boundary layer velocity profiles and the boundary layer integral parameters are used to affirm the two-dimensionality and full development of a flat plate turbulent boundary layer approaching the disc. The skin friction coefficient determined from the law-of-the-wall fit is also used to establish the two-dimensionality of the boundary layer. A qualitative picture of the flow field near the surface of rotating disc is obtained by tuft flow visualization method. The flow pattern suggests that: (a) at spin ratios ($r\omega/U_{ref}$, where r is the disc's radius and U_{ref} is the free stream velocity) near unity the flow is radially outward near the disc surface, but at spin ratios of about 0.5, some pockets of vortical flows exist at small radii and radially outward flows only occur at large radii. This latter pattern is observed in the flow on the part of the disc that moves against the mainstream flow, (b)

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this general flow pattern, described in (a) is not noticeably altered by a two-fold change in the free stream velocity. The 3-component Laser Doppler Velocimeter (LDV) measurements on the rotating disc are now underway. My involvement with the project is expected to continue. Archival publication of this work will follow the analysis of the LDV data.

APPLIED COMPUTER SCIENCE

Shahid Bokhari

Work has been focused in two areas.

1. A study of load balancing on large networks. This research addresses the problem of load balancing on very large networks of processors. It is assumed that each processor has some arbitrary number of indivisible 'atoms' of load on it and the objective is to obtain ideal load balance (i.e. two processors should not differ by one atom of load). The constraints I am working under are that (1) the entire load balancing process be performed without knowledge of the global state of the system. A processor can look only at its neighboring processors, in order to decide whether to ship out load, and (2) only one atom of load can be transmitted and/or received during one time step. These constraints realistically describe the state of affairs that can be expected to exist on real large networks.

I have established that optimal load balance can be achieved only under certain conditions and on certain types of networks. I am in the process of obtaining bounds for the load achieved for classes of networks. An exact expression for the number of time steps required to achieve balance has turned out to be surprisingly difficult to obtain, although I have made progress in this direction also.

2. The number of optimal multiphase algorithms for complete exchange. Prior research has shown how a multiphase approach can be beneficial when carrying out the complete exchange on a circuit switched hypercube. I am now exploring the maximum number of optimal algorithms possible under this approach. A bound on this number will eliminate the need to enumerate over all possible partitions of the integer describing the dimension of the hypercube.

Tom Crockett

Transfer of the iPSC/860 complex from ICASE to ACD was completed. As part of this process, the existing ACD user ID database was integrated with the distributed community's "checkuid" database. This provides uniform UIDs between ACD and participating organizations within Langley's distributed computing community. Uniform UIDs, in turn, allow cross-mounting of filesystems among cooperating organizations. The new "universal mount point" naming convention for shared filesystems was implemented on the iPSC complex and across all of the ICASE systems, allowing users transparent access to files regardless of which system they log in on.

Specific requirements for visualization infrastructure were identified in consultation with other members of the staff. The top-priority items were obtained in two procurements, giving a needed boost to ICASE's visualization and computational capabilities. Recruiting of visualization research staff was also a major focus during the summer and fall.

Design and development of a parallel graphics library continued, along with further analysis of the Orloff/Crockett rendering algorithm. As part of this activity, a fast, semi-parallel color-quantization method was developed and tested in our prototype renderer. The color quantization problem also served as partial motivation for work by Bokhari on a high-speed partitioning algorithm, which we plan to evaluate in coming months. We are also trying to develop new parallel rendering algorithms which include the positive characteristics of the Orloff/Crockett algorithm, but exhibit improved load balancing and scalability to very large numbers of processors.

Contacts were established with a number of other researchers who are active in the parallel rendering field. A mailing list is being maintained at ICASE for members of this community to keep in touch, and a Birds-of-a-Feather meeting on the subject was organized at SIGGRAPH '92. A workshop on Massively Parallel Rendering is being developed in conjunction with Scott Whitman of LLNL and Chuck Hansen of LANL.

Raja Das

We have been working on tools and techniques to efficiently parallelize irregular problems. Using the methods that are being developed we have parallelized the computationally intensive parts of a molecular dynamics code CHARMM and a 3-D unstructured multigrid Euler solver. Both these codes run on the Touchstone Delta machine.

We have also developed a dataflow framework which provides a basis for rigorously using the runtime preprocessing methods aimed at loops in which some array references are made through a level of indirection. This work was done with Reinhard von Hanxleden and Chuck Koebel at Rice University and Joel Saltz. A detailed report on this work can be found in ICASE Report No. 92-22.

A detailed algorithm for parallelizing irregular loops has been developed. Parts of this algorithm was implemented in a prototype compiler. At the moment we are in the process of implementing the general algorithm in the Parascope environment. This will let us parallelize loops with more than a single level of indirection.

Graham Horton

Time-parallelism is a technique for using parallelism to accelerate the solution of time-dependent partial differential equations. Standard parallel strategies utilize space-parallelism,

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i.e. they decompose the problem in one or more space-dimensions and distribute segments of the computation at one time-step to different processors. The time-parallel strategy differs in that it computes solutions to the P.D.E. at several points in time simultaneously. Speedup is obtained by reducing the total number of iterations performed to integrate over a given time interval.

The two-dimensional incompressible Navier-Stokes equations were considered as a model problem. An existing time-parallel code was adapted to additionally allow standard (space) parallelism and implemented on an iPSC/860. The question of interest was to determine how a fixed number of nodes may best be allocated to a time- or a space-parallel mode in order to maximize overall efficiency. It was found that for a Reynolds number of 1000, the time-parallel approach yielded the highest efficiency in all cases. For the low Reynolds number of 10, however, it was seen that time- and space parallelism yielded approximately the same efficiencies.

David Keyes

Implicit methods for PDEs can be parallelized by decomposing the domain into subdomains, and applying standard implicit solvers to each subdomain, as is commonly done in multiblock aerodynamics codes. Faster convergence may be obtained by using the set of subdomain solves as a preconditioner for an iterative method such as conjugate gradients or its generalizations to nonsymmetric systems. However, the convergence rate of a block-diagonal preconditioner based on subdomain solves alone will degrade as the number of subdomains is increased in pursuit of large-scale parallelism, the condition number typically rising as some power of the number of subdomains.

A granularity-independent convergence rate can be achieved – even for nonsymmetric and indefinite systems – by solving a coarse-grid problem with one point per subdomains as part of each preconditioner application, in addition to the subdomain solves. The coarse-grid problem is difficult to parallelize but may be solved simultaneously with the subdomains.

We have tested a variety of such preconditioners on Navier-Stokes problems and parallelized some of them up to modest granularity on the Intel Hypercube. We have also tested most of the nonsymmetric Krylov iterative methods in the active literature on a collection of Jacobians from CFD problems and found GMRES and BiCGSTAB very effective in conjunction with domain decomposition preconditioners. Our current effort focuses on transonic aerodynamics, and the Jacobians from Newton methods applied to find the steady states.

Piyush Mehrotra

Exploiting the full potential of parallel architectures requires a cooperative effort between the user and the language system. There is a clear a trade-off between the amount of information the user has to provide and the amount of effort the compiler has to expend to generate optimal code. At one end of the spectrum are message passing languages where the user has full control and has to provide all the details while the compiler effort is minimal. At the other end of the spectrum is sequential languages where the compiler has the full responsibility for extracting the parallelism. For the past few years, we have been exploring median solutions, such as Kali and Vienna Fortran, which provide a fairly high level environment for distributed memory machines while giving the user some control over the placement of data and computation. These efforts have been very influential in the design of High Performance Fortran (HPF), an international effort to build a set of standard extensions for exploiting a wide variety of parallel architectures.

However, it is clear that such HPF-like languages may not have enough expressive power to provide all the information needed by the compiler to generate the most optimal code. One area of focus has been that of inter-disciplinary optimization. For example, a full design of an airplane requires the coupling of codes from vastly different disciplines such as aerodynamics, structural analysis and controls. These codes are internally data parallel and thus can be expressed via HPF-like languages but exhibit more asynchronous parallelism at the outer level. In a joint effort with John Van Rosendale, Barbara Chapman and Hans Zima, we have been designing a set of language constructs which would allow the user to explicitly control this outer level of asynchronous interaction. The goal is to provide an environment which allows a seamless integration of different parallel programming paradigms in a manner which is is portable across a wide variety of systems ranging from a single parallel architecture to a heterogeneous network of machines.

Another area that we have been studying is that of parallel input-output. I/O provides a means for independent programs to interact with each other. For parallel programs running on distributed memory machines the input and output of distributed data can become a major performance bottleneck. For example, enforcing the Fortran column-major serial order when writing to a file may imply that the data is unnecessarily redistributed, particularly if it is to be subsequently read into a similarly distributed array. In a joint effort with Hans Zima and some members of his group, we have designed a set of language extensions (within the context of Vienna Fortran) which allow the user to give hints about the subsequent usage of data that is being output. This gives the compiler the opportunity to optimize both

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the writing and the reading of distributed data. Preliminary experiments on an iPSC/860 indicate that use of such constructs can significantly enhance the performance of codes running on such machines.

David Nicol

In collaboration with with Albert Greenberg and Bruno Gaujal (AT&T Bell Labs) we have developed a new algorithmic paradigm for parallel simulation, called "sweeps". Sweeps are particularly useful on SIMD machines, as their constituent parts are parallel-prefix operations. Simulation event rates approaching 1.5 million events/sec have been achieved on a 16K MasPar-1.

In collaboration with Phil Heidelberger (IBM Research) we are developing new synchronization algorithms for parallel simulation, to be used when the underlying system is a Markov chain. Our approach is based on the method of uniformization, which essentially gives us a mechanism by which we can predict exactly when communications occur. We have implemented both conservative and optimistic versions of the method, achieving speedups of at least 220 on 256 Touchstone Delta nodes. New work on this project has produced versions that adaptive to the underlying behavior of the simulation.

Barrier synchronization is a fundamental component of many parallel algorithms. All previously known algorithms assume that a processor does not enter a barrier until it is certain that it has already performed all necessary pre-synchronization work. This is not always the case, especially when the computation's processing is largely driven by the arrival of messages from other processors. We have developed a new barrier algorithm, based on the notion of optimism, for handling such cases. We have test the algorithm on Intel iPSC/860 and Touchstone Delta architectures, and found it to have approximately twice the cost of the standard `gsync()` algorithm.

Terrence Pratt

PISCES 5 is a software environment that provides automatic generation of parallel programs from existing serial/vector codes. The current version of the software is being revised to encorporate a new method for handling the partitioning and distribution of large data arrays for MIMD, distributed memory, parallel machines. This project has been moved to CESDIS at the NASA Goddard Space Flight Center.

Matthew Rosing

Work in developing a low latency message interface and language and compiler techniques for the efficient use of distributed memory multiprocessors continues.

A simplified operating system for the iPSC/860 that supports direct access to the communication hardware has been built. This has allowed the reduction of the software component of message latency to drop from approximately 50 μs to less than 1 μs. Work continues in developing an interface that is both portable and efficiently implementable on a range of distributed memory multiprocessors. This work is being done in conjunction with J. Saltz.

We have defined a fortran based language that is extensible. This language provides the ability for compiler modules to be easily added to the base language. Each module is a set of constructs that are appropriate for an application domain. As an example, we have defined a module that is similar in nature but simpler than Dino, a language we have previously implemented, and HPF, a language that is currently being developed elsewhere. This work is being done in conjunction with R. Schnabel at the University of Colorado.

Joel Saltz

We developed several optimizations that can be used to implement irregular codes on distributed memory architectures, incorporated these optimizations into a toolkit (PARTI - Parallel Automated Runtime Toolkit at ICASE), and employed PARTI to port the unstructured explicit and multigrid codes. The three dimensional compressible gas dynamics equations which comprise a non-linear system of five partial differential equations, are discretized on an unstructured mesh using a Galerkin finite-element approach. The resulting code consists of a sequence of loops over mesh edges and boundary faces. The data access pattern is determined by indirection patterns determined by large arrays of integers used to define mesh edges. The PARTI primitives are designed to ease the implementation of irregular computational problems on distributed memory machines. The PARTI primitives handle the distribution and retrieval of globally indexed but irregularly distributed data-sets over the numerous local processor memories. The version of PARTI described in Saltz et. al. in the December 1991 issue of Concurrency Practice and Experience was initially used to port the unstructured mesh Euler solvers. We then proceeded to identify ways in which the performance of unstructured codes could be optimized. The optimizations that involved reduction of communication overheads resulted in an improved version of PARTI. This improved version was used to port the unstructured mesh codes. The optimizations that involved reduction of computation time were manually implemented.

The single processor performance of computationally important loops over the types of meshes we wanted to handle originally ranged from 2.5 to 3 Mflops. It seemed likely that

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this relatively poor performance is due to the effects of irregular data access patterns on the i860 memory hierarchy The single processor performance was improved by reordering the data and by changing the order in which mesh edges were traversed in loops. These optimizations led to roughly a factor of two improvement in single processor performance.

We have run two test cases. The first was a Mach 0.84 flow over a ONERA M6 wing at 3.06 degrees incidence. The finest mesh used for the problem had 357,900 vertices and just over 2 million tetrahedra. The second test case consisted of computing a highly resolved flow over a three-dimensional aircraft configuration. The mesh contained 804,056 points and approximately 4.5 million tetrahedra. We employed a recursive spectral partitioning code kindly given to us by Horst Simon at NASA Ames to partition both problems. We ran the explicit unstructured mesh code on the larger problem and achieved a rate of 1.5 Gflops on 512 Delta processors, we ran V Cycle unstructured multigrid and obtained a computational rate of 1.2 Gflops, and ran W cycle multigrid and obtained a computational rate of 1.0 Gflops.

Both V and W cycle multigrid required roughly a factor of 8 fewer operations to solve the three dimensional configuration than did the explicit solver. The parallel multigrid codes were able to compute a converged flowfield around a full aircraft configuration in approximately 10 minutes on the Intel Delta. This work is joint with Raja Das, Dimitri Mavriplis and S. Gupta

We have developed a suite of primitives that track runtime data dependencies. These primitives employ a static task and communication schedule on each processor. A preprocessing phase determines the precise sequence in which work and communication are to be carried out. These primitives have been used to port sparse sparse direct methods to the iPSC/860. Results are very favorable relative to hand coded sparse factorization methods. The absolute performance results for these and other distributed memory implementations of sparse factorization methods are still unimpressive and we are actively seeking improved performance. Longer term, these primitives will evolve into the runtime support needed to handle problems with runtime determined loop carried dependencies such as sparse factorizations and sparse triangular solves. This work is joint with Sesh Venugopal (Rutgers University) and Vijay Naik (IBM Hawthorne).

We developed a dataflow framework which provides a basis for rigorously defining strategies to make use of runtime preprocessing methods for distributed memory multiprocessors.

In many programs, several loops access the same off-processor memory locations. Our runtime support gives us a mechanism for for tracking and reusing copies of off-processor data. A key aspect of our compiler analysis strategy is to determine when it is safe to reuse copies of off-processor data. Another crucial function of the compiler analysis is to identify

situations which allow runtime preprocessing overheads to be amortized. This dataflow analysis will make it possible to effectively use the results of interprocedural analysis in our efforts to reduce interprocessor communication and the need for runtime preprocessing. This is joint work with Raja Das at ICASE, Rinehard von Hanxleden, Ken Kennedy, Chuck Koelbel at Rice; Geoffrey Fox and Alok Choudhary at Syracuse.

Hong Zhang Sun

In collaboration with V. Ervin (Clemson University) and W. Layton (University of Pittsburgh), we have generalized the alternating direction implicit method (ADI), used in numerical solution of differential equations, into a framework especially well suited for modern massively parallel computers. Our new method combines the operator splitting inherent in ADI with domain decomposition. Therefore the resulting linear systems are block diagonal with reduced band-width and perfectly suited to parallel processing. In addition, the method does not depend upon a symmetric discretization operator, or a particular shape of the domain. We recently began investigating a new variant of ADI which uses a diagonal parameter matrix at each iteration, rather than the usual scalar relaxation parameter. The optimization is motivated by concern for parallel implementation, since minimizing the number of iterations is necessary for reaching high efficiency on parallel machines.

The remaining problem in this work is finding the optimal diagonal iteration matrix. We are presently investigating several approaches for calculating this matrix in order to reduce communication overhead on parallel machines. While studying and testing these algorithm, several interesting properties have been established. Thus far, the rapid convergence of these schemes under consideration has been observed in our experiments, and for some, it has been proven.

Xian-He Sun

Tensor product algorithms, such as ADI (alternating direction implicit) are a standard approach to numerical simulation of fluids. However, on parallel computers, the large amounts of communication and synchronization inherent in these algorithms can be a severe performance bottleneck. Recent work, done in collobarion with John Van Rosendale, has focused on an ICASE/NASA turbulence code, written by Gordon Erlebacher, which is analogous to an ADI code in that it uses compact differences requiring multiple tridiagonal solves in all three coordinate directions at each time step. This is a well tuned code recently implemented on the Intel I/860 hypercube by Gordon Erlebacher and Tom Eidson. On the 32 processor ICASE machine, it was found that about 30% of the time was consumed by

communication overhead on large meshes. With larger machines, the fraction of time spent on communication would increase.

There are two natural approaches to reducing the communications and synchronization overhead, one can either improve the tridiagonal solver used, or change the discretization to one which is less communication intensive. Following the first approach, we are studying the use of alternate tridiagonal solvers which increase the arithmetic complexity but decrease communications. We are also exploring the possibility of using an iterative solver, which will approximately invert the tridiagonal systems to sufficient accuracy. Following the second approach, we are exploring the use of a standard finite difference schemes coupled with the use of defect correction to obtain a high order scheme comparable to the compact scheme. Balancing numerical accuracy against communication overhead is a subtle problem, and one which is not well understood.

Alan Sussman

We have been working on the development of tools for mapping multi-block multigrid applications onto distributed memory parallel processors. With Satyanarayan Gupta, I have implemented a library of routines that provides Fortran D style declarations of distributed arrays, for both Fortran and C programs, along with routines for managing the communication required to maintain globally consistent distributed arrays. I have built an example application that incorporates the library routines and runs on the iPSC/860, to demonstrate the capabilities of the library. Work is continuing on incorporating these routines into the multi-block, multigrid Navier Stokes code written by V. Vatsa and M. Sanetrik (Fluid Mechanics Division, LaRC), with the eventual goal of building a compiler that can transform a sequential block structured program into a distributed memory parallel program.

Once the complete multi-block code runs on the iPSC/860, we will be investigating the performance of the application and library routines on several distributed memory parallel machines, including the Intel Delta, Intel Paragon, TMC CM-5 and Intel/CMU iWarp machines.

We have also begun to investigate the application of the block structured library routines to structured adaptive problems. We will be working with a structured adaptive grid program developed by J. Quirk and a combustion code developed by M. Smooke (at Yale), to augment our current set of routines with the additional functionality required to support adaptive grids on a distributed memory parallel machine.

John Van Rosendale

While mapping of standard multigrid to parallel architectures has been well studied, new issues arise in mapping more complex multigrid algorithms. Algorithms based on line- or plane-relaxation, or algorithms using multiple semicoarsened grids (MSG algorithms) are needed for problems having stretched grids or anisotropic operators. Mapping these algorithms to parallel architectures is challenging, because of the large amount of communication required and the complex load balancing issues arising. Parallel implementation of these algorithm is important in many applications areas, including computational fluid dynamics.

In collaboration with Andrea Overman of the Computational Sciences branch, we are currently studying the issues involved in mapping MSG (multiple semicoarsened grid) multigrid to scalable memory machines like the Intel Paragon. One version of this algorithm uses standard V-cycle multigrid, in which the smoothing iteration is done on only one multigrid level at a time. This is an effective numerical algorithm, but raises very difficult mapping issues on distributed memory architectures. There is also a more parallel version of this algorithm, using a C-cycle in which all levels are smoothed simultaneously. The latter is simpler to map to parallel machines, but does not appear to be as efficient.

The approach currently being explored to mapping the V-cycle algorithm is based on a dynamic programming algorithm, designed by Dave Nicol. In MSG, one has multiple grids on each level, each having a different shape. The dynamic programming algorithm assigns mesh points to processors in a near optimal manner. The resulting parallel algorithm is then implemented on parallel machines using a version of the PARTI runtime primitives developed by Alan Sussman and Satyanarayan Gupta.

A related project, recently begun in collaboration with Piyush Mehrotra, is studying the expressivity of HPF (High Performance Fortran) for NASA applications. Tools like PARTI, while very useful for expert programmers, are quite low level, and unsuited to most applications programmers. High Performance Fortran is a new Fortran standard, expressely designed for highly parallel machines, and incorporating ideas from Kali, Vienna Fortran, Fortran D, and other previous languages for distributed memory machines. HPF will allow applications programmers to express parallel algorithms without descending below the Fortran level, a major advance. However, while HPF seems well suited to a broad class of NASA codes, including most tensor product algorithms, it may not be well suited for problems on block structured codes, and clearly cannot currently handle unstructured codes or sparse matrix applications. We are studying the problems of expressivity in HPF, and looking at which additional constructs might be needed to handle applications in these other classes.

Mohammed Zubair

In order to obtain good performance on a distributed memory parallel machine, it is important to minimize communication overheads. Furthermore, it is equally important to have good single node computation performance as any improvement in the computation performance of a single node will have a multiplicative effect on the overall performance. In this research, we are focusing on the design of algorithms for numerically intensive kernels commonly encountered in large scientific computations arising out of NASA applications. These algorithms are being designed for various distributed memory parallel machines. The basic strategy being followed in the designing and testing of these scientific kernels is as follows:

- Study various data distributions and their impact on the performance.

- Design and implement algorithms that maximize single node performance and minimize communication overheads.

- Integrate the kernel with a real NASA code and evaluate its performance.

The availability of basic computational kernels will help in porting existing applications or implementing new NASA applications on parallel machines. These kernels will be tuned to a particular architecture and will result in an efficient implementation of the complete application. Thus a scientist or an engineer wishing to perform massively parallel computations need not be aware of various hardware/software features of a parallel machine that are critical for obtaining good performance.

The two kernels which we are currently investigating are the three-dimensional FFT kernel and the sparse direct solver.

REPORTS AND ABSTRACTS

Engquist, Bjorn, Stanley Osher and Sifen Zhong: *Fast wavelet based algorithms for linear evolution equations.* ICASE Report No. 92-14, April 16, 1992, 28 pages. Submitted to SIAM Journal on Scientific and Statistical Computing.

We devise a class of fast wavelet based algorithms for linear evolution equations whose coefficients are time independent. The method draws on the work of Beylkin, Coifman, and Rokhlin [*Comm. Pure Appl. Math* **64** (1991)] which they applied to general Calderon-Zygmund type integral operators. We apply a modification of their idea to linear hyperbolic and parabolic equations, with spatially varying coefficients. A significant speedup over standard methods is obtained when applied to hyperbolic equations in one space dimension and parabolic equations in multidimensions.

Bassom, Andrew P., and S.R. Otto: *On the stability of nonlinear viscous vortices in three-dimensional boundary layers.* ICASE Report No. 92-15, April 17, 49 pages. Submitted to Journal of Fluid Mechanics.

Recently it has been demonstrated that three-dimensionality can play an important role in dictating the stability properties of any Görtler vortices which a particular boundary layer may support. According to a linearised theory, vortices within a high Görtler number flow can take one of two possible forms within a two-dimensional flow supplemented by a small crossflow of size $O(R_e^{-1/2}G^{3/5})$ where R_e is the Reynolds number of the flow and G the Görtler number. Bassom & Hall [*J. Fluid Mech.* **232** (1991)] showed that these forms are characterised by $O(1)$ wavenumber inviscid disturbances and larger, $O(G^{1/5})$, wavenumber modes which are trapped within a thin layer adjacent to the bounding surface. Here we concentrate on the latter, essentially viscous vortices and describe their weakly nonlinear stability properties in the presence of crossflow. It is shown conclusively that the effect of crossflow is to stabilise the nonlinear disturbances and the calculations herein allow stable, finite amplitude perturbations to be found. Predictions are made concerning the likelihood of observing some of these viscous modes within a practical setting and asymptotic work permits discussion of the stability properties of modes with wavenumbers which are small relative to the implied $O(G^{1/5})$ scaling.

Speziale, C.G., T.B. Gatski, and S. Sarkar: *On testing models for the pressure-strain correlation of turbulence using direct simulations.* ICASE Report No. 92-16, April 21, 1992, 42 pages. To be submitted to the Physics of Fluids A.

Direct simulations of homogeneous turbulence have, in recent years, come into widespread use for the evaluation of models for the pressure-strain correlation of turbulence. While work in this area has been beneficial, the increasingly common practice of testing the slow and rapid parts of these models separately in uniformly strained turbulent flows is shown in this paper to be unsound. For such flows, the decomposition of models for the pressure-strain correlation into slow and rapid parts is ambiguous. Consequently, when tested in

this manner, misleading conclusions can be drawn about the performance of pressure-strain models. This point is amplified by illustrative calculations of homogeneous shear flow where other pitfalls in the evaluation of models are also uncovered. More meaningful measures for testing the performance of pressure-strain models in uniformly strained turbulent flows are proposed and the implications for turbulence modeling are discussed.

Banks, H.T., R.J. Silcox, and R.C. Smith: *The modeling and control of acoustic/structure interaction problems via piezoceramic actuators: 2-D numerical examples.* ICASE Report No. 92-17, April 24, 1992, 30 pages. Submitted to the ASME Journal of Vibration and Acoustics.

The modeling and active control of acoustic pressure in a 2-D cavity with a flexible boundary (a beam) is considered. Control is implemented in the model via piezoceramic patches on the beam which are excited in a manner so as to produce pure bending moments. The incorporation of the feedback control in this manner leads to a system with an unbounded input term. Approximation techniques are discussed and by writing the resulting system as an abstract Cauchy equation, the problem of reducing interior pressure fluctuations can be posed in the context of an LQR time domain state space formulation. Examples illustrating the dynamic behavior of the coupled system as well as demonstrating the viability of the control method on a variety of problems with periodic forcing functions are presented.

Erlebacher, Gordon, and Sutanu Sarkar: *Statistical analysis of the rate of strain tensor in compressible homogeneous turbulence.* ICASE Report No. 92-18, April 29, 1992, 39 pages. Submitted to Physics of Fluids A.

Recent analysis of direct numerical simulations of compressible homogeneous shear flow turbulence has unraveled some of the energy transfer mechanisms responsible for the decrease of kinetic energy production when the flow becomes more compressible. In this complementary study, we focus our attention on the rate of stain tensor. A Helmholtz decomposition of the velocity field leads us to consider a solenoidal and an irrotational rate of strain tensor. Their eigenvalue distributions, eigenvector orientations, and the relative alignment between the eigenvectors and the vorticity and pressure gradient vectors are examined with the use of probability density functions. The irrotational rate of strain tensor is found to have a preferred structure in regions of strong dilatation. This structure depends on the mean shear, and is quite different from that of the solenoidal rate of strain tensor. Compressibility strongly affects the orientation properties of the pressure gradient vector.

Demuren, A.O., and S. Sarkar: *Systemic study of Reynolds stress closure models in the computations of plane channel flows.* ICASE Report No. 92-19, April 29, 1992, 28 pages. Submitted to ASME Journal of Fluids Engineering.

This paper investigates the roles of pressure-strain and turbulent diffusion models in the numerical calculation of turbulent plane channel flows with second-moment closure models. Three turbulent diffusion and five pressure-strain models are utilized in the computations. The main characteristics of the mean flow and the turbulent fields are compared against experimental data. All the features of the mean flow are correctly predicted by all but one

of the Reynolds stress closure models. The Reynolds stress anisotropies in the log layer are predicted to varying degrees of accuracy (good to fair) by the models. None of the models could predict correctly the extent of relaxation towards isotropy in the wake region near the center of the channel. Results from the direct numerical simulation are used to further clarify this behaviour of the models.

Jackson, T.L., M.Y. Hussaini, and H.S. Ribner: *Shock-turbulence interactions in a reacting flow*. ICASE Report No. 92-20, April 30, 1992, 18 pages. Submitted to Physics of Fluids A.

This paper addresses a specific reactive-flow configuration, namely, the interaction of a detonation wave with convected homogeneous isotropic weak turbulence (which can be constructed by a Fourier synthesis of small-amplitude shear waves). The effect of chemical heat release on the rms fluctuations downstream of the detonation is presented as a function of Mach number. In addition, for the particular case of the von Karman spectrum, the one-dimensional power spectra of these flow quantities is given.

Cockburn, Bernardo, and Chi-Wang Shu: *Nonlinearly stable compact schemes for shock calculations*. ICASE Report No. 92-21, May 21, 1992, 25 pages. Submitted to SIAM Journal of Numerical Analysis.

In this paper we discuss the applications of high order compact finite difference methods for shock calculations. The main idea is the definition of a local mean which serves as a reference for introducing a local nonlinear limiting to control spurious numerical oscillations while keeping the formal accuracy of the scheme. For scalar conservation laws, the resulting schemes can be proven total variation stable in one space dimension and maximum norm stable in multiple space dimensions. Numerical examples are shown to verify accuracy and stability of such schemes for problems containing shocks. The idea in this paper can also be applied to other implicit schemes such as the continuous Galerkin finite element methods.

von Hanxleden, Reinhard, Ken Kennedy, Charles Koelbel, Raja Das, and Joel Saltz: *Compiler analysis for irregular problems in Fortran D*. ICASE Report No. 92-22, June 15, 1992, 24 pages. Submitted to the 5th Workshop on Languages and Compilers for Parallel Computing, New Haven, CT, August 3-5, 1992.

We developed a dataflow framework which provides a basis for rigorously defining strategies to make use of runtime preprocessing methods for distributed memory multiprocessors.

In many programs, several loops access the same off-processor memory locations. Our runtime support gives us a mechanism for tracking and reusing copies of off-processor data. A key aspect of our compiler analysis strategy is to determine when it is safe to reuse copies of off-processor data. Another crucial function of the compiler analysis is to identify situations which allow runtime preprocessing overheads to be amortized. This dataflow analysis will make it possible to effectively use the results of interprocedural analysis in our efforts to reduce interprocessor communication and the need for runtime preprocessing.

Hall, Philip: *Streamwise vortices in heated boundary layers*. ICASE Report No. 92-23, June 5, 1992, 39 pages. Submitted to Journal of Fluid Mechanics.

The nonlinear instability of the boundary layer on a heated flat plate placed in an on-coming flow is investigated. Such flows are unstable to stationary vortex instabilities and inviscid traveling wave disturbances governed by the Taylor-Goldstein equation. For small temperature differences the Taylor-Goldstein equation reduces to Rayleigh's equation. When the temperature difference between the wall and free stream is small the preferred mode of instability is a streamwise vortex. It is shown in this case that the vortex, assumed to be of small wavelength, restructures the underlying mean flow to produce a profile which can be massively unstable to inviscid traveling waves. The mean state is shown to be destabilized or stabilized to inviscid waves depending on whether the Prandtl number is less or greater than unity.

Bryan, Kurt, and Michael Vogelius: *A computational algorithm for crack determination. The multiple crack case*. ICASE Report No. 92-24, June 11, 1992, 40 pages. Submitted to International Journal of Engineering Sciences.

This paper develops an algorithm for recovering a collection of linear cracks in a homogeneous electrical conductor from boundary measurements of voltages induced by specified current fluxes. The technique is a variation of Newton's method and is based on taking weighted averages of the boundary data. The method also adaptively changes the applied current flux at each iteration to maintain maximum sensitivity to the estimated locations of the cracks.

Jackson, Thomas L., and Moshe Matalon: *Stability of a premixed flame in stagnation-point flow against general disturbances*. ICASE Report No. 92-25, June 19, 33 pages. Submitted to Journal – Combustion Science Technology.

Previously, the stability of a premixed flame in a stagnation flow was discussed for a restricted class of disturbances that are self-similar to the basic undisturbed flow; thus, flame fronts with corrugations only in the cross stream direction were considered. Here, we consider a more general class of three-dimensional flame front perturbations which also permits corrugations in the streamwise direction. It is shown that, because of the stretch experienced by the flame, the hydrodynamic instability is limited only to disturbances of short wavelength. If in addition diffusions effects have a stabilizing influence, as would be the case for mixtures with Lewis number greater than one, a stretched flame could be absolutely stable. Instabilities occur when the Lewis number is below some critical value less than one. Neutral stability boundaries are presented in terms of the Lewis number, the strain rate and the appropriate wavenumbers. Beyond the stability threshold the two-dimensional self-similar modes always grow first. However, if disturbances of long wavelength are excluded, it is possible for the three-dimensional modes to be the least stable one. Accordingly, the pattern that will be observed on the flame front, at the onset of instability, will consist of either ridges in the direction of stretch or the more common three-dimensional cellular structure.

Fu, Yibin, and Philip Hall: *Crossflow effects on the growth rate of inviscid Görtler vortices in a hypersonic boundary layer.* ICASE Report No. 92-26, June 24, 1992, 36 pages. Submitted to JFM.

The effects of crossflow on the growth rate of inviscid Görtler vortices in a hypersonic boundary layer with pressure gradient are studied in this paper. Attention is focussed on the inviscid mode trapped in the temperature adjustment layer; this mode has greater growth rate than any other mode. The eigenvalue problem which governs the relationship between the growth rate, the crossflow amplitude and the wavenumber is solved numerically, and the results are then used to clarify the effects of crossflow on the growth rate of inviscid Görtler vortices. It is shown that crossflow effects on Görtler vortices are fundamentally different for incompressible and hypersonic flows. The neutral mode eigenvalue problem is found to have an exact solution, and as a by-product, we have also found the exact solution to a neutral mode eigenvalue problem which was formulated, but unsolved before, by Bassom and Hall [*J. Fluid Mech.* **232** (1991)].

Gottlieb, David, and Chi-Wang Shu: *Resolution properties of the Fourier method for discontinuous waves.* ICASE Report No. 92-27, June 25, 1992, 16 pages. Submitted to Proc. of ICOSAHOM '92 and to be submitted to Computer Methods in Applied Mechanics and Engineering.

In this paper we discuss the wave-resolution properties of the Fourier approximations of a wave function with discontinuities. It is well known that a minimum of two points per wave is needed to resolve a periodic wave function using Fourier expansions. For Chebyshev approximations of a wave function, a minimum of π points per wave is needed [Gottlieb and Orszag *SIAM-CBMS* (1977)]. Here we obtain an estimate for the minimum number of points per wave to resolve a discontinuous wave based on its Fourier coefficients.

In our recent work on overcoming the Gibbs phenomenon, we have shown that the Fourier coefficients of a discontinuous function contain enough information to reconstruct with exponential accuracy the coefficients of a rapidly converging Gegenbauer expansion. We therefore study the resolution properties of a Gegenbauer expansion where both the number of terms and the order increase.

Abid, R., and C.G. Speziale: *Predicting equilibrium states with Reynolds stress closures in channel flow and homogeneous shear flow.* ICASE Report No. 92-28, June 30, 16 pages. To be submitted to the Phys. Fluids A.

Turbulent channel flow and homogeneous shear flow have served as basic building block flows for the testing and calibration of Reynolds stress models. In this paper, a direct theoretical connection is made between homogeneous shear flow in equilibrium and the log-layer of fully-developed turbulent channel flow. It is shown that if a second-order closure model is calibrated to yield good equilibrium values for homogeneous shear flow it will also yield good results for the log-layer of channel flow provided that the Rotta coefficient is not too far removed from one. Most of the commonly used second-order closure models introduce an ad hoc wall reflection term in order to mask deficient predictions for the log-layer of channel flow that arise either from an inaccurate calibration of homogeneous shear flow or from the use of a Rotta coefficient that is too large. Illustrative model calculations

are presented to demonstrate this point which has important implications for turbulence modeling.

Denier, James P., and Philip Hall: *Fully nonlinear Görtler vortices in constricted channel flows and their effect on the onset of separation.* ICASE Report No. 92-29, July 10, 1992, 33 pages. Submitted to Journal of Fluid Mechanics.

The development of fully nonlinear Görtler vortices in the high Reynolds number flow in a symmetrically constricted channel is investigated. Attention is restricted to the case of 'strongly' constricted channels considered by Smith and Daniels [*J. Fluid Mech.* **110** (1981)] for which the scaled constriction height is asymptotically large. Such flows are known to develop a Goldstein singularity and subsequently become separated at some downstream station past the point of maximum channel constriction. It is shown that these flows can support fully nonlinear Görtler vortices, of the form elucidated by Hall and Lakin [*Proc. Roy. Soc. Lond. A* **415** (1988)], for constrictions which have an appreciable region of local concave curvature upstream of the position at which separation occurs. The effect on the onset of separation due to the nonlinear Görtler modes will be discussed. A brief discussion of other possible nonlinear states which may also have a dramatic effect in delaying (or promoting) separation will be given.

Nicol, David M., Bruno Gaujal and Albert G. Greenberg: *A sweep algorithm for massively parallel simulation of circuit-switched networks.* ICASE Report No. 92-30, July 14, 1992, 28 pages. Submitted to Journal of Parallel and Distributed Computing.

A new massively parallel algorithm is presented for simulating large asymmetric circuit-switched networks, controlled by a randomized-routing policy that includes trunk-reservation. A single instruction multiple data (SIMD) implementation is described and corresponding experiments on a 16384 processor MasPar parallel computer are reported. A multiple instruction multiple data (MIMD) implementation is also described and corresponding experiments on an Intel IPSC/860 parallel computer, using 16 processors, are reported. By exploiting parallelism, our algorithm increases the possible execution rate of such complex simulations by as much as an order of magnitude.

Choudhari, Meelan, Philip Hall and Craig Streett: *On the spatial evolution of long-wavelength Görtler vortices governed by a viscous-inviscid interaction. Part 1: The linear case.* ICASE Report No. 92-31, July 22, 1992, 28 pages. Submitted to Q.J.M.A.M.

The generation of long-wavelength, viscous-inviscid interactive Görtler vortices is studied in the linear regime by numerically solving the time-dependent governing equations. It is found that time dependent surface deformations, which assume a fixed nonzero shape at large times, generate steady Görtler vortices that amplify in the downstream direction. Thus, the Görtler instability in this regime is shown to be convective in nature, contrary to the earlier findings of Ruban and Savenkov. The disturbance pattern created by steady and streamwise-elongated surface obstacles on a concave surface is examined in detail, and also contrasted with the flow pattern due to roughness elements with aspect ratio of order unity on flat

surfaces. Finally, the applicability of the Briggs-Bers criterion to unstable physical systems of this type is questioned by providing a counterexample in the form of the inviscid limit of interactive Görtler vortices.

Speziale, Charles G., and R. Abid: *Reynolds stress calculations of homogeneous turbulent shear flow with bounded energy states.* ICASE Report No. 92-32, July 22, 1992, 17 pages. To be submitted to the ASME Journal of Fluids Engng.

Reynolds stress calculations of homogeneous turbulent shear flow are conducted with a second-order closure model modified to account for non-equilibrium vortex stretching in the dissipation rate transport equation as recently proposed by Bernard and Speziale [*J. Fluids Engng.* **114**, 29 (1992)]. As with the earlier reported $K - \varepsilon$ model calculations incorporating this vortex stretching effect, a production-equals-dissipation equilibrium is obtained with bounded turbulent kinetic energy and dissipation. However, this equilibrium is now not achieved until the dimensionless time $St > 60$ – an elapsed time that is at least twice as large as any of those considered in previous numerical and physical experiments on homogeneous shear flow. Direct quantitative comparisons between the model predictions and the results of experiments are quite favorable. In particular, it is shown that the inclusion of this non-equilibrium vortex stretching effect has the capability of explaining the significant range of production to dissipation ratios observed in experiments.

Schmid, Peter J., Dan S. Henningson, Mehdi R. Khorrami and Mujeeb R. Malik: *Sensitivity analysis of hydrodynamic stability operators.* ICASE Report No. 92-33, July 24, 1992, 26 pages. Submitted to Journal – Theoretical and Computational Fluid Dynamics.

The eigenvalue sensitivity for hydrodynamic stability operators is investigated. Classical matrix perturbation techniques as well as the concept of ε-pseudoeigenvalues are applied to show that parts of the spectrum are highly sensitive to small perturbations. Applications are drawn from incompressible plane Couette, trailing line vortex flow and compressible Blasius boundary layer flow. Parametric studies indicate a monotonically increasing effect of the Reynolds number on the sensitivity. The phenomenon of eigenvalue sensitivity is due to the non-normality of the operators and their discrete matrix analogs and may be associated with large transient growth of the corresponding initial value problem.

Nicol, David M.: *Optimistic Barrier Synchronization.* ICASE Report No. 92-34, July 27, 1992, 22 pages. Submitted to Parallel Computing.

Barrier synchronization is a fundamental operation in parallel computation. In many contexts, at the point a processor enters a barrier it knows that it has already processed all work required of it prior to the synchronization. This paper treats the alternative case, when a processor cannot enter a barrier with the assurance that it has already performed all necessary pre-synchronization computation. The problem arises when the number of pre-synchronization messages to be received by a processor is unknown, for example, in a parallel discrete simulation or any other computation that is largely driven by an unpredictable exchange of messages. We describe an optimistic $O(\log^2 P)$ barrier algorithm for such problems,

study its performance on a large-scale parallel system, and consider extensions to general associative reductions, as well as associative parallel prefix computations.

Mavriplis, D.J.: *Unstructured mesh algorithms for aerodynamic calculations.* ICASE Report No. 92-35, July 28, 1992, 34 pages. To appear in Proceedings of the 13th International Conference on Numerical Methods in Fluid Dynamics (Springer-Verlag).

The use of unstructured mesh techniques for solving complex aerodynamic flows is discussed. The principle advantages of unstructured mesh strategies, as they relate to complex geometries, adaptive meshing capabilities, and parallel processing are emphasized. The various aspects required for the efficient and accurate solution of aerodynamic flows are addressed. These include mesh generation, mesh adaptivity, solution algorithms, convergence acceleration and turbulence modeling. Computations of viscous turbulent two-dimensional flows and inviscid three-dimensional flows about complex configurations are demonstrated. Remaining obstacles and directions for future research are also outlined.

Mavriplis, Catherine: *Adaptive mesh strategies for the spectral element method.* ICASE Report No. 92-36, July 28, 1992, 21 pages. Submitted to Proc. of ICOSAHOM '92 Conference; to appear in the Journal "Computer Methods in Applied Mechanics and Engineering".

An adaptive spectral element method has been developed for the efficient solution of time dependent partial differential equations. Adaptive mesh strategies that include resolution refinement and coarsening by three different methods are illustrated on solutions to the one-dimensional viscous Burgers equation and the two-dimensional Navier-Stokes equations for driven flow in a cavity. Sharp gradients, singularities and regions of poor resolution are resolved optimally as they develop in time using error estimators which indicate the choice of refinement to be used. The adaptive formulation presents significant increases in efficiency, flexibility and general capabilities for high order spectral methods.

Tanveer, Saleh: *Singularities in the classical Rayleigh-Taylor flow: Formation and subsequent motion.* ICASE Report No. 92-37, August 5, 1992, 43 pages. Submitted to Proc. Roy. Soc. London A – June '92.

This paper is concerned with the creation and subsequent motion of singularities of solution to classical Rayleigh-Taylor flow (two dimensional inviscid, incompressible fluid over a vacuum). For a specific set of initial conditions, we give analytical evidence to suggest the instantaneous formation of one or more singularity(ies) at specific point(s) in the unphysical plane, whose locations depend sensitively to small changes in initial conditions in the physical domain. One-half power singularities are created in accordance with an earlier conjecture; however, depending on initial conditions, other forms of singularities are also possible.

For a specific initial condition, we follow a numerical procedure in the unphysical plane to compute the motion of a one-half singularity. This computation confirms our previous conjecture that the approach of a one-half singularity towards the physical domain corresponds to the development of a spike at the physical interface. Under some assumptions that appear to be consistent with numerical calculations, we present analytical evidence to

suggest that a singularity of the one-half type cannot impinge the physical domain in finite time.

Bryan, Kurt: *A boundary integral method for an inverse problem in thermal imaging.* <u>ICASE Report No. 92-38</u>, August 18, 1992, 29 pages. Submitted to Journal of Mathematical Systems, Estimation and Control.

This paper examines an inverse problem in thermal imaging, that of recovering a void in a material from its surface temperature response to external heating. Uniqueness and continuous dependence results for the inverse problem are demonstrated and a numerical method for its solution developed. This method is based on an optimization approach, coupled with a boundary integral equation formulation of the forward heat conduction problem. Some convergence results for the method are proved and several examples are presented using computationally generated data.

Weinan E and Chi-Wang Shu: *A numerical resolution study of high order essentially non-oscillatory schemes applied to incompressible flow.* <u>ICASE Report No. 92-39</u>, August 20, 1992, 17 pages. Submitted to Journal of Computational Physics.

High order essentially non-oscillatory (ENO) schemes, originally designed for compressible flow and in general for hyperbolic conservation laws, are applied to incompressible Euler and Navier-Stokes equations with periodic boundary conditions. The projection to divergence-free velocity fields is achieved by fourth order central differences through Fast Fourier Transforms (FFT) and a mild high-order filtering. The objective of this work is to assess the resolution of ENO schemes for large scale features of the flow when a coarse grid is used and small scale features of the flow, such as shears and roll-ups, are not fully resolved. It is found that high-order ENO schemes remain stable under such situations and quantities related to large-scale features, such as the total circulation around the roll-up region, are adequately resolved.

Weinan E and Chi-Wang Shu: *Numerical study of the small scale structures in Boussinesq convection.* <u>ICASE Report No. 92-40</u>, August 28, 1992, 39 pages. Submitted to Physics of Fluids, A.

Two-dimensional Boussinesq convection is studied numerically using two different methods: a filtered pseudospectral method and a high order accurate ENO scheme. The issue whether finite time singularity occurs for initially smooth flows is investigated. The numerical results suggest that the collapse of the bubble cap reported by Pumir and Siggia is unlikely to occur in resolved calculations. The strain rate corresponding to the intensification of the density gradient across the front saturates at the bubble cap. We also found that the cascade of energy to small scales is dominated by the formation of thin and sharp fronts across which density jumps.

Blackaby, Nik and Meelan Choudhari: *Inviscid vortex motions in weakly three-dimensional boundary layers and their relation with instabilities in stratified shear flows.* ICASE Report No. 92-41, August 28, 1992, 19 pages. Submitted to Proc. Roy. Soc. London A.

In this report we consider the inviscid instability of three dimensional boundary–layer flows with a small crossflow over locally concave or convex walls, along with the inviscid instability of stratified shear flows. We show how these two problems are closely related through the forms of their governing equations. A proposed definition of a generalised Richardson number for the neutrally stable inviscid vortex motions is given. Implications of the similarity between the two problems are discussed.

Frendi, Abdelkader, Lucio Maestrello and Alvin Bayliss: *On the coupling between a supersonic boundary layer and a flexible surface.* ICASE Report No. 92-42, September 2, 1992, 23 pages. Submitted to AIAA Journal.

The coupling between a two-dimensional, supersonic, laminar boundary layer and a flexible surface is studied using direct numerical computations of the Navier-Stokes equations coupled with the plate equation. The flexible surface is forced to vibrate by plane acoustic waves at normal incidence emanated by a sound source located on the side of the flexible surface opposite to the boundary layer. The effect of the source excitation frequency on the surface vibration and boundary layer stability is analyzed. We find that, for frequencies near the fifth natural frequency of the surface or lower, large disturbances are introduced in the boundary layer which may alter its stability characteristics. The interaction between a stable two-dimensional disturbance of Tollmien-Schlichting (TS) type with the vibrating surface is also studied. We find that the disturbance level is higher over the vibrating flexible surface than that obtained when the surface is rigid, which indicates a strong coupling between flow and structure. However, in the absence of the sound source the disturbance level over the rigid and flexible surfaces are identical. This result is due to the high frequency of the TS disturbance which does not couple with the flexible surface.

van Leer, Bram: *Progress in multidimensional upwind differences.* ICASE Report No. 92-43, September 4, 1992, 30 pages. To appear in Proceedings of the 13th International Conference on Numerical Methods in Fluid Dynamics, Rome, July 6-10, 1992; Springer, Lecture Notes in Physics, 1992.

Multi-dimensional upwind-differencing schemes for the Euler equations are reviewed. On the basis of the first-order upwind scheme for a one-dimensional convection equation the two approaches to upwind differencing are discussed: the fluctuation approach and the finite-volume approach. The usual extension of the finite-volume method to the multi-dimensional Euler equations is not entirely satisfactory, because the direction of wave propagation is always assumed to be normal to the cell faces. This leads to smearing of shock and shear waves when these are not grid-aligned. Multi-directional methods, in which upwind-biased fluxes are computed in a frame aligned with a dominant wave, overcome this problem, but at the expense of robustness. The same is true for the schemes incorporating a multi-dimensional wave model not based on multi-dimensional data but on an "educated guess" of what they could be.

The fluctuation approach offers the best possibilities for the development of genuinely multi-dimensional upwind schemes. Three building blocks are needed for such schemes: a wave model, a way to achieve conservation, and a compact convection scheme. Recent advances in each of these components are discussed; putting them all together is the present focus of a worldwide research effort. Some numerical results are presented, illustrating the potential of the new multi-dimensional schemes.

Keyes, David E.: *Domain decomposition: A bridge between nature and parallel computers.* ICASE Report No. 92-44, September 10, 1992, 43 pages. To appear in the Proceedings of the Symposium on Adaptive, Multilevel and Hierarchical Computational Strategies, Edited by A.K. Noor, November 1992.

Domain decomposition is an intuitive organizing principle for a PDE computation, both physically and architecturally. However, its significance extends beyond the readily apparent issues of geometry and discretization, on one hand, and of modular software and distributed hardware, on the other. Engineering and computer science aspects are bridged by an old but recently enriched mathematical theory that offers the subject not only unity, but also tools for analysis and generalization. Domain decomposition induces function-space and operator decompositions with valuable properties. Function-space bases and operator splittings that are not derived from domain decompositions generally lack one or more of these properties. The evolution of domain decomposition methods for elliptically dominated problems has linked two major algorithmic developments of the last 15 years: multilevel and Krylov methods. Domain decomposition methods may be considered descendants of both classes with an inheritance from each: they are nearly optimal and at the same time efficiently parallelizable. Many computationally driven application areas are ripe for these developments. This paper progresses from a mathematically informal motivation for domain decomposition methods to a specific focus on fluid dynamics applications. Introductory rather than comprehensive, it employs simple examples, and leaves convergence proofs and algorithmic details to the original references; however, an attempt is made to convey their most salient features, especially where this leads to algorithmic insight.

Otto, S.R., and Andrew P. Bassom: *Fully nonlinear development of the most unstable Görtler vortex in a three dimensional boundary layer.* ICASE Report No. 92-45, September 15, 1992, 24 pages. Submitted to Studies in Applied Maths.

In this paper we investigate the nonlinear development of the most unstable Görtler mode within a general three–dimensional boundary layer upon a suitably concave surface. The structure of this mode was first identified by Denier, Hall & Seddougui [*Phil. Trans. Roy. Soc. Lond. A* **335** (1991)] who demonstrated that the growth rate of this instability is $O(G^{3/5})$ where G is the Görtler number (taken to be large here), which is effectively a measure of the curvature of the surface. Previous researches have described the fate of the most unstable mode within a two–dimensional boundary layer. Denier & Hall [To appear in *J. Fluid Mech.* (1992)] discussed the fully nonlinear development of the vortex in this case and showed that the nonlinearity causes a breakdown of the flow structure.

The effect of crossflow and unsteadiness upon an infinitesimal unstable mode was elucidated by Bassom & Hall [*J. Fluid Mech.* **232** (1991)]. They demonstrated that crossflow tends to stabilise the most unstable Görtler mode, and for certain crossflow/frequency combinations the Görtler mode may be made neutrally stable. These vortex configurations

naturally lend themselves to a weakly nonlinear stability analysis; work which is described in a previous article by the present authors. Here we extend the ideas of Denier and Hall [To appear in *J. Fluid Mech.* (1992)] to the three–dimensional boundary layer problem. It is found that the numerical solution of the fully nonlinear equations is best conducted using a method which is essentially an adaption of that utilised by Denier and Hall [To appear in *J. Fluid Mech.* (1992)]. The influence of crossflow and unsteadiness upon the breakdown of the flow is described.

Brezany, Peter, Michael Gerndt, Piyush Mehrotra and Hans Zima: *Concurrent file operations in a high performance Fortran*. ICASE Report No. 92-46, September 15, 1992, 17 pages. Submitted to Proceedings of Supercomputing '92, November 1992.

Distributed memory multiprocessor systems can provide the computing power necessary for large-scale scientific applications. A critical performance issue for a number of these applications is the efficient transfer of data to secondary storage. Recently several research groups have proposed FORTRAN language extensions for exploiting the data parallelism of such scientific codes on distributed memory architectures. However, few of these high performance FORTRANs provide appropriate constructs for controlling the use of the parallel I/O capabilities of modern multiprocessing machines. In this paper, we propose constructs to specify I/O operations for distributed data structures in the context of Vienna Fortran. These operations can be used by the programmer to provide information which can help the compiler and runtime environment make the most efficient use of the I/O subsystem.

Turkel, Eli: *Review of preconditioning methods for fluid dynamics*. ICASE Report No. 92-47, September 22, 1992, 35 pages. To appear in Applied Numerical Mathematics.

We consider the use of preconditioning methods to accelerate the convergence to a steady state for both the incompressible and compressible fluid dynamic equations. Most of the analysis relies on the inviscid equations though some applications for viscous flow are considered. The preconditioning can consist of either a matrix or a differential operator acting on the time derivatives. Hence, in the steady state the original steady solution is obtained. For finite difference methods the preconditioning can change and improve the steady state solutions. Several preconditioners previously discussed are reviewed and some new approaches are presented.

Balachandar, S., and Ravi K. Madabhushi: *Spurious modes in spectral collocation methods with two non-periodic directions*. ICASE Report No. 92-48, September 22, 1992, 11 pages. Submitted to Journal of Computational Physics.

Collocation implementation of the Kleiser-Schumann's method in geometries with two non-periodic directions is shown to suffer from three spurious modes – *line, column* and *checkerboard* – contaminating the computed pressure field. The *corner* spurious modes are also present but they do not affect evaluation of pressure related quantities. A simple methodology in the inversion of the influence matrix will efficiently filter out these spurious modes.

ICASE INTERIM REPORTS

Sussman, Alan, Joel Saltz, Raja Das, S. Gupta, Dimitri Mavriplis, Ravi Ponnusamy, and Kay Crowley: *PARTI primitives for unstructured and block structured problems.* Interim Report 22, June 25, 1992, 32 pages. Symposium on High Performance Computing for Flight Vehicles, Dec. 7-9, 1992.

This paper describes a set of primitives (PARTI) developed to efficiently execute unstructured and block structured problems on distributed memory parallel machines. We present experimental data from a 3-D unstructured Euler solver run on the Intel Touchstone Delta to demonstrate the usefulness of our methods.

Bertelrud, A., G. Erlebacher, Ph. Dussouillez, M.P. Liandrat, J. Liandrat, F. Moret Bailly, and Ph. Tchamitchian: *Development of wavelet analysis tools for turbulence.* Interim Report 23, July 8, 1992, 21 pages.

This paper is devoted to the presentation of the general framework and the initial results of a joint effort to derive novel research tools and easy to use software to analyze and model turbulence and transition.

After a brief review of the issues and a summary of some basic properties of wavelets, we present our preliminary results. Both the technical aspects of the implementation and the physical conclusions reached at this time are discussed.

Current developments are summarized in the last section.

ICASE COLLOQUIA

April 1, 1992 - September 30, 1992

Name/Affiliation/Title	Date
Joseph M. Powers, University of Notre Dame "Summary of Oblique Detonation Theory and Topics for Future Research"	April 20
Jaroslaw Sobieszczanski-Sobieski, NASA Langley Research Center "A System Approach to Aircraft Optimization"	April 22
Fabio Bertolotti, ICASE "PSE-Based Transition Studies Relevant to the Swept-Wing Geometry"	April 23
Xian-He Sun, Clemson University "Parallel Numerical Algorithms for High Performance Computing"	April 30
Ralph Smith, ICASE "Active Noise Suppression in Acoustic/Structure Interaction Models: Feedback Control via Piezoceramic Actuators"	May 5
Amit Tandon, Cornell University "Floquet Analysis and Simulation of Langmuir Circulations"	May 8
N. Narayanswami, Rutgers University "Theoretical Investigation of Crossing Shock Wave/Turbulent Boundary Layer Interactions"	May 11
J. R. Ristorcelli, Cornell University "Second Order Turbulence Model and Simulation of the Rotating Buoyant Recirculating Flow in the Czochralski Silicon Crystal Growth"	May 13
Abdel Zebib, Rutgers University "Thermocapillary/Buoyant Convection in a Rectangular Cavity"	May 14
Ye Zhou, Stanford University and NASA Ames Research Center "Scaling Analysis of the Energy Transfer Process Utilizing Numerical Simulation Databases"	May 15

Name/Affiliation/Title	Date
R. R. Rosales, Masschusetts Institute of Technology "Focusing of Weak Shocks and the Von Neumann Paradox"	May 18
Haym Benaroya, Rutgers University "Vibrations with Uncertainty and Complexity"	May 19
Stanley Rubin, University of Cincinnati "RNS, Segmented Domain, and Multigrid Strategies: Application for Internal Flows"	May 22
J. E. Shepherd, Rensselaer Polytechnic Institute "Oblique Detonations, Fact and Fancy"	May 27
Anders Petersson, University of California, Los Angeles "Computing the Flow Around a Submerged Body"	May 29
Robert Rubenstein, Sverdrup Technology "Renormalization Group Methods Applied to Second Order Closures"	June 1
Emad Fatemi, Institute for Mathematics and its Applications "Finite Difference Solution of Boltzmann Equation with Application to Electron Transport in Semiconductor Devices"	June 8
Phillip M. Dickens, University of Virginia "Performance and Scalability Results for an Aggressive Global Windowing Algorithm"	June 9
Robert Schnabel, University of Colorado at Boulder "Experience in Developing a Parallel Thin-Layer Navier Stokes Code and Implications for Parallel CFD Methods and Parallel Language Design"	June 18
K.R. Rajagopal, University of Pittsburgh "On the Flows of Non-Newtonian Fluids and Some Open Questions in the Field"	June 19
Ulf R. Hanebutte, Northwestern University "Solving the Neutron Transport Equation on Massively Parallel Computers"	June 22

Name/Affiliation/Title	Date
William K. George, State University of New York at Buffalo "A New Look at Turbulent Boundary Layers"	June 23
David Goldstein, Brown University "Recent Simulations of Near-Continuum Flow Using a Discrete-Velocity Molecular Model"	June 26
John E. Dennis, Jr., Rice University "Domain Decomposition for Parameter ID and Control"	June 30
Robert Pitz, Vanderbilt University "Simultaneous Chemical Species and Temperature Measurement to Study Finite-Rate Chemistry in Reacting Flows"	July 2
Nadine Aubry, The City College of the City University of New York "Spatio-Temporal Structure of Compressible Turbulence"	July 7
Alvin Bayliss, Northwestern University "Nonlinear Dynamics and Spatial Pattern Formation in Gaseous Combustion"	July 8
Saul Abarbanel, Tel-Aviv University and ICASE "On Sufficient Conditions for the Stability of Viscous Incompressible Parallel Flows"	July 16
Scott Whitman, Lawrence Livermore National Laboratory "Parallel Scientific Visualization: A Holy Grail or a Can of Worms?"	July 17
Paul Hammerton, University of Arizona "Boundary-Layer Receptivity for a Parabolic Leading Edge"	July 20
Joseph Flaherty, Rensselaer Polytechnic Institute "Adaptive Methods for Time-Dependent Partial Differential Equations"	July 23
Manhar Dhanak, Florida Atlantic University "Evolution of an Elliptical Vortex Under Applied Periodic Strain"	July 24
Richard Moore, Moore Applied Physics Company "Analytic, Non-Linear, Damped, Space and Time Periodic Solutions of the Navier-Stokes Equation"	July 27

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Name/Affiliation/Title	Date
Peter Schmid, Massachusetts Institute of Technology "Spectra and Pseudospectra in Hydrodynamic Stability Theory"	July 29
Chandrajit L. Bajaj, Purdue University "Distributed and Collaborative Geometric Design"	August 4
Sharath S. Girimaji, Analytical Services and Materials, Inc. "Time-Evolving Mapping Closure Method for Scalar Mixing in Turbulence"	August 5
Boleslaw Szymanski, Rensselaer Polytechnic Institute "Software Tools for Scalable Parallel Computations"	August 6
Marina Chen, Yale University "Prototyping Fortran-99 and C++ Compilers for Massively Parallel Machines"	August 7
A. W. Date, Indian Institute of Technology "Prediction of Turbulent Flow in Compressor Blade Cascade"	August 7
Graham Horton, Universitat Erlangen-Numberg, Germany "Experiments with the Time-Parallel Multigrid Method"	August 14
Ph. Blanc-Benon, Laboratoire de Mecanique des Fluides et d'Acoustique, France "A Numerical Approach to Acoustic Wave Transmission through Turbulence"	August 17
Smadar Karni, University of Michigan, Ann Arbor "Multicomponent Flow Computations by a Consistent Primitive Algorithm"	August 20
Ami Harten, Tel-Aviv University "Fast Multiresolution Algorithms for Matrix-Vector Multiplication"	August 28
David Banks, University of North Carolina at Chapel Hill "Interacting with Surfaces in 4-Space"	August 31
Paul Garrett and Gerald Talbot, Meiko Scientific Corporation "The Meiko CS-2 Massively Parallel Supercomputer System"	September 3

Name/Affiliation/Title	Date
Gregory A. Kriegsmann, New Jersey Institute of Technology "Sound Radiation and Caustic Formation from a Point Source in a Wall Shear Layer"	September 17
Lakshmi N. Sankar, Georgia Institute of Technology "Iterative Time Marching Algorithms for Unsteady External Flows"	September 18
Sekhar R. Sarukkai, Indiana University "Sieve: A Performance Debugging Environment for Parallel Programs"	September 21
Graham Horton, Universitat Erlangen-Numberg, Germany "The Performance of a Time- and Space-Parallel Solution Method for the Navier-Stokes Equations"	September 23
Bernd Mohr, University of Erlangen-Nuernberg, Germany "Event-Based Analysis of Non-Sequential Systems"	September 24
Kwan-Liu Ma, University of Utah "Interactive Volume Data Visualization"	September 25

ICASE SUMMER ACTIVITIES

The summer program for 1992 included the following visitors:

NAME/AFFILIATION	DATE OF VISIT	AREA OF INTEREST
Saul Abarbanel Tel-Aviv University, Israel	7/6 - 9/18	Numerical Methods for Partial Differential Equations
Remi Abgrall INRIA, France	8/3 - 8/28	ENO Schemes on Unstructured Meshes
Anwar Ahmed Texas A & M University	6/1 - 8/21	Receptivity (Experiment)
Eyal Arian Weizmann Institute of Science, Israel	5/18 - 6/5	Optimal Shape Design Problems
Shapour Azarm University of Maryland, College Park	8/17 - 12/18	Optimization-based Design of Multi-objective Nonhierarchic Engineering Systems
S. Balachandar University of Illinois	6/22 - 8/21	Instability and Transition
Thomas Banks North Carolina State University	6/1 - 6/5 9/8 - 9/11	Control Theory
Andrew Bassom University of Exeter, England	8/10 - 9/18	Nonlinear Stability of Görtler Vortices
Alvin Bayliss Northwestern University	6/22 - 6/26 7/7 - 7/10	Computational Aeroacoustics
Stanley Berger University of California, Berkeley	6/15 - 7/10	Analytical and Numerical Studies of Vortex Breakdown
Nicholas Blackaby University of Manchester, England	6/29 - 9/25	Stability Theory of Compressible Flow
Gregory Blaisdell Purdue University	5/29 - 6/26	Compressible Turbulence

NAME/AFFILIATION	DATE OF VISIT	AREA OF INTEREST
Shahid Bokhari Pakistan University of Engineering and Technology	6/15 - 9/4	Parallel Computing Systems
Thomas Bridges Rijksuniversiteit Utrecht, The Netherlands	8/10 - 8/27	Aspects of Dynamical Systems Theory Applied to Shear Flow Transitions
John Buckmaster University of Illinois	8/3 - 8/14	Mathematical Combustion
Barbara Chapman University of Vienna, Austria	8/17 - 9/9	Compiler Development for Parallel and Distributed Multiprocessors
Thomas Corke Illinois Institute of Technology	7/6 - 7/10 8/10 - 8/14	Instability and Transition (Experiment)
William Criminale University of Washington	8/24 - 9/18	Instability and Transition
Herman Deconinck Von Karman Institute for Fluid Dynamics, Belgium	7/27 - 8/7	Multidimensional Upwind Schemes in Computational Fluid Dynamics
Ayodeji Demuren Old Dominion University	5/11 - 5/15 6/29 - 7/3	Turbulence Modeling
J. P. Denier The University of New South Wales, Australia	6/19 - 7/10	Vortex/Wave Interaction Theory
Manhar Dhanak Florida Atlantic University	6/29 - 7/31	Instability and Transition in an Axial Corner Flow
Wai Sun Don Brown University	6/1 - 7/17	Numerical Methods for Partial Differential Equations
Peter Duck University of Manchester, England	7/6 - 8/28	Stability Theory
Daniele Funaro Universita de Pavia, Italy	7/20 - 7/31	Spectral Methods

NAME/AFFILIATION	DATE OF VISIT	AREA OF INTEREST
Michael Gaster Cambridge University, England	9/6 - 9/19	Stability of Boundary Layers
James Geer State University of New York, Binghamton	5/26 - 5/29	Approximation Method of Solutions for Partial Differential Equations
David Gottlieb Brown University	7/13 - 7/16 8/17 - 8/28 9/14 - 18	Numerical Methods for Partial Differential Equations
Chester Grosch Old Dominion University	5/11 - 6/11 8/3 - 8/28 (2 days a week)	Computational Fluid Mechanics
Philip Hall University of Manchester, England	6/15 - 7/17	Instability and Transition Theories
Zigo Haras Weizmann Institute of Science, Israel	5/4 - 5/22	LDS Methods for Time-Dependent Problem
Amiram Harten Tel-Aviv University, Israel	8/17 - 9/4	Numerical Methods for Partial Differential Equations
Dan Henningson Massachusetts Institute of Technology	6/15 - 6/19	Transition in Shear Flows
Graham Horton Universitat Erlangen-Numberg, Germany	8/3 - 9/25	Parallel Multigrid Method for Navier-Stokes Equations
Daniel Inman State University of New York, Buffalo	5/26 - 6/5	Numerical Methods for Inverse Problems in Distributed Systems
Thomas Jackson Old Dominion University	5/18 - 8/28	Numerical and Analytical Methods for Chemically Reacting Flows
Ashwani Kapila Rensselaer Polytechnic Institute	7/27 - 8/7	Mathematical Aspects of Combustion Processes
Smadar Karni University of Michigan, Ann Arbor	8/3 - 8/21	Numerical Methods for Fluids

NAME/AFFILIATION	DATE OF VISIT	AREA OF INTEREST
David Keyes Yale University	8/10 - 8/14	Parallel Numerical Procedures for Combustion
Fumio Kojima Osaka Institute of Technology, Japan	9/8 - 9/11	Probabilistic and Stochastic for Optimal Control Problems
David Kopriva Florida State University	7/20 - 7/31	Spectral Methods for Viscous Compressible Flows
Glenn Lasseigne Old Dominion University	7/13 - 8/7	Computational Fluid Dynamics
Anthony Leonard California Institute of Technology	9/21 - 9/25	Fluid Mechanics
Jennifer Levin Northwestern University	6/22 - 8/14	Numerical Computation of the Interaction between Jet Noise and a Flexible Structure
Cathy Mavriplis George Washington University	6/1 - 8/14	Adaptive Spectral-Element Algorithms for Direct Simulation of Incompressible Flows
Tommy Minyard University of Texas, Austin	7/6 - 8/5	Spectral Method Solver for Compressible Viscous Flows
David Nicol College of William and Mary	5/18 - 5/29	Mapping Algorithms for Parallel Systems
Demetrius Papageorgiou New Jersey Institute of Technology	6/8 - 6/19	Stability Theory
Ijaz Parpia University of Texas, Austin	6/15 - 6/26	Multidimensional Schemes for the Euler Equations
Ugo Piomelli University of Maryland, College Park	7/27 - 8/7	Subgrid Scale Reynolds Stress Models for Large Eddy Simulation of Turbulent Flows
Peter Protzel FORWISS Germany	9/8 - 9/18	Application of Neural Networks to Pattern Classification and Control
Saad Ragab VPI and State University	6/15 - 8/21	Large-Eddy Simulations

NAME/AFFILIATION	DATE OF VISIT	AREA OF INTEREST
Helen Reed Arizona State University	7/13 - 7/31	Instability and Transition
Philip Roe University of Michigan, Ann Arbor	7/20 - 8/7	Computational Aerodynamics
Milton Rose	7/13 - 7/24	Numerical Solution of Partial Differential Equations
Cord-Christian Rossow DLR - Institute for Design Aerodynamics, Germany	7/13 - 7/24	3-D Semicoarsening Multigrid Scheme for Viscous Hypersonic Flow
Peter Schmid Massachusetts Institute of Technology	6/1 - 7/31	Instability and Transition
Chi-Wang Shu Brown University	7/27 - 8/28	Computational Fluid Dynamics
C. S. Subramanian Florida State University	6/15 - 9/4	Boundary Layer Studies Using LDV System (Experiment)
N. Sundararajan Nanyang Technological University, Singapore	6/1 - 6/26	Adaptive Identification and Control of Flexible Structure
Eitan Tadmor Tel-Aviv University, Isarel	7/13 - 7/17	Numerical Methods for Partial Differential Equations
Hillel Tal-Ezer Tel-Aviv University, Israel	7/6 - 8/7	Numerical Methods for Partial Differential Equations
Siva Thangam Stevens Institute of Technology	7/6 - 7/31	Turbulence Modeling
Lu Ting Courant Institute of Mathematical Sciences	6/15 - 6/19	Fluid Mechanics
Eli Turkel Tel-Aviv University, Israel	7/1 - 9/1	Numerical Methods for Partial Differential Equations
Bram van Leer University of Michigan, Ann Arbor	8/3 - 8/28	Computational Aerodynamics

NAME/AFFILIATION	DATE OF VISIT	AREA OF INTEREST
Nick Verhaagen Delft University of Technology, Holland	8/3 - 10/30	Experimental and Numerical Study of the Interaction Process of Vortices over Slender Sharp-Edg Double-Delta Wings
Eric Voth Brown University	7/6- 7/17	Numerical Analysis
Krzysvtof Wlodarski Courant Institute of Mathematical Sciences	7/6 - 7/17	Nonlinear Oscillations of a Flexible Wall
Bassam Younis City University, London, England	6/22 - 7/31	Turbulence Modeling for Unsteady Separated Flows
Hans Zima University of Vienna, Austria	8/6 - 9/4	Instability of Supersonic and Hypersonic Boundary Layers
Yousef Zurigat University of Jordan	6/15 - 9/11	Instability of Supersonic and Hypersonic Boundary Layers

OTHER ACTIVITIES

A workshop on Computational Aeroacoustics cosponsored by ICASE and NASA Langley Research Center was held April 6-9, 1992 at the Radisson Hotel in Hampton, Virginia. One hundred and two people attended this workshop.

In 1951, Sir James Lighthill posed the problem of estimating the sound radiated by "a fluctuating fluid flow occupying a limited part of a very large volume of fluid of which the remainder is at rest". The purpose of the Workshop was to reconsider the same problem given the advances in computational fluid dynamics and computer technology over intervening forty years.

A volume of the proceedings from this conference will be published by Springer-Verlag in the near future.

ICASE STAFF

I. ADMINISTRATIVE

M. Yousuff Hussaini, Director. Ph.D., Mechanical Engineering, University of California, 1970.

Linda T. Johnson, Office and Financial Administrator

Etta M. Blair, Personnel/Bookkeeping Secretary

Cynthia C. Cokus, PC System Coordinator

Barbara A. Cardasis, Administrative Secretary

Tamiko J. Hackett, Office Clerk

Rachel A. Lomas, Bookkeeping Clerk

Rosa H. Milby, Short-term Housing/Office Secretary

Shelly D. Millen, Technical Publications Secretary

Emily N. Todd, Executive Secretary/Visitor Coordinator

II. SCIENCE COUNCIL for APPLIED MATHEMATICS and COMPUTER SCIENCE

Ashwani Kapila, Professor, Department of Mathematics and Science, Rensselaer Polytechnic Institute.

James P. Kendall, Jet Propulsion Laboratory.

Heinz-Otto Kreiss, Professor, Department of Mathematics, University of California at Los Angeles.

Sanjoy Mitter, Professor of Electrical Engineering, Massachusetts Institute of Technology.

Robert O'Malley, Jr., Chairman, Department of Applied Mathematics, Univeristy of Washington.

Stanley J. Osher, Professor, Mathematics Department, University of California.

Eli Reshotko, Department of Mechanical and Aerospace Engineering, Case Western University.

John Rice, Head, Department of Computer Science, Purdue University.

Ahmed Sameh, Professor, Center for Supercomputing Research and Development, University of Illinois at Urbana.

M. Y. Hussaini, Director, Institute for Computer Applications in Science and Engineering, NASA Langley Research Center.

III. ASSOCIATE MEMBERS

Saul S. Abarbanel, Professor, Department of Applied Mathematics, Tel-Aviv University, Israel.

H. Thomas Banks, Director, Center for Research in Scientific Computation, North Carolina State University.

David Gottlieb, Professor, Division of Applied Mathematics, Brown University.

Peter D. Lax, Professor, Courant Institute of Mathematical Sciences, New York University.

V. LEAD COMPUTER SCIENTIST

Joel H. Saltz - Ph.D., Computer Science, Duke University, 1985. Parallel Computing with Emphasis on Systems and Algorithmic Issues. (Through August 14, 1992)

V. SENIOR STAFF SCIENTIST

Gordon Erlebacher - Ph.D., Plasma Physics, Columbia University, 1983. Computational Fluid Dynamics. (November 1989 to November 1994)

Dimitri Mavriplis - Ph.D., Mechanical and Aerospace Engineering, Princeton University, 1988. Grid Techniques for Computational Fluid Dynamics. (February 1987 to September 1995)

Piyush Mehrotra - Ph.D., Computer Science, Univeristy of Virginia, 1982. Programming Languages for Multiprocessor Systems. (January 1991 to September 1994)

Charles G. Speziale - Ph.D., Aerospace and Mechanical Sciences, Princeton University, 1978. Fluid Dynamics with Emphasis on Turbulence Modeling and the Transition Process. (September 1987 to October 1992)

Shlomo Ta'asan - Ph.D., Applied Mathematics, The Weizmann Institute of Science, 1985. Multigrid Methods for Partial Differential Equations. (July 1991 to July 1994)

John R. Van Rosendale - Ph.D., Computer Science, University of Illinois, 1980. Parallel Systems and Algorithms. (July 1989 to September 1993)

VI. SCIENTIFIC STAFF

Fabio Bertolotti - Ph.D., Mechanical Engineering, Ohio State University, 1991. Stability Theory in Fluid Mechanics. (September 1991 to September 1993)

Kurt M. Bryan - Ph.D., Mathematics, University of Washington, 1990. Theoretical and Computational Methods for Inverse Problems. (August 1990 to September 1993)

Leon M. Clancy - B.S., Mechanical Engineering, University of Washington, 1971. System Manager. (December 1989 to Present)

Thomas W. Crockett - B.S., Mathematics, College of William and Mary, 1977. Parallel Systems Research. (February 1987 to September 1993)

Subhendu Das - M.S., Computer Science, College of William and Mary, 1990. Parallel Tools and Environments for Unstructured Scientific Computations. (June 1991 to October 1992)

Scott T. Leutenegger - Ph.D., Computer Science, University of Wisconsin-Madison, 1990. Performance Analysis. (September 1992 to September 1994)

Stephen Otto - Ph.D., Mathematics, Exeter University, England, 1991. Symptotic Theories of Stability and Transition. (November 1991 to November 1993)

James Quirk - Ph.D., Computational Fluid Dynamics, Cranfield Institute of Technology, 1991. Adaptive Methods for Partial Differential Equations. (June 1991 to June 1993)

Mathew Rosing - Ph.D., Computer Science, University of Colorado, Boulder, 1991. Tools and Compilers for Scalable Multiprocessors. (November 1991 to November 1994)

Sutanu Sarkar - Ph.D., Mechanical and Aerospace Engineering, Cornell University, 1988. Fluid Dynamics, Turbulence Modeling, Compressible Turbulence. (September 1988 to December 1992)

Ralph C. Smith - Ph.D., Mathematics, Montana State University, 1990. Theoretical and Computational Issues Associated with Inverse Problems. (August 1990 to August 1993)

Xian-He Sun - Ph.D., Computer Science, Michigan State University, 1990. Applied Computer Science. (September 1992 to September 1994)

Alan Sussman - Ph.D., Computer Science, Carnegie-Mellon University, 1991. Quantifying and Predicting Performance of Realistic Applications on Distributed Memory Parallel Computers. (August 1991 to August 1993)

VII. VISITING SCIENTISTS

Remi Abgrall - Ph.D., Mechanical Engineering, University of Paris, France, 1987. Research Scientist, INRIA (France). ENO Schemes on Unstructured Meshes. (August 1992)

Anwar Ahmed - Ph.D., Aerospace Engineering, Wichita State University, 1985. Assistant Professor, Department of Aerospace Engineering, Texas A & M University. Receptivity (Experiment) (June to August 1992)

Shapour Azarm - Ph.D., Mechanical Engineering, University of Michigan, 1977. Associate Professor, Department of Mechanical Engineering, University of Maryland. Optimization-Based Design. (August to December 1992)

S. Balachandar - Ph.D., Engineering, Brown University, 1988. Assistant Professor, Department of Theoretical & Applied Mechanics, University of Illinois-Urbana. (June to August 1992)

Andrew Bassom - Ph.D., Mathematics, University of Exeter, United Kingdom, 1988. Lecturer, Department of Applied Mathematics, University of Exeter. Nonlinear Stability of Gortler Vortices. (August to September 1992)

Stanley A. Berger - Ph.D., Applied Mathematics, Brown University, 1959. Professor, Department of Mechanical Engineering, University of California-Berkeley. Analytical & Numerical Studies of Vortex Breakdown. (June to July 1992)

Nicholas D. Blackaby - Ph.D., Fluid Mechanics, University College, London, United Kingdom, 1991. Research Associate, Department of Mathematics, University of Manchester, United Kingdom. (June to September 1992)

Gregory A. Blaisdell - Ph.D., Mechanical Engineering, Stanford University, 1991. Assistant Professor, Department of Aeronautics and Astronautics, Purdue University. Compressible Turbulence. (June 1992)

Shahid Bokhari - Ph.D., Electrical and Computer Engineering, University of Massachusetts-Amherst, 1978. Professor, Electrical Engineering, University of Engineering & Technology, Lahore, Pakistan. Parallel Computing Systems. (June to August 1992)

Thomas Bridges - Ph.D., Aerospace Engineering, Penn State University, 1984. Lecturer, Mathematics Institute, University of Warwick, United Kingdom. Aspects of Dynamical Systems Theory Applied to Shear Flow Transition. (August 1992)

Barbara Chapman - M.S., Mathematics, University of Canterbury, Christchurch, New Zealand, 1985. Research Associate, Computer Science Department, University of Vienna. Compiler Development for Multiprocessors. (August to September 1992)

William O. Criminale - Ph.D., Aeronautics, The Johns Hopkins University, 1960. Professor, Department of Applied Mathematics, University of Washington. Instability and Transition. (August to September 1992)

Herman Deconinck - Ph.D., Applied Sciences, Vrije Universiteit Brussel, Belgium, 1983. Associate Professor, CFD Group, von Karman Institute for Fluid Dynamics, Belgium. Multidimensional Upwind Schemes in Computational Fluid Dynamics. (July to August 1992)

J.P. Denier - Ph.D., Mathematics, University of New South Wales, 1989. Lecturer, School of Mathematics, University of New South Wales, Australia. Vortex/Wave Interaction Theory. (June to July 1992)

Manhar R. Dhanak - Ph.D., Applied Mathematics, Imperial College, University of London, United Kingdom, 1980. Assistant Professor, Department of Ocean Engineering, Florida Atlantic University. Instability and Transition in a Axial Corner Flow. (July to July 1992)

Wai Sun Don - Ph.D., Numerical Analysis, Brown University, 1989. Visiting Research Assistant Professor, Division of Applied Mathematics, Brown University. Numerical Methods for PDE's. (July to July 1992)

Peter W. Duck - Ph.D., Fluid Mechanics, University of Southampton, United Kingdom, 1975. Lecturer in Mathematics, Department of Mathematics, University of Manchester, United Kingdom. Numerical Solution of Unsteady Boundary Layer Equations. (December 1991 to January 1992)

Daniele Funaro - Ph.D., Mathematics, University of Pavia, Italy, 1981. Associate Professor, Mathematics Department, University of Pavia,. Spectral Methods. (July 1992)

Michael Gaster - Ph.D., Aerodynamics, Queen Mary College, London, United Kingdom. Professor, Department of Engineering, Cambridge University, United Kingdom. Spectral Methods. (July 1992)

Dan Henningson - Ph.D., Mechanics, Royal Institute of Technology, Stockholm, Sweden, 1988. Assistant Professor, Department of Mathematics, Massachusetts Institute of Technology. Transition in Shear Flows. (June 1992)

Graham A. Horton - Ph.D., Computer Science, Universitat Erlangen-Nurnberg, Germany, 1991. Researcher/Lecturer, Universitat Erlangen-Nurnberg, Germany. Parallel Multigrid Method for Navier-Stokes Equations. (August to September 1992)

Smadar Karni - Ph.D., CFD, Cranfield Institute of Technology, 1990. Assistant Professor, Department of Mathematics, University of Michigan. Numerical Methods for Fluids. (August 1992)

Fumio Kojima - Ph.D., Control Theory, Kyoto University, Japan, 1985. Professor, Department of Mechanical Engineering, Osaka Institute of Technology, Japan. Probabilistic and Stochastic for Optimal Control Problems. (September 1992)

David Kopriva - Ph.D., Applied Mathematics, University of Arizona, 1982. Associate Professor, Supercomputer Computations Research Institute, Florida State University. Spectral Methods for Viscous Compressible Flows. (July 1992)

Geoffrey M. Lilley - Ph.D., Engineering, Imperial College, London, England, 1945. Professor Emeritus, Department of Aeronautics and Astronautics of Southampton, United Kingdom. Fluid Mechanics. (August to December 1992)

Catherine Mavriplis - Ph.D., Aeronautics and Astronautics, Massachusetts Institute of Technology, 1989. Assistant Professor, Department of Civil, Mechanical and Environmental Engineering, The George Washington University. Adaptive Spectral Element Algorithms for Direct Simulation of Incompressible Flows. (June to July 1992)

Ijaz H. Parpia - Ph.D., Aerospace Engineering, Purdue University, 1986. Assistant Professor, Department of Aerospace Engineering, University of Texas at Arlington. Multidimensional Schemes for the Euler Equations. (June 1992)

Merrell L. Patrick - Ph.D., Mathematics, Carnegie-Mellon University, 1964. New Technologies Program Director, National Science Foundation. (August 1991-August 1992)

Peter W. Protzel - Ph.D., Electrical Engineering, Technical University of Braunschweig, Germany. Chief Engineer, Bavarian Research Center for Knowledge-Based Systems (FORWISS), Erlangen-Tennenlohe, Germany. Application of Neural Networks to Pattern Classification and Control. (September 1992)

Saad Ragab - Ph.D., Engineering Mechanics, VPI & State University, 1979. Associate Professor, Department of Engineering Science and Mechanics, VPI & State University. Large-Eddy Simulaitons. (September 1992)

Philip L. Roe - Ph.D., Aeronautics, Cambridge University, United Kingdom, 1962. Professor, Department of Aerospace Engineering, University of Michigan. Computational Aerodynamics. (July to August 1992)

Milton E. Rose - Ph.D., Mathematics, New York University, 1953. Retired. Numerical Solution of of Partial Differential Equations. (July 1992)

Cord-Christian Rossow - Ph.D., Aerospace Engineering, Technische Universitat Braunschweig, Germany, 1988. Scientist, DLR-Institute for Design Aerodynamics, Germany. 3-D Semi-coarsening Multigrid Scheme for Viscous Hypersonic Flow. (July 1922)

John V. Shebalin - Ph.D., Physics, College of William & Mary, 1982. Aerospace Technologist, NASA Langley Research Center. Compressible Turbulence. (July 1992 to Present)

C. S. Subramanian - Ph.D., Mechanical Engineering, University of Newcastle, New South Wales, Australia, 1983. Associate Professor, Department of Mechanical & Aerospace Engineering, Florida Institute of Technology. Boundary Layer Studies Using LDV System (Experiment). (June to September 1992)

N. Sundararajan - Ph.D., Electrical Engineering, University of Illinois, Champaign-Urbana, 1971. Associate Professor, School of Electronic & Electrical Engineering, Nanyang Technological University, Singapore. Adaptive Identification and Control of Flexible Structures. (June 1992)

Eitan Tadmor - Ph.D., Numerical Analysis, Tel-Aviv University, 1979. Professor, Department of Applied Mathematics, Tel-Aviv University. Numerical Methods for Partial Differential Equations. (January 1992)

Hillel Tal-Ezer - Ph.D., Applied Mathematics, Tel-Aviv University, 1985. Director of Center of Mathematical Simulation in Industry, School of Mathematics, Tel-Aviv University. Numerical Methods for Partial Differential Equations. (July to August 1992)

Siva Thangham - Ph.D., Mechanical Engineering, Rutgers University, 1980. Professor, Department of Mechanical Engineering, Stevens Institute of Technology. Turbulence Modeling. (June to July 1992)

Nicolas G. Verhaagen - Ph.D., Aeronautics, Delft University of Technology, The Netherlands, 1970. Research Scientist, Department of Aerospace Engineering, Delft University of Technology, The Netherlands. Experimental and Numerical Studies of Vortex Flows. (August to October 1992)

Bassam A. Younis - Ph.D., Mechanical Engineering-Fluid Mechanics, Imperial College, London, England, 1984. Lecturer, Department of Civil Engineering, City University, London, England. Turbulence Modeling for Unsteady Separated Flows. (June to July 1992)

Hong Zhang-Sun - Ph.D., Applied Mathematics, Michigan State University, 1989. Assistant Professor, Department of Mathematical Sciences, Clemson University. Parallel Numerical Algorithms. (September 1992 to Present)

Yousef H. Zurigat - Ph.D., Mechanical Engineering, Oklahoma State University, 1988. Assistant Professor, Department of Mechanical Engineering, The University of Jordan. Instability of Supersonic and Hypersonic Boundary Layers. (June to September 1992)

VIII. CONSULTANTS

Alvin Bayliss - Ph.D., Mathematics, New York University, 1975. Associate Professor, Technological Institute, Northwestern University. Numerical Methods for Partial Differential Equations.

Marsha J. Berger - Ph.D., Numerical Analysis, Stanford University, 1982. Research Associate, Courant Institute of Mathematical Sciences. Numerical Methods for Partial Differential Equations.

John D. Buckmaster - Ph.D., Applied Mathematics, Cornell University, 1969. Professor, Department of Aeronautical and Astronautical Engineering, University of Illinois. Mathematical Combustion.

John A. Burns - Ph.D., Mathematics, University of Oklahoma, 1973. Professor, Virginia Polytechnic Institute and State University. Numerical Methods in Feedback Control and Parameter Estimation.

Jeffrey L. Clark - B.A., Business Administration, James Madison University, 1986. Programmer/Analyst, Unisys Corporation. Administration of the ICASE Computer System.

Thomas C. Corke - Ph.D., Mechanical and Aerospace Engineering, Illinois Institute of Technology, 1981. Professor, Department of Mechanical and Aerospace Engineering, Armour College of Engineering, Illinois Institute of Technology. Transition and Stability to Turbulence.

Ayodeji O. Demuren - Ph.D., Mechanical Engineering, Imperial College London, United Kingdom, 1979. Associate Professor, Department of Mechanical Engineeringand Mechanics, Old Dominion University. Numerical Modeling of Turbulent Flows.

Peter R. Eiseman - Ph.D., Mathematics, University of Illinois, 1970. Senior Research Scientist and Adjunct Professor, Department of Applied Physics and of Nuclear Engineering, Columbia University. Computational Fluid Dynamics.

Dennis B. Gannon - Ph.D., Computer Science, University of Illinois, 1980. Associate Professor, Department of Computer Science, Indiana University. Parallel Computation.

James F. Geer - Ph.D., Applied Mathematics, New York University, 1967. Professor, Systems Science and Mathematical Sciences, Watson School of Engineering, Applied Science

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and Technology, SUNY-Binghamton. Perturbation Methods and Asymptotic Expansions of Solutions to Partial Differential Equations.

Chester E. Grosch - Ph.D., Physics - Fluid Dynamics, Stevens Institute of Technology, 1967. Professor, Department of Computer Science and Slover Professor, Department of Oceanography, Old Dominion University. Computational Fluid Mechanics and Algorithms for Array Processor Computers.

Philip Hall - Ph.D., Mathematics, Imperial College, England, 1973. Professor, Department of Mathematics, University of Manchester, England. Computational Fluid Dynamics.

Amiram Harten - Ph.D., Mathematics, New York University, 1974. Associate Professor, Department of Mathematics, Tel-Aviv University, Israel. Numerical Solution for Partial Differential Equations.

Fang Q. Hu - Ph.D., Applied Mathematics, Florida State University, 1990. Assistant Professor, Department of Mathematics and Statistics, Old Dominion University. Instability and Transition.

Thomas L. Jackson - Ph.D., Mathematics, Rensselaer Polytechnic Institute, 1985. Assistant Professor, Department of Mathematics, Old Dominion University. Numerical and Analytical Methods for Chemically Reacting Flows.

Harry F. Jordan - Ph.D., Physics, University of Illinois, 1967. Professor Department of Electrical and Computer Engineering, University of Colorado at Boulder. Parallel Computation.

Ashwani K. Kapila - Ph.D., Theoretical and Applied Mechanics, Cornell University, 1975. Associate Professor, Department of Mathematical Sciences, Rensselaer Polytechnic Institute. Ordinary and Partial Differential Equations, Asymptotic Methods.

Edward J. Kerschen - Ph.D., Mechanical Engineering, Stanford University, 1978. Associate Professor, Department of Aerospace and Mechanical Engineering, University of Arizona. Flow Dynamics.

David E. Keyes - Ph.D., Applied Mathematics, Harvard University, 1984. Assistant Professor, Mechanical Engineering, Yale University. Parallelization of Numerical Procedures Appropriate for the Study of Combustion.

Heinz-Otto Kreiss - Ph.D., Mathematics, Royal Institute of Technology, Sweden 1960. Professor, Department of Applied Mathematics, California Institute of Technology. Numerical Analysis.

David G. Lasseigne - Ph.D., Applied Mathematics, Northwestern University, 1985. Assistant Professor, Department of Mathematics and Statistics, Old Dominion University. Computational Fluid Dynamics.

Anthony Leonard - Ph.D., Nuclear Engineering, Stanford University, 1963. Professor of Aeronautics, California Institute of Technology. Fluid Physics.

Robert W. MacCormack - M.S., Mathematics, Stanford University. Professor, Department of Aeronautics and Astronautics, Stanford University. Computational Fluid Dynamics and Numerical Analysis.

Seema Mirchandaney - M.S., Computer Science, University of Massachusetts, Amherst, 1990. Research Programmer, Science and Technology Center, Rice University. Parallel Programming Environments.

Mark V. Morkovin - Ph.D., Applied Mathematics, University of Wisconsin, 1942. Professor Emeritus, Department of Mechanical and Aerospace Engineering, Illinois Institute of Technology. Transition Process in Aerodynamics.

Kirsten A. Morris - Ph.D., Electrical Engineering, University of Waterloo, 1989. Assistant Professor, Department of Applied Mathematics, University of Waterloo-Ontario, Canada. Control Theory.

Naomi H. Naik - Ph.D., Mathematics, University of Wisconsin-Madison, 1987. Senior Staff Associate, Department of Physical Oceanography, Columbia University. Multi-Grid Methods.

David M. Nicol - Ph.D., Computer Science, University of Virginia, 1985. Professor, Department of Computer Science, College of William and Mary. Mapping Algorithms onto Parallel Computing Systems.

James M. Ortega - Ph.D., Mathematics, Stanford University, 1962. Professor and Chairman, Department of Applied Mathematics, University of Virginia. Numerical Analysis of Methods for Parallel Computers.

Stanley J. Osher - Ph.D., Functional Analysis, New York University, 1966. Professor, Department of Mathematics, University of California at Los Angeles. Methods for the Numerical Analysis of Partial Differential Equations.

Demetrius Papageorgiou - Ph.D., Mathematics, University of London, 1985. Assistant Professor, Department of Mathematics, New Jersey Institute of Technology. Computational Fluid Dynamics.

Ugo Piomelli - Ph.D., Mechanical Engineering, Stanford University 1987. Professor, Department of Mechanical Engineering, University of Maryland. Subgrid Scale Reynold's Stress Modelling and Large Eddy Simulation of Turbulent Flows.

Terrence W. Pratt - Ph.D., Mathematics/Computer Science, University of Texas at Austin, 1965. Professor, Department of Computer Science, University of Virginia. Programming Languages.

Daniel A. Reed - Ph.D., Computer Science, Purdue University, 1983. Assistant Professor, Department of Computer Science, University of Illinois. Parallel Processing.

Helen L. Reed - Ph.D., Engineering Mechanics, Virginia Polytechnic Institute and State University, 1981. Associate Professor, Department of Mechanical Engineering, Arizona State University. Computional Fluid Dynamics.

Eli Reshotko - Ph.D., Aeronautics and Physics, California Institute of Technology, 1960. Kent H. Smith Professor of Engineering, Case Western Reserve University. High Speed Aerodynamics with an Emphasis on Transition, Turbulence and Combustion.

Joel E. Saltz - Ph.D., Computer Science, Duke University, 1985. Professor, Department of Computer Science, University of Maryland. System Software.

Paul E. Saylor - Ph.D., Mathematics, Rice University, 1986. Associate Professor, Computer Science Department, University of Illinois, Urbana. Iterative Solution of Linear Algebraic Equations and Algorithms for Parallel Computers.

Robert B. Schnabel - Ph.D., Computer Science, Cornell University, 1977. Chair, Computer Science Department, University of Colorado-Boulder. System Software and Numerical Methods for Optimization.

Jeffrey S. Scroggs - Ph.D., Computer Science, University of Illinois at Urbana, 1988. Assistant Professor, Department of Mathematics, North Carolina State University. Domain Decomposition Techniques for Partial Differential Equations.

Joseph E. Shepherd - Ph.D., Applied Physics, California Institute of Technology, 1980. Associate Professor, Department of Mechanical Engineering, Rensselaer Polytechnic Institute. Combustion.

Chi-Wang Shu - Ph.D., Mathematics, University of California, Los Angeles, 1986. Associate Professor, Division of Applied Mathematics, Brown University. Numerical Partial Differential Equations and Computational Fluid Dynamics.

Katepalli R. Sreenivason - Ph.D., Aeronautical Engineering, Indian Institute of Science, 1975. Professor and Chairman, Department of Mechanical Engineering, Yale University. Transition and Turbulence.

Saleh Tanveer - Ph.D., Applied Mathematics, California Institute of Technology, 1984. Professor, Department of Mathematics, Ohio State University. Problems for Crystal Growth.

Lu Ting - Ph.D., Aeronautics, New York University, 1951. Professor, Courant Institute of Mathematical Sciences, New York University. Fluid Mechanics.

Eli Turkel - Ph.D., Applied Mathematics, New York University, 1970. Associate Professor, Department of Applied Mathematics, Tel-Aviv University, Israel. Computational Fluid Dynamics.

Bram van Leer - Ph.D., Theoretical Astrophysic, Leiden State University, The Netherlands, 1970. Professor, Department of Aerospace Engineering, University of Michigan. Computational Fluid Dynamics.

Hans Zima - Ph.D., Mathematics, University of Vienna, Austria, 1964. Professor, Computer Science Department, University of Vienna, Austria. Compiler Development for Parallel and Distributed Multiprocessors.

Mohammad Zubair - Ph.D., Computer Science, Indian Institute of Technology, New Delhi, India, 1987. Assistant Professor, Department of Computer Science, Old Dominion University. Performance of Unstructured Flow-Solvers on Multi Processor Machines.

IX. STUDENT ASSISTANTS

Avik Banerjee - Graduate Student at Hampton University (May 1992 to Present)

John Otten - Graduate Student at The College of William and Mary. (May 1991 to Present)

X. GRADUATE STUDENTS

Satyanarayan Gupta - Graduate Student at Old Dominion University. (June 1991 to July 1992)

Eyal Arian - Graduate Student at Weizmann Institute of Science, Israel. (May 1992)

Zigo Haras - Graduate Student at Weizmann Institute of Science, Israel. (May 1992)

Jennifer Levin - Graduate Student at Northwestern University. (June to August 1992)

Tommy K. Minyard - Graduate Student at the University of Texas-Austin (July to August 1992)

Peter Schmid - Graduate Student at Massachusetts Institute of Technology (June to July 1992)

Krzysvtof M. Wlodarshi - Graduate Student at Courant Institute of Mathematical Sciences (June to August 1992)

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Mail Stop 132C, NASA Langley Research Center
Hampton, VA 23681-0001

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Langley Research Center
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