2006 SUMMARY OF ENGINEERING RESEARCH

A Report of Activities during 2005

This report is part of the larger 2006 Summary of Engineering Research, available on the Web at www.engr.uiuc.edu/research and on CD-ROM. The Summary of Engineering Research represents the extensive engineering research program conducted in 2005 at the University of Illinois at Urbana-Champaign. Detailed statistics about research in the College of Engineering are included in the Directory of Engineering and Engineering Technology Programs and Research, published by the American Society for Engineering Education, Washington, D.C.

How to use the Summary of Engineering Research: Research projects are listed by title, followed by the names of the investigators and the sponsoring agencies. Projects are sorted by major topic areas. Project descriptions are brief. Additional information on each project may be obtained from the investigator in charge (denoted by an asterisk). Mailing addresses are provided on the introductory page.

How to obtain publications: Please consult academic and public libraries for the journal articles, papers, and books listed in this report. Information about technical reports is available from the Engineering Documents Center, Grainger Engineering Library Information Center, 1301 West Springfield Avenue, Urbana, IL 61801, USA. To search the center's collection on the Internet, please visit the website at search.grainger.uiuc.edu/top. Copies of theses can be found at the University of Illinois Library, www.library.uiuc.edu, or may be purchased from University Microfilms, 300 Zeeb Road, Ann Arbor, MI 48106, USA, www.umi.com.

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Abbreviation key for College of Engineering departments and major labs:

- Advanced Transportation Research and Engineering Laboratory (ATREL)
- Aerospace Engineering (Aerosp. Engr.)
- Agricultural and Biological Engineering (Ag. & Biol. Engr.)
- Bioengineering (Bioengr.)
- Chemical and Biomolecular Engineering (Chem. & Biomol. Engr.)
- Civil and Environmental Engineering (Civil & Environ. Engr.)
- Computer Science (Comput. Sci.)
- Coordinated Science Laboratory (CSL)
- Electrical and Computer Engineering (Elect. & Comput. Engr.)
- Frederick Seitz Materials Research Laboratory (FS-MRL)
- General Engineering (Gen. Engr.) or Industrial & Enterprise Systems Engineering (Indus. & Enter. Syst. Engr.)*
- Materials Science and Engineering (Mat. Sci. & Engr.)
- Mechanical and Industrial Engineering (Mech. & Indus. Engr.) or Mechanical Science and Engineering (Mech. Sci. & Engr.)*
- Micro and Nanotechnology Laboratory (MNTL)
- Nuclear, Plasma, and Radiological Engineering (Nucl., Plasma, & Radiol. Engr.)
- Physics
- Theoretical and Applied Mechanics (Theoret. & Appl. Mech.)*

*In August 2006, the Industrial Engineering program was merged with the General Engineering Department, which became the Industrial and Enterprise Systems Engineering Department. The Theoretical and Applied Mechanics Department merged with the Mechanical and Industrial Engineering Department, which became the Mechanical Science and Engineering Department. Please check department links at www.engr.uiuc.edu for current faculty lists.
The Department of Theoretical and Applied Mechanics is the academic and intellectual home of the science of mechanics.* The missions of the department are to nurture mechanics as a scientific discipline in its own right and to serve as an interface between basic work and applications in the many engineering disciplines that use mechanics. Because of the interdisciplinary nature of work in mechanics, the department strives to strengthen ties with programs in related fields, such as physics, applied mathematics, geology, materials science, and scientific computing.

Founded in 1890 to provide instruction in mechanics for all College of Engineering students—a duty that the department still fulfills—Theoretical and Applied Mechanics (TAM) has evolved into a broad, interdisciplinary group of faculty members and students tackling problems in applied and computational mathematics, dynamics, solid mechanics, fluid mechanics, and mechanics of materials.

- Work in applied and computational mathematics focuses on asymptotic analysis, mathematical modeling, stochastic estimation, and advanced algorithms for large-scale computing.
- In dynamics, there are projects on elastic waves, the role of heterogeneity on acoustic signatures, and aspects of modern dynamical systems theory including chaos.
- The emphasis in solid mechanics is on characterizing, understanding, and modeling the behavior of modern materials, such as composites and shape-memory alloys, and on basic mechanisms, such as localization, embrittlement, and phase transformations.
- The main activity in fluid mechanics is the problem of turbulent flow, and approaches range from advanced experimental techniques, such as holographic particle image velocimetry, to very large-scale numerical simulations that also address problems in convection and combustion.

Graduate research is an integral part of the educational program in TAM. Most of the research projects involve master's and doctoral students engaged in thesis research. The department is an active participant in the college-wide Computational Science and Engineering Program.

Several laboratories, both for research and instruction, are maintained in TAM and service a large number of students each year. An active program of visitors, seminars, and short courses hosted by the department helps further the science of mechanics within the college and across the university.

Editor's Note: This is the final edition of the TAM Summary of Engineering Research report. The College of Engineering reorganized in August 2006, moving the engineering mechanics curriculum to the new Department of Mechanical Science and Engineering (formerly Mechanical and Industrial Engineering). Faculty members joined various departments and are continuing their research. In the future, their project updates will be in the Summary reports of their home departments. To find out more about faculty, please use the "Faculty Directory" at www.engr.uiuc.edu.

Faculty and Their Interests

Ronald J. Adrian
Turbulent boundary layers, turbulent thermal convection, experimental fluid mechanics, geophysical fluid dynamics, microfluidics, turbulence physics

Donald E. Carlson
Continuum thermomechanics, elasticity

Jonathan B. Freund
Mechanics of nonometer-scale systems, numerical methods, molecular dynamics simulation, biomedical fluid mechanics, aerodynamic sound

Gustavo Gioia
Biological mechanics, boundary layers, constitutive theory, continuum mechanics, foams, granular materials, phase transitions, turbulence physics
Robert B. Haber
Atomistic models, computational fluid dynamics, computational solid mechanics, continuum mechanics, elasticity, fracture, materials processing, numerical methods, material microstructure evolution

Kimberly M. Hill
Experimental fluid mechanics, granular materials, multiphase flows, particulate flows

Richard D. Keane
Experimental fluid mechanics

James W. Phillips
Experimental solid mechanics

William R. C. Phillips
Biological mechanics, boundary layers, environmental effects, flow instability, geophysical fluid dynamics, nonlinear waves, turbulence physics, vortex dynamics

Daniel N. Riahi
Boundary layers, convection, flow instability, geophysical fluid dynamics, materials processing, multiphase flows, nonlinear waves, turbulence physics

Mark Short
Combustion, compressible flow, detonation and shock physics, nonlinear waves

Nancy R. Sottos
Experimental solid mechanics, micro- and nano-mechanics, self-healing materials, composite materials, thin film reliability

Richard L. Weaver
Ultrasonics, stochastic waves, structural acoustics, disordered and complex structures, quantitative nondestructive evaluation

Applied Mathematics

Ultrasound-Induced Lung Damage Assessment
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National Institutes of Health, R01 HL58218-05

This is a multifaceted project, involving an experimental (animal based) and theoretical (mechanism based) study, to evaluate ultrasound levels at which minimum detectable lung hemorrhage occurs and to develop a theory that addresses a particular class of damage mechanisms. The work in the Theoretical and Applied Mechanics Department is concerned with the latter, which is modeled by liquid with a free surface that is driven from below by focused ultrasound. The flow at the free surface is described by the nonlinear Schrodinger NLS equation. The flow is axisymmetric and gives rise to a solitary wave. Small changes in the focal point of the ultrasound, however, cause the liquid to spit out droplets that correspond to NLS developing singularities in finite time.

Behavior of Engineering Materials

Multiscale Experimental and Numerical Design of a Self-Healing Epoxy Adhesive
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National Science Foundation

A collaborative experimental and analytical effort is being carried out to design a new class of multifunctional, epoxy-based adhesives that possess the ability to heal autonomically under fatigue loading. To achieve self-healing capability, sub-micron-size capsules containing either a healing agent or catalyst are dispersed in the epoxy adhesive layer. Fatigue-induced microcracks in the adhesive layer rupture the capsules, releasing the healing agent and rebonding the crack faces. This research project focuses on material development with the processing and characterization of the nanocapsules and the identification of viable self-healing chemistries for epoxy adhesives, and the multilevel numerical and experimental investigation of the fatigue response of the self-healing adhesive joint.

Foam Models for Occupant-Seat Interaction Engineering
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National Science Foundation

The objective of this five-year research plan is to develop and calibrate a model of polyether polyurethane solid foams for a specific application of direct industrial interest: the computational simulation of occupant-seat interaction in automotive engineering. The project involves theoretical, experimental, and computational components. Because foams are governed by nonconvex potentials, even a simple uniaxial foam model involves a vast phenomenological universe, including large deformations, lack of uniqueness, multiple-phase, multiple-length-scale fields, and metastable states. Our model will rely on a

* Denotes principal investigator.
detailed description of the nonlinear behavior of the individual open cells of the microstructure of the foam. A tensorial stress-stretch constitutive relation will be based on the homogenization of periodic cell structures.

**Mechanics of Cohesive Powder Compaction**

G. Gioia*
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*University of Illinois Research Board*

This project is focused on the particle rearrangement process that dominates the first 30% to 45% of the compaction stroke during the densification of cohesive powders. The research is relevant to such applications as forming of ceramic components and pharmaceutical tablets. We have shown both experimentally and computationally that, contrary to currently prevalent notions, particle rearrangement is a highly inhomogeneous process. In fact, the evidence indicates that particle rearrangement occurs in the form of a phase transformation. We are studying the energetics associated with this phenomenon. Computational work will be based on a novel, mixed finite-element/discrete approach.

**Controlled Segregation in Granular Flows**

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Granular materials tend to unmix, or spontaneously segregate, based on even small differences in particle properties when jostled, sheared, or otherwise disturbed. There is no universal explanation as to why granular segregation occurs, nor is there a method for eliminating, predicting, or controlling the segregation structure(s). We have recently found that systematically varying the speed of dense granular flow can lead to systematic changes in the segregation pattern. We study this phenomenon experimentally and theoretically to understand segregation in dense granular flow more fully and to develop a method for systematically controlling granular segregation structures.

**Additive Patterning of Integrated Functional Materials on a Chip**

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*National Science Foundation, CMS 00-88206*

A novel, additive method of patterning is investigated that enables integration of thin-film electroceramics on a chip, rather than as a discrete component added into the circuit and system. In this soft lithographic method, substrate surfaces are selectively functionalized by self-assembled monolayers through microcontact printing, and manipulation of surface forces leads to subsequent lift-off and patterning. We seek to develop a fundamental understanding of the residual stresses generated in the films during patterning and the effects of these stresses on the novel oxide lift-off process, the patterned film structure, the electromechanical properties of the films, and the overall reliability of the device.

**Adhesion and Fracture of Nanostructured Thin Films**

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*Motorola MRC*

This research seeks to characterize adhesion and fracture problems associated with nanostructured thin film devices of interest to Motorola. Experiments are under way to characterize the influence of film thickness, processing methods, substrate material, surface roughness, and residual stress on the fracture properties and failure mechanisms of nanostructured materials. The results of this project are expected to have direct impact on mechanical testing and consequent design of nanoscale thin film materials with significance for a wide variety of applications in multilayered electronic and optical structures.

**Multifunctional Polymers and Composite for Self-Healing Applications**

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*U.S. Air Force Office of Scientific Research, AFOSR F49620-03-1-0179*

This research seeks to develop the next generation of structural polymers, adhesives, and polymeric composite materials that combine structural function with self-healing capability. New healing chemistries and methods of delivery are under investigation, which offer the potential for dramatic improvements in use temperatures, kinetic rates, and physical properties. A large number of potential systems have been screened and the most promising selected for detailed analysis. These screened systems are further developed and form the basic materials set for a comprehensive experimental program to quantify the healing structural performance of these multifunctional systems.

* Denotes principal investigator.
Nanostructured Materials for Self-Healing
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Self-healing polymers are achieved by incorporating small capsules that rupture and release healing agent in the presence of a crack and a catalyst phase that polymerizes the healing agent, bonding the crack faces closed. While promising self-healing results have been obtained with microcapsules 10–200 microns in diameter, many applications require nanoscale integration of self-healing functionality. In this research through the Nano-CEMMS, several processing methods are investigated to develop nano-compartmentalized healing systems. Through precise, localized control over the distribution of the nanoscale self-healing constituents, a functionally graded material can be created that has healing capability only where needed.

Self-Healing Tires
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Grainger Foundation Technology Fund

The objective of this late-stage seed proposal is to transition the newly developed University of Illinois at Urbana-Champaign technology of self-healing polymers to passenger car and light truck tires. This tire market is valued in excess of $21B in the U.S. alone and self-healing technology has the potential to solve one of the most costly problems facing tire manufacturers recently—tire-tread separation. In collaboration with Goodyear Tire & Rubber Company, we are identifying new materials systems that are compatible with current tire manufacturing practices.

Structural Health System for Crew Habitats
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Research and development efforts are undertaken to demonstrate a prototype structural health system for Lunar and Mars Exploration crew habitats. The goal is to design a system that continuously monitors the health of the habitat structure, alerts the crew in real time when adverse conditions are detected, and autonomically corrects for these conditions when possible. Materials systems that incorporate embedded sensors and self-healing functionality are being developed for these purposes.

Thin Film Fracture and Decohesion in Micro- and Nano-Patterned Devices
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This research focuses on the unique fracture and decohesion problems associated with micro- and nano-patterned thin film devices fabricated via soft lithographic methods. Thin film adhesive strength is characterized via a dynamic edge delamination test that uses a laser induced pulsed loading technique. Numerical schemes that combine spectral methods with cohesive volumetric finite methods are developed to accurately extract interfacial fracture toughness. The experimental and computational tools developed will provide a quantitative understanding of patterned film fracture that can guide the design and development of new inks, transfer chemistries, and stamps for devices fabricated by soft lithography.

Development of Self-Healing Polymer Coatings and Composites
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A novel approach is proposed for improving the durability of polymeric coatings and composites used in naval applications through the use of self-healing polymers. The initiation of cracks in polymer coatings leads to environmental damage and reduced lifetime of coated components. The proposed investigation will apply recent breakthroughs in self-healing technology to repair cracks in polymeric coatings autonomically, increasing durability and lifetime of coated components. A comprehensive experimental program will be initiated to screen appropriate material systems based on healing efficiency and environmental stability and to develop appropriate processing techniques and mechanical characterization of thin film coatings.
Microvascular Autonomic Composites
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FA9550-05-1-0346

The University of Illinois at Urbana-Champaign together
with Duke University and the University of California, Los
Angeles has established the Microvascular Autonomic
Composites (μVAC) research program through the support
of the DoD Multidisciplinary University Research
Initiative. μVAC was conceived in response to a new
paradigm in materials design, that of autonomy—the
ability to achieve adaptation and response in an
independent and automatic fashion. The central vision of
μVAC is the synthetic reproduction of autonomic
biological functions, obtained through the creation and
integration of complex materials systems with three-
dimensional microvascular network architectures.

Multiscale Modeling and Experiments for Design of
Self-Healing Structural Composite Material
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F49620-02-1-0080

This research seeks to develop a set of multiscale materials
systems design tools focused on issues relevant to fatigue
of self-healing structural composites, which relies on the
careful selection of both mechanical and chemical
components. A computational framework is created for
self-healing materials systems design that spans atomistic
to macroscopic (structural) length scales and is properly
validated with relevant experimental databases.
Simulations at three distinct levels are carried out with a
coupling approach that utilizes not only the transfer of
relevant variables between levels, but supporting and
validating experiments at a number of different length and
time scales.

Self-Healing Composite Armor
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Self-healing structural polymers and composites are one
approach to designing multifunctional composites
combining structural and ballistic protection functions. In
this study, the feasibility of applying self-healing
technology to composite armor systems currently under
development by ARL will be investigated. The recovery of
structural properties of self-healing composite armor
subjected to impact and ballistic loads will be assessed. The
operative mechanisms (e.g., inherent toughening vs. self-
healing) will be identified and refinements in material
design proposed.

Self-Healing Polymers for Improved Fatigue Life
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National Science Foundation, NSF CMS 02-18863

This project addresses critical issues relevant to self-
healing of fatigue damage. Local fracture behavior is
examined through a comprehensive experimental program
delineating the contribution of constituent material
properties and fracture mechanisms on fatigue
performance. The effects of such dynamic loading
parameters as frequency, stress amplitude, and rest periods
are investigated. The critical role that in situ healing
kinetics plays in the healing process for fatigue damage is
also assessed using a variety of experimental techniques.
As a deeper understanding of the mechanisms controlling
self-healing in fatigue emerges, refinement of the material
system will occur with a view toward industrial
applications.

Use of Composite Materials to Refurbish the Civil and
Military Infrastructure
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Department of Energy, Sandia National Laboratories

The goal of this project is to establish bonded composite
doublers as a reliable and cost-effective structural repair
method for civil and military structures and to develop
adequate real-time monitoring and self-healing systems to
ensure the long-term integrity of such structures with
minimal need for human intervention. This investigation
will establish the effectiveness of composite materials to
strengthen damaged or deficient steel structures.

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Computational Mechanics

Adaptive Space–Time Meshing for Discontinuous Galerkin Finite Elements
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This project supports numerical research in both the Center for Process Simulation and Design and the Center for Simulation of Advanced Rockets at the University of Illinois at Urbana-Champaign. The objective is to develop algorithms for mesh generation and adaptive refinement that are responsive to the special requirements of discontinuous Galerkin (DG) finite-element methods as applied to problems with moving boundaries and evolving topologies. Specific topics include unstructured mesh generation algorithms for space–time grids subject to nonlinear causality constraints, algorithms for adaptive space–time meshing, space–time meshing algorithms for problems with moving interfaces, and an object-oriented geometry library for space–time DG methods.

Computational Methods for Coupling Continuum and Atomistic Models
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Physical processes that scan multiple length and time scales, from nanometer and femtosecond scales, where atomistic models are required, to macroscopic length scales, where continuum models are appropriate, govern many phenomena of interest in the mechanics of materials. For example, fracture processes might involve dislocation dynamics and the breaking of individual bonds at atomic length scales, but they are driven by loads and influence at macroscopic scales. This project involves multiscale computational methods that directly couple continuum and atomistic models in a single computation. In contrast to methods based solely on kinematic coupling, we also use balance laws to achieve more accurate and robust simulations.

Discontinuous Galerkin Method for Thermomechanical Response Using Hyperbolic Conduction Models
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The standard, parabolic Fourier conduction model is inappropriate for applications that exhibit very small length and time scales, such as pulsed lasers impinging on thin films. In such cases, conduction models with finite propagation speeds, such as the Maxwell-Cattaneo-Vernotte (MCV) model, are more appropriate. This project implements the MCV model within a space–time discontinuous Galerkin finite element scheme; a purely thermal and a coupled thermoelastodynamic model have been tested. We are investigating possible adaptive schemes that would approximate the Fourier model within the hyperbolic framework or adaptively switch between the Fourier and MCV conduction rules in multiscale problems.

Fictitious Domain Methods for Variable-Topology Shape Optimization
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This project involves new fictitious domain techniques for shape design, which are especially useful for variable-topology shape optimization. An implicit geometry model is used to parameterize the design space; the finite element grid that covers the fictitious domain is used only to facilitate the response analysis and does not serve as a surrogate geometry model. The numerical method has been shown to converge to well-defined analytical optimal designs in the limit of mesh refinement, and the analytical geometry model disambiguates the precise boundary geometry. Combined with a topological-derivative-based optimality criterion, the fictitious domain method provides an effective method for topology optimization.

* Denotes principal investigator.
Improved Time Marching Schemes for Molecular Dynamics
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This project involves new time integration algorithms for molecular dynamics derived by combining SDG methods with Hamilton's equations. An implicit method with exact energy and momentum balance (to within machine precision) has been realized. However, this scheme is impractical for very large collections of atoms as are required in many applications. We are investigating iterative solution schemes and semi-explicit methods to address this issue.

Multiscale Models for Microstructure Simulation and Process Design
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M. Garland (Comput. Sci.), R. L. Jerrard (Mathem.),
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This research initiative establishes new collaborations among materials scientists, mechanicians, mathematicians, and computer scientists to enable multiscale simulations of the complex material response. Specifically, the investigators are developing numerical models for microstructure evolution in manufacturing processes (e.g., dendritic growth in casting processes) and new methods for coupling atomistic and continuum simulation models. Information technology is an important component of the research, where development of discontinuous Galerkin finite element methods, space–time meshing and visualization algorithms, variable-topology geometry models, and parallel/adaptive analysis techniques support the scientific goals of the project.

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This project addresses the problem of interfacing solid-mechanics simulations of propellant and casing structures with simulations of combustion and turbulent flow. Space–time discontinuous Galerkin (SDG) finite-element models are under development to represent time-varying material domains (due to combustion) and to support time-dependent mesh adaptation. Adaptive element-by-element SDG methods for elastodynamics and gas dynamics, with high efficiency and local conservation properties, have been demonstrated. Proper treatment of the jump conditions that arise at moving material interfaces is intrinsic to the method. Continuing work involves coupled simulations of gas and solid response in the presence of shocks, as well as problems with phase-boundary motion due to combustion.

A Space–Time Discontinuous Galerkin Framework for Cohesive Damage Models
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This project involves an implementation of a cohesive damage model within the space–time discontinuous Galerkin (SDG) finite element method for elastodynamics. Cohesive models can be used to simulate fracture and particle dewetting in composite materials. The SDG implementation features an efficient patch-by-patch solution method that localizes the cohesive nonlinearities and exact conservation over every space–time element. We use an adaptive analysis that ensures accuracy in the solid domain, as well as the fidelity of the cohesive traction-separation model. Simulations led to the discovery of singular velocity response for dynamic crack growth, despite the nonsingular traction model.

* Denotes principal investigator.
**Discrete Element Method (DEM) Simulations of Dense Granular Flow**

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While energetically excited granular materials are well described using models based on kinetic theory of dense gases, densely sheared granular materials are still poorly understood. Unlike energetic granular materials, the dynamics of dense granular flow do not appear dominated by relatively infrequent binary collisions; instead, the enduring frictional and normal contact forces dominate the interparticle interactions. This makes for a more difficult system to model, and to this point, no satisfactory constitutive laws have been developed for dense granular flow. We are developing a DEM model to study the behavior of spherical particles in a densely flowing state in conjunction with experimental studies in thin chutes and drums. We study the apparent interplay between the particle packing and the kinematics of the flow.

**Parallel Implementations of Discontinuous Galerkin Finite Element Methods**


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*NSF Center for Process Simulation and Design, DMR 01-21695; DOE Center for Simulation of Advanced Rockets, DOE B341494*

This project supports numerical research in both the Center for Process Simulation and Design and the Center for Simulation of Advanced Rockets at the University of Illinois at Urbana-Champaign. The objective is to develop parallel algorithms for discontinuous Galerkin (DG) finite-element methods for hyperbolic, parabolic, and elliptic boundary-value problems. Maintaining good parallel performance for hp-adaptive space–time finite elements is of particular interest. An adaptive distributed-memory algorithm using data-driven objects in the CHARM++ system is under development. Excellent speed-ups have been obtained for element-by-element solutions of DG approximations to hyperbolic problems.

**Direct Numerical Simulation of 2-D Cellular Detonation Waves**

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Using modern finite-volume techniques and adaptive mesh-refinement methods, we seek to simulate the formation of cellular detonations in very wide rectangular channels. Several different finite-volume methods are being investigated to determine those that best overcome the many numerical irregularities associated with the computation of high-speed flow. We are also seeking efficient methods for including complex chemical reactions in the detonation flow.

**Pulsed-Detonation Engines**

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The pulsed-detonation engine (PDE) is a novel type of propulsion mechanism for hypersonic flight. The operating principle relies on the following: igniting a detonation at one end of a tube (engine) and generating thrust; allowing the detonation to pass out of the tube; evacuating the exhaust material; and refilling the engine with fuel and reigniting the detonation (all at a rate of 100 Hz). Currently, we are simulating this complex process numerically in order to develop simplified models of the PDE operation.

**Dynamics, Vibrations, and Waves**

**Weakly Nonlinear Stochastic Elastic Waves**

A. V. Akolzin, R. L. Weaver*

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*University of Illinois*

We study the evolution of acoustic spectral energy density, in time and frequency, due to absorption and to weak nonlinearity. Migration of energy from lower to higher frequencies is found to be generic. In bulk solids, the migration rate depends in a discontinuous manner on frequency ratios. Measurements in a curved shell, e.g. a Chinese tam-tam, are found to conform well to theoretical predictions.

* Denotes principal investigator.
Mesoscopic Elastic Waves, Ultrasound, and Seismology
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National Science Foundation, EAR-0543328, University of Illinois Critical Research Initiative

We investigate diffuse ultrasonics in random solid structures to explore the applicability of modern concepts in mesoscopic wave phenomena to seismic waves in the earth's crust. Particular emphasis is devoted to enhanced backscatter, residual coherence, and the retrieval of the system Green's function from the correlations of a diffuse field.

Statistical Elastodynamics of Large Structures
R. L. Weaver,* O. I. Lobkis, I. S. Rozhkov, N. L. Wolff, A. Akolzin
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National Science Foundation, CMS-0528096

This dynamical systems project uses numerical simulations, analytic theory, and laboratory measurements to investigate the statistics of vibrational and acoustic energy (its mean flow and its fluctuations) in complex irregular reverberant structures. We seek to develop methods to predict mean energy flow over long times based on the results of direct numerical simulations over short times. We also investigate the familiar rapid fluctuations in response spectra whose statistics are presumably universal. These two thrusts are complementary in the sense that the first predicts mean energy, and the second considers the fluctuations around the mean, thus describing the variance and reliability of the predicted mean.

Vibration Measurements of Rail Stress
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Association of American Railroads, Transportation Research Board

We are developing and designing methods for measuring longitudinal stress in rails. Rail stress leads to broken and buckled rails, and consequently to service delays and derailments. The effect of longitudinal stress on the free vibrations of beams is well understood: compressive forces decrease the flexural frequencies and tensile stresses increase the frequencies. Past efforts attempting to use this dependence for measurements of stress in railroad rails have failed due to an inability to control, or measure adequately, other influences. Here, we investigate a new method that should have minimal sensitivity to these other influences.

An Ultrasonic Analog for a Laser
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University of Illinois

Ultrasonic systems analogous to random lasers are designed and studied. We construct auto-oscillating electronic circuits for which one element is a piezoelectric transducer in contact with an acoustic body. Over a wide range of parameters we observe entrainment of the many oscillators, stimulated emission and spontaneous emission, narrow single emission lines, sensitivity to linear cavity properties, complex multimode emissions, and line narrowing.

Mechanics of Fluids

Microscale Fluidic Transport
R. J. Adrian,* E. Yamaguchi
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University of Illinois

Flow of particle suspensions in microchannels having dimensions that approach the size of the particles is being characterized. Mechanisms by which blockages form are being explained and studied parametrically.

Aeroacoustic Super-Resonances in Jet Engine Altitude Test Cells
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Air Force Office of Scientific Research

Certain indoor facilities for testing new jet engines at flight altitude conditions are observed to resonate destructively under repeatable, but unpredictable conditions. Our project studying this phenomena has two components. The first involves the use of analysis and scientific simulations of idealized geometries to identify the mechanisms of the resonance. The second is the adaptation of an advance complex-geometry flow solver for predicting them and guiding mitigation in actual test cell geometries.

Effect of Fine Combustions Scales on Turbulence in a Solid Rocket Motor
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DOE Center for Simulation of Advanced Rockets

Two objectives of this work support the large-scale modeling and simulation efforts of the Center for Simulation of Advanced Rockets at the University of Illinois at Urbana-Champaign. The first is to provide a high-fidelity, direct-numerical simulation database for

* Denotes principal investigator.
validation of turbulence models employed in the rocket simulator. We will conduct a simulation of a model junction between the star grain-axisymmetric geometries common in solid-fuel rocket motors. The second objective is to study the role of the fine scales generated by the burning propellant surfaces on the larger turbulence scales above the wall. There is a pressing need for appropriate near-wall turbulence inflow models for the rocket simulator and, at the same time, interesting questions concerning turbulence scale selection to be investigated. A high-fidelity research code is being developed with a novel staggered mesh formulation of the compressible flow equations.

**Healing Hydrodynamics in Microvascular Autonomic Composites**

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*Air Force Office of Scientific Research*

This is a collaborative project involving the chemical and structural design and fabrication of materials with autonomic properties, such as possessed by most biological systems. The main focus is on materials that will automatically heal cracks. The team includes faculty investigators in organic chemistry, materials, experimental mechanics, optimization, fluid mechanics, and computational mechanics. Our role involves the modeling and optimization of the micro-hydrodynamics of self-healing, which involves coupled capillary driven flow, diffusive transport of a catalyst, and solidification in the crack.

**Jet Noise Physics and Modeling Using Direct Numerical Simulation**

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*NASA Glenn Research Center*

The theoretical sources of turbulent jet noise that have been proposed are impossible to measure in experiments due to their complexity, but their details are essential for developing predictive simulation tools for jet noise. To provide the detailed description of the flow necessary for studying noise sources, we have developed a capability to compute noise without any modeling approximation. This approach is, of course, computationally expensive, but agreement with experiment is excellent since no approximations are made. The resulting databases are being analyzed to examine the details of the mechanisms and evaluate complex quantities that are not currently available by any other means.

**Optimal Control of Jet Noise**

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*U.S. Air Force Office of Scientific Research*

Regulations are driving intense efforts to reduce aircraft noise, of which jet noise is a major component. However, there are presently neither accurate models nor efficient simulation tools to improve designs. Nozzle modifications are determined via expensive trial-and-error experimentation. In light of this, we have developed optimal control techniques to automatically identify effective controls. They are used in conjunction with highly accurate (and computationally expensive) simulations of turbulent jets and their noise. A substantial noise reduction has been achieved. We are currently pursuing multiple avenues for deducing general control rules.

**Thermal Transport in Nanostructured Semiconductors**

J. B. Freund,* G. Chen* (MIT), H. Zhao
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*National Science Foundation*

The mean free path and, in some case, the wave lengths of the lattice waves (phonons) that carry heat are on the same scale of nanostructures that are being fabricated for solid-state electrical, electrical/thermal, and electrical/optical applications. Because of this, the transport of heat can be very different than it is in bulk materials. In some cases, thermal conductivities are suppressed by as much as a factor of 10 from predictions using bulk continuum models. In this work, we use atomistic simulation techniques to study processes at Si-Ge material interfaces and thermal transport in carbon nanotubes. Our objectives are to understand the mechanics of the processes and develop Boltzmann transport models that can bridge the gap between large-scale devices and their small-scale features.

**The Atomic Detail of Evaporating Menisci**

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*National Science Foundation*

Under a vapor bubble growing on a hot surface, whether in a nucleate boiling application or in a MEMS device, there is a "singular" region where the liquid-vapor interface contacts the solid surface. Here, the standard continuum models of fluid mechanics fail. Asymptotic theories have been developed to regularize over all bubble growth dynamics models, but this region is too small to diagnose in detail with experimental observations. We are studying

* Denotes principal investigator.
the fluid physics in this singular region using atomistic simulations.

**A Large-Deformation Fluid-Structure Simulation Algorithm**
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*DOE, Center for Simulation of Advanced Rockets*

In simulations, simple elastic solids are most naturally represented from a Lagrangian perspective, which tracks their reference state. The current position relative to this reference condition sets the elastic energy of restoration. However, simple fluids more naturally are represented in a fixed-space (Eulerian) framework. Their resistance to deformation depends only upon their current shear rates, not their initial configuration. These differences make simulation of a coupled system difficult. We are developing a unified approach in which the momentum equation for both solid and fluid regions is on a fixed mesh.

**A Multiscale Simulation Model of Cell Mechanics in the Microcirculation**
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*University of Illinois, Computer Science and Engineering*

The recruitment of leukocytes (white blood cells) to the endothelial lining of the microvasculature is a complex physiological response to injury or infection, the understanding of which is lacking but important for crafting therapies that affect this response. We are developing a simulation tool for studying the dynamics of large numbers of flexible flowing blood cells to study the dynamics of this and other processes in the microcirculation.

**Atomistic Origins of Ion Bombardment Nanoscale Surface Instability**
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*National Science Foundation, CMS 05-10624*

Molecular dynamics and continuum models are used to explain the tendency of medium energy ions incident on an initially flat surface to preferentially amplify surface roughness, even as thermally activated mass transport tends to smoothen surfaces out to longer length-scale features. Numerous possible stabilizing and ordering mechanisms occurring at the atomistic scale are investigated, including viscous relaxation, sputtered atom redeposition, and other short time-scale correlations between change in surface height and spatial derivatives of the local surface morphology. A large database of molecular dynamics results as a function of variables including temperature, stress, incident angle, energy, and surface characteristics is developed and compared to experimental data obtained by collaborators working in a range of processing regimes. The goal is to develop a comprehensive, accurate, atomistically informed continuum model that will be useful in not only explaining experimental observations but also in predicting results under new processing conditions. Calculations of the resulting nanostructure electrical and optical properties will lead to significant progress toward the nanomanufacturing of useful structures for application purposes.

**Langmuir Circulation Beneath Growing and Deforming Surface Waves**
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*National Science Foundation, OCE 98-18092*

Laboratory data and a mathematical formulation known as Generalized Lagrangian Mean equations will be used to investigate the physical realizability of an instability mechanism (generalized Craik-Leibovich or Craik-Leibovich type 2) thought to be responsible for Langmuir circulation. The influence of growing and decaying waves to the instability will be investigated. The ultimate goal of the work is to develop a set of evolution equations that can be used to estimate heat, mass, and momentum transport credibly within the ocean mixed layer.

**Langmuir Circulations Beneath Breaking Waves**
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*National Science Foundation, OCE 01-16921*

The aim of this project is to study the role of mixing and vorticity generated by breaking waves on the formation and evolution of Langmuir circulations in the oceanic surface mixed layer. A theoretical model, consistent with data from recent field experiments, will be developed. This model will extend Generalized Lagrangian mean theory from the weak-wave regime to a regime in which the surface waves have a more realistic steepness. The model will include a representation of vorticity injection by breaking waves. The dynamics of the model will be explored with numerical methods. The anticipated outcome is a better model of the development and structure of Langmuir-cell scale vortical motions in the ocean mixed layer. If successful, this may be useful in the development of better mixed-layer representations in large-scale ocean and climate models.

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**Langmuir Supercells**
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*University of Illinois*

Recent measurements at the sea floor in shallow water off the New Jersey coast indicate that under extended storm conditions, Langmuir circulation (LC) achieve vertical scales equal to the water depth and are also an important mechanism for major sediment resuspension events on the extensive shallow shelves off the U.S. eastern seaboard. Such LC are denoted as Langmuir supercells. Working in littoral water, our intent is to study LC that evolve to become Langmuir supercells in wind- and current-driven shear in the presence of wavebreaking and stratification. We plan to carry out linear and nonlinear instability analysis along with large eddy simulations. Wherever possible, we will compare our findings with observations, in particular with observed LC spacings and, if available, perturbation velocity distributions in the water column.

**Convection during Alloy Solidification**
D. N. Riahi,* B. S. Okhuysen
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*University of Illinois; Los Alamos National Laboratory*

Nonlinear convection during alloy solidification in both single- and double-layer systems are investigated. Emphasis is given to examination of the mushy layer near the solidification front. Finite-amplitude effects are studied under certain controlling processes by analytical and computational techniques. The models include the basic physical conditions that are of interest in the field of materials processing.

**Mathematical Analyses and Modeling for Flows over Structured Walls**
D. N. Riahi*
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*University of Illinois*

Mathematical analyses and modeling techniques are being developed for laminar and turbulent flows over rough or corrugated walls. The goal is to develop reliable and rational models that can be used to determine the effects of rough and structured surfaces on laminar and turbulent flow features.

**Microgravity Thermocapillary Effects**
D. N. Riahi,* N. Ramachandran, P. Bhattacharjee
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*University of Illinois; Universities Space Research Association; National Center for Supercomputing Applications*

We investigate thermocapillary effects in a microgravity environment by considering thermocapillary convection in different flow systems under an external constraint due to rotation or magnetic field and in a microgravity space environment. Both theoretical and numerical methods are used to determine optimum conditions under which undesirable effects of thermocapillarity are minimized.

**Modeling Flows in Geophysics**
D. N. Riahi,* A. Hsui* (Geol.), F. Dong
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*University of Illinois; National Center for Supercomputing Applications*

In cooperation with the San Diego Center for Supercomputing

Computational and theoretical investigations of some models of nonlinear flows in geophysics with or without rotation are carried out to determine various flow features, such as flow structure, heat flux, and nonlinear properties. These studies are also important for geological and engineering applications. Presently, investigations are restricted to planar layers but will be extended later to spherical geometries.

**Direct Initiation of Detonation in a Nonuniform Reactive Atmosphere**
M. Short*
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*University of Illinois*

This project is concerned with obtaining a complete description for the initiation of a detonation in a multidimensional, nonuniformly perturbed reactive fluid. Various forms of initial hydrodynamic perturbations in temperature, pressure, and velocity are being considered. By a combination of asymptotic and numerical methods, we aim to describe the role that each nonuniformity, which typically acts to induce nonuniform compression and expansion flow rates in the fluid, has on influencing the dynamics of detonation initiation.

* Denotes principal investigator.
Ignition of Solid Propellant in Rocket Motors
M. Short*
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DOE Center for Simulation of Advanced Rockets

This project is concerned with describing the complex multidimensional ignition dynamics of the solid propellant found in a rocket motor, such as the solid rocket booster on the space shuttle. We are deriving a fluid model that contains all the essential physical dynamics of the ignition process, including solid-to-gas phase transitions, nonuniform surface pyrolysis, and chemical reaction. The effectiveness of various ignition mechanisms is also being calculated.

Mechanics of Solids

On the Domain of Validity of Linearized Elasticity
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University of Illinois

It is widely recognized that the validity of the linearized theory of elasticity rests on the assumption that the deformation be "small" in some appropriate sense. Careful elasticians know that the basic equations of the linearized theory are implied by the nonlinear theory under the assumption that the displacement gradient be small. Here, we note that justification of the substitution of the linearized constitutive equation into the stress equations of motion or equilibrium requires that the nondimensionalized second gradient of the displacement also be small. We show by example that the resulting limitation on the domain of validity of the linearized theory can be severe.

On the Theory of Thermoelasticity in the Presence of Internal Constraints
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University of Illinois

Generally, in internally constrained nonlinear thermoelasticity, it is hypothesized that the dependent fields are given by constitutive functions of appropriate independent fields to within indeterminate reaction fields. The assumption that the reactions do not contribute to the rate of entropy production in processes that satisfy the internal constraints leads to the form of the reactions. Here, we automatically obtain this same decomposition of the dependent fields in terms of the normal and tangent spaces of the space of the constrained independent fields.

Compressed Thin Film Diaphragms
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National Science Foundation, CMS-9820823

This project involves experimental, theoretical, and computational research into the mechanics of anisotropically compressed thin film diaphragms. We have carried out experiments showing that in lieu of the well-behaved folding patterns that are obtained in the isotropic case, the anisotropic case leads to microstructures, that is, fine folding patterns that lack a length scale associated with the boundary conditions. We have clarified this behavior by means of theoretical work, proving that the observed microstructures are traceable to the spinodal structure of the underlying energy function. We have also estimated the regularizing effect of bending and verified conclusions both computationally and experimentally.

Kinematics of Boundary Layer Granular Flow
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University of Illinois Research Board

We experimentally and theoretically investigate dense boundary-layer granular flow. We use a high-speed, high-resolution digital camera to experimentally determine the trajectories of individual identical particles rotated in a drum. From these we determine how the densities, velocities, and velocity fluctuations vary across the thickness of the boundary layer. We use the measured structure of the flow to model the velocity fluctuation correlations, the diffusion, and other details of the boundary layer.

Scaling Effects in Dense Granular Flow
K. M. Hill,* A. Caprihan,
E. Fukushima (New Mexico Resonance)
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University of Illinois

A prototypical system for studying granular flow is a partially filled rotating drum. Certain measurement techniques (e.g. particle tracking) are generally limited to thin (pseudo-2-D) drums, though the diameter of the drums is essentially unlimited. Nuclear magnetic resonance imaging (MRI) and other techniques may be used to measure granular flow in long drums, though the drum diameter is limited by the RF coils within the magnet. We use MRI techniques in conjunction with particle tracking techniques to study the importance of scaling effects on
granular flow and to study experimentally the transition from 2-D to 3-D granular flows.

The Effects of Interstitial Fluid Properties on Particle-Laden Flows
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National Science Foundation, EEC-0354102

The influence of certain properties of interstitial fluids on the details of particle-laden flows is critical for industrial powder processing of, for example, ceramics and pharmaceuticals as well as understanding sediment transport in rivers and the damaging effects of mudslides. Increasing the density and viscosity of the interstitial fluids has been observed to increase the ordered structure in particle-laden flow while it simultaneously increases the speed of granular segregation in mixtures. We seek to characterize the effect of the interstitial fluid properties on the structure and kinematics of the flow itself and also on the segregation and mixing properties in granular mixtures.

A Generalized Formulation of Linearized Elastodynamics
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University of Illinois

The conventional theory of linearized elastodynamics addresses the case of motions that have small displacement gradients with respect to a reference configuration of the elastic body that is unstressed and at rest. Here, we develop a theory of much wider applicability in which the linearization is with respect to a reference configuration that is loaded and in rigid motion.

Journal Articles

Behavior of Engineering Materials


Computational Mechanics


* Denotes principal investigator.

Dynamics, Vibrations, and Waves


Mechanics of Fluids


Freund, J. B. The atomic detail of an evaporating meniscus [art. no. 022104]. The Physics of Fluids, 17:2, 22104 (Feb. 2005).


Sharp, K. V. and Adrian, R. J. Transition from laminar to turbulent flow in liquid filled microtubes [erratum]. Experiments in Fluids, 38:1, 132 (Jan. 2005).


**Mechanics of Solids**


**Papers Presented at Conferences and Symposia**

**Behavior of Engineering Materials**


**Computational Mechanics**

Mechanics of Fluids


Awards and Honors

Ronald J. Adrian
Member, National Academy of Engineering
Fellow, American Physical Society
Associate Fellow, American Institute of Aeronautics and Astronautics
Honorary Doctorate, Technical University, Libson
Tau Beta Pi Daniel C. Drucker Eminent Faculty Award, University of Illinois College of Engineering, 1988
Colwell Merit Award, Society of Automotive Engineers, 1989, 1991
Arnold O. Beckman Research Award, University of Illinois, 1990
Editor, Experiments in Fluids Journal, 1990-
Best Paper Award, Institute of Physics Measurement Science and Technology, 1995
Fellow, American Academy of Mechanics, 2000
Nusselt-Reynolds Prize, World Congress of Heat Transfer Societies, 2001
Fellow, American Society of Mechanical Engineers, 2002
Asanuma Award, Flow Visualization Society, 2002
Aerodynamic Measurement Technology Award, American Institute of Aeronautics and Astronautics, 2002
Fellow, World Innovation Foundation, 2002
Fluid Dynamics Prize, American Physical Society, 2005
Donald E. Carlson
Editorial Board, Journal of Elasticity, 1971-
Fellow, American Academy of Mechanics, 1988
Multi-Year Faculty "Three Year" Achievement Award, College of Engineering, University of Illinois, Accenture, 2003, 2004
Robert E. Miller Award for Excellence in Teaching, University of Illinois Department of Theoretical and Applied Mechanics, 2004
Lifetime Service Award, American Academy of Mechanics, 2005

Jonathan B. Freund
17th Annual Picture Gallery of Fluid Motion Exhibit, APS Division of Fluid Dynamics, 2000

Gustavo Gioia
Faculty Early Career Development Program (CAREER) Award, National Science Foundation, 2001
Xerox Award for Faculty Research, University of Illinois, College of Engineering, 2006

Robert B. Haber
Beckman Associate, University of Illinois Center for Advanced Study, 1982
Cray University Research Affiliate, 1985-1993
Director, Center for Process Simulation and Design, 1998-
Editorial Board, Journal of Computational and Applied Mathematics, 2001-
Fellow, International Association for Computational Mechanics, 2002
Editorial Board, Journal of Multiscale Computational Engineering, 2002-
Fellow, U.S. Association for Computational Mechanics, 2003

Kimberly M. Hill
Collins Scholar, Academy for Excellence in Engineering Education, 2002
Best Advisors List, University of Illinois, 2002

Richard D. Keane
Best Paper Award, Institute of Physics Measurement Science and Technology, 1995

James W. Phillips
Experimental Techniques Award, Society for Experimental Mechanics, 1987
Certificate of Merit, Plastic Surgery Educational Foundation, 1998
Special Citation, International Union of Theoretical and Applied Mechanics, 2000
Robert E. Miller Award for Excellence in Teaching, 2005

William R. C. Phillips
Research Initiation Award, National Science Foundation, 1990
Outstanding Adviser Award, 1993

Daniel N. Riahi
Outstanding Service Recognition Certificate, University of Illinois, 1987
Research Award, University of Illinois, College of Engineering, 1994
Associate Editor, Advances in Fluid Mechanics, 2000-
Honorary Editor, Far East Journal of Applied Mathematics, 2001-
Editor, International Review in Pure and Applied Mathematics, 2004-
Fellow, Wessex Institute of Great Britain, 2004
Editor, the Global Journal of Applied Mathematics and Mathematical Sciences, 2005-

Nancy R. Sottos
Young Investigator Award, Office of Naval Research, 1992
University of Illinois Award for Excellence in Undergraduate Research, Honorable Mention, 1999
Robert E. Miller Award for Excellence in Teaching, University of Illinois Department of Theoretical and Applied Mechanics, 1999
Tech Museum of Innovation Award Finalist, Technology Benefiting Humanity, 2001
Best Paper Award, American Society for Composites, 2002, 2003
Editorial Board Member, Composites Science and Technology, 2002-
Presidential Citation for Outstanding Achievement, University of Delaware, 2002
University Scholar, University of Illinois, 2002
Senior Technical Editor, Experimental Mechanics, 2003-
Hetenyi Award, Society for Experimental Mechanics, 2004
Donald Biggar Willett Professor of Engineering, University of Illinois College of Engineering, 2005

Richard L. Weaver
Fellow, Acoustical Society of America, 1996
Associate editor, *Journal of the Acoustical Society of America*, 2001-
Hetenyi Award, Society for Experimental Mechanics, 2004