CAV Review '16-'17

CENTER FOR ACOUSTICS & VIBRATION

CAV Update

Spring workshop dates set

The CAV's annual workshop will be held at the Penn State Nittany Lion Inn 25—26 April, 2017. This year the workshop will have a format similar to that of previous years with the event lasting for two full days. During each technical group's presentation there will be a few minutes to highlight special areas of interests. As in the past, laboratory tours will be given to familiarize attendees with some CAV facilities. Tuesday evening we will host a student poster session and reception. This year it will be held in Robb Hall in the Hintz Alumni Center. The program will bring a mix of presentations from technical group leaders, international liaisons, and several corporate sponsors. Graduate students and their advisors are available for discussions concerning their research. While formal presentations are organized to allow for the exchange of technical information, we lengthened the allotted time for breaks to offer ample opportunities for informal discussions.

Student poster session held during workshop

The student poster competition will be held at our Tuesday evening social in Robb Hall, between 6 and 9 pm. Our corporate sponsors, government guests, and international liaisons will be asked to cast votes for the best posters, and we will award prizes for 1st, 2nd, and 3rd places ($200, $150, and $100).

Last year's winners were first place-Matthew Neal, second place Saad Ahmed and third place Phil Feurtado .

CAV seminars archived online

Remember that CAV members may now access our previous lunchtime seminar series online. Videos of the presentations from Fall 2009 to present may be viewed. This is a service to our members only, so please contact us for the site location.

Penn State hosts 2nd International Symposium on Flow-Induced Noise and Vibration – Issues and Aspects (FLINOVIA II)

Drs. Steve Hambric and Amanda Hanford are teaming with an international organizing committee to host the 2nd International Symposium on Flow-Induced Noise and Vibration – Issues and Aspects (FLINOVIA II) at Penn State immediately following the CAV 2017 Spring workshop. The two day symposium will feature over 30 talks from international and US speakers representing industry, academia, and government organizations. The presentations cover a wide range of applications, from slow moving underwater vehicles to high speed supersonic jets, and include a good mix of experimental and computational research. This diversity leads naturally to large ranges of flow speeds, Reynolds Numbers, and Strouhal Numbers. The structural and acoustic response to these aero- and hydro-dynamic forces varies considerably over this wide range of conditions.

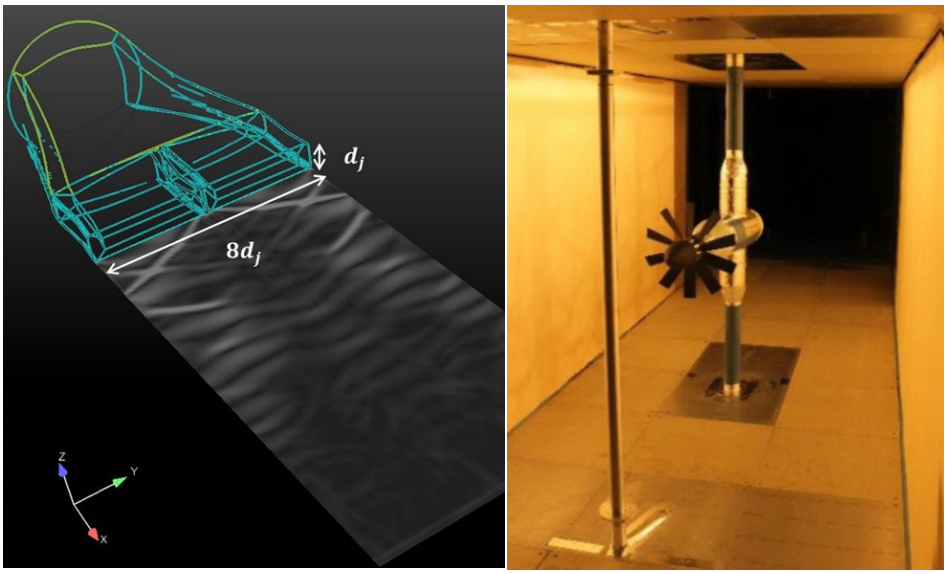


Figure 1. Left – Pratt and Whitney simulation of supersonic jet discharge flow over a downstream structural panel; Right – measurement of turbomachinery noise in Virginia Tech wind tunnel

Figure 1 shows examples of research into flow-induced forcing functions, with a CFD simulation (by CAV corporate sponsor Pratt and Whitney) of supersonic jet discharge flow and a wind tunnel experiment at Virginia Tech of turbomachinery noise. Figure 2 shows examples of in-service measurements on an instrumented underwater towed body (from the Bundeswehr Technical Center in Germany) and an instrumented aircraft (from the German Aerospace Center [DLR] in Germany).

The first FLINOVIA was held in Rome in 2013, and organized by our colleagues from Italy: Elena Ciappi of CNR-INSEAN; Sergio DeRosa and Francesco Franco from the

Continues on page 3

Corporate Members & International Liaisons

Corporate Members & Representatives
American Acoustical Products—Emanuele Bianchini
3M Science –Ron Gerdes
Babcock & Wilcox—Suzana Rufener
Bechtel Marine Propulsion Corp. —Eric Salesky (PA), Steve Dunn (NY)
Boeing— Brent Paul
Bose—Ray Wakeland
Bridgestone Americas—Paul Zakelj
Bristol Compressors—David Gilliam
Carrier—Lee Tetu
Corning—Shane Seyler
Fisher Valves and Instruments— Shawn Anderson
Gulfstream—Kristopher Lynch
ITT—Mark Downing
Johnson Controls—R. Troy Taylor
Martin Guitar—Josh Parker
Moog—Chris Layer
Newport News Shipbuilding—Kevin Smith
Pratt & Whitney— Richard Labelle
Praxair— Reh-Lin Chen
United Launch Alliance—Matt Bloom
Volvo - Hongan Xu

International Liaisons and Representatives
ISVR (UK) - Paul White
DLR (Germany) - Lars Enghardt
CIRA (Italy) - Antonio Concilio
GAUS (Canada) - Robin Olivier Robin
INSA de Lyon (France)—Etienne Parizet
KAIST (Korea)—Jeong-Guin Ih
KU-Leuven (Belgium)—Wim Desmet
Hong Kong Polytechnic University (Hong Kong)— Li Cheng

CAV Welcomes New Corporate Members

American Acoustical Products
a division of Ward Process, Inc.

Ward Process Inc. was founded in 1963 in Natick, Massachusetts as a fabricator of thermal insulation materials. American Acoustical Products was formed in 1972 as a wholly owned division of Ward Process to develop the growing range of acoustical materials. Today the capabilities have expanded to include vinyl casting and extrusion lines for manufacturing barrier, composites and damping materials. Die cutting, laminating, embossing, sewing and assembly lines create a complete range of acoustical solutions. We are now a well established ISO 9001 registered company in the thermal and acoustical manufacturing and fabricating manufacturing industry. For more information please visit www.aapusa.com. Emanuele Bianchini is the company's liaison.

CORNING

Corning is one of the world's leafing innovators in materials science. For over 160 years they have applied unparalleled expertise in specialty glass, ceramics and optical physics to develop products. Corning employees approximately 40,000 workers worldwide and has research centers in North America, Europe, and Asia. For more information please visit www.corning.com. Shane Seyler is the company's liaison

Johnson Controls

Johnson Controls is a global diversified technology and multi industrial leader serving a wide range of customers in more than 150 countries. Our 130,000 employees create intelligent buildings, efficient energy solutions, and integrated infrastructure that work seamlessly together to deliver on the promise of smart cities and communities. Our Buildings division is a leading provider of building technology, products and solutions- controls, equipment and services for HVAC, security, fire and refrigeration. We create healthier, quieter and more productive building environments that deliver energy savings, operational savings and sustainable solutions. The acoustics and vibration team at Johnson Controls York performs research, product development, testing and evaluation geared to creating and sustaining quiet and reliable chillers and air handling systems for our customers. R. Troy Taylor is the liaison.

PRAXAIR

Praxair, Inc. is an American worldwide industrial gases company. It is the largest industrial gases company in North and South America, and the third-largest worldwide by revenue. Praxair was spun off from Union Carbide Industrial Gases Inc. in 1989. It was the first company in North America to commercialize cryogenically separated oxygen. Praxair is a Fortune 300 company and has 26,000 employees in more than 50 countries. The company's slogan is "making our planet more productive. Reh-Lin Chen is the liaison for the company

CAV Welcomes New International Liaison

GAUS

Please welcome our 8th International Liaison – the Group d'Acoustique de L'Universite de Sherbrooke (GAUS). GAUS researches several topics of interest to CAV members:

Vibroacoustic modelling tools to minimize noise radiation and transmission from structures, such as fuselages or car chassis
Models and experimental techniques to characterize the acoustic performance of sound absorbing materials
Active approaches for noise control, superimposing a secondary field over a disturbing field to create silence
Imaging techniques to characterize acoustic sources or ultrasound reflectors
Characterize and modify the perception of acoustic and vibration fields to improve comfort

CAV Members Receive Honors and Awards

Geroge Lesieutre was appointed as Associate Dean of Research for College of Engineering.

Lyle Long receives the 2017 American Institute of Aeronautics and Astronautics Aerospace Software Engineering Award.

Richard Marboe is the Senior Vice President for Technical Events and Content at the American Society of Mechanical Engineers. He will serve three years.

Chris Rahn was appointed as Associate Dean of Innovation for College of Engineering.

Edward Smith was named American Institute of Aeronautics Associate Fellow.

Victor Sparrow was invited to give the Rayleigh Lecture at ASME IMECE.

Kenji Uchino received the International Ceramic Award at the Global Academy of Ceramics meeting in June 2016.

Miguel Alvarez received a 2016 American Helicopter Society Vertical Flight Foundation Scholarship.

Minkyu Choi received Second Place for her Poster at the 2016 International Workshop on Acoustic Transduction Materials and Devices.

Bryce Connelly received a 2016 American Helicopter Society Vertical Flight Foundation Scholarship.

Ethan Corle received a 2016 American Helicopter Society Vertical Flight Foundation Scholarship.

Jason Cornelius received a 2016 American Helicopter Society Vertical Flight Foundation Scholarship.

Philip Feurtado received the 2016 Skudrzyk Award from the Graduate Program in Acoustics; the Michiko So Finegold travel award for NoiseCon 2016; the Applied Research Laboratory Student Contribution Award.

Peter Kerrian received First Place for the Best Student Paper Award in Structural Acoustics and Vibration at the 171st meeting of the Acoustical Society of America in May 2016.

Veronica Koh was awarded Best Student Paper in Engineering Acoustics at the Hawaii meeting of the Acoustical Society of America.

Martin Lawless received the 2016 Kenneth T. Simowitz Memorial Award from the Graduate Program in Acoustics.

Matthew Neal received the 2016 Kenneth T. Simowitz Memorial Citation from the Graduate Program in Acoustic.

Edward T. Rocco received a 2016 American Helicopter Society Vertical Flight Foundation Scholarship.

Jared Soltis received a 2016 American Helicopter Society Vertical Flight Foundation Scholarship.

Andrew Suprock received the Silver Award for his poster at the July 2016 Conference on Progress in Quantitative Nondestructive Evaluation

Belen Veras-Alba received a 2016 American Helicopter Society Vertical Flight Foundation Scholarship.

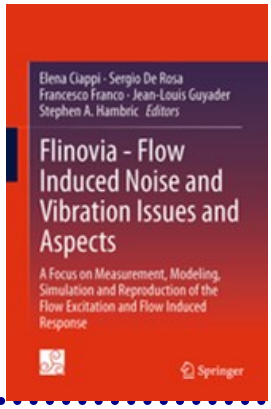
Penn State Hosts FLINOVA II

continued from page 1

Figure 2. Surface pressure measurements on vehicles: Top – underwater towed body with internal hydrophone array from Bundeswehr Technical Center, Germany; Bottom – instrumented aircraft (colored regions indicated high sensor density) from DLR, Germany.

University of Naples; and Jean-Louis Guyader, from INSA de Lyon (one of our CAV International Liaisons). The 2013 proceedings is available from Springer, and this year's proceedings will also be published by Springer (available in 2018). We are pleased to welcome two new co-organizers: Amanda Hanford of Penn State and Randolph C.K. Leung from CAV International Liaison Hong Kong Polytechnic University.

We are grateful for the generous sponsorship of the Penn State CAV, The International Institute of Noise Control Engineering (I-INCE) and the Penn State Institute for CyberScience. We look forward to this international gathering of top researchers in the area of flow-induced noise and vibration, and a productive exchange of information and ideas.



Acoustics professor Vic Sparrow delivered lecture at international conference

Stefanie Tomlinson

Vic Sparrow, director of Penn State's graduate program in acoustics, was invited to deliver the Rayleigh Lecture during the American Society of Mechanical Engineers (ASME) International Mechanical Engineering Congress and Exposition (IMECE), Nov. 11-17 in Phoenix, Arizona. Rayleigh Lecture speakers are selected for their pioneering contributions in the fields of noise control and acoustics.

"It is humbling to be honored by the ASME in this way, and to follow in the footsteps of others who have been so honored," said Sparrow.

His talk, titled "Two approaches to reduce the noise impact of overland civilian supersonic flight," provided a basis for ASME members to understand sonic booms and the ongoing work to enable overland supersonic flight for civilian aircraft.

"U.S. and international regulations currently prohibit unrestricted civil supersonic flight. There is a lot of interest by NASA and industry to develop the technology for small supersonic aircraft that will sound much less objectionable to the public," said Sparrow. "My presentation outlined the technical basis for the two proposed approaches."

His research focuses on all aspects of outdoor sound propagation, aircraft noise, nonlinear acoustics, computational acoustics, structural acoustics, virtual acoustics and scientific visualization.

Nominated by the Federal Aviation Administration and appointed by the International Civil Aviation Organization (ICAO), Sparrow has served in various roles for the ICAO Committee on Aviation Environmental Protection's Noise Working Group and Supersonic Task Group since 2005.

Sparrow has been a Penn State faculty member since 1990. He is a fellow of the Acoustical Society of America and an associate fellow of the American Institute of Aeronautics and Astronautics, and has been an ASME member since 1993.

Smith named American Institute of Aeronautics and Astronautics Associate Fellow

Lindsay Edling

Edward Smith, professor of aerospace engineering at Penn State and director of the Penn State Vertical Lift Research Center of Excellence (VLRCOE), has been named an American Institute of Aeronautics and Astronautics (AIAA) Associate Fellow. Smith will be inducted as a member of the Class of 2017 Associate Fellows.

The grade of Associate Fellow recognizes individuals "who have accomplished or been in charge of important engineering or scientific work, or who have done original work of outstanding merit, or who have otherwise made outstanding contributions to the arts, sciences or technology of aeronautics or astronautics."

"I feel very proud," said Smith. "I owe a lot of gratitude to several of my colleagues here at Penn State and those that have conducted research with me in teams. It's a great honor to be recognized by the professional society in my field."

With an in-depth grasp in helicopter and rotorcraft dynamics, Smith has spent his career exploring many modernized aspects of flight vehicles including vibration control, aeromechanical stability and anti-icing systems. As director of the VLRCOE, he administers flight simulations, conducts research in flight acoustics and helps design advanced flight vehicles.

Smith has been actively involved with the AIAA for many years. He has served on its Structural Dynamics Technical Committee and has been a regular presenter, along with his students, at the AIAA Science and Technology Forum and Exposition (SciTech).

A Penn State faculty member since 1992, Smith has been recognized with awards and honors including a 1994 American Helicopter Society (AHS) Director's Award for outstanding contributions to vertical flight technology, the 2002 AIAA Lawrence Sperry Award, a 2002 Penn State Engineering Alumni Society (PSEAS) Outstanding Research Award, and a 2007 PSEAS Outstanding Advising Award. He is also an AHS Technical Fellow.

Karen Thal is retiring!

After more than 25 years of service to Penn State, our CAV Communications Coordinator, Karen Thal is retiring. Karen started at PSU around 1990, and found herself in Mechanical Engineering in 1995, when she started assisting the founding CAV Director, Prof. Gary Koopmann. She played a special role in organizing myriad CAV events -- including a series of international workshops on Engineered Adaptive Structures -- forging personal connections with many of our faculty members, students, corporate sponsors, and international liaisons along the way. Karen made a brief foray into another part of the College of Engineering, then returned to the Graduate Program in Acoustics to assist Prof. Vic Sparrow, and picked right up where she left off with the CAV. We thank her for more than two decades of cheerful service to all those associated with our Center for Acoustics and Vibration! Karen and her husband Mike, who preceded her in retirement by mere months, plan to travel and work on their golf games. They would welcome news and visits from friends of the CAV any time!

-George Lesieutre & Steve Hambric

Thal is shown with Dr. George Lesieutre receiving recognition for 25 years of service to Penn State

CAV 2016 Graduate Student Theses

Here are this year's CAV graduate student PhD and MS theses. Most of them are available in PDF format through Penn State's library system. We have archived all of our student theses in a CAV database on our website (see the 'CAV bookshelf' page). Just search for the student's name or thesis title and you will be taken to a link of the thesis abstract and, if available, a downloadable PDF file.

PhD

Coyle, Whitney, Acoustics, *A study of the acoustical properties of the clarinet in order to predict playing frequencies*

Esplin, John, Acoustics, *Bulk cavitation extent modeling: an energy-based approach*

Foster, Norman, Acoustics, A*dvanced overset methods for vortex dominated flows*

Paul, Brent, Acoustics, *Aeroacoustic computation of tones generated from low Mach Number cavity flows, using a preconditioned method*

Cheng, Baofeng, Aerospace Engineering, *Helicopter rotor noise investigation during ice accretion*

Choephel, Tenzin, Aerospace Engineering, *Aerodynamic analysis of helicopter rotors using a higher order free-wake method*

McKay, Vernecia, Aerospace Engineering, *Numerical Simulation of Conditionally Turbulent Oscillatory Boundary Layers in Thermoacoustic Devices*

Skidmore, Grant, Aerospace Engineering, *The mitigation of pulsation in ventilated supercavities*

McPhail, Michael, Bioengineering, *Glottal aerodynamics from a Lagrangian perspective*

Xie, Yuliang, Chemical Engineering, *Optoacoustic tweezers*

Chen, Yuchao, Engineering Science and Mechanics, *Acoustofluidics in biomedical applications*

Guo, Feng, Engineering Science and Mechanics, *Acoustic tweezers: manipulating micro-objects with the power of sound*

Huang, Po-Hsun, Engineering Science and Mechanics, *Sharp-edge-based acoustofluidics*

Ozcelik, Adem, Engineering Science and Mechanics, *Applications of acoustofluidics in biotechnology*

Reinhardt, Brian, Engineering Science and Mechanics, *Nonlinear ultrasonic measurements in nuclear reactor environments*

Bowen, Landen, Mechanical Engineering, *A dynamic modeling method and optimization framework for the design of self-folding origami structures*

Miura, Kentaro, Mechanical Engineering, *Modeling, design, and experimental validation of a tailboom vibration absorber using fluidic flexible matrix composite tubes*

Li, Sixing, Molecular, Cellular and Integrative Biosciences, *Application of acoustofluidic technologies in cell biology*

MS

Axtell, Wesley, Acoustics, *Force reconstruction using force gauges and modal analysis*

Hrisko, Joshua, Acoustics, *Detectability prediction for a thermoacoustic sensor in the breazeale nuclear reactor pool*

Kerrian, Peter, Acoustics, *Acoustic and vibrational analysis of golf club drivers*

Orr, Alison, Acoustics, *A bond stiffness study of sol-gel spray-on transducers*

Saetti, Umberto, Aerospace Engineering, *Rotorcraft simulations with coupled flight dynamics, free wake, and acoustics*

Sharma, Kalki, Aerospace Engineering, *Incorporating acoustic assessment into the design and analysis of rotorcraft*

Villafana, Willca, Aerospace Engineering, *Rotorcraft noise abatement procedures development*

Walsh, Gregory, Aerospace Engineering, *A preliminary acoustic investigation of a coaxial helicopter in high-speed flight*

Orbay, Sinem, Bioengineering, *Acoustically driven micro electro-mechanical mixers for biomedical applications*

Kaynak, Murat, Engineering Science and Mechanics, *Acoustically actuated microstructures*

Suprock, Andrew, Engineering Science and Mechanics, *An investigation into the temperature effect on the performance of ultrasonic transducers for high temperature and harsh environment applications*

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MARK YOUR CALENDARS

CAV WORKSHOP 2018

Tuesday—Wednesday

25-26 April

Nittany Lion Inn

Technical Research Group Highlights

Acoustics Characterization of Materials
Bernhard Tittmann, Group Leader
brt4@psu.edu

The mission of the Acoustics Characterization of Materials group is to develop a new understanding of how various types of waves, i.e., ultrasonic x-ray, thermal, optical, electromagnetic, acoustic, etc., interact with advanced materials; to translate this understanding into techniques for monitoring and controlling industrial processes; and to apply these techniques to the development of materials processes. A major thrust is in the research and development of sensors for harsh environments, including high temperature (up to 1000C) and nuclear irradiation (Nuclear Reactors).

Our group has been fortunate to receive major funding from DOE for ATR-NSUF tests in the MIT Nuclear Reactor of 6 different piezoelectric sensors for possible use in harsh environments. The results of these tests have been evaluated and show that 4 of the sensors survived the irradiation for a period of 18 months which was the length of the program.

The group has been fortunate to receive rare and expensive piezoelectric wafers from Bechtel Bettis for phased array design, construction and testing for high temperature and high pressure.

One of the students graduating last year Andrew Suprock received the coveted Silver Award for Outstanding Poster at the annual conference for Progress in Quantitative Nondestructive Evaluation held at Georgia Tech University, in Atlanta, GA. Another graduate a Ph.D in ESM Xiaoning Xi published her thesis paper in the prestigious Journal of Applied Research. The group published chapters in three different books.

Two of our recent graduates, Dr. Matt Guers and Dr. Brian Reinhardt have permanent positions at the PSU Applied Research Laboratory. Dr. Guers is also part-time instructor in the ESM Department. Kyle Sinding graduating last year with an MS from ESM is now doing research for a PhD in the ARL Water Tunnel facility.

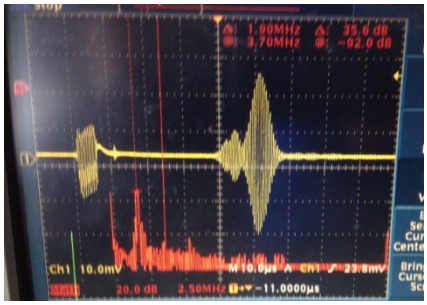
Projects and Students:
Title: Ultrasonic Phased Array Design, Construction and Testing
Sponsor: Bettis Atomic Power Laboratory
PI: B. R. Tittmann
Students: Brian Reinhardt Galestan Meckertich (ESM, PhD Candidate), Andrew Suprock (ESM, MS)

Title: Enhancement of Spray-On Transducer Technology for Field Deployment
Sponsor: Electric Power Research Institute
PI: B. R. Tittmann
Students: Janet Xu (Acoustics, MS), Yaman Trivedi (ESM, MS)

Title: Creep Specimens
Sponsor: Battelle-PNNL DOE
PI: C. J. Lissenden, Co-PI B. R. Tittmann (Undergrad ESM)
Students: Caio Batista (ESM, MS), R. Underhood (Undergrad ESM), J. Wittreich (Undergrad ESM)

The figures below are part of the M.S. Thesis of Nathan Malarich, whose thesis focused on generation and detection of guided waves in pipes using high temperature spray-on transducers. Nathan won the prestigious Fenlon Award for his thesis.

Pipe #N3, the test sample for 2nd harmonic generation. In theory, the transmitting comb on the left generates a pulse of the L(0,4) mode, which generates some 2nd harmonic, the L(0,5) mode, as the wave packet propagates towards the receiver. The transmitter comb has a spacing of λ_0 = 3.25mm corresponding to the L(0,4) wavelength at frequency f_0 = 1.83MHz; the receiving comb's ½ λ_0 = 1.82mm spacing matches the wavelength of the L(0,5) mode at $2f_0$ = 3.86MHz.



Adaptive Structures
George Lesieutre—Group Leader
g-lesieutre@psu.edu

The mission of the Adaptive Structures and Noise Control Technical Group is to pursue strategies for reducing vibration and noise in engineering systems. This involves the development of active materials and devices, accurate modeling approaches, passive control methods, discrete and distributed sensors and actuators as well as placement strategies, structural integration methods, fast and stable adaptive control algorithms,
and experiments to evaluate real-world performance. In complex mechanical/acoustical systems with multiple sensing and source/actuator locations, significant challenges remain.

Professor George Lesieutre and his students are pursuing a number of projects in vibration control and adaptive structures.

Title: Piezoelectric Actuators for Synthetic Jets
Sponsor: Boeing
Summary: Synthetic jet devices are attractive for active flow control because they do not require a pressurized air source. Instead, they cyclically ingest and expel air with zero net mass flow. High-performance ferroelectric materials can effectively drive synthetic jets; however, which materials and what associated optimal actuator geometries yield the best performance are unknown.
Collaborators: Dr. Tom Shrout (MatSci)
Student: Tianliang Yu, Ph.D. December 2018 (expected). Paper at 2017 SPIE Smart Structures.

Title: Dynamic Tensegrity for Deployable Structures
Sponsor: PSU / external Fellowship
Summary: Tensegrity structures offer the potential of very high packing efficiency for launch to space, but are relatively soft in the classical deployed configuration. Higher stiffness should be possible with strut-to-strut load transfer, requiring dynamic cable actuation and higher joint fixity.
Student: Yaan Kildiz, Ph.D. December 2018 (expected). Paper at 2016 International Conference on Adaptive Structures Technologies (ICAST).

Projects completed in 2016 and graduated students

Title: Placement of Circular Force Generators for Vibration Cancellation
Sponsor: Lockheed / Sikorsky
Summary: Relatively new devices, "circular force generators" can be used to cancel hub forces and moments in helicopters, typically

Technical Group Research Highlights

at N/rev. We seek optimal approaches to placement of such devices, along with heuristic insight into the best approaches.
Student: Keerti Prakhash, M.S. expected 2017 (with E.C. Smith). Paper at 2017 AHS Forum.

Title: A Two-Material Topology Optimization Method for the Design of Spacecraft Structures under Thermo-Mechanical Loads
Sponsor: AFOSR
Summary: Passive spacecraft thermal control systems could be lighter and simpler than the electrically-driven systems that are in wide use today. Thermal control of a two-dimensional sandwich panel could be achieved by forcing contact at internal interfaces via differential thermal expansion. Ongoing research addresses thermo-mechanical topology optimization of a two-material sandwich panel core to achieve a broad range of effective thermal conductivity, as well as associated advances in 3-D printing.
Collaborators: Dr. Mary Frecker (ME), Dr. Jim Adair (MatSci)
Student: Tianliang Yu, Ph.D. December 2018 (expected)

Title: Deployable Solar Arrays for Cubesats
Sponsor: PSU
Summary: High power, compact solar arrays are needed to enable ever more ambitious Cubesat missions. These are initially stowed and must withstand high vibratory and acoustic launch loads. Finite-thickness panels require novel, structurally integrated current-carrying hinges.
Student: Amey Chaudhari, M.Eng., August 2016

Professor Mary Frecker and her students are pursuing a number of projects related to active structures

Title: Multi-field responsive origami structures: advancing the emerging frontier of active compliant mechanisms. https://wikispaces.psu.edu/display/NEO/Welcome
Sponsor: NSF & AFOSR
Summary: The objective is to develop methods to design origami structures that actively fold from an initially flat sheet to complex three-dimensional shapes in response to multiple fields (e.g., electric, thermal, magnetic). These multi-field responsive origami shapes are being developed through collaboration with a visual artist. The artistically inspired shapes provide targets for designing novel active compliant mechanisms, which along with predictive multi-scale modeling and multi-physics simulations, guide the development of new active materials. A design optimization framework has been developed to integrate the modeling, design and active materials efforts and enable system trade studies from the nano to the macro scale.
Collaborators: Dr. Zoubeida Ounaies (ME), Dr. Paris von Lockette (ME), Dr. Tim Simpson (ME & IE), Prof. Rebecca Strzelec (Visual Art), Dr. Jyh-Ming Lien (George Mason University)
Students: Landen Bowen, Ph.D. August 2016, Katherine Reichert, B.S. expected May 2019, Wei Zhang, Ph.D. expected December 2018, Brad Hanks, Ph.D. expected May 2019.

Title: Spatially Distributed Compliant Passive Elements for Aerodynamic Structural Tailoring
Sponsor: AFOSR
Summary: The objectives are to develop methods to design spatially distributed passive 3D compliant elements and to develop the associated models to predict the dynamic coupling between those elements. The compliant elements are being structurally integrated to create an appropriate spatially distributed wing stiffness. The modeling efforts include an analytical spar structural model and a numerical compliant element design and optimization model. Validation and verification are being performed by applying the techniques developed to an avian-scale ornithopter test platform in both
Bench top and flight testing.
Collaborators: Dr. James Hubbard (Univ. of Maryland)
Students: Joseph Calogero, Ph.D. expected December 2017.

Dr. Zoubeida Ounaies reports on the Relevant Research at the Electroactive Materials Characterization Laboratory

Work completed in 2015 and graduated student

Title: Individual PZT 5A Fiber Mechanical and Electrical Characterization
Sponsor: NSF
Summary: The mechanical and piezoelectric properties of small PZT 5A fibers commonly used in active fiber composites (AFCs) are typically estimated based on bulk PZT property values. Experimental characterization of these fibers between both parallel electrodes and interdigitated electrodes (IDEs), though, has shown that various properties do not follow similar estimation trends compared to bulk PZT. Characterizing individual PZT fiber mechanical and electrical properties will help better predict the behaviors of AFCs.
Student: Nicholas Wyckoff, M.S. 2015. Thesis, "Systematic Characterization of PZT 5A Fibers with Parallel and Interdigitated Electrodes" (completed work)

Upcoming work in 2017 and graduating student (expected)

Title: Improving Electromechanical Characterization of Individual PZT 5A Fibers
Sponsor: NSF
Summary: Experimentally obtained and FEA model predicted electromechanical induced stress responses of PZT 5A fibers do not align due to various issues with the experimental processes used and the assumptions applied in the FEA models. Furthermore, a fiber's piezoelectric response is highly impacted by the geometry of the electrode used. The principles of induced stress testing can be applied to piezoelectric induced strain testing as well to expand the electromechanical characterization of individual PZT fibers.
Student: Travis Carroll, M.S. 2017 (expected). Thesis, "On the Impact of Electrode Geometry on the Piezoelectric Properties of PZT 5A Fibers" (upcoming work)

Professor Chris Rahn reports that current activities in the Mechatronics Research Lab focuses on vibration damping augmentation using fluidlastic technology, energy harvesting from human motion, and hop instabilities in mining haul trucks. Under support from the Vertical Lift Research Center of Excellence and in collaboration with Ed Smith and Chuck Bakis, students Matt Krott and Shawn Treacy are investigating damping augmentation for rotor blades and rotor stabilization through fluidlastic pitch links. In both of these application areas, devices are designed to pump fluid and provide added stiffness, damping, and inertia. Through the National Science Foundation ASSIST Engineering Research Center and in collaboration with Zoubeida Ounaies, graduate student Tahzib Safwat is building PVDF devices that can be integrated into apparel and generate power from breathing. GE Transportation is sponsoring Nick Paparizas in his study of a coupled powertrain/suspension vibration instability that occurs in haul trucks.

Technical Group Research Highlights

Faculty member Kenji Uchino reports on ICAT Research Activities in 2016

Dr. Kenji Uchino gave a Convocation Address as Chief Guest Speaker at 34th Annual Convocation of Sri Sathya Sai Institute of Higher Learning, Prasanthi Nilayam, India, in the end of 2016. He was also awarded one of the most prestigious international awards, International Ceramic Award from Global Academy of Ceramics on June 14, 2016, in Ravenna, Italy, which is presented to the most eminent ceramist every 4 years. The award citation is on his lifetime contribution on 'Piezoelectric Actuators'.

Uchino is operating a 5-year ONR program on 'High Power Piezoelectrics and Their Loss Mechanisms' with five Ph. D. students and five visiting research scholars.

Students Summary:
Title: Characterization of the high power properties of piezoelectric ceramics using the burst method: methodology, analysis, and experimental approach
Summary: This research proposed a new methodology to determine all piezoelectric parameters, including loss parameters under high vibration excitation, using a burst method without changing the sample temperature. This method may add a new IEEE Standard in the piezoelectric measurement.
Sponsor: ONR
Student: Hussain N. Shekhani, Ph.D. in EE, August 2016

Title: Crystal orientation dependence of losses in piezoelectric ceramics
Summary: Three losses in piezoelectrics (dielectric, elastic and piezoelectric losses) have significant anisotropy with regard to the crystal orientation or the polarization direction in piezoelectrics. After clarifying the phenomena experimentally, new domain wall dynamic models in terms of the crystal orientation are proposed.
Sponsor: ONR
Student: Minkyu Choi, Ph.D. in MatSE

Title: Advanced Methodology for Measuring the Extensive Elastic Compliance and Mechanical Loss Directly in k31 Mode Piezoelectric Ceramic Plates
Summary: The research proposes a new mechanical-excitation methodology, using a non-destructive testing approach by means of a partial electrode configuration, instead of the conventional full electrode configuration. This research verified the practical feasibility of using various electrode configurations, including the NE (non-electrode) sample, for measuring both the intensive and extensive parameters and losses directly in the k31-like mode from the resonance and anti-resonance modes.
Sponsor: ONR
Student: Maryam Majzoubi, Ph.D. in EE

Title: Bias Electric Field Dependence of High Power Characteristics in PZT Piezoelectric Ceramics
Summary: This thesis reports the effect of application of external DC bias field on the low and high power piezoelectric properties of hard and soft Lead Zirconate Titanates (PZT's) in the k31 resonance mode (transverse extensional). The mechanical quality factor Qm, with regards to edge vibration velocity (RMS), degraded by 17% per 0.1 m/s for the hard and 22% per 0.1 m/s for the soft under a DC bias field of 300 V/mm. However, it increased by 1.7% per 100 V/mm for the hard and 3.1% per 100 V/mm for the soft PZT with the applied positive DC bias field under a constant vibration velocity of 0.3 m/s. The deterioration of the mechanical quality factor Qm with an increase in vibration velocity can be recovered by externally applying positive DC bias field. The DC bias field of 200 V/mm exhibits an almost equivalent "opposite" change rate to the vibration velocity of 100 mm/sec.
Sponsor: ONR
Student: Anushka Bansal, MS in MatSE, May 2017

Title: Precise determination of the permittivity of a piezoelectric at the resonance frequency.
Summary: A new trial is conducted to determine the dielectric permittivity of a piezoelectric ceramic under it resonance frequency. Using a force & voltage factors obtained by the Burst Method, we can derive the permittivity experimentally at the resonance; which is the world-first trial.
Sponsor: ONR
Student: Hossein Daneshpajooh, Ph.D. in EE

Visiting Scholars Summary

Title: A new equivalent circuit for piezoelectrics with three losses and external loads
Summary: A new equivalent circuit was proposed for a piezoelectric specimen with three dielectric, elastic and piezoelectric losses and external loads.
Sponsor: ONR
Student: Xiaoxiao Dong, Visiting Ph.D. Student from China, September 2016

Title: Driving an Inductive Piezoelectric Transducer with Class E Inverter
Summary: A new driving circuit was designed to drive a piezoelectric transducer at its inductive frequency region (between the resonance and antiresonance), which can provide 3 fold higher efficiency that the transducer driven at the conventional resonance frequency.
Sponsor: ONR
Student: Tao Yuan, Visiting Ph.D. Student from China, November 2016

Title: Commercialization of the Metal Tube Motors
Summary: This project is an industry-supported program for mass-producing the metal-tube ultrasonic motors developed at ICAT. The targets are on how to establish the designing principle, how to minimize the manufacturing processes and cost.
Sponsor: Portescap, India
Sunil Kedia, Visiting Professor from India, April 2017

Title: Resonant-type inertia impact motor with asymmetric rectangular pulse drive
Summary: A resonant-type piezoelectric inertial motor driven by asymmetric rectangular pulse is developed. The asymmetric rectangular pulse

2016 ICAT Members

drive methodology is explained and its influence on output displacement of the stator is discussed in relation to four factors: frequency ratio, duty ratio, vibration amplitude ratio and phase difference.
Sponsor: ONR
Yuting Ma, Visiting Professor from China, August 2016

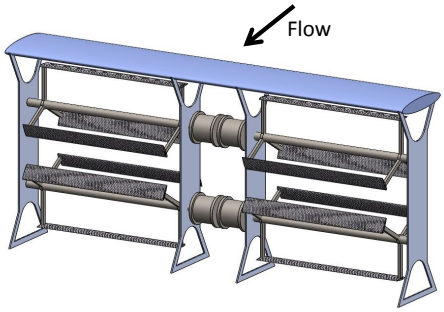
Title: A compact ring type multi-degree-of-freedom piezoelectric ultrasonic motor using combination of axial bending and non-axisymmetric modes
Summary: A simple ultrasonic motor (USM) was proposed to meet the increasing demands for simple and compact actuators, which can drive visual surveillance instruments such as humanoid eyeball to realize multi-degree-of-freedom (MDOF) motion. It has a ring shape composite stator, and employs combinations of sixth-order axial bending modes and in-plane non-axisymmetric fundamental modes to achieve the three-DOF motion of a sphere rotor.
Sponsor: ONR
Shengjun Shi, Visiting Professor from China, March 2017

Flow-Induced Noise

Mike Jonson — Group Leader
mxj6@arl.psu.edu

The mission of the Flow Induced Noise Group of the Center for Acoustics and Vibration is the understanding and control of acoustic noise and structural vibration induced by fluid flow. A summary of the ongoing work of the members of the Flow Induced Noise Technical Group is presented below:

Title: Radiated Sound from a Cross-Flow Turbine with Pitching Hydrofoils
Sponsor: ARPA-E
Advisors: Michael Jonson and Joseph Horn
Summary: The Ocean Renewable Power Company (ORPC) has been developing power-generating turbines for a few years. These cross flow turbines have a non-pitching foil geometry that generates power regardless of the tide flow direction. The direction of rotation remains the same because the foils contain a prescribed cambered airfoil with a rounded leading edge and a sharp trailing edge. To smooth out the torque generated by the flow, the turbine foils are skewed along the span. Two-dimensional analysis has shown that turbine performance can be improved by oscillating the foils during each rotation. Furthermore, applying the mechanisms of airborne cyclocopters to a cross-flow turbine to produce lift and drag have shown that such hydro-crossflow rotors could be used to self-deploy with the turbine acting as a propulsor.



A Rapid Prototype Device (RPD) was designed and manufactured. The main objectives of the RPD are to ascertain in the near term the performance of a submerged single turbine so testing knowledge can be put into more complex underwater systems. To expedite fabrication and testing, the RPD has components that are operated in air and water. Ideally the whole system would be operated submerged but the required waterproof motor could not be acquired in the short term. The RPD uses a barge with the motor and 90 degree gearhead mounted on top. The axis of the turbine is oriented vertically and submerged below the barge. This configuration allows for any thrust to be oriented in the horizontal plane. Radiated sound power from such a device is unknown and may have environmental impact on marine mammals and fish. Since the RPD hydrodynamic testing was performed in a reverberant tank, little effort was required to place hydrophones within the tank and make acoustic measurements at the same time. For lower frequencies below where sufficient modal overlap occurs, the sound was estimated using a six degree-of-freedom load cell through a dipole transfer function. For the higher frequency noise, standard reverberant tank processing was used. The radiated sound spectra from the RPD straight pitching foils was then scaled up to full scale and compared to field measurements of a conventional ORPC cross flow turbine.
Student: Margalit Goldschmidt

Title: Finite Volume, CFD Based Investigation of Supercavity Pulsations
Sponsor: Office of Naval Research
PI(s): Drs. Timothy A. Brungart and Jules W. Lindau
Student: Grant M. Skidmore, Ph.D. in Aerospace Engineering, May 2016 and Samuel E. Hansford, Ph.D. in Mechanical Engineering, May 2018
Summary: The three main dynamic closure modes (i.e. reentrant jet, pulsation, and twin vortex) of supercavities developed behind an axisymmetric cavitator may be properly resolved using finite volume CFD. The physics required to capture the reentrant jet and twin vortex conditions are incompressible and have been demonstrated previously [22]. The physics required to capture pulsation are compressible (in the gas phase). This is in agreement with the basic theory of [2] and has been demonstrated here. A number of unsteady supercavity computational simulations have been completed and mesh convergence has been demonstrated. The conditions were determined by varying the Froude number (based on upstream velocity and cavitator diameter) and the ventilation flow rate. The CFD solutions presented here collectively fit the expected interdependencies of cavitation number, ventilation rate, and Froude number. Three different Froude conditions were modeled, and for conditions exhibiting pulsation, reentrant jet-twin vortex hysteresis was observed.

The computed dynamics of pulsation have been correlated between cavity shape and pressure time histories. As confirmation supporting the applicability and accuracy of the chosen CFD approach, the conditions of cavity closure including unsteady pulsation, were successfully and pleasingly captured using cavity size and shape histories and pressure histories. In addition, by assemblage of unsteady results in CQ-σ phase space, the expected patterns [4] were observed. Similarly, the results were found to be in agreement to a linear stability criterion due to Paryshev [2].

Finally, a computationally simulated ventilated, pulsing cavity was compared to an experimentally similar pulsing cavity at identical Froude conditions. Computational ventilation rate was adjusted to capture cavity pulsation, and the results were compared. The cavitation number, cavity pulsation order, pulsation frequency, cavity interior pressure, and radiated sound pressure spectrum levels were all found to be captured well as represented in the computational results. On the other hand, the computational air entrainment rate (ventilation rate) differed greatly between CFD and the experiment. It is conjectured here that this discrepancy is due to the many real physical mechanisms of cavity gas entrainment that are extremely difficult (if possible) to simultaneously resolve in a finite volume CFD method. Fortunately, in order to properly capture all of the modes of cavity

closure, the expected dependencies of these modes on the ventilation rate, and also capture the pulsation phenomenon, it seems only necessary to capture some of these air entrainment mechanisms. Thus there are mechanisms of gas leakage from the supercavity that have only a tertiary effect on cavity closure mode and dynamics, and so long as a controlling mode of gas leakage is sufficiently captured, the cavity dynamics may be resolved in a finite volume approach.

It has been shown that this method of computationally simulating pulsating supercavities is capable of modeling the majority of dynamics and closure of experimental supercavities; thus, considering the limits of what may be done in water tunnels and tow basins, the present CFD method may be applied to investigate physical supercavity dynamics beyond what is experimentally feasible.

Title: Carbon Nanotube Sound Generation Technology Development
Sponsor: Joint Non-Lethal Weapons Directorate
PI(s): Drs. Timothy A. Brungart and Benjamin S. Beck
Student: James J. Chatterley, Ph.D. in Acoustics, May 2019
Summary: Carbon nanotube thermophones, at sufficiently high input power levels, suffer from thermal saturation where an increase in the input power does not result in a corresponding increase in the sound pressure level generated. Thermal saturation appears to be particularly acute for CNT thermophones designed for compactness or when placed inside a protective or loudspeaker enclosure, where natural convection or heat transfer from the film is inhibited. In order to better understand thermal saturation and how it can be mitigated, a compact, CNT thermophone was constructed and excited with a 200 Hz to 20 kHz white noise signal at 25, 50, 75 and 100 W input power levels. Thermal saturation reduced the sound generation efficiency from the thermophone at frequencies as low as 1,250 Hz at a 25 W input power level and became increasingly acute with both increasing frequency and input power level. At frequencies of 8 kHz and above, the sound pressure spectrum level measured with 100 W of input power was equal to or lower than the levels measured with 25 W of input power due to thermal saturation!

Fan cooling was integrated into the CNT thermophone in order to suppress thermal saturation. It was necessary to "pull" the airflow over the CNT film with the fan as opposed to "push" it in order to avoid destroying the film. Fan cooling was effective at reducing the temperature of the CNT film and surrounding air and recovered, to a large extent, the input power level squared scaling of the thermophone's sound pressure spectrum level. It is likely to be necessary to integrate such fan cooling into any high power CNT thermophone designed for compactness or when placed inside a protective or loudspeaker enclosure, where natural convection or heat transfer from the film is inhibited.

Project: Glottal jet aerodynamics
Sponsor: NIH
PI: Michael Krane (ARL PSU)
Collaborators: Michael McPhail (ARL PSU), Lucy Zhang (Rensselaer Polytechnic Inst.), Timothy Wei (Univ. Nebraska- Lincoln), Daryush Mehta (Massachusetts General Hospital), Robert Hillman (Massachusetts General Hospital), Sid Khosla (Univ. of Cincinnati Med. School)
Summary: Project uses a combination of reduced-order modeling, aeroacoustic-aeroelastic computer simulation, and physical model measurements to address current openj questions regarding the physics of human phonation, and to translate these findings into improved clinical measures. Current focus is on energy utilization and voice efficiency. This program, which began in 2002, was recently renewed through 2020.
Students:
Michael McPhail (PhD Bioengineering, PSU 2016): now employed by ARL Penn State
Gage Walters (MS Mechanical Engineering, PSU)
Jubiao Yang (PhD Mechanical Engineering, Rensselaer Polytechnic Inst. 2016): now employed by Goldman-Sachs
Dylan Rogers (BS Mechanical Engineering, UNL)
Hunter Ringenberg (BS Mechanical Engineering, UNL)

Recent news:
Conference presentations:
Krane, M. "Power flow in normal human voice production," 68th Annual Meeting of the American Physical Society (Division of Fluid Dynamics), Portland, OR, Nov. 20-22, 2016.
Sinding, K., Krane, M. "Tip vortex core pressure estimates derived from velocity field measurements," 68th Annual Meeting of the American Physical Society (Division of Fluid Dynamics), Portland, OR, Nov. 20-22, 2016.
McPhail, M., Krane, M. "Glottal jet inertance," 68th Annual Meeting of the American Physical Society (Division of Fluid Dynamics), Portland, OR, Nov. 20-22, 2016.
Walters, G., Krane, M. "Does a pneumotach accurately characterize voice function?," 68th Annual Meeting of the American Physical Fluid Dynamics), Portland, OR, Nov. 20-22, 2016.
Krane, M. "Phonation energy utilization and efficiency," 10th International Conference on Voice Physiology and Biomechanics, Mar. 14-17, 2016, Viña del Mar, Chile.
McPhail, M., Krane, M. "Phonatory aeroacoustics – a Lagrangian perspective," 10th International Conference on Vocal Fold Physiology and Biomechanics, Mar. 14-17, 2016, Viña del Mar, Chile.

Archival journal publications:
J. Yang, X. Wang, L. Zhang, M. Krane, "Fully-Coupled Aeroelastic Simulation with Fluid Compressibility - for Application to Vocal Fold Vibration ," *Computer Methods in Applied Mechanics and Engineering*, 315 (2017): 584-606.

Propagation and Radiation

Victor Sparrow, Group Leader
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The mission of the Propagation and Radiation Technical Group is to develop a new understanding of how sound is generated and propagated in realistic environments, to translate this understanding into techniques for making decisions about the use and control of sound, and for making inferences about sources and the environment, and to apply this understanding to the design of devices and systems. Understanding the perception of sound by individuals and estimating noise impacts on people are two of the primary applications of the research.

In the 2016-2017 academic year Penn State has continued to participate in the FAA Center of Excellence in Alternative Jet Fuels and the Environment. Called ASCENT for Aviation Sustainability CENter, Dr. Vic Sparrow is continuing to work on multiple FAA ASCENT projects as well as serving as the overall ASCENT Lead Investigator at Penn State. Some of the ongoing research has focused on the understanding and overcoming the limitations of current FAA noise tools, particularly in improving the propagation modeling using updated atmospheric absorption and atmospheric profiles models. Further work has

Technical Group Research Highlights

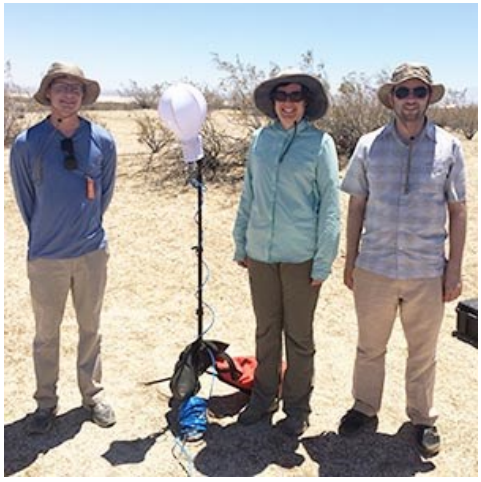
centered on improving our understanding of the limitations of metrics for sonic booms, the stability of those metrics due to the effects of atmospheric turbulence distortions, and the number and arrangement of ground microphones needed for sonic boom certification measurements.

Dr. Sparrow is also participating in the 2nd year continuation of a NASA project, SonicBAT, which focuses on the effects of atmospheric turbulence on low-boom sonic booms. The lead for this project is KBRwyle, and Penn State is a subcontractor on the effort. Penn State is developing a new propagation code that includes the effects of atmospheric turbulence in addition to nonlinearity and loss mechanisms. On the topic of sonic booms, Dr. Sparrow is a co-organizer of four special technical sessions on sonic boom at the upcoming June 2017 joint meeting of the Acoustical Society of America and the European Acoustics Association in Boston, MA.

Dr. Michelle Vigeant is an Assistant Professor of Acoustics and Architectural Engineering who leads the Sound Perception and Room Acoustics Laboratory (SPRAL), her research group, which currently consists of 4 Ph.D., 2 M.S. and 1 undergraduate student. She is currently pursuing research in three areas: (1) concert hall acoustics, (2) the emotional response to acoustics stimuli, and (3) aircraft noise. She currently has three students working on projects related to concert hall acoustics, two of which are supported by NSF, with specific topics of: a) developing a metric to predict listener envelopment, the sense of being immersed in the sound field, based on reproductions of measured and simulated halls in the AUralization and Reproduction of Acoustic Sound-fields (AURAS) facility, which employs third-order Ambisonic reproduction over a 30-channel loudspeaker array that is installed in the CAV anechoic chamber; b) developing a metric to predict the perception of overall acoustic quality in concert halls, which will consist of taking measurements in a number of American and European concert halls in Summer 2017, where these measurements will be used in subjective studies to correlate with specific components of the measured sound fields. This project also includes the design and construction of a 20-sided loudspeaker that will be used as the sound source for the hall measurements; but rather than using it as an omnidirectional source, it will be used to take measurements of reproduced instrument directivities.; and c) evaluating the metric of bass ratio to predict warmth in halls, which was found to poorly correlate as hypothesized, but hadn't yet been formally studied in a systematic way.

In the second topic area of emotional response to acoustics stimuli, she currently has two students working on projects where neuroimaging is used to quantify the responses to the stimuli, specifically functional magnetic resonance imaging (fMRI). One student is using fMRI to predict the response of reward regions to room acoustics stimuli with different concert hall conditions. The second student's project is in collaboration with Dr. Pamela Cole, professor of psychology at PSU and project PI, which is supported by NIH. The purpose of the project is to evaluate the developmental effects on children who are exposed to hearing angry conversations.

For aircraft noise Dr. Vigeant is working in collaboration with Dr. Sparrow on two projects. Drs. Vigeant and Sparrow have recently started working on a NIH-funded project in collaboration with Boston University researchers in the School of Public Health. The project aims to examine the effects of both road and rail traffic on cardiovascular disease, where Penn State's contribution to the project is historical noise modeling of regions around several U.S. airports.



Summer 2016 novel sonic boom measurements in the Mojave Desert near NASA's Armstrong Flight Research Center. Left to right: Will Doebler (Acoustics Ph.D. Candidate), Eigenmike 32 element spherical microphone array with white wind screen, Michelle Vigeant (Assistant Professor of Acoustics and Architectural Engineering), Trevor Stout (Acoustics Ph.D. Candidate). Image provided by Will Doebler.

For the second project, which is funded through the FAA, she is studying human response to a special type of sonic booms that are produced when aircraft fly slightly above the speed of sound around Mach 1.1 to 1.5 – known as Mach cut-off. She will be supervising a series of listening tests to study the effects of Mach cut-off flyovers on annoyance, where the stimuli will be recordings obtained by NASA.

The current graduate students working in the Propagation and Radiation Group include …

Current Graduate Students:

Mansi Biwalkar, M.S. expected Summer 2017
Thesis topic: Validation and extension of noise tools using existing airport noise data
Sponsor: FAA
Advisor: V. Sparrow

David Dick, Ph.D. expected Summer 2017
Thesis topic: Listener envelopment in concert halls through listening tests and spherical microphone array measurements
Sponsor: NSF
Advisor: M. Vigeant

William Doebler, Ph.D. expected Summer 2019
Thesis topic: Improved sonic boom models for lateral cutoff and over the top booms
Sponsor: FAA and NASA
Advisor: V. Sparrow

Beom Soo Kim, Ph.D. expected Fall 2017
Thesis topic: Low frequency noise of aircraft noise transmission from outdoors to indoors
Sponsor: FAA
Advisor: V. Sparrow

Martin Lawless, Ph.D. expected Spring 2018
Thesis topic: Emotional response to room acoustics stimuli using functional neuroimaging
Sponsor: Penn State College of Engineering
Advisor: M. Vigeant

Amanda Lind, M.S. spring 2011, Ph.D. expected Summer 2017
Thesis topic: Diffraction effects for predicting the impact of low-boom sonic booms around buildings
Sponsor: FAA
Advisor: V. Sparrow

Technical Group Research Highlights

Peter Moriarty, M.S. expected Summer 2017
Thesis topic: Children's neural processing of the emotional environment: angry voices
Sponsor: NIH
Advisor: M. Vigeant

Matthew Neal, Ph.D. expected Fall 2018
Thesis topic: Predicting perceived acoustical quality of concert halls using a combination of room acoustics metrics
Sponsor: NSF
Advisor: M. Vigeant

Nick Ortega, Ph.D. expected Fall 2020
Thesis topic: The effects of Mach cut-off sonic booms on annoyance.
Sponsor: FAA
Advisor: M. Vigeant

Joshua Palmer, M.S. expected Summer 2017
Thesis topic: Variability in noise metrics due to the effects of atmospheric turbulence on sonic boom signatures
Sponsor: FAA
Advisor: V. Sparrow

Rachel Romond, Ph.D. expected Fall 2017
Thesis topic: Including meteorological reanalysis for atmospheric models to improve subsonic aircraft noise prediction
Sponsor: FAA
Advisor: V. Sparrow

Kristina Sorensen, M.S. expected Summer 2017
Thesis topic: Study of the perception of warmth in concert halls and correlation with room acoustics metrics
Sponsor: Penn State College of Engineering
Advisor: M. Vigeant

Trevor Stout, Ph.D. expected Summer 2018
Thesis topic: KZK predictions of sonic booms propagating through atmospheric turbulence in three dimensions
Sponsor: KBRwyle/NASA
Advisor: V. Sparrow

Zhendong Huang, Ph.D. expected Summer 2019
Thesis topic: Corrected three-dimensional ray theory for the prediction of Mach cut-off sonic boom
Sponsor: FAA
Advisor: V. Sparrow

Rotorcraft Acoustics and Dynamics

Ed Smith, Group Leader
ecs5@psu.edu

The Penn State's CAV Rotorcraft Acoustics and Dynamics Group continues to be at the core of our Vertical Lift Research Center. Penn State is home to one of only three NRTC Vertical Lift Research Centers of Excellence (VLRCOE) in the country. In summer of 2016, our Center was successfully renewed for another 5 years. As part of our new program, we started 14 new research projects. We are grateful to our industry partners at LORD Corp., Bell, and Sikorsky for their support of our proposal. New projects include: Fundamental Investigations into Future Low-Drag Single-/ and Co-axial Rotor Hub Systems (Prof. Schmitz et al), Advanced Transition and Turbulence Modeling for Rotorcraft CFD Applications (Prof. Coder et al), Nonlinear Laser Ultrasonics for Reduced Variability in Additive Manufacturing Parts (Profs. Lissenden and Reutzel), Ice Adhesion Strength Modeling and Mitigation Via Low Surface Roughness Erosion Resistant Coatings for Rotor Blades (Profs. Palacios and Wolfe), Seamless Manufacturing of Hybrid-Material Turbines for High Temperature Rotorcraft Propulsion System by Field Assisted Sintering (Profs. Singh and Yamamoto), Fidelity Requirements for Ship Airwake Modeling in Dynamic Interface Simulations (Prof. Horn et al, High Airspeed Carriage of External Loads (Profs. Horn, Langelaan, et al), Load Alleviation Control Design Using High Order Dynamic Models (Prof. Horn et al), Slung Load State and Parameter Estimation for Autonomous Multi-lift Systems (Profs. Langelaan and Horn), Fundamental Aeroacoustics of Coaxial Helicopter Rotors (Profs. Brentner and Lee), Enhanced Damping for High-Speed Rigid Rotors via Tailored Hybrid Nanocomposites and Flexible Fluidic Matrix Composite Blade Dampers (Profs. Smith, Rahn, and Bakis), Experimental and Computational Analysis of Thermal and Dynamic Performance of Hybrid Gears Under Normal and Loss-of-Lubrication Operation (Prof. McIntyre et al), Experimental Validation, Noise and Dynamic Analysis and Variable Speed Attributes of High Power Density Pericyclic Transmission (Prof. Smith et al), and Active Clutch Engagement Control and Maneuver-Assisted Shifting for Two-Speed Rotorcraft Transmissions (Prof. DeSmidt et al). This Center currently supports more than 50 full-time graduate students and involves more than 25 Penn State faculty members in a wide range of technologies supporting rotary-wing aircraft. Seeking cost and weight efficient solutions to lower interior noise and vibration we have a suite of research tasks, and reduced exterior noise signatures is a high priority. We have experienced particular growth in programs focused on structural health monitoring, pneumatic ice protection systems, and naval-oriented flight dynamics/controls. Our various research projects are presently supported by the US Army, US Navy, NASA, and the industry sector (including large airframe manufacturers, sub-system vendors, and numerous small high- technology companies). Emphasis areas include; advanced flight controls and vehicle dynamics simulation, interactional source noise, acoustical scattering of rotor noise, gearbox noise, active and passive airframe vibration control, crashworthy and impact resistant structures, anti-icing systems, variable speed rotors, structural health monitoring, and rotor loads monitoring. Several new facilities have recently been brought online. The Adverse Environment Rotor Test Stand (rotor icing chamber) has proven to be a versatile and heavily used facility. Additionally, experimental testing has also been recently conducted for new compact energy harvesters, tiltrotor whirl flutter wind tunnel models, rotor hub-flow visualizations, and new rotor system dampers. Our annual Rotorcraft Technology Short Course will be offered for the 50th consecutive year on August 7-11. Topics in the comprehensive course include rotorcraft aerodynamics, dynamics, acoustics, composite structures, flight controls and propulsion.

Projects and Graduate Students:
Title: Flutter Stability of Rotors with Fluidlastic Pitch Links
Sponsor: LORD Corp. PIs: Ed Smith, Chris Rahn
Student: Shawn Treacy (PhD candidate)

Title: ***Tailboom Vibration Control via F2MC Devices***
Sponsor: NSF. PIs: Ed Smith, Chris Rahn
Student: Kentaro Miura (PhD 2016), Matt Krott (PhD Candidate)

Title: High Fidelity CFD Analysis and Validation of Rotorcraft Gear Box Aerodynamics
Sponsor: NASA
PIs: Rob Kunz
Students: Sean MacIntyre (PhD 2015), Qingtao Yu (PhD 2016)

Title: Wind Turbine Ice Protection Coating Performance Evaluation
Sponsor: GE Global Research
PI: Jose Palacios

Technical Group Research Highlights

Title: Experimental Measurement of Ice Crystal Dynamics
Sponsor: NASA
PI: Jose Palacios
Student: Sihong Yan (PhD candidate)

Title: Helicopter Icing Physics, Modeling and Detection
Sponsor: NRTC VLRCOE Program
PIs: Jose Palacios, Ken Brentner, Michael Kinzel
Students: Yiquian Han (PhD 2015), Baofeng Chen (PhD 2015), David Hanson (PhD candidate)

Title: Centrifugally Powered Pneumatic Deicing for Helicopter Rotors
Sponsor: NASA
PIs: Jose Palacios, Doug Wolfe
Students: Matthew Drury (MS 2016)

Title: Acoustic Capability for NDARC
Sponsor: NRTC VLRCOE Program
PI: Ken Brentner
Student: Kalki Sharma (MS 2017)

Title: Civil Certification Noise Prediction Tools
Sponsor: Bell Helicopter TEXTRON
PI: Ken Brentner
Student: Abhishek Jain (PhD Candidate)

Title: Fundamental Physics of Active Rotor Concepts for Acoustics and Performance Enhancement
Sponsor: NRTC VLRCOE
PIs: Ken Brentner, Mark Maughmer, Sven Schmitz
Students: Ethan Corle (PhD Candidate), Tenzin Choephel (PhD Candidate), Tianxiao Yang (PhD Candidate), Kevin Ferguson (PhD Candidate)

Title: Rotorcraft Airfoil Design for Unsteady Aerodynamics
Sponsor: NRTC VLRCOE
PI: Mark Maughmer
Student: Bernardo Vieira (PhD Candidate)

Title: Tailored Wing Extensions and Winglets for Large Civil Tiltrotors
Sponsor: NRTC VLRCOE
PIs: Ed Smith, Mark Maughmer
Students: Willie Costa (MS 2015), Sandilya Kambampati (PhD 2016), Taylor Hoover (MS 2015), Julia Cole (PhD 2017)

Title: Control Redundancy to Enhance Rotorcraft Performance, Handling Qualities, and Survivability
Sponsor: NRTC VRCOE
PIs: Joe Horn, Ken Brentner
Student: Adam Thorsen (MS 2014, PhD 2016), Greg Walsh (MS 2016)

Title: Advanced Response Types and Cueing Systems for Naval Operations
Sponsor: NRTC VRCOE
PI: Joe Horn
Student: Albert Zheng (MS 2016)

Title: Autonomous Multi-lift Systems
Sponsor: NRTC VRCOE
PIs: Joe Horn, Jack Langelaan
Student: ZuQun Li (MS 2015), Jacob Enciu (Postdoc)

Title: Rotorcraft Noise Abatement Operating Conditions Modeling
Sponsor: FAA
PI: Ken Brentner
Students: Yaowei Li (MS 2016), Willca Villafana (MS 2016),

Title: Flight Test Measurement of Airwake Disturbances for Validation of Virtual Dynamic Interface Simulations
Sponsor: Office of Naval Research
PI: Joe Horn
Student: Sylvie Shafer (MS 2015)

Title: Pilot-in-the-Loop CFD Method Development
Sponsor: Office of Naval Research
PI: Joe Horn
Student: Ilker Oruc (PhD Candidate)

Title: Autonomous Control Modes for Shipboard Landing in High Sea States
Sponsor: Office of Naval Research
PI: Joe Horn
Student: Junfeng Yang (PhD Candidate)

Title: Fundamental Physics of Rotor Hub Flows Towards Reduction of Helicopter Parasite Drag
Sponsor: NRTC VLRCOE
PIs: Sven Schmitz, Steve Willits
Student: David Reich (PhD Candidate)

Title: Placement of Circular Force Generators for Vibration Cancellation
Sponsor: Sikorsky Aircraft
PI: George Lesieutre
Students: Brad Sottile, (Ph.D. candidate), Keerti Prakash (MS Candidate)

Title: Efficiency, Dynamics, and Noise Characteristics of Pericyclic Transmissions
Sponsors: NASA, Vertical Lift Consortium
PI: Ed Smith, Bob Bill,
Students: Tanmay Mathur, (Ph.D. candidate), Zach Cameron (MS 2017)

Title: Computational and Experimental Investigation of Interactional Aerodynamics Relevant to Rotor Hub and Empennage Flows
Sponsors: Vertical Lift Consortium
PIs: Schmitz, Coder, Foster + GA TECH

Title: Next Generation Rotorcraft Electric and Hydraulic Actuation System Design and Optimization
Sponsor: Vertical Lift Consortium
PIs: Merenich, Yukish + EATON

Title: Design Tool for Gearbox Loss-of-Lubrication Performance
Sponsor: Vertical Lift Consortium
PIs: Kunz, McIntyre

Title: Rotorcraft Handling Qualities Requirements for Future Missions and Configurations
Sponsor: Vertical Lift Consortium
PIs: Horn with SIKORSKY et al

Title: DURIP - Computing/Simulation High-Performance Computing System for RealTime Analysis of Rotorcraft Aeromechanics
Sponsor: ONR
PIs: Schmitz and Brentner

Title: 1D-patterned Nanocomposites Structured Using Oscillating Magnetic Fields
Sponsor: ONR
PI: Yamamoto

Title: Bearing Loads Analysis for Pericyclic Transmissions
Sponsor: NASA Glenn
Student: Zach Cameron (MS 2017)

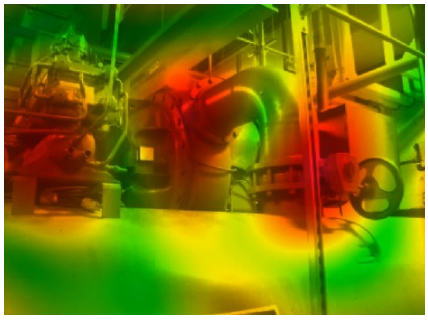
Structural Vibration and Acoustics
Steve Hambric, - Group Leader sah19@psu.edu

The Structural Vibration and Acoustics Technical Group investigates vibration in structures and its interaction with acoustic media. The group develops novel methods to analyze, measure, and control structural vibrations and radiated noise.

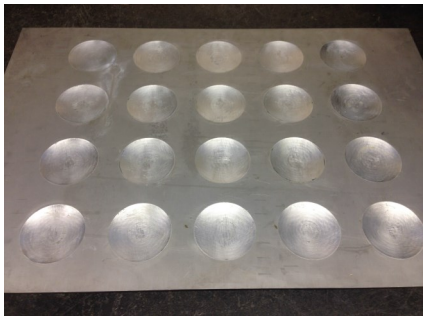
In 2016-2017 the group members investigated a wide range of topics, as shown below. One of our projects, by PhD

Technical Group Research Highlights

student Steve Wells under the direction of Drs. Hambric and Brungart, is to help Carrier quiet their large industrial chillers. The image below shows an Acoustic Camera scan of the compressor and discharge pipe on top of the condenser shell of a Carrier chiller at Penn State's West Chiller Plant. In this image, the compressor discharge and bottom of the discharge pipe are strong sound radiators. Thanks to current Acoustic Camera employee and Acoustic Program PhD graduate Dan Domme for the image!



Also, Phil Feurtado recently graduated with his PhD in Acoustics, researching Acoustic Black Hole theory under the direction of Dr. Stephen Conlon. A panel with several black holes is shown below. The holes, when treated with viscoelastic damping material, reduce vibration significantly above a cuton frequency. The holes also reduce radiation efficiency, thereby reducing radiated sound.



Projects and Graduate Students:
Title: Adaptive Acoustic Metamaterials
Sponsor: NAVSEA 073
PIs: Ben Beck and Rob Campbell
Student: Aaron Stearns (PhD Mechanical Engineering)
Title: CNT Turnkey Thermophone
Sponsor: Joint Non-Lethal Weapons Directorate
PIs: Ben Beck, Tim Brungart

Title: Materials Development Future Naval Capabilities (FNC)
Sponsor: ONR
PIs: Dean Capone, Tom Donnellan, Ben Beck

Title: High performance structural-acoustics computing
Sponsor: ONR
PIs: Dean Capone, Rob Campbell, John Fahnline

Title: Large journal bearing modeling and measurements
Sponsor: NAVSEA PMS 397
PI: Rob Campbell

Title: Fluid Structure Interaction Modeling of Blood Clot Migration and Entrapment in the Inferior Vena Cava
Sponsor: ARL Walker Fellowship
PIs: Rob Campbell, Brent Craven
Student: Ken Aycock (PhD – Biomedical Engineering)

Title: Performance Optimization of an Intake Port Shape Design for an Internal Combustion Engine
Sponsor: Self-funded
PIs: Rob Campbell, Justin Watson
Student: Michael Donnelly (MS – Mechanical Engineering)

Title: Wireless sensing technologies
Sponsor: NAVSEA PMS397
PI: Steve Conlon

Title: Improved Advanced Hybrid Propulsor
Sponsor: NAVSEA PMS 450
PI: Steve Conlon

Title: Quiet Structure Design Using Embedded Acoustic Black Holes
Sponsor: ARL Walker Fellowship and Industry
PI: Steve Conlon
Students: Phil Feurtado (Ph.D., Acoustics), Angelina Conti (B.S –Honors Aerospace Engineering), Yu Xiong (PhD Aerospace Engineering), Robert Veltre (B.S. – Honors Aerospace Engineering)

Title: Force Reconstruction using Force Gauges and Modal Analysis
Sponsor: ARL Walker Fellowship
PIs: Tyler Dare
Student: Wesley Axtell (MS – Acoustics)

Title: Pulsation of Small Industrial Boiler
Sponsor: Babcock & Wilcox
PI: Tyler Dare
Title: Accelerated fatigue characterization of composites
Sponsor: NAVSEA 073R
PI: Steve Hambric and Rob Campbell **Student:** Chester Kupchella (MS, Acoustics)

Title: Nonlinear structural joint dynamics
Sponsor: Pratt and Whitney and US Navy
PIs: Steve Hambric, Micah Shepherd
Student: Trevor Jerome (Ph.D., Acoustics)

Title: Columbia Class Submarine Propulsor design
Sponsor: NAVSEA 073R
PI: Steve Hambric

Title: Large chiller noise and vibration
Sponsor: UTC Building and Information Systems
PIs: Steve Hambric, Tim Brungart
Student: Stephen Wells (Ph.D., Acoustics)

Title: Small reciprocating compressor noise and vibration
Sponsor: Bristol Compressors
PIs: Tim Brungart, Steve Hambric
Student: John Cunsolo (MS - Acoustics)

Title: Acoustic Scattering from Elastic cylindrical shells reinforced by internal circular plates- 3D solution
Sponsor: NUWC, Newport RI
PI: Sabih Hayek and J.E.Boisvert

Title: Vibro-acoustic Analysis of Table Tennis Rackets and Balls: The Acoustics of Ping-Pong
Sponsor: Self-funded
PI: Dan Russell

Title: Acoustics of the Golf Putter-Ball Impact
Sponsor: Nike Golf
PI: Dan Russell
Student: Arjun Shankar (M.S. Acoustics)

Title: Optimization of Acoustic Black Hole Design for improved Structural Acoustics
Sponsor: ARL Walker Fellowship
PI: Micah Shepherd
Student: Cameron McCormick (PhD - Acoustics)

Technical Group Research Highlights

Systems and Structures Health Management
Group Leaders
Karl Reichard -kmr5@psu.edu
Cliff Lissenden – Lissenden@psu.edu

One project sponsored by the Department of Energy is to inspect dry storage casks for spent nuclear fuel so that the storage sites can be re-certified by the NRC. The photograph shows a prototype robotic inspection system for stress corrosion cracking in the heat affected zones of welded stainless steel storage canisters. Electromagnetic acoustic transducers send and receive shear horizontal guided waves that interact with cracks for detection. A new project this year aims to nondestructively inspect metal parts as they go through additive manufacturing. In this project laser ultrasonics using through-transmission of Rayleigh surface waves is being researched for quality assurance testing, process control, and improved part reliability for the rotorcraft industry. Another new project (sponsored by the College of Engineering through a seed grant) is researching protection of critical civil infrastructure with seismic metamaterials.

MS Theses
Christopher Hakoda, MS ESM, 12/16, A tool and a process for finding a damage feature for guided waves that is independent of temperature (Profs Rose & Lissenden)
Russell Love, MS ESM, 5/17, Guide wave structural health monitoring for large diameter storage tank floors (Prof Rose)

Projects
Title: Multi-Sensor Inspection and Robotic Systems for Dry Storage Casks
Sponsor: DOE NEUP IRP
PIs: Cliff Lissenden, Arthur Motta, Igor Jovanovic, Sean Brennan, Karl Reichard, Travis Knight, John Popovics
Students: Hwanjeong Cho (PhD – Engineering Science and Mechanics), Sungho Choi (Post Doc - Engineering Science and Mechanics)

Title: Higher Harmonic Ultrasonic Guided Waves for Structural Integrity Assessment of Infrastructure
Sponsor: NSF
PI: Cliff Lissenden
Student: Gloria Choi (PhD –Engineering Science and Mechanics)

Title: Health Monitoring Methods for Joints in Rotorcraft Composite Structures
Sponsor: National Rotorcraft Technology Center (VLRCOE)
PIs: Cliff Lissenden and Joe Rose
Student: Baiyang Ren (Post Doc - Engineering Science and Mechanics)

Title: Nonlinear Laser Ultrasonics for Reduced Variability in Additive Manufacturing Parts
Sponsor: National Rotorcraft Technology Center (VLRCOE)
PIs: Cliff Lissenden and Ted Reutzel
Student: Mostafa Hasanian (PhD - Engineering Science and Mechanics)

Title: High-temperature Sensor Technology in Support of In-situ Monitoring of Creep Specimens
Sponsor: Pacific Northwest National Lab
PIs: Cliff Lissenden and Bernie Tittmann
Student: Ken Ledford (PhD – Engineering Science and Mechanics)

Title: Robot Delivered Laser Ultrasonics System for Inspection of Stress Corrosion Cracking in Harsh Environments
Sponsor: American Society for Nondestructive Testing
PIs: Cliff Lissenden and Sungho Choi
Student: Mostafa Hasanian (PhD – Engineering Science and Mechanics)

Title: Engineering a Giant Meta-Material: a Band-Stop Seismic/Blast Filter to Shield Critical Civil Infrastructure
Sponsor: Penn State College of Engineering
PIs: Parisa Shokouhi and Cliff Lissenden
Student: Christopher Hakoda (PhD – Engineering Science and Mechanics)

Underwater Acoustics and Instrumentation
Amanda Hanford, Group Leader
ald227@psu.edu

The Underwater Acoustics and Instrumentation Technical Group conducts basic and applied research related to the propagation of sound in the ocean and the systems, natural and manmade, that generate and receive sound underwater. This year, the technical group has also an expanded focus to include work in acoustic metamaterials. Acoustic metamaterials are engineered materials that are designed to control, direct, and manipulate sound waves. Acoustic metamaterials use sub wavelength microstructures to tailor acoustic propagation requirements that often rely on anisotropic or unique material properties. Previous work in the open literature has described three potential ways to create an acoustic metamaterial with anisotropic mass density and isotropic bulk modulus: 1) alternating layers of two homogeneous isotropic materials, 2) perforated plates, and 3) solid inclusions. Work this year focused on evaluating analytic models for the designing of such materials and experimentally demonstrating the anisotropic behavior of a metamaterial comprised of a multi-solid inclusion unit cell in water.

Projects in underwater propagation often involve large scale multi-vessel ocean acoustic experiments for studies such as low-frequency continuous active sonar for sonar clutter and reverberation, or adaptive sonar for seabed characterization. The Penn State - Applied Research Lab is in charge of operation and maintenance of the Five Octave Research Array (FORA) data acquisition system. This year Penn State researchers and the FORA are currently participating in the 2017 Seabed Characterization Experiment (SCEX17). The overarching goal of SCEX17 is understanding the impact that low-soundspeed seabeds have on acoustic propagation and acoustic inversion of seabed properties

The FORA system has been used in many different areas of acoustics and oceanographic research including geoacoustic inversion, long-range propagation, target

characterization, continuous and pulsed-active sonar comparison, signal coherences studies, biologic surveys, and acoustic clutter. Acoustic clutter is a term use to describe acoustic backscatter returns which appear similar to target returns. These returns cause false alarms for traditional sonar systems and can be challenging for even experienced sonar operators to distinguish from targets in a timely manner. This work involves analyzing the statistics of acoustic clutter returns to characterize these events and link them to the environment (i.e. fish schools and other biologics, geoacoustics, and surface dynamics). Acoustic and environmental modeling includes range-dependent normal mode propagation model used to help understand the impact of environmental parameters in the shallow-water littoral sonar environment

CAV Faculty Books

We have compiled books written and edited by CAV faculty members below. The books are also listed on our CAV website under 'CAV bookshelf'.

Books

Atchley, A., Sparrow, V., Keolian, R., (Eds.), *Innovations in Nonlinear Acoustics: 17th Intl. Symposium on Nonlinear Acoustics*, AIP Conf. Proc. Vol. 838, American Institute of Physics Publishing, Melville, NY, 2006.

Blanc-Benon, P., Sparrow, V., Dragna, D., (Eds.), *Recent Developments in Nonlinear Acoustics: 20th Intl. Symposium on Nonlinear Acoustics, AIP Conf. Proc. Vol. 1685*, American Institute of Physics Publishing, Melville, NY, 2015.

Bradley, D.T., Ryherd, E.E., and Vigeant, M.C. (Eds.), *Acoustical Design of Theatres for Drama Performance: 1985-2010*, American Institute of Physics, Melville, NY, 2010.

Ciappi, E., De Rosa, S., Franco, F., Guyader, J-L., and Hambric, S.A. (Eds), *Flinovia - Flow Induced Noise and Vibration Issues and Aspects*, Springer, 2015.

Crandall, S.H., and Mark, W.D., *Random Vibration in Mechanical Systems*, Academic Press, 1963.

Hambric, S.A., Sung, S., and Nefske, D. (Eds.), *Engineering Vibroacoustic Analysis: Methods and Applications*, Wiley, 2016.

Hayek, S., *Advanced mathematical methods in science and engineering, 2nd edition*, Taylor and Francis (CSC publications), 2000.

Johnson, S.B., Gormley, T., Kessler, S.S., Mott, C., Patterson-Hines, A., Reichard, K., Scandura, P.A. (eds), *System Health Management with Aerospace Applications*, Wiley, 2011.

Koopmann, G.H., and Fahnline, J.B., *Designing Quiet Structures*, Academic Press, 1997.

Mark, W.D., *Performance-based Gear Metrology*, John Wiley and Sons, 2013.

Rahn, C., *Mechatronic Control of Distributed Noise and Vibration: A Lyapunov Approach*, Springer-Verlag, Berlin, 2001.

Rahn, C., and Wang, C.Y., *Battery Systems Engineering*, John Wiley & Sons, Ltd, Chichester, UK, 2013.

Rose, J.L., *Ultrasonic Waves in Solid Media*, Cambridge University Press, 1999

Rose, J.L., *Ultrasonic Guided Waves in Solid Media*, Cambridge University Press, 2014

Sinha, A., *Linear Systems: Optimal and Robust Control*, CRC/Taylor and Francis Publishing Group, February 2007.

Sinha, A., *Vibration of Mechanical Systems*, Cambridge University Press, October 2010.

Swanson, D.C., *Signal Processing for Intelligent Sensor Systems with Matlab(r), 2nd ed.*, CRC Press, Boca Raton, 2012.

Uchino, K., *Ferroelectric Devices, 2nd Edition*, CRC Press, 2009.

Uchino, K., *Advanced Piezoelectric Materials*, Woodhead Publishing, Cambridge, UK, 2010.

Uchino, K., *Ferroelectric Devices & Piezoelectric Actuators*, DEStech Pub., Lancaster, PA, 2016.