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THE SECOND ICASE/LARC INDUSTRY ROUNDTABLE: SESSION PROCEEDINGS

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ABSTRACT

The second ICASE/LaRC Industry Roundtable was held October 7-9, 1996 at the Williamsburg Hospitality House, Williamsburg, Virginia. Like the first roundtable in 1994, this meeting had two objectives: (i) to expose ICASE and LaRC scientists to industrial research agendas, and (ii) to acquaint industry with the capabilities and technology available at ICASE, LaRC and academic partners of ICASE. Nineteen sessions were held in three parallel tracks. Of the 170 participants, over one third were affiliated with various industries. Proceedings from the different sessions are summarized in this report.

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FOREWORD

The Second ICASE/LaRC Industry Roundtable was held October 7-9, 1996 at the Williamsburg Hospitality House, Williamsburg, Virginia. Like the first Roundtable in 1994, the meeting had two objectives: (i) to expose ICASE and LaRC scientists to industrial research agendas, and (ii) to acquaint industry with the capabilities and technology available at ICASE, LaRC and academic partners of ICASE. Industry participants were invited to discuss their future research needs in semi-formal presentations and informal around-the-table discussions.

Nineteen sessions were held in three parallel tracks broadly classified as fluid mechanics, applied numerical methods, and computer science. There were over 170 participants of which approximately one-third were affiliated with various industries. Many of the sessions were organized and chaired by ICASE consultants from universities, industrial researchers and government funding agency program managers. This gave the sessions a unique perspective not usually experienced in technical meetings. The participant mix ranged from theoretical researchers to engineering practitioners, all interested in the same issues. This made for some very interesting exchanges during the round table discussions following the presentations.

The topics covered in fluid mechanics included acoustics (aerodynamic and structural), flow control, aerothermodynamics, turbulence, combustion, and general aerodynamic issues in the aircraft and automobile industries. The applied numerical methods track had sessions on computational electromagnetics, computational material science, and technology-transfer issues in CFD. The computer science track covered software reliability, parallel solvers, high-performance computing, cluster computing and visualization. Important issues pertaining to structures and materials were covered.

In addition to the technical sessions, there were three invited keynote talks. Dennis Bushnell, Senior Scientist at NASA Langley Research Center, spoke about futuristic trends in aeronautics in his talk, "The frontiers of the responsibly imaginable in aeronautics." Robert Whitehead, Associate Administrator for Aeronautics at NASA Headquarters, discussed the future of aeronautic research at NASA in his talk,

"Aeronautics research and technology at the crossroads." William Ballhaus, Vice President for Science and Engineering at Lockheed Martin Corporation, gave an industry perspective on managing scientific research in his talk, "Change: Managing your way through it."

ICASE would especially like to acknowledge the participating industries: BBN, Northrop Grumman, Lockheed Martin, United Technologies, Rocketdyne, Boeing, McDonnell Douglas Aerospace, Altair Engineering, Metacomp Technologies, Ford Motor, GE Aircraft Engines, Rockwell International, Bellcore, Cessna Aircraft, Lucent Technologies, Chrysler Corporation, Digital Equipment Corporation, Arvin NA Automotive, AVS, Fluent, Sonnet Software, Alcoa Technical Center, Silicon Graphics, General Motors, and Newport News Shipbuilding.

ICASE gratefully acknowledges the help of all session chairs who made this meeting possible: Roger Arndt (NSF); Gregory Buck (LaRC); Namas Chandra (Florida State U.); Thomas Crockett (ICASE); Jerry Housner (LaRC); Ronald Joslin (LaRC); David Keyes (Old Dominion U. and ICASE); Michele Macaraeg (LaRC); Mujeeb Malik (High Technology Corporation); Dimitri Mavriplis (ICASE); Piyush Mehrota (ICASE); Alex Pothen (Old Dominion U. and ICASE); Ivatury Raju (LaRC); C. J. Reddy (Hampton U.); Len Sakell (AFOSR); Richard Silcox (LaRC); Munir Sindir (Rocketdyne); Arun Somani (U. of Washington, Seattle); Kishor Trivedi (Duke U.); and Richard Wlezien (LaRC). Thanks are also due to Ms. Emily Todd for her excellent organization of this Roundtable and to Dr. Robert Rubinstein for his editorial assistance.

Sharath S. Girimaji

SESSION A1: ACOUSTICS

Michele G. Macaraeg, NASA LaRC

An active roundtable discussion occurred after the Acoustics Session presentation. Questions were initially directed to Dr. Thawani from Ford Motor Company. Dr. Street of NASA LaRC asked if the transfer matrices could be used to study the acoustics of multi-stage mufflers. Dr. Thawani indicated that extensive testing was required to address that application so that empirical data became a salient component. An issue raised by Dr. Silcox of NASA LaRC involved the assumption of linearity for the seemingly nonlinear problem of duct and muffler acoustics. Dr. Thawani indicated that this assumption was valid over a limited frequency range of up to 4-5 harmonics. Further questions clarified that the problems discussed by Dr. Thawani ignored the flow through these ducts.

A question to Dr. Sen from the Boeing Commercial Airplane Company concerned a definition of "quick turn around time", which was mentioned in Dr. Sen's talk as an important Boeing standard. Sen indicated that a few days is considered acceptable for most design work, although this timeline can change depending on the particular phase of the design process. A further question to Dr. Sen from Dr. Guo of McDonnell Douglas concerned the acceptance of traditional CFD tools for acoustic design issues. Dr. Sen indicated that the traditional CFD tools in the Boeing High-Lift Program have an 8-10 hour turn around time. Applying this same technology to noise problems would require several days, which is unacceptable. In addition, the accuracy of these traditional tools may not be sufficient for aeroacoustic applications. Dr. Guo suggested that a semi-empirical approach may be a useable compromise to increase efficiency and accuracy. Dr. Barson from Rocketdyne indicated that there is also a cultural acceptance of CFD tools for unsteady flow problems which is still lacking, although the acceptance of steady CFD tools in industry is now common.

Maurice Sancer from Northrop Grumman Corp. asked if attention was being paid to Computational Electromagnetics (CEM) since it was clear to him that the field of linear acoustics was still evolving. Participants pointed out that algorithms to solve linear acoustics---i.e. noise radiation-- is an area well in-hand. However, Dr. Ristorcelli from

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ICASE pointed out that the acoustic source is very nonlinear, and that is the major obstacle in computational aeroacoustics at the present time.

Dr. Hardin from NASA Langley asked if Mr. Wayne Walters (of Newport News Shipbuilding) could give some examples of unsolved problems in the area of hydroacoustics. Mr. Walters indicated that there are numerous system resonance problems which are difficult to define. Mr. Walters indicated that typically commercial codes such as NASTRAN are utilized to study these issues.

Dr. Barson from Rocketdyne was asked which frequency domains are of most interest to the Computational Aeroacoustic Analysis System (CAAS) team he described during his presentation. Dr. Barson indicated that both Rocketdyne and Ford are most interested in low frequency applications. The most difficult aspects of these problems involve complex geometry grid generation, three dimensionality and rotating systems.

Dr. Zang from NASA Langley asked if Dr. Sen's acoustic group at Boeing had any interaction with Boeing engineers working in structures and controls. Dr. Sen indicated that this interaction was more the case in the experimental and hardware side more than in algorithm and tool development.

Dr. Ristorcelli asked Mr. Walters if he could categorize the most dominant hydroacoustic noise sources. The question was whether it was the coherent structures or the small scale (broadband) noise sources that were most dominant. Mr. Walters indicated that although the broadband noise sources can be a problem, filters are often used to decrease their contribution so that tonal noise usually became the more dominant source. Dr. Barson added that in the area of propulsion, mostly large scale structures associated with shedding dominated noise source problems. He estimated that 80% of sheet metal cracks occur from acoustic issues in the very dynamic environment associated with turbomachinery---presently no tools exist to address this problem. Dr. Thawani further added that in automotive noise, most of the tonal sources are associated with structural issues, as in the case of a compressor which can excite an entire system of interacting sources. The need to understand the physics of the source excitation is critical. Dr. Sen indicated that in the past Boeing focused on broadband noise sources

solely. However, presently the importance of tonal noise and coherent structures is being addressed. The relative contribution of each is still an unanswered question.

SESSION A2: AUTOMOTIVE RESEARCH ISSUES

Roger E. A. Arndt, National Science Foundation

SUMMARY

The 2nd ICASE/LaRC Industry Roundtable had one session on automotive research needs. The structure of this session was slightly different than other sessions since the material covered was an outgrowth of a NSF/Big3/MSU workshop that had identified basic needs for fluid mechanics research in the automotive industry. The focus of the discussion was on three major areas: i) external aerodynamics including drag, stability and control, and aeroacoustics, ii) internal aerodynamics, including passenger compartment comfort and underhood thermal management, and iii) the fluid mechanics of induction and exhaust systems. Issues related to combustion processes was specifically excluded from the discussion.

INTRODUCTION

This is the first roundtable in which an entire session was devoted to automotive research issues. The topics presented here are an outgrowth of a two day meeting held at the Michigan State University in August 1995. Representatives from government (NSF), industry (Chrysler, Ford and General Motors) and academia were able to identify a broad range of fluid mechanics topics that were of mutual interest. Topics discussed included issues related to external aerodynamics, with specific interest in drag, stability and control problems, and noise. Internal aerodynamics issues include a broad range of problems that can be broken down into three categories relating to underhood thermal management, induction and exhaust from the engine, and passenger compartment climate control.

These issues were brought into sharper focus in a follow-on session held in April 1996 where specific research issues were articulated as "Challenge Problems".

This roundtable discussion focused on those issues that relate to CFD and the challenges for experimental work that can verify and strengthen existing computational

routines. The session was started with an overview by Professor J.W. Foss on the specific challenges that were identified in the NSF/Big3/MSU workshop. Computational climate control was discussed by Dr. Hsien-Ren Lee from Chrysler. Internal gas flows in engine induction and exhaust flows was discussed by Dr. James M. Novak of Ford and a discussion of external aerodynamics was presented by Dr. V. Sumantran of General Motors.

PRESENTATIONS

Challenge problems from the NSF/Big3/MSU Workshop was discussed by John Foss of Michigan State University. Given the substantial ongoing efforts in combustion chamber flows and the limited resources to address automotive fluid mechanics problems, the workshop organizers elected to focus on four areas: 1) External Aerodynamics, ii) Underhood Cooling-Thermal Management, iii) Passenger Compartment-Climate Control, and iv) Induction and Exhaust Flows. The Big 3 representatives were able to clarify the salient issues in these four technological areas, the academic and NSF representatives contributed suggestions of how to express these issues in a research context.

The essential results from this session can be summarized as stated below. These will be clarified in the presentation:

1) The A-pillar vortex was identified as a paradigm problem for automotive aerodynamics; aeroacoustic and aerodynamic loading are two of the central concerns for this flow problem.

2) The complexity of the underhood environment led to the proposal of a "paradigm flow channel." Simulated heat transfer elements, an axial fan, and outflow obstructions will be incorporated. The unit will provide a standard "proof test" unit for CFD codes.

3) The Climate Control focus group identified the transfers of heat, mass, and momentum in an obliquely impinging, finite length jet (defrost/defog) as a principal problem area. Also, minimization of pressure drops in internal flows and correlation of noise measurements with flow field variables are central issues in this technical area.

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4) The challenge problem for the induction and exhaust focus area is a specified duct with contractions and 90 degree plus 45 degree bends. An oscillatory flow is specified at 1,000-6,000 rpm where the flow rate varies symmetrically from zero at 0 degrees of "crank angle", through a maximum and back to zero at 180 degrees followed by no flow for 180 < 0 < 360. The duct geometry is specified in terms of Strouhal and Reynolds number. The committee felt that this problem would establish a "universal test case" for the unsteady, 3-D, developing flows of interest.

Computational climate control of automotive industries was discussed by Hsien-Ren Lee of Chrysler Corporation. He pointed out that passenger safety and comfort in modern vehicles have become among the most important climate control design considerations. During the design process, the prototype's climate control systems need to be evaluated and modified based on several testing data including cold room and hot room tests. In order to meet Federal Motor Vehicle Safety Standard No. 103 (FMVSS 103), cold room tests require that certain vision regions of the windshield should be cleared effectively by the defroster system. In the hot room tests, the vehicle's HVAC cooling system efficiency should be evaluated and modified when the vehicle is exposed to pre-soaking hot room and external thermal radiative flux. There are several computational issues that relate to the physics of wall jets.

A numerical simulation of the vehicle in cold room and hot room tests was successfully performed and correlated with the experimental data in Chrysler. Some examples of how Computational Fluid Dynamics (CFD) technology can be used as a tool to analyze existing design, evaluate proposed modifications, optimize products and processes for automotive climate control systems were given. CFD also can be used as a tool to reduce expensive and time-consuming practice of trial-and-error prototype testing and hardware modifications.

As discussed by James M. Novak of the Ford Motor Company, the flow of gases within the induction and exhaust systems of automotive internal combustion engines, including air, fuel vapor and combustion products, has a profound influence on several important vehicle/powertrain attributes - most notably: performance, fuel economy, noise,

and exhaust emissions. Because of the complexity of the associated flow processes, the automotive industry continues to pursue the development and application of both one- and multi-dimensional computational fluid dynamic (CFD) simulation tools to improve the quality of its vehicles. Competitive pressures in recent years have made the use of such CFD methods imperative for reducing the "concept-to-customer" times of automotive powertrains.

Dr. Novak's presentation described how one of the primary CFD tools is used at Ford Motor Company to simulate the overall unsteady, compressible gas flow throughout the entire "breathing" system of an automotive reciprocating engine. It is used to predict the engine's torque and horsepower, volumetric efficiency, and wave dynamic sound levels and frequency content at the air inlet and exhaust tailpipe - all as functions of the flow geometry (centerline lengths and cross-sectional areas), valve/cam lift profiles, and overall engine geometry (e.g., bore and stroke). Known as MANDY, this model uses an explicit, second-order, finite-difference technique to solve the "Quasi-1D" conservation equations of gasdynamics within all the flow passages of the engine's intake and exhaust ducting. Key sub-models of MANDY simulate: (1) in-cylinder combustion and thermodynamic conditions, (2) flow discharge coefficients for the intake and exhaust ports in the cylinder head, and (3) flow loss factors for "system elements" such as throttle body, airmeter, catalysts, mufflers, etc. Typically, such flow loss information in the literature, or obtained within the flowlab at Ford, represent steady state values. Research is needed to determine these coefficients under the more realistic conditions of: (1) unsteady pulsating flow, and (2) flow geometries involving the interaction of two or more elements (e.g. a duct bend followed by a sudden or gradual expansion).

Three-dimensional CFD codes are finding increasing use as computer hardware capabilities improve and commercial codes become more user-friendly and accurate. However, 3D models are still impractical for simulating the entire intake and/or exhaust tracts of typical automotive engines, especially for the unsteady flow conditions inherently present in these systems. Recent efforts in this area provide for a "linkage" between the 3D and Quasi-1D codes, in which the full 3-dimensional calculation is done for complex system elements (e.g., junctions of three or more ducts) and the one-

dimensional calculations provide upstream and downstream boundary conditions at each time step. Effective, accurate, and efficient means to carry out this linkage are needed.

Finally, validation of these models with representative experimental data using modem flow diagnostic techniques are extremely important to calibrate and improve such models.

As discussed by V. Sumantran of the General Motors Research and Development Center, several factors, notably government regulations and customer expectations, have served to provide additional fuel to on-going global efforts in road vehicle aerodynamics and aeroacoustics, over the last three decades. The progress made in these as well as other areas of automobile technology has seen continual acceleration as the level of competition in this global industry intensifies. Yet, there remain several areas where research efforts and technical breakthroughs are eagerly awaited in the quest for further improvements of both product and the process.

While aerodynamics is a crucial discipline in aircraft design, the auto industry must be more acutely reconciled among other considerations like safety, comfort, utility and indeed aesthetics. Consequently, while most aerospace forms are designed to be "aerodynamic", most vehicle shapes may be classified as "bluff bodies". Therein lie many unique sources of complexity. For example, the large separated flow regions, typical of bluff bodies, implies increased difficulty in both simulation and some measurements.

Common elements among the two industry segments are numerous. Both involve product development that consumes large amounts of resources and time. The financial flak, inherent in this situation to any manufacturer, has led to significant focus on both the product (performance and quality) and the process (design and manufacture). For example, the average fuel economy of cars in the US, which increased two-fold between 1974 and 1994, has been assisted by reductions in aerodynamic drag. As overall vehicle shapes see evolution to more "aerodynamic" forms, additional effort is being expanded into such areas as underbody airflow, engine-cooling systems and aerodynamic vehicle stability. Similarly, wind-noise levels in vehicle interiors have seen significant reduction. Much of this progress has been achieved through improved methods used in

wind-tunnel testing. The last decade has witnessed the inauguration of several new automotive wind-tunnels around the world, incorporating sophisticated data acquisition systems, ground boundary-layer treatment and "low noise" test sections.

Computational fluid dynamics (CFD) is becoming a key enabler in the acceleration of the product development process. The growing use of CFD today has also served to highlight critical limitations in areas such as geometric modeling, grid generation as well as accuracy, economy and functionality of the simulations. In the future, CFD will also be expected to perform within a multi-disciplinary framework and tackle such complex problems as wind-noise prediction for realistic shapes.

As one looks ahead to these challenges, there is much that researchers and engineers in the auto industry and the aerospace industry can share with each other. In an environment of constrained resources, this opportunity to share in mutually beneficial development deserves keen attention.

RESEARCH AREAS

In addition to the research topics highlighted in the presentations, it became apparent that experimental research must plays an important role in further development of CFD. There are experimental needs for development, verification, and validation of computational codes in fluid dynamics. The need for more efficient and accurate CFD codes that are applicable to a wide range of flows in automotive applications highlights the need for a strong interaction between the experimentalist and the numerical modeler. Specifically, research is needed in the following areas:

Identification of special experimental data required for validation and verification of CFD codes.

- Identification of the types of flows that require bench-marking, including a discussion of the experimental challenges in this area.

- The role of experimentation in developing and verifying the physics involved in various types of turbulence closure models ranging from the assumptions inherent in K-e, etc. to the more recent needs for refined sub-grid models for LES.

There also a need for establishing a national data base where archival experimental and numerical data can be made available to researchers involved in code development.

SESSION A3: GENERAL AVIATION

Mujeeb R. Malik, High Technology Corporation

There were three main objectives of this session on General Aviation (GA): (1) the future vision for the GA industry, (2) technical challenges faced by GA community in various disciplines such as aerodynamics/structural design, acoustics, flight control, safety/reliability, etc. and (3) what is being done or needs to be done to address these challenges. There were three speakers. The fourth talk was canceled due to a last minute illness.

Dr. Bruce Holmes who is the manager of General Aviation/Commuter Office at NASA Langley Research Center was a natural choice for this session. He delivered a very insightful lecture entitled "The Ingredients of a Renaissance: A Vision and Technology Strategy for U.S. Industry, NASA, FAA and Universities." Dr. Holmes described NASA's vision to "revitalize the U.S. General Aviation Industry through technologies for single pilot, light, near all-weather small aircraft transportation system." Advances in communications, navigation, computers and display technologies offer a new opportunity to expand the utility of GA to help meet our nation's needs for short and medium range as well as specialty air transportation. This expanded, affordable, GA based transportation system will help bring small US communities into fold of the greater business enterprise and will have a revolutionary impact on US economy, as past advancements in transportation and communication always did.

In order to help realize the above vision, a consortium of U.S. Government and industry as well as universities has been established. The stated goal of the consortium which is named AGATE (Advanced General Aviation Transport Experiments) is "to create bases for a small aircraft transportation system and revitalize U.S. general aviation through development and deployment of advanced technologies in new designs and certain retrofit system products." Currently, there are about 70 members of AGATE in 36 states. The technologies which AGATE aims to bring together to create a viable transport system are outlined in the following chart.

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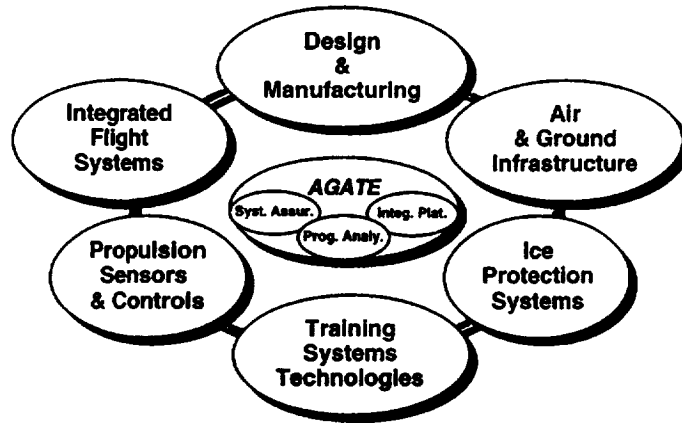
Dr. Holmes also touched upon the benefits of "third generation R&D" as opposed to conventional Government contracting. His views on this subject are described in NASA TM 110271 entitled "(Re)inventing Government-Industry R&D Collaboration." This TM also lists the members of AGATE.

Mr. Robert Howes is the Supervisor of Acoustics and Structural Dynamics at Cessna Aircraft which produces a broad range of products, from single engine propeller aircraft to Mach 0.9 business jets. In his talk, he emphasized that the general aviation market is very competitive and cost sensitive and, therefore, any new technology must "buy its way" onto the airplane by providing increased utility and value to the customer.

Mr. Howes outlined the technical areas in which GA industry welcomes research. This includes lightweight materials, systems technology, active noise control, aircraft design and manufacturing techniques. He also described some of the cooperative projects that Cessna is involved in with NASA, Naval Research Lab, and Universities such as Wichita State University, Kansas State University and Virginia Polytechnic Institute and State University.

Mr. James Meer is the Manager for Strategic Plans & Policies at Digital Equipment Corporation, a member of AGATE. In his talk, he gave an Industry Perspective of AGATE. He pointed out that there was a general decline in the GA industry since 1970's, both in manufacturing and operations. In the 10 year period (1983-93), for example, new aircraft deliveries decreased by almost 85 percent. Some of the reasons for this general decline were:

* Dealers and distributors overstocked from the late 1970's production
* High interest rates and elimination of the investment tax credit inhibited sales
* New airplanes perceived to be little improved over much less costly used models
* New airplanes less and less affordable
    - Prices increased faster than consumer price index
    - Escalating product liability costs
    - lower production rates
* Complexity of operating in U.S. airspace
* Reduced growth rate for disposable income
* Slowed growth in small businesses
* Increased business failure rate
* Expansion of regional airline travel
* Elimination of GI bill for flight training

However, there is a renewed interest in GA due to new technologies such as Global Positioning System (GPS) and general purpose computers which allow automation of navigation and much less dependence on the pilot. AGATE has been created to serve as a focal point to help integrate these technologies to revolutionize this transport system. Both Holmes and Meer argue that, for mid-range travel, there is potential to make aircraft travel almost as cost effective as automobile with much less human fatigue (a 500 mile round trip which takes 16 hours on a car will only take 5 hours on an aircraft). However, the "aircraft solution" must be psychologically acceptable to the customers. Pilot surveys suggested following success metrics for AGATE:

Impact (User Decision Factors) Success Requirement

1. Safety - Safety rates similar to cars and airlines
2. Affordability - Portal-to-portal cost and time per trip similar to cars and airlines for mid-range travel
3. Reliability - Operational reliability similar to cars

4.   Utility - Near all-weather availability in GA airport infrastructure

5.   Ease-of-use - Proficiency in time and cost, ground and air infrastructure complexity, preparation time reduced to "fit" user requirements

6.   Environmental Compatibility - Noise and emissions for piston/propeller powerplants must permit unrestricted access to airspace and airports.

Mr. Meer also narrated some AGATE success stories. One of the most recent one is the "highways in the sky" capability which was created for the 1996 Olympics in Atlanta for less than $2 million. Advanced navigation, digital radio datalink communications, and flat-panel displays technologies were integrated in less than 7 months and installed in 50 aircraft operated during the Atlanta Olympics. This system provided pilots and controllers graphical traffic, weather, moving maps, and other pertinent information in real time.

In the end, discussion was held on what ICASE can do to help. Three areas were outlined:

*   aeroacoustics

*   automation

*   information systems

Among these, ICASE may wish to concentrate on the subject of aeroacoustics. Passenger comfort will be one of the key factors in wide-spread acceptance of the GA-based transportation system and cabin noise has an adverse effect on passenger comfort. Therefore, innovative methods (active or passive) for noise alleviation are needed. It is recommended that special attention to GA problems be given during any workshops held on aeroacoustics.

SESSION A4: AEROTHERMODYNAMICS: CURRENT STATUS AND FUTURE CHALLENGES

G. M. Buck, NASA Langley Research Center

Complex and non-linear aerothermodynamic solutions have forced the vehicle designer to use approximate theoretical techniques relying heavily on experimental methods. The dominant theoretical approximation in aerodynamics in general has been to neglect the influence of viscosity and hence focus on understanding and taking advantage of inviscid flow phenomena while minimizing the effects of viscosity in the flowfield. This mind set is evident in the early development of experimental facilities for understanding and manipulating compressibility effects.

Three developments have turned the focus of aerothermodynamics to the understanding and manipulation of viscous flow phenomena. The first is the need to remove uncertainty from the design process of hypersonic vehicles with ever more challenging performance requirements and ever increasing development costs. The second is the maturation of CFD which can now predict nonlinear, inviscid flows efficiently for complex geometries including non-equilibrium flow, wall catalyticity, radiative heat transfer and rarefied flow. Yet, computations struggle with prediction of viscous flows. Major uncertainties still exist in predicting the effects of Reynolds number with current CFD technology. The third development is the growth of information technology which allows us to visualize, analyze and control complex systems such as flight vehicles and experiments. New global measurement techniques provide the ability to visualize and quantify surface heating with ever increasing resolution but fall short of measuring pressure, skin friction and velocity fields in hypersonic environments. Further development of global measurement techniques are required for better understanding of viscous flow phenomena.

In the long term, the development of air-breathing propulsion will greatly increase efficiency of hypersonic vehicles over rocket propulsion. Active control of viscous flow through smart structures is needed to reduce drag, increase inlet and nozzle efficiencies and reduce aerodynamic heating in these vehicles. Such structures do not yet exist but the

development of piezo-ceramic materials for hingeless control surfaces and adaptive inlets and nozzles may prove to be the cost effective, if not the aerodynamic and structural solutions to the future.

"Predicting and Controlling Drag and Heating", J. W. Haney, Rockwell Aerospace

Predicting and controlling drag and heating is a challenge to vehicle designers and has a first order impact on vehicle performance and weight. In addressing drag and heating predictions many phenomena that vary with flight velocity and altitude must be considered. Some of these phenomena are easily characterized while others such as surface catalytic and boundary layer transition still elude complete modeling. Advances have been achieved in developing computational tools and experimental techniques to understand the phenomena affecting drag and heating as well as to predict their magnitude. However, the ability of the designer to accurately predict and control drag and heating for any shape at any flight condition remains outside their reach. Boundary layer transition is one of the phenomena which prevent accurate predictions. Therefore, vehicle designers must continue to carry structural weight and fuel margin to accommodate prediction and control uncertainties until determined during flight test.

"Controlling Transition in Hypersonic Boundary Layers", M. R. Malik, High Technology Corporation

Control requires understanding of the mechanism and the ability to predict parametric effects on boundary-layer transition. Therefore, we first present the current status of hypersonic boundary-layer transition prediction including the recently developed parabolized stability equations (PSE) method for chemically reacting flows. The significance of supersonic modes and finite-rate chemistry in high Mach number boundary-layer transition were discussed. Various control techniques and methods for hypersonic transition tripping were also considered.

"Increasing Experimental Productivity with Global Surface Measurement Techniques",

N. R. Merski, NASA Langley Research Center

During the last decade, global surface measurement techniques have emerged as a practical means to obtain quantitative experimental data in hypersonic wind tunnel testing. These techniques, which include infrared radiometry, liquid crystals, temperature and pressure sensitive paints, and thermographic phosphors, are optically based and are used to measure a variable at every single "point" on a surface which is in the field of view of a digital camera. These measurements are carried out in an efficient manner because of enabling technologies such as solid-state CCD (Charge Coupled Device) cameras, video-rate digitizers, fast computer processors, and high capacity digital storage devices. NASA Langley's two-color relative-intensity phosphor thermography method is a representative example of the state-of-the-art in such techniques.

Two primary elements of global surface measurements enhance experimental productivity. First, an image mapping is obtained on a wind tunnel model which simplifies interpretation of complex flow phenomena immensely. Second, model fabrication time is reduced an order of magnitude from conventional models since the models do not have to be instrumented with discrete gauges. Application of these two elements can greatly increase the productivity of various aspects of experimental testing including experimental technique, parametrics and code comparisons. With this increase in productivity, global surface measurement techniques are valuable to reentry vehicle programs since they provide parametric information in the design/optimization phase of a vehicle and because the global data can provide information for TPS sizing and structural loads in the final vehicle design.

While global surface measurement techniques have many advantages, there are a number of improvements which can still be made. Future challenges include "bench-marking" data and image photogrammetry.

"Smart Structures for Control and Performance of Hypersonic Vehicles",

S. Joshi, Mechanical and Aerospace Engineering Department, The University
of Texas at Arlington

How state of the art smart structural concepts could improve the design of: hypersonic vehicles, including winged single stage to orbit (SSTO), sub-orbital cruise aircraft, and supersonic and hypersonic missiles with demanding airframe and systems requirements, that may not be sufficiently met with the traditional structural designs. Smart structural concepts can help solve some of these demanding requirements. The operating environment of hypersonic vehicles were surveyed first. Following the survey, capabilities of currently used structural materials and actuators were compared with those of smart materials and structures. It was argued that available smart materials can be used in a hypersonic vehicle because the environment in which these materials function is achievable within the vehicle. It is possible because extremely hot and cold temperatures are present in the vehicle. Possible smart structures' applications were presented as modifications of existing designs as well as new structural concepts. Specific concepts were discussed in terms of short and long term applicability of them. Wing flutter, engine vibration, fuel slosh, coolant flow, thermal expansion mismatch, surface blowing and inlet unstart were also discussed. Conclusions were made on the suitability of various smart structures' concepts for current and future hypersonic applications. The problems identified in this presentation are outcome of interviews with various designers from industries involved in the structural and aerodynamic design of missiles as well as the now defunct NASP program. It is hoped that by identifying possible applications in advance that industry will be encouraged to pursue more smart structures' solutions in the design and production of hypersonic vehicles.

Roundtable Discussion

J. W. Haney, Rockwell Aerospace

M. R. Malik, High Technology Corporation

N. R. Merski, NASA Langley Research Center

S. Joshi, Mechanical and Aerospace Engineering Department, The University of Texas at Arlington

L. Sakell, Air Force Office of Science and Research

G. M. Buck, NASA Langley Research Center

Discussion centered around the need in aerothermodynamics to maintain an educated base to draw from in the future development of hypersonic vehicles. In the past, large steps were taken toward understanding hypersonic boundary layers. Theoretical methods introduced during the NASP program require further systematic analysis to test these methods and refine their parameters. Continued government support of research and development in this area is critical as independent or industry support of such efforts is unlikely until the technologies for air-breathing propulsion are commercially viable. Although possible smart structure applications were identified, such systems and materials have yet to be developed or tested. Unlike lower-speed applications, aerothermodynamic analysis of fully integrated vehicles is necessary to evaluate propulsion and structures as well as flight performance. In the future, efficient and integrated test methods will be required as well as refined prediction methods for viscous flows in the development of hypersonic air-breathing vehicles.

SESSION A5: TURBULENCE AND COMBUSTION - INDUSTRIAL APPLICATIONS AND TECHNOLOGY TRANSFER

Munir Sindir, Rocketdyne

INTRODUCTION

Four talks were included in the Turbulence and Combustion - Industrial Applications and Technology Transfer Session of the 2nd ICASE Industry Roundtable. Speakers from various industries were invited to have different views and perspectives represented in the Session. The titles of the talks and speakers are given below:

1. Turbulence and Combustion Modeling Requirements for Aerospace and Commercial Applications - Thomas J. Barber, United Technologies Research Center

2. Overview of Turbulence and Combustion Modeling in Automotive Industry- Derlon Chu, Ford Motor Company

3. Application of Turbulence Modeling in Gas Turbine Combustion Design Current Status and Future Direction - Chandar Prakash, GE Aircraft Engines

4. Turbulence Modeling Needs and Practices for Tactical Aircraft - Brian R. Smith, Lockheed Martin Tactical Aircraft Systems

To maintain consistency in the talks, each speaker adhered to the following format as much as possible in the presentations:

1. Brief discussion of that industry's (e.g. automotive) products/applications/ areas of concentration that require turbulence/combustion modeling.

2. Current use, state-of-the-practice (SOP), of turbulence and combustion models in that industry (substantiated with examples if possible.)

3. Assessment of the SOP in terms needs and expectations.

4. Suggestions for research and development in these areas to overcome the technology gaps identified in 3.

SUMMARY OF THE PRESENTATIONS

1.   Turbulence and Combustion Modeling Requirements for Aerospace and
      Commercial Applications-

At United Technologies Corporation (UTC), turbulence and turbulent/
combustion processes dominate several gas turbine component design processes
(combustor and nozzle) and the improvement of aerospace manufacturing processes
(thermal spraying/HVOF). This is also true for the design of non-aerospace products of
our Carrier Division, i.e. residential furnaces and air management systems (axial/radial
fans, centrifugal chillers). The primary drivers for both requires turbulence control in
order to reduce noise emissions for both aerospace and commercial products. Similarly,
NOx emissions are the primary driver for control of turbulent/combustion processes.

In all of these situations, the effects of swirl, heat release, kinetics, compressibility
complicate the predictability of design tools using models developed for low speed flows
over flat plates. Additional problems are faced when unsteady effects, due to either
natural or forced mechanisms, significantly affect the operability or performance of the
product.

All Navier-Stokes codes at UTC have either (k-e) or (q-w) two-equation
turbulence models, some with compressibility corrections. In the design environment,
wall functions are typically used, however wall integration, using a low Reynolds number
model are available. Combustion processes modeled using heat release models
(Magnussen) and some limited use of reduced kinetics models. This model crudely
includes the effects of turbulence through the time scale definition.

Examples of modeling shortfalls using these SOP models will be shown for
benchmark and practical applications. At least three case studies will be presented,
including flow within a swirling duct or model combustor (Johnson & Roback), flow
over a triangular bluff body or flameholder (Volvo), and flow from a thermal spray
combustion gun. The capability of turbulent-combustion of SOP models will be
demonstrated using the step combustor of Durban.

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In the case studies cited above, several non-production advanced physical models will be examined and compared to the production turbulence models and to available experimental data. More specifically, (k-e) predictions will be compared to Reynolds stress, RNG, Very Large Eddy Simulation (VLES) and in limited cases to LES results. Disagreements with experimental data will be quantified in terms of their effect on critical design requirements.

Improvements for turbulent-combustion effects include assorted PDF models. Scalar PDF models are being investigated with limited degrees of success. For premixed systems, a g-equation flame front tracking model is also under investigation.

Technology gaps have been identified and some advanced physical models have been shown to improve the modeling for specific problem applications. In the industrial environment, one typically would like a single model to apply across the large range of product applications. A better scenario would allow for models to be tailored for specific classes of problems and allow the user to adapt one' solver to their own problem. The research community needs to appreciate the range of problems encountered and the need to understand the range of credibility of their models, i.e. show the bad with the good. Furthermore, the research community needs to measure their modeling results using more realistic data bases, in addition to more fundamental data bases.

2.   Overview of Turbulence and Combustion Modeling in Automotive Industry

The automotive industry is striving to improve product quality and to reduce cycle time due to customer satisfaction and competitive market. The analytical technique has been identified as the key enabler to achieve those goals. Among those upfront CAE tools, the Computational Fluid Dynamics (CFD) is mainly used on modeling fluid flows (such as air, fuel, gas, oil and water) and heat transfer to improve performance, fuel economy, emission and thermal management. The typical applications of CFD in auto industry can be roughly categorized as:

* Vehicle area: underhood/underbody air flow and thermal management, aerodynamics and brake cooling etc.

* Powertrain (engine and transmission) area : in-cylinder flow and combustion, manifold, catalytic converter, water jacket, torque converter and pump, etc.

* Climate control area : windshield de-icing, passenger comfort, HVAC, etc.

* Manufacturing area : casting, injection molding, paint booth, thermal spray, etc.

Almost all the CFD applications in auto industry are turbulent flows which require some kind of turbulence modeling. Despite of all the criticisms, the two-equation k-epsilon model is still used on wide range of applications due to common availability from commercial CFD software and lack of better yet general and practical models. Other type of models, such as mixing length, one-equation model even LES (Large Eddy Simulation) have limited success on certain applications. Some efforts are directed to calibrate the model constants based on experimental data or to modify the source term to account for special flow features, such as rotational effect. In general, auto manufactures heavily rely on commercial CFD software, in which k-epsilon model with wall function is the common practice to perform the applications.

In terms of combustion modeling, the thermodynamics-based model is still the major tool to predict the combustion characteristics, such as burn rate and flame propagation to help design trade-off studies. However, some hardware test data are required to calibrate these models before analysis. The three-dimensional CFD is becoming more popular due to the capabilities of predicting the flow (swirl/tumble/turbulence) structure and combustion based on detailed geometry. Various combustion models are used in auto industry, such as the Eddy Break Up model and PDF (Probability Density Function) model, to gain more understanding about internal combustion engines. The effort is still more on research, rather than practical applications due to the complex physics, tedious model setup (moving valves and piston) and long running time.

In summary, the research should concentrate on the understanding of the physics through experiments as well as analytical techniques to build the foundation for better turbulence and combustion models. Also practical CFD applications should be put on fast turn-around time (including the development effort for CAD/CAE seamless interface, automeshing, analysis setup, parallel computing and quick postprocessing) and accuracy

improvement (including numerical algorithm, physical sub-model, correlation study and knowledge-based engineering.)

3.   Application of Turbulence Modeling in Gas Turbine Combustion Design -
        Current Status and Future Direction

Gas turbine combustion design has come a long way with regard to heat release rates, operating pressures (exceeding 40 atm) and temperatures (3000 F in commercial technology engines and near-stoichiometric in high-performance military engine demonstrators), durability, and combustor length. Single annular combustors (SAC) are being pushed to the lowest possible levels of NOx consistent with the other propulsion combustion system requirements. The dual annular combustors (DAC) have been certified for low emissions turbopropulsion engines that produce an even lower levels of NOx emissions during the landing-takeoff cycle (LTO) as well as for typical flight missions. The triple annular combustion system for dry ultralow NOx (with potential exhaust Nox levels down to single digits) has been successfully introduced as an alternate to the wet low-emissions control technology for industrial application of aeroderivative gas turbines with nominal pressure ratios of 30 or higher.

Empirical/analytical combustor design approach has become industry's standard for advance technology, new product introduction and current product support activities. Nonintrusive measurement techniques have made significant progress that has helped create an extensive benchmark quality database for assessing the quality of current turbulent combustion models and providing direction for further improvements.

Extensive validation activities on the k-e based turbulence models, fast chemistry or finite-chemistry laminar flamelet concepts with specified PDF have established the limitations of these models. A brief overview is given of the three turbulence modeling approaches relevant to the gas turbine combustors, namely the k-e, algebraic and differential stress models. The algebraic stress models have not provided any advantage over the full Reynolds stress transport models (RSTM) in regard to computer time savings etc. Even though the RSTM provide slightly better agreement with data than the k-e model, the latter continue to be preferred by industry for several reasons including computer time. However, recent progress in turbulence and combustion modeling has

provided impetus to further assess its use in gas turbine combustion including the advanced second-order closure turbulent combustion models; conditional moment closure modeling; Monte-Carlo scalar and/or joint velocity/scalar PDF models; random vortex and large eddy simulations for practical flows.

4.   Turbulence Modeling Needs and Practices for Tactical Aircraft-

We are responsible for the design and integration of fighter aircraft. As an "airframer", we design the inlet, diffuser and nozzle of fighter aircraft and integrate the propulsion system. We use CFD extensively for aerodynamic and propulsion design. Turbulence modeling is the critical factor in obtaining accurate solutions, particularly in propulsion applications. In inlet design, prediction of shock boundary layer interactions, leading edge separation, and streamwise curvature are necessary. For nozzle flow simulation, entrainment and shear layer compressibility effects are important. For aerodynamics and stability and control, leading edge separation, shock boundary layer interaction, transition and Reynolds number effects are critical. Nozzle signature simulation requires multiple species mixing prediction.

Industry practice is to apply "enhanced" two transport equation turbulence models for most turbulent simulations. Examples of these enhancements include non-equilibrium turbulent viscosity and shear layer compressibility. At Lockheed-Martin we make extensive use of a unique wall function boundary condition formulation that reduces required computational grid resolution without sacrificing accuracy. We also use a near wall model that includes transitional flow modeling capability. Examples of current turbulence model applications to fighter aircraft will be shown.

There is a continuing need for models of improved accuracy for complex turbulent phenomena including shock boundary layer interactions, curvature and leading edge separation. One particular problem is the prediction and modeling of transition on complex configurations. Frequently, prediction of performance increments between full scale and model scale requires accurate prediction of transitional flows on inlet cowls and wing leading edges. Another challenging area is modeling of high Reynolds number unsteady flows such as the found in transonic flow over weapons bays. Large Eddy Simulation is a candidate for application in this area. In tactical aircraft design, high

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fidelity solutions over a wide range of flow conditions are needed. As a result, computational efficiency and robustness are critical factors in any turbulence modeling improvement.

SUMMARY OF ROUNDTABLE DISCUSSIONS

Roundtable discussions concentrated in two areas: turbulence modeling and combustion modeling. Turbulence modeling discussions indicated that most industrial applications use variations of the two-equation Reynolds averaged Navier-Stokes (RANS) models with k-e, k-w, and k-l models being the most widely utilized. The performance of these models appear to be application dependent and range from good to fair for most cases. Algebraic and full Reynolds stress RANS models are less widely used due to increased computational cost and model complexity even though they generally produce better agreement with test data. Large eddy simulation (LES) models, if can be successfully extended to high Reynolds numbers with acceptable turnaround times, seem to offer the best promise for modeling complex turbulent flow fields. Lack of high quality experimental data continues to be a serious drawback to model validation.

Simple pdf based turbulence/chemistry interaction models are being used in gas turbine applications with modest success. Extension of the use of these models to other industries is anticipated. Computational cost, model complexity, and lack of validation appear to be the problem areas.

Complete kinetics models are available for both hydrocarbon- and hydrogen-air combustion. High computational cost makes the use of these models impractical for industrial applications. Reduced kinetics mechanisms traceable to these complete models appear to be sufficient for most engineering problems.

LIST OF GENERAL RESEARCH AREAS THAT NEED DEVELOPMENT AT THE FUNDAMENTAL SCIENCE LEVEL

1. Full Reynolds stress closures and near wall treatments for complex flow geometries.
2. Heat transfer closures for separated and rotating flows.
3. Replacement for the e equation or time scale equation.

4. Robust and computationally efficient LES models.

5. Turbulence/chemistry interaction models.

6. Reduced sets of hydrocarbon/air kinetics models.

7. Reduced sets of hydrogen/air kinetics models.

SUGGESTIONS OF SPECIFIC TOPICS FOR ICASE SUMMER SESSION WORKSHOPS

1. Development and assessment of LES models for high Reynolds number flows.

2. Assessment of turbulence/chemistry interaction models for industrial applications.

3. Development and demonstration of numerical platforms and algorithms for LES model use.

SESSION A6: AIRCRAFT INTEGRATION

Len Sakell, Air Force Office of Scientific Research

The Aircraft Integration session was held on October 9, 1996. Many industry representatives were in attendance. Key representatives from the U.S. Aerospace industry were invited to present papers on their company's views as well as their own views regarding needs in aircraft integration. The speakers were: Wen Jou of the Boeing Commercial Airplane Group, Vijaya Shankar of Rockwell International Corporation, Munir Sindir of the Rocketdyne International Corporation and Tom Weir of the Northrop-Grumman Corporation. Each of the speakers raised issues critical to aircraft integration. This report will be organized in the following manner. I will give a brief discussion of my views on aircraft integration from my perspective as the Program Manager for External Aerodynamics and Hypersonics at the Air Force Office of Scientific Research (AFOSR) in Washington, DC. This will be followed by summaries of the presentations as well as the roundtable discussions. The report will conclude with a discussion on the basic research areas which need development to support aircraft integration.

The old way of designing commercial or military aircraft involves a serial approach to system design. The external configuration is developed first. This is followed in rough sequence by the airframe structure, avionics, propulsion, flight controls, etc. For military aircraft, additional issues related to weapons are weapons loading and weapons release. This is still the method employed today for vehicle design and it is extremely inefficient in both time and monetary resources. A new approach is required and that approach is best described as a parallel process design method. This requires that the aircraft design process be looked at from a new perspective. The aircraft is not merely an airplane but is a complex flight system comprised of many complex, integrated sub-systems. These sub-systems must fit together and operate effectively as an integrated system. Historically, much attention has been paid to the selection of an external aerodynamic configuration shape in the vehicle design process. Todays advanced design and performance aircraft, commercial and military, are actually inter-

related complex systems. All components must perform together as a system for the aircraft to accomplish its mission. The design process approach must reflect this reality. At AFOSR I am aggressively supporting research programs multi-disciplinary simulation and modeling. This includes the traditional external configuration flow simulation but with linear and non-linear non-rigid body effects, active propulsion-airframe interaction, flight controls and, for military flight vehicles, weapons integration and weapons release. I invite the community at-large to join me in this endeavor. I strongly believe that the future success of the U.S. commercial aviation business is directly dependent upon this new approach to doing business. The cost-effective acquisition of military weapons systems cannot be accomplished through the old way of doing business. I will now discuss the presentations.

Dr. Jou's presentation, "Fluid Mechanics Relevant to Commercial Aircraft Airplane Aerodynamics", stressed several key points and issues. In the corporate environment business objectives do and must drive research needs. He outlined a design process ranging from conceptual design through to manufacturing and flight test which ideally would operate in a seamless, i.e., fully coordinated, manner in transitioning from one phase to the next. He stressed that computational fluid dynamic (CFD) predictive capabilities are required. That is, the CFD codes must be able to accurately predict the effects of the flows around full configuration flight vehicles. An example of such a need is airplane-wake vortex effects. Engine-aircraft integration was another key area for CFD simulation. Industry routinely performs many design studies. Simulations must be performed quickly and efficiently. Today's CFD codes require massive mainframes and take far too long to run to be useful for design studies. Convergence acceleration techniques must be developed to reduce required CPU times to levels which are practical for design studies. He indicated that large eddy simulation (LES) might become a tool in the future if such a code could be validated and the solutions demonstrated against experimental data. CFD gridding capabilities must be improved. Excrescence drag, the drag due to small surface geometric imperfections which arise during aircraft fabrication, is a key issue. Grid generators capable of gridding very fine surface imperfections must be developed.

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Dr. Shankar spoke next. His presentation, "Large Parallel Computation", raised the urgent need for faster, and cheaper CFD tools. He stressed the need for CFD tools which provide quick turnaround and can be used for design applications. For design studies it is necessary to go from raw computer aided design (CAD) data to a full Euler solution in less than three days. Solution evaluation via graphics based post-processing is also key. The large data sets generated by CFD codes are far too complex to be analyzed "by hand". The use of unstructured grids in design analyses is key since Rockwell can generate a complete unstructured grid from raw CAD data in less than three days while, it takes three weeks for structured grids. There is increasing need to perform multi-disciplinary flow field simulations. Computational Electromagnetics (CEM) is one such example. There is a need to develop CFD based methods which can simultaneously predict wave propagation effects together with the aerodynamic flowfields. CFD must be expanded for integrated vehicle system analyses and design. Additionally, the simulation of manufacturing processes should be developed. One example is the simulation of the laser welding process. Examples of current work-in-progress include: development of higher order algorithms to minimize the number of cells required for simulation, development of an unstructured grid Navier-Stokes code and, the development of dynamic solution adaption methods.

Dr. Sindir's presentation was entitled "Assessment of Computational Modeling Practices for Ram- and Scramjet Engine Design and Analysis." He outlined four categories needing attention: (1) Component level issues and needs, (2) Integrated flowpath issues, (3) Enabling Technology enhancements and, (4) Technology development and transfer issues. Dr. Sindir believes that CFD should be used for hypersonic propulsion system design at several levels. CFD output can be used as input to engine cycle and performance prediction codes. CFD can be used as an engineering tool for detailed design and analysis and, CFD can be used to compliment flight test programs. The latter for pre-test-analyses and complete flow prediction to supplement test data. He described a hypersonic vehicle as a system composed of a forebody, inlet, combustor, internal nozzle and an aft body external nozzle. Important inlet flow issues are viscous effects, compressibility effects, boundary layer transition and, high leading

edge thermal loads. A factor of five increase in Navier-Stokes solver efficiency must be developed. Dynamic grid adaption and the accurate simulation of time dependent flows must be achieved. LES models and detailed models of boundary layer transition are needed. Finally, efficient graphical post processing of large, complicated solution datasets are required. A wide range of flow speeds and flow regions exist in the combustor. Complicated kinetics and finite rate oxidation are present together with non-equilibrium transfer of turbulence energy. Despite these realities the state-of-practice is limited to steady state parabolized Navier-Stokes (PNS) or steady state full Navier-Stokes (FNS) simulations. CFD technology needs for combustor flows are: (1) factor of ten more efficient Navier-Stokes codes, (2) dynamic grid adaption for vortical motion and shocks, (3) computationally tractable turbulence/chemistry models, (4) fast reduced kinetics models, (5) post-processing software for diagnostic interpretation and, (6) data for code validation. The last item includes heat transfer and skin friction data, shock structure data, and species concentration measurements. Nozzle flow physics include strong chemical and aero-thermodynamic non-uniformities, high velocities and temperatures, temporally and spatially changing thermochemical states and potential re-laminarization and vibrational relaxation processes. The state-of-practice in CFD simulation is limited to steady state Euler and Euler plus boundary-layer approximations. CFD needs include a five factor increase in solution convergence, dynamic grid adaption and, post-processing software development. Technology needs for integrated flow path physics include the development of efficient Navier-Stokes solvers and consistent procedures for interfacing different codes. The latter would allow any code or code component to be used with any other interchangeably. Finally Dr. Sindir discussed his assessment of the need for LES codes. LES codes must be developed for realistic geometries and flow conditions. Examples of the latter are: boundary layer transition inside scramjet inlets, chemistry-turbulence interactions and, adaptive gridding. Dr. Sindir concluded by discussing needs for multidisciplinary design optimization. Codes to analyze the coupled aerodynamics and aerothermodynamics, thermodynamics, structural dynamics, and stress concentrations must be developed. There must be coordinated technology transfer throughout the stages of flight vehicle development (i.e., applied

research, initial testing, research level technology, extended testing, engineering level technologies).

Dr. Weir's presentation was entitled "Advanced Computerized Design Methods in Aircraft Integration". He discussed aircraft integration on two levels. Physical integration involves the structural component mating of wings and tails to the fuselage. System management integration involves issues such as thermal protection systems. He believes that it is important that the integrated end-product be developed better, faster, cheaper. He mentioned three computer application technologies which are needed to significantly improve the product development and design. The technologies are (1) Automated grid generation that can be standardized for CFD, CEM and other computational disciplines and which will reduce the time to get high quality data, (2) development of generic codes that are somewhat independent of specific applications. This would allow computerized methods to be exploited more in the design process; and, (3) Faster running codes that can provide better (i.e., more accurate) results faster. Alternatively these three areas may be looked at as follows: (1) unification of gridding that allows both unstructured and structured or hybrid grid arrangements, (2) unification of disciplines that allows the same computational framework to handle CFD, CEM, and other disciplines; and, (3) parallel computing including workstation clusters. At present it takes longer to run a high quality CFD or CEM code than to perform a test to quantify a similar number of data points. While more efficient Navier-Stokes codes are needed, better/faster/cheaper manufacturing processes must also be developed. To facilitate the latter we need common feature, multi-disciplinary based product definition. Vastly improved software must be developed which can quickly evaluate system performance. Grid generators that can quickly generate grids over complex 3-D configurations must be developed. A capability to perform vulnerability assessments for military aircraft must be developed. This involves assessing aircraft flight and mission performance damage caused by weapons fire direct hits. We must develop the capability to do both virtual prototyping and virtual manufacturing. Computer models of the product fabrication and manufacturing processes must be developed so as to develop the most efficient manufacturing process before any hardware is produced. The proposed steps to virtual

manufacturing are (1) product design, (2) develop extended CAD database, (3a) process design, (3b) shop floor production; and, (4) factory floor plan i.e., can the aircraft actually be put together. Items 3a and 3b would be performed iteratively.

Roundtable discussion was remarkably consistent. Multidisciplinary flight vehicle system simulation is an increasingly important issue. Simulation methodologies must treat the aircraft as an integrated system. There are many complicated flow features and scientific aspects of these flows which at present are not being considered. This limitation must be addressed. The simulations must accurately reproduce the flow features, be affordable, and run quickly to be useful for design studies. Simulations of the manufacturing and fabrication processes must be developed and exploited to reduce the cost of component assembly into the final product flight vehicle. Numerical simulation must be expanded to multidisciplinary areas which can be used to accurately and efficiently predict product development, manufacturing, and performance.

SESSION B1: STRUCTURES
(initially scheduled as SESSION D3)

Jerry Housner, NASA Langley Research Center

INTRODUCTION

Four presentations were made in this session – all by representatives from the aerospace industry. The titles of the presentations and the names and affiliation of the speakers were:

1. Advanced Structural Concepts for Military and Commercial Aerostructures – Harry Armen, Director, Research and Development, Northrop Grumman Advanced Technology and Development Center.

2. Airplane Preliminary Design in the Early 21st Century – Kumar G. Bhatia, The Boeing Company.

3. Current Work and Needs at the Transport Division of McDonnell Douglas, Long Beach, California – Joseph P. Giesing, McDonnell Douglas Fellow, McDonnell Douglas Aerospace.

4. The World of Structures at Lockheed Martin Missiles & Space – Phil Underwood, Manager, Structures, Advanced Technology Center, Lockheed Martin Missiles & Space.

SUMMARY OF THE PRESENTATIONS

In each case, the author's abstract is presented and is followed by several points made in the presentation.

1. Advanced Structural Concepts for Military and Commercial Aerostructures – Harry Armen, Director, Research and Development, Northrop Grumman Advanced Technology and Development Center.

<u>Abstract</u>

Northrop Grumman's Advanced Technology and Development Center, Bethpage, New York, has underway several projects that address the needs of advanced aerospace structures for both military and commercial applications. These include: development of

unitized polymer matrix composite structures for primary structural applications, composite noise attenuating engine nacelles, adaptive/smart wing structures, and associated developments in materials and process sciences. The major thrust of these activities is to develop high strength, low weight structures that are affordable to both commercial and military customers. Fulfillment of these goals requires advances in material science, manufacturing technology, design techniques, and structural mechanics.

The development of affordable, high performance, large unitized structural design is based on resin infused three-dimensional graphite fiber textile preforms. Use of these architectures requires the optimal design of textile preforms, tow placement and fiber steering, Z-pinning for translaminar reinforcement, stitching for delamination arrestment control, and cross continuous fiber elements for improved structural efficiency and performance. Coupled to these structural considerations are manufacturing process developments such as resin film infusion (RFI), resin transfer molding (RTM), and one-step integral curing.

Manufacturing process development must address issues associated with reliability, process robustness, and cost. Resin transfer and infusion techniques afford economy through part integration and reduced labor, but only when processing schemes assure thorough fiber wetting and preclude matrix resin void formation. Insight into this problem can be obtained by cure monitoring and control, and advanced numerical and analytical simulation of mold fill supported by experimental verification programs. Traditional autoclave cure techniques have also been simulated, with particular emphasis on optimizing thermal cycle control. Other important issues that must be investigated are associated with fiber matrix interface, crucial in micromechanical design calculations. New evolving techniques such as single stage forming of composite structures have great potential to substantially reduce cost by reducing touch labor.

Significant research and exploratory studies for optimized nacelles and thrust reversers for jet engines for commercial aircraft are providing encouraging results to meet future noise regulations. These include utilizing active control technology techniques and advanced composites to develop jet engine noise suppression systems that meet impending, more stringent noise regulations for a new generation of subsonic commercial

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aircraft. Also, these technologies are particularly important for NASA's High Speed Civil Transport Program.

Advanced development efforts are underway to investigate the use of adaptive wing structures for future applications in both military and commercial structures. Optimally shaped airfoils can dramatically eliminate or reduce shock induced drag during transonic cruise enabling significant fuel savings. However, wings that are optimized for a single cruise condition usually have high drag at other cruise conditions. Optimum performance can be maintained as the flight condition changes by automatically varying the airfoil cross-sectional shape by small amounts during transonic cruise (on the order of 5% of the wing thickness). A low-weight, reliable method is needed to accomplish the shape change and simultaneously satisfy wing strength and stiffness requirements.

The structural concepts outlined above offer unique design and manufacturing challenges requiring computational mechanics tools that can be used to analyze the unique three-dimensional structural architectures found in composite material and complex manufacturing processes. Other issues such as damage tolerance and maintainability must also be addressed. This presentation will give examples of some of these structural concepts as a means of identifying required technology thrusts in structural mechanics. It is hoped that these examples will identify and stimulate research in these areas.

Comments on Presentation

Several technology trends in DOD and commercial aerospace business were described. These are summarized below.

- Hard weapons are being augmented with soft weapons. For example, electronic techniques are being used to disable an enemy's military platforms, and software is being used to corrupt information flow.

- Manned fighters are being augmented with uninhabited tactical and surveillance vehicles.

- Specialized mission aircraft are giving way to multimission aircraft. The Common Support Aircraft is a concept being developed by the Navy to have one flexible aircraft that can replace 3-4 special-purpose aircraft.

- Technologies for performance are giving way to technologies for affordability. This is the common thread for the entire talk. If performance is desired, it must be produced within the constraints of affordability.

- Long production runs are giving way to flexible, small lots of production.

- Long development cycles are being replaced by rapid prototyping.

- Large inventories are giving way to just-in-time deliveries.

- Special suppliers for military aircraft are giving way to commercial off-the-shelf equipment, supplies, and technology.

- Conventional skin-stiffened structures are giving way to integral metallic and composite components.

- Reactive maintenance is giving way to smart maintenance procedures using software to schedule maintenance.

- Defect detection is giving way to defect prevention.

- Hard tooling for manufacturing is giving way to soft, reconfigurable tooling to accommodate small production lots. The concept is called agile manufacturing.

- Goal is to reduce touch labor in the manufacturing of the vehicles, to reduce maintenance costs in the servicing of the vehicles, and to reduce down time in the use of the vehicles.

- Multidisciplinary analysis and design optimization (MDO) is the key to integrated product and process development (IPPD). The goal is to break down walls between disciplines and to reduce the entire initial design cycle time by 50%. MDO has the potential for having a big effect on the cost.

- The speaker said that when he started his career, the theme was better, faster, cheaper – pick any two of the three. The theme is now all three.

2.   Airplane Preliminary Design in the Early 21st Century – Kumar G. Bhatia,
        The Boeing Company

Abstract

The presentation will describe the current progress in airplane structural design and the need for rapid yet accurate structural inputs into the design process. The improvements in application of nonlinear mathematical optimization procedures as a part of everyday airplane design effort will be discussed. Aeroservoelastic perspective in preliminary design and structural optimization will be emphasized.

The inability to meet the project time constraints affects the level of optimization that can be accomplished for a given design. In spite of improvements in computer power, and engineering analysis and design tools, the number of engineers required to design and certify an airplane has not decreased. The total number of engineers actually may have increased due to more stringent design requirements. The increased number of engineers, particularly in a preliminary design environment, can adversely affect the close teaming and information flow desired for an effective preliminary design team. These and several other considerations provide impetus for incorporation of Knowledge Based Engineering methods (KBE) in the preliminary design process. Some of the issues involved in development of KBE methods will be discussed.

Relationships between the industry and government laboratories as well as the industry and universities will need to be reexamined. Partnerships will have to recognize better the proprietary nature of the knowledge content of the industry contributions.

(Please note that the views presented will be the personal views of the speaker and do not represent a Boeing position.)

Comments on Presentation

The talk considered preliminary aircraft design – current procedures, problems, and recommended solutions. Particular emphasis was placed on the need for computerized "knowledge-based engineering" or "knowledge-based systems" that can act as a designer's assistant when the work is routine.

Preliminary Design (PD) is Characterized by

- Iterative processes

- Multiple levels of detail in the analyses

- Criticized for being too slow

- Need for increased accuracy – particularly if object is unfamiliar

- Limited resources – both money and skilled people

Areas that Need Improvement

- Substantial time is spent checking the integrity of the analysis –   consistency checks, resolving anomalies, routine work

- The fact that people are doing this work means there is uncertainty

- To what degree are the mathematical models correct? How reliable?

Goals for Improving the PD Process

- Reduce cycle time

- Increase fidelity, increase confidence

- Process should be set up so that it is easy to change and improve

Although computers used in PD are speeding up, the number of people required for PD keeps increasing. The reason: we want to increase goodness. If we can introduce knowledge-based systems to take care of routine things, we can reduce the number of people. Emphasis should be on providing an assistant rather than on a push-button system.

In addition to introducing knowledge-based systems, there needs to be a change in the organization that is responsible for design integration. At present the integrating organization/discipline is performance. Aeroelasticity is a better bridging discipline.

Authoritative knowledge of design and cost resides in the aerospace industry - not in universities or NASA. It would be difficult and unrealistic for NASA or a university to produce detailed life-cycle cost estimates. However, NASA and university researchers could collaborate with industry to develop a software framework which is separate from the proprietary content.

There are opportunities in NASA focused programs to experiment with some of these PD ideas, but in most cases, bureaucracy prevents us from making use of these focused programs to push technology ahead. Collaboration between industry, NASA, and universities is possible and should be encouraged.

3. Current Work and Needs at the Transport Division of McDonnell Douglas, Long Beach, California – Joseph P. Giesing, McDonnell Douglas Fellow, McDonnell Douglas Aerospace.

Abstract

This presentation will deal with several activities and issues currently of interest and importance to the transport sector of the McDonnell Douglas Company. Several of these are currently being perused in collaboration with NASA and Universities and others have potential to be perused in the future. The areas to be covered will include: 1) durability and damage tolerance (monolithic crack growth analysis, and wide-spread fatigue damage), 2) advanced structural analysis (practical biaxial joint analysis and nonlinear post-buckling analysis), 3) manufacturing fabrication simulation (forming, quenching, and resin fusion injection), 4) automated structural analysis (knowledge-based engineering, and structural analysis for the automated MDO processes), and 5) structural aeroelastic loads (nonlinear loads corrections, and structural nodal point forces from loads). A balance will be maintained between presentation of results of current activities and a call for practical solutions of difficult problems.

Comments on Presentation

A general theme is that there is a need for "intermediate" levels of analysis that do an adequate job. Conventional finite element methods are too complex and slow, and simplified methods are often inadequate. Specific topics follow.

Nonlinear Structural Analysis

We need practical, semi-empirical analysis methods for joints with biaxial loads. Current methods are either too simple or too complex. We need adequate analysis methods that are of intermediate complexity.

We need practical nonlinear analysis methods – simple or closed form – to calculate postbuckling response.

Manufacturing Process Simulation

We need practical solutions, not just rules-of-thumb or full-blown numerical simulation, but something in between. We need to be able to predict residual stresses. We need the capability to optimize the manufacturing process.

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FEM is a poor design tool and can require great expertise for a valid analysis.

Automated Structural Analysis

We need rapid, automatic FEM mesh generators that would idealize solid CAD geometries into simpler geometries appropriate for FEM, and that would provide different idealizations depending on the purpose of the analysis. We also need knowledge-based engineering systems.

Crack Turning and Closure

Crack turning behavior is not well understood. We need investigations of crack turning from the point of view of fracture mechanics and material science. The integral structure is the driver. We need an improved crack closure model.

Corrosion and Stress Fatigue

There is a lack of understanding of the interaction between corrosion and material fatigue due to cyclic loads. We need a semi-empirical procedure to predict or assess durability and damage in materials with corrosion.

Simplified Structural Design and Analysis for MDO

We need a simplified and automated FEM analysis that is accurate to within 5-10% in weight and accounts for all important aeroelastic constraints. Brute-force FEM analysis approach is an option, but creating a typical 30,000 DOF model takes 6 months and maybe 1-2 months to cycle the optimization. The idea is to make the analysis simple, and have it tuned to a baseline finite element model.

Nonlinear Aeroelastic Loads

When carrying out structural design of an aircraft, direct CFD-FEM iteration for aeroelastic loads analysis is impractical because of the large number of loads that must be searched for the critical cases and because current aeroelastic loads optimization requires a linear representation of loads (AIC). An alternate scheme utilizes a CFD (or wind tunnel) generated data base (~ 30-50 cases) to correct linear theory to predict the correct load point and local (nonlinear) slope of the load. These load corrections are influenced by the aeroelastic shape (stiffness and mass) and thus are easily updated periodically as the shape and trim change. The CFD data base uses representative deflected trimmed

shapes which are parameterized by Mach number, load factor, dynamic pressure, and mass condition.

An accurate, automated process is needed for mapping aerodynamic loads to structural FEM nodes. The process should apply to aerodynamic loads generated by both crude (doublet-lattice) and fine (CFD) aerodynamic models, and it should simultaneously satisfy local and global accuracy. Local accuracy prevents local erroneous stress risers. Global accuracy assumes accurate bending loads at the wing root.

4. The World of Structures at Lockheed Martin Missiles & Space – Phil
    Underwood, Manager, Structures, Advanced Technology Center,   Lockheed
    Martin Missiles & Space.

Abstract

This presentation focuses on issues that face structural engineers working for a missiles and spacecraft company, Lockheed Martin Missiles and Space (LMMS). There will be some history, some recent happenings, and some speculation on the future. Although technology will be the central theme, the reality of the current business environment will be applied to the technologist's dreams.

The content of the presentation includes some pictures of the typical structures designed, analyzed, tested, and built by LMMS. Next, a series of technology/economics issues are presented: in-house structural analysis software versus commercial software; integration of design, analysis, and manufacturing; analysis versus testing; multidiscipline analysis; optimization; etc. This is followed by some business issues: the decline of research and development; in-house technology versus out-source technology; affordability; etc. The talk concludes with my comments of the future of structures at large aerospace companies.

(The views presented on the business issues and the future are solely my personal thoughts and in no way represent the thoughts of Lockheed Martin.)

Comments on Presentation

Big changes are taking place within large aerospace companies. The companies are asking themselves many questions, redefining their businesses, and determining

where they want to go. Since technology is an integral part of the aerospace industry, an important question regarding technology is – how much should be developed within the company and how much should be bought from outside sources? What's the right mix? In the future, research is probably not going to be done in large companies. For that reason, large aerospace companies need to improve ways in which they can work with universities. Perhaps NASA can help provide a good mechanism by which universities and industry can cooperate.

There are many analysis tools available in the form of off-the-shelf, inexpensive software. However, the commercial software should be supplemented with in-house-developed software to maintain core competency and a competitive edge. If not, the company can become indistinguishable from its competitors.

Bright, well-trained employees are very important.

It is exceedingly difficult to perform high-quality analyses and high-quality tests.

The common goal is "better, faster, and cheaper." In order to reduce product cycle time, it is necessary to integrate at least the following four tasks: design, analysis, testing, and manufacturing. Note "testing."

A capability is being developed to carry out simulation-based design of satellites.

SUMMARY OF THE ROUNDTABLE DISCUSSION

The following comments were made to the question: "If we had asked individuals who are deeply involved in the design of aircraft and spacecraft – the folks in the trenches – to make these presentations, how would their message differ from what you presented?" (The speakers were senior people and managers, rather than designers.)

- Like the speakers, designers are also interested in better, faster, and cheaper. They don't want to bother with meshing and modeling. They want tools that they can use without resorting to manuals and training. They need analysis tools that are effective, accurate, and transparent. Although designers use a lot of instinct and intuition, their comments would be similar to those of the four speakers. We also need backup people who have a good understanding of the physics of the computational phenomena and the anomalies that are occurring.

- Designers are aware of the desire for faster, better, cheaper. Some are frustrated that things are going too fast for them to understand the design.

- Some designers want to hold on to their current jobs by doing things the same old way. They need to put their design rules into the computers so that they can concentrate on more creative issues.

- Some designers are myopic. In their opinion, to achieve the goal of faster, better, cheaper, you should give them a better tool and you should tell the person who gives them the data to give it to them earlier. They know their job, and if someone else tries to do it, they believe that it will mess up the design. They want some autonomy. When we talk about MDO we have a cultural problem illustrated by this true story: Several years ago a competent aerospace engineer was starting to use MDO. He saw that his MDO tools were allowing him to save a substantial amount of weight in the vehicle he was working on. He thought this was terrific – that his findings would be appreciated. So he presented his findings. Perhaps he did get a pat on the back, but he also got a bomb threat. Possible reasons – someone thought "This guy is saying that I am not doing my job right," or "This guy's computer program is going to replace me." In any MDO activity the participants have to be convinced that trades must be made amongst the disciplines – that to produce a better design the participants have to think globally. This needs to be explained and demonstrated in a non-threatening way so that the benefits of cooperation are clear.

- Suppose we interpret better, faster, cheaper in terms of bringing better tools to the designers. Who pays for the better tools? Industry doesn't want to do it. Industry regards the improved tools as costs. The concepts are at cross purposes.

- Instead of associating the words better, faster, cheaper with the engineering process, those words should be associated with the final product. When we use better tools we may not do the engineering faster or cheaper, but the product at the end is better and the customer gets it faster and cheaper. For example, in the case of the 777 and the F-18, engineering might have taken longer, but the product was better - the parts fit together. The companies are not selling engineering. They are selling the product.

You can be down on the learning curve with the first article. On the F-18 it was like the 100th airplane – the airplane goes together with little rework.

- At Boeing, the market demands that we bring out certain products at certain times – that means time is a big driver. To us, cycle time is the cycle time of the whole system – not just analysis or design or test. Suppose we reduce the time for a certain process to one tenth the original time, but suppose it doesn't affect the whole overall cycle time. Then, it doesn't do much good. Prioritization is done with that in mind.

- At McDonnell Douglas, concurrent engineering is being made possible by the new feature-based design tools. The first product that comes out the door is manufactured in one tenth the number of hours as previously. The tools may not allow us to do the engineering design in one tenth the time. It's the final product that is the target.

- The present approach is to use IPPD teams for communication, but for the most part, the people use the same old tools. In one case we used new MDO integrating tools for the IPPD teams. It was a good experience. People could see how their part fit in – how their constraints affected the design. MDO tools give insight.

- Question: How far has the aerospace industry gone with MDO?

- Things are in a development stage. People are moving in the direction of MDO, but are not there. The process is not automated.

- At Boeing, we have the CATIA/ELFINI systems which contain some global-level optimization. We have enhanced those systems with our own tools, especially at the local level. We solve fairly large optimization problems – close to one thousand design variables and several thousand constraints – maybe hundreds of thousands of constraints. We are in an era of departmental optimization – that is, MDO within a department. But suppose I go to the aero department and propose a scheme. I tell them that I'm already working with one thousand design variables when I perform aeroelastic optimization, and that I could add wing shape, camber, and twist for less than one hundred additional design variables. Why don't we combine our processes and do this together? However, that becomes an inter-departmental optimization, which is much harder to do, because people want to remain autonomous. People are afraid of changes in which they may lose their control over design. It is not lack of

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tools or lack of understanding of the tools that is preventing the use of moderate or large-scale MDO. It is because we really don't want to use MDO if it means losing control. Everybody wants to do it, but only if they control the whole process. There has to be a change at a very high level – a paradigm shift – to see the process through.

- As far as MDO goes, it appears that the aerospace industry and the automotive industry are at about the same place.

- We need a new breed of engineers that are trained to understand MDO.

- To some, the term <u>MDO</u> gives the impression of everybody putting their data into a computer, pushing the button, and out comes the design. They see their job in jeopardy. It would be more acceptable to use the term <u>multidisciplinary analysis</u>. Sounds more traditional. It helps remove the fear factor. Just sharing a common database would be a big improvement.

- I use the term <u>configuration design optimization and trades</u>. We are trying to design a configuration, and we use some optimization techniques, some trade techniques, and we have to use lots of analysis.

- Question: Considering just the structures area, what particular computational tools would have an impact in industry?

- We would like to have analysis software for which the input is limited to basics such as part geometry, material properties, and loads. We don't want to bother with the modeling and idealization. We want smart software that will develop a model that would give us reasonably accurate answers.

- It will be difficult to make the translation from the solid model to an idealization because, at present, every discipline uses a different idealization of what the actual piece looks like.

- Computer programs provided by government labs to industry should be robust and validated. Many times it is difficult to make the NASA developed codes do what we need them to do.

- The aerospace industry is shifting from in-house-developed codes to codes that others develop. Some commercial codes do the entire analysis; other codes are built so that

we can add on to them. How do we know if they are OK? How can we be sure they are being used properly? That is a big problem.

PROPOSED RESEARCH AREAS

- Develop prototype structural design tool that use knowledge-based engineering and functions as designer's assistant.

- Develop analysis methods that are appropriate for design. They can be semi-empirical. Should account for nonlinear behavior such as postbuckling.

- Develop techniques to simulate and optimize the manufacturing process. Include 3-D analysis of composite structures during manufacturing.

- Develop automatic FEM mesh generator that translates solid CAD geometry into geometry appropriate for FEM, and that provides different idealizations depending on the purpose of the analysis.

- Develop technique for analyzing crack turning. Analysis is to be based on fracture mechanics and material science.

- Develop improved crack closure model.Develop semi-empirical procedure to predict or assess the durability of and damage process in materials with corrosion.

- Develop accurate, automated process for mapping aerodynamic loads to structural FEM nodes. Process should account for aeroelastic effects.

- Develop a software framework for MDO that allows both ready access for research and security for industry proprietary content.

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SESSION B2: MATERIALS

Ivatury S. Raju, NASA LaRC

SUMMARY

Materials are enabling technologies in various fields. The demands for producing cost-efficient structures and structural components and tailoring the materials for a specific need are more than ever. New research initiatives such as computational materials should be started. Studies into advanced computational modeling and simulation technologies along with integrated product and process designs (IPPD) should be undertaken. Scale up issues from laboratory components to the real structure need to be studied.

INTRODUCTION

The first of the two sessions on Materials took place on the second day of the Roundtable and had four speakers. The organizer planned two speakers from the industry and two from academia. Each presentation was about 30 minutes long and the question and answers were deferred until all the speakers completed their presentations. After a short break, the discussion period was held.

The organizer asked each speaker to summarize (a) the status of where we are in the general materials area, (b) what are the significant barriers that are impeding breakthroughs, and (c) what we need to do to overcome these barriers. Each of the speakers drew upon their experiences, looked into their crystal balls, and presented their viewpoints.

The speakers, in the order of presentation, were: William F. Bozich, Senior MDC Fellow Staff Director, Advanced Structures and Materials, Design and Technology Center, McDonnell Douglas Co., Long Beach, CA; Satya N. Atluri, Institute and Regent Professor, Georgia Institute of Technology, Atlanta, GA; Wolfgang Knauss, Professor of Aeronautics and Applied Mechanics, California Institute of Technology, Pasadena, CA; Matthew Miller, Manager HSCT Structures, Boeing Airplane Co., Seattle, WA.

PRESENTATIONS

The following summaries are based on notes taken during the presentations:

Dr. Bozich opened this materials session with emphasis on costs and performance of aircraft materials. In commercial aircraft 39 percent of the cost is for the structure and eight percent for materials. For launch vehicles, costs are still very high to put a pound of payload in orbit. Aerospace engineers, thus, are always looking for new light weight materials and structures. To be able to achieve affordable light weight vehicles, research efforts into advanced materials, innovative fabric concepts (such as composite lattice), advanced joining concepts (such as friction stir welding), and supportive analyses and modeling methods are urgently needed.

Some advanced materials under study are the 2195 Al-Li alloy, 2090-T83 Al alloy, Ti-62222 (these materials have high strength in superplastically formed and aged conditions), IMI-550 Ti alloy, g-Ti Al alloy (used extensively for heat shield applications), and 7055 Al alloy (in use for upper wing skin applications).

Dr. Atluri discussed scenarios in which advanced computational modeling and simulation technologies can be put to use, along with concepts of integrated product and process design (IPPD) with life-cycle costs in mind. Materials are enabling technologies in various fields. High performance materials are being sought in fields such as aerospace, microelectronics, semiconductors, bioengineering and biotechnologies. Durability and damage tolerance are an important consideration to reduce life-cycle costs and make the structure affordable. Wide-spread and multi-site damages need to be considered early in the design cycle. Durability problems tend to limit the life of a well-designed airplane. Dr. Atluri gave an example of well-designed large military transport that suffered durability problems. Structural changes (weep holes were drilled near the bottom of an integral stiffener) were made without consideration to the long-term effects. These changes led to fatigue problems that need to be overcome and considerable amount of money is being spent on the repair efforts.

The time had come to integrate the complete design, development, manufacturing into a single process. Weight, materials and structures, stiffness, life-cycle costs, schedules, production costs, and other costs should be viewed upon as constraints for the

structural component in the IPPD processes. Such integrated efforts should lead to affordable structures.

Dr. Knauss discussed nonlinear time-dependent constitutive response of nonmetallic (matrix) materials. When materials approach failure they pass through a range of mechanical response that is nonlinear to varying degrees. This is true of metals in terms of plasticity as well as of ceramics, though the extent of nonlinear evidence is much more confined for these materials. Similarly, when matrix polymers fail, their constitutive behavior impacts the strength and durability predictions and analyses. As a consequence it is necessary to characterize such materials for computational purposes. Dr. Knauss discussed phenomena that set polymers apart from the traditional engineering materials in that their shear and bulk responses are not independent materials functions, but shear and bulk deformations can influence each other mutually. These observations have consequences for conducting analyses that are modeled along lines of current formulations of plasticity and visco-plasticity. Dr. Knauss suggests that studies need to be undertaken at micron and submicron scales that address the following questions. What are the system parameters and how are they defined? How strongly do these parameters control mechanical behavior? How can these parameters be determined?

Dr. Miller presented issues associated with structures and materials for high speed civil transport (HSCT) airplanes. For subsonic airplanes, the durability issues are fatigue life (in flight cycles) and corrosion. In contrast, in a HSCT aircraft most of the wing and fuselage experience temperatures up to $300°$ F at cruise and $0°$ F soon after take off. At the radome temperatures up to $370°$ F is experienced. The Al alloys are candidates in the range 2 to 2.1 Mach, while polymeric composites are candidates in the range 2.2 to 2.6 Mach. Above 2.6 Mach Ti-alloys are preferred. The Ti-alloys under study are the Ti-62222 and these alloys show excellent properties but suffer from a large scatter in the fatigue life experiments. Ti/Gr metal matrix composites show excellent properties and have good fatigue crack growth rates (at least one to two orders of magnitude reduction compared to other candidate materials).

For the frame structure bismalimides are under consideration. The polyimides like K3B show microcracking at high temperatures and therefore are under scrutiny. Another newer material called PETI5 is being considered as a replacement for K3B.

A honeycomb structure is being proposed for the wing. The issues that need to be considered and studied are moisture ingress, handling, lightning strike, process constraints, damage resistance durability and damage tolerance.

Thus, the search for high performance materials and structures continues as more stringent requirements are demanded by the newer vehicles.

LIST OF RESEARCH TOPICS

The discussion session was informal and lasted about an hour. The discussion was very productive and lively. The following are the issues raised and these can be viewed as the future research topics.

* There is a need for characterizing material behavior and generalization of measurements with regard to constitutive behavior, time and rate dependence, environmental effects, failure and fracture, durability.

* There is a need for optimization in making and selecting materials.

* There is an increased need for tailoring materials for specific needs.

* The future materials models need to consider the wide range of length (from nano-meters to several meters) and time (pico-second to years) scales involved in computational material science. Renormalization group theory was suggested as starting point for these considerations.

* Methods that need to be pursued are table look-up and numerical extrapolation, self-contained materials models, use of mechanics-based models to extrapolate the data. However, some extrapolations have limitations. For example, material behavior often accepted for some materials do not transfer to others, such as plasticity and polymers.

* Thermo-mechanical testing of complete airframes will be time consuming and may not be practical. Then how does one extrapolate the mechanical damage induced during test at ambient or simulated high temperature to the thermo-

mechanical damage induced during service? What is the equivalence that need to be demonstrated on the largest subcomponents that are practical to test?

WORKSHOP TOPICS

Computational Materials is well suited as a summer workshop topic.

SESSION B3: COMPUTATIONAL ELECTROMAGNETICS

C. J. Reddy, Hampton University

SUMMARY:

The session on Computational Electromagnetics (CEM) was organized to bring out the current topics of mutual interest for ICASE/LaRC and industry. There were four speakers. Fred Beck from NASA Langley Research Center summarized the work being conducted in the Electromagnetics Research Branch (ERB). Vladimir Oliker from Emory University highlighted the geometrical and computational issues in the analysis of creeping waves over airframes. James Rautio of Sonnet Software Inc. addressed the importance of EM error analysis on microwave engineering. Maurice Sancer of Northrop Grumman Corporation summarized the CEM work being carried out at Northrop Grumman and also presented results of a survey he conducted for solving 'grand challenge' problems. Overall the session provided a good mix of views from the government, university and industry.

PRESENTATIONS:

The first speaker was Fred B. Beck from NASA Langley Research Center. He summarized primarily the EM research activities that are currently going on within the Electromagnetics Research Branch (ERB) of Langley Research Center along with several future CEM applications. A description of the EM test facilities and laboratories, including measurement capabilities was presented. A low frequency test chamber for antenna radiation characteristics measurement and an Experimental Test Range (ETR) for EM scattering measurements was described. ERB is also developing test facilities for High Intensity Radiation Fields, which can be used to assess the 'Electromagnetic Upset' of electronic instrumentation applicable to many systems including aircraft and automobiles. He mentioned that ERB will entertain and evaluate requests for measurements from any US industry or academia for EM scattering, radiation experiments, HIRF measurements or material characterization measurements. The data can be delivered uninterpreted or interpreted depending upon a mutual agreement with

the customer. He invited industry and university community to take advantage of the facilities that exist at NASA Langley Research Center. Beck also gave an overview of the CEM codes which have been developed and being developed at ERB. For the past several years, ERB has acquired many CEM codes developed through grants to universities such as Ohio State University, University of Michigan and Arizona Sate University. Helicopter Antenna Radiation Prediction (HARP) code is one such code developed over the years in collaboration with Ohio State University. This is a versatile code with a Graphical User Interface (GUI) for generating computer models from the cross sections of vehicles such as helicopters. This code uses a powerful method of moments (MoM) analysis for low frequencies and Uniform Theory of Diffraction (UTD) for high frequencies. ERB is involved in development of its own MoM codes using a triangular subdomain approach for EM scattering and radiation. The Finite Element Method (FEM) combined with MoM and Geometrical Theory of Diffraction (GTD) has been developed to characterize cavity backed aperture antennas with finite rectangular ground plane. A hybrid FEM/MoM technique is being used for characterizing the slots in waveguide walls. Using waveguide measurements and FEM modeling, material parameters such as dielectric permittivity are estimated. The computer codes developed at ERB will be available through the Langley Software Service (LSS). The executables of the codes will be made available to US companies and universities on request. The source codes can be exchanged with a cooperative agreement with NASA. Finally, Beck presented some recent results on the application of Asymptotic Waveform Evaluation (AWE) technique in conjunction with the MoM for backscatter computations over a frequency band. The application of AWE gives the frequency response of Radar Cross Section with calculations done at a single frequency. This reduces considerably the CPU time required for the frequency response calculations.

In his presentation, Vladimir Oliker of Emory University emphasized the importance of geometrical and computational issues in predicting creeping waves over airframes. It is very important to predict the electromagnetic interference (EMI) characteristics between two antennas placed on an aircraft body to ensure their required performance. This leads to the problem of computing creeping wave along the complex

geometry of an airframe. In the past creeping waves were computed over well defined generic shapes. The computation of these waves over an aircraft body leads to modeling the aircraft geometry, to building the coupling paths between antennas, to computing the geometric characteristics of the path, such as length, curvature, torsion, geodesic curvature etc., to computing EMI characteristics of the path, such as Fock parameter, path losses, antenna gain etc., and finally to invoking an optimization cycle by re-positioning the antennas and repeating all the above steps. The above computations should have proper speed, accuracy, reliability and adequate user interface to be of use in a practical design. Oliker discussed pros and cons of approximating airframes with canonical shapes and realistic models. Canonical shapes are easy to model, algorithms are available for computing the coupling paths. But the accuracy of geometry representation suffers and hence the accuracy of EM predictions is low. On the other hand, the realistic models generated by CAD models or by the use of scanning devices have an accurate geometrical representation. But as the computational algorithms for coupling paths are not available, new algorithms need to be developed. The software developed by Oliker in collaboration with MATIS Inc. use realistic (CAD) models and employs new computational algorithms developed for modeling of wave propagation and EM interactions between two antennas and also between the antenna and the aircraft. The software also enables the optimization of EMI parameters and employs 3D visualization. The first crucial step in the above process is to model the aircraft in real time. The software developed addresses the model suitability for computations by addressing a common problem of CAD files reusability. The software builds the coupling paths in real time from initial point to the terminal point, from initial point in initial direction going through intermediate points. For optimizing EMI characteristics antennas are repositioned (by point & click) new path is built and characteristics computed. The computer code is tested for canonical shapes and compared with the results predicted analytically.

James Rautio of Sonnet Software Inc. was the third speaker of the session. Having to deal with customers who would like to know the error in their design (rather than the accuracy!!!), Rautio presented the importance of EM error analysis for a microwave engineer. Everyone who develops electromagnetic software, both commercial and

academic researcher talks about accuracy. But what the engineer needs to know is the error. And as an engineer, he needs to understand what causes the error and how to control it. Error tolerance depends on the application. An error of between 10% and 1% may be tolerable for EMI analysis or fast coarse analysis or analysis of circuits insensitive to error. Most common microwave circuit design for high probability of design success may have an error tolerance of 1.5% to 0.5%. Special design solutions may have to have error below 0.5%. To quantify the error, one needs to go through different validation processes. a) Regression Testing to make sure that same answer is repeated after every enhancement or modification. b) Have a good agreement between measured and calculated. This is necessary, but may not quantify the error. c) Exact Benchmarks can precisely quantify the error, but there exists only a few such bench marks. d) Take a parameter to a limit for which a known result exists. Once the code is validated, the only way to estimate the error for a specific problem is to do convergence analysis. The analysis converge uniformly if there is no error cancellation, otherwise the analysis does not converge uniformly indicating the error cancellation. In the case of error cancellation, it is difficult to estimate the error. Rautio presented some of the benchmark results and convergence analysis results to demonstrate the above points.

Maurice Sancer presented his group's efforts at Northrop Grumman in monitoring frequency domain CEM developments to enhance their SWITCH code based on a hybrid finite element/integral equation formulation. The main application of SWITCH code is RCS and antenna design. SWITCH has been used to compute all the available Electromagnetic Code Consortium benchmarks as well as a number of real life applications. Sancer presented some of the validations done with SWITCH to demonstrate the maturity of the code. They are now focusing on speed and memory enhancements. Maurice Sancer also presented some important survey results he conducted on the current status of CEM. The following surveys were conducted. a) CEM application survey b) FMM and AIM survey c) Dense matrix iterative solver survey d)Sparse solver survey e) Error estimate survey. The response from Northrop Grumman for CEM application survey showed that they completed all 27 Electromagnetic Code Consortium (EMCC) bench marks with "wiggle for wiggle" agreement on vast majority.

Performed sector median comparison on the conesphere at 500 MHz and VFY218 aircraft, H-Pol with the results meeting 1.5dB sector requirement. Their most significant successes were a) the ability to change the final design of a major component of a real system in a radical manner from the last test configuration and b) the design of an antenna for a real system and then build it. Response from University of Illinois to the FMM survey indicated that they could run EMCC VFY218 fighter bench mark at 1GHz for both polarizations, with 187,212/198,486 unknown, 8.5/13.5 days time and 1.131/1.204GB memory. Response for AIM survey showed that a coated VFY218 was computed at 1GHz with 260K unknowns, 8min/Angle on 38 SP2 nodes and with 3GB memory. The response for dense iterative solver survey showed that a 225K unknown problem can be solved in 9.6 hours for 200 right hand side solutions with 40GB memory on MP Paragon. With the current state of CEM, Northrop Grumman is investigating the best possible use of SWITCH to various industrial applications. Some of the possible actions could be a) providing code to selected government agencies and universities so they can use and enhance SWITCH b) with the government's funding, providing SWITCH to qualified industrial users c) incorporate sparse solvers and port to largest government computers d) incorporating duct cascading procedure e) adding advanced feed model f) incorporate frequency interpolation and extrapolation method and g) incorporating advanced dense and sparse solver approaches to get to 95% use scenario.

ROUNDTABLE DISCUSSION

Roundtable discussion was conducted after the presentation by the four speakers. The main topic of interest expressed by Maurice Sancer of Northrop Grumman is fast and efficient matrix solvers for CEM applications. At Northrop Grumman they intend to deal with electrically large problems which will result in thousands of unknowns. Due to the hybrid nature of SWITCH code, matrices will be partly sparse and partly tense. It has been opined by many participants that efforts should be made to utilize the already existing matrix solvers in other disciplines. This requires modifying them for complex matrices and special matrix structures encountered in CEM. Maurice Sancer is also conducting a nationwide survey of the capability of CEM to solve big problems. It was

felt that involvement of a government agency such as NASA would bring a broad prospective to the survey and the outcome of the survey can be used as a yardstick for the status of CEM today.

Later discussion was focused on time domain methods as Vijay Shankar of Rockwell pointed out the time domain methods also suffer from memory and discretization error for large problems and frequency domain method may compete with the time domain methods with the availability of fast and efficient matrix solvers.

Other topics of interest to the CEM community are the geometry modeling and meshing. It was felt that there is not enough attention paid to the CEM needs while developing CAD tools for geometry building and meshing routines for various applications.

All the participants agreed that the interest in CEM is lacking at the higher levels of research management. It is essential to demonstrate the use of CEM in everyday life by emphasizing various applications of CEM in EMI/EMC, electronic packaging, automobile communications, personnel communications and medical applications.

RESEARCH AREAS

* Matrix methods for CEM applications

* Mesh generators for CEM

* FMM/AIM techniques

TOPICS FOR ICASE SUMMER SESSION WORKSHOPS

* Applications of CEM to Medical, EMI/EMC applications

* Procedures for Validation of CEM codes

* Application of CEM to Automobile applications

* Mesh truncation Methods

SESSION B4: TECHNOLOGY TRANSFER ISSUES

Dimitri Mavriplis, ICASE

Jim Brancheau, from Altair Engineering opened with an overview of who Altair is and what they do. In addition to providing engineering services (mainly to the automotive industry), Altair has been developing its own software for structural analysis and optimization, and more recently for CFD, with their acquisition of COMCO. He then went on to describe Altair's view of what is required for successful technology transfer, which was followed up with a specific example.

Successful technology transfer requires that:

1) the user makes an investment

2) the technology is applied, not just communicated to the user

3) the technology results in an increase of productivity

4) the technology results in a positive contribution to society.

The principal phases of technology transfer were described as communication, connection of technology source and user, negotiation, and commercialization. Connecting the technology source with the user involves seeking out new technology, seeking out appropriate users and evaluating the technology. The negotiation phase usually involves intellectual property, responsibility, and financial arrangements between technology source and the commercializing entity. The commercialization phase is an ongoing one, characterized by continued software development, and one which requires infrastructure for support, marketing and sales.

As an example of how lengthy and involved the technology transfer process can be, Altair's own experience in commercializing the OPTI-STRUCT topology optimization technology for structural analysis problems was described. This technology, which was originally developed in the academic world, was acquired by Altair. They used this capability in a consulting mode for two years before releasing production software for topology optimization.

Mark Halpern, from D.H. Brown and Associates, Inc. opened with a description of his company. D.H. Brown and Associates is an industry analyst and research

organization specializing in information technologies. One of their areas of expertise is in the application of new technologies to engineering design and manufacturing. They provide services for end-users, software vendors and the investment community. Mark Halpern's theme was that, while there is a wealth of new technology on the market, it is not having the desired or potential impact on the design cycle. In industry wide surveys of companies using CAE (computer-aided-engineering), only marginal reductions in design cycles were reported. The problem is that most companies do not appreciate the value of simulation, at least at the management level, and CAE suppliers are also to blame for attempting to create a market that does not exist, with exaggerated claims. In addition, the simulation process is often either too slow, or is called upon to late in the design cycle to have a major impact on the final design. The role of CAE should be to increase the reliability of the design process, and to decrease the time to market and price of the product. Rather than decrease the design cycle time, the largest benefits will be achieved by producing better and more reliable designs, which can be manufactured in less time for lower cost. Finally, the need for customized software was addressed, and new enabling technologies based on object oriented approaches were described. In this framework, one can use basic modules such as linear structural analysis solvers, mesh generation, visualization, etc.. and combine them with other capabilities such as optimization techniques.

Mike Heroux, from Cray Research Inc., began by pointing out the dramatic decrease in the cost of a given numerical simulation over the last decade. The example of a car crash simulation which cost $60,000 in 1985 and only costs $200 today was given. He then went on to make the case that the object of a simulation was not to be as cheap as possible, but to be as useful as possible. The result of decreasing computational costs should not be to enable cheaper simulations, but to enable more complex and thus more useful simulations for the same investment. Single point analysis which can be performed cheaply has become a commodity item destined for workstation type environments. Cray is not in the commodity business, their hardware is expensive but has exceptional capabilities which can be used to enable the use of more valuable technology. In fact, for extremely valuable simulations, the cost of the hardware

becomes irrelevant. The issue is then to make industry aware of the large potential benefits of new technologies. Such large returns on investment will not longer be found in single point analysis, but in multi-point designs optimizations, parameter studies and interactive modeling.

Bart Patel began with a description of Fluent Inc. Fluent is the largest CFD software vendor. They employ approximately 200 people and have been growing at an average annual rate of 25% since their inception in 1983. He stressed the fact that being a commercial CFD company meant more than just software development. Equally important aspects of sales, marketing, and customer training need to be addressed. He also stressed the need to sell to the right customer. As an example, many small companies with no expertise in CFD have been unsuccessful at getting value out of commercially purchased CFD software, while larger companies with more experience and capabilities have thrived on commercial CFD software. The development realities of commercial software were outlined; these include new releases every 12 months, wide range of applicability, extreme validation and testing, uniform GUI, and code maintainability. The need to keep a code maintainable results in a complete rewrite of the code almost every four years, as new algorithms and data-structures which are introduced gradually into the original version eventually render it difficult to maintain. All this results in the need to reinvest 25% of company revenues in software development.

Three mechanisms for technology transfer were then outlined, with examples given for each one. The three mechanisms are:

1) License technology, implement it internally.

2) License software and resell it.

3) Have third parties implement their own technology into Fluent software.

Although successful examples were given for each approach, the first approach was deemed to be by far the preferable one, in spite of the fact that it requires the most resources on the part of Fluent Inc. Finally, the role of government labs in research and technology transfer was addressed. Government labs should focus on basic numerics and physics. Government labs were said to lack the expertise and commitment to develop

production quality software. In cases were they attempt to do so, they hurt the commercial software industry.

The ensuing discussion centered around the role government labs and software vendors should play in the technology transfer process. Bart Patel backed up his point of view with an example in the automotive industry, where a government lab agreed to develop and deliver free of charge a simulation code to the three auto company research departments. The software quality and support was less than adequate and the project eventually failed. Munir Sindir from Rocketdyne agreed that government labs are better suited for developing basic technology rather than delivering codes. However, given the example of the use of NASA CFD codes by the major airframers, it was conceded that in cases where the technology has a well defined use and a knowledgeable customer, the process can be successful. "The problem comes about when technology is transferred to users that cannot handle it."

Another idea put forth was that validation was very difficult for industry, and perhaps government labs could play a role in validating new technology. This comment was repeated in the session on turbulence modeling were it was suggested that the constant confusion over the multitude of turbulence models could be alleviated by a government effort to validate the most promising turbulence models on an on-going basis. This could be done with a relatively small investment, although it would have to be an on-going project.

Another issue in favor of commercial software which was brought up was that of commonality. Commercial software tends to be more standardized and presents a lower learning curve to the user, which can translate into considerable savings in training expenses. For example, the widespread use of NASTRAN
for structural analysis permits companies to hire engineers which already have extensive experience with NASTRAN and who need not be retrained. While this is important for disciplines that are very widespread in a company, it is less so for more specialized and perhaps critical disciplines such as CFD.

As mentioned in the talk of Mike Heroux from Cray Research Inc, there is good reason to encourage large value-added simulations, rather simply than those which are

inexpensive. Hardware and software vendors alike, as well as the research community have a stake in demonstrating and educating the end-user and their management as to what can be achieved with the latest technologies. This in turn brought up the question whether the domination of a particular commercial software product in one discipline can hinder the progress of research and technology transfer. As was mentioned in the session on structural analysis, many companies are frustrated because they do not get what they need out of their commercial simulation codes, but they are entirely dependent on them since no internal development is done in structural analysis anymore.

Finally, as the technology matures, it appears evident that the trend will be more towards commercially developed software, simply due to economies of scale. However, the market forces which guide the development of commercial software may not always coincide with the requirements of all industries, especially for difficult and highly specialized non-linear problems. In particular, for industries were a good capability in a particular discipline is seen as essential to their core business, and can lead to a competitive advantage, other mechanisms of technology transfer such as co-operative agreements and in-house development are likely to persist.

SESSION B5: COMPUTATIONAL MATERIALS SCIENCE

Namas Chandra, Florida State University

SUMMARY

The session on computational materials science consisted of four speakers, two from universities, one from industry and one from government laboratory. In general, the role of mathematical modeling and computing in the development of new materials and structures is well recognized, the speakers addressed specific issues and identified research topics that needs to be pursued. It was recognized that computational materials science is very timely and critical and requires a coherent and comprehensive effort by applied mathematicians, applied mechanicians, material scientists and computer scientists. It was also recognized that a common "lingo" needs to be developed before the basic and applied research topics can be fully identified and effectively communicated across the different discipline.

INTRODUCTION

Computational materials science generally relates to the application of computational analyses to the field of materials science. The field broadly ranges from the discovery of new materials to the innovative use of materials in the manufacture of new structures and products. Though computers have been used to solve pieces of the puzzle, a comprehensive effort to understand the behavior of materials at different scales is important before they are effectively used in the ever more demanding applications of the future. The session was tailored to identify critical issues at the various stages of the evolution of materials into product.

Dr. N. Chandra (Florida State University) set the stage by describing the different scales in the simulation of materials including atomistic, micro-continuum and continuum scales, each governed by different sets of equations solving specific problems.

Dr. J. Malas (Wright Patterson Air Force Base, Materials Directorate) spoke about the future computational directions for design and control of materials processes. This

talk focused on the optimized design and manufacturing method using computational tools to increase the productivity by as much as 50%.

Dr. D. L. McDowell (Georgia Institute of Technology) addressed a key issue of how to develop accurate mathematical models of the behavior of materials. He described a framework of evolving internal state variables through which phenomenon occurring at disparate length scales can be captured.

Dr. O. Richmond (Aluminum Corporation of America Technical Center) presented a comprehensive science-based methodology for designing structural products concurrently with their manufacturing processes and their composition. His holistic design framework covered not only the different dimensional scales of a product but also different stages of life cycle evolution of a product.

Dr. D. Srolovitz (University of Michigan) presented a novel application of materials modeling from the atomic to equipment scale, specifically considering the chemical vapor deposition of diamond.

PRESENTATIONS

Dr. Chandra, in his opening remarks observed that the atomistic, mesoscopic and macroscopic simulations of materials pertain to three distinct length scales and all are very useful computational tools to analyze problems at those scales. They are presently pursued as investigative tools for gaining insight and comparison with experimental data. At the macroscopic level, computational mechanics has been extensively used in the modeling of structures through the use of finite element methods. At the mesoscopic scale, use of various analytical and computational technique are employed to understand the effect of interacting constituents or phases on the mechanical behavior. Atomistic simulations is an excellent analytical tool, presently used in computational chemistry and pharmaceuticals, yet to be fully exploited in the study of structural behavior of materials. He showed an example of superplastic materials in which the process modeling of sheet metal forming is simulated at the macroscopic level using finite element methods. At the intermediate grain level, the fundamental deformation mechanism causing superplasticity are modeled using a micromechanics based approach in which the diffusional and

dislocational flow within the grains are independently computed. Using atomistic simulations, the structure and energetic of grain boundaries in material can be simulated which can then be used to track the evolution of grain boundary sliding. The success of all these techniques lies in effectively transferring the information to one specific scale from a next lower level which is an extremely challenging issue.

Dr. Malas addressed the macroscopic modeling issue in detail. Computer simulation is routinely used as a process design tool in many metal forming and casting industries. Process modeling and analysis tools (e.g., finite element method) have provided valuable insight into complex thermomechanical phenomena. However, the state-of-the-art approach still involves trial-and-error determination of process design variables. Thus the computer solutions are usually not optimized with respect to process efficiency, process stability and robustness, and process equipment characteristics. In process design and control, a plausible goal is to simplify and decouple design parameters and process variables as much as possible to obtain the best design solutions. Tracking simpler stress states and velocity fields would produce better design than more complex information, and will lead to feature-based design systems for material processing applications. Material processing operation can be analyzed as the combined response of several sub-systems whose features are simple enough for expeditious analysis and optimization. Such a system comprises of reliable geometric data base, customized software and enhanced visualization. He showed many case studies including aluminum extrusion, disk forging and thermomechanical processing of an integral blade and rotor component. In summary, he emphasized the need for systematic approaches using simplified techniques in the process optimization and pointed out that exhaustive analysis need not always result in better designs.

Dr. McDowell showcased a fundamental problem in the application of computers in the design of materials and structures, the development of constitutive relations at the meso and macro levels. The behavior of solids, especially in the inelastic range is typified by memory of prior history and mechanisms occurring at various length scales, all contributing to the balance of energy storage and dissipation. The internal variable formulation of the thermodynamics of irreversible process offers a powerful framework

for the introduction of mechanisms at their appropriate scales, along with homogenization to the macroscale. The selected internal state variables should be a minimal set that should represent the salient features of the materials including, composition and composition gradients, microstructural arrangement including defect and damage structure. This approach is very amenable to mathematical formulation and computational implementation and is consistent with the principles of continuum mechanics at the macroscopic and mesoscopic levels. Also the framework allows the development of a unified constitutive and damage relationships with evolution equations tracking the changing state of the material. At any scale there are certain sources of uncertainty associated in the formulation or the numerical value of the coefficients entering the equations. They introduce certain non-uniqueness not only at that scale but also a propagating effect at the higher scales regardless of the homogenization scheme used in the scale-up process. Simulation at the atomistic levels to understand some of the fundamental deformation and damage mechanisms and incorporating their effect in an internal state variable framework is one way to link microstructural effects to performance of structures.

Dr. Richmond presented the needs for a holistic design approach in developing material products based on computational modeling. He added a new dimension to the problem in the form of the various stages of the life cycle of a product including synthesis, manufacture, use and disposal; these stages are akin to birth, nurture, maturity and death. On a dimensional scale, a product assembly is comprised of component, material element, grains (particles), dislocations (and nano precipitates), and molecules which are dealt within the realms of engineering specialists, material scientists, physicists and chemists. The holistic design should incorporate state variable-based constitutive equations for spanning the various scales in the holistic design. Such a state model is governed by conservation laws in the interior and constitutive equations prescribed separately in the interior and at the surface. Some key issues to be addressed include mesh generation of the three-dimensional design based on material state (microstructure) rather than geometry (high stress regions), multi scale modeling (especially from atomistic to continuum levels) and optimization of microstructure to achieve optimum specimen level

properties. At the overall product level, integration of physics of the process and cost in a unified model is essential before a global optimization of material, process and product can be achieved.

Dr. Srolovitz focused on an approach of applying atomistic level modeling to the prediction of microstructure evolution in the chemical vapor deposition of diamond films. Since the evolution is governed by reactions at the surface influenced by the various species in the reacting gas environment, the chemistry of the reaction determines the physics of the growth. The probability of a specific reaction at a specific site determines the rate of reaction and hence the crystal growth at that location. Significantly, molecular dynamics simulations were useful for establishing the crystallographic deposition rate for thin films, but was not useful as the thickness increased due to complex morphology of the thick film (in addition to level of computation required). Other principles were used to correlate thick film growth, still using information from the MD analysis.

RESEARCH TOPICS

Specific research topics were identified:

- Mathematical description of material microstructure. Microstructures are thermodynamically unstable features that evolve with time. Micrographs or planar images are two-dimensional slices of the three-dimensional microstructure. In general, materials are polycrystalline in nature, with grains varying from a few nanometer to a few micrometers in diameter. These 3-D grains have many facets and are separated by grain boundaries only a few angstroms wide. Each of the grains have their own orientation and properties (anisotropic) and make up the agglomerate the material of our interest. These structural features are observed when a specimen is cut, mechanically polished and chemically etched to reveal the grains and the grain boundary. A magnification of 100 to 1000 is necessary to examine the structural feature called the MICROSTUCTURE. The problem is to describe the geometric and mechanical features of the microstructure uniquely.

- Description of materials at different length scales and methods to transfer information to one scale from the next lower level.
- Multi scale optimization.

SESSION B6: STRUCTURAL ACOUSTICS

Richard J. Silcox, NASA LaRC

The session on structural acoustics overviewed a range of topics ranging from the application of finite element and boundary element methods to underwater acoustics and aircraft acoustics to design optimization and active structural acoustic control. The first presentation were made by Henno Allik from BBN Systems and Technologies, New London, CT where much of the work is supported by the Navy and therefore relates to underwater acoustics and the acoustics of underwater vehicles. The author was involved in the development of the SARA-2D and SARA-3D finite element prediction code for the U.S. Navy and continues to develop new capability in this area. The second speaker was Yueping Guo from the Acoustics Technology group of McDonnell Douglas Aerospace in Long Beach, CA. Mr. Guo is involved in developing and applying noise prediction tools to the interior noise of McDonnell Douglas aircraft. These tools primarily consist of an in-house developed prediction called the Matrix Difference Equation (MDE) finite element code which takes advantage of the periodicity of aircraft structures in order to reduce the order of the problem. The third speaker was Jay Robinson of the Structural Acoustics Branch of NASA Langley Research Center in Hampton VA. Mr. Robinson discussed ongoing in-house and supported research on structural design optimization for interior noise and efforts to extend and apply higher order finite element methods to two and three dimensional problems. The final speaker was Dr. Ralph Smith from the Department of Mathematics of Iowa State University. Dr. Smith spoke on various aspects of active control of the structure for minimum interior noise. These included the form and accuracy of the model, the inherent importance of the time delays of the acoustic system, actuator and sensor placement and control law design.

A Review of Structural Acoustic Analysis Using Finite Element and Infinite Elements - Henno Allik

The solution of three-dimensional structures submerged in an infinite fluid and subjected to time harmonic loading is a computationally intensive problem. Over the past

decade BBN has developed a combined finite/infinite element method for solving this class of problems that is more efficient than boundary element methods. This solution utilizes an infinite element approach to fully couple the structural response to the fluid and to the acoustic farfield. This approach has been implemented as a comprehensive set of computer problems called SARA-2D and SARA-3D which are now widely used in the Navy structural acoustics community to solve acoustic design problems.

This presentation reviewed the relevant theoretical developments that characterize the finite element/infinite element method and discussed features that contribute to its efficiency. Also discussed is the evolution of SARA from a 2-D prediction code developed in 1982 to the more general and computationally intensive 3-D code in 1991. This has been augmented recently with a substructures method that combines the fluid loaded shell from SARA 2D with 3D internal structures from SARA-3D. These codes have been validated with a series of small scale experiments; the first using the SARA-2D code under DARPA sponsorship and the second using the SARA-3D code under ONR sponsorship. These tests demonstrated accurate results out to non-dimensional frequencies of ka=20 where a is the characteristic dimension of the structure. Calculation times of 25 seconds/frequency for calculation of the surface quantities increased to 35 seconds/frequency for nearfield calculations on a Cray C-90.

Despite the efficiency of the method, the solution of complex three dimensional problems is still too expensive to use in routine design work. Fortunately for Navy underwater shell problems much useful information can be obtained from axisymmetric analysis and hence SARA-2D is currently more widely used than SARA-3D. For this class of problems, solutions well into the mid-frequency range are possible.

A combined axisymmetric and three dimensional analysis provides an economical solution strategy for basically axisymmetric shells, but containing arbitrary internal structures. The response of an axisymmetric hull with arbitrary internal substructures are modeled as the sum of the hull response plus the response of the hull due to the interaction forces of the internal substructures. This latter term is built up in terms of the internal impedances of the substructure. This approach was found to compare very favorably to a full 3D formulation but with a distinct advantage in computational effort.

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Finally, the effect of the loss factors associated with internal structures is compared to that derived from a "fuzzy substructure" approach. The model utilizing fuzzy substructures attached at discrete points as opposed to more distributed attachments yielded better agreement with an exact prediction.

Numerical Modeling in Structural Acoustics: An Airframe Manufacturer's
Perspective - Yueping Guo

This talk discussed the need for numerical modeling tools from the perspective of a designer's requirements and a research criteria. The latter requires enough detail in the model to encompass all of the mechanisms of sound transmission for evaluation and the former requires only those that contribute to that particular design. The capability must consider the important frequency ranges of interest, and how they contribute to passenger and crew annoyance and speech interference. Analytical approaches are desirable due to their concise solution and easily understood physics, however they are typically restricted to simple geometries and linearity assumptions. Numerical approaches easily apply to general geometries and materials and model the full fluid structure interaction problem, but generally have large computational requirements which results in model size and frequency limitations. Currently used techniques are finite element and boundary element methods (FEM/BEM) and statistical energy analysis (SEA).

At McDonnell Douglas a combination of the finite element method and periodic structure theory has been synthesized into a code referred to as the Matrix Difference Equation (MDE) method. This approach applies very well to the inherently periodic structure of aircraft. A finite element model is constructed for one single substructure, either structural or acoustic or both. The periodic structure theory is used to combine these components into the overall aircraft structure. This approach allows for a full coupling of the structure to the fluid and most recently allows for small non-periodicities such as windows and for spectral input. This approach permits aircraft models to be cast as much smaller computational problems yielding better accuracy to higher frequencies.

Ideally an airframer would like to have design tools that provide accurate results on a general workstation environment. It must accept tonal and broadband inputs due to

both point and distributed sources, either acoustic or mechanical. It must model the fuselage with floor, pylon/wing and engine structures and cover a frequency range from about 50 Hz to 12 kHz. It should output a SPL prediction accurate to 2 dB with impacts of changes to the structure accurate to 0.5 dB. It should predict modal frequencies to within 5% and resonant responses to within 7 dB and must identify all dominant noise sources.

Future research should be directed to improved source modeling, including turbulent boundary layer, engine noise source characteristics, local separations, and shock/boundary layer interaction. Noise reduction treatments utilizing viscoelastic material, conventional trim panel and fiberglass insulation on both composite and conventional fuselage construction should be investigated. Further, this should be optimized as part of a active/passive noise control package.

The "Redesign" of Structures for Interior Noise - Jay H. Robinson

The design of a structural system with respect to the spacing and amplitude of structural resonances has been successfully demonstrated in the past. A more difficult task is the design of a structural system with respect to the amplitudes and spacing of the resonances of the cavity which the structure encloses. This presentation overviewed recent efforts both within and supported by the Structural Acoustics Branch in the optimization of structures for interior noise for both resonant and broadband behavior of the interior cavity.

The first effort described the feasibility of reducing aircraft interior noise through an optimization of the composite lamination angles. The standard configuration of the Beech Starship was taken as the baseline case. The fuselage of this aircraft is constructed as a sandwich composite with a honeycomb core 0.75" thick with graphite epoxy face sheets forming the inner and outer surfaces, each of which is formed from four 0.01 inch layers. There are no conventional stiffeners on this aircraft as the honeycomb composite carries the load. MSC NASTRAN was combined with an optimizer such that the lamination angle of each of the four inner and outer carbon epoxy layers was varied in order to produce the lowest interior noise levels over a bandwidth from 185 Hz to 210

Hz. The noise was minimized over the 10 interior seat locations of the passenger cabin. The results demonstrated approximately a 4 dB reduction in acoustic levels using only the lamination angles as the design variables. There was no increase in weight for this optimizations as a result of the constraint on the design variables. However, the results were found to be sensitive to the design model and careful consideration must be given to the out-of-band performance such that an increase in overall noise is obtained.

A second case study used the stiffener design variables of an conventional stiffened cylindrical shell to provide for both tonal and broadband interior noise control. The approach again integrated an optimizer with commercial finite element and boundary element prediction codes (MSC NASTRAN and COMET/Acoustics). In this work, the stiffener cross section shapes and spatial distribution were used as the design variables across a frequency band. In this study, the weight is also a consideration. Approaches where the noise was minimized with weight as a side constraint, minimizing the weight with noise as a side constraint, or with both noise and weight minimized were considered. The CONMIN optimizer was the primary tool but other algorithms were also considered.

The results verified the importance of the stiffeners to noise transmission loss. Various cases were considered with noise reductions up to 9 dB over a bandwidth of 50 Hz obtained from the predictions with no increase in weight. The optimizer typically varied the cross section (and stiffness parameters) of both the ring frames and longitudinal stiffeners from section to section on the cylindrical fuselage model with significant benefit over the frequency of interest.

Finally, Mr. Robinson overviewed development work by the Naval Research Lab on finite element methods for coupled air filled elastic structures at frequencies significantly higher than can currently be predicted. The approach utilizes high-order FEM, rapid automeshing and accurate geometric interpolation for very large elements. Comparable results for a cylindrical axisymmetric shell modeled with a single 47 degree of freedom element with linear elements with 23,400 degrees of freedom were shown for eigenvalues up to and greater than 5.0. This approach has been utilized for fully 3D elastic structures and fluid elements and an automesh generation capability for the solid model developed. This code is now being exercised for some validation problems.

Model-Based Controllers for Structural Acoustic Systems - Ralph C. Smith

Applications of active noise control involve the reduction of sound pressure levels in both interior acoustic fields such as those found in a fuselage or muffler, or exterior fields (e.g. fields generated by a transformer or submarine). This talk focused primarily on techniques for interior fields although many components also apply to exterior field applications. The relative merits of active versus passive noise control were discussed, and included references to the early work of Lueg and Olson and May for noise control in ducts, free space and headphones.

Interior noise reduction has been achieved both through cancellation via secondary acoustic sources and structural actuators which reduce the effective structural acoustic coupling and/or provide structural damping. The use of secondary acoustic sources has proven successful in some applications (e.g. industrial ducts and aircraft) but in large cavities, this approach yields only local attenuation with an often prohibitive amount of required hardware. Control systems utilizing structural actuators (active structural acoustic control or ASAC) are designed around the physical mechanism which couples the structural vibrations and resulting acoustic fields. Control can be provided by smart material transducers, such as piezoceramic patches, which have both actuator and sensor capabilities.

Adequate modeling of the structural, acoustic and coupling components is crucial to the success of the controller. Modeling approaches discussed included modal, finite element, and PDE and the issues such as boundary condition incorporation, model accuracy, computational efficiency and damping models were discussed. An important criterion which must be addressed when designing model-based controllers is the relatively slow transmission of information in the acoustic field. The natural time delays which result must be incorporated in either the model or control laws. Also, the real-time implementation of the controller also necessitates highly efficient numerical techniques and model reduction for many applications.

Issues relating to incorporation of the sensor and actuators into a control system were discussed as was optimum placement thereof. The non-linear characteristics of

piezoelectric and magnetostrictive transducers were also discussed as was the need for non-linear control laws.

Discussion

One of the most important noise sources for interior noise in high speed aircraft is that generated by the turbulent boundary layer flow over the surface of the fuselage. This noise source is broadband in frequency with a peak around 800 Hz for subsonic aircraft. Not only is this source random in time but also in space with relatively short correlation lengths, especially perpendicular to the flow. This flow structure interaction problem is generally accepted to be important for Mach numbers above 0.5. The fully coupled problem is non-linear, but is often cast for engineering solutions as an uncoupled problem where the effect of the elastic panel on the flow is ignored. Recent work in this area has attempted to model the structural damping imposed by the flow as that imposed on a moving piston with damping constants derived from a fully coupled model. While past work has utilized the Corcos two point correlation model, more recent evaluations suggest that the Efimtsov correlation model yields results closer to that found for large commercial aircraft.

This particular source is not important for the underwater problem and even for automotive applications due to the relatively low speed of the flow. However, even for these low speed applications, flow generated large scale structures (i.e. vortices and separated flow) can generate high amounts of acoustic energy which then impinges on the structure and transmits to the interior. This is the dominant source of so called "wind noise" in automobiles. This type of source is important in underwater applications both as sources for detection as well as masking sources for on-board passive sonar.

For underwater problem, the exterior noise problem is often of most interest. This problem occurs for interior sounds propagating to the far field or for the scattered field from external sources impinging and scattering/reflecting from the cylindrical shell and back to the source. Here the response of the structure to an incoming planar wave is of most importance. The effect of the frames on the scattered wave can be calculated using a 2-D FEM code, but the effect of equipment scattered throughout the structure is more

difficult. Here, the emergence of the "fuzzy structures" approach accounts for this effect using a statistical approach that is found in some cases to yield reasonable results. Here an infinite plate coupling impedance yields satisfactory results for coupling the structure to the fluid.

The emergence of the infinite element as a cousin to conventional finite elements has greatly reduced the computational domain required for exterior noise problems. This approach models the external fluid using several layers of conventional finite elements adjacent to the elastic structure and then extends the computational domain using an infinite element that inherently possess the properties to match the results to the far field allowing only outgoing waves. This approach has also been used to model the noise radiation from aircraft engines.

Another topic of discussion was the need for predicting the delta vs. absolute noise levels. In order to meet delivery guarantees for products, the manufacturer would like to have as much confidence in his capability to predict the absolute interior or exterior noise levels as possible. However, for the design problem, often it is important only to know in which direction to vary a design parameter. If there is confidence in the differences in the noise level due to some design variation, then that will often suffice. However, experience has shown that predictions beyond non-dimensional frequencies (ka) of about 20 are not reliable in general. By utilizing the periodic structure analysis (MDE) or infinite elements, finite element methods can be extended. However, for these frequency ranges beyond this capability, techniques such as statistical energy analysis (SEA) are gaining acceptance with the emergence of commercial products. However, it is often the intermediate frequencies that are of most concern.

Finally, a consensus of the participants was generated on the need for experimental databases of structural acoustic response. This has been shown to be extremely useful for underwater acoustics problems. In order to extend this capability, detailed, well documented measurements of the physics described by this process are required. These will be required for each class of structure (i.e. underwater vehicles, aircraft, automobiles, etc.) as each has different requirements from the modeling standpoint.

SESSION C1: SOFTWARE RELIABILITY AND TESTABILITY

Kishor Trivedi, Duke University

BRIEF SUMMARY OF THE PRESENTATIONS

In the session entitled, "Software Reliability and Testability" chaired by Kishor Trivedi of Duke University, there were five speakers: Amrit Goel of Syracuse University, Bob Horgan of Bellcore, Chandra Kintala of Lucent Technologies, Aditya Mathur of Purdue University and Tilak Sharma of Boeing Commercial Airplane Group.

Amrit Goel reviewed software reliability methodology in the context of software readiness evaluation. The three step methodology he proposed consists of trend analysis, reliability growth modeling, and readiness evaluation. The recommended statistical test for trend analysis is the Laplace test. The Goel-Okumoto model and the Musa-Okumoto model are the most widely used reliability growth models. Goel then discussed a real test case where it was important to distinguish between the number of bugs (problems, faults) reported (detected) and the number of problems fixed (closed). He suggested the need to extend the current software reliability models to account for the finite time to fix problems. He also pointed out the need for tool support.

Bob Horgan of Bellcore discussed a suite of tools, Xsuds, being developed at Bellcore for understanding the dynamic behavior of programs. The most well-known of these suite of tools is XATAC which allows the measurement of test coverage for C and C++ programs. Other tools in the suite are: XVue, a tool which supports software maintenance by visualizing code features; Xslice, a dynamic slicing debugger which graphically localizes bugs and XProf, a fine-grained execution count based profiler. He discussed the use of these tools in the development, testing, repair and maintenance of large Bellcore systems. He reported that experienced programmers found that XVue dramatically reduces the time to repair a field error report. XAtac is being used by system testers to find small, efficient subsets of huge regression test sets to run on incremental system releases. Unit testers are able to quickly and easily create very high coverage test sets using XAtac and localize faults using XSlice.

Chandra Kintala discussed "Distributed Systems Software Reliability" and pointed out the shift in focus for understanding reliability of programs to reliability of processes. Reliability from the application point of view depends not only on the program but also on the environment in which it is operating. Since complex distributed systems with many off-the-shelf components are being used, transient faults are increasingly the norm. In addition to reactive techniques such as failure detection and restart, proactive techniques such as software rejuvenation are being pursued. A set of library routines are being developed for embedding desired kind and level of reliability in an application.

Aditya Mathur spoke about the testing work ongoing in their Center, pointed out pitfalls of extent software reliability growth models, and advocated developing a structural theory of software reliability. A structural theory of software reliability should incorporate reliability estimates of individual components of a software system under test in order to give an overall estimate of system reliability.

Tilak Sharma related his experience with hardware/software safety and reliability. He pointed out that the current approach of separately modeling hardware and software is not acceptable. Combined hardware/software reliability models are needed that take into account the interfaces between hardware and software.

BRIEF SUMMARY OF THE ROUNDTABLE DISCUSSION

The discussion centered around the following topics:

a)   Given that there are three separate ways of quantifying software quality, how can they be combined? These three are: complexity metrics, test coverage metrics, and software reliability metrics. It was felt that there is a need to merge the three different types of metrics. It was noted that some recent progress has been made in combining test coverage with software reliability.

b)   Most prevalent software reliability growth models assume that soon as a defect is detected, it is fixed instantaneously without introducing additional defects. This is clearly not true in practice. A queuing theoretic approach to this problem is being pursued at Syracuse University and a non-homogeneous Markov chain approach is being studied at Duke University.

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c)   The need for a structural theory of software reliability was stated. This is particularly important as the use of COTS software increases. Such a theory will enable the prediction of large software systems reliability based on the measured reliabilities of individual modules and the known interfaces. There is an effort along these lines at Purdue. There is a strong possibility of a joint project between Purdue and Duke on this topic.

LIST OF GENERAL RESEARCH AREAS THAT NEED DEVELOPMENT AT THE FUNDAMENTAL SCIENCE LEVEL

* Development of a structural theory of software reliability
* Models of software quality that include complexity metrics, test coverage and traditional reliability growth models.

SUGGESTIONS OF SPECIFIC TOPICS FOR ICASE SUMMER SESSION WORKSHOPS

* Software Quality Metrics and How to make use of them in a Project.

C2: PARALLEL SOLVERS IN INDUSTRIAL APPLICATIONS

Alex Pothen, Old Dominion University & ICASE

SUMMARY OF PRESENTATIONS:

The four members in this session were: Ed Rothberg, Silicon Graphics, Inc. -- Observations on Commercial Applications of Sparse Direct Solver Libraries; Roger Grimes, Boeing Information and Support Services, Seattle, WA -- Applications of Sparse Linear Algebra at Boeing; Manohar D. Deshpande, VIGYAN Inc., NASA Langley Research Center, Hampton, VA -- Applications of Matrix Solvers for Computational Electromagnetics; and Yogin Campbell, Old Dominion University -- A Parallel Sparse Indefinite Solver for Distributed-Memory Multiprocessors. A summary of their presentations follows.

Dr. Ed Rothberg has been working for several years in the development of parallel direct solvers as part of applications performance optimization for SGI. The direct solvers that he has developed are included in the standard software package available with every SGI workstation. He has worked with structural analysis and fluid dynamics packages such as ABAQUS, ADINA, ANSYS, FIDAP, MARC, and NASTRAN, and linear programming packages such as CPLEX. Ed had several interesting observations to make from his extensive practical experience.

Sparse direct solvers are surprisingly new to software vendors. For instance, MSC/NAST-RAN included a general sparse direct solver only in 1991. Most vendors included an iterative solver before they provided a general sparse direct solver. The sparse direct solvers have greatly reduced the space and time requirements of the skyline solvers they have replaced.

After a general sparse direct solver is introduced into an application software package, the largest fraction of the time is not consumed by the linear solver. Often the finite element assembly requires greater time. However, this observation is not true if a skyline solver is used. This also means that to get an efficient parallel code in an application, the element formation and assembly steps should be parallelized as well.

Platform specific optimization can often yield more than five-fold improvement in running times. This tuning is not too hard to do; however, most software vendors do not have the time to do it.

An observation that went against conventional wisdom was that direct solvers were faster than iterative solvers for most industrial problems that Ed has worked with. The advantage of the direct solvers increases with problem size, even for three-dimensional problems, because of the poor conditioning of the problems. This observation explains why direct methods are the method of choice in most structures codes, with the exception of the ANSYS Power Solver.

For large industrial problems, out-of-core direct solvers can work with less in-core memory than iterative solvers; incomplete factorization preconditioners in the latter typically require more than four times the memory needed for the initial matrix. Out-of-core iterative solvers are not as feasible as direct solvers due to the necessity of disk accesses in every iteration.

Symmetric indefinite problems arise commonly in nonlinear codes due to the presence of equations corresponding to Lagrange multipliers. It is possible to handle most of these problems by a simple reordering that ensures that nonzero values appear to the left of the diagonal in every row with a zero diagonal element. This modification is easy to make in a minimum-degree code, but harder to do in nested dissection orderings. None of the current commercial codes have this capability.

Rothberg also made some observations on building a general purpose library. The design of a general purpose software library is difficult because of the different data structures used for matrix storage. Diagonal, point or block, row or column oriented storage schemes are used in application codes. The cost of a data structure mismatch between application and solver can be severe, with the data structure transformation requiring more time than the sparse direct solver.

Rothberg's conclusions were as follows: The enhancement and replacement of less efficient skyline or band solvers in commercial applications remains a fruitful activity. Direct solvers are still the method of choice since they are robust, and usually faster; however, the trends for the future are not obvious. There are also opportunities to

improve applications performance outside the solver, especially in the finite element assembly step.

Roger Grimes is Manager of a group that has developed and supports the BCSLIB-EXT software library. He organized his talk into four parts: the applications of

1. iterative solvers for linear systems of equations,

2. direct solvers for these problems,

3. eigensolvers, and

4. future plans for development of linear algebra libraries at Boeing.

Iterative solvers have been used in aerodynamic analysis, aerodynamic optimization, and analysis of electromagnetic scattering from vehicular models. Many of the linear equations have unsymmetric coefficient matrices, and have many right-hand-side vectors. An important application of iterative solvers was in the design of the Boeing 747 airplane to integrate the engine-nacelle with the wing.

Direct solvers have been used in finite element models in statics and dynamics. Applications have included the design of the Boeing 777 aircraft's landing gear, the effect of landing gear configurations on runways, and the manufacturing processes for the wing and rivets. They have also been an integral part of nonlinear sparse optimization software used at Boeing in metrology and trajectory optimization.

An industrial-strength eigensolver based on the Lanczos method developed by the Boeing group has been used in vibration analysis of structures.

Software implementing these various solvers is commercially available in the package BCSLIB-EXT; it is part of the Convex scientific software library. The package includes a multifrontal code for real symmetric, and complex coefficient matrices that can work with matrices larger than the core memory. This solver is a factor of 10-100 times faster than band methods.

There is also a rank-revealing sparse orthogonal factorization code, which is widely used in surface-fitting applications.

In the future, as part of an ARPA-funded project, the Boeing group will develop a linear algebra library for parallel computers.

Dr. Deshpande presented the experience of a team consisting of himself, F.B. Beck and C.R. Cockrell at NASA LaRC, and C.J. Reddy at Hampton University. He described two applications in Computational Electromagnetics (CEM) in which linear equations solvers play a vital role: design of smart skin antennas, which are conformal antennas mounted on aircraft and automobiles, and the study of electronic upset due to electromagnetic interference.

Three classes of frequency domain methods are used in CEM: the Method of Moments (MoM), the finite element method (FEM), and a hybrid FEM/MoM method.

The first method, MoM, results from an integral equations approach. Here the coefficient matrix is complex, symmetric, and dense, and there are several right-hand-side vectors. The FEM arises from formulating the problem as a partial differential equation. Here the coefficient matrix is sparse, complex-valued, and symmetric. The hybrid method FEM/MoM leads to a coefficient matrix with the structure

$$\begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix},$$

where A_{11} sparse and complex-symmetric, A_{22} is dense and complex-symmetric, and $A_{12} \neq A_{21}^{T}$. This system can be solved by a Schur complement technique, using a sparse solver on A_{11} and then applying a dense unsymmetric solver to the Schur complement of A_{11} in A_{22}.

Dr. Deshpande's results showed that in general, direct solvers were faster than diagonally preconditioned iterative solvers on serial computers, although there were a few notable exceptions. The generation of the matrices required a substantial amount of time for MoM; hence this step needs to be parallelized. He concluded that efficient parallel solvers would revolutionize design by CEM.

Dr. Yogin Campbell of Old Dominion University described joint work with Alex Pothen, the organizer of this session, on a parallel solver for sparse, symmetric indefinite systems of equations. The parallel solver uses the MPI communication library so that it is portable across many multiprocessors. This appears to be the first parallel indefinite

solver to be documented. This project was supported by an IBM-University research partnership; the IBM technical monitor was Dr. Raj Pandian of IBM Kingston.

Indefinite problems require both 1 x 1 and block 2 x 2 pivoting for numerical stability. Several steps are taken to ensure that the expense associated with pivoting are kept low. The code adapts a new pivoting strategy, described by Cleve Ashcraft, Roger Grimes, and John Lewis of Boeing Information Services, that controls the growth of elements in the factors, and that has been proven to be stable. The pivot strategy reduces the chance of pivot failures by examining all available elements as candidates to be pivots. It also reduces the serial bottlenecks introduced by earlier pivot selection strategies. A loose value of the numerical pivoting threshold is used to reduce the number of times pivoting takes place, since pivots are expensive in the parallel context. A few steps of iterative refinement are then used to obtain higher accuracy in the solution.

The code makes use of the multifrontal algorithm to perform the computation. This algorithm has regular dense matrix kernels in the numerical factorization, and also limits the communication necessary in the algorithm. High level BLAS operations are used to make the numerical factorization efficient.

The code is written in C, and uses the MPI message passing library for portability. Results from the code on a collection of problems from structural analysis (Boeing-Harwell, NASA, some structural analysis vendors), from CFD (Boeing-Harwell, Matrix Market), and linear programming problems (Argonne National Labs) were reported. All the problems tested were solved to high accuracy relative to the conditioning of the problems.

Current work involves performance-tuning the code, developing better ordering algorithms for the combinatorial preprocessing steps, and enhancing the scalability of the algorithm. This software will be available freely in the public domain.

SUMMARY OF PANEL DISCUSSIONS:

In addition to the four speakers, the panel for the discussion session afterwards also included Dr. Michael Heroux of Cray Research Inc. He briefly discussed the use of

computer simulation in the engineering design process. "Single point analysis", the simulation of a single, challenging, nonlinear problem, is the most common use of simulation today. Such analysis helps validate physical models, but has little impact on the design engineering process. More meaningful to the designer is the capability to (1) vary key independent parameters to determine their effect on key dependent functions, (2) optimize the design within specified constraints, and (3) model the system interactively. These features would make simulation an essential tool for design teams. Software requirements for this capability include fast, robust single-point analyses, good optimization algorithms, and tightly integrated computing and visualization: Hardware with the requisite computing power would be needed as well, since simulation would be on the critical path in engineering design. Dr. Heroux discussed an acoustic optimization example in which the design goal was to reduce the interior sound pressure in a certain frequency range without increasing the weight of the structure. This optimization had 210,000 structure degrees of freedom, 40,000 fluid degrees of freedom, and 110 design variables. It required four hours of CPU time on a Cray C94, and transferred almost 700 GB of data.

There was also a discussion of the "life-cycle" of a linear equations solver from algorithm research, to research code, to industrial software, and to its continued maintenance and support by industrial software vendors. For the development of a general purpose industrial solver, Dr. Heroux felt that experience in creating solvers for several different applications was essential. Professor David Keyes of ICASE and ODU pointed out the recent development of block iterative methods for multiple right-hand-side vectors.

RESEARCH AREAS AND ICASE WORKSHOP TOPICS:

There seemed to be consensus that sparse direct solvers and iterative solvers (preconditioned Krylov space methods, domain decomposition, and multigrid methods) are sufficiently mature that it is appropriate to consider the creation of general-purpose software toolkits implementing them on serial and parallel computers. Such toolkits will make it easier to implement future algorithms, and to write problem-specific code. The

PETSc (Portable, Extensible Toolkit for Scientific Computing) effort at Argonne National Laboratories, due to Bill Gropp, Barry Smith, Lois Curfman McInnes, and Satish Balay, is one step towards this goal for linear and nonlinear solvers for partial differential equations.

An important issue is dealing with the data structure mismatch between the applications context and the solver algorithm. It should be possible to make use of abstraction, one of the features of object-oriented design, to ameliorate this problem. PETSc deals with this issue in the iterative methods context; for direct methods, this is an issue that needs to be considered, especially since they rely on reordering and remapping the data to achieve low computational requirements. However, the data associated with the nonlinear problem is already partitioned among the processors, and redistributing the data is expensive. Hence direct methods need to be developed that can work with the given data distribution, and yet maintain high parallelism and low time and storage requirements.

It was also felt that close interactions with applications scientists who use the software is necessary to develop truly general purpose software. For this effort to be useful to them, it is also necessary for software to be compatible with visualization and post-processing capabilities for the interactive solution of the application problems.

Two topics for ICASE workshops were suggested: (1) Problem-solving environments in scientific computing, (2) Development of and experience with solvers in diverse applications such as CEM, computational structural mechanics, circuit and device simulation, manufacturing processes, and design optimization.

C3: HARDWARE AND SOFTWARE ISSUES
IN HIGH-PERFORMANCE COMPUTING

Arun K. Somani, University of Washington, Seattle
and
Piyush Mehrotra, ICASE

INTRODUCTION

The panel, "Hardware and Software Issues in High-Performance Computing" took place on October 8, 1996 in the morning session. The moderators were Arun K. Somani and Piyush Mehrotra. The panelists were Bruce Blaylock, Burton Smith, and Robert Voigt. Dr. Olaf Lubeck was absent; therefore his talk was replaced by a talk "Practical Issues in Parallel Processing," by Arun K. Somani.

Each panelist spoke for 20-25 minutes. The talks were followed by a discussion.

INITIAL ISSUES

The main discussion started with a review of current states including the following:

1. Computational Issues

2. Software and Tool Support

3. Challenges in Tools

4. Software Research

5. Architecture and Hardware/Software Interface

The following issues were raised by the moderators:

1. Major Software Issues in Tools and Support

2. How to facilitate the interactions between the designer and user of systems?

3. User Interfaces

4. How much the architecture is to be blamed?

5. Is Fault-Tolerance a Concern?

SUMMARY OF THE TALKS

Bruce Blaylock of NASA Ames Research Center described the NASA/ARC plan outline. It included:

1. Meeting the needs of Grand Challenge Uses
2. Few projects; Near term useful results
3. Application Creation Process Support
4. Application Usage / Operation Support
5. Advanced Support Software and Tools Concepts
6. Metrics Based Monitoring and Management
7. The major issue is support and using metrics for measurement.

Bruce listed the following metrics and discussed their implications.

1. Scalability - The efficiency measure observed when the problem grows and the number of processors grows.
2. Throughput - The efficiency measure observed when a problem is replicated (data set growth) and the number of processors grows.
3. Speedup - The efficiency measure observed when the problem size is held constant but the number of processors grows.
4. Portability - The scalability, throughput and speedup achieved when an application is moved to another platform.

Robert Voigt discussed the NSF perspective on high performance software research. A major portion of the effort is focused on software research to improve the effectiveness of scalable parallel systems. Recently, a series of workshops has focused on the requirements for assembling a Peta-flops system. His talk provided an overview of the HPCC organization with particular emphasis on the support of research directed at software development in support of the Peta-flops effort. He reviewed the state of the art in programming, explicit message passing and coarse grain messaging, OS tools and their marginal value, and discussed the available market (or lack thereof) and its implications.

Arun Somani discussed design and implementation of a coarse grain messaging passing-based computing and communication effort at the University of Washington and

the "PROTEUS" machine designed and built there. His talk mainly focused on difficulties in actually achieving performance and how they solved some of the problems by overlapping the computing and communication steps by proper scheduling of tasks. He also talked about the role of cache memory and the new modes that can help achieve higher performance.

Finally, Burton Smith presented his view on how architecture plays its role. He reviewed various system architectures and discussed memory latency techniques. Latency tolerance is "doing something else while you wait". Parallelism is clearly needed in some form. One can use:

1. Vector pipelining, given vectorizable inner loop parallelism

2. Long cache lines, given good spatial locality

3. Prefetching, given instruction-level parallelism

4. Multi-threading, given loop, task, or job parallelism.

He then explained how new TERA machines achieve latency tolerance. He also discussed performance inhibitors as discussed below, taking examples from structural analysis, circuits simulation, automobile crash simulation, and aircraft interior design. He listed several performance inhibitors:

1. VEC: incomplete vectorization (V)

2. LENGTH: short vector lengths(V)

3. PAR: incomplete parallelization (V,M)

4. SYNC: too-frequent synchronization (V,M)

6. SPACE: restricted memory space (V,M)

7. STRIDE: irregular or long-stride memory accesses (M)

8. REUSE: insufficient reuse of cached data (M)

9. COMM: inadequate interprocessor communications (M)

DISCUSSION AND CONCLUSION

At the end of the talks the following issues were identified and discussed.

1. How will the development of supporting technologies affect the Peta Flops?

2. Is latency the most important issue?

3. How do you come up with reasonable (problem) solutions with shrinking budgets?

4. How do you expand the market?

5. Performance Inhibitors for TERA.

6. Network Computing

7. Speculation on utilizing complexity

8. How for can we go?

9. Performance Inhibitor for multi-threading

A discussion followed. Some thoughts on role of networks of workstations and cluster-based computing were discussed. Most people felt that it was too difficult to program them, although a few stated that they were able to get reasonable performance at reasonable cost. Role of programmable cache memory was also brought up. Everyone agreed that: a) the market for high performance computing remains small; and b) tools and support are not adequate.

SESSION C4: VISUALIZATION

Thomas W. Crockett, ICASE

The participants in the visualization session featured four speakers from corporate R&D laboratories: Lawrence D. Bergman, IBM T. J. Watson Research Center; David Edwards, United Technologies Research Center; Gary Oberbrunner, Advanced Visual Systems; and William J. Schroeder, GE Corporate Research and Development. The session chairman also provided a brief overview of ICASE visualization and graphics research.

SUMMARY OF PRESENTATIONS:

"Visualization Activities at IBM Research", Lawrence Bergman

This presentation surveyed a number of projects which are underway at IBM's T. J. Watson Research Center. The IBM Visualization Data Explorer provides a visual programming environment and data-flow execution model for the construction of data visualization and analysis applications. It is capable of exploiting both inter-module (functional) and intra-module (data) parallelism. Modules support polymorphic data (multiple data types) and access data by reference for efficient execution and reduced memory consumption.

The Satellite Image Explorer is being developed to support content-based searching of digital image archives. It uses a multi-resolution progressive approach to enhance search speeds, allowing the user to specify matches at the level of pixels, features, or objects. Wavelet techniques are used to encode image data at multiple resolutions.

Diamond is an interactive tool for data mining applications. It is designed to facilitate the identification and display of statistical patterns within large multivariate datasets. Multiple linked views are dynamically updated in response to direct manipulation by the user. Diamond is available commercially from SPSS.

Another project is the development of compression techniques for geometric models. Compression ratios of 50:1 have been achieved on VRML 1.0 datasets, and this technology is being proposed as a standard binary representation for VRML 2.0.

Other projects include artifact removal and registration of medical images, automatic model simplification for interactive rendering of complex scenes, and a system for producing low-cost, real-time VR from 2D input images.

"pV3-Gold: Visualization Using Parallel Processing in a Co-Processing Mode", David Edwards

As part of NASA's Affordable High-Performance Computing Project, Pratt and Whitney is reducing the time required for CFD simulations by distributing applications across workstation networks. As simulation times come down, there is a corresponding need to improve the data analysis component. Towards this end, UTRC is adapting the pV3 visualization system (developed by Bob Haimes at MIT) to run as a co-processing task in conjunction with distributed applications. The central idea in pV3-Gold is to cull "data extracts" from the application and route them to the visualization system which is running at the user's desktop. pV3-Gold includes support for both unsteady and unstructured data, and is capable of operating in either batch or interactive mode. To support long-running applications, pV3-Gold has the ability to connect and disconnect from the application, allowing the user to monitor its progress periodically.

"MP/Express: A Parallel Visualization Environment", Gary Oberbrunner

MP/Express is a data-parallel extension of the AVS/Express application development system. AVS/Express enhances the visual programming/dataflow model of the AVS 5 visualization systems to provide a flexible, object-oriented environment which facilitates reuse of functional modules. As in IBM's Data Explorer, AVS/Express accesses data by reference, utilizing a "pull" model to reduce the amount of data which must be transferred between modules.

Currently a research project, MP/Express is being designed to exploit data parallelism within modules (in addition to functional parallelism between modules).

MP/Express is intended to run on a wide range of parallel architectures, including MPPs, SMPs, and clusters. For portability, it uses MPI to provide message-based communication among processes. A master-slave paradigm is used to organize the data parallel computations within the modular AVS/Express architecture.

"Visualization Research Topics at GE CRD", William Schroeder

General Electric's Corporate Research and Development laboratory is working on a variety of visualization-related projects. Areas of interest include medical imaging, scientific visualization, virtual reality, and modeling. Visualization and VR techniques are being applied to large industrial CAD databases in order to provide feedback about assembly and maintainability early in the design process. Modeling work is focussed on decimation techniques and implicit representation of surfaces using contouring algorithms.

CRD places a heavy emphasis on object-oriented software systems. An example of this is the "vtk" visualization toolkit, which contains 100,000 lines of C++ class libraries and another 75,000 lines of Tcl wrappers. The toolkit approach facilitates reusability, and the combination of compiled and interpreted languages provides both rapid development and high performance. "vtk" is freely available in source form, a strategy which CRD believes is more cost-effective than the development of equivalent proprietary tools.

"ICASE Visualization and Computer Graphics Research", Thomas W. Crockett

ICASE launched its visualization research activity in 1993 as a new initiative within the computer science program. The focus is on NASA applications, particularly those of relevance to Langley Research Center, with an emphasis on large, time-varying datasets and complex 3D problems. The visualization program builds on existing ICASE expertise in the areas of fluid mechanics and parallel and high-performance computing. A partial list of research topics includes vector-field, volume, and flow visualization; visualization methods for complex and unstructured grids; feature extraction; and parallel rendering.

Research results are disseminated through conference and journal publications, ICASE Reports, and focused workshops. ICASE organized and hosted the first Symposium on Visualizing Time-Varying Data, and ICASE scientists have been active in establishing and perpetuating the IEEE-CS/ACM-SIGGRAPH Parallel Rendering Symposium series.

ROUNDTABLE DISCUSSION

To stimulate the discussion, the session chairman posed the following questions:

- What do you see as fundamental research issues in visualization?

- What applications are difficult to visualize due to:

  * inadequate tools

  * inadequate techniques

  * inadequate computing or rendering power

- Is volume rendering useful for your applications? Why not?

- Visualization for parallel and distributed applications:

  * Is there a need?

  * How do you do it now?

  * How would you like to do it?

- Why isn't visual output routine? What should be done about it?

The ensuing discussion addressed these and other topics both directly and indirectly. Several suggestions emerged regarding the relatively slow pace at which visualization technology is being put into use. Part of the problem is simply educating and training potential users about what tools and techniques are available and how to apply them.

The lack of standardization is also perceived to be a contributing factor. While most programming languages have features to support text-based output, similar support for visual output is absent. Instead, a variety of vendor-specific visualization products are available, each with its own data representations and library and user interfaces.

It was pointed out that support for visualization is needed in more than just programming environments. CAD systems, databases, and a variety of other tools need to provide standard visualization tools in a consistent and integrated fashion.

Of course, the process of generating meaningful visual output is considerably more complex than that of generating ASCII text. There appears to be considerable potential for emerging technologies such as Java, CORBA, and VRML to contribute to the development of richer visualization environments. Cross-platform portability of visualization software would be of considerable value to developers as well as users. The development of 3D widgets, visualization plug-ins, and Java visualization classes would all tend to encourage the wider adoption of visualization technology.

SUGGESTED RESEARCH AREAS

The participants identified several areas which are ripe for further research. The problem of visualizing multivariate and high-dimensional data persists, despite ongoing efforts to develop effective techniques. Unstructured and irregular (topology-free) data also poses challenging problems. How do you impose useful topology on data which is sparse and/or irregularly sampled in space?

A related problem is 3D feature extraction. To what extent can this process be automated, and how do we validate our automated techniques? Feature extraction methods should be general and stable. Appropriate test suites need to be developed to ensure that feature extraction methods are robust across a range of applications.

Virtual reality is another area in which additional development is needed. The participants cited real-time collision detection and six-degree-of-freedom haptic interfaces as capabilities which would be particularly useful in industrial settings.

Other suggested research topics included volume rendering with adaptive data structures, data reduction techniques, and progressive visualization methods.

WORKSHOP TOPICS

No specific workshop topics were proposed during the course of the discussion. However, given NASA's interest in MDO, multivariate visualization might be a useful topic for a focused meeting. Feature extraction in 3D data is another possibility, and there appears to be some interest in a follow-on to the original ICASE Symposium on Visualizing Time-Varying Data. Although ICASE has little expertise in virtual reality, Langley's Data Visualization and Analysis Laboratory is developing some experience, and could be approached about co-sponsoring a VR workshop.

SESSION C5: WORKSTATION CLUSTER COMPUTING

David E. Keyes, Old Dominion University & ICASE

The ICASE/LaRC Second Industry Roundtable, October 7-9, 1996, in Williamsburg VA, devoted a morning session on Wednesday, October 9 to workstation cluster computing. It is summarized here for the purposes of:

- documenting examples of ways in which cluster computing has already matured as a technology, in hardware and software,

- highlighting two challenges to the acceptance and progress of cluster computing, namely remote credentialing and benchmarking, and

- providing some points of contact for future collaborative research between industry, academia, and ICASE.

PRESENTERS

There were four speakers, each of whom was invited to present material of their own choice for twenty minutes and then to guide group discussion for another ten minutes. These presentations were followed by forty-five minutes of open panel discussion.

Two of the speakers were from industry, one from NASA, and one from academia. The industrial speakers were "consumers" of cluster technology, and the other two were "providers" of some aspect of the technology.

In order of presentation, they were:

1. Sukumar Chakravarthy, Metacomp Technologies, Inc.

   SukumarCR@aol.com

   Parallel Computing Experiences with a Unified Grid CFD Code

   (joint credit with Oshin Peroomian of Metacomp)

2.	Frederic Lafon, Corporate Research Lab, Thomson-CSF

	lafon@thomson-lcr.fr

	Parallel Methods for Solving Large Electromagnetics Problems on Clusters of Workstations

3.	Michael Nelson, NASA Langley Research Center

	m.l.nelson@larc.nasa.gov

	Using DCE/DFS in a Production Workstation Cluster

4.	Kurt Maly, Computer Science Department, Old Dominion University

	maly@cs.odu.edu

	BTU: A Communication Benchmark

	(joint credit with Ajay Gupta and Satish Mynam of ODU)

SYNOPSES OF PRESENTATIONS

Chakravarthy described the design and implementation of CFD++, a Navier-Stokes CFD software suite that runs on various single-CPU and multiple-CPU platforms, including workstation clusters and various MPPs such as the IBM SP2, the Cray T3D, the SGI Power Challenge, and the Intel Paragon. In contrast with demonstration projects that streamline modeling capability in order to focus on communication and parallel computing aspects, CFD++ is a commercial-grade code with features such as generalized gridding, pointwise turbulence modeling, and multidimensional Essentially Non-Oscillatory (ENO) discretization of convection. Single-block, multi-block, and unstructured grids in patched-aligned, patched-nonaligned, and overset connectivities, made up of hexahedral, prismatic, and tetrahedral grid cells, are all accommodated. In three dimensions, approximately 30 double precision words are stored per grid point.

The decomposition of the flow domain and assignment to processors in CFD++ is static, with each cell owned and updated by exactly one workstation processor. The message-passing interface (MPI) is used to complete discretization stencils that straddle processor boundaries.

On MPPs with dedicated fast communication hardware, CFD++ performs with high parallel efficiency. Examples were furnished for fixed-size problems of moderate

size (10^5 gridpoints) of 93% efficiency (14.9 speedup on 16 nodes) on an SP2 and of 89% efficiency (7.1 speedup on 8 nodes) on a Power Challenge. Such performance is close to that of optimally balanced structured grid problems with explicit update schemes, and is obtained in a code with data structures that support versatile discretizations.

Lafon followed with a similar perspective on the Maxwell Equations, claiming that parallel computations are of practical interest today to industries under pressure to become more competitive in project development. The Corporate Research Laboratory of Thomson (the parent company of RCA), is implementing parallel solution strategies to deal with bigger and more complex problems --- nonlinear, coupled, and with multiple-scales --- that arise in high-fidelity physical models. Their computational resources are mainly heterogeneous clusters of workstations.

Problems from multiple disciplines are approached using a simple iterative coupling master/slave framework. A large spectrum of applications, ranging from antenna design to the optimization of optical components, requires that the software accommodate virtually any type of material properties and boundary conditions.

Like Metacomp, Thomson adopts a domain decomposition approach. Lafon discussed briefly the convergence of domain decomposition algorithms for electromagnetic problems and dynamic load balancing strategies.

He reported on an index called the "message-equivalent," the number of floating point operations required to exchange a message. The time required to exchange a message generally depends upon the message size (in Bytes) and is expressed in two-parameter form as the sum of a latency term and a term which is the product of message size and reciprocal bandwidth. Multiplying this time (for a typical message size) by the peak floating point rate of the CPU gives the message-equivalent, which ranges from 3 x 10^5 flops for a typical PDE-based cluster computation to a hundred times less for a tightly coupled MPP.

A case study was quoted for a fixed-size problem of approximately one-half million tetrahedra which ran on 16 Ethernetworked workstations with 77% parallel efficiency and on 32 workstations with 62% efficiency, employing the same preconditioned iterative method of choice for the serial case.

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Nelson turned the focus of the session from demonstration calculations to reliably and securely supporting engineering group workloads. The Integrated Computing Environment (ICE) project underway at the NASA Langley Research Center seeks to evaluate the potential of capturing latent, wasted workstation cycles without disrupting primary users. Workstations are more cost-effective than special-purpose parallel machines for mid-range facilities for several reasons. Among them: workstations are commodity products that do not require expensive maintenance contracts, workstation clusters avoid the expensive custom interconnect of a special purpose parallel machine, and workstation-based resources may be purchased and upgraded in steady increments that fit into level acquisition budgets and allow steady increase in computing capacity for constant dollars, rather than jerky jumps to the technology frontier followed by periods of gradual obsolescence.

Nelson emphasized, however, that workstations plus MPI or PVM do not, by themselves, a production cluster environment make. A network queuing system to schedule jobs onto the cluster and a load balancing facility to automatically allocate compute nodes to processes are also required. ICE has decided to build its system software environment on top of the distributed file service (DFS), which, in turn, requires the distributed computing environment (DCE) security features.

DCE's emphasis on security, availability, and hierarchical grouping of distributed resources provides the infrastructure needed to effectively manage distributed computers. Additionally, DFS provides a sophisticated file service that is secure, fault tolerant, supports load balancing, and provides a universally accessible canonical filespace so that distributed processes will be able to access file locations without concern as to which server the file actually resides upon. DCE/DFS is available or under development for all major implementations of Unix and Windows NT. Indeed, DCE/DFS promises to be a significant integration point for Unix and Windows NT.

Langley has both a homogeneous, dedicated, tightly coupled cluster for general production work, and a heterogeneous, loosely coupled part-time cluster for cycle reclamation. Though workstation clusters are widely used, DCE/DFS has not yet found

wide acceptance in the scientific computing environment. While DCE/DFS has great application for systems and file management, it is less mature than other Unix and cluster management facilities. In particular, DCE/DFS's emphasis on security prevents much of the remote execution that clustered systems utilize.

Nelson presented lessons learned including: migrating an installed user base to DCE/DFS; working around the credential forwarding/remote execution restriction; integrating DCE/DFS systems from multiple vendors; handling DCE/DFS interactions with non-DCE/DFS systems; performance tuning; and future plans to use DCE/DFS as a core technology for non-scientific computing initiatives.

Regarding performance, DCE/DFS is designed for scalability and efficiency. It has reduced system time by factors of 5 or more and wallclock time by factors of 3 or more, compared to the standard network file system (NFS), for out-of-core production runs of computational structures applications at NASA, with irregular sparse matrix computation as the main kernel. As a result of these improvements, DFS lags behind local disk out-of-core performance by a factor of no more than 2.

Maly introduced a novel benchmark suite, called "Bits To the User" (BTU) for measuring the communication performance of Unix workstations. Compared with extensive benchmarking available for different types of processor performance (floating point, integer, graphical rendering, etc.), communication is a relatively neglected area of performance benchmarking.

In the BTU benchmarking process, a vendor supplies a workstation running UNIX. The BTU program is installed and the workstation is connected to a testbed that emulates a LAN/WAN environment. The benchmark program submits the workstation to a carefully designed combination of tests. The result is a predictor of what a user, at the application level, can expect in terms of bits sent to or received from a remote host.

BTU takes into account concurrent activities, such as CPU and I/O activities, that compete for resources on the test machine. The combination of these activities and concurrent activities on the network interferes with the test machine's communication performance.

The automated BTU benchmark test suite produces results at various levels of abstraction ranging from a single number, characterizing geometrically averaged performance in the style of SPEC92, to a TCP time sequence chart for abnormal behaviors. Maly, et al. intend to serve the user community by providing information that should enable reasonable quantitative comparisons when in the process of acquiring a workstation with a specific configuration within certain cost constraints.

Maly presented aggregate and itemized BTU data for five workstations (a PC running Linux, a Sparc5 running SunOS 4.1.4, a Sparc5 running Solaris 2.3, a Sparc20 running Solaris 2.3, and an SGI Indy running IRIX 5.3) on five types of communication tasks (a telnet session, an ftp session, a netscape session, realtime audio, and realtime video). The actual performance in Mb/s and the relative rankings of the individual platforms vary considerably over the five communication tasks, except for the PC, which is fairly level at 2.75 Mb/s across the tasks, and is the best platform for audio and telnet.

Neither price nor SPECmarks are as good a predictor of communication performance as that measured by BTUs. When used along with existing benchmarks, BTU should complete a powerful combination for predicting overall performance.

SUMMARY OF DISCUSSION

The panel portion of the roundtable was initially dominated by strong reactions of the audience to the latter two talks, as the merits individual hardware and system software products were debated in the light of the unambiguously expressed preferences of the speakers.

Maly handled several questions on the effect of different LAN/WAN simulators as the BTU testbed. He agreed that the simulating the LAN/WAN communication load on a machine of identical architecture to the machine being tested might provide an advantage to the machine tested, but stated that the rankings of the tested machine remain independent of the testbed simulator. A matrix of rankings when each machine is tested by each other machine as the simulator would be a more complete way of presenting the (already complex) array of results.

In response to another question, Maly said that the WAN-based ranking correlates with the LAN-based.

It was suggested that the BTU test facility could serve as a network "weather" monitor as well as a benchmark, and thus be used as part of a network load allocation scheme. However, the overhead would be significant, and the results would not be long-lasting.

Security holes of DCE/DFS were debated.

To call the focus back to the practicality of cluster computing as a source of parallel cycles, Keyes quoted for the panel a selection of a longer list of questions that were debated at the October 1994 Industry Roundtable, namely:

1. Is a consensus emerging on the most useful programming paradigms (e.g., user-controlled message passing, global virtual address space, global associative memory)?

2. Will the message-passing interface (MPI) standard provide a long-awaited platform independence for distributed memory programs and blur the distinction of developing for clusters versus developing for MPPs?

3. What is the largest practically achievable parallel granularity for a nearest neighbor code, such as an explicit CFD code?

4. What is the largest practically achievable parallel granularity for a code with global operations, such as an implicit CFD code?

5. What is the median degree of parallelism desired by engineering users, from the point of view of data structures and programming convenience?

6. What are the social and human factor impediments to workplace cluster computing?

7. Why are some industries (e.g., automakers) still adding conventional supercomputing capacity at the same time others (e.g., engine manufacturers) are turning away from in-house support of a conventional supercomputer?

8. What provisions are being made in cluster computing environments for working with large-scale distributed data sets, in terms of archiving

distributed restarts, distributed data base inquiry, and real-time and post-processing visualization of distributed sets?

Chakravarthy ran through this set of questions for the panel.

He argued in favor of programming as close to the hardware as possible, using message-passing between physically distributed memories.

He said that MPI had not yet provided platform independence, but that MPI-2 probably would. [MPI-2 provides dynamic process creation and multiple threads, and should enable hybrid shared-distributed memory architectures to optimize communications for processes "exchanging" on-board data.]

In the production engineering environment, the number of nodes desired by and available to a particular user is generally less than the critical break-even number, beyond which execution time increases again. Processor allocation is based less in practice on optimizing the execution time than it is on garnering the memory needed.

Cultural factors and inertia induced by software support contracts are often more important than raw computational performance or price-per-performance in computer acquisition decisions.

Significant work is definitely needed to bring cluster computing environments up to the level of support provided by vendors of large unified systems. Indeed, a chief argument in favor of large centralized computing resources is the set of queuing, profiling, archiving, and I/O-related services that come with them. Commercial attention to providing such systems software for clusters has not been as great as the opportunity suggests, so far.

PROBLEMS FOR COLLABORATION

Time ran out before the industrial speakers could be polled for "pre-competitive" problems for collaborative research to be undertaken with ICASE/LaRC or with academia. To fulfill this portion of the write-up, we repeat some of the well thought-out answers obtained during at the 1994 Roundtable. There are echoes of some of these topics in the summaries above. Some of these are actively being pursued today by industry-laboratory or industry-academia project teams.

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1. Making cluster computing systems safe for owners: permitting rapid preemptiveness, insuring security, minimizing the possibility of crashes or deadlocks brought about by parallel applications gone awry, and prioritizing network traffic so that cluster jobs do not degrade remote file or remote host access during certain work periods.

2. Making cluster computing systems safe for users: facilitating migration of processes that are shut out on a preempted processor, monitoring distributed (perhaps migrating) jobs, user-directed checkpointing and automatic routine checkpointing for restart recovery, restart techniques and standards

3. Cluster computing tools: flexible process scheduling and mapping, parallel emulation, debugging and performance visualization tools, tools for working with distributed data sets.

4. Cluster computing on networks of multiple-CPU computers, including heterogeneous MPPs.

5. General algorithmic research motivated by the non-dedicated high-latency environment: useful paradigms for PDEs besides domain decomposition, chaotic relaxations, dependence of convergence rates on interprocessor update frequency, partitioning strategies (including adaptive solution-dependent schemes) that minimize communication needs, and dynamic repartitioning, implicit versus explicit methods.

6. General systems research motivated by the high-latency non-dedicated environment: multiple threads, prefetching, message bundling.

7. The use of parallel networks to cost-effectively and flexibly "grow" network capacity.

Not all of these projects would be appropriate for ICASE or NASA. Some would seem most appropriate for vendors; others, for systems software research in the abstract.

TOPICS FOR FUTURE WORKSHOPS

We remark that one suggestion for an ICASE workshop that arose at the 1994 Roundtable has been brought to fruition as of December 1996.

A "B.Y.O.C." Workshop for the Parallel Computation of PDEs:

User training in the message-passing software environment is required before important scientific and engineering codes are ported onto clusters. ICASE could sponsor a "bring-your-own-code" workshop, particularly focused on implicit methods, which are harder than explicit methods to effectively parallelize. Implicit methods are increasingly important in aerodynamics and other areas because envelope problems for which increased computer power is needed tend to have larger ranges of spatial and temporal scales than their quotidian counterparts. Recommended environments for ICASE to use and assist others in using are MPI and the Argonne National Lab Portable, Extensible Toolkit for Scientific Computing (PETSc).

SESSION D1: LAMINAR FLOW CONTROL

Ronald D. Joslin, NASA LaRC

SUMMARY

I was very pleased to see that the session was standing room only, with members from the senior management of NASA Langley Research Center and many U.S. industry managers and engineers.

The LFC session had 4 speakers/papers with one talk focusing on the flight testing of anti-insect coatings and 3 talks focusing on design tool development and validation.

Daryl Bonhaus (NASA LaRC): The talk focused on the validation or calibration of a CFD generated mean-flow solver (USM3D) by comparing surface pressure calculations with measurements on the Boeing 757 Hybrid Laminar Flow Control flight experiment. The comparison of flight and computed results indicated that with careful attention to the grid placement and resolution, a good match with the experiments can be obtained. No boundary-layer calculations were reported during the talk. Mr. Bonhaus noted that refinement of the inviscid mesh led to the most significant improvement in the comparison. Questions/comments from the audience included: (1) how would we use the tool for prediction? (2) results emphasized the need for self-adaptive techniques, (3) how good was the match in the attachment-line region?

Jeff Crouch (BCAG): The talk focused on the application of LFC design tools (specifically transition prediction) to LFC, high-lift, and nacelle issues. For LFC, the issue of determining cost of the technology (including operations) versus value (return/benefit) was discussed. In estimating the value, an accurate determination of the laminar flow region (transition location) is very important. Conclusions indicate that the tools need more of the process flow physics in the tools/models. Fundamental to this issue is the need to characterize the receptivity (ingestion of the flow instability into the boundary-layer flow) and validate the prediction of these predictions with NEEDED experimental data.

Don Dietrich (GEAE): The talk focused on the history of the anti-insect coatings in relation to the interests of GEAE for nacelle applications. Successful hybrid laminar flow control (HLFC) wind-tunnel and flight experiments were highlighted. Some of the wind-tunnel experiments carried out at GE were found to be successful. The flight test revealed a need for anti-insect technologies (like coatings). A flight test cooperatively performed by GE and NASA is scheduled for November 1996 to test some of the coatings effectiveness in preventing insect accumulation.

Mujeeb Malik (HTC): The talk focused on the future of LFC design tools. The predictive capability and operational cost of the available tools were discussed. Linear stability theory (N-factor, Parabolized Stability Equations theory, receptivity tools, linear Navier-Stokes solvers, and direct numerical simulation solvers were described in relation to their predictive capability for the unsteady viscous flow. A key question as to the composition of the disturbance forcing was raised.

FUTURE RESEARCH DIRECTIONS

    (1) Need for self-adaptive techniques for design tools.
    (2) Need advanced transition prediction capability (enhanced tools).
    (3) Need fundamental experimental data for validation of tools which predict
         the composition of disturbances entering boundary-layer and causing
         the breakdown of laminar flow.
    (4) Need concepts to address insect accumulation problem for laminar flow.

SESSION D2: ACTIVE FLOW CONTROL

Richard Wlezien, NASA LaRC

SUMMARY OF PRESENTATIONS

A series of four presentations highlighted a range of ongoing activities for the active control of unsteady flows. Valdis Kibens and Linda Kral of McDonnell Douglas Aerospace discussed new horizons in active flow control at McDonnell Douglas. With affordability being a driving focus for the aerospace industry, one might initially question the desirability of introducing the added complexity and cost of active flow control technology. The objection would be valid if such introduction would simply replace passive devices with active ones having the same function. However, if one develops active flow control devices that can enable optimized performance at multiple design points, significantly enhance survivability, enable multiple or new missions, or simplify manufacturing and maintenance, one can demonstrate not only enhanced performance but also system-level gains in affordability. Affordability can be achieved by using this advanced technology to enable improvements and derivatives of existing products.

They provided an overview of active flow control at McDonnell Douglas not only from a technical standpoint but also from a technology development perspective. Current active flow control activities span a broad range of propulsion and aerodynamic applications. These include mixing enhancement and thrust vectoring for control of engine exhaust flows. On the aerodynamic side, synthetic jet aerodynamic control, micro-blowing for forebody vortex control, and smart structures for active shape control are promising technologies being developed. Highlights of innovative applications of active flow control to non-traditional aerospace applications were also presented.

From a technical standpoint, active flow control typically involves leveraging flow phenomena to amplify the control authority of small but intelligent control devices. From a technology development perspective, effectiveness in developing active flow control concepts requires teaming across organizations and disciplines.

Lou Cattafesta, Sanjay Garg, and John Won of High Technology Corporation discussed the application of active control to flow-induced cavity oscillations. The

interaction between a cavity and the shear layer spanning the cavity can result in the generation of high levels of tonal acoustic disturbances. The excitation and growth of instabilities in the shear layer are a fundamental part of this phenomenon. Control of such shear layer instabilities at low Mach number was attempted in a resonant cavity flow by actuating piezoelectric flaps at the leading edge of the cavity. Under natural flow conditions, a sound pressure level (SPL) of 140 dB was measured on the cavity floor; use of the actuators in an open-loop mode resulted in a 12 dB reduction in overall SPL. In addition, the magnitude of the primary tone was attenuated by almost 25 dB. The mean flow profiles change from that of a turbulent boundary layer at separation to one representative of a self-similar shear layer further downstream; this exerts significant influence on the development of the measured profile. An initial region of exponential growth is observed followed by a region in which nonlinear effects become important resulting in finite amplitude equilibration of disturbances. In the controlled case, nonlinear mode competition appears to determine the overall amplification experienced by any one mode.

Richard Wlezien presented an overview of active flow control research at NASA Langley Research Center. Performance improvements in airframe systems have historically been accomplished passively (for example by pressure gradient shaping, winglets, or vortex generators). The rapid evolution of advanced materials and microelectronics opens new opportunities for the application of active systems for airframe performance improvement. Current research activities are focused on flow separation control, dynamic load alleviation, drag reduction, aerodynamic force generation, and noise reduction. The goal of the Langley program is to move flow control out of the laboratory and onto flight vehicles. Novel actuation methods, sensor arrays, and control system technologies are currently in development.

Nagi Mansour and Petros Koumoutsakos of NASA Ames Research Center presented a numerical simulation study of active vortex generators. Vortex generators are generally used to modify the inner part of the boundary layer or to control separation, thus enhancing the performance and maneuverability of aerodynamic configurations. They considered generators consisting of a surface cavity elongated in the streamwise direction

and partially covered with a moving lid that at rest lies flush with the boundary. Streamwise vorticity is generated and ejected due to the oscillatory motion of the lid.

The simulations complemented experimental investigations of active vortex generators that have been conducted by Saddoughi (1994), Jacobson and Reynolds (1993), and Lachowicz and Wlezien (1996). They simulate the flows generated by these devices and are conducting a parametric study that helps elucidate the physical mechanisms present in the flow. Conventional computational schemes encounter difficulties when simulating flows around complex configurations undergoing arbitrary motions. They presented a formulation that achieves this task on a purely Lagrangian frame by extending the formulation presented by Koumoutsakos, Leonard and Pepin (1994).

SUMMARY OF ROUNDTABLE DISCUSSIONS

The control of viscous flows for airframe performance improvement is at first glance a highly innovative concept, but has been practiced in one form or another over the history of aircraft design. One might argue that the camber control used in the Wright Flyer was an early form of viscous flow control, in which attached flow was maintained to higher lift levels by actively warping the wing. Vortex generators, pressure gradient shaping, and programmed devices such as slats and flaps are commonplace on modern transport aircraft.

The limitation on applying flow control to aircraft aerodynamics is not the range of flow phenomena that can be influenced. Physical concepts already exist for flow separation control, viscous drag reduction, control of shock boundary interactions, three-dimensional separated flows, noise-generating shear flows, and transition to turbulence. The present limitation exists in the devices that can be used to effectively influence viscous flows for net performance improvement.

Innovative new airframe concepts such as the blended wing body will need innovative new approaches to drag reduction, noise reduction, and flow separation control. The aerodynamic equivalent of integrated electronics is required for quantum advances to occur in aircraft performance and economics. Highly reliable integrated

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systems which are capable of passively or actively modifying shear flows, which autonomously activate in flight regimes and airframe locations when they are needed, and which revert to passive states with no adverse performance penalty are the target of much present day flow control research.

Passive flow control has found its way onto conventional aircraft in many forms. Vortex generators are commonly used for separation and lift control, and often appear when problems arise in the management of viscous flows. Rows of small devices appear on the wings of modern transport aircraft. The negative aspect of passive devices is that a performance penalty can occur in flow regimes for which the devices are not directly required. The cruise drag penalty is generally accepted as a "tax" for simplicity. Recent advances in developing sizing relationships have optimized the impact of these devices relative to any accompanying performance penalties.

System robustness is paramount for any active flow control system to make its way onto production aircraft systems. Maintenance, reliability, and reparability are first order issues for airframe applications. An active system must be able to degrade and fail gracefully. This is particularly true for distributed systems, where massive replication can compensate for the loss of individual flow control elements.

The roundtable discussion often became entwined in the strong philosophical arguments that are prompted by the consideration of radical new technologies. Application engineers do not see a near-term need for these technologies, and in some sense regard them as a solution without a problem. The point was made that a poor track record exists for transitioning advanced technologies to applications. It is not clear whether this is an issue for the researcher, the technologist, or the applications engineer. One must also consider the "carrot" that these new technologies offer.

A similar case can be made with respect to the integration of microprocessor technologies into critical control functions, for example in automotive applications. In the 1950's it would have been preposterous to consider the application of vacuum tube processor technology to transport vehicles. In the 60's the advent of the minicomputer offered laboratory-scale demonstrations of technology applications. In the 70's, the microprocessor offered the promise of onboard controllers, although system robustness

severely limited the application of these systems. It was not until the advances of the 80's that the application of microprocessors became a realistic consideration. However in the 90's the microcontrollers are commonplace and so affordable that systems cannot be cost-effectively designed without them. We must be careful to learn from these examples when stamping advanced technologies as non-feasible.

GENERAL RESEARCH AREAS / TOPICS FOR SUMMER SESSIONS AT ICASE

- Generalized approaches to flow actuation, including response to moving boundaries, unsteady injection and unsteady suction
- Low order models of unsteady flows, including separating flows, free shear flows, flows interacting with boundaries, and transitional flows
- Control algorithms for closed-loop flow control
- Multidisciplinary modeling of actuator, flow, sensor, and control systems
- Flow control Reynolds number scaling issues
- Optimal control of flows using discrete actuators and sensors
- On-surface sensing and its relationship to unsteady flow characteristics
- Concepts for advanced smart and actuated structures
- Integration of actuation, sensing, and control electronics into composite structures
- The role of micro-actuation and micro-fabrication in the active control of flows

ICASE

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

The Institute conducts an unclassified basic research program in three major areas: i) applied and numerical mathematics, including numerical analysis and algorithm development; ii) theoretical and computational research in fluid mechanics and acoustics in areas of interest to LaRC; iii) applied computer science and parallel computing.

The Institute helps promote cooperative research activities among scientists and their institutions, and in addition, enhances communication among researchers in related disciplines by providing an academic setting within which academic and industrial scientists can collaborate with NASA scientists and engineers on problems of mutual interest.

The Institute serves as NASA's gateway to a large pool of prominent scientists from major universities. During the last year about 100 researchers from 88 universities visited ICASE. Individual stays range from a few days to a full year; typical activities include formal and informal seminars, workshops, and interaction with NASA scientists. In addition, ICASE has approximately 24 staff scientists. The synergy between scientists from ICASE, NASA, and academia advantageously positions ICASE for dealing with multidisciplinary problems. An opportunity now exists for interested industries to utilize the synergy of this group to conduct fundamental research of economic importance.

ICASE's vision of industrial cooperation is that it serve as a focal point where ICASE affiliates make industrial representatives aware of on-going research interests and talents, while industrial representatives share fundamental pre-competitive problems. The goal is for industrial input to spark interest and help guide ICASE affiliates in the selection and formulation of problems they choose to attack. ICASE welcomes extended visits (e.g., sabbaticals) by industrial representatives.

ICASE benefits from the experimental and computational facilities and resources available at Langley Research Center and the Numerical Aerodynamic Simulation (NAS) facility. Of particular importance are the extensive scientific computing facilities which include machines of advanced and novel architectures, e.g., IBM SP-2 and SGI Power Challenge. To complement these facilities, ICASE operates its own network of SUN and Silicon Graphics workstations.

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The second ICASE/LaRC Industry Roundtable was held October 7-9, 1996 at the Williamsburg Hospitality House, Williamsburg, Virginia. Like the first roundtable in 1994, this meeting had two objectives: (i) to expose ICASE and LaRC scientists to industrial research agendas, and (ii) to acquaint industry with the capabilities and technology available at ICASE, LaRC and academic partners of ICASE. Nineteen sessions were held in three parallel tracks. Of the 170 participants, over one third were affiliated with various industries. Proceedings from the different sessions are summarized in this report.

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