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**Naval Postgraduate School**
Monterey, California 93943-5138

# *SUMMARY OF RESEARCH 1998*

## Department of Mechanical Engineering

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**Chair**

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Prepared for: Naval Postgraduate School
Monterey, CA 93943-5000

**NAVAL POSTGRADUATE SCHOOL**
**Monterey, California**

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This report contains summaries of research projects in the Department of Mechanical Engineering. A list of recent publications is also included which consists of conference presentations and publications, books, contributions to books, published journal papers, technical reports, and thesis abstracts.

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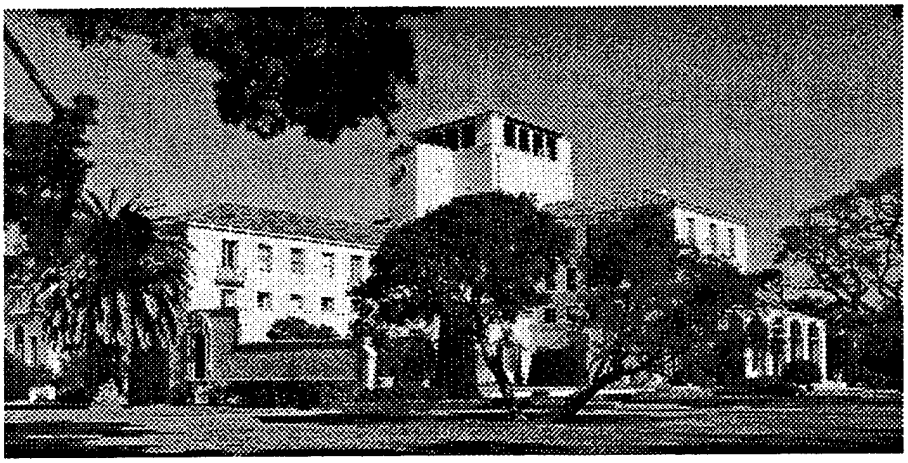
# DEPARTMENT OF MECHANICAL ENGINEERING

**Terry R. McNelley**
**Chair**

## THE NAVAL POSTGRADUATE SCHOOL MISSION

The mission of the Naval Postgraduate School is to increase the combat effectiveness of U.S. and Allied armed forces and enhance the security of the USA through advanced education and research programs focused on the technical, analytical, and managerial tools needed to confront defense-related challenges.



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## PREFACE

Research at the Naval Postgraduate School is carried out by faculty in the School's eleven academic departments, seven interdisciplinary groups, and the School of Aviation Safety. This volume contains research summaries for the projects undertaken by faculty in the Department of Mechanical Engineering during 1998. Also included is an overview of the department, faculty listing, a compilation of publications/presentations, and abstracts from theses directed by the department faculty.

Questions about particular projects may be directed to the faculty Principal Investigator listed, the Department Chair, or the Department Associate Chair for Research. Questions may also be directed to the Office of the Associate Provost and Dean of Research. General questions about the NPS Research Program should be directed to the Office of the Associate Provost and Dean of Research at (831) 656-2099 (voice) or research@nps.navy.mil (e-mail). Additional information is also available at the RESEARCH AT NPS website, http://web.nps.navy.mil~code09/.

## INTRODUCTION

The research program at the Naval Postgraduate School exits to support the graduate education of our students. It does so by providing militarily relevant thesis topics that address issues from the current needs of the Fleet and Joint Forces to the science and technology that is required to sustain the long-term superiority of the Navy/DoD. It keeps our faculty current on Navy/DoD issues, permitting them to maintain the content of the upper division courses at the cutting edge of their disciplines. At the same time, the students and faculty together provide a very unique capability within the DoD for addressing warfighting problems. This capability is especially important at the present time when technology in general, and information operations in particular, are changing rapidly. Our officers must be able to think innovatively and have the knowledge and skills that will let them apply technologies that are being rapidly developed in both the commercial and military sectors. Their unique knowledge of the operational Navy, when combined with a challenging thesis project that requires them to apply their focussed graduate education, is one of the most effective methods for both solving Fleet problems and instilling the life-long capability for applying basic principles to the creative solution of complex problems.

The research program at NPS consists of both reimbursable (sponsored) and institutionally funded research. The research varies from very fundamental to very applied, from unclassified to all levels of classification.

- Reimbursable (Sponsored) Program: This program includes those projects externally funded on the basis of proposals submitted to outside sponsors by the School's faculty. These funds allow the faculty to interact closely with RDT&E program managers and high-level policymakers throughout the Navy, DoD, and other government agencies as well as with the private sector in defense-related technologies. The sponsored program utilizes Cooperative Research and Development Agreements (CRADAs) with private industry, participates in consortia with other government laboratories and universities, provides off-campus courses either on-site at the recipient command or by VTC, and provides short courses for technology updates.

- NPS Institutionally Funded Research Program (NIFR): The institutionally funded research program has several purposes: (1) to provide the initial support required for new faculty to establish a Navy/DoD relevant research area, (2) to provide support for major new initiatives that address near-term Fleet and OPNAV needs, (3) to enhance productive research that is reimbursable sponsored, (4) to contribute to the recapitalization of major scientific equipment, and (5) to cost-share the support of a strong post-doctoral program.

- Institute for Joint Warfare Analysis (IJWA) Program: The IJWA Program provides funding to stimulate innovative research ideas with a strong emphasis on joint, interdisciplinary areas. This funding ensures that joint relevance is a consideration of research faculty.

In 1998 the overall level of research effort at NPS was 145 faculty workyears and exceeded $35 million. The Department of Mechanical Engineering's effort was 8.82 faculty workyears and exceeded $1.7 million. The sponsored research program has grown steadily to provide the faculty and staff support that is required to sustain a strong and viable graduate school in times of reduced budgets. In FY98, over 81% percent of the NPS research program was externally supported. In the Department of Mechanical Engineering 90% was externally supported.

The department's research sponsorship in FY98 is provided in Figure 1.

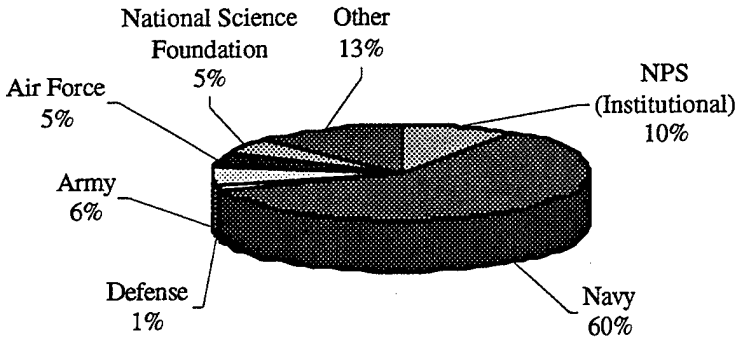


Figure 1. FY98 Sponsor Profile of the Department of Mechanical Engineering

These are both challenging and exciting times at NPS and the research program exists to help ensure that we remain unique in our ability to provide graduate education for the warfighter.

DAVID W. NETZER
Associate Provost and Dean of Research

October 1999

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## DEPARTMENT SUMMARY

The Mechanical Engineering Department's research activities are distributed mainly among five distinct areas of the discipline: the thermal/fluid sciences; solid mechanics, shock and vibration; dynamic systems and controls; materials science; and total ship systems engineering. Most of the efforts are individual investigator programs, although the emphasis on interdisciplinary programs is increasing. Relevance to the needs of the Navy and DoD is a theme in all programs. Results are usually disseminated initially in student theses and NPS Technical Reports. Results are also more widely published in both written and oral presentations at various national and international conferences, as well as in papers in various scientific and engineering journals. The programs associated with each faculty member are described in the following overviews, which are arranged to correspond to the main discipline areas of the Department.

**Fluid Dynamics, Heat Transfer and Turbomachinery**

TURGUT SARPKAYA, Distinguished Professor

In 1998, Professor Sarpkaya directed four research projects, sponsored by NASA, NSF, and ONR.

THE NASA PROJECT is a *continuing* basic and applied research towards the understanding of the phenomena associated with the motion of trailing of vortices of large aircraft. Its purpose is to alleviate the wake-vortex hazard posed to following aircraft and for decreasing the time-separation between the two landings to increase airport capacity. This research has so far led to the creation of a physics-based turbulence decay model. It is now being verified through the use of field data obtained at major airports.

THE FIRST ONR PROJECT is a *continuing* investigation to perform combined analytical, numerical, physical, and thought experiments to devise a physics-based model for the prediction of flow-induced unsteady forces on bluff bodies immersed in time-dependent flows. The new model, based on a sounder scientific rational, is expected to replace the current models and offer greater universality and higher engineering reliability, particularly in the so-called drag-inertia regime.

THE SECOND ONR PROJECT is a *continuing* investigation of the spray generation from bow-sheets. A series of new experiments have been designed to understand the influence of several competing internal/external influences such as turbulence, gravity, surface tension, liquid-sheet geometry, surface shear, roughness of the contact surfaces, velocity distribution in the sheet, and pressure fluctuations within and outside the sheet to understand, model and predict droplet and spray formation. The technological importance (IR signatures) and intellectual challenges (stability of a two phase flow) presented by this non-trivial flow phenomena demand a scientific understanding of its physics through judiciously conceived physical experiments and numerical analyses which are now underway with both free and wall jets.

THE NSF PROJECT is a *continuing* fundamental research towards the understanding of the characteristics of the conical vortex breakdown discovered by this writer. Trailing vortices, swirling flows in pipes, vortical flows above sweptback wings at large angles-of-attack, flows in closed containers with a rotating lid, and columnar vortices in atmosphere may experience breakdown. Where, how, and under what circumstances does this transformation occur in *viscous* vortical flows constitute the essence of the breakdown problem.

The foregoing four *continuing* sponsored fundamental/applied research projects resulted in numerous journal papers, conference papers, conference presentations, two Ph.D. dissertations and two M.S. theses.

MATTHEW D. KELLEHER, Professor

Professor Kelleher has been continuing studies to model the propagation of fire and smoke in compartments and passageways of surface combatant ships. Detailed computational fluid dynamics models are being used to determine the effects on the missile of fire in the vicinity of and within the missile magazines. It is very important that an understanding of the propagation of fires in the various missile magazines be developed and that some means be developed to apply that under-

standing to the design of future combatants and to the development of fire fighting procedures. The thermal effects in the Concentric Cannister Launcher due to a fire in an adjacent compartment have been simulated using computational fluid dynamics. A commercial code developed by CFD Research Corporation (CFDRC) has been used to implement the process.

Professor Kelleher has also recently begun work to apply optimization techniques to the design of surface combatants. This study has coupled the MIT Ship Synthesis Model (written in MATHCAD) to the optimization module within MATHCAD. This has provided results for ship designs optimized for a minimum displacement function. This work will continue with efforts to develop optimal designs based on other objectives such as minimum cost.

ASHOK GOPINATH, Assistant Professor

Asistant Professor Gopinath has been conducting research in "Time-Averaged Thermo-Fluid Phenomena induced by Strong Acoustic Fields" as part of an ongoing program on thermoacoustic transport sponsored by two grants from the NASA Microgravity Program. The goal is to obtain a better understanding and quantify the thermoacoustic behavior in strong zero-mean oscillatory flows with potential application to the design of heat exchangers in thermoacoustic engines. Much fundamental insight has been gained into the role of various properties and parameters in the flow using analytical means. With relevance to thermoacoustic engine design, this has helped deduce optimal stack spacing and location that would maximize the performance of such engines.

Also, during CY-98, an experimental project was carried out to explore the use of a standing wave acoustic field in a high-pressure gas to simulate the hydrodynamic wave loading on an offshore structure. Data gathered for lift and drag forces on a cylinder under such loading conditions corroborate well with existing data in the literature. The technique appears to hold promise for future testing under larger values of the parameter regime, and a patent application for the technique is being prepared.

In addition unsponsored research on the role of intergranular liquid phase on the ability to achieve superplastic-like deformation in covalent ceramic materials is being explored in collaboration with departmental colleague Prof. I. Dutta. The study looks into the fundamental issue of the ability of such liquids to support tensile forces, and the eventual modes of failure.

KNOX T. MILLSAPS, Assistant Professor

A method for determining a Diesel engines cylinder firing pressures, based on instantaneous output shaft speed was developed. A high-fidelity torsional engine model was developed and calibrated for a 3-cylinder, 2-stroke Diesel engine. Experimental measurements of near instantaneous speed fluctuations from this engine were made and good agreement was found between the measurements and the model over a range of speeds and applied torques. A new method for representing the speed fluctuations using integrated deviation from a constant speed shaft phasor was developed. This method is effective in identifying cylinders with low firing pressures. An efficient method for determining the periodic motion of a crankshaft based on dynamic finite elements, which requires less than 1% of the computational resources of a time-marching "shooting" method was developed and verified.

An analytical and experimental research program into enhanced mixing technology for gas turbine exhausts for surface ship, IR signature suppression is being conducted. Methods to increase secondary flow into mixing eductors (ejectors) and hence reduce the mixed-out plume temperature are being investigated. Multiple high aspect ratio slot primary nozzles are being investigated along with enhanced axial vorticity generated by lobed mixing nozzles. A 1-D lumped parameter model was developed and used to obtain preliminary designs for enhanced mixing eductors for signature suppression. These enhanced designs were verified in a 1/5 scale cold flow facility.

**Solid Mechanics, Shock and Vibration**

YOUNG S. SHIN, Professor

Professor Shin has continued his investigation of "Response of Naval Structures to Underwater Explosion" under the sponsorship of the Naval Sea Systems Command (NAVSEA), and Naval Postgraduate School. Modeling and surface ship shock simulation of DDG-53 has been conducted. This task is a part of team project consisting of NAVSEA, NSWC, Electric Boat, Weidlinger Associates, Gibs & Cox, and NPS. The task includes investigating whether the ship shock modeling and simulation can predict the dynamic transient responses of ship system and subsystem structures accurately. The analysis takes into accounts of the effects of the fluid-ship structure interaction and cavitation effects on a surface ship model(DDG-53) due to a large scale underwater explosion.

Professor Shin has also been conducting an additional research project, "Survivability of Shipboard Personnel Subjected to High Amplitude, Low Frequency Shock Induced By Underwater Explosion." In an effort to develop a method for estimating crew survivability to a given underwater explosion event, biodynamic simulations of human response to shock induced deck excitation were performed for both male and female subjects using the Articulated Total Body (ATB) program. Subsequently, the results were used to estimate the biodynamic response and injury potentials for human males and females in various positions in a vessel to an underwater explosion event.

YOUNG W. KWON, Associate Professor

The first sponsored research was about the damage and crack study in solid rocket propellant. The Air Force Laboratory and the Naval Postgraduate School as cost sharing supported this work. This was a continuing research project from past years during which a numerical modeling and simulation technique had been developed and evaluated against experimental results. The developed method was called a micro/macro approach. The last year's effort was to investigate the effects of specimen thickness on the crack tip behavior including onset of crack propagation. A three-dimensional finite element analysis was conducted for the macrolevel analysis. Results showed that damage saturation (i.e. the on set of crack propagation) occurred at the same applied strain level for both thick and thin specimens. For the thick specimens, the damage saturation was uniform more than 90 percent of the thickness. Thus, uniform crack propagation through the thickness was predicted and observed for thick specimens. The short crack had a long delay (about 100 percent larger applied strain) in damage initiation than the long crack, but the damage growth rate in the long crack was about 15 percent greater than the short crack. The slower damage growth in the short crack resulted in the higher maximum stress in the loading direction. At the onset of damage saturation, the longer crack had more damage concentration around the crack tip.

The second project was also a continuing effort from the previous year. It was about development of a robust, higher-order shell element with pressure variation through the shell thickness. It was funded by the Naval Surface Warfare Center. During the project period, a shell element including both transverse shear and normal deformations was developed and the Gurson constitutive model for void growth with plastic deformation was also implemented into the shell element for transient analysis using the central time integration scheme. An algorithm for stable time solutions for the void model was developed and hourglass model control was implemented caused by under-integration. Various examples were analyzed to check the accuracy and the efficiency of the element.

The last project was a biomechanical study of the human injury exposed impact loading. A computer simulation model was developed and validated using some experimental data. Three kinds of studies were conducted. The first one investigated the head and neck injury of a solider with a helmet impacted by a bullet at different angle. The second study evaluated the effectiveness of countermine boots against AP mine explosion. Finally, the last study investigated possible injury of a solider in a HUMVEE vehicle when the vehicle drove on a land mine. The biomechanical responses of the human were predicted under each different impact condition and they were assessed using available injury criteria. The study showed that there was a great chance of injury of the human body, which varied depending on the loading conditions.

JOSHUA GORDIS, Associate Professor

Associate Professor Joshua H. Gordis of the Department of Mechanical Engineering is conducting research in several areas in structural dynamics, vibration, and acoustics. In structural synthesis, a family of analytic methods have been developed which allow the direct calculation of modified dynamic response of structural dynamic system computer models which have been arbitrarily modified and/or combined with other models. These methods are distinguished by their ability to treat modifications of arbitrary size, distribution and damping, and that the methods provide a highly efficient and exact solution in all cases, where the synthesis is independent of model size. The time domain synthesis formulation is recently been extended to address local nonlinearities in large linear systems. The formulation provides an order of magnitude reduction in the time required to solve large, locally nonlinear structural dynamics problems. The nonlinear synthesis theory is being applied to the optimal design of seismic isolation.
Research is also being performed in structural system identification, where deficiencies in math models are identified through the use of measured dynamic response data. Recent results here include the identification of an non-standard set of eigenvalues which provide a additional, independent data with which to tackle the underdetermined system identification problem. The system identification methods are being applied in the area of structural damage detection, which seeks to uncover structural damage in components using measured dynamic response data.

Research and development continues in the structural dynamic analysis of the Boeing-Sikorsky RAH-66 Comanche helicopter. Working with two additional faculty members, identification of random airloads on the Comanche empennage was performed using a combination of flight test data and finite element modeling.

**Dynamic Systems, Controls and Robotics**

ANTHONY H. HEALEY, Professor

Professor Healey was active in furthering the technology of Autonomous Underwater Vehicles and land based robot systems for minefield and unexploded ordnance clearance. In particular, the ***Center for Autonomous Underwater Vehicle Research,*** directed by Professor Healey, has facilities that include the AUV laboratory in Building 230. In late 1997, a major advance was made towards performing the first experimental operation in open water outside the Monterey Harbor in the Monterey Bay. This work continued during 1998 with major software developments being performed including the purchase and networked integration of a Pentium based processor running the QNX operating system in the Phoenix vehicle. The AUV has been equipped with a 900 MHz. Radio modem for communications between shore and vehicle when surfaced. The vehicle has a new propulsion system using two 1/4 horsepower DC brushless motors and larger propellers giving an expected forward speed of 3-4 knots when submerged. Reconnaissance operations in the Monterey Bay have been conducted with the use of imaging sonar and a newly purchased acoustic doppler velocimeter (ADV) to combine with a bottom locked acoustic doppler navigator for ground speed sensing and dead-reckoning navigation. Contributions have been made to the compensation of magnetic compass bias errors using extended kalman filtering.

International visitors to the Center included Professor Antonio Pascoal, and his doctoral student Carlos Silvestri from the University of Lisbon in Portugal. Professor Pascoal spent his sabbatical year in the Center. Three French students spent their 6-month advanced training in the Center and studied the use of the Lon-Works operating system for system data acquisition and distributed control networking. Working with Professor Pascoal, significant work has been accomplished in optimum design of controls configured vehicle design, and research has shown that compensation and even cancellation of wave motions induced by wave action could be feasible, if proper measurement of wave velocities becomes practical.

A major new program was begun in late 1998 with ONR funding to participate in the AUVFEST 98 demonstration in the Gulf of Mexico in November 1998. We mobilized the Phoenix vehicle and its support equipment for deployment off the R/V Gyre. This successful ocean experiment verified that 3 hour duration runs could be made, and most importantly, that ocean direction wave spectra and short term current data could be obtained from a moving AUV. The program is supported by NICOP funds to join with Professor Pascoal in Lisbon in a joint vent survey mission which will involve multi-vehicle coordination control.

## DEPARTMENT SUMMARY

Continued work to develop software for the Navy's 21 UUV Tactical Size Vehicle that will automatically detect control subsystem faults and make appropriate control reconfiguration actions was undertaken. This program also focuses on fault tolerant control architectures and in particular studying the vehicle motion control in very shallow waters with wave conditions. Robust observer designs are being studied for error generation in the detection of actuator and sensor faults. It has been shown that fin faults can be reliably detected by roll system observers and likelihood function processing.

During this year, the final steps in the studies of BUGS were made to simulate the cooperative behavior between a high resolution, fast, detection robot, and a fleet of low resolution robots in UXO clearance operations. This work has led to the development of a new ONR funded program to study modeling and simulation tools for evaluating multi-robot cooperation in reconnaissance of VSW minefields.

MORRIS DRIELS, Professor

Professor Driels' research focused on the following research areas:

TARGET ACQUISITION MODEL EVALUATION: The Handbook is intended to support the Target Acquisition Models Library under development by Australia, Britain, Canada and America (ABCA). The library will research, collate and document target acquisition models available to modelers so that the selection of a specific model for a particular combat simulation is enhanced. This work completes release 1.1 of the Handbook, summarizing and documents seven of the most widely used models.

TARGET ACQUISITION MODULE UPDATE: A stand-alone module was developed in FY97 and validated against data and other sources. In FY98, this program was interfaced with the JAWS database, and included in JAWS version 2.0, due for release in 1999. In transitioning from an analyst's model to a user model, the inputs were made more operationally relevant, and data imported directly from the weaponeering part of the program. This research program is on-going, and will be extended into FY99. The planned work will be to complete the integration of the current TA module into JAWS, and extend it to cover FLIR sensors.

A/S and S/S TARGET ACQUISITION METHODOLOGIES: This program uses target imagery, and a DTED terrain data base to define local natural features in the vicinity of a specific target which will be attacked by aircraft. Cultural features are then raised up from the terrain to provide detailed masking contours, based on the approach angle and altitude of the attacking aircraft. The user then types in data regarding the weapon to be used and the program generates release conditions for the attack. In addition, a perspective view allows pilots to visualize the target area at a user-specified range.

IMPLEMENTATION OF THE DELPHI TARGET ACQUISITION MODEL: Previous work in FY97 laid the theoretical basis for the foveal component of a visual performance model based on proprietary work in the UK. This phase of the work completed the development of the model and allowed it to be compared to the US Acquire model. In addition, work was done on the peripheral channel, allowing the development of a search component.

REVIEW OF DELIVERY ACCURACY METHODOLOGY: The standard methodologies used to determine statistical descriptions of weapon accuracy was applied to a new class of GPS/INS guided weapon. Using field data, the accuracy was described in a manner allowing it to be included into the Joint Air to surface Weaponeering System JAWS. In doing so several issues regarding the methodology were highlighted, and improvements made. This work will be continued into FY99.

SCALABLE SEARCH METRICS: This was a collaborative project with UC Berkeley, where Professor Stark's team had a proposed way to define spatial locations within a field of regard. This allows eye movements to be specified in terms of these locations, rather than segmenting the image into regions of fixed size. This allows the scanpath to be defined independently of the segmentation sizes, and leads to a way of describing search that is applicable to mere general imagery.

FOTIS A. PAPOULIAS, Associate Professor

Prof. Papoulias conducted research on maneuvering and control of submersible vehicles in varying operational specifications and environmental conditions. The objective of this work, which was funded in 1997, is the development of a control strategy, which allows for on-the-fly reconfiguration of integrated guidance and control strategies of an underwater vehicle in shallow and littoral waters. In 1998, work performed was in the areas of accurate assessment of dive plane reversal bifurcation envelopes in the presence of biased external excitation. Further studies were conducted in order to assess the importance of nonlinearities in coupled sway, yaw, and roll stability of motion.

Additional work that was initiated in FY 97 demonstrated the feasibility of using Matlab based code to model the quasistatic response of a ship under conditions of progressive flooding. Two main limitations of this work are the applicability to rectangular compartments and the lack of an intuitive human interface in order to study "what-if" scenarios and counter-flooding actions. Current and future work in this area concentrates on overcoming these limitations as follows: First, a Matlab interface is under development to process the output of existing ship hydrostatic calculations programs. Second, a graphical user interface (GUI) will be constructed in order to allow the user to manipulate the data and interact with the results in an intuitive way. This GUI will be written using primitive Matlab and/or Visual Basic functions. The results will be tested against results produced by using the software package "Simsmart" which is more powerful but less commonly available.

**Ship Systems**

CHARLES N. CALVANO, Associate Professor

Professor Calvano's work with the Institute for Defense Analyses (IDA) culminated in 1998 with the presentation of the paper Operationally Oriented Vulnerability Requirements (OOVRs) in Ship Design, presented at the annual meeting of the American Society of Naval Engineers (ASNE) in March 1998 and published in the January 1998 edition of the Society's Journal. The Navy partially adopted the principles espoused in this work, in the first draft of the SC-21 Operational Requirements Document (ORD) which includes them in some ship performance areas. Adoption of this approach is expected to increase the likelihood that ships will be able to "fight hurt" after receiving expected levels of damage.

Surface ship survivability work, under OPNAV N86D sponsorship, continues, building on the start made in 1997. Fourteen faculty members working in research areas relatable to surface ship survivability were identified and expressed an interest in becoming part of a Surface Ship Survivability Resource Center AT NPS. As part of his work with N86D, in promoting surface ship survivability, Professor Calvano was requested to participate in the preparation of a Surface Ship Survivability Handbook for the fleet. This work will commence in FY 99, and will incorporate the work of individuals at the Naval Surface Warfare Center and, perhaps, others.

A new, and highly interesting, research effort was undertaken in 1998. This was the exploration of methods for applying numerical optimization to existing ship synthesis tools and resulted in the work described under the sponsorship of NAVSEA 03D. Further development of these ideas in 1999, to include optimization based on characteristics other than displacement is expected to occur.

Exploration of the nature of, and design tools for, such ship survivability-related concerns as progressive flooding and ship damaged stability is continuing. The first design tool using SIMSMART software to evaluate progressive flooding was brought to near completion in 1998. The future will see this work extended to generalized ship geometries, beyond the mathematically determinate hull form used for the initial development.

## Materials Science

### TERRY R. MCNELLEY, Professor

Professor McNelley's current research efforts are concentrated in the areas of mechanical behavior of particle-reinforced aluminum (PRA) metal matrix composites, and deformation processing and recrystallization in aluminum alloys. During 1998 work continued work on processing, deformation behavior and fracture toughness enhancement of particle-reinforced aluminum (PRA) metal matrix composites. Over a period of time this work has been sponsored by the Army Research Office, the Army Research Laboratory, the Air Force Wright Aeronautical Laboratories, and was initiated under of CRADA agreement with Duralcan-USA, a composites manufacturer located near Detroit, MI. The role of particle cracking during tensile extension of an aluminum–alumina PRA has been evaluated by measurement of the axial and diametral strains of deformed and unloaded tensile samples. These measurements have shown that the material experiences dilatation during tensile extension, and that this effect is accompanied by particle cracking. Analysis has shown that the observed dilatation can be modeled in terms of the fraction of cracked particles and the separation of the resulting particle fragments. The cracking process occurs throughout straining of this material and is not confined to a brief strain interval near the point of fracture. This work suggests that there is a critical condition involving the state of the matrix, the interfacial strength and the extent of particle cracking that leads to the nucleation of a macroscopic crack and unstable fracture. The evolution of microstructure and mechanical properties, and especially the strength – fracture toughness relationship has been examined in aluminum – silicon carbide PRA material. By control particulate distribution, matrix grain and subgrain structure, and matrix precipitate state the strength – fracture toughness combination can be optimized. Following an appropriate combination of processing and novel heat treatments the composite may possess better stiffness and strength as well as fracture toughness when compared to a similar unreinforced matrix alloy.

A program of research into processing, recrystallization and superplasticity of aluminum alloys also continued. Particular attention has been given to materials such as Supral 2004, Al-10Mg-0.1Zr and Al-5Ca-5Zn, which all transform by continuous recrystallzation reactions under appropriate post-processing annealing or annealing/straining conditions. The grain boundary geometry of these materials becomes established in a cellular dislocation structure produced during deformation processing. Most of the higher angle grain boundaries (misorientation > 30_) are interfaces between symmetric variants of the main texture components, while lower misorientation boundaries (misorientation _ 30_) are the result of random dislocation interaction within the texture variants. Bimodal misorientation distributions that persist through prolonged annealing treatments are frequently seen in such materials. The distribution of the high-angle boundaries can be modeled if a distribution of orientations around the main texture components is assumed. The superplastic response appears to be sensitive to the population of boundaries of misorientation in the range of 5_ - 20_. The role of particle size and size distribution in discontinuous recrystallzation reactions has been investigated. Because the critical size for particle-stimulated nucleation (PSN) of recrystallzation is relatively large and also strain dependent it is necessary to incorporate the particle size distribution into models for grain refinement via PSN. Accordingly, overaging treatments should be designed to increase the density of particles of size exceeding some critical value. This may suggest increased rather than decreased overaging temperatures as a means of increasing the density of nucleation sites in order to refine grain size.

### ALAN G. FOX, Professor

During 1998 the members of Professor Fox's research team in the Center of Materials Science and Engineering were Professor E.S.K. Menon, Dr Martin Saunders (NRC Research Associate), Dr Nagarajan Rajagopalan (NRC Research Associate), Mr R. Y. Hashimoto (Materials Engineer) and Graduate Students, Lts J.D. Walters, R.D. Manning, T. Halladay and D.J. Chisholm.

In 1998 these group members have been pursuing various projects. Work has been continuing in collaboration with the Carderock Division of the Naval Surface Warfare Center and the Naval Research Laboratory on studies of the mechanical properties of Navy high strength steels and their weldments so that new weld consumables and parent steels for Naval applications can be developed. As in 1997, projects were undertaken in collaboration with the Naval Air Warfare Center, Pax River, MD. These concerned the microstructural characterisation of new high temperature intermetallic alloys (including TiAl and NiAl) using new methods in x-ray and electron diffraction. Also during 1998 an ongoing project on the topic

of underwater wet welding was continued in collaboration with the Underwater Ship Husbandry Division of the Office of the Director of Ocean Engineering/Supervisor of Salvage and Diving, Naval Sea Systems Command. Finally, a new project on the microstructural characterization of glass-ceramic composites was started in collaboration with Systran Corp. and the Wright-Patterson Air Force Base.

In 1998, the Fox group presented and published eight conference papers and two journal articles were published with two others accepted for publication.

INDRANATH DUTTA, Associate Professor

Professor Dutta's current research efforts are concentrated in the areas of Mechanical Behavior and Electronics Packaging Materials Science. In the area of Mechanical Behavior, there are two programs. One is on creep and thermal cycling behavior of fiber reinforced metal-matrix composites at elevated temperatures, which is currently supported by the National Science Foundation. During 1998, constitutive laws for interfacial deformation were identified, and the effect of such interfacial sliding on the overall creep response of a model composite was evaluated by experimental and analytical means. The second program is on the improvement of fracture toughness of discontinuously reinforced aluminum (DRA) composites to via innovative processing routes, and was supported in 1998 by the Wright Patterson Air Force Base. During 1998, in an extension of previous work, it was demonstrated that both fracture and strength properties of DRA can be improved relative to unreinforced aluminum if the process and microstructural conditions are precise understood and controlled. In the area of Electronics Packaging, Professor Dutta is continuing his work on adhesion between metallizations and substrates for hybrid micro-electronics packaging applications. Also, Professor Dutta is initiating a new research program on Liquid Phase Sintering of Ceramics (LPSF) in collaboration with Prof. A. Gopinath.

## TOTAL SHIP SYSTEMS ENGINEERING CVNX AIRCRAFT CARRIER DESIGN EXPLORATION AND SUPPORT

**Charles N. Calvano, Associate Professor**
**Department of Mechanical Engineering**
**Robert C. Harney, Associate Professor**
**Department of Physics**
**Sponsor: CVNX Program Office**

**OBJECTIVE:** To explore innovative design approaches for a future U.S. Navy aircraft carrier and contribute to discussions of CVNX developments by participation in and support of the CVNX Analysis of Alternatives (AOA) process. Introduce officer students to the unique design challenges associated with aircraft carriers.

**SUMMARY:** Numerous fiscal and other constraints prohibited the CVNX Program Office and other participating Navy organizations from exploring the implications of a carrier designed solely for the operation of Short Takeoff, Vertical Landing (STOVL) aircraft, yet such a design would both force and permit significant deviations from recent past carrier design practice. Under this project, the investigators guided the student-performed design of a STOVL aircraft carrier. In addition to exploring the implications for ship and flight deck size and architectures, the effort included exploration of innovative approaches to reduced flight deck manning and increased aircraft ordnance handling. The final design report was made available widely within the Navy community supporting the Program Office.

**PUBLICATION:**

Calvano, C.N., Harney, R.C., et al., "A Short Take-Off/Vertical Landing (STOVL) Aircraft Carrier," Naval Postgraduate School Technical Report, NPS-ME-98-003, May 1998.

**DoD KEY TECHNOLOGY AREA:** Surface/Under Surface Vehicles – Ships and Watercraft

**KEYWORDS:** Aircraft Carrier, STOVL, Ship Design

## TOTAL SHIP AND BATTLE FORCE SURVIVABILITY STUDIES AT THE NAVAL POSTGRADUATE SCHOOL

**Charles N. Calvano, Associate Professor**
**Department of Mechanical Engineering**
**Sponsor: Chief of Naval Operations (N86DC)**

**OBJECTIVE:** To explore the viability of and begin the implementation of a research and teaching program which explores methods for improving U.S. Navy ship and battle force survivability and which makes increased knowledge and expertise of serving Navy officers an integral part of the program. To be guided by the reasons for this work, which include:

- The Navy will operate in the littorals where clutter is high and defense in depth is difficult;
- Increasingly sophisticated weapons are available to a growing number of nations;
- The nature of modern weapons, coupled with operations in the littorals, results in drastically reduced reaction times, making susceptibility reduction more difficult and the need for vulnerability reduction more acute;
- Budgetary pressures resulting in smaller numbers of Navy ships make the ability of the ships that are built to survive and continue to fight of greater importance; and
- Protecting the lives of U.S. sailors, always of utmost importance, takes on increasing criticality as the U.S. becomes more intolerant of casualties. Even if ships are hit or lost, the crew's ability to survive must be enhanced.

**SUMMARY:** The investigator has undertaken the organization of a Surface Ship Survivability Resource Center at NPS, obtaining statements of interest from 14 faculty members in several departments. Working with these other researchers in ship-survivability-related areas, areas of potentially high payoff for more intensive application of effort are being identified. Opportunities to combine and coordinate research in disparate areas and promote useful synergies have begun to be identi-

fied. Liaison with the CVXN (formerly CVX) program office has identified certain damaged ship stability concerns that lend themselves to further exploration via simulation at NPS and this work is now being defined. Groundwork has been laid and an outline developed for the writing of a Fleet Survivability Handbook to be made available to all Navy surface ships, with the book to be co-authored by the investigator.

**DoD KEY TECHNOLOGY AREA:** Surface/Under Surface Vehicles – Ships and Watercraft

**KEYWORDS:** Ship Survivability, Progressive Flooding, Damaged Stability

### MODELING OF PROGRESSIVE FLOODING DYNAMICS USING SIMULINK®

**Charles N. Calvano, Associate Professor**
**Fotis A. Papoulias, Associate Professor**
**Department of Mechanical Engineering**
**Sponsor: Naval Sea Systems Command**

**OBJECTIVE:** To complement work being done for OPNAV N86D using SIMSMART software to model progressive flooding by exploring the use of MATLAB and SIMULINK software for similar work and evaluate the relative utility, viability and user-friendliness of the two approaches. To simulate a ship with a compartment opened to the sea, with the bounding watertight bulkheads damaged. To incorporate human responses and decision-making results and explore various combinations and levels of flooding damage, to include the use of de-watering pumps and systems with varied configurations.

**SUMMARY:** The study to date concluded that: (1) The computational power of MATLAB can be combined with the ease of implementation of SIMULINK in order to set the fundamentals for a user friendly, modular, and expandable ship progressive flooding design tool. This approach has the added advantage of evaluating the degree of accuracy versus difficulty of implementation during each program upgrade. Extension to arbitrary ship compartment geometries is feasible through the use of lookup tables; (2) Since SIMULINK lacks the internal description of piping properties and de-watering pump characteristics, which SIMSMART possesses, it is necessary to build a collection of standard blocks which will contain a mathematical description of these properties. This will become a "library" which will be accessible to the end user from within the SIMULINK graphical environment. The standard pump characteristics library will be as identical as possible to the library that has been developed for NAVSEA and has been incorporated in the simulation package SIMSMART; and (3) The complete package of MATLAB functions and SIMULINK block diagrams will be accessible from a user friendly Graphical User Interface (GUI) with the appropriate callback functions. In this way, the complete system will be event driven and will be used in order to establish or assess the effectiveness of various countermeasure actions.

**DoD KEY TECHNOLOGY AREA:** Surface/Under Surface Vehicles – Ships and Watercraft

**KEYWORDS:** Ship Survivability, Progressive Flooding, Damaged Stability

### COMPUTER OPTIMIZATION TECHNIQUES AS A TOOL FOR SHIP DESIGN

**Charles N. Calvano, Associate Professor**
**Matthew D. Kelleher, Professor**
**Department of Mechanical Engineering**
**Sponsor: Naval Sea Systems Command**

**OBJECTIVE:** The existing MIT Ship Synthesis Model estimates important characteristics of existing and conceptual surface displacement ships for engineering design and synthesis. The operator chooses the payload and certain gross characteristics of the ship and the computer model determines whether a design which meets these characteristics is feasible. If not, the operator chooses different characteristics and tries again. When a feasible design is arrived at, there is no indication of if, or how nearly, the design approaches an optimum. This work combines the MIT model, as the integration

"engine," with numerical optimization techniques to explore the possibility of producing a tool which arrives at a design which is both feasible and optimum for a given payload.

**SUMMARY:** The MIT model, written in the MATHCAD personal computer language was coupled with the MATLAB computing environment where the optimization calculations were performed. The MATHCONNEX module available with MATHCAD Professional, Version 7 or later, was used as the medium for integrating the software packages. The Integrated Ship Design Software produced under this effort uses Microsoft Excel to determine the weight and volume characteristics of a specified payload and uses these as inputs to the MIT model in MATHCAD, where an initial ship design is produced. An optimization package, based on existing MATLAB optimization tools was developed and integrated with the other modules to allow the output from the MIT model to be optimized based on a minimum displacement objective function and subject to the same constraints applied in the MIT model. The optimized characteristics are then returned to the MIT model in MATHCAD, where the characteristics of the optimized model are verified. The accuracy and robustness of the model produced were verified using a series of extreme design starting points and, in each case, with a given payload, the same optimum point was arrived at. Future work by the investigators will attempt to apply the model with optimization objective functions based on characteristics other than displacement, such as cost, or a combination of cost and displacement.

**THESIS DIRECTED:**

Meister, Neil, "Application of Numerical Optimization Techniques to Surface Combatant Design Synthesis," Master's Thesis, Naval Postgraduate School, September 1998.

**DoD KEY TECHNOLOGY AREA:** Surface/Under Surface Vehicles – Ships and Watercraft

**KEYWORDS:** Ship Design, Combatant Design, Optimization

## TARGET ACQUISITION MODEL EVALUATION

**Morris Driels, Professor**
**Department of Mechanical Engineering**
**Sponsor: U.S. Army Training and Doctrine Analysis Command-Monterey**

**OBJECTIVE:** To update a previous version of the Handbook, and include recently found work on the U.K. Oracle Visual Performance Model.

**SUMMARY:** The Handbook is intended to support the Target Acquisition Models Library under development by Australia, Britain, Canada, and America (ABCA). The library will research, collate and document target acquisition models available to modelers so that the selection of a specific model for a particular combat simulation is enhanced. This work completes release 1.1 of the Handbook, summarizing and documents seven of the most widely used models.

**PUBLICATION:**

Driels, Morris, "Handbook of Target Acquisition Models Release 1.1," U.S. Army Training and Doctrine Analysis Command-Monterey, 1998.

**DoD KEY TECHNOLOGY AREA:** Computing and Software

**KEYWORDS:** Software, Target Acquisition, Combat Models

## TARGET ACQUISITION MODULE UPDATE

**Morris Driels, Professor**
**Department of Mechanical Engineering**
**Sponsors: Joint Technical Coordinating Group-Eglin Air Force Base and Naval Postgraduate School**

**OBJECTIVE:** To develop and enhance the target acquisition to the Joint Air to surface Weaponeering System – JAWS.

**SUMMARY:** A stand-alone module was developed in FY97 and validated against data and other sources. In FY98, this program was interfaced with the JAWS database, and included in JAWS version 2.0, due for release in 1999. In transitioning from an analyst's model to a user model, the inputs were made more operationally relevant, and data imported directly from the weaponeering part of the program.

This research program is on going, and will be extended into FY99. The planned work will be to complete the integration of the current TA module into JAWS, and extend it to cover FLIR sensors.

**OTHER:**

Driels, Morris, "JMEM Target Acquisition Program Analyst's Manual."

Driels, Morris, "Target Acquisition Program User Guide."

Driels, Morris, "JAWS Target Acquisition Program."

**DoD KEY TECHNOLOGY AREA:** Computing and Software

**KEYWORDS:** Software, Target Acquisition

## AIR-TO-SURFACE AND SURFACE-TO-SURFACE TARGET ACQUISITION METHODOLOGIES

**Morris Driels, Professor**
**Department of Mechanical Engineering**
**Sponsor: Joint Technical Coordinating Group-Army Materiel Systems Analysis Activity**

**OBJECTIVE:** To develop a high-fidelity target acquisition and mission-planning program.

**SUMMARY:** This program uses target imagery, and a DTED terrain data base to define local natural features in the vicinity of a specific target which will be attacked by aircraft. Cultural features are then raised up from the terrain to provide detailed masking contours, based on the approach angle and altitude of the attacking aircraft. The user then types in data regarding the weapon to be used and the program generates release conditions for the attack. In addition, a perspective view allows pilots to visualize the target area at a user-specified range.

**DoD KEY TECHNOLOGY AREA:** Computing and Software

**KEYWORDS:** Software, Target Acquisition

## IMPLEMENTATION OF THE DELPHI TARGET ACQUISITION MODEL

**Morris Driels, Professor**
**Department of Mechanical Engineering**
**Sponsor: U.S. Army Training and Doctrine Analysis Command-Monterey**

**OBJECTIVE:** To further refine earlier work on the development of a visual performance model based on a public domain version of the BAe ORACLE model.

**SUMMARY:** Previous work in FY97 laid the theoretical basis for the foveal component of a visual performance model based on proprietary work in the UK. This phase of the work completed the development of the model and allowed it to be compared to the U.S. Acquire model. In addition, work was done on the peripheral channel, allowing the development of a search component.

**CONFERENCE PRESENTATION:**

Driels, Morris, "An Investigation into the Public Domain Basis for the BAe ORACLE Visual Performance Model," 1998 Acquisition and Simulation (ACQSIM) Meeting, White Sands Missile Range, NM, June 1998.

**DoD KEY TECHNOLOGY AREA:** Computing and Software

**KEYWORDS:** Software, Target Acquisition, Combat Models

## REVIEW OF DELIVERY ACCURACY METHODOLOGY

**Morris Driels, Professor**
**Department of Mechanical Engineering**
**Sponsor: Joint Technical Coordinating Group-Eglin Air Force Base**

**OBJECTIVE:** To review the algorithms used for assessing the accuracy of guided weapons.

**SUMMARY:** The standard methodologies used to determine statistical descriptions of weapon accuracy was applied to a new class of GPS/INS guided weapon. Using field data, the accuracy was described in a manner allowing it to be included into the Joint Air to surface Weaponeering System JAWS. In doing so several issues regarding the methodology were highlighted, and improvements made. This work will be continued into FY99.

**DoD KEY TECHNOLOGY AREA:** Computing and Software

**KEYWORDS:** Software, Target Acquisition

## SCALABLE SEARCH METRICS

**Morris Driels, Professor**
**Department of Mechanical Engineering**
**Sponsor: U.S. Army Training and Doctrine Analysis Command-Monterey**

**OBJECTIVE:** To assist in the development of a way to characterize eye movements over a field of regard which does not rely on spatial segmentation of fixed size bins.

**SUMMARY:** This was a collaborative project with UC Berkeley, where Professor Stark's team had a proposed way to define spatial locations within a field of regard. This allows eye movements to be specified in terms of these locations, rather than segmenting the image into regions of fixed size. This allows the scanpath to be defined independently of the segmentation sizes, and leads to a way of describing search that is applicable to mere general imagery.

**DoD KEY TECHNOLOGY AREA:** Computing and Software

**KEYWORDS:** Human Vision, Search, Target Detection

## CREEP OF FIBER REINFORCED METAL MATRIX COMPOSITES

**Indranath Dutta, Associate Professor**
**Department of Mechanical Engineering**
**Sponsors: National Science Foundation and Naval Postgraduate School**

**OBJECTIVE:** To investigate the mechanisms of creep in metal-matrix composites.

**SUMMARY:** The goal of this project is to develop a phenomenological understanding of the mechanisms operative during high temperature deformation of metal matrix composites reinforced by continuous fibers. A combination of experimental and analytical means are being utilized to develop a model for creep/thermal cycling, with the eventual objective of generating transient deformation mechanism maps.

**PUBLICATIONS:**

Dutta, I. and Funn, J.E., "Creep Behavior of Interfaces in Fiber Reinforced Metal-Matrix Composites," *Acta Materialia*, Vol. 47, No. 1, pp. 149-164, January 1999.

Nagarajan, R., Dutta, I., Funn, J.V., and Esmele, M., "Role of Interfacial Sliding on the Longitudinal Creep Response of Continuous Fiber Reinforced Metal-Matrix Composites," *Materials Science and Engineering A*, Vol. 259, Issue 2, pp. 237-252, January 1999.

Nagarajan, R., Dutta, I., Funn, J.V., and Esmele, M., "Role of Interfacial Sliding on the Longitudinal Creep Response of Continuous Fiber Reinforced Metal-Matrix Composites," *Proceedings of the 127th TMS Annual Meeting*, San Antonio, TX, 15-19 February 1998.

**CONFERENCE PRESENTATION:**

Nagarajan, R., Dutta, I., Funn, J.V., and Esmele, M., "Role of Interfacial Sliding on the Longitudinal Creep Response of Continuous Fiber Reinforced Metal-Matrix Composites," 127th TMS Annual Meeting, San Antonio, TX, 15-19 February 1998.

**OTHER:**

Dutta, I., "Role of the Near Interface Region in Creep and Fracture of Metal-Matrix Composite," invited seminar at Los Alamos National Laboratory, April 1998.

**DoD KEY TECHNOLOGY AREA:** Materials, Processes, and Structures

**KEYWORDS:** Composite, Creep, Interfacial Sliding

## PROCESSING AND FRACTURE OF PARTICULATE REINFORCED METAL-MATRIX COMPOSITES

**Indranath Dutta, Associate Professor**
**Department of Mechanical Engineering**
**Sponsor: Air Force Research Laboratory**

**OBJECTIVE:** To correlate processing, microstructure, and fracture properties in particulate reinforced aluminum (PRA) composites.

**SUMMARY:** The purpose of this project is to investigate microstructural development during processing of PRA, specifically with respect to the evolution of particulate distribution and matrix grain and precipitate structure, and to evaluate the impact of fracture properties and mechanisms. The eventual goal is to design the material microstructure in such a way so as to result in substantially improved fracture toughness, while retaining the stiffness and strength advantage of PRA relative to unreinforced aluminum alloys.

**PUBLICATIONS:**

Dutta, I., Quiles, F.N., McNelley, T.R., and Nagarajan, R., "Optimization of the Strength-Fracture Toughness Relation in Particulate Reinforced Al Composites via Control of Matrix Microstructure," *Metallurgical and Materials Transactions A,* 29A , p. 2433, 1998.

Chakravartty, J.K., Nagarajan, R., Dutta, I., and McNelley, T.R., "Improvement of Fracture Behavior of SiCp-Al Composites by Tailoring Matrix Microstructure," *Proceedings of the 1998 TMS Fall Meeting*, Rosemont, IL, 11-15 October 1998.

Dutta, I. and McNelley, T.R., "Matrix Effects on Deformation and Fracture of Discontinuously Reinforced Aluminum (DRA) Composites," *Proceedings of the ASM Materials Week 98*, Rosemont, IL, 11-15 October 1998.

**CONFERENCE PRESENTATIONS:**

Chakravartty, J.K., Nagarajan, R., Dutta, I., and McNelley, T.R., "Improvement of Fracture Behavior of SiCp-Al Composites by Tailoring Matrix Microstructure," 1998 TMS Fall Meeting, Rosemont, IL, 11-15 October 1998.

Dutta, I. and McNelley, T.R., "Matrix Effects on Deformation and Fracture of Discontinuously Reinforced Aluminum (DRA) Composites," ASM Materials Week 98, Rosemont, IL, 11-15 October 1998.

**DoD KEY TECHNOLOGY AREA:** Materials, Processes, and Structures

**KEYWORDS:** Composites, Fracture, Matrix Microstructure

## METALLIZATION OF CVD DIAMOND FOR ELECTRONIC PACKAGING

**Indranath Dutta, Associate Professor**
**Department of Mechanical Engineering**
**Sponsor: Unfunded**

**OBJECTIVE:** To develop approaches for metallization of CVD Diamond.

**SUMMARY:** The purpose of this project is to develop innovative approaches for producing adherent metallizations on CVD Diamond, which is an excellent thermal management material that is being currently considered for high-end electronic packages. Since metals do not naturally adhere to diamond, there is a need to develop new surface modifications for diamond to make metals stick to diamond.

**PUBLICATION:**

Menon, E.S.K. and Dutta, I., "Processing and Characterization of Aumina Thin Films on CVD Diamond Substrates for Producing Adherent Metallizations," *Journal of Material Research*, 14, p.359, 1999.

**OTHER:**

Dutta, I. and Menon, S.K., "Surface Modification of Synthetic Diamond for Producing Adherent Thick and Thin Film Metallizations for Electronic Packaging," U.S. Patent # 5, 853, 888, 1998.

**DoD KEY TECHNOLOGY AREA:** Materials, Processes, and Structures

**KEYWORDS:** Electronic Packaging, Diamond, Metallization

## MICROSTRUCTURES AND MECHANICAL PROPERTIES OF HIGH-STRENGTH, LOW-ALLOY (HSLA) STEELS AND THEIR WELDMENTS

**Alan G. Fox, Professor**
**E.S.K. Menon, Research Associate Professor**
**M. Saunders, National Research Council Postdoctoral Research Associate**
**Center for Materials Science and Engineering**
**Department of Mechanical Engineering**
**Sponsors: Naval Surface Warfare Center-Carderock Division, Office of Naval Research, Naval Research Laboratory, and Naval Postgraduate School**

**OBJECTIVE:** To investigate the microstructure and mechanical properties of ULC, HY, and HSLA 80-130 series steels and their weldments to evaluate new weld consumables and parent steels for Naval shipbuilding applications.

**SUMMARY:** In recent years the U.S. Navy has been replacing the HY80-100 series of high strength alloy steels with their high-strength, low-alloy (HSLA) equivalents. This is being done because the stringent weld pre-heat requirements associated with the HY steels are not necessary for the HSLA series. So, despite the higher manufacturing costs of high-strength, low-alloy steels, the U.S. Navy should make significant savings by changing over to HSLA or ultra low carbon (ULC) steels for ship and submarine construction. In order to extract the maximum benefit from these newly developed steels it is also necessary to develop improved weld filler wires. This project supports these objectives with fundamental physical metallurgy studies at NPS using advanced optical and electron microscopy techniques.

**PUBLICATIONS:**

Blackburn, J.M., Brandemarte, A., and Fox, A.G., "The Effect of Inclusions and Austenite Grain Size on the CVN Impact Behavior of a Newly Developed Low-Carbon Steel Weld Metal," *Proceedings of the Third Pacific Rim International Conference,* 1998.

Menon, E.S.K., Fox, A.G., and Spanos, G., "Carbon in Retained Austenite," *Proceedings of the Electron Microscopy 1998* (ICEM 14), pp. 211-212, Cancun, Mexico, 31 August-4 September 1998.

**CONFERENCE PRESENTATIONS:**

Blackburn, J.M., Brandemarte, A., and Fox, A.G., "The Effect of Inclusions and Austenite Grain Size on the CVN Impact Behavior of a Newly Developed Low-Carbon Steel Weld Metal," Third Pacific Rim International Conference, 1998.

Menon, E.S.K., Fox, A.G., and Spanos, G., "Carbon in Retained Austenite," Electron Microscopy 1998 (ICEM 14, Cancun, Mexico, 31 August-4 September 1998.

**THESIS DIRECTED:**

Walters, J.D., "Microchemical Analysis of Non-Metallic Inclusions in C-Mn Steel Shielded Metal Arc Weld Metals by Analytical Transmission Electron Microscopy," Master's Thesis, Naval Postgraduate School, June 1998.

**DoD KEY TECHNOLOGY AREA:** Materials, Processes, and Structures

**KEYWORDS:** Ultra Low Carbon Steel, Welding

## CHEMISTRY, MICROSTRUCTURE, AND DUCTILITY OF Ti-44Al-11Nb ALLOYS

**Alan G. Fox, Professor**
**E.S.K. Menon, Research Associate Professor**
**Center for Materials Science and Engineering**
**Department of Mechanical Engineering**
**Sponsors: Naval Air Warfare Center-Patuxent River and Naval Postgraduate School**

**OBJECTIVE:** To investigate the microstructure of Ti-44Al-11Nb alloys by optical, scanning, and transmission electron microscopies with a view to understanding the improved ductility that results from adding Nb to $\gamma$-TiAl alloys.

**SUMMARY:** The overall objective of this research is to quantitatively correlate the microstructure and chemical composition of the various phases, the interfaces between them and the grain boundaries between like phases in a Ti-44Al-11Nb alloy in the as-processed condition using optical, scanning, and scanning transmission electron microscopies. In particular, the effects of alloying element segregation to grain boundaries and interfaces between different phases will be carefully studied. This includes oxygen and boron which are usually present in significant amounts in TiAl alloys and, since they are small atoms, they can rapidly segregate to grain boundaries and interfaces during processing. This analysis of the nature of microstructure, segregation, and interfaces in Ti-44Al-11Nb will hopefully allow an understanding of why Nb additions and certain processing conditions lead to improved ductilities in these alloy systems.

**THESIS DIRECTED:**

Halladay, T., "The Microstructure of Directionally Solidified Ti-44-11Nb Alloy," Master's Thesis, Naval Postgraduate School, December 1998.

**DoD KEY TECHNOLOGY AREA:** Materials, Processes, and Structures

**KEYWORDS:** Ductility of Ti-Al-Nb Alloys, Optical and Electron Microscopy

## MICROSTRUCTURAL STUDIES OF SILICON FIBER REINFORCED GLASS-CERAMIC COMPOSITES FOR GAS TURBINE APPLICATIONS

**A.G. Fox, Professor**
**E.S.K. Menon, Research Associate Professor**
**N. Rajagopalan, National Research Council Postdoctoral Research Associate**
**Center for Materials Science and Engineering**
**Department of Mechanical Engineering**
**Sponsors: Systran Corp., Air Force Research Laboratory, and Naval Postgraduate School**

**OBJECTIVE:** To investigate the microstructure of silicon fiber reinforced glass-ceramic matrix composites.

**SUMMARY:** The U.S. Navy and Air Force have ongoing programs of research into silicon fiber reinforced glass-ceramic matrix composites (CMCs) which have many potential uses for gas turbine components. The high strength, toughness and

resistance to high temperatures and low density of CMCs could allow a considerable increase in gas turbine engine efficiency if they could be used to replace heavy metallic parts. Unfortunately, aircraft operating environments are often very severe and any CMC components developed must be resistant to high temperature environments containing salt and aviation fuel which may be rich in sulfur. This work is using electron microscopy and x-ray diffraction to elucidate the microstructure of new glass-ceramic matrix composites which are capable of operating in severe environments.

**PUBLICATION:**

Kumar, A. and Fox, A.G., "Hot Corrosion of a Calcium Aluminosilicate Glass-Ceramic and a Si-C-O Fiber-Reinforced Calcium Aluminosilicate Matrix Composite," *Journal of the American Ceramic Society*, Vol. 81, pp. 613-623, 1998.

**DoD KEY TECHNOLOGY AREA:** Materials, Processes, and Structures

**KEYWORDS:** Electron Microscopy, X-Ray Diffraction, Fiber-Reinforced Glass-Ceramic Matrix Composites

## QUANTITATIVE AND QUALITATIVE PEELS AND EDX SPECTROSCOPY USING THE NPS TRANSMISSION ELECTRON MICROSCOPE

**Alan G. Fox, Professor**
**E.S.K. Menon, Research Associate Professor**
**M. Saunders, National Research Council Postdoctoral Research Associate**
**R. Hashimoto, Materials Technician**
**Center for Materials Science and Engineering**
**Department of Mechanical Engineering**
**Sponsor: Unfunded**

**OBJECTIVE:** To investigate the capability of the NPS Topcon 002B transmission electron microscope (TEM) and to perform both quantitative and qualitative parallel electron energy loss spectroscopy (PEELS) and energy dispersive x-ray (EDX) spectroscopy.

**SUMMARY:** Parallel electron energy loss spectroscopy (PEELS) and energy dispersive x-ray (EDX) spectroscopy are commonly used to obtain microchemical information in the transmission electron microscope (TEM). Indeed most of the TEM research carried out in the Center for Materials Science and Engineering involves the use of PEELS or EDX to some extent. It has been found that novel techniques for treating PEELS and EDX data, including the use of multivariate statistical analysis, can provide important chemical information about interfaces in multiphase systems. Recently an EMiSPEC vision system was installed on the Topcon 002B TEM and this will allow simultaneous acquisition of EDX and PEELS spectra to be made which will significantly improve the capability to perform quantitative EDX and PEELS.

**PUBLICATIONS:**

Saunders, M., Menon, E.S.K., Chisholm, D.J., and Fox, A.G., "Extracting Chemical Information from Energy-Dispersive X-Ray Spectra by Multivariate Statistical Analysis," *Proceedings of Microscopy and Microanalysis 1998*, pp. 204-205, Atlanta, GA, 12-16 July 1998.

Saunders, M., Menon, E.S.K., and Fox, A.G., "Using Statistical Methods to Identify and Map Interface Reaction Phases from EDS Spectra," *Proceedings of Electron Microscopy 1998* (ICEM 14), pp. 598-598, Cancun, Mexico, 31 August-4 September 1998.

Saunders, M., Menon, E.S.K., Hashimoto, R.Y., and Fox, A.G., "Interface Electron Energy Loss Spectroscopy (EELS) Analysis: Comparison of Spatial Difference and Multivariate Statistical Analysis (MSA) Techniques," *Proceedings of Electron Microscopy 1998* (ICEM 14), pp. 571-572, Cancun, Mexico, 31 August-4 September 1998.

Saunders M., Menon E.S.K., and Fox A.G., "Determination of Interface Composition Variations by the Application of Multivariate Statistical Analysis to Energy Dispersive X-Ray Spectra and Electron Energy Loss Spectra," *Proceedings of Scandem 98,* Helsinki, Finland, July 1998.

**CONFERENCE PRESENTATIONS:**

Saunders, M., Menon, E.S.K., Chisholm, D.J., and Fox, A.G., "Extracting Chemical Information from Energy-Dispersive X-Ray Spectra by Multivariate Statistical Analysis," Microscopy and Microanalysis 1998, Atlanta, GA, 12-16 July 1998.

Saunders, M., Menon, E.S.K., and Fox, A.G., "Using Statistical Methods to Identify and Map Interface Reaction Phases from EDS Spectra," Electron Microscopy 1998 (ICEM 14), Cancun, Mexico, 31 August-4 September 1998.

Saunders, M., Menon, E.S.K., Hashimoto, R.Y., and Fox, A.G., "Interface Electron Energy Loss Spectroscopy (EELS) Analysis: Comparison of Spatial Difference and Multivariate Statistical Analysis (MSA) Techniques," Electron Microscopy 1998 (ICEM 14, Cancun, Mexico, 31 August-4 September 1998.

Saunders, M., Menon, E.S.K., and Fox, A.G., "Determination of Interface Composition Variations by the Application of Multivariate Statistical Analysis to Energy Dispersive X-Ray Spectra and Electron Energy Loss Spectra," Scandem 98, Helsinki, Finland, July 1998.

**THESIS DIRECTED:**

Chisholm, D.J., "Use of Principal Component Analysis for the Identification and Mapping of Phases from Energy Dispersive X-Ray Spectra," Master's Thesis, Naval Postgraduate School, December 1998.

**DoD KEY TECHNOLOGY AREA:** Materials, Processes, and Structures

**KEYWORDS:** Transmission Electron Microscopy, PEELS, EDX

## EVALUATION OF THE INFLUENCE OF WATER TEMPERATURE ON CRACKING IN UNDERWATER WET WELDS

**Alan G. Fox, Professor**
**E.S.K. Menon, Research Associate Professor**
**Center for Materials Science and Engineering**
**Department of Mechanical Engineering**
**Sponsor: Naval Sea Systems Command**

**OBJECTIVE:** To investigate the underbead cracking present in the heat affected zones of underwater shielded metal arc weldments.

**SUMMARY:** In recent years the U.S. Navy has been making a concerted effort to reduce maintenance costs, in particular the costs of dry docking. As a result, attempts are currently being made to underwater wet weld structural steels with carbon equivalents of 0.4 or less. Unfortunately, in fully restrained situations, it has proved difficult to produce such weldments without underbead cracking especially in low temperature water (less than 10 C). In this work fully restrained underwater wet welds are being produced on ASTM A516 Grade 70 steel under carefully controlled conditions at different temperatures. The microstructure and thermal history of these weldments is being carefully monitored in order that the precise mechanism of cracking can be understood.

**PUBLICATION:**

Fox, A.G., Johnson, R.L., and Dill, J.F., "The Effect of Water Temperature on the Underwater Wet Weldability of ASTM A516 Grade 70 Steel," *Proceedings of the 17th International Conference on Offshore Mechanics and Arctic Engineering*, pp. 2262-2267, Lisbon, Portugal, 5-9 July 1998.

**CONFERENCE PRESENTATION:**

Fox, A.G., Johnson, R.L., and Dill, J.F., "The Effect of Water Temperature on the Underwater Wet Weldability of ASTM A516 Grade 70 Steel," 17th International Conference on Offshore Mechanics and Artic Engineering, Lisbon, Portugal, 5-9 July 1998.

**THESIS DIRECTED:**

Manning, R.D., "Analysis of Underbead Cracking in Underwater Wet Weldments on A516 Grade 70 Steel," Master's Thesis, Naval Postgraduate School, September 1998.

**DoD KEY TECHNOLOGY AREA:** Materials, Processes, and Structures

**KEYWORDS:** Underwater Wet Welding, Underbead Cracking, Hydrogen Induced Cracking

## DIFFRACTION METHODS FOR THE ACCURATE MEASUREMENT OF STRUCTURE FACTORS AND CHARGE DENSITIES OF ELEMENTS AND INTERMETALLIC ALLOYS

**Alan G. Fox, Professor**
**E.S.K. Menon, Research Associate Professor**
**M. Saunders, National Research Council Postdoctoral Associate**
**Center for Materials Science and Engineering**
**Department of Mechanical Engineering**
**Sponsors: Wright-Patterson Air Force Base, Naval Air Warfare Center-Patuxent River, and Naval Postgraduate School**

**OBJECTIVE:** To accurately measure the low-angle structure factors of elements and alloys by various diffraction methods so that their electronic bonding mechanisms can be investigated.

**SUMMARY:** A knowledge of the distribution of bonding electrons in crystalline solids can give important information about their physical properties. One way to gain such knowledge is to accurately measure the low-angle structure factors of the materials of interest by some means, and then use these to generate maps of the electron charge distributions. In the past both electron and x-ray diffraction have been used to measure the low-angle structure factors of several elements and intermetallic alloys with high accuracy. The lattice parameters and Debye-Waller factors were measured by x-ray diffraction and the structure factors by the critical voltage technique in electron diffraction. More recently these measurements have been made using the energy filtering transmission electron microscope which has been recently installed at NPS. This has allowed fully quantifying energy filtered convergent beam electron diffraction patterns and determining the low-angle structure factors of elements and alloys with an accuracy far greater than previously achieved and, in addition, it has been shown that it is possible to measure Debye-Waller factors by this method. This is leading to a vastly improved understanding of the nature of bonding in crystalline solids.

**PUBLICATIONS:**

Fox, A.G. and Menon, E.S.K., "Debye-Waller Factors of Stoichiometric and Al-rich γ-TiAl Alloys," *Philosophical Magazine A,* Vol. 77, pp. 577-592, 1998.

Saunders, M., Menon, E.S.K., and Fox, A.G., "Quantitative Convergent Beam Electron Diffraction (CBED) Studies of Metals and Alloys," *Proceedings of Electron Microscopy 1998* (ICEM 14), pp. 779-780, Cancun, Mexico, 31 August-4 September 1998.

**CONFERENCE PRESENTATION:**

Saunders, M., Menon, E.S.K., and Fox, A.G., "Quantitative Convergent Beam Electron Diffraction (CBED) Studies of Metals and Alloys," Electron Microscopy 1998 (ICEM 14), Cancun, Mexico, 31 August-4 September 1998.

**DoD KEY TECHNOLOGY AREA:** Materials, Processes, and Structures

**KEYWORDS:** Convergent Beam Electron Diffraction, Structure Factor Measurement, Bonding Charge Density

## THERMOACOUSTIC EFFECTS AT A SOLID-FLUID BOUNDARY: THE ROLE OF A SECOND ORDER THERMAL EXPANSION COEFFICIENT

**Ashok Gopinath, Assistant Professor**
**Department of Mechanical Engineering**
**Sponsor: National Aeronautics and Space Administration-Lewis Research Center**

**OBJECTIVE:** To conduct fundamental material and transport studies on thermoacoustic phenomena in microgravity with future application to thermodynamic engines aboard the Space Station.

**SUMMARY:** An analytical study has been conducted of the thermoacoustic effects induced by the interaction of a strong acoustic field with a rigid boundary such as that in a thermoacoustic engine. With the sphere as a representative object, it's been found that the acoustic field can create a spatially periodic heating and cooling pattern on its surface just as in the stack of a thermoacoustic engine. The thermoacoustic effects are generated primarily in the narrow Stokes boundary layer region on the sphere and are diffused and convected over the remaining part of the fluid domain. The unexpected role of a second-order thermal expansion coefficient in this process is explained.

**PUBLICATIONS:**

Gopinath, A., Tait, N.L., and Garrett, S.L., "Thermoacoustic Streaming in a Resonant Channel: the Time-Averaged Temperature Distribution," *Journal of the Acoustical Society of America*, Vol.103, No.3, pp.1388-1405, March 1998.

Gopinath, A., "Thermoacoustic Streaming from a Rigid Sphere," in review.

**DoD KEY TECHNOLOGY AREAS:** Modeling and Simulation, Other (Materials, Basic Science)

**KEYWORDS:** Thermoacoustics, Acoustic Streaming, Acoustic Levitation, Thermophysical Property Measurement, Thermodynamic Moduli, Oscillatory Flows, Asymptotic Techniques

## ACOUSTIC STREAMING IN MICROGRAVITY: FLOW STABILITY AND HEAT TRANSFER ENHANCEMENT

**Ashok Gopinath, Assistant Professor**
**Department of Mechanical Engineering**
**Sponsor: National Aeronautics and Space Administration-Jet Propulsion Laboratory**

**OBJECTIVE:** To conduct fundamental material and transport studies on the role of acoustic streaming in enhancing transport rates in microgravity with application to materials processing.

**SUMMARY:** Analytical studies have been conducted on the role of steady streaming in enhancing heat and mass transport rates in a zero-mean acoustic field under microgravity conditions. In particular the compressible flow situation has been considered for which the object in question in the acoustic field is non-compact. This requires a Helmholtz decomposition of the vector velocity field requiring the solution of both a velocity potential and a stream function. The streaming flow pattern indicates some unique features resulting from the nonlinear interaction of both the rotational and irrotational velocity fields. Some preliminary numerical studies (on steady flows) based on the spectral method have also been initiated with the goal of application to oscillatory flows.

**PUBLICATIONS:**

Gopinath, A. and Harder, D.H., "An Experimental Study of Heat Transfer from a Cylinder in Low-Amplitude Oscillatory Flows," *International Journal of Heat and Mass Transfer,* to appear.

Gopinath, A. and Bridenstine, M., "An Experimental Study of Heat Transfer from a Cylinder in High-Amplitude Oscillatory Flows," in review.

Gopinath, A. and Trinh, E., "Steady Streaming from a Non-Compact Sphere," abstract, *Journal of the Acoustical Society of America*, Vol.103, No.5, Pt.2, p.2763, May 1998.

**CONFERENCE PRESENTATIONS:**

Gopinath, A. and Trinh, E., "Steady Streaming from a Non-Compact Sphere," 16th International Congress on Acoustics and 135th Meeting of the Acoustical Society of America, Seattle, WA, June 1998.

Gopinath, A., "Thermoacoustic Effects at a Solid-Fluid Boundary," 4th NASA Microgravity Fluid Physics and Transport Phenomena Conference, Cleveland, OH, August 1998.

**DoD KEY TECHNOLOGY AREA:** Other (Energy Systems)

**KEYWORDS:** Acoustic Streaming, Heat Transport, Asymptotic Techniques

## FURTHER EVALUATION OF TEMPERATURE ON CRACKING OF UNDERWATER WELDS

**Ashok Gopinath, Assistant Professor**
**Alan G. Fox, Professor**
**Department of Mechanical Engineering**
**Sponsor: Naval Sea Systems Command**

**OBJECTIVE:** To understand the role of water temperature and cooling on the rapid heat transfer rates in determining the material structure and strength of underwater welds.

**SUMMARY:** The rapid cooling rates encountered in underwater wet welding are crucial in determining the resulting material structure and strength of the welded joints. A numerical model was developed to determine the three-dimensional conduction based temperature distribution in a thick plate being welded underwater. A fully implicit finite-volume model was developed and a variable mesh size with temperature dependent transport properties was used. Boiling was (as expected) found to be the principal mode of heat transfer giving cooling times significantly lower than noted in the literature. However the cooling times themselves were not found to be sensitive to the water temperature.

**THESIS DIRECTED:**

Isiklar, Y.V., "A Numerical Study of Heat Transfer Behavior in Welding," Master's Thesis, Naval Postgraduate School, June 1998.

**DoD KEY TECHNOLOGY AREA:** Materials, Processes, and Structures

**KEYWORDS:** Underwater Wet Welding, Carbon Steels, Cracking, Heat Transfer, Ship Repair, Numerical Modeling

## ACOUSTIC MODELING OF HYDRODYNAMIC WAVE LOADING

**Ashok Gopinath, Assistant Professor**
**Department of Mechanical Engineering**
**Sponsor: Naval Postgraduate School**

**OBJECTIVE:** To be able to use acoustics to simulate oscillatory wave loading on marine offshore structures.

**SUMMARY:** An experimental study was conducted to measure the forces on a cylinder in a standing acoustic field. The cylinder is representative of the leg of an offshore structure or platform, while the acoustic field is representative of the oscillatory wave loading on such a structure. The working fluid is high pressure nitrogen so chosen to reduce the viscosity to allow high values of the Reynolds number to be achieved. Both in-line (drag) and transverse (lift) coefficients have been measured and corroborated with existing data in the literature. The experimental technique appears to have promising potential for extension to larger values of the parameter regime which need further study.

**THESIS DIRECTED:**

Dufek, M., "Experimental Study of Zero Mean Oscillatory Flow Forces on Circular Cylinders," Master's Thesis, Naval Postgraduate School, March 1998.

**DoD KEY TECHNOLOGY AREAS:** Modeling and Simulation, Other (Structures, Basic Science)

**KEYWORDS:** Hydrodynamic Loading, Fluid-Structure Interaction, Acoustics, Reynolds Number, Lift and Drag, Offshore Marine Structures, Oscillatory Wave Loading

## LIQUID PHASE SINTER-FORMING OF CERAMICS

**Ashok Gopinath, Assistant Professor**
**Indranath Dutta, Associate Professor**
**Department of Mechanical Engineering**
**Sponsor: Unfunded**

**OBJECTIVE:** To study the feasibility of sinter-forming covalent ceramics using superplastic-like deformations.

**SUMMARY:** An unsponsored feasibility study has been initiated to explore the possibility of net-shape part formation from hard to machine materials such as (covalent) ceramics. The goal is to combine the processes of liquid phase sintering, and forming, in a novel manner and exploit a suitable process parameter window to effect the forming operation with superplastic-like strains. A suitable model ceramic system has been identified and the work of the first thesis student although preliminary has yielded promising results. The study is being continued by two additional students, particularly to explore the role of the intergranular liquid phase in supporting the tensile forces encountered during forming, and to understand the subsequent modes of failure.

**THESIS DIRECTED:**

Lloyd, J.M., "A Feasibility Study of Liquid Phase Sinter-Forming of a Model Ceramic System," Master's Thesis, Naval Postgraduate School, September 1998.

**DoD KEY TECHNOLOGY AREA:** Materials, Processes, and Structures

**KEYWORDS:** Ceramic Powder Processing, Liquid Phase Sintering, High Temperature Deformation, Superplasticity

## EFFICIENT NONLINEAR TRANSIENT DYNAMIC ANALYSIS FOR STRUCTURAL OPTIMIZATION USING AN EXACT INTEGRAL EQUATION FORMULATION

**Joshua H. Gordis, Associate Professor**
**Department of Mechanical Engineering**
**Beny Neta, Professor**
**Department of Mathematics**
**Sponsor: National Science Foundation**

**OBJECTIVE:** This project is concerned with the theoretical development and computational implementation of a time domain theory for locally nonlinear transient structural synthesis. Application principally will be made to seismic isolation.

**SUMMARY:** This research concerns the continued development of a time domain theory for structural synthesis. This theory provides the previously unavailable capability of performing exact damped transient structural synthesis for systems with localized nonlinear components with the order of the synthesis being independent of model size. The method is based on Volterra integral equations derived from the convolution integral which describe substructure coupling and structural modification. Current results demonstrate an order of magnitude reduction in compute times as compared with widely-used commercial finite element analysis packages. The use of the formulation for the optimal design of seismic isolation is under development.

**PUBLICATION:**

Durant, B.R. and Gordis, J.H., "Time Domain Synthesis in the Optimal Design of Nonlinear Shock and Vibration Isolation for Large Structures," *Proceedings of the 69th Shock and Vibration Symposium*, Minneapolis, MN, 12-15 October 1998. (Also submitted to *Shock and Vibration.*)

**CONFERENCE PRESENTATION:**

Durant, B.R. and Gordis, J.H., "Time Domain Synthesis in the Optimal Design of Nonlinear Shock and Vibration Isolation for Large Structures," 69th Shock and Vibration Symposium, Minneapolis, MN, 12-15 October 1998.

**THESIS DIRECTED:**

Florence, D., "Optimal Design of Nonlinear Shock Isolation for Large, Locally Nonlinear Structures," Master's Thesis, Naval Postgraduate School, December 1998.

**DoD KEY TECHNOLOGY AREA:** Modeling and Simulation

**KEYWORDS:** Structural Dynamics, Transient Response, Synthesis, Nonlinear Dynamics, Seismic Isolation

## STRUCTURAL DYNAMICS OF THE RAH-66 COMANCHE HELICOPTER

**Joshua H. Gordis, Associate Professor**
**Department of Mechanical Engineering**
**E. Roberts Wood, Professor**
**Department of Aeronautics and Astronautics**
**Don Danielson, Professor**
**Department of Mathematics**
**Sponsors: U.S. Army Aviation and Technology Command and Naval Postgraduate School**

**OBJECTIVE:** Technical support is provided to the U.S. Army Aviation and Technology Command, St. Louis, for the structural dynamics and vibration of the RAH-66 Comanche.

**SUMMARY:** The RAH-66 Comanche helicopter is the U.S. Army's attack helicopter for the 21st Century. During 1995, the Comanche began a program of ground vibration and flight tests, intended to validate structural dynamic performance of the airframe and to demonstrate the helicopter's performance characteristics. These tests typically uncover dynamics problems with rotor-fuselage coupling and forced response. In order to ensure the survival of the Comanche program, these problems, when discovered, must be quickly resolved. This effort provides rapid technical support to the Comanche Program, to resolve structural dynamics problems. FY98 efforts focused on the identification of airloads on the empennage using a combination of flight test dynamic response data and fuselage finite element modeling.

**OTHER:**

Wood, E.R., Danielson, D.A., and Gordis, J.H., "Research in the Structural Dynamic Response of the RAH-66 Comanche Helicopter," report submitted to Comanche Program Manager's Office, 1 January 1998 to 31 December 1998.

**THESIS DIRECTED:**

Mason, P.H., "Identification of Random Loads Impinging on the RAH-66 Comanche Helicopter Empennage Using Spectral Analysis," Master's Thesis, Naval Postgraduate School, June 1998.

**DoD KEY TECHNOLOGY AREA:** Air Vehicles

**KEYWORDS:** Helicopter, Comanche, Structural Dynamics

## BUGS: BASIC UNEXPLODED (UXO) GATHERING SYSTEM - MODELING AND SIMULATION

**Anthony J. Healey, Professor**
**Joung K. Kim, Research Assistant**
**Department of Mechanical Engineering**
**Sponsor: Naval Ordnance Technical Center**

**OBJECTIVE:** This work is being undertaken to provide a modeling and simulation capability for evaluating the clearance performance of multiple cooperating vehicles in UXO gathering and minefield operations. The work involves the development and the evaluation of various robot system control concepts as proposed for the BUGS system and shallow water minefield.

**SUMMARY:** The graphics simulator code runs on a high end SGI workstation, currently an ONYX Reality Engine workstation, and has been developed using the "inventor" and "performer" tool kit. It is planned to use the simulator and its complementary modeling tools to evaluate sensor technology as well as control methodologies in relation to the performance of the overall BUGS/AUTORECORM system concepts for land-based ordnance clearance operations.

The simulator is built around a terrain base taken from the Marine Corps 29 Palms facility and a small subset of that data base has been selected as a test site for evaluation of clearance operations. Vegetation has been included as uniformly distributed randomly dispersed objects added to the data base.

Munitions simulated include Mk 118 anti-personnel mines, and "softball" and "baseball" munitions that would have been dispensed from an airborne canister. These munitions are randomly distributed around a nominal center with an average density, selectable by the user.

Clearance operations are then simulated by a fleet of vehicles (BUGS) that can be controlled to a speed, heading and altitude above ground command. Walking machines are rendered as full kinematically faithful hexapods walking with a double tripod fixed gait, where each bug has an arm (boom) to support a camera, tactile, or magnetic sensor. The sensor has a defined radius of detection so that if a munition is encountered, a command is registered in the machine controller to manipulate the boom and retrieve the object.

Search patterns can be simulated that are directed exhaustive searches if motion sensors are presumed to have sufficient accuracy for navigation to way points, or random searches if no navigation sensors are presumed to be available.

The characteristics of random versus exhaustive search including obstacle avoidance have been established as part of this research, and the influence of various levels of navigation sensor accuracy and "inter bug communication" on search effectiveness are being sought.

Recently, questions concerning the comparison of random search as opposed to supervised autonomous directed searches for both PUCA and minefield operations are being analyzed. The effectiveness of obstacle avoidance methodology, path planning, and autonomous map building techniques, and the comparison of wheeled and tracked vehicle locomotion methods are being studied.

Five scenarios have been studied in detail. These are: (1) a cluster of UXO being cleared by a fleet of robots (BUGS) using random searching; (2) field of clusters of differing densities; (3) clearance using an upgraded version of the EOD RECORM vehicle with optical sensing; and (4) cooperating behavior with AUTORECORM and a fleet of BUGS.

**PUBLICATION:**

Healey, A.J. and Kim, J., "AUTORECORM Control Algorithms and Cooperative Behavior for Enhancing UXO Clearance," Naval Postgraduate School Technical Report, NPS-ME-98-006, December 1998.

**DoD KEY TECHNOLOGY AREAS:** Simulation and Modeling, Other (Robotics, Mine Warfare)

**KEYWORDS:** Robotics, Simulation and Modeling, Mine Warfare

## STUDIES IN INTELLIGENT CONTROL OF AUTONOMOUS VEHICLES

**Anthony J. Healey, Professor**
**Department of Mechanical Engineering**
**Sponsor: Ford Motor Company**

**OBJECTIVE:** This grant is in the support of research in the subject matter without restriction, and serves to aid the ongoing programs in the Center for Autonomous Underwater Vehicle Research.

**SUMMARY:** This project has supported the purchase of radio Ethernet communications devices and radio modem connections between the *Phoenix* robot and a shore based operator station. Also, it has supported the purchase of mobile laboratory equipment necessary to the deployment of *Phoenix* in Monterey Bay.

**DoD KEY TECHNOLOGY AREAS:** Surface/Under Surface Vehicles - Ships and Watercraft

**KEYWORDS:** Autonomous Systems, Robotics, Vehicles, Navigation

## NAVIGATION OF REMOTE PLATFORMS

**Anthony J. Healey, Professor**
**Department of Mechanical Engineering**
**Sponsor: Florida Atlantic University**

**OBJECTIVE:** This project is aimed at a cooperative study between NPS and Florida Atlantic University (FAU) with the purpose of developing theories and algorithms for the asynchronous data fusion of autonomous underwater vehicle (AUV) navigation sensory information.

**SUMMARY:** New navigation algorithms are needed for small AUV systems as they are limited in size and cost. Low cost sensor suites are less accurate than their higher cost counterparts, and their sensory data arrive at times that are not necessarily synchronized at control loop rates. With the new capabilities of networked embedded microprocessor systems, system control may be dispersed leading to distributed intelligent nodes that are capable of performing local area control functions coordinated by a higher level node. Sensory data arrive at arbitrary times when processed. For example, DGPS position data arrives at approximately 1 second intervals. Acoustic Doppler sonar returns when bottom locked, give information at about 2 Hz. Magnetic compass and inertial sensors for rotational rate may be available at high rates.

This work has developed a model-based Extended Kalman Filter provide position and other state estimates between updates using new data from all sensors as available. Bias and scale factor errors are included in the model and learned through the fusion of disparate sensors and compensated if constant.

Real time implementation in the QNX operating system on an embedded Pentium processor (with connectivity to Lon Works network protocols) as used by the FAU Ocean Voyager II AUV has been used to provide real time computability of the algorithms. It has been shown that filter computations are easily managed within the typical rates required for AUV navigation. Further real time implementation work into the FAU vehicles remains.

**PUBLICATIONS:**

Healey, A.J., An, E.P., and Marco, D.B., "On-Line Compensation of Heading Sensor Bias for Low Cost AUVs Using EKF," *Proceedings of IEEE AUV '98*, Cambridge, MA, 20-21 August 1998.

Yun, X., McGhee, R., Healey, A.J., et al., "Testing and Evaluation of an Integrated GPS/INS System for Small AUV Navigation," *IEEE Journal of Oceanic Engineering*, accepted for publication, 1998.

**DoD KEY TECHNOLOGY AREA:** Other (Robotics and Automation, Underwater Vehicles, Mine Countermeasures)

**KEYWORDS:** Autonomous Systems, Robotics, Vehicles, Navigation

## CONTROL ARCHITECTURES AND NON-LINEAR CONTROLLERS FOR UNMANNED UNDERWATER VEHICLES

**Anthony J. Healey, Professor**
**Department of Mechanical Engineering**
**Sponsor: Office of Naval Research**

**OBJECTIVE:** This project is funded through ONR to jointly collaborate with researchers from Florida Atlantic University (FAU) and Virginia Polytechnic Institute (VPI) as part of a Multi-University Research Initiative to seek enhancements in robustness in control systems of interest to the Navy. Robustness will be sought through multi-level hierarchical control schemes using robust nonlinear servo control laws at the lowest level and discrete state switching using elastic constraint and fuzzy reasoning at higher levels.

**SUMMARY:** The work is just starting and collaborative discussions are ongoing between VPI, FAU, and NPS. The review of available simulation and modeling tools for UUV applications is beginning. Not only are existing simulation tools being

evaluated, but others used for both lower level servo control development such as MATLAB/SIMULINK but higher level simulation tools for the design of discrete state controllers using Petri Net methods and Finite State Machine simulators are being evaluated.

Robust nonlinear control methodology is expected to be used for ships underway replenishment, and at - sea transfer operations improvements, power electronic building block (PEBBS) systems, as well as for UUV and other underwater systems.

Building on robust control theory, this work has led to methodology for the automatic detection of subsystem faults arising from items such as control fin jams, or fin loss. Detection of faults is accomplished by a combination of model free and model-based methods using both sensor information as well as the analytical redundancy afforded by the model based filters.

**DoD KEY TECHNOLOGY AREA:** Other (Robotics and Automation, Underwater Vehicles, Control)

**KEYWORDS:** Autonomous Systems, Robotics, Vehicles, Nonlinear and Robust Control

## AUTOMATIC FAULT DETECTION AND CONTROL RECONFIGURATION

**Anthony J. Healey, Professor**
**Department of Mechanical Engineering**
**Sponsor: Office of Naval Research**

**OBJECTIVE:** Long-term deployments of autonomous systems in the ocean require replenishment of energy supplies and reliable, fault free operation. It is recognized that fault free operation will not always be possible, so that system design must pay attention to a study of failure modes and their effects. In spite of the use of good engineering practice, faults can occur. Two kinds of "faults" identified are: (1) those that arise from malfunctions in the hardware and software subsystems in the vehicle and (2) those that arise from environmental conditions that are viewed as disturbances, and while these may not be directly "faults," they have the effect that the completion of a mission is jeopardized.

An example of a hardware fault would be the loss of steering resulting from a stuck or loose fin. An example of a type 2 fault would the inability of the vehicle to take a data measurement because of high sea state in shallow water operation.

To design a system that will automatically detect the presence of a "fault" is the subject of many papers. This problem is common to the aircraft, spacecraft, and process industries, and much has been written about methods available. In general we can classify the methods into those that use simple limits and trends analysis, those that use detection techniques but which are without the use of analytical models, and those that provide analytical models as the basis for detection filters. The detection of status signals such as battery voltage, motor winding temperature, computer bay temperatures, is relatively easy and accomplished by the comparison of the measured signal with a previously set threshold. Exceeding those thresholds indicates a fault condition for which some action is taken – for instance either to slow down the vehicle speed or to abort the mission and surface. The detection of dynamic signal faults is more complex and requires the design of specially constructed residual generators, and is the subject of this activity. Special application to the U.S. Navy's 21 UUV vehicle is implied.

**SUMMARY:** A new fault detection architecture has been defined based on a bank of observers, decomposed by control mode and designed to be robust for residual generation. Residual processing is performed using maximum likelihood methodology and actuator faults have been detected and identified. Use of a fuzzy inference system has been proposed for performing the reconfiguration of actuator inputs so that a stable, but degraded control may still be achieved after fault occurrence.

**PUBLICATIONS:**

Healey, A.J., "Analytical Redundancy and Fuzzy Inference in AUV Fault Detection and Compensation," *Proceedings of Oceanology 1998,* 11-14 March, 1998, http://web.nps.navy.mil/~me/healey/papers/oceanology98.pdf.

Riedel, J.S. and Healey, A.J., "Model Based Predictive Control of AUVs for Station Keeping in a Shallow Water Wave Environment," *Proceedings of the International Advanced Robotics Program IARP 98,* 18 February 1998, http://web.nps.navy.mil/~me/healey/papers/iarp_jeff.PDF.

**THESIS DIRECTED:**

Melvin, J.E., "AUV Fault Detection Using Model-Based Observer Residuals," Master's Thesis and Naval Postgraduate School Technical Report, NPS-ME-98-004, June 1998.

**DoD KEY TECHNOLOGY AREA:** Other (Robotics, Autonomous Systems, Fault Detection)

**KEYWORDS:** Autonomous Systems, Robotics, Vehicles, Navigation

## MODELING OF FIRE AND SMOKE PROPAGATION IN SHIPBOARD SPACES

**Matthew D. Kelleher, Professor**
**Department of Mechanical Engineering**
**Sponsor: Naval Sea Systems Command**

**OBJECTIVE:** The objective of this proposed work is to model the propagation of fire and smoke in the shipboard environment. Specifically the effects of fire on the thermal environment of missiles in the launch systems of surface combatant ships has been modeled. Distributed lumped capacitance and thermal resistance models have been formulated to obtain time response behavior of a missile in a canister within a cell in the Concentric Canister Launcher (CCL) system. More detailed computational fluid dynamics models of the fire induced environment within the these systems has also been used to determine the effects on the missile of fire in the vicinity of and within the missile magazines. Work has recently begun to investigate the modeling of smoke propagation in shipboard compartments and passageways. It is very important that an understanding of the propagation of fire and smoke in the various shipboard spaces be developed and that some means be developed to apply that understanding to incorporate survivability considerations in the design of future combatants and to the development of fire fighting procedures.

**SUMMARY:** A commercial code developed by CFD Research Corporation (CFDRC) has been used to model the effects of fire in various shipboard spaces. A model has been developed to predict the effects of a fire in an adjacent compartment on the environment in a missile magazine. The model has been used to predict the effects of a high temperature fire caused by burning missile propellant such as that experienced by the USS STARK (FFG-31) on the time and location of the critical cook-off temperatures of the missile's propellants.

**DoD KEY TECHNOLOGY AREA:** Modeling and Simulation

**KEYWORDS:** Fire Propagation, Ship Survivability, Damage Control, Missile Magazines

## MODELING AND SIMULATION OF DAMAGE AND CRACKS IN PARTICULATE COMPOSITE MATERIALS: STUDY OF THICKNESS EFFECTS AND INITIAL CRACK SIZE

**Young W. Kwon, Associate Professor**
**Department of Mechanical Engineering**
**Sponsors: Air Force Research Laboratory and Naval Postgraduate School**

**OBJECTIVE:** This was a continuing research project from past years during which a numerical modeling and simulation technique had been developed and evaluated against experimental results. The developed method was called a micro/macro approach. This year's effort was to investigate the effects of specimen thickness on the crack tip behavior including onset of crack propagation. A three-dimensional finite element analysis was conducted for the macrolevel analysis.

**SUMMARY:** Damage saturation (i.e., the on set of crack propagation) occurred at the same applied strain level for both thick and thin specimens. For the thick specimens, the damage saturation was uniform more than 90 percent of the thickness. Thus, uniform crack propagation through the thickness was predicted and observed for thick specimens. The short crack had a long delay (about 100 percent larger applied strain) in damage initiation than the long crack, but the damage growth rate in the long crack was about 15 percent greater than the short crack. The slower damage growth in the short crack resulted in the higher maximum stress in the loading direction. At the onset of damage saturation, the longer crack had more damage concentration around the crack tip.

**PUBLICATIONS:**

Kwon, Y.W. and Kim, C., "Micromechanical Model for Thermal Analysis of Particulate and Fibrous Composites," *Journal of Thermal Stresses*, Vol. 21, pp. 21-39, 1998.

Kwon, Y.W. and Baron, D.T., "Numerical Predictions of Progressive Damage Evolution in Particulate Composites," *Journal of Reinforced Plastics and Composites*, Vol. 17, No. 8, pp. 691-711, 1998.

Kwon, Y.W. and Liu, C.T., "Damage Growth in a Particulate Composite Under a High Strain Rate Loading," *Mechanics Research Communication*, Vol. 25, No. 3, pp. 329-336, 1998.

Kwon, Y.W., Lee, J.H., and Liu, C.T., "Study of Damage and Crack in Particulate Composites," *Composites, Part B: Engineering*, Vol. 29B, pp. 443-450, 1998.

Kwon, Y. W. and Liu, C. T., "Effects of Non-Uniform Particle Distributions on Damage Evolution in Pre-Cracked, Particulate Composite Specimens," *Polymers and Polymer Composites*, accepted for publication, 1998.

Liu, C.T. and Kwon, Y.W., "Numerical Modeling of Damage Initiation and Evolution Processes in a Particulate Composite Material," *Proceedings of the International Conference on Computational Engineering Science*, 1998.

Kwon, Y.W. and Liu, C.T., "Progressive Damage Around the Crack Tip in a Particulate Composite Made of Rubber-Like Matrix Material," *Proceeding of the Fifth International Conference on Composites Engineering*, Las Vegas, NV, July 1998.

Kwon, Y.W. and Liu, C.T., "Damage Evolution Near Crack Tips of Hard Particle Filled Rubber-Like Composites: Effects of Specimen Thickness and Crack Size," *Proceeding of the International Mechanical Engineering Congress and Exhibition*, November 1998.

**CONFERENCE PRESENTATIONS:**

Liu, C.T. and Kwon, Y.W., "Numerical Modeling of Damage Initiation and Evolution Processes in a Particulate Composite Material," International Conference Computational Engineering Science, Atlanta, GA, October 1998.

Kwon, Y.W. and Liu, C.T., "Progressive Damage Around the Crack Tip in a Particulate Composite Made of Rubber-Like Matrix Material," Fifth International Conference on Composites Engineering, Las Vegas, NV, July 1998.

Kwon, Y.W. and Liu, C.T., "Damage Evolution Near Crack Tips of Hard Particle Filled Rubber-Like Composites: Effects of Specimen Thickness and Crack Size," International Mechanical Engineering Congress and Exhibition, Anaheim, CA, November 1998.

**DoD KEY TECHNOLOGY AREA:** Aerospace Propulsion and Power

**KEYWORDS:** Particle Reinforced Composite, Solid Rocket Propellant, Damage and Crack, Modeling and Simulation, Thickness Effects

# PROJECT SUMMARIES

## DEVELOPMENT OF A ROBUST, HIGHER-ORDER SHELL ELEMENT WITH PRESSURE VARIATION THROUGH THE SHELL THICKNESS FOR DYSMAS PROGRAM

**Young W. Kwon, Associate Professor**
**Department of Mechanical Engineering**
**Sponsor: Naval Surface Warfare Center**

**OBJECTIVE:** This was a continuing research project from the previous year. This year's effort was to implement the plastic constitutive model including void effects into the shell element developed from the previous years.

**SUMMARY:** The shell element developed during the previous year was extended to include an elastoplastic constitutive model including void growth and nucleation. Gurson's void model was used. The shell element included both transverse shear and normal strains. It was also implemented into a transient analysis program using the central time integration technique. An algorithm for a stable solution with nonlinear deformation was developed. Furthermore, an hourglass control scheme was developed and applied to the shell element. Several test problems were solved for verification of the developed computer program.

**PUBLICATION:**

McMermott, P.M. and Kwon, Y.W., "Development of a Shell Element with Pressure Variation Through the Thickness-Part II," Naval Postgraduate School Technical Report, NPS-ME-98-005, September 1998.

**DoD KEY TECHNOLOGY AREAS:** Materials, Processes, and Structures, Modeling and Simulation

**KEYWORDS:** Finite Element Method, Higher-Order Shell Element, Constitutive Model for Void

## BIOMECHANICAL STUDY OF HUMAN BODY INJURY UNDER EXTREME LOADING

**Young W. Kwon, Associate Professor**
**Department of Mechanical Engineering**
**Sponsor: Unfunded**

**OBJECTIVE:** This was a continuing research project from a previous funded project. The effort was to model, simulate, and evaluate potential injury of the human body at various parts when subjected to an extreme loading such as mechanical impact and explosion.

**SUMMARY:** Three parts of the project were completed. The first study investigated the injury potential of the human head and neck of a solider wearing a helmet that was impacted by a bullet. The focus was placed on the cervical spine injury. The second part examined the effectiveness of countermine boots against an AP mine. The study examined the protection of the boots from possible amputation of the lower leg caused by mine explosion. The last part studied the injury potential of a soldier in a military vehicle called HUMVEE when it rode on an explosive mine. The studies validated the modeling and results by comparing to available experimental results. In addition, the study investigated several possible scenarios under various conditions to predict injury potentials.

**PUBLICATIONS:**

Kwon, Y.W. and King, Q.M., "Biomechanical Study of Ballistic Impact on Helmets: Injury of Head and Neck," *Recent Advances in Solids and Structures*, ASME PVP-Vol. 381, pp. 55-62, 1998.

Kwon, Y.W. and Muschek, R.C., "Study of Effectiveness of Countermine Boots," *Recent Advances in Solids and Structures*, ASME PVP-Vol. 381, pp. 63-70, 1998.

**CONFERENCE PRESENTATIONS:**

Kwon, Y.W. and King, Q.M., "Biomechanical Study of Ballistic Impact on Helmets: Injury of Head and Neck," 1998 ASME International Mechanical Engineering Congress and Exposition, Anaheim, CA, November 1998.

Kwon, Y.W. and Muschek, R.C., "Study of Effectiveness of Countermine Boots," 1998 ASME International Mechanical Engineering Congress and Exposition, Anaheim, CA, November 1998.

**THESES DIRECTED:**

King, Q.M., "Investigation of Biomechanical Response due to Fragment Impact on Ballistic Protective Helmet," Master's Thesis, Naval Postgraduate School, March 1998.

Muschek, R.C., "Evaluation of the Mechanical Properties and Effectiveness of Countermine Boots," Master's Thesis, Naval Postgraduate School, March 1998.

Lee, K.-S., "Biomechanical Response of the Human Body Inside a Military Vehicle Exposed to Mine Explosion," Master's Thesis, Naval Postgraduate School, December 1998.

**DoD KEY TECHNOLOGY AREAS:** Biomedical, Modeling and Simulation

**KEYWORDS:** Biomechanics, Injury of Human Body, Finite Element Model

## PROCESSING GRAIN BOUNDARIES AND SUPERPLASTICITY IN ALUMINUM

**Terry R. McNelley, Professor**
**Department of Mechanical Engineering**
**Sponsor: Unfunded**

**OBJECTIVE:** The goal of this program is to determine the mechanisms of grain boundary development during deformation processing, and the mechanisms by which deformation microstructures may transform to a fine-grained superplastic state.

**SUMMARY:** Recently developed computer-aided electron microscopy diffraction analysis methods have been applied to the investigation of the mechanisms of grain boundary development during deformation processing and annealing of pure aluminum and several superplastic aluminum alloys. Materials have been examined following various thermomechanical processing schedules and deformation histories. A program of investigation into pure Aluminum processed by equi-channel angular (ECA) pressing has been initiated. Research has continued on Aluminum alloys 5083, 7475 and laboratory-processed 2519, which are all observed to transform to a refined, superplastic microstructure via a primary (discontinuous) recrystallization reaction involving the formation and migration of high-angle grain boundaries. However, Supral 2004, Al-10Mg-0.1Zr and Al-5Ca-5Zn materials transform by a continuous process. These different transformation processes may be distinguished by distinctly different grain boundary misorientation distributions. Primary recrystallization produces a random distribution similar to that predicted by Mackenzie for randomly oriented cubes and the resultant superplastic response is often relatively limited. The continuous reaction results in a bi-modal misorientation distribution, with many moderately misoriented boundaries of misorientation near 10 degrees, and a much more highly superplastic response.

**PUBLICATIONS:**

Pérez-Prado, M.T., McNelley, T.R., Ruano, O.A., and González-Doncel, G., "Microtexture Evolution During Annealing and Superplastic Deformation," *Metallurgical and Materials Transactions A*, 29A, pp. 485-492, 1998.

Pérez-Prado M.T., McMahon, M.E., and McNelley, T.R., "A Model for Texture-Related Grain Boundary Misorientations in a Superplastic Aluminum Alloy," *Modeling the Mechanical Response of Structural Materials,* E.M. Taleff and R.K. Mahidhara, (eds.), pp. 181-190, TMS, Warrendale, PA, 1998.

McNelley, T.R. and McMahon, M.E., "Recrystallization and Superplasticity in Aluminum Alloys," *Superplasticity and Superplastic Forming,* A. K. Ghosh and T. R. Bieler, (eds.), pp. 75-87, TMS, Warrendale, PA, 1998.

McNelley, T.R., Pérez-Prado, M.T., and McMahon, M.E., "Grain Boundary Evolution During Elevated Temperature Deformation of Two Superplastic Aluminum Alloys," *Hot Deformation of Aluminum Alloys II,* T.R. Bieler, L.A. Lalli, and S.R. MacEwen, (eds.), pp. 229-242, TMS, Warrendale, PA, 1998.

McNelley, T.R., McMahon, M.E., and Pérez-Prado, M.T., "Grain Boundary Evolution and Continuous Recrystallization of a Superplastic Al-Cr-Zr Alloy," *Philosophical Transactions: Mathematical, Physical and Engineering Sciences,* in press.

Pérez-Prado, M.T. and McNelley, T.R., "Dependence of the Grain Boundary Misorientation Distribution in Supral 2004 on the Plane of Observation," *Scripta Materialia,* in review.

**CONFERENCE PRESENTATIONS:**

McNelley, T.R. and McMahon, M.E., "Recrystallization and Superplasticity in Aluminum Alloys," Symposium on Superplasticity and Superplastic Forming, 1998 Annual Meeting of the Metals, Minerals, and Materials Society (TMS), San Antonio, TX, 16 February 1998.

Pérez-Prado, M.T., McMahon, M.E., and McNelley, T.R., "A Model for Texture-Related Grain Boundary Misorientations in a Superplastic Aluminum Alloy," Symposium on Modeling the Mechanical Response of Structural Materials, 1998 Annual Meeting of the Metals, Minerals, and Materials Society (TMS), San Antonio, TX, 18 February 1998.

McNelley, T.R., McMahon, M.E., and Pérez-Prado, M.T., "Grain Boundary Evolution During Processing and Deformation of Superplastic Aluminum Alloys," Symposium on Superplasticity and Superplastic Forming, 35th Annual Technical Meeting of the Society of Engineering Science, Washington State University, Pullman, WA, 28 September 1998.

McNelley, T.R., McMahon, M.E., and Pérez-Prado, M.T., "Processing, Grain Boundaries, and Superplastic Deformation of Aluminum," Symposium on Hot Deformation of Aluminum Alloys, 1998 Annual Fall Meeting of the Metals, Minerals, and Materials Society (TMS), Chicago, IL, 13 October 1998.

McNelley, T.R., "Deformation Processing and Grain Boundaries in a Superplastic Al-Cu-Zr Alloy," Discussion Meeting on Deformation Processing of Metals, the Royal Society, London, United Kingdom, 22 October 1998.

**THESIS DIRECTED:**

Terhune, Shannon D., "An Electron Backscatter Diffraction Analysis of the Microstructure of Pure Aluminum Processed by Equal-Channel Angular Pressing," Master's Thesis, Naval Postgraduate School, December 1998.

**DoD KEY TECHNOLOGY AREA:** Materials, Processes, and Structures

**KEYWORDS:** Aluminum, Superplasticity, Recrystallization, Grain Boundaries, Thermomechanical Processing

## A KNOWLEDGE-BASED APPROACH TO FRACTURE TOUGHNESS IMPROVEMENT VIA PROCESSING FOR PARTICULATE-REINFORCED ALUMINUM METAL MATRIX COMPOSITES

**Terry R. McNelley, Professor**
**Department of Mechanical Engineering**
**Sponsor: U.S. Army Research Office/Army Research Laboratory**

**OBJECTIVE:** The goal of this program is obtain improved combinations of strength, ductility, and toughness in Al-based metal-matrix composite materials by thermomechanical processing.

**SUMMARY:** Discontinuously reinforced Al matrix composite materials have many attractive properties but lack adequate ductility and toughness for many applications. Dramatic improvements in composite ductility have been attained in extruded 6061 Al-$Al_2O_3$ composites processed using methods designed to redistribute the $Al_2O_3$ particles as well as achieve a fully recrystallized matrix grain structure via particle-stimulated nucleation of recrystallization. Further improvements in ductility have been obtained with use of controlled heat treatments on processed material. The influence of deformation temperature on redistribution of particles during processing has been investigated by controlled deformation of samples in a channel die. Fracture toughness improvements in extruded powder metallurgy 6092 Al-SiC material have been demonstrated and strength-toughness combinations equivalent to those of the unreinforced matrix alloy have been attained.

**PUBLICATION:**

Dutta, I., Quiles, F.N., McNelley, T.R., and Nagarajan, R., "Optimization of the Strength-Fracture Toughness Relation in Particulate Reinforced Aluminum Composites via Control of Matrix Microstructure," *Metallurgical and Materials Transactions A*, 29A, pp. 2433-2446, 1998.

**CONFERENCE PRESENTATION:**

McNelley, T.R. and Dutta, I., "Matrix Effects on Deformation and Fracture of DRA Composites Symposium on Discontinuously Reinforced Composites: Present and Future," 1998 Annual Fall Meeting of the Metals, Minerals, and Materials Society (TMS), Chicago, IL, 13 October 1998.

**THESIS DIRECTED:**

Markovich, John J., "Evaluation of Microstructure of a 6092 Al - 17.5 vol. pct. $SiC_p$ Particle Reinforced Composite Using Electron Backscatter Pattern (EBSP) Analysis Methods," Master's Thesis, Naval Postgraduate School, March 1998.

**DoD KEY TECHNOLOGY AREA:** Materials, Processes, and Structures

**KEYWORDS:** Metal-Matrix Composites, Processing, Particle Distribution, Fracture Toughness

## CONDITION-BASED MAINTENANCE FOR DIESEL ENGINES

**Knox T. Millsaps, Associate Professor**
**Department of Mechanical Engineering**
**Sponsor: Office of Naval Research**

**OBJECTIVE:** To develop a method for determining cylinder firing pressure based on the instantaneous shaft speed. This technique is used to identify and localize faults in internal combustion engines.

**SUMMARY:** A torsional, dynamic engine model for a 3-cylinder, 2-stroke Diesel engine was developed and calibrated. Measurements of near instantaneous shaft speed at both ends of the engine were made on a real engine for a wide range of applied torques and speeds. The model is capable of predicting shaft speed variations. An inverse method, for determination

of gas torques based of these speed fluctuations was developed and verified. Finally a dynamic finite element method was developed to predict the angular motion of the crankshaft. This method was proven to be more than 100 times more efficient than the time-marching "shooting" method that was previously used.

**PUBLICATIONS:**

Millsaps, K.T., Swanson. W.J., Bell, J.A., and Hudson, J., "Development and Calibration of a High Fidelity Torsional Engine Model for a 3-Cylinder Diesel Engine," submitted to SAE, 1998.

Millsaps, K.T. and Swanson, W.J., "Determination of Diesel Cylinder Gas Torques from Speed Fluctuation High-Fidelity Crankshaft Torsional Model," submitted to SAE, 1998.

Swanson, W.J. and Millsaps, K.T., "An Efficient Method for the Determination of Periodic Torsional Motion of a Crankshaft Using Dynamic Finite Elements," submitted to SAE 1998.

**THESIS DIRECTED:**

Swanson, W.J., "Determination of Diesel Engine Cylinder Gas Torques from Speed Fluctuation with a High-Fidelity Crankshaft Torsional Model," Master's Thesis, Naval Postgraduate School, December 1998.

**DoD KEY TECHNOLOGY AREAS:** Modeling and Simulation, Sensors

**KEYWORDS:** Condition Based Maintenance, Diesel Engines, Cylinder Firing Pressure, Torsional Vibrations, Finite Element Methods

## ENHANCED SUPPRESSION EDUCTOR FOR THE LOW OBSERVABLE MULTI-FUNCTION STACK (LMS) ADVANCED TECHNOLOGY DEMONSTRATOR (ATD)

**Knox T. Millsaps, Associate Professor**
**Department of Mechanical Engineering**
**Garth V. Hobson, Associate Professor**
**Department of Aeronautics and Astronautics**
**Sponsors: Naval Surface Warfare Center-Carderock Division**
**Naval Sea Systems Command, and Office of Naval Research**

**OBJECTIVE:** To develop and verify an enhanced mixing performance eductor design for the Low Observable Multi-Function Stack (LMS) Advanced Technology Demonstrator (ATD). Also to provide consulting services as necessary to the ATD program.

**SUMMARY:** A 1-D design code for preliminary design of suppressing eductors was developed and used to obtain the preliminary scaling for the LMS enhanced mixing eductor. A sub-scale, cold-flow facility was designed, constructed and is operational. It was used to verify two design concepts developed at NPS for the LMS program. Specifically, the secondary induction and outlet flow profiles were measured for both parallel slot and radial slot enhanced mixing eductor designs. The performance was within 5% of that predicted, based on a 1-D design code. Additional support to the ATD program was supplied. Specifically, the instrumentation package for measuring the baseline engine exhaust flow was designed and the data from the tests were analyzed. Concepts for installing the suppressor were proposed and analyzed.

**OTHER:**

Millsaps, K.T. and Hobson, G.V., "Preliminary Design Report for the NPS LMS Eductor," 1 March 1998.

Millsaps, K.T., "Title Omitted," Classified Report to NSWC-Carderock, June 1998.

**THESIS DIRECTED:**

Otis, R., "Modeling and Design of an Enhanced Warship Signature Suppression Eductor," Master's Thesis, Naval Postgraduate School, March 1998.

**DoD KEY TECHNOLOGY AREAS:** Modeling and Simulation, Other (Surface Vehicles)

**KEYWORDS:** Infrared Signature Suppression, Ejectors, Eductors, Plume Temperature Reduction, Gas Turbine Exhausts

## DEVELOPMENT OF MATLAB-BASED PROGRESSIVE FLOODING DYNAMICS WITH A GRAPHICS INTERFACE

**Fotis A. Papoulias, Associate Professor**
**Charles N. Calvano, Associate Professor**
**Department of Mechanical Engineering**
**Sponsor: Naval Sea Systems Command**

**OBJECTIVE:** The objective of this project is to utilizing modeling and simulation methods based on MATLAB and SIMULINK in order to predict the fundamental dynamics of ship progressive flooding and develop the means to assess various flooding scenarios and countermeasures in a systematic way.

**SUMMARY:** The computational power of MATLAB can be combined with the ease of implementation of SIMULINK in order to set the fundamentals for a user friendly, modular, and expandable ship progressive flooding design tool. This approach has the added advantage of evaluating the degree of accuracy versus difficulty of implementation during each program upgrade. Extension to arbitrary ship compartment geometries is feasible through the use of look-up tables. Since SIMULINK lacks the internal description of piping properties and dewatering pump characteristics, it is necessary to build a collection of standard blocks which will contain a mathematical description of these properties. This can become a standard library that will be accessible to the end user from within the SIMULINK graphical environment. The standard pump characteristics library must be as identical as possible to the library that has been developed for NAVSEA and has been incorporated in the simulation package SIMSMART. The complete package of MATLAB functions and SIMULINK block diagrams will be accessible from a user friendly Graphical User Interface with the appropriate callback functions. In this way, the complete system will be event-driven and will be used in order to establish or assess the effectiveness of various countermeasure actions.

**THESIS DIRECTED:**

Wright, Russell A., "Improved Computer Modeling of Ship Progressive Flooding as a Design Tool," Naval Postgraduate School, September 1998.

**DoD KEY TECHNOLOGY AREA:** Surface/Under Surface Vehicles - Ships and Watercraft

**KEYWORDS:** Ship Motions, Stability, Flooding, Progressive Flooding

## DEVELOPMENT OF A NEW VORTEX-DECAY MODEL IN THE ATMOSPHERE

**Turgut Sarpkaya, Distinguished Professor**
**Department of Mechanical Engineering**
**Sponsor: National Aeronautics and Space Administration-Langley**

**OBJECTIVE:** The purpose of this continuing investigation is: (1) to develop a new vortex decay model for the prediction of the descent of aircraft trailing vortices subjected to realistic environmental conditions (stratification, turbulence, cross

wind, headwind, shear effects, and ground effect) and (2) to apply the model to field data obtained with Lidar in Memphis and Dallas–Fort Worth airports.

**SUMMARY:** A robust and relatively simple physics-based vortex decay model has been devised. It does not violate any hydrodynamical principles, has only one model constant, uses the turbulence eddy dissipation rate in conjunction with a theoretical model (as verified by experiments and numerical simulations), and it requires no cumbersome algorithms to account for the ground effects. Acquisition of better and more detailed field data (vortex velocities and positions; wind, shear, and their gradients; better temperature, humidity, and eddy dissipation profiles), the quantification of the consequences of unstable stratification, and the optimization of the new model parameters constitute the essence of this continuing research of vital international importance.

**PUBLICATIONS:**

Feyedelem, M.S. and Sarpkaya, T., "Free- and Near-Free-Surface Swirling Turbulent Jets," *American Institute of Aeronautics and Astronautics (AIAA) Journal*, Vol. 36, No. 3, pp. 359-364, March 1998.

Sarpkaya, T., "Decay of Wake Vortices of Large Aircraft," *American Institute of Aeronautics and Astronautics (AIAA) Journal*, Vol. 36, No. 9, pp. 1671-1679, September 1998.

**CONFERENCE PRESENTATIONS:**

Sarpkaya, T., "Decay of Wake Vortices of Large Aircraft," American Institute of Aeronautics and Astronautics Aerospace Sciences Meeting, Reno, NV, January 1998.

Sarpkaya, T., "A New Model for Vortex Decay in the Atmosphere," AIAA Paper No: 99-0761, (to be presented at the American Institute of Aeronautics and Astronautics Aerospace Sciences Meeting, Reno, NV, January 1999).

**THESIS DIRECTED:**

Murat, M., "Aircraft Trailing Vortices: Greene's Model Versus Field Data," Master's Thesis, Naval Postgraduate School, June 1998.

**DoD KEY TECHNOLOGY AREA:** Air Vehicles

**KEYWORDS:** Trailing Vortices, Aircraft Wakes, Wake Hazard

## A UNIVERSAL FORCE MODEL FOR BLUFF BODIES IN UNSTEADY FLOW

**Turgut Sarpkaya, Distinguished Professor**
**Department of Mechanical Engineering**
**Sponsor: Office of Naval Research**

**OBJECTIVE:** The purpose of this investigation is to carry out combined analytical, numerical, physical, and thought experiments to devise a physics-based model for the prediction of flow-induced unsteady forces on bluff bodies immersed in time-dependent flows. The new model, based on a sounder scientific rational, is expected to modify the well-known Morison equation and offer greater universality and higher engineering reliability, particularly in the so-called drag-inertia regime.

**SUMMARY:** Over 3,000 digital force-time-data files have been evaluated during the course of the investigation in order to evaluate the residue for each combination of the Keulegan-Carpenter number Kc, Frequency parameter b, the Reynolds number Re, and the relative roughness $k_s/D$. It has been shown that the viscous drag force and the inviscid inertia force do not operate independently and it is not possible to divide the measured time-dependent force into an inviscid inertial force

and a viscous drag force. The modification proposed herein to the existing Morison equation through the addition of a third term offers greater universality and higher engineering reliability, particularly in the so-called drag–inertia regime.

**PUBLICATION:**

Sarpkaya, T., "Resistance in Unsteady Flow: Search for a Physics-Based Model," *Proceedings of the 22nd Symposium on Naval Hydrodynamics,* Vol. 1, pp. 312-323, National Academy Press, Washington, DC, 1998.

**CONFERENCE PRESENTATION:**

Sarpkaya, T., "Resistance in Unsteady Flow: Search for a Physics-Based Model," 22nd Symposium on Naval Hydrodynamics, Washington, DC, 9-14 August 1998.

**DoD KEY TECHNOLOGY AREA:** Modeling and Simulation

**KEYWORDS:** Bluff Body, Resistance, Unsteady Flows, Vorticity

## SPRAY FORMATION AT THE FREE SURFACE OF LIQUID WALL JETS

**Turgut Sarpkaya, Distinguished Professor**
**Department of Mechanical Engineering**
**Sponsor: Office of Naval Research**

**OBJECTIVE:** This continuing basic research is an experimental investigation of the ligament and drop formation at the free surface of liquid wall jets, flowing over smooth and sand-roughened plates towards the understanding of the physics of droplet formation, in general, and of the spray formation on bow-sheets, in particular.

**SUMMARY:** Measurements were made with several high-speed imagers, a pulsating laser, and a Digital Particle Image Velocimeter (DPIV) system and analyzed through the use of appropriate software. The wall-jet Reynolds number ranged from $2.4 \times 10^4$ to $4 \times 10^4$, the Froude number from 15 to 30, and the Weber number from 1,500 to 3,000. The characteristics of the ligament forest and droplets were determined from the digitized images.

**PUBLICATIONS:**

Merrill, C.F. and Sarpkaya, T., "Spray Formation at the Free Surface of a Wall Jet," *American Institute of Aeronautics and Astronautics (AIAA) Paper,* No. 98-0442, 1998.

Sarpkaya, T. and Merrill, C., "Spray Formation at the Free Surface of Rough-Wall Jets," *Proceedings of the Third International Conference on Multiphase Flow, ICMF'98*, Paper No. 105, pp. 1-8, Lyon, France, 8-12 June 1998.

Sarpkaya, T. and Merrill, G., "Spray Formation at the Free Surface of Liquid Wall Jets," *Proceedings of the Symposium on 22nd Naval Hydrodynamics,* pp. 145-154, 9-14 August 1998.

**CONFERENCE PRESENTATIONS:**

Merrill, C.F. and Sarpkaya, T., "Spray Formation at the Free Surface of a Wall Jet," American Institute of Aeronautics and Astronautics Aerospace Sciences Meeting, Reno, NV, January 1998.

Sarpkaya, T. and Merrill, C., "Spray Formation at the Free Surface of Rough Wall Jets," Third International Conference on Multiphase Flow, ICMF'98, Lyon, France, 8-12 June 1998.

Sarpkaya, T. and Merrill, G., "Spray Formation at the Free Surface of Liquid Wall Jets," 22nd Symposium on Naval Hydrodynamics, Washington, DC, 9-14 August 1998.

**DISSERTATION DIRECTED:**

Merrill, C.F., "Spray Generation from Liquid Wall Jets Over Smooth and Rough Surfaces," Doctor of Philosophy Dissertation, Naval Postgraduate School, September 1998.

**DoD KEY TECHNOLOGY AREA:** Surface/Under Surface Vehicles - Ships and Watercraft

**KEYWORDS:** Hydrodynamics, Drop Formation, Spray

## VORTEX BREAKDOWN IN TURBULENT SWIRLING FLOWS

**Turgut Sarpkaya, Distinguished Professor**
**Department of Mechanical Engineering**
**Sponsors: National Science Foundation and Naval Postgraduate School**

**OBJECTIVE:** Trailing vortices, swirling flows in pipes, vortical flows above sweptback wings at large angles-of-attack, flows in closed containers with a rotating lid, and columnar vortices in atmosphere may experience breakdown: *The transformation of a slender vortex into three-dimensional forms.* Where, how, and under what circumstances does this transformation occur in *viscous* vortical flows constitute the essence of the breakdown problem.

**SUMMARY:** The mean velocities and turbulence intensities were measured in forward-scattering mode with a three-component Laser Doppler Anemometer. The results refute the conjectures that the circumstances of breakdown are insensitive to the Reynolds number and the local turbulence properties. These two factors have a strong influence on the evolution of the flow. Of all the known forms, the spiral emerges as the most fundamental breakdown form. All other forms may be regarded as transient states affected by various types of instabilities. At very high Reynolds numbers the breakdown acquires forms and characteristics never seen before: Extremely high rates of revolution, onset of core-bifurcation or core-trifurcation, intense nonisotropic turbulence, and a conical shape.

**PUBLICATION:**

Sarpkaya, T. and Novak, F., "Turbulent Vortex Breakdown: Experiments in Tubes at High Reynolds Numbers," Book Chapter in *Slender Vortices,* pp. 287-296, E. Krause and K. Gersten, (eds.), Kluwer Press, Dordrecht, The Netherlands, 1998.

**CONFERENCE PRESENTATION:**

Novak, F. and Sarpkaya, T., "Turbulent Vortex Breakdown at High Reynolds Numbers," Aerospace Sciences Meeting of the American Institute of Aeronautics and Astronautics, Reno, NV, to be presented, January 1999.

**DISSERTATION DIRECTED:**

Novak, F., "An Experimental Investigation of Vortex Breakdown in Tubes at High Reynolds Numbers," Doctor of Philosophy Dissertation, Naval Postgraduate School, September 1998.

**DoD KEY TECHNOLOGY AREAS:** Aerospace Propulsion and Power, Air Vehicles

**KEYWORDS:** Vortex Breakdown, Vorticity, Swirling Flow

## SHOCK AND VIBRATION ANALYSIS IN SUPPORT OF DDG-51 CLASS SHOCK FOLLOW-ON ACTIONS

**Young S. Shin, Professor**
**Department of Mechanical Engineering**
**Sponsors: Naval Sea Systems Command and Naval Postgraduate School**

**OBJECTIVE:** To perform shock and vibration analysis in support of DDG-51 Class shock follow-on actions including DDG-51 Flight IIA ship shock analysis to predict dynamic responses of ship system and subsystem structures to underwater explosions.

**SUMMARY:** This task is a part of team project consisting of NAVSEA, NSWC, Electric Boat, Weindlinger Associates, Gibs and Cox, and NPS. The FY98-task was to conduct surface ship shock modeling and simulation of DDG-53. The task includes investigating whether the ship shock modeling and simulation can predict the dynamic transient responses of ship system and subsystem structures accurately. The analysis takes into account of the effects of the fluid-ship structure interaction and cavitation effects on a surface ship model (DDG-53) due to a large scale underwater explosion.

**PUBLICATION:**

Shin, Y.S. and Santiago, L.D., "Surface Ship Shock Modeling and Simulation: 2D Analysis," *Journal of Shock and Vibration*, Vol. 5, No. 2, 1998.

**CONFERENCE PRESENTATIONS:**

Shin, Y.S., Wood, S.L., and Park, S.Y., "Ship Shock Simulation of DDG53 John Paul Jones," 69th Shock and Vibration Symposium, Minneapolis/St. Paul, MN, 12-16 October 1998.

Shin, Y.S. and Wood, S.L., "Cavitation Effects to Ship-Like-Box Structure for Underwater Explosion," 69th Shock and Vibration Symposium, Minneapolis/St. Paul, MN, 12-16 October 1998.

**THESES DIRECTED:**

Wood, S.L., "Cavitation Effects on a Ship-Like Box Structure Subjected to an Underwater Explosion," Master's Thesis, Naval Postgraduate School, September 1998.

Beiter, K.A., "The Effect of Stiffener Smearing in a Ship-Like-box Structure Subjected to an Underwater Explosion," Master's Thesis, Naval Postgraduate School, June 1998.

**DoD KEY TECHNOLOGY AREAS:** Surface/Under Surface Vehicles-Ships and Watercraft, Modeling and Simulation

**KEYWORDS:** Surface Ship, Underwater Explosion, Cavitation, Fluid-Structure Interaction

## SURVIVABILITY OF SHIPBOARD PERSONNEL SUBJECTED TO HIGH AMPLITUDE, LOW FREQUENCY SHOCK INDUCED BY UNDERWATER EXPLOSION

**Young S. Shin, Professor**
**Department of Mechanical Engineering**
**Sponsor: Unfunded**

**OBJECTIVE:** The goal is to develop a method for estimating crew survivability to a given underwater explosion event. Biodynamic simulations of human response to shock induced deck excitation were performed for both male and female subjects using the Articulated Total Body (ATB) program. Subsequently, the results were used to estimate the biodynamic

response and injury potentials for human males and females in various positions in a vessel to an underwater explosion event.

**SUMMARY:** The Articulated Total Body (ATB) modeling approach was used to model the motion of a human (or test dummy such as the Hybrid III) in response to ship shock. The investigation was conducted to simulate the response such as the gross motion, the contact forces between body parts and the surrounding environment, the torque within the body's joints, and the relative accelerations of the body parts (head acceleration with respect to the upper torso, for example). In addition, the description of the injuries investigated and their associated injury tolerances were studied.

**PUBLICATIONS:**

Oglesby, D.B. and Shin, Y.S., "Simulation of Human Male and Female Biodynamic Response to UNDEX Events," *Proceedings of the 69th Shock and Vibration Symposium,* CD-ROM, Minneapolis/St. Paul, MN, 12-16 1998.

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**THESIS DIRECTED:**

Oglesby, D.B., "Human Male and Female Biodynamic Response to Underwater Explosion Events," Master's and Engineers Thesis, Naval Postgraduate School, Monterey, CA, March 1998.

**DoD KEY TECHNOLOGY AREA:** Materials, Processes, and Structures

**KEYWORDS:** Underwater Explosion, Human Survivability, Biodynamic Response

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## THE EFFECT OF STIFFENER SMEARING IN A SHIP-LIKE BOX STRUCTURE SUBJECTED TO AN UNDERWATER EXPLOSION

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**Master of Science in Mechanical Engineering-June 1998**
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Shock trials for naval vessels are a requirement for each new class of surface ships in the U.S. Navy. With understanding the technology of underwater shock analysis and considering the rising costs of conducting actual shock tests, computer simulation of shock trials is becoming more and more attractive. Unfortunately, finite element models can be quite large and require sufficient amounts of computer memory and time to run a shock analysis. This thesis investigates the effects of reducing the element size of a shiplike box model subject to an underwater explosion. Known as smearing, this process combines the density and stiffness properties of the removed elements into the remaining material of the model. Positive results from computer simulation could greatly affect the manner in which shock trials are conducted with future ship classes.

**DoD KEY TECHNOLOGY AREA:** Modeling and Simulation

**KEYWORDS:** Underwater Explosion, Smearing, Surface Model

## THEORETICAL INVESTIGATION OF ROTOR ACCELERATION SCHEDULING THROUGH CRITICAL SPEED

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**B.S., University of Missouri-Rolla, 1988**
**Master of Science in Mechanical Engineering-December 1997**
**Advisor: Knox T. Millsaps, Jr., Department of Mechanical Engineering**

An analytical investigation was conducted to study the amplitude of lateral vibrations and vibrational energy and power of an unbalanced rotor passing through its first lateral bending critical speed. A two degree-of-freedom lumped mass, damping and stiffness model was developed to simulate the response of a simply supported, single disk rotor. Given an arbitrary input acceleration or deceleration, the equations of motion were solved numerically using a fourth order Runge-Kutta routine. The routine used a time step that corresponded to a constant angular phase of rotation. The relationship between the forcing function and lateral vibrational velocity was determined in order to predict the instantaneous power input to the rotor due to the unbalanced rotor. The computer model incorporating an acceleration schedule yielded a result that predicts acceleration scheduling in the location about the critical speed is unable to lower the amplitude of lateral vibrations.

**KEYWORD:** Accelerating Rotor

**DoD KEY TECHNOLOGY AREAS:** Aerospace Propulsion and Power, Modeling and Simulation

## MEASUREMENT OF SYNCHRONOUS FORCES AND FLOW NON-UNIFORMITY IN AN AXIAL COMPRESSOR

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**Master of Science in Mechanical Engineering-December 1997**
**Advisor: Knox T. Millsaps, Jr., Department of Mechanical Engineering**

Time resolved pressure measurements on a compressor case were acquired for several uniform and non-uniform tip clearances. High frequency response pressure transducers were placed at several axial locations near the second stage axial rotor on the outer casing of an Allison C-250 compressor. Data were acquired at several fixed time intervals. The amplitude of the

blade-to-blade variations and once per revolution static pressure distributions on the case were recorded for an "as is" compressor. The synchronous forces due to possible imperfections were determined using a high hub-tip ratio assumption.

**KEYWORDS:** Turbomachinery, Rotor Dynamics

**DoD KEY TECHNOLOGY AREAS:** Other (Turbomachinery, Rotor Dynamics)

## MODEL FOR ESTIMATION OF THERMAL HISTORY PRODUCED BY A SINGLE PASS UNDERWATER WET WELD

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**B.S., United States Naval Academy, 1989**
**Master of Science in Mechanical Engineering-December 1997**
**Advisor: Alan G. Fox, Department of Mechanical Engineering**

Thermal history calculations for single pass underwater wet weldments were made by solving the appropriate heat transfer equations using the three-dimensional Crank-Nicholson finite difference method. The Adams approach, which defines the fusion line temperature as a boundary condition, was adopted. Tsai and Masubuchi's semi-empirical correlation, defining the surface heat transfer coefficient of underwater weldments, was used to determine the heat loss through the surface of the welded plate. As expected, the calculated cooling rates in heat affected zones (HAZs) of underwater wet welded ferritic steels were found to be somewhat faster than equivalent cooling rates calculated for the same weldments generated in air. However, the effect of water temperature on cooling times in the HAZ between 800∞ and 500∞C (the parameter conventionally used to measure the cooling rate in the HAZ ) was found to be minimal. These calculations suggest that HAZ microstructure of underwater wet welded ferritic steels should be independent of water temperature. This prediction was confirmed by microstructural studies of samples of ASTM A516 grade 70 steel which were underwater wet welded at water temperatures of 31∞, 10∞ and 3∞C respectively and for which similar HAZ microsructures were obtained in each case.

**KEYWORDS:** Underwater Wet Welding, Modeling of Heat Transfer in Welding

**DoD KEY TECHNOLOGY AREA:** Materials, Processes, and Structures

## EXPERIMENTAL STUDY OF ZERO MEAN OSCILLATORY FLOW FORCES ON CIRCULAR CYLINDERS

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**B.S., University of Miami, 1990**
**Master of Science in Mechanical Engineering-March 1998**
**Advisor: Ashok Gopinath, Department of Mechanical Engineering**

This thesis examines the forces in a zero mean current oscillatory fluid flow on circular cylinders. Experimental force data on different sized aluminum rods exposed to a standing acoustic wave in a nitrogen filled acoustic chamber is obtained from suitably mounted strain gages. Drag, inertia, and lift coefficients and KC, Reynolds, and beta numbers are determined, and the rods' temporal and spatial deformations are examined. The use of high nitrogen pressures reduces kinematic viscosity yielding high Reynolds number flow regimes. This technique can be used in the prediction of forces on ocean structures exposed to oscillatory flows.

**DoD KEY TECHNOLOGY AREAS:** Modeling and Simulation, Other (Marine and Offshore Structures)

**KEYWORDS:** Oscillatory Flow, Acoustic Standing Wave, Sea Forces, Offshore Structures, Cable Runs, Structural Response, Drag Coefficient

## A MODEL FOR DEFORMATION OF CONTINUOUS FIBER COMPOSITES UNDER ISOTHERMAL CREEP AND THERMAL CYCLING CONDITIONS

**Myles Esmele II-Lieutenant Commander, United States Navy**
**B.S., University of the State of New York, Albany, 1980**
**Master of Science in Mechanical Engineering-December 1997**
**Advisor: Indranath Dutta, Department of Mechanical Engineering**

A model to describe the internal stress and strain states in a continuous fiber composite during thermal cycling and/or isothermal excursion has been developed. The model extends a previously developed model by incorporating the effects of: (1) changing matrix creep mechanisms and (2) fiber-matrix interfacial sliding via diffusional creep. Results from sample calculations incorporating these effects during both thermal cycling and isothermal creep are presented. It is envisioned that such a model will be useful in discerning the predominant matrix creep mechanism at various times for a given applied stress and temperature, and thus enable the generation of transient deformation mechanism maps for the composite.

**KEYWORDS:** Continuous Fiber, Metal Matrix Composites, Creep Mechanisms, Isostrain, Non-isostrain Deformation, Interfacial Sliding, Deformation Mechanism Maps

**DoD KEY TECHNOLOGY AREAS:** Materials, Processes, and Structures, Modeling and Simulation

## AXIAL CONDUCTION EFFECTS IN LAMINAR DUCT FLOWS

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**B.S., Turkish Naval Academy, 1992**
**Master of Science in Mechanical Engineering-June 1998**
**Advisor: Ashok Gopinath, Department of Mechanical Engineering**

A numerical model for heat transfer in laminar duct flows has been developed using the finite difference method to explore the significance and extent of "back-conduction" at low Peclet numbers. The calculations have been carried out for flows between parallel plates and in circular tubes by using different Peclet numbers in the range of 0.05 to 100. For both situations constant heat flux and constant wall temperature boundary conditions were used. The validity of the results has been checked by comparison with some existing results in the literature, and extended to a wider range of parameters including conjugate wall conduction effects. The results are presented for bulk mean temperature variation, Nusselt number behavior, and energy absorbed before the heated section, for cases with and without wall conduction. Such axial conduction effects may be an important feature in the thermal characterization of microtubes, which are to be used in microheat exchangers.

**DoD KEY TECHNOLOGY AREA:** Modeling and Simulation

**KEYWORDS:** Laminar Duct Flows, Convection and Conduction Heat Transfer, Axial Conduction, Micro-heat Exchangers

## DEVELOPMENT AND CALIBRATION OF A TORSIONAL ENGINE MODEL FOR A THREE-CYLINDER, TWO-STROKE DIESEL ENGINE

**James W. Hudson-Lieutenant, United States Navy**
**B. S., United States Naval Academy, 1990**
**Master of Science in Mechanical Engineering-December 1997**
**Advisor: Knox T. Millsaps, Jr., Department of Mechanical Engineering**

An experimental and analytical investigation was conducted to develop a calibrated torsional model of a three-cylinder, two-stroke diesel engine. A Detroit Diesel 3-53 engine was instrumented for time-resolved measurement of cylinder firing pressures and high resolution near instantaneous shaft speed using a 720 and a 3,600 count per revolution optical encoder. Data were taken for three speeds and three torques for a total of nine conditions. A six degree-of-freedom torsional vibra-

tion model of the crankshaft, connecting rods, and pistons was developed. The nonlinear inertias, due to the reciprocating pistons, were included along with linear stiffness and damping. The equations of motion were numerically integrated over a cycle to obtain predicted response. The predicted response was compared to the measured response at the free end of the crankshaft.

**KEYWORDS:** Diesel, Torsional Vibration Model, Cylinder Pressure Prediction

**DoD KEY TECHNOLOGY AREAS:** Aerospace Propulsion and Power, Environmental Quality, Ground Vehicles, Modeling and Simulation

## INVESTIGATION OF BIOMECHANICAL RESPONSE DUE TO FRAGMENT IMPACT ON BALLISTIC PROTECTIVE HELMET

**Quinten M, King-Lieutenant, United States Navy**
**B.S., Renssaeler Polytechnic Institute, 1990**
**Master of Science in Mechanical Engineering-March 1998**
**Advisor: Young W. Kwon, Department of Mechanical Engineering**

Technology has increased dramatically over the last 25 years. It has allowed the development of personnel body armor capable of preventing penetration of fragments traveling in excess of 2000 ft/s (609 m/s). However these strides have also exposed the body to greater impact energies without a lethal penetration. The objective of this research was to examine how the body in particular the Head-Neck Complex responds to these impacts. A finite element model was developed to characterize the behavior of this biomechanical system. This model was then validated against existing experimental work from the automotive industry. The validated model was then subjected to impacts at different positions to induce different load cases. Each set of results was then compared to Head Injury Criteria (HIC), Abbreviated Injury Scale (AIS), and the Injury Assessment Reference Values (IARVS) for evidence of injury potential. Disc stiffness was found to be proportional to the injury potential. Rupture of the disc was considered likely for five of the six cases examined. Fracture of the vertebral body was considered likely in three of the six cases. Suggestions for future research are included in the hopes of furthering research into this area.

**DoD KEY TECHNOLOGY AREA:** Modeling and Simulation

**KEYWORDS:** Finite Element Modeling, Spine, Cervical, Biomechanics, Body Armor

## A NUMERICAL STUDY OF HEAT TRANSFER BEHAVIOR IN WELDING

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**B.S., Turkish Naval Academy, 1992**
**Master of Science in Mechanical Engineering-June 1998**
**Advisor: Ashok Gopinath, Department of Mechanical Engineering**

A numerical model has been developed for three-dimensional transient conduction based temperature calculations in underwater wet welding on a thick rectangular plate. The numerical scheme is based on a fully implicit finite volume method. A variable mesh size centered around the moving heat source, and temperature dependent thermal properties have been used in the calculations. Convective, radiative and boiling surface thermal conditions have also been included. The weld pool region itself has been modeled as a solid region of thermal conductivity higher than the surrounding unmelted region. The validity of the results was checked by comparison with Rosenthal's three-dimensional solution for a moving point heat source, and other results in the literature.

**DoD KEY TECHNOLOGY AREAS:** Materials, Processes, and Structures, Modeling and Simulation

**KEYWORDS**: Underwater Wet Welding, Heat Transfer, Finite-Volume Numerical Method

## INVESTIGATION OF BIOMECHANICAL RESPONSE DUE TO FRAGMENT IMPACT ON BALLISTIC PROTECTIVE HELMET

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**B.S., Renssaeler Polytechnic Institute, 1990**
**Master of Science in Mechanical Engineering-March 1998**
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**DoD KEY TECHNOLOGY AREA:** Modeling and Simulation

**KEYWORDS:** Finite Element Modeling, Spine, Cervical, Biomechanics, Body Armor

## PHASE SINTER FORMING OF A MODEL CERAMIC SYSTEM

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**Master of Science in Mechanical Engineering-September 1998**
**Advisors: Indranath Dutta, Department of Mechanical Engineering**
**Ashok Gopinath, Department of Mechanical Engineering**

The feasibility of a new manufacturing process of ceramic materials in which net shaped products are produced via sintering and simultaneously deforming is studied. A suitable model system of $SiO_2$-$B_2O_3$ is chosen due to its desirable properties for liquid phase sintering and its ability to be tested under atmospheric conditions. Samples of compacted powder are prepared and characterized via x-ray diffraction and scanning electron microscopy. Tests to determine the ability of the system to undergo Liquid Phase Sintering are studied. Deformation of samples in compression with concomitant liquid phase sintering at nominally constant true strain rates is performed, and the effects of the amount of liquid phase present are investigated. Problems associated with the liquid phase sinter forming process are identified, and recommendations are suggested for future studies.

**DoD KEY TECHNOLOGY AREA:** Materials, Processes, and Structures

**KEYWORDS:** Ceramic Powder Processing, Liquid Phase Sintering, High Temperature Deformation, Superplasticity in Ceramics, Creep Mechanisms, Deformation in the Presence of a Liquid Phase

## ANALYSIS OF UNDERBEAD CRACKING IN UNDERWATER WET WELDMENTS ON A516 GRADE 70 STEEL

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**B.S., United States Coast Guard Academy, 1994**
**Master of Science in Mechanical Engineering-September 1998**
**Advisor: Alan G. Fox, Department of Mechanical Engineering**

The use of underwater weldments on U.S. Naval Vessels is highly desirable due to the ability of performing repairs without costly dry dock expenses. The primary problem with underwater wet weldments is underbead cracking in the heat affected zone (HAZ). The fundamental factors causing underbead cracking in underwater wet weldments using a shielded metal arc welding (SMAW) process are high quench rates, slag inclusions, diffusible hydrogen levels and porosity.

The weld metal analysis included use of optical and scanning microscopy as well as microhardness testing. Three weld samples made at 5∞C, 12∞C, and 25∞C water temperature were analyzed in this thesis. HAZ underbead cracking was present in all three welds analyzed although the 5∞C sample was the only weld that exhibited extensive cracking whereas the 25∞C sample only had cracking near the upper 50% of the weld passes. Crack origination in all three samples near the cap was evident and was most likely due to small levels of bead tempering at this location.

This thesis addresses the mechanisms of the cracking as well as the effects of diffusible hydrogen, cooling rates, and water temperatures on wet weldments.

**DoD KEY TECHNOLOGY AREAS:** Materials, Processes, and Structures, Surface/Under Surface Vehicles – Ships and Watercraft

**KEYWORDS:** Underwater Wet Welding, Hydrogen Cracking, Underbead Cracking, Non-Metallic Inclusions, Shielded Metal Arc Welding

## IDENTIFICATION OF RANDOM LOADS IMPINGING ON THE RAH-66 COMANCHE HELICOPTER EMPENNAGE USING SPECTRAL ANALYSIS

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**B.S., Georgia Institute of Technology, 1986**
**Master of Science in Aeronautical Engineering-June 1998**
**Advisors: E. Roberts Wood, Department of Aeronautics and Astronautics**
**Donald A. Danielson, Department of Mathematics**
**Joshua H. Gordis, Department of Mechanical Engineering**

The Army RAH-66 Comanche Helicopter is currently undergoing developmental flight testing. The empennage of the aircraft is experiencing buffeting where the horizontal and vertical tail vibrate at resonant frequencies. These high buffet loads are manifested in higher than anticipated fitting loads, particularly on the tail, and vibrations in the crew stations and at the nose cone where the targeting sensors are located. Significant effort has been devoted to identifying the sources of excitation and the nature of the structural response. This thesis determines the location and magnitude of empennage vibratory airloads. Because the nature of the excitation is a random function, spectral analysis is used. To obtain the loads, a three-step process was utilized. First, from aircraft differential pressure transducers and accelerometers, the spectral content of the response and excitation was determined Then, using a NASTRAN model modified to replicate the flight test aircraft, frequency response functions were determined between selected points on the aircraft's tail and the accelerometers. Finally, using this information, a solution was obtained for the vibratory airloads. Having provided information on the nature of the driving forces, structural modifications can be made that move the natural frequencies away from the frequencies of the applied airloads.

**DoD KEY TECHNOLOGY AREA:** Air Vehicles

**KEYWORDS:** RAH-66 Comanche Helicopter, Random Vibrations, Comanche Tail Section, Structural Analysis, Spectral Analysis, NASTRAN Analysis

## FREQUENCY MODULATION TECHNIQUE FOR MACHINERY NOISE REDUCTION

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**B.S., University of Maryland, College Park, 1990**
**Master of Science in Mechanical Engineering-March 1998**
**Advisor: Young S. Shin, Department of Mechanical Engineering**

A ship's or submarine's acoustic signature is often characterized by the low frequency narrow band noise components of its rotating machinery. By reducing or altering machinery noise components, a naval vessel can reduce its vulnerability to detection and classification. This study presents and evaluates the frequency modulation technique as a potential method to reduce machinery narrow band noise levels.

The research examines both the experimental and numerical implementation of frequency modulation for the case of rotating machinery. Specifically, a dc motor's operating frequency is modulated about a center frequency of 50 hertz by adding a sinusoidally varying voltage to the base voltage. The amplitude and frequency of the sinusoidal signal are varied and the resultant effects on the noise spectra are studied. Experimental results demonstrate that machinery narrow band signatures may be reduced at the expense of elevated broad band levels. The numerical simulation characterizes general trends and the relative reductions obtainable with frequency modulation.

**DoD KEY TECHNOLOGY AREAS:** Surface/Under Surface Vehicles - Ships and Watercraft, Modeling and Simulation, Other (Vibration Reduction)

**KEYWORDS:** Frequency Modulation, Vibration Reduction, Noise Reduction, Permanent Magnet Motor, Quieting

## APPLICATION OF NUMERICAL OPTIMIZATION TECHNIQUES TO SURFACE COMBATANT DESIGN SYNTHESIS

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**Master of Science in Mechanical Engineering-September 1998**
**Advisors: Matthew D. Kelleher, Department of Mechanical Engineering**
**Charles N. Calvano, Department of Mechanical Engineering**

This thesis presents the effort to incorporate a numerical optimizer into an existing ship design synthesis math model. The goal is to improve the functionality of the model while retaining the intrinsic value of the model's friendly user interface, which is greatly advantageous for its use as a learning tool. A description of the math model and its origin and intent are presented along with a discussion of numerical optimization techniques and tools. The integration and linking software is described along with the actual Integrated Ship Design System. Results of comparison and sensitivity studies are also presented.

**DoD KEY TECHNOLOGY AREAS:** Surface/Under Surface Vehicles - Ships and Watercraft, Modeling and Simulation, Computing and Software

**KEYWORDS:** Ship Design Synthesis, Numerical Optimization, MIT Simplified Math Model, Mathcad, Matlab Optimization, MathConnex, Objective Function, Constraint Function

## AUV FAULT DETECTION USING MODEL BASED OBSERVER RESIDUALS

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**M.B.A., National University, 1995**
**Mechanical Engineer-June 1998**
**Advisor: Anthony J. Healey, Department of Mechanical Engineering**

In order for the Navy's next generation Unmanned Undersea Vehicles to be more robust to software/hardware faults, on-line failure detection and resolution is needed. Typically, fault detection methods include limits and trends analysis, model free, and model based techniques. Here, model based observers are proposed for the detection of fault induced dynamic signals in the diving, steering, and roll control systems. Such automatic fault detection systems were designed and implemented in a *Simulink* model of the "2 1UUV." In the course of conducting simulations with the model, numerous vehicle behaviors were studied and detection response was verified. In addition, the model based observer residuals may be designed to distinguish actuator faults from wave disturbances and fin faults from maneuvering responses.

**DoD KEY TECHNOLOGY AREAS:** Surface/Under Surface Vehicles-Ships and Watercraft, Modeling and Simulation

**KEYWORDS:** Model Based Observers, 21UUV, AUVs, Fault Detection

## SPRAY GENERATION FROM LIQUID WALL JETS OVER SMOOTH AND ROUGH SURFACES

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**M.S., Naval Postgraduate School, 1993**
**M.E., Naval Postgraduate School, 1993**
**Doctor of Philosophy in Mechanical Engineering-September 1998**
**Advisor: Turgut Sarpkaya, Department of Mechanical Engineering**
**Committee: Matthew D. Kelleher, Department of Mechanical Engineering**
**Knox T. Millsaps, Department of Mechanical Engineering**
**Garth V. Hobson, Department of Aeronautics and Astronautics**
**David Canright, Department of Mathematics**

This is an experimental investigation of the filaments and drops generated at the free surface of liquid wall jets formed over smooth- and sand-roughened surfaces. The jet characteristics and the geometric properties of the filaments and drops were measured from images captured using high-speed digital cameras. A statistical investigation of the various properties revealed the characteristic behavior of the filaments and drops as a function of the relative wall roughness, wall curvature and jet inertia. For this investigation, the wall jet Reynolds number ranged from $2.6¥10^4$ to $4.5¥10^4$, the Froude number from 19 to 33 and the Weber number from 1600 to 4700.

The emphasis herein was on the physics of the process rather than the development of empirical relationships. As such, the results indicate that spray generation from a wall jet is a boundary-layer-driven phenomenon, requiring that the jet be in a highly supercritical state (Fr » 1). Wall roughness reduces the minimum necessary level of supercriticality, but it is not a prerequisite condition for the formation of drops. While increasing the jet inertia enhances the drop formation process, concave wall curvature tends to reduce the quantity and the energy of the drop forming events.

**DoD KEY TECHNOLOGY AREA:** Surface/Under Surface Vehicles - Ships and Watercraft

**KEYWORDS:** Spray, Drops, Jets, Bow Sheets, Turbulent Boundary Layers, Liquid Sheets

## AIRCRAFT TRAILING VORTICES: GREENE'S MODEL VERSUS FIELD DATA

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**B.S.M.E, Turkish Naval Academy, 1992**
**Master of Science in Mechanical Engineering-June 1998**
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Trailing vortices shed from aircraft pose great danger to following aircraft. Too much separation time reduces the effective use of airports, while too little separation poses grave dangers. The accurate determination of the optimal separation time between two following aircraft in a landing corridor became a major international concern. The LIDAR data, obtained by the Lincoln/MIT laboratories at various airports, have been used to analyze in as much detail as possible the velocity, circulation, and the decay mechanisms of trailing vortices. The results have been used to assess the predictions of Greene's model for a number of cases towards the creation of a more reliable model for use in all types of environmental conditions.

**DoD KEY TECHNOLOGY AREA:** Air Vehicles

**KEYWORDS:** Vortex, Aircraft, Wake

## EVALUATION OF THE MECHANICAL PROPERTIES AND EFFECTIVENESS OF COUNTERMINE BOOTS

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**Master of Science in Mechanical Engineering-March 1998**
**Advisor: Young W. Kwon, Department of Mechanical Engineering**

The first goal of this project was to determine the mechanical properties of countermine boots and protective overboots that are currently available to U.S. soldiers. The second goal of this project was to conduct a qualitative analysis to determine the effectiveness of the boots. This was done by determining their ability to dissipate a blast force equivalent to a typical anti-personnel landmine. This was followed by a parametric study which involved altering the component materials in an effort to determine if the effectiveness of the boots varied as the materials changed.

The soles of both boots were made from identical materials. All the materials used in the boots' soles were tested to determine their mechanical material properties using an Instron uniaxial testing machine. All testing was conducted on multiple specimens to verify repeatability. The material data was tabulated and the stress-strain curves are included in this report.

A finite element analysis was conducted to evaluate the effectiveness of the countermine boot based upon accepted tolerance levels of the lower bones of the body. Next, the materials and their dimensions were modified in the finite element model to determine how these modifications would impact the boots' effectiveness.

**DoD KEY TECHNOLOGY AREAS:** Modeling and Simulation, Other (Biomechanical)

**KEYWORDS:** Finite Element Method, Material Properties, Mechanical Testing

## AN EXPERIMENTAL INVESTIGATION OF VORTEX BREAKDOWN IN TUBES AT HIGH REYNOLDS NUMBERS

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**M.S., Naval Postgraduate School, 1992**
**M.E., Naval Postgraduate School, 1992**
**Doctor of Philosophy in Mechanical Engineering-September 1998**
**Advisor: T. Sarpkaya, Department of Mechanical Engineering**
**Committee: Matthew Kelleher, Department of Engineering**
**F. Kevin Owen, Department of Mechanical Engineering**
**David Netzer, Department of Aeronautics and Astronautics**
**Richard Franke, Department of Mathematics**

This thesis deals with non-cavitating swirling flows with vortex breakdown in various tubes. Phenomenological and quantitative investigations were carried out at Reynolds numbers ($Re_D = U_0D_0/n$) as high as 300,000. It was shown that a high $Re_D$ vortex transitions to its new state (breaks down) via a rapidly spinning spiral form, as demonstrated with 4,000 frame per second video, short exposure time (6 ns) imaging, and Digital Particle Image Velocimetry. Of the known types, the spiral emerges as the fundamental breakdown form, and the axisymmetric bubble may now be regarded as a relatively low $Re_D$ occurrence that is bypassed at sufficiently high $Re_D$. Some new phenomena were observed at high $Re_D$: Extremely rapid spiral rotation (over 1,000 revolutions per second), core bifurcation, and reversals in the sense of the spiral windings. Familiar features of breakdowns, such as the transition from jet-like to wake-like axial velocity profiles and the rapidly expanding vortex core, were observed in extensive time averaged velocity and turbulence profiles ascertained with Laser Doppler Velocimetry. However, a mean stagnation point and recirculation were absent in the highest $Re_D$ flow. The core meandering and stagnation point darting in the turbulent flow field were quantified and discussed in detail.

**DoD KEY TECHNOLOGY AREA:** Air Vehicles

**KEYWORDS:** Vortex Breakdown, Turbulence, Laser Doppler Velocimetry, Particle Image Velocimetry, Swirling Flow, Spectra

## TRANSIENT RESPONSE ANALYSIS OF THE 72 INCH TAC-4 RUGGEDIZED SHIPBOARD RACK SUBJECTED TO AN UNDERWATER EXPLOSION EVENT

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**Master of Science in Mechanical Engineering-June 1998**
**Mechanical Engineer-June 1998**
**Advisor: Young S. Shin, Department of Mechanical Engineering**

The finite element modeling and subsequent transient analysis of the 72 Inch TAC-4 Rugged Rack computer system (configurations 000 1AA and OOO3AA only), currently employed in U.S. Navy shipboard applications, has been performed to determine the system's response to simulated shock inputs. This rack is designed to allow incorporation of commercial-off-the-shelf (COTS) computer systems for naval tactical computing requirements while still meeting MJL-STD-901D, the applicable shock specification. By showing the viability of this computer simulation of the shock response of the current TAC-4 rack system, an argument for a lessening of the actual physical testing requirements for acceptance of future TAC systems can be made.

**DoD KEY TECHNOLOGY AREA:** Modeling and Simulation

**KEYWORDS:** Transient Analysis, Finite Element Method, TAC-4, COTS, Shock Analysis, UNDEX

## HUMAN MALE AND FEMALE BIODYNAMIC RESPONSE TO UNDERWATER EXPLOSION EVENTS

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**Master of Science in Mechanical Engineering-June 1998**
**Mechanical Engineer-June 1998**
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Ship survivability is a complex issue. For a ship to remain a viable warfighting asset following damage resulting from enemy munitions such as mines or torpedoes, the ship's crew must remain sufficiently uninjured to be capable of employing the ship's weapons systems. Sophisticated computer simulations of human response, such as those made possible by the Articulated Total Body (ATB) Model, may be used to estimate injury potentials, and thus crew survivability, during underwater explosion events. With this goal in mind, accelerometer data and video footage recorded during live fire testing were used to generate and validate ATB models for both a seated and a standing Hybrid III Anthropomorphic Test Device (ATD). Subsequently, these models were used to estimate the biodynamic response and injury potentials for both male and female human subjects in a vessel subjected to underwater explosion events. This established a method for evaluating crew survivability for a given underwater explosion induced deck excitation.

**DoD KEY TECHNOLOGY AREA:** Modeling and Simulation

**KEYWORDS:** Biodynamic Response, Underwater Explosion, Articulated Total Body Program

## PRELIMINARY DESIGN STUDY FOR AN ENHANCED MIXING EDUCTOR FOR GAS TURBINE EXHAUST SYSTEMS

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**Master of Science in Mechanical Engineering-March 1998**
**Advisor: Knox T. Millsaps, Jr., Department of Mechanical Engineering**

A preliminary design study was conducted to scale the geometry for a new, enhanced mixing eductor for gas turbine exhaust systems. An analytical model was developed to predict the secondary flow and hence the exhaust temperature at the exit to the mixing tube. The model consists of an ideal one-dimensional flow model with a correction factor applied to the secondary mass flow. This factor was chosen to match existing experimental data. This calibrated model was then used to perform a design study to scale the cross sectional areas and assess pressure loss versus performance. A concept with a square mixing tube and multiple high aspect ratio primary nozzles was developed and the baseline geometry was scaled. Two primary nozzles pattern arrangements are provided that should obtain the required mixing in the reduced length.

**DoD KEY TECHNOLOGY AREAS:** Modeling and Simulation, Other (Surface Ships)

**KEYWORDS:** Modeling and Simulation, Gas Turbines, Eductors

## BIAS EFFECTS ON MOTION STABILITY OF SUBMERSIBLE VEHICLES

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**B.S., Maine Maritime Academy, 1991**
**Master of Science in Mechanical Engineering-September 1998**
**Advisor: Fotis A. Papoulias, Department of Mechanical Engineering**

This thesis analyzes the nonlinear characteristics of motion stability of a submersible vehicle in combined sway, yaw, and roll motions. Previous results, at zero pitch angles, indicate that limit cycles are generated as a result of loss of stability. In

this work, these results are extended to include nonzero pitch angles. This analysis can determine how changes in vehicle parameters and loading conditions will affect its operation and performance. Stability domains are generated for a variety of vehicle and environmental parameters. A nonlinear analysis is conducted in order to assess the stability characteristics of the resulting limit cycles. The results can lead to design guidelines for improving vehicle operational envelopes.

**DoD KEY TECHNOLOGY AREAS:** Surface/Under Surface Vehicles – Ships and Watercraft, Modeling and Simulation

**KEYWORDS:** Roll, Sway, Yaw, Stability of Motion, Periodic Solutions, Bifurcations

## COMPUTER SIMULATION OF A TWO-PHASE CAPILLARY PUMPED LOOP (CPL) USING SINDA/FLUINT

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**B.S., United States Naval Academy, 1991**
**Master of Science in Mechanical Engineering-December 1997**
**Advisor: Matthew D. Kelleher, Department of Mechanical Engineering**

The heat transfer performance of a prototype capillary pumped loop (CPL) test bed from the U.S. Air Force Phillips Laboratory is modeled using numerical differencing techniques. A commercial computer code was used to create the model and simulate performance over a wide range of operating conditions. Steady-state and transient performance were modeled as part of the initial phase of testing in a program designed to evaluate the effectiveness and reliability of capillary pumped loop technology for use in spacecraft thermal control. The performance baseline developed in this phase of testing will serve as the foundation for continued research and development of this technology.

**KEYWORDS**: Capillary Pumped Loop (CPL), Evaporator, Noncondensible Gas (NCG) Trap

**DoD KEY TECHNOLOGY AREAS**: Space Vehicles, Modeling and Simulation

## MULTIPLE AUTONOMOUS VEHICLES FOR MINEFIELD RECONNAISSANCE AND MAPPING

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**Master of Science in Mechanical Engineering-December 1997**
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The development of numerical search modeling for Autonomous Search Vehicles (ASV's) is an essential tool for development of ASV strategy using groups of small, crawling vehicles. Reconnaissance of surf-zone bottoms for mines and obstacles, as well as providing an environmental mapping capability, is the objective. These models allow numerical simulations to be conducted that determine the relationships between search times, target and obstacle sensing radius, vehicle speed and numbers of vehicles using simple, preprogrammed search strategies. The results from these simulations on initial models can then be used to determine the overall system performance. More complex models can then be developed using search strategies that include directed search, avoidance behaviors, networking and mapping with sufficient navigational accuracy. With sufficient information on the behavior of these vehicles, the ultimate goal of providing an autonomous reconnaissance and neutralization capability in very shallow water and surf zones can be realized.

**KEYWORDS:** ASV, Surf Zone Reconnaissance Mission, Simulation, State-Based Robotics

**DoD KEY TECHNOLOGY AREA:** Modeling and Simulation

## DEVELOPMENT OF A CONTROL SYSTEM FOR A SHAPE MEMORY ALLOY (SMA) ACTUATED MEDICAL MANIPULATOR

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**Mechanical Engineer-December 1997**
**Master of Science in Mechanical Engineering-December 1997**
**Advisor: Ranjan Mukherjee, Department of Mechanical Engineering, Michigan State University**

This thesis discusses the development of a digital control system used to operate a conceptual robotic manipulator for use in minimally invasive surgery. The motion of the manipulator is envisioned to be accomplished with actuators made of a Shape Memory Alloy (SMA). SMA has the ability to recover permanent deformation by undergoing a phase transformation. The recovery of the deformation results in motion of the SMA material which can be exploited for useful work. SMA was chosen as the actuator because it can be miniaturized and has a very high power density as compared to conventional actuators. An Actuator Matrix Driver (AMD) board was designed, as part of the digital control system, to power and control the SMA actuators. The matrix configuration of the AMD architecture and the use of Amplitude Modulated Pulsed (AMP) current allows for a reduction in the number of leads for the powering and control of the actuators. The electrical resistance, a physical property of SMA which characteristically changes with phase transformation, can be used to determine the state or phase of the SMA actuators and can therefore be used for closed loop control.

**KEYWORDS**: Shape Memory Alloy (SMA), Actuator Matrix Driver (AMD) Board, Amplitude Modulated Pulsed (AMP) Current

**DoD KEY TECHNOLOGY AREA**: Sensors

## MICROCHEMICAL ANALYSIS OF NON-METALLIC INCLUSIONS IN C-MN STEEL SHIELDED METAL ARC WELDS BY ANALYTICAL TRANSMISSION ELECTRON MICROSCOPY

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**Master of Science in Mechanical Engineering-June 1998**
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Microchemical analyses of the inclusions present in several shielded metal-arc steel weld metals were made by analytical transmission electron microscopy (TEM). Low alloy C-Mn steel weld metal samples were studied in which only the titanium and aluminum contents varied significantly. Carbon extraction replicas were made from each of the weldments and the inclusions were analyzed in the TEM by energy dispersive x-ray (EDX) and parallel electron energy loss spectroscopy (PEELS). The results indicated that, for weld metals containing small amounts of Al (13 ppm), the inclusions were comprised of $MnO\text{-}Si0_2$, Tig (maybe as a compound) and Cu(Mn)S. As the Al content was increased to 160 ppm, Mn and Si no longer took part in the deoxidization process and the inclusion compositions were dominated by TiO and $A1_20_3$ along with some sulfides. For weld metal containing a much higher amount of Al (580 ppm) the inclusions became essentially mixtures of TiO, $A1_20_3$ and TiN sometimes complexed with sulfides. These inclusion chemistries were predicted by the use of equilibrium thermodynamics and their effect on the microstructure and mechanical properties of the steel weld metals investigated.

**DoD KEY TECHNOLOGY AREA:** Materials, Processes and Structures

**KEYWORDS:** Shielded Metal Arc Welding, C-Mn Steel Weldments, Non-Metallic Inclusions, Transmission Electron Microscopy

## A MATHEMATICAL MODEL OF KNEE KINEMATICS UTILIZING THE PRINCIPLE OF MINIMUM ENERGY

**Patricia F. Warren-Lieutenant Colonel, United States Marine Corps**
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**Master of Science in Applied Physics-June 1998**
**Advisors: Young W. Kwon, Department of Mechanical Engineering**
**William B. Maier II, Department of Physics**

This thesis seeks to determine if the path of motion of the knee in passive flexion results from the minimization of potential energy in the joint ligaments. To investigate this hypothesis, a simulation modeling both collateral and cruciate ligaments was developed, with each cruciate ligament represented as two separate fibers. The model computed almost 8000 possible orientations of the femur during flexion through 120, with the surfaces of the femur and tibia serving as a constraint to motion. Each orientation of the femur inherently provided the position of the individual ligament attachment points, from which the extension or contraction and the potential energy of the ligament were derived. The energy of the entire six-ligament system resulted from the summation of the potential energy of individual ligaments. For each 10 of flexion, the femur position that produced the minimum energy of this six-ligament system was identified. Finally, the motion of the femur as it followed these positions was evaluated: it did not mirror known joint motion. There are several areas where further refinement of the simulation can be made before a complete evaluation of the hypothesis can be made.

**DoD KEY TECHNOLOGY AREA:** Biomedical

**KEYWORDS:** Energy Minimization, Knee, Flexion, Ligament

## SENSITIVITY ANALYSIS OF DIVE PLANE REVERSAL OF SUBMERSIBLE VEHICLES AT LOW SPEEDS

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**Master of Science in Mechanical Engineering-September 1998**
**Advisor: Fotis A. Papoulias, Department of Mechanical Engineering**
**Second Reader: Terry McNelley, Department of Mechanical Engineering**

The capability of a submersible vehicle to accurately maintain its commanded depth in a variety of operating speeds, depths and loading conditions is critical for mission accomplishment. Below a certain critical speed a phenomenon known as dive plane reversal occurs, where depth response changes sign with respect to a given dive plane command. This thesis builds on previous studies of the phenomenon and it presents a comprehensive sensitivity study of dive plane reversal envelopes in the presence of external forces and moments on the vehicle. Based on these results, rational design and operational decisions can be made in order to avoid unpredictable vehicle responses.

**DoD KEY TECHNOLOGY AREA:** Surface/Under Surface Vehicles – Ships and Watercraft

**KEYWORDS:** Dive Planes, Critical Speed

## CAVITATION EFFECTS ON A SHIP-LIKE BOX STRUCTURE SUBJECTED TO AN UNDERWATER EXPLOSION

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**Master of Science in Mechanical Engineering-September 1998**
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Shock trials are required for the lead ship of each new construction shock hardened ship class. Live fire shock trials are both complex and expensive. Finite element modeling and simulation provides a viable, cost effective alternative to live fire shock trials. This thesis investigates the effect of bulk and local cavitation on a three-dimensional ship-like box model. The fluid surrounding the structure will be modeled
to capture the effect of cavitation. Viable results will validate the modeling and simulation method used and provide the basis for further investigation into the use of fluid modeling in underwater explosion simulation.

**DoD KEY TECHNOLOGY AREAS:** Modeling and Simulation, Surface/Under Surface Vehicles-Ships and Watercraft

**KEYWORDS**: Underwater Explosion, Cavitation, Surface Model

## IMPROVED COMPUTER MODELING OF SHIP PROGRESSIVE FLOODING AS A DESIGN TOOL

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**Second Reader: Terry McNelley, Department of Mechanical Engineering**

When a ship suffers underwater damage, there is a rapid influx of water, followed by a period of slower progressive flooding. This results in flooding of compartments whose hull boundaries, but not interior bulkheads, are still intact. An existing computer model uses the FORTRAN computer language and formatted input files to model progressive flooding. This thesis uses MATLAB computer language and SIMULINK graphical user interface to provide a modular, expandable progressive flooding design tool.

**DoD KEY TECHNOLOGY AREA:** Surface/Under Surface Vehicles – Ships and Watercraft

**KEYWORDS:** Progressive Flooding, Computer Model

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