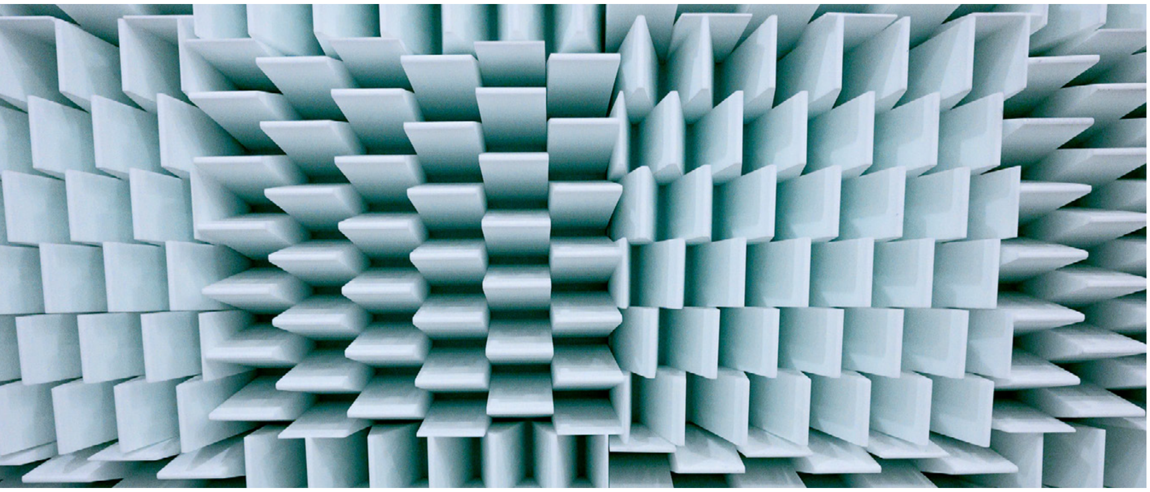
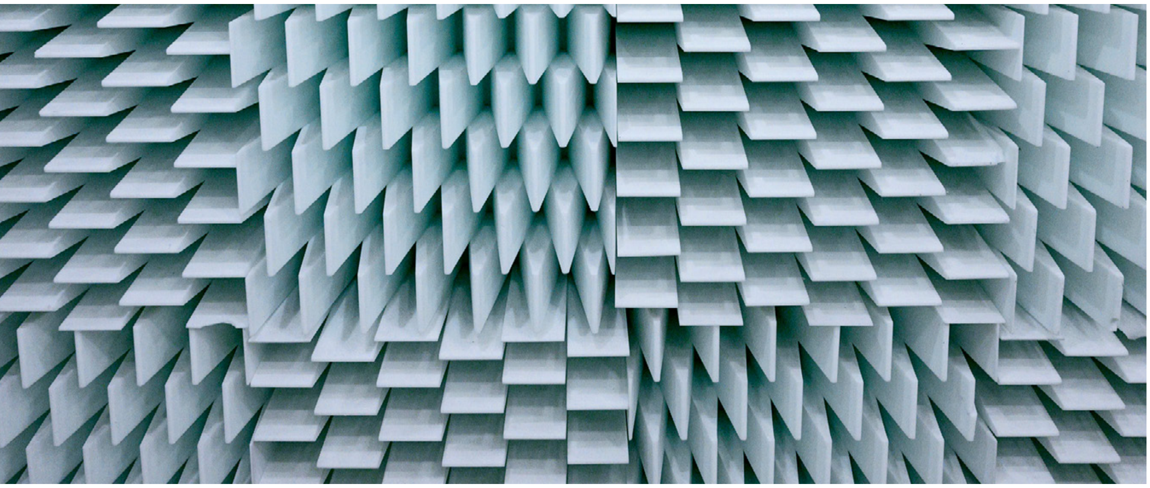


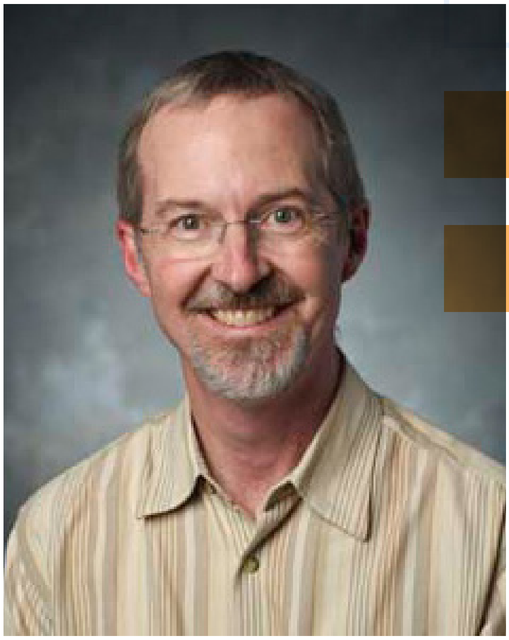


CENTER FOR ACOUSTICS AND VIBRATION

Newsletter 2022

PennState
College of Engineering

CENTER FOR ACOUSTICS
AND VIBRATION



Note from the Director

The past year has been one of transition at the CAV. We returned to an in-person annual workshop, but added online attendance and streaming of our talks – a feature we intend to continue this year and going forward. We continued to archive our workshop talks, as well as our periodic technical seminars on our YouTube channel (https://www.youtube.com/channel/UCG1jhLJmP3urA7mDYoiq1aQ). Our Graduate Program in Acoustics transitioned to a new director – Dr. Andrew Barnard. Andrew is an alumnus, and after several years at Michigan Tech has returned to lead our program into new technical areas. We also began transitioning our CAV and Acoustics lab spaces, working with architects to design improved labs in the new Engineering buildings planned for our West Campus. Penn State researchers will have access to improved anechoic and reverberant rooms, as well as a sound power transmission loss window.

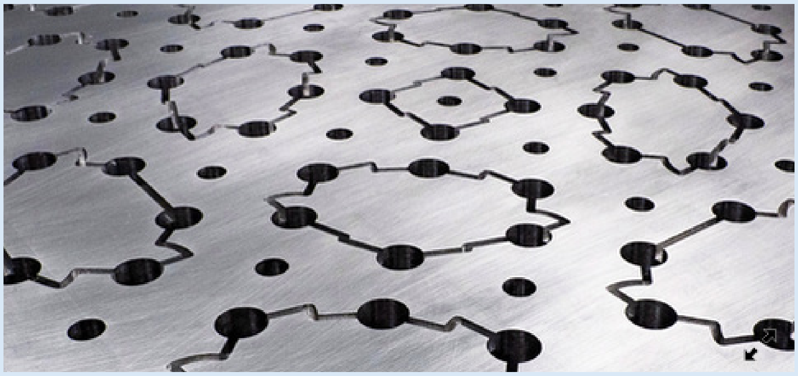
We were also pleased to welcome new faculty to the CAV. Dr. Greg Banyay joined the ARL after many years at Westinghouse Electric Company. Dr. Mark Miller, a Princeton PhD graduate, joined our Aerospace Department. Finally, Dr. Yang Yu is now on our Architectural Engineering faculty after completing his PhD at LSU and post-doctoral work at Arizona State. We're also grateful to our new corporate sponsors: Cummins and GM/Cruise.

The coming year is full of exciting opportunities for our members. Along with our annual workshop 18-19 October we have two CAV co-sponsored meetings to announce. The Transportation Research Board (TRB) is holding its annual Symposium on Transportation Noise and Vibration at Penn State 18-20 July. the meeting will cover all aspects of transportation noise and vibration including road, rail, mass transit, and aircraft noise, as well as noise policy. Also, the Office of Naval Research is sponsoring the Frontiers in Acoustics Metamaterials Symposium 6-7 September. For more details on all these events, please visit our CAV events page: https://www.cav.psu.edu/resources/events.aspx

We hope to see many of you at some or all of these events!

– Steve Hambric // sah19@psu.edu

Contents



Featured Stories

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“The longer I am in the acoustics field, the more opportunities I see for acoustical engineers in many different industries and many different areas of research. I want to get Penn State’s name out there and really work to grow the program.”

– Andrew Barnard, Director of Graduate Program in Acoustics

Andrew Barnard takes over Penn State Graduate Program in Acoustics

Andrew Barnard, a Penn State alumnus and former associate professor of mechanical engineering at Michigan Technological University, has joined Penn State as the director of the Graduate Program in Acoustics, housed within the College of Engineering, on Jan. 1, 2022.

“The acoustics program at Penn State is extraordinarily unique,” Barnard said. “It is world-renowned for what it has accomplished, and having the opportunity to lead this program is a unique opportunity in academia. There is no other program like the Graduate Program in Acoustics at Penn State, and this opportunity was too good to pass up.”

Barnard, who formerly directed the Great Lakes Research Center and Marine Research Assets Facility at Michigan Technological University, plans to teach courses on noise-control engineering in addition to his responsibilities as program director.

“Acoustics is a very customer-centric field, which really excites me because everyone in the world is a customer,” Barnard said. “We are designing products and spaces for people. Acoustics is very people-oriented and multidisciplinary.”

In his new role, Barnard will act as a catalyst for interdisciplinary research and help the acoustics program expand its research portfolio by better incorporating itself into the college and the University. One of his main goals is to increase the program’s enrollment by working to educate students about the multidisciplinary aspects of acoustics. He specifically plans to focus on recruiting Penn State engineering undergraduate students to the graduate program.

“The longer I am in the acoustics field, the more opportunities I see for acoustical engineers in many different industries and many different areas of research,” Barnard said. “I want to get Penn State’s name out there and really work to grow the program.”

Barnard said he also plans to incorporate entrepreneurship into the program and motivate students to pursue every opportunity that comes their way.

"What excites me the most is helping others be successful, and that goes for both students and faculty," Barnard said. "I want to mentor new faculty and help them grow their research and teaching skills and help our students not only learn acoustics but also learn how to interact professionally in whatever field they choose to pursue. I am really looking forward to the people-building part of the program."

Barnard earned his bachelor's and master's degrees in mechanical engineering from Michigan Technological University. He earned his doctoral degree in acoustics from Penn State. While at Penn State, Barnard worked in the Applied Research Laboratory, focusing on structural acoustics and underwater acoustics.

Barnard first became interested in acoustics when he was an undergraduate student. The concepts of acoustics combined his love for music and his passion for engineering, making it the perfect marriage of his hobbies and educational background.

Throughout his collegiate and professional career, Barnard has worked on a wide range of projects focused on a variety of acoustics applications, including: advancing marine technology, fire extinguisher noise control, underwater vehicle noise and vibration, and carbon nanotube loudspeakers. Barnard also co-founded two startup companies with former students of his, NanoSound Inc. and SwimSmart LLC.

Barnard succeeds Victor Sparrow, former director of the Graduate Program in Acoustics, who has led the program since 2010.

"We are so excited to see Dr. Barnard return to his alma mater," said Justin Schwartz, the Harold and Inge Marcus Dean in the College of Engineering. "His experience across multiple disciplines aligns perfectly with the multidisciplinary nature of our Graduate Program in Acoustics. I am confident he will hit the ground running and continue the exceptional work that Dr. Sparrow has done for the program over the years."

"What excites me the most is helping others be successful, and that goes for both students and faculty. I want to mentor new faculty and help them grow their research and teaching skills and help our students not only learn acoustics but also learn how to interact professionally in whatever field they choose to pursue. I am really looking forward to the people-building part of the program."

– Andrew Barnard, Director of Graduate Program in Acoustics

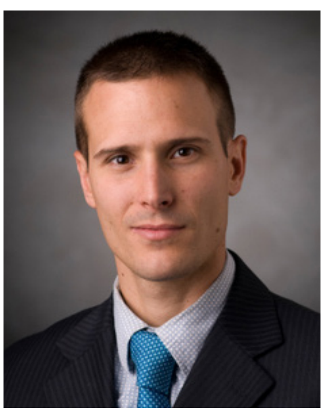
Save the Date: CAV Annual Workshop 2022

Mark your calendars for the 2022 CAV Annual Workshop, to be held Oct. 18-19, 2022 at the Penn State Hetzel Union Building (HUB). We plan to hold an in person workshop, but also plan to stream and archive the talks.

CAV Workshop 2021 and Short Course

The 2021 CAV annual workshop was held 19-21 October as a hybrid event. We were pleased to welcome back some of our sponsors in person, but also streamed the workshop online for those unable to travel. We also recorded all of the presentations (thanks to WPSU for doing such a professional job!), including several from sponsors and a few international liaisons. You can find them on our YouTube site (https://www.youtube.com/channel/UCG1jhLJmP3urA7mDYoiq1aQ)— look for the 2021 CAV workshop playlist.

In person attendees enjoyed our evening social, held at the State College minor league baseball park, where our graduate students hosted the annual student poster competition. The winners are at right.



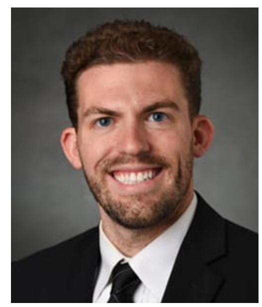
Jose Palacios
Assistant Professor
Aerospace Engineering

Eric Greenwood
Assistant Professor
Aerospace Engineering

The annual CAV short course was held immediately after the workshop on Electrical Vertical Take-Off and Landing (eVTOL) Noise by Drs. Jose Palacios and Eric Greenwood.

The four student poster award winners were:

Prabhav Borate
"Prediction of shear failure by deep learning from automatically extracted ultrasonic features"



Jonathan Broyles
"Assessment of concrete floors for sound transmission and sustainable performance"

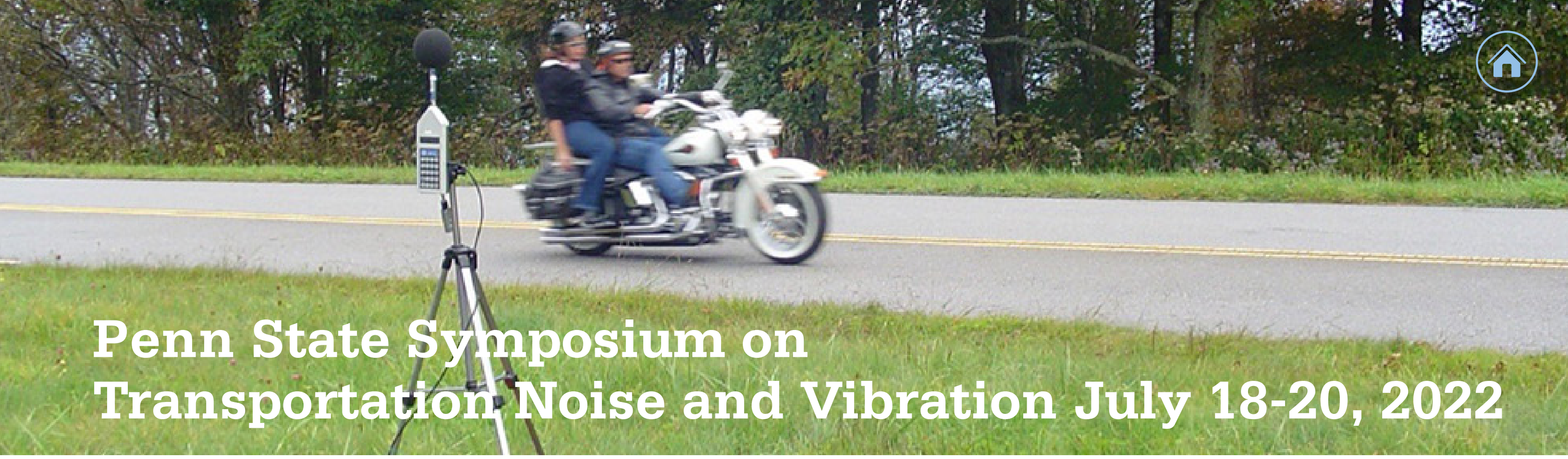
Lauren Katch
"High frequency ultrasonic scattering from cracks in orthotropic silicon wafers"

Joel Rachaprolu
"Helicopter Noise Source Separation Using an Order Tracking Filter"

CAV Seminars Information

CAV members may access our previous lunchtime seminar series online. Each CAV group hosts seminars every semester. You can find links to our most recent archived seminars on the CAV YouTube channel (bit.ly/CAVW-channel) and links to older seminars on the CAV website (bit.ly/CAV-SeminarArchive).

Speaker	Affiliation	Date	Seminar Topic
Yang Yu	Penn State	December 7, 2021	Physics-Guided Machine Learning for Data-Driven Modeling and Discovery of Dynamic Systems
Mehdi Kiani	Penn State	November 16, 2021	Advanced Biomedical Interfaces with Innovative Integrated Circuits and Systems
Ted Worden	Naval Surface Warfare Center, Carderock Division	May 11, 2021	Aeroacoustic Characteristics of Supersonic Impinging Jets
Roland Platz	Deggendorf Institute of Technology, Germany	May 6, 2021	Approaches for Semi-Active and Active State Control in Structural Dynamics under Uncertainty
Andrea Arguelles	Penn State Engineering Science and Mechanics	April 28, 2021	Ultrasound Beyond Imaging: Quantitative Tools for Materials Characterization
Hong Chen	Washington University in St. Louis	April 14, 2021	Targeting the Brain with Focused Ultrasound
Yun Jing	Penn State Graduate Program in Acoustics	April 1, 2021	Bilayer Phononic and Photonic Graphene: A New Playground for Twistronics
Daning Huang	Penn State Aerospace Engineering	February 23, 2021	Surrogate and Reduced-Order Modeling for Enabling Efficient Aerothermoelastic Design and Analysis of Hypersonic Structures



Penn State Symposium on Transportation Noise and Vibration July 18-20, 2022

Penn State will host the 2022 Penn State Symposium on Transportation Noise and Vibration July 18-20, 2022.

Location

The 2022 meeting will be held in the HUB-Robeson Center at Penn State University Park—immediately following the Central Pennsylvania Festival of the Arts.

Sponsoring Organizations

Externally sponsored by the Transportation Research Board (TRB) standing committee on noise and vibration (AEP80), as well as the Institute of Noise Control Engineering of the U.S. subcommittee on Transportation Noise, this specialized meeting on transportation noise and vibration is held every summer at a different location.

Locally sponsored by the Penn State College of Engineering, Center for Acoustics and Vibration, Graduate Program in Acoustics, Department of Aerospace Engineering, and the Thomas D. Larson Pennsylvania Transportation Institute, the meeting will cover all aspects of transportation noise and vibration including road, rail, mass transit, and aircraft noise, as well as noise policy. The meeting will be held primarily in-person with a Zoom option.

Registration

Registration is now open here. Registration is free for all, including Penn State faculty and students. If you are unable to register online, you may request a printable registration form by emailing Jeremy Krebs at **jbk5697@psu.edu**.

The registration deadline is Friday, July 8.

Abstract Submission Process

Abstracts for presentations—using the usual methods of TRB's AEP80—are currently being accepted. Students considering presenting should carefully coordinate this with their academic advisers. The majority of presenters are expected to participate in person. Individuals may submit an abstract and a biography to Ahmed El-Aassar at **aelaassar@gfnet.com**.

The deadline to submit abstracts is Friday, June 3, 2022.

Presentations should be 15 minutes and allow for an additional five minutes of questions and answers, although this may be adjusted depending on the number of submittals.

The following information is required for all presentation submissions:

- First and last name of presenter
- Organization
- Title of the presentation
- Brief abstract (max 200 words)
- Bio paragraph (2-3 sentences)

About the Symposium

Organized by Dr. Victor Sparrow and Dr. Tyler Dare, in conjunction with Penn State Conferences and Institutes, the meeting is expected to bring together 75–100 individuals from industry and other external organizations with representatives from the U.S. Department of Transportation, Federal Aviation Administration, Volpe, state departments of transportation, consultants, and vendors. The symposium provides an opportunity for attendees to interface with government and industry movers and shakers in the transportation noise and vibration world.

Questions

For additional information, please contact Jeremy Krebs at Penn State Conferences and Institutes at **jbk5697@psu.edu** and/or Dr. Victor Sparrow at **vws1@psu.edu**.

Cancellations

Cancellation requests must be received in writing by emailing PSUconferences@psu.edu no later than Friday, July 8.

Accessibility

Penn State encourages qualified persons with disabilities to participate in its programs and activities. If you anticipate needing any type of accommodation or have questions about access provided, please email Jeremy Krebs, **jbk5697@psu.edu**, in advance of your participation.

Lodging

There are no rooms blocked for this symposium and participants are free to select from any of the wide selection of local hotels. The following options are closest to the location of the symposium.

Scholar State College, Tapestry Collection by Hilton
205 E Beaver Avenue, State College, PA 16801
(0.4 miles from the HUB)

Hyatt Place State College
219 W Beaver Avenue State College, PA 16801
(0.5 miles from the HUB)

The Graduate State College
125 S Atherton Street State College, PA 16801
(0.6 miles from the HUB)

Contact Us

For questions about registration, please contact:
Outreach Non-Credit Registration Office
8:00 a.m. - 5:00 p.m. ET, Monday-Friday
Phone: 814-867-4973; Fax: 814-863-2765
Email: noncredit@psu.edu

Additional Information

Conferences and Institutes
The Pennsylvania State University
Email: PSUconferences@psu.edu
Phone: 814-863-5100

Penn State Symposium on Transportation Noise and Vibration:
https://www.cav.psu.edu/resources/symposium-on-transportation-noise-and-vibration.aspx

Penn State researchers investigated a method for better balancing sustainability with desirable acoustic properties in concrete floor slabs similar to the one shown in this photo with, left, Jonathan Broyles, an architectural engineering doctoral candidate, and Nathan Brown, assistant professor of architectural engineering. This scaled-down slab, fabricated in collaboration with Jonathan C. Boliek, an independent contractor, is a model for future research with Micah Shepherd, assistant research professor of acoustics and a paper co-author.

Credit: Kelby Hochreither.

Balancing sustainability, safety and comfort in engineered floor slabs

By Gabrielle Stewart

Using less material in floors is a viable strategy for improving sustainability in buildings, as it can reduce the structure's environmental footprint. Prioritizing only this goal, however, can lead to unwanted effects — such as an echo in a room or noise traveling between floors, according to Nathan Brown, assistant professor of architectural engineering.

Penn State researchers explored a method for optimizing the acoustic and structural properties of concrete floor slabs. Their findings were published online ahead of the March print edition of the Journal of Architectural Engineering.

"The exciting result of our research is that shaped structures can improve sound insulation performance in buildings while reducing the embodied carbon emissions of the structural system," said Jonathan Broyles, an architectural engineering doctoral candidate and the first author of the paper.

To begin their investigation, the team used 3D modeling software to create shaped concrete slabs made up of many curves connected by movable control points. By providing the program with parameters to follow when moving these points, the researchers allowed the software to generate a variety of possible designs with realistic, customized constraints.

Continuing the effort to find a favorable design — a process called optimization — the researchers needed to test the generated designs' performance in two areas. They analyzed structural properties, for meeting building engineering standards, and acoustic properties, for minimizing undesirable sounds.

"Traditional optimization is focused on targeting one value as a good or bad design, but in this case, we have two values: one to evaluate structural performance and another for acoustic performance," said Brown, corresponding author on the paper. "We set up a model with some variables and used a computer algorithm to move through potential designs, targeting better options for both values at the same time."

The team used a number of equations to inform their optimization constraints. In addition to considering mass, with a goal of reducing mass to reduce the emissions required to make and install a slab, the researchers also took shape and stiffness into account. Understanding the effect of each of these variables on acoustic properties would allow the team to reduce the power of transmitted sound waves hitting the slab, according to Brown.

Using optimization, the researchers identified concrete slab designs that used less concrete than a conventionally shaped slab and maintained desirable acoustic properties. These findings, Brown said, build a foundation for the design of shaped concrete floors that can be optimized for better interaction with sound without compromising sustainability.

Broyles said the research was motivated in part by his interdisciplinary interests.

"I came to Penn State to pursue research at the intersection of structural engineering and acoustic design," Broyles said. "After I met with Dr. Brown, I realized that this topic could be explored in optimization studies of shaped concrete floors to help understand the relationship between sustainability and building acoustics."

The team plans to apply the methods used in this research to understand the trade-offs between sustainability and performance in areas beyond acoustics. According to Brown, exploring this connection can lead to more sustainable buildings that do not compromise quality of life.

"This is what's interesting to me about the design process — especially for building components that have to do many different things and achieve many quantitative performance targets while still possessing qualitative traits that make buildings places we want to dwell in," Brown said. "A lot of my core research agenda lies in considering these quantitative objectives we can measure while still giving designers freedom and flexibility to think about those qualitative aspects."

Micah Shepherd, assistant research professor of acoustics, also contributed to this work.

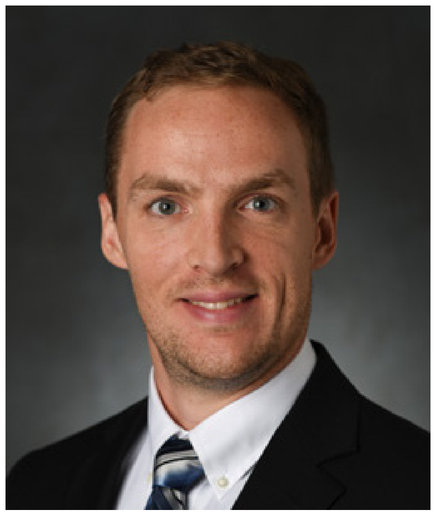
"Traditional optimization is focused on targeting one value as a good or bad design, but in this case, we have two values: one to evaluate structural performance and another for acoustic performance."

– Nathan Brown, assistant professor of architectural engineering

New Faculty Biographies

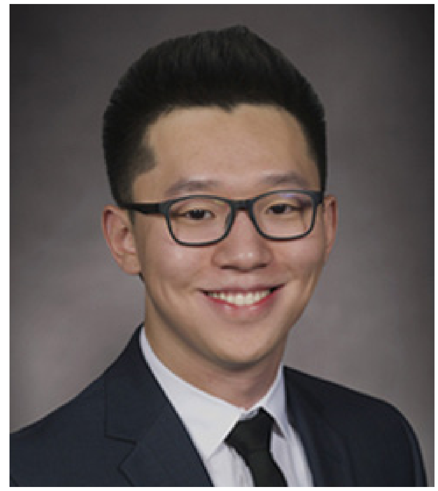
Greg Banyay
ASSISTANT RESEARCH PROFESSOR
Applied Research Lab

Gregory Banyay joined The Pennsylvania State University Applied Research Laboratory (PSU|ARL) as an assistant research professor in 2021, focusing on structural acoustics and associated computational mechanics. Prior to joining PSU, he worked for Westinghouse Electric Company for 11 years and Parker Hannifin for five years, in the nuclear and aerospace industries, respectively. Gregory is a registered professional engineer, regularly contributes to ASME, has earned B.S. and M.S. degrees in Mechanical Engineering from The Ohio University, and Ph.D. in Civil & Environmental Engineering from University of Pittsburgh. Greg is part of the CAV Artificial Intelligence and Machine Learning group. Greg recently published a paper on the opacity of digital twins: https://asa.scitation.org/doi/10.1121/2.0001537.



Mark Miller
ASSISTANT PROFESSOR
Aerospace Engineering

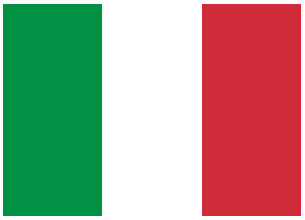
Mark A. Miller joined the faculty of the Aerospace Engineering Department as an Assistant Professor in 2019. Prior to this, he earned his Ph.D. in Mechanical and Aerospace Engineering at Princeton University in 2018 for the study of high Reynolds number wind turbine performance scaling, work which he continued as a postdoctoral scholar. He also holds M.S. and B.S. degrees in Mechanical Engineering from the University of Kentucky. Miller's research at Penn State focusses on the fundamental fluid dynamics of unsteady and rotating systems by using a multifaceted experimental and theoretical approach. Ongoing projects span a wide range of fluid systems including multi-rotor electric Vertical Take-Off and Landing (eVTOL) performance and acoustic characterization, wind turbine aerodynamics and acoustics, turbulent structure modifications due to roughness, and development of innovative sensor systems which are tailored to these specific flow regimes. He is an active member of the AIAA, the American Physical Society, the ASA, and the Vertical Flight Society, where he currently serves on the Test and Evaluation Committee.



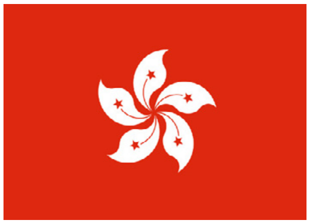
Yang Yu
ASSISTANT PROFESSOR
Architectural Engineering

Dr. Yang Yu is an Assistant Research Professor in the Department of Architectural Engineering at Penn State. Prior to joining Penn State, he was a postdoctoral scholar in Mechanical and Aerospace Engineering at Arizona State University. Dr. Yu obtained his Ph.D. in Civil Engineering from Louisiana State University and B.S. in Civil Engineering from Hunan University in China. His research interests lie broadly in engineering applications of artificial intelligence, smart systems, structural safety, and diagnostics and prognostics of engineering systems. His current research focuses on developing physics-guided data analytics for data-driven modeling and discovery of dynamic systems. One of his papers on physics-guided machine learning won the Best Paper Award from the Prognostics and Health Management Society (PHM Society). Yang is part of the CAV Artificial Intelligence and Machine Learning group.

International Liaisons



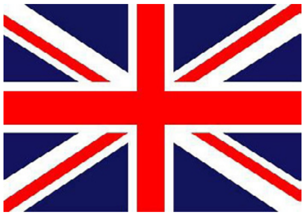
Centro Italiano Ricerche Aerospaziali (CIRA), Italy



Consortium for Sound and Vibration Research at Hong Kong Polytechnic University, Hong Kong

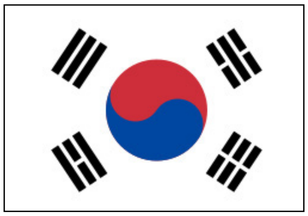
Deutsches Zentrum fur Luft und Raumfahrt (DLR), Germany

Groupe d'Acoustique de L'Universite de Sherbrooke, Canada

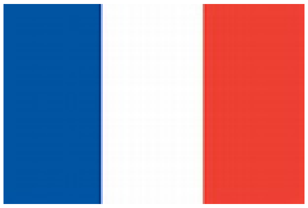


Institute of Sound and Vibration Research (ISVR), United Kingdom

Noise and Vibration Research Group at Katholieke Universiteit in Leuven (KU-Leuven), Belgium



Sound and Vibration Lab at the Korean Advanced Institute for Science and Technology (KAIST), South Korea



Vibration and Acoustics Laboratory at INSA de Lyon, France

Government Liaisons

Corporate Sponsors

New Corporate Sponsors

The CAV is pleased to welcome two new corporate sponsors:

Cummins Inc. is an American multinational corporation that designs, manufactures, and distributes engines, filtration, and power generation products. Cummins also services engines and related equipment, including fuel systems, controls, air handling, filtration, emission control, electrical power generation systems, and trucks.

www.cummins.com

Cruise LLC is an American self-driving car company headquartered in San Francisco, California. Founded in 2013 by Kyle Vogt and Dan Kan, Cruise tests and develops autonomous car technology.

www.getcruise.com

CAV Member and Student Honors and Awards

Dr. Stephen Hambric, research professor, Penn State Applied Research Lab (ARL), presented the 2021 American Society of Mechanical Engineers (ASME) Rayleigh Lecture during the November International Mechanical Engineering Congress and Exposition (IMECE).

Hambric's lecture included a tutorial on vibro-acoustics. To view the tutorial, audience members must enter their names and contact information, but do not need to set up an account. An option to opt out of future communications from ASME is available.

The Penn State Graduate Program in Acoustics awards its students for high quality journal articles and conference papers. Below are this year's winners.

Eugen J. Skudrzyk Award Winner:

- **Yuanchen Deng-** Yuanchen Deng, Wladimir A. Benalcazar, Ze-Guo Chen, Mourad Oudich, Guancong Ma, and Yun Jing, "Observation of degenerate zero-energy topological states at disclinations in an acoustic lattice," Physical Review Letters, 2022, in print.

Kenneth T.Simowitz Award Winners:

- **Jacob Elliott-** Elliott J, Khandare S, Butt AA, Smallcomb M, Vidt ME, Simon JC (2022). "Automated tissue strain calculations using Harris corner detection." Annals Biomedical Engr. Accepted March 15, 2022. In Press.
- **Fernando del Solar Dorrego-** JASA Peer Review Journal Article January 2022; del Solar Dorrego, F. and Vigeant, M.C. (2022)."A study of the just noticeable difference of early decay time for symphonic halls." J. Acoust. Soc. Am. 151:80-94

Kenneth T. Simowitz Citation Winners:

- **Sean Collier-** Collier, S., Dare, T. (2022). A Practical Guide to Motion Magnification. In:Di Maio, D.,Baqersad ,J.(eds) Rotating Machinery, Optical Methods & Scanning LDV Methods, Volume 6. Conference Proceedings of the Society for Experimental Mechanics Series. Springer, Cham.
- **Adwait Ambaskar-** Presented paper at Internoise 2021. Ambaskar, A., Sparrow, V.W. (Co-Author), & Reigner, N. (2021). Open-source acoustic model development for natural & protected environments. In T. Dare, S. Bolton, P. Davies, Y. Xue, & G. Ebbitt (Eds.), Proceedings of Internoise 2021. (pp.12). Washington, DC: Institute of Noise Control Engineering of the USA. DOI:10.3397/IN-2021-2070
- **Lucas Wade-** Wade, L., Sparrow, V.W. (Co-Author), Acoustics in Focus, Acoustical Society of America, Online due to Covid-19."An extension of the geometrical-acoustics model near a caustic with application to off-track sonic boom focusing" Invited. (June 9, 2021). National. Abstract published as J. Acoust. Soc. Am. 149(4)A74(2021).

CAV 2021 Graduate Student Theses

You can access graduate students' theses on the CAV website at: bit.ly/cav-stu-theses.

NAME	PROGRAM	DEGREE	TITLE
Shreedharan, Srisharan	Geosciences	Ph.D.	Frictional mechanics of stable and unstable fault slip: Insights from ultrasonic imaging of experimental fault zones
Agrawal, Sumit	Bioengineering	Ph.D.	Intelligent Ultrasound and Photoacoustic Imaging Systems: Design, Development and Beyond
Gauntt, Sean	Mechanical Engineering	Ph.D.	Dynamic Analysis of Aerospace Gearboxes Featuring Hybrid Steel-Composite Gears

NAME	PROGRAM	DEGREE	TITLE
Chen, Xiaoling	Mechanical Engineering	Ph.D.	Modeling and control of thermoacoustics in a one-dimensional combustor
Almadih, Mustafa	Mechanical Engineering	Ph.D.	Acoustic Analysis and Detection of the Effects of Vapor-Liquid Interfacial Morphology on Pool-Boiling Heat Transfer for Different Materials
Daneshpajooh, Hossein	Electrical Engineering	Ph.D.	Comprehensive study of external field and stress bias effect on piezoelectric properties and loss factors
Cheng, Christopher	Materials Science and Engineering	Ph.D.	Piezoelectric Micromachined Ultrasound Transducers Using Lead Zirconate Titanate Films
Bolton, David	Geosciences	Ph.D.	Characterizing Acoustic Emission Signals Throughout The Laboratory Seismic Cycle: Insights On Seismic Precursors
Yenigelen, Evren	Aerospace Engineering	Ph.D.	Numerical Analysis of Rocket Launch Acoustics
Sloand, Janna	Bioengineering	Ph.D.	Exploiting The Fluorous Effect To Create Supramolecular Fluoropeptide Materials
Smith, Chad	Acoustics	Ph.D.	Modeling and analysis of transverse horizontal spatial coherence statistics for reverberation-limited active littoral sonar
Romond, Rachel	Acoustics	Ph.D.	Meteorological Reanalysis Data Inputs for Improved Aviation Noise Modeling
Xiong, Yu	Aerospace Engineering	Ph.D.	Vibroacoustics of Lightweight Structures with Embedded Acoustic Black Holes
McCluskey, Connor	Acoustics	Ph.D.	Extreme value statistics of flow-induced response and fatigue
McCormick, Cameron	Acoustics	Ph.D.	Optimization of Acoustic Black Holes for Vibration Reduction
Yoas, Zachary	Bioengineering	M.S.	Passive Trailing Edge Noise Attenuation With Porosity, Inspired By Owl Plumage
Girkar, Vrushali	Computer Science	M.S.	Laboratory Earthquake Prediction using Deep Learning
Brown, Avery	Engineering Science and Mechanics	M.S.	Experimental Evaluation of Carbon/Epoxy Laminates with Concentrated Carbon Nanotube Interlayers for High Damping
Jaep, Daniel	Mechanical Engineering	M.S.	Acoustic Emission Damage Detection for Bonded Metal-Elastomer Components
Elston, Jacob	Mechanical Engineering	M.S.	Investigation of Various Factors Affecting Noise Emission from Roller Element Bearings
Carder, Nicholas	Acoustics	M.S.	Viability of Motor Current Sensors for Tool Condition Monitoring During Peck Drilling Operations with Coolant and Inverter-Fed AC Motors
Furlong, Trent	Acoustics	M.S.	Tool Condition Monitoring Using the Hilbert-Huang Transform: An Application to Vibration and Motor Current Signals
Gan, Ze Feng	Aerospace Engineering	M.S.	Time-Varying Rotor Noise Computations and Analysis of Electric Vertical Take-Off and Landing Aircraft

Penn State Graduate Program in Acoustics Distance Education Courses

The Graduate Program in Acoustics at Penn State is a unique interdisciplinary program leading to master of science and doctorate in acoustics. The program is focused entirely on acoustics, a subject touching many diverse disciplines such as architectural acoustics, biomedical ultrasound, noise and vibration control, transducer design, underwater acoustics, signal processing, aeroacoustics, structural vibration, speech and communication, outdoor propagation, computational methods, and more.

www.acs.psu.edu

Fall 2022 Distance Education Course Schedule

CLASS DATES

Class Dates: August 22–December 16

- All classes video streamed and archived for review
- All courses available for credit or audit

TUITION FEE

Tuition rate and IT fee for fall 2022 is approximately $3,000. The exact amount will be determined by the Penn State Board of Trustees in July.

In order to guarantee fall course enrollment:
All NEW nondegree student applications and application fees or resume study nondegree student requests must be completed with The Graduate School no later than 5:00 p.m. ET, Friday, August 12.

All resume study DEGREE student requests must be completed with The Graduate School no later than 5:00 p.m. ET, Monday, August 15.

COURSE SCHEDULE

ACS 501: ELEMENTS OF ACOUSTICS AND VIBRATION

Instructor: Dr. Dan Russell

Credits: 3

Tentative Class Time: Tuesday and Thursday, 1:35 – 2:50 p.m. ET.

Tuition: See Tuition Fee announcement above.

Prerequisite: Undergraduate physics, differential equations, and complex numbers.

Course Material: This course introduces the fundamentals of acoustics and vibration, focusing on structural vibration and sound waves in simple objects such as mass-spring systems, strings, rods, and plates. The fundamental concepts of vibration are presented along with applications to engineering and industrial problems. Topics covered: simple harmonic oscillator; mechanical resonance and damping; forced vibration and normal modes; transverse waves on strings; boundary conditions and standing waves; elasticity; longitudinal, torsional, and transverse vibration of bars; transverse vibrations of membranes; and flexural vibrations of thin plates.

Text: *Understanding Acoustics: An Experimentalist's View of Sound and Vibration*, 2nd Ed., Garrett, Steven L., 2020 (Springer) ISBN-10: 3030447863

Free PDF available after course registration.

ACS 502: ELEMENTS OF SOUND WAVES IN FLUIDS

Instructor: Dr. Yun Jing

Credits: 3

Tentative Class Time: Monday and Wednesday, 9:05 – 10:20 a.m. ET

Tuition: See Tuition Fee announcement above.

Prerequisite: Undergraduate physics and differential equations.

Course Material: This course lays the fundamental groundwork for the propagation of acoustic waves in fluids. Topics include: basic equations of fluid dynamics, development of the linear wave equation, acoustic lumped elements, speed of sound, linear acoustic wave propagation of plane and spherical waves, radiation of sound from sources and arrays, sound intensity and power, reflection and transmission of sound at boundaries, absorption of sound, propagation of sound in pipes and acoustic filters.

Text: *Fundamentals of Physical Acoustics*, Blackstock, David T., 2000 (Wiley) ISBN-10: 0471319791

ACS 503: SIGNAL ANALYSIS FOR ACOUSTICS AND VIBRATION

Instructor: Dr. Dan Brown

Credits: 3

Tentative Class Time: Tuesday and Thursday, 9:05 – 10:20 a.m. ET

Tuition: See Tuition Fee announcement above.

Prerequisite: Undergraduate physics, differential equations, and complex numbers as well as some familiarity with programming in MatLab or equivalent.

Note: This course replaces ACS 516, Acoustical Data Measurement and Analysis. Students may enroll in this course if they have not taken ACS 516. Students who have previously taken ACS 516 may not enroll in this course.

Course Material: Time- and frequency-domain analyses for sampled, discrete-time acoustic and vibration measurements. Development, application, and consequences of filtering, spectral analysis, and correlation for single- and multi-channel data.

Text: Instructor notes.

Software: MatLab or MatLab Student Version, available at webapps.psu.edu.

ACS 597: COMPUTATIONAL ACOUSTICS

Instructor: Dr. Vic Sparrow

Credits: 3

Tentative Class Time: Monday and Wednesday, 1:00 – 2:15 p.m. ET

Tuition: See Tuition Fee announcement above.

Prerequisite: Co-Requisite Registration: ACS 501, Elements of Acoustics and Vibration, and ACS 502, Elements of Waves in Fluids.

Course Material: The purpose of this course is to provide a good background in computational acoustics by providing instruction in using modern commercial packages for solving acoustics problems as well as a good understanding of the fundamental background knowledge so that the commercial packages can be used correctly and effectively. Students will be exposed to many important tools in acoustics including symbolic manipulation programs such as Mathematica; finite differences, finite elements and boundary elements; scientific visualization; and sound propagation algorithms. Topics covered include: using PCs and UNIX workstations; visualizing and postprocessing acoustic data; transient analysis of acoustics waves; modal and forced responses of arbitrary cavities using finite elements; acoustic radiation and scattering predicted using boundary elements and/or infinite elements; and first pass at parallel processing.

Text: Instructor notes.

Software: MatLab or MatLab Student Version, available at webapps.psu.edu. Mathematica or Mathematica for Students, available at webapps.psu.edu.

ACS 597: NOISE CONTROL APPLICATIONS

Instructor: Dr. Andrew Barnard

Credits: 3

Tentative Class Time: Tuesday and Thursday, 3:05 – 4:20 p.m. ET

Tuition: See Tuition Fee announcement above.

Prerequisite: This course does not have prerequisites, however, is intended to generally be taken after ACS 537—Noise Control Engineering. Students with industry or acoustical consulting backgrounds can be successful in this course if they have not taken ACS 537.

Course Material: This course focuses on applications in noise control engineering. The course is split into three main overlapping themes: advanced measurement methods, machinery noise control, and business techniques for noise and vibration specialists. The advanced measurement methods will cover topics such as sound intensity, sound power, sound quality, impedance and transmission loss tubes, and coherent output power. The machinery noise control topics include noise generation and control from systems such as gears, pulleys, fans, HVAC systems, muffler systems, and rotating machinery. Finally, throughout the course, business development and business model generation techniques will be introduced with specific examples in noise control engineering.

Text: Instructor notes.

Software: Working knowledge of (MATLAB, Octave, OR Python) AND Microsoft Excel.

Spring 2023 Distance Education Course Schedule

CLASS DATES

January 9-May 5, 2023

TENTATIVE COURSE OFFERING

(Suggestions can be sent to acousticsde@psu.edu.)

ACS 514: ELECTROACOUSTIC TRANSDUCERS

Credits: 3

Prerequisite: Undergraduate physics, basic linear circuit theory, differential equations, and complex numbers. Must have working knowledge of required software.

ACS 515: ACOUSTICS IN FLUID WAVES

Credits: 3

Prerequisite: ACS 502, Elements of Sound Waves in Fluids or ACS 597B, Introduction to Acoustics and Fluid Media, ACS 598E, Engineering Mathematics I or equivalent, or instructor consent.

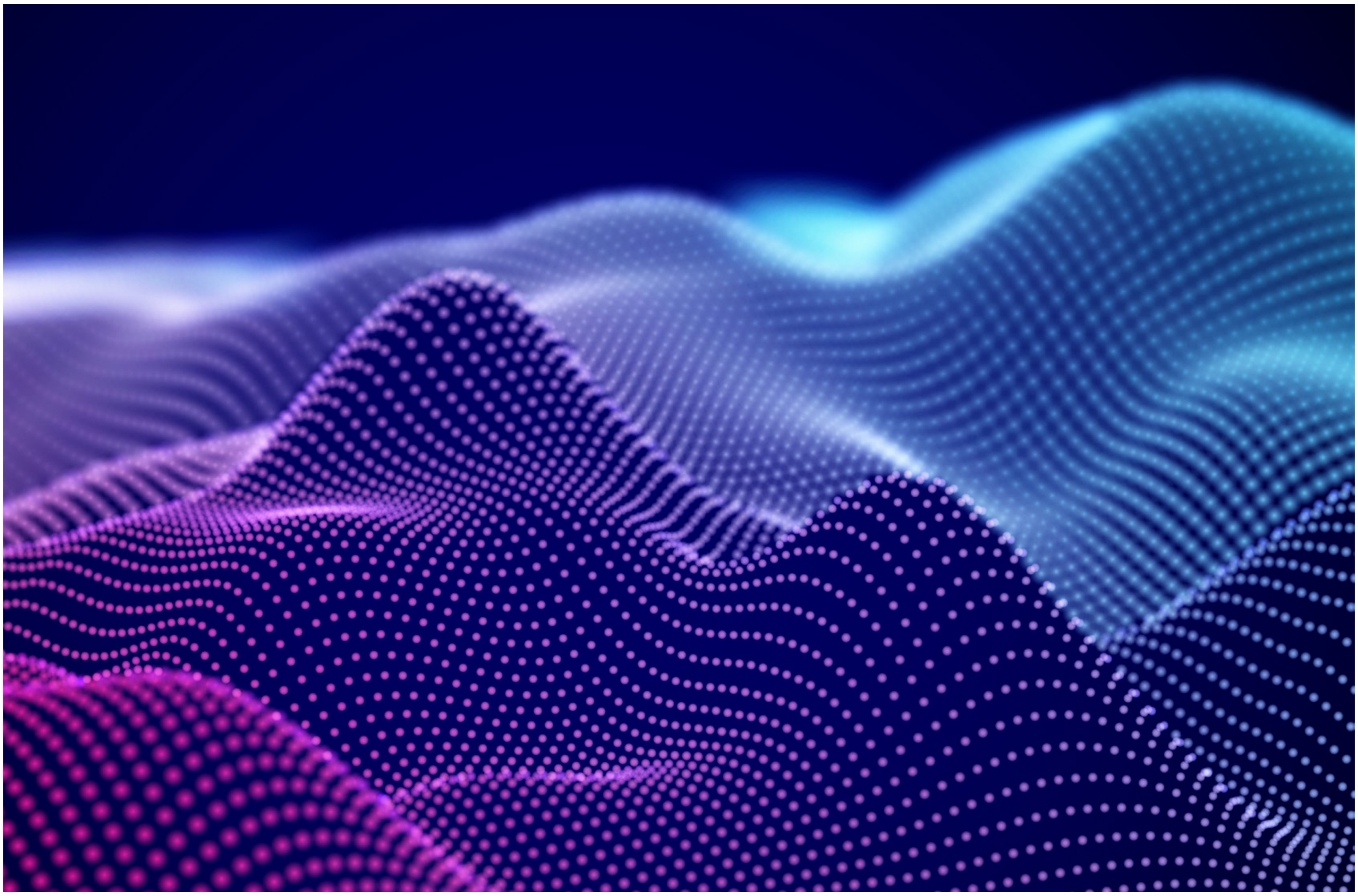
ACS 597: ADVANCED SIGNAL ANALYSIS FOR ACOUSTICS AND VIBRATION

Credits: 3

Prerequisite: ACS 503 or ACS 597, Signal Analysis for Acoustics and Vibration

Note: This course replaces ACS 513, Digital Signal Processing. Students may enroll in this course if they have not taken ACS 513. Students who have previously taken ACS 513 may not enroll in this course.

Technical Research Group Highlights



Acoustic Materials and Metamaterials

Group Summary

Group Leader: Amanda Hanford
Assistant research professor in acoustics

The Acoustic Materials and Metamaterials technical group performs research in many areas involving the interaction between acoustics and materials. Example topics include material characterization, manufacturing techniques for novel materials, novel applications such as acoustic cloaking, metamaterial inverse design, active metamaterials, and structural vibration control through novel materials.

The Acoustic Materials and Metamaterials technical group is happy to announce the support the Frontiers in Acoustic metamaterials Symposium co-sponsored by the Office of Naval Research (ONR), Applied Research Lab (ARL) and the CAV, scheduled for Sept 6 and 7 hosted at Penn State. See here for more information: https://sites.psu.edu/meta2022/.

Below are some highlights of this group's recent work.

Projects and Graduate Students:

Active and Adaptable Acoustic Metamaterial Plates

Sponsor: NAVSEA 073

Principal investigators: Benjamin Beck, assistant research professor in the Penn State Applied Research Laboratory and engineering program manager in the Radiation Science & Engineering Center

Student: Aaron Stearns, doctoral student in mechanical engineering

Publication: A. Stearns, B. Beck, "Design of a 2D plate adaptable metamaterial unit cell using finite elements," *Proc SPIE 12043*, April 2022.

Summary: Acoustic metamaterials are composite materials exhibiting effective properties and acoustic behavior not found in traditional materials. Through periodic subwavelength resonant inclusions, acoustic metamaterials enable steering, cloaking, lensing, and frequency band control of acoustic waves. A common drawback of acoustic metamaterials is that the properties are limited to narrow frequency bands. Investigation of practical active and adaptable acoustic metamaterials is valuable in achieving wider operation frequency bands. In this work, we explore different geometric configurations for a cutaway plate metamaterial unit cell with the purpose of vibration suppression. Resonators cut directly in a thin uniform plate function as local resonators. We examine the wavenumber band structure seeking wide and low frequency band gaps in the vicinity of the resonant frequencies of the local resonators. Variations in the geometry of the unit cell are examined to obtain band gaps for broadband vibration suppression. Wave shapes of the unit cell associated with the band gaps are also examined to aid in the parametric design of the unit cell. Additionally, as a means of tuning stiffness of the local resonators we attach piezoelectric actuators to the cutaway resonators with the goal of increasing the bandwidth of the vibration suppression and enabling frequency tunability of the system.

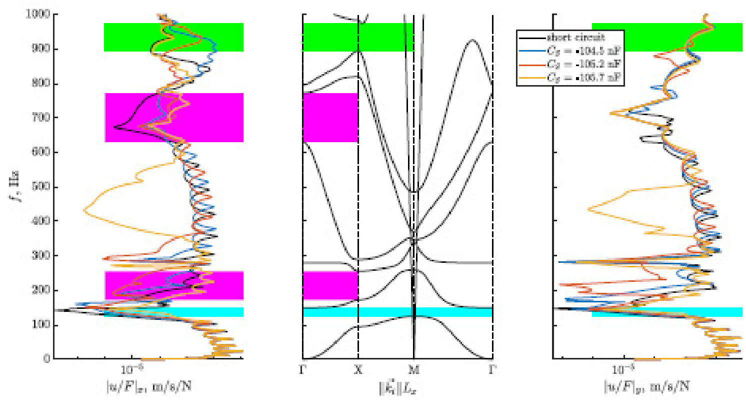


Figure 1: Band Structure and frequency response results for several shunt tunings

Control of Rayleigh Wave Propagation

Sponsors: National Science Foundation, PSU College of Engineering

Principal investigators: Parisa Shokouhi, associate professor in engineering science and mechanics and acoustics; Cliff Lissenden, professor of engineering science and mechanics and acoustics

Student: Lalith Pillarisetti

Publication: LSS Pillarisetti, C. Lissenden, P. Shokouhi, "Control of Rayleigh wave propagation through imposing Mindlin boundary conditions on the surface," *J. Sound and Vibration*, 530, (2022).

Summary: A resonant metasurface design based on boundary condition (BC) manipulation was recently established to control low-frequency Lamb waves in a plate. This study identifies the necessary BCs that forbid Rayleigh wave propagation in order to find a rational design methodology for an optimized BC-controlled meta-surface. An analytical study of Mindlin BCs, a type of Cauchy BCs, shows promise in surface wave control. The frequency-domain and time-domain finite element studies performed by imposing Mindlin BCs in the path of Rayleigh wave propagation are consistent with analytical predictions, exhibiting no Rayleigh wave transmission. The simulations reveal mode conversions from Rayleigh wave to bulk waves directed into the half-space and a low amplitude Rayleigh wave reflection. For a finite-sized BC patch, the radial beam spreading of the mode-converted bulk waves keeps some energy near the surface, which could convert back to Rayleigh waves at the end of the BC patch. Thus, the BC patch must be sufficiently long to effectively suppress surface waves. Finally, we show that the Mindlin BCs can be imposed by a rod-like prismatic resonator at the resonator's longitudinal frequency. These findings provide new insights into the coupling that promotes surface wave control, potentially leading to novel metasurface designs.

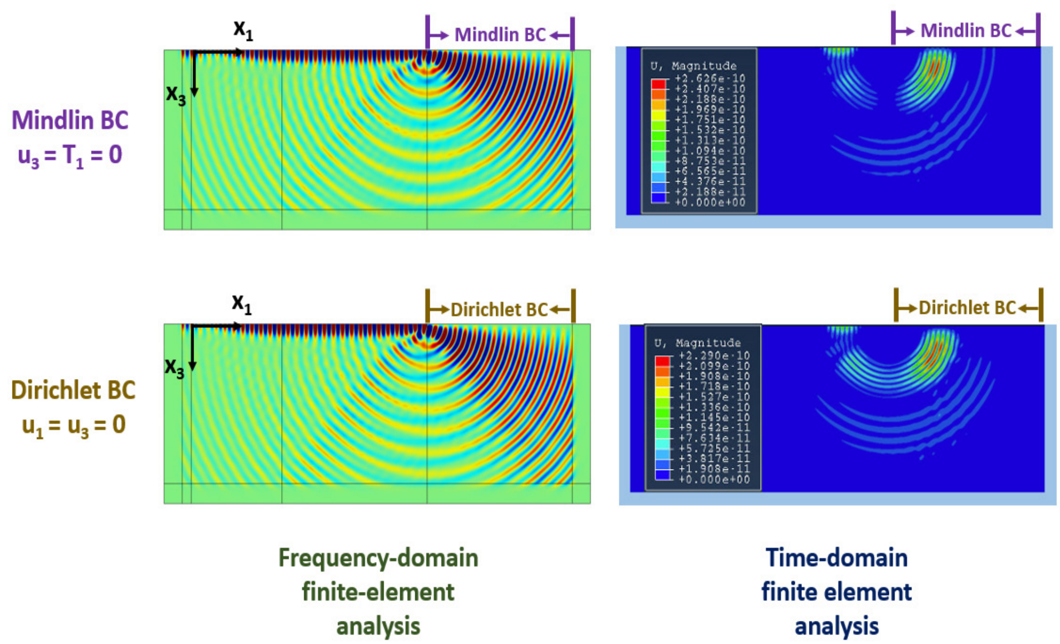


Figure 2: Mindlin boundary conditions and Dirichlet boundary conditions exhibit the desired surface wave control behavior

Architected micro-lattices for wide-band vibration attenuation

Sponsor: National Science Foundation CMMI

Principal investigator: Dr. Yun Jing

Summary: Elastic metamaterials are artificial periodic structures that exhibit frequency ranges known as bandgaps, where wave propagation is prhibited. Conventional elastic metamaterials are limited in their bandwidth, since they require impractical mass and size, with respect to the operating wavelength. Additionally, their designs also greatly restrict them from catering more than one functionality. This project introduces a micro-lattice-based metamaterial that can attenuate elastic waves in all directions and over a wide frequency range, alongside possessing the second order functionality of exhibiting a negative Poisson's ratio. Such a thin lightweight material with dual functionality could thus pave way for a variety of unconventional wave-based devices, alongside bolstering the interest for futuristic multi-functional materials.

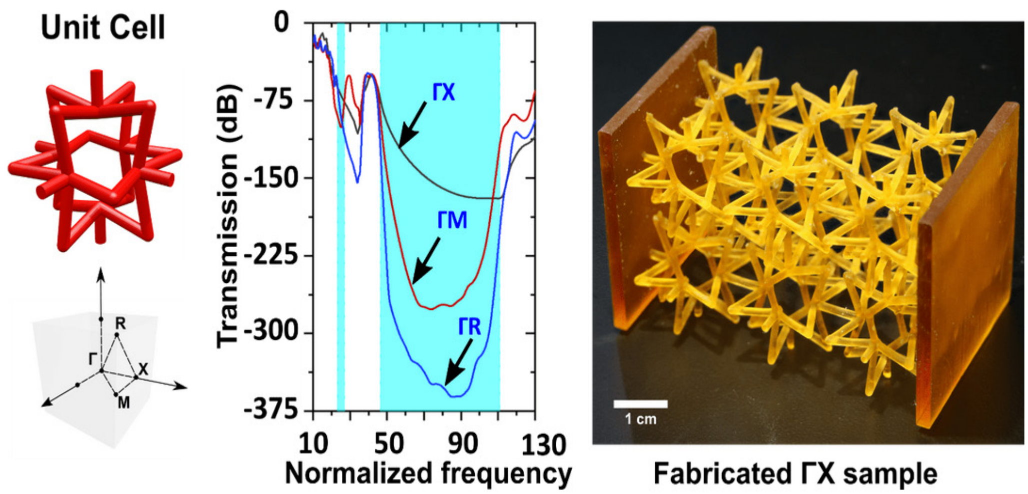


Figure 3: (left) Unit Cell for elastic metamaterial. (center) Transmission loss of designed metamaterial. (right) Photo of fabricated elastic metamaterial

Observation of degenerate zero-energy topological states at disclinations in an acoustic lattice

Sponsor: National Science Foundation

Principal investigator: Dr. Yun Jing

Student: Yuanchen Deng

Publication: Y. Deng *et al.*, "Observation of degenerate zero-energy topological states at disclinations in an acoustic lattice," *Phys. Rev. Lett.* 128, 174301 (2022). This article has been published in Physical Review Letters Editor's Suggestion

Summary: In a material with a so-called topologically protected state, particles—electrons, photons, or phonons, for example—can move around boundaries in the material without losing energy or being scattered. One way to make a material with such a state is to add into its lattice one or more defects that violate the lattice's rotational symmetry—for example, disclinations (line defects). However, such defects can break the lattice's chiral symmetry, which helps protect the topological state. Now, Yun Jing of Pennsylvania State University and colleagues propose and demonstrate a way to ensure chiral symmetry is preserved in the presence of such a defect.

When a system has chiral symmetry, its energy spectrum is symmetrical around a "privileged zero frequency." However, disclinations can move the system away from this zero frequency. Jing and his team found, theoretically, that they could prevent that from happening by making the spectrums of the "cores" of the disclinations symmetric. If they do that, they predict that the system's chiral symmetry and its topological state will be protected. To validate their theory, the team made an acoustic honeycomb lattice using aluminum plates and introduced into it a disclination by removing a $2\pi/3$ section of a central honeycomb. They then acoustically excited the lattice using speakers and measured its acoustic response using a small microphone. The team found that the peak of the energy spectrum of the disclination core was symmetric about the system's zero frequency and that the honeycomb lattice maintained its chiral symmetry in the presence of the disclination, confirming their predictions.

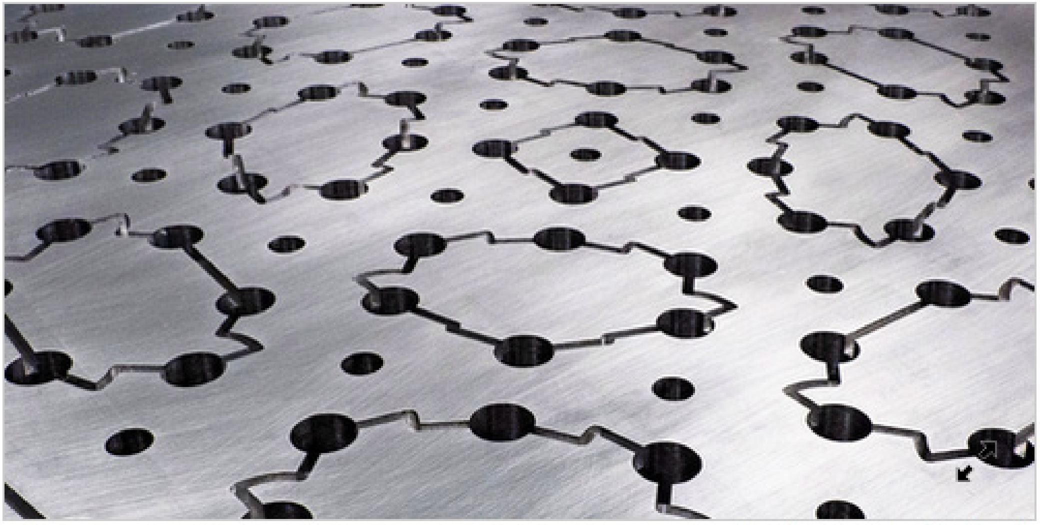


Figure 4:

The Use of Pulse Waves to Increase Carbon Nanotube Thermophone Efficiency

Principal investigators: Benjamin Beck and Tim Brungart

Student: James Chatterley

Summary: The use of pulse wave drive signals has the potential to greatly increase the efficiency of carbon nanotube (CNT) thin-film thermophones. Although numerous researchers have investigated various aspects of CNT thin-film sound generation, little focus has been given to input signals and their effect on efficiency. The research that has been accomplished to-date indicates that significant efficiency gains are available with pulse wave drive signals. The testing and experimentation performed to-date in the current investigation has demonstrated up to a 25-fold increase in sound generation efficiency with pulse waves compared to conventional continuous sine wave drive signals. Experiments also demonstrate that the overall sound pressure level versus total input power efficiency of pulse wave driven CNT thin-film thermophones is up to 14-times more efficient compared to a continuously driven CNT thin-film thermophone.

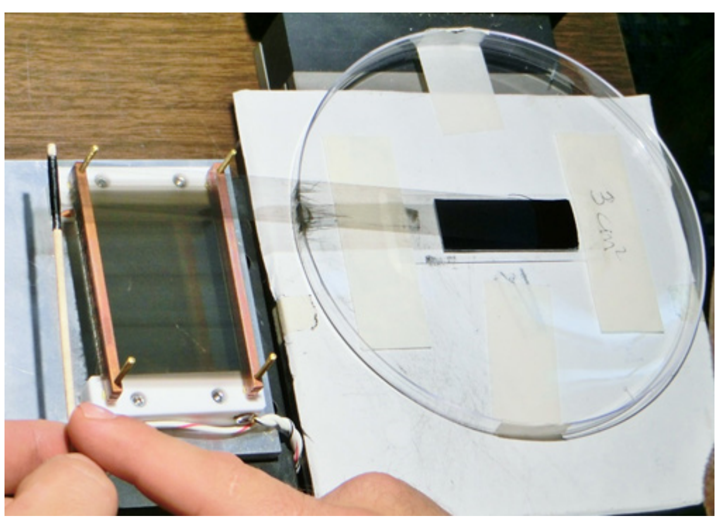


Figure 6: Drawing of CNT Forest into Thin-film Across Copper Rods in CNT Thermophone Construction.

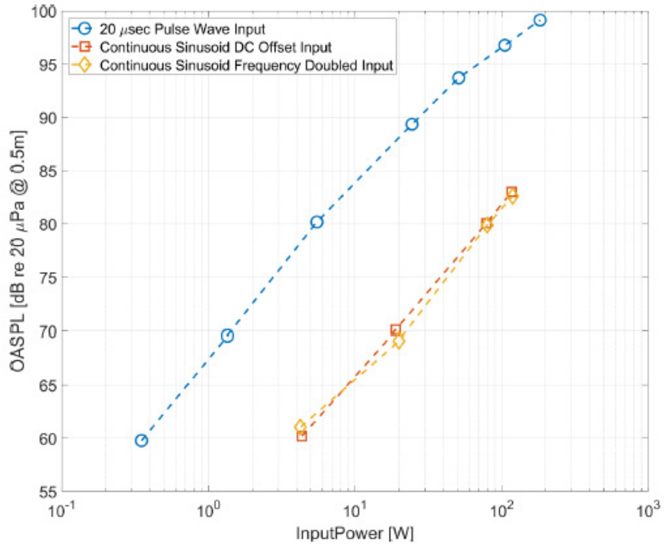


Figure 7:Overall sound pressure level versus input power of pulse wave drive signal and two continuous sinusoid drive signals producing a 4 kHz tone

Structurally Integrated Metamaterials

Sponsor: National Science Foundation

Principal investigator: Ryan Harne

Student: Sih-Ling Yeh

Publication: S. Yeh, R. Harne,"Cut-out resonators for tuned vibration suppression of plates," *Thin-walled Structures*, 167 (2021).

Summary: This research investigates a concept for cut-out resonators that exploit a small area of active mass of a host plate structure for sake of tuned, low frequency vibration attenuation. Integrated computational and experimental studies reveal that embedding the resonators at locations offering high bending moment gradient and arranging the central resonator beam along a nodal line of bending moment best excite the first resonator eigenmode for targeted vibration suppression. These results are independent of plate boundary conditions and do not require periodic resonators to achieve notable vibration suppression outcomes. These design concepts may guide the development of resonators for vibration absorption of plates with arbitrary boundary conditions.

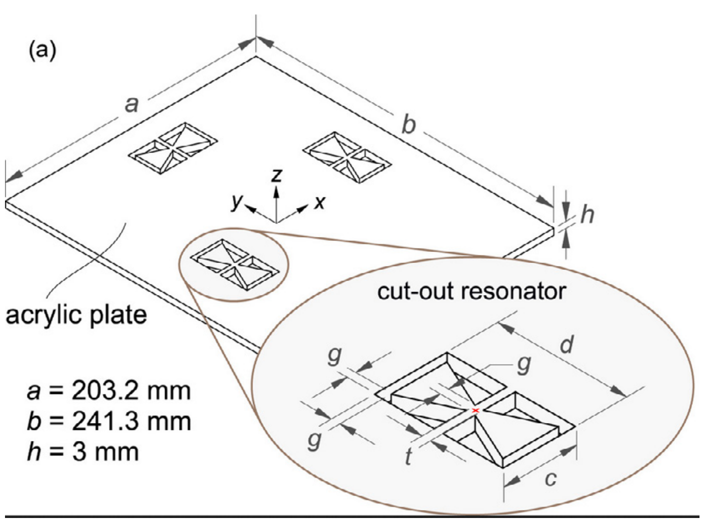


Figure 8: Schematic of host plate with cut-out resonator

Adaptive Structures and Noice Control

Group Summary

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.

Group Leader: Jose Palacios
Associate professor
of aerospace engineering

Associate Prof. Jose Palacios and his students are pursuing several projects in vibration control, acoustic measurements and adaptive structures fields. Dr. Palacios' group is also active on the field of aircraft icing. The following are on-going projects currently pursued by Dr. Palacios: 1) Ice Adhesion Strength Modeling and Verification of Controlled Surface Roughness Erosion Resistant Coatings (Vertical Lift Research Center of Excellence Task); 2) Semi-Passive, Low Power Ice Protection Systems for eVTOL; 3) Rain Erosion Testing of Ice protective Coatings (HRL/ Boeing); 4) Anechoic Wind Tunnel Testing of Co-axial Rotors (NASA Langley); 5) Urban Mobility Vehicle Rotor Performance Degradation and Protection against Ice Accretion (FAA).

Below are some highlights of this group's recent work.

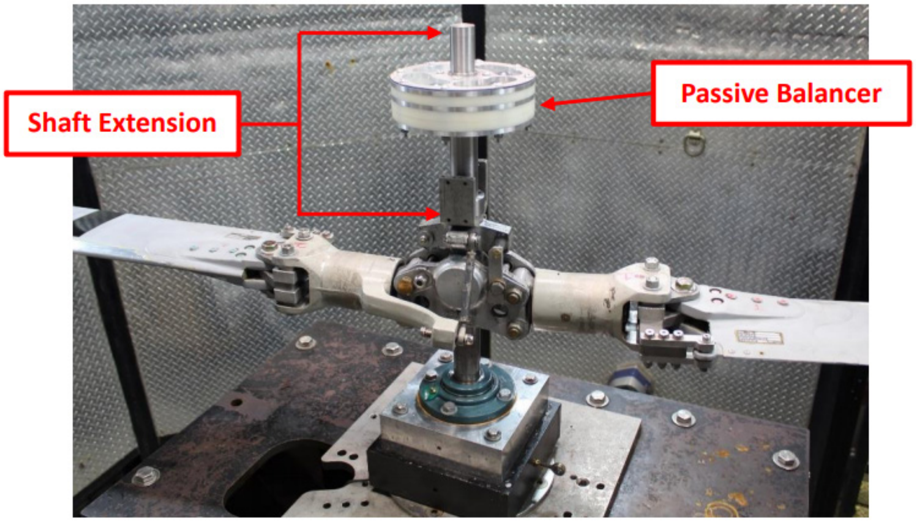
Supercritical Rotor Passive Balancing Modeling for Reduction of Ice Shedding Imbalance

Sponsor: HRL/Boeing

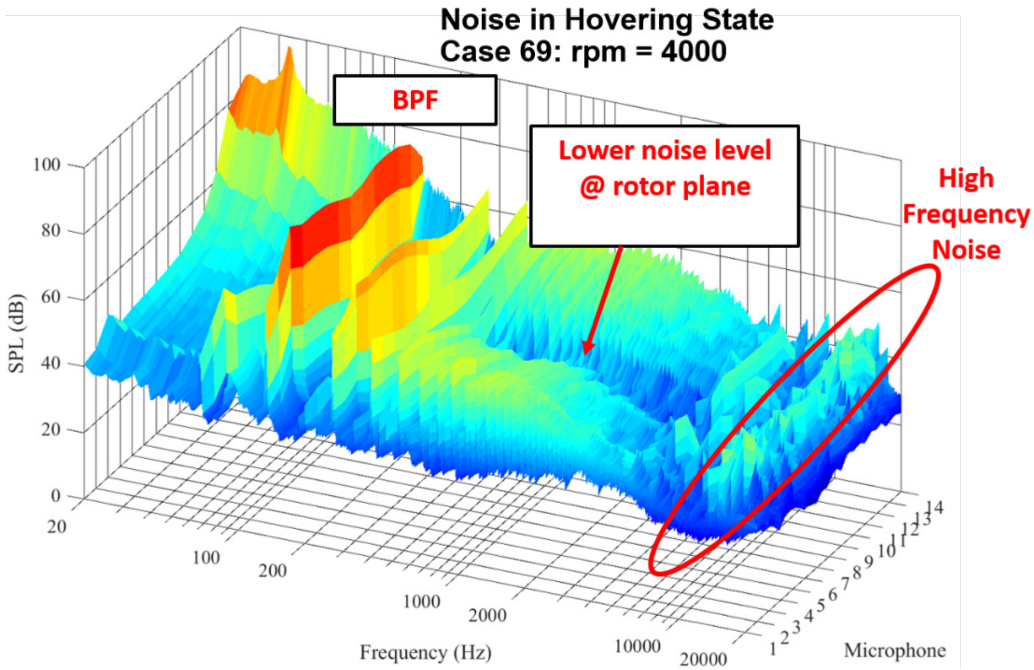
Principal investigator: Jose Palacios, associate professor of aerospace engineering

Student: Kenjiro Lay, MS, 2023 Graduate

Summary: Passive balancing devices for rotary systems consist of masses that are free to move in concentric guides about a shaft axis. At supercritical shaft speeds, the balancing masses automatically assume positions that counter any imbalance due to uneven mass distribution in the system. The problem is highly nonlinear and requires comprehensive modeling to achieve satisfactory prediction of the balancing behavior. A passive balancing device on a supercritical 10 ft. diameter rotor has been designed and fabricated based on prior developed comprehensive model. The device has allowed for consecutive ice shedding event testing as well as performing rain erosion testing on 10 ft. diameter rotors spinning at 1000 RPMs. The technology reduces vibrations at supercritical speeds but increases vibrations pre-resonance. A centrifugal clamping mechanism is being design such that the balancing masses are only released post resonance and are clamped back in a balanced position as the system spins down.



Photograph of passive balancer in the ten-foot diameter rotor in the Penn State hover stand.



Sound pressure collected by the microphone array for a hover condition. The facility can provide forward speeds of up to ten m/sec.

Anechoic Wind Tunnel Testing of Co-axial Rotors

Sponsor: NASA Langley

Principal investigators: Eric Greenwood, assistant professor of aerospace engineering; Jose Palacios, associate professor of aerospace engineering

Students: Sihong Yan, Raja Akif Bin Raja Zahirudin

Summary: Palacios' group has also become active in the field of Unmanned Aerial System (UAS) Acoustic testing. Commercial manufacturers are developing heavy-lift multi-rotor UAS for cargo and transportation purposes. Certification procedures will be needed to ensure the safety of commercial UAS units in the future. Companies planning drone delivery could cause noise pollution that is more annoying than that of ground vehicles even at the same noise level. One of the key reasons is related to how slowly most commercially available UAS move, providing "loitering" noise. The integration of UAS to commercial applications is inevitable, but the acceptance of such applications will require understanding and mitigation of UAS acoustics perceived as irritating to the population. The team has designed, fabricated, and calibrated a rotor stand to test co-axial rotors (with the capability to control rotor spacing and relative angular position) and is working with NASA Langley to verify the facility capability. The capabilities of the configuration are valuable for the comparison of the baseline rotor of and the novel anti-phase vortex rotor, and for the fundamental understanding of UAS rotor and motor noise. An example result is shown below. Currently the team is working on techniques to provide phase control to the two independent rotors. The effects of blade phasing position between two rotors on noise are being investigated. Also, the team has started exploring the effects on acoustics of rotor separation and off-set.

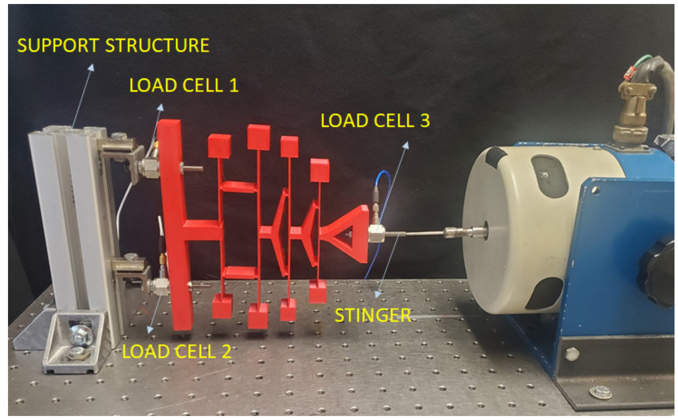
Nodal Beam Stack Vibration Isolators

Sponsor: Parker Lord corporation

Principal investigators: Christopher Rahn, Edward Smith

Student: George Rai

Summary: Passive vibration isolation is widely used in a multitude of engineering applications to mitigate the effect of periodic disturbances. These isolators are usually tuned to operate over a limited frequency range, making the isolator performance sensitive to operating frequency variations. Band stop or band gap vibration isolators have a larger stop band frequency range making them less susceptible to disturbance frequency variations. This work introduces a monolithic compliant beam-network vibration isolator that is capable of generating several broad band gaps. The proposed nodal beam stack isolators can be fabricated using additive manufacturing by using features from compliant mechanisms such as flexure hinges. An n-n beam analytical model is introduced to predict the force transmissibility. The analytical model is experimentally validated and used to design isolators with several broad band gaps.

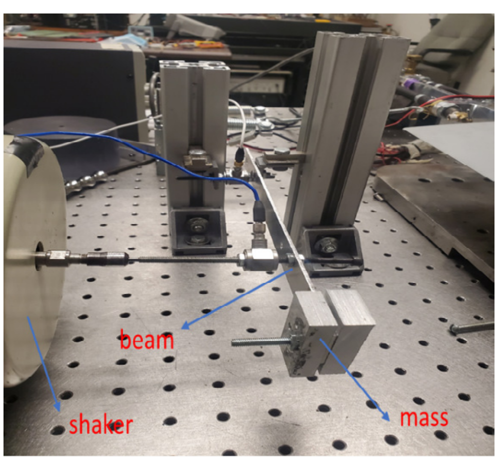


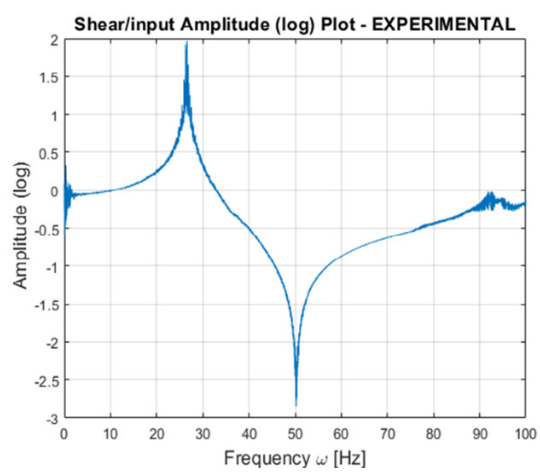
Fluid Free Tuned Vibration Absorber

Sponsor: Parker Lord corporation

Principal investigators: Christopher Rahn, Edward Smith

Summary: Fluidic vibration absorbers are often used due to their improved isolation, performance, and low maintenance requirements under normal design conditions. However, they exhibit an increased sensitivity to thermodynamic variations as compared to a strictly elastomeric or other typical mechanical absorber. This project investigates the feasibility of designing a fluid free vibration absorber that matches the performance of a fluid filled device. The design utilizes the concept of antiresonance on continuous dynamic systems, whereby an oscillating mass would cancel the excitation forces acting on the isolated body. Experimental results below show the promise of flexible structures for vibration isolation (see notch at 50 Hz in frequency response plot).





Experimental Testing Set-up and Sample Results

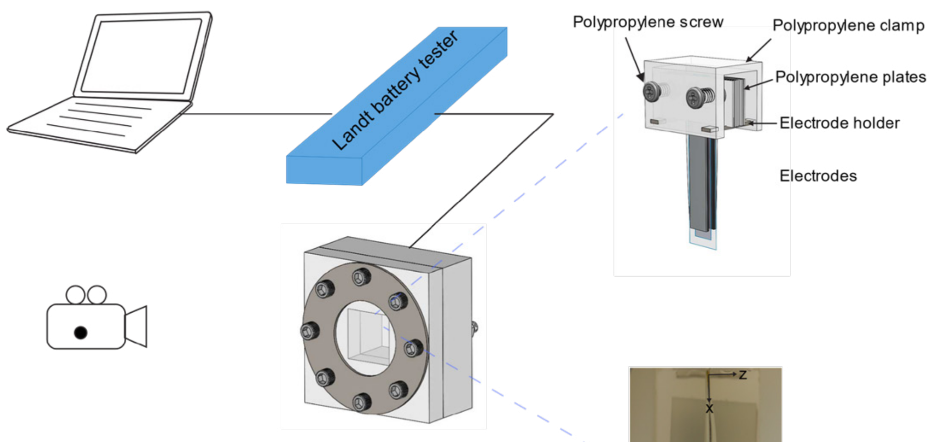
Multifunctional Lithium-ion Batteries with Silicon Anodes

Sponsor: National Science Foundation

Principal investigators: Christopher Rahn, Mary Frecker, and Donghai Wang

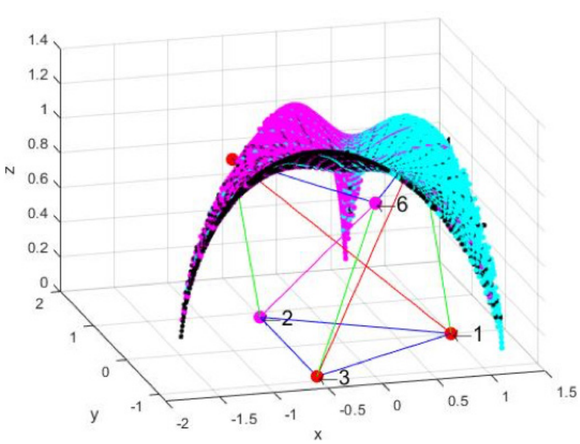
Students: Shuhua Shan, Cody Gonzalez, doctoral candidate in mechanical engineering

Summary: The volume expansion of Si during lithiation is over 300%, indicating its promise as a large strain electrochemical actuator. A Si-anode battery is multifunctional, storing electrical energy, and actuating through volume change by lithium-ion insertion. To utilize the property of large volume expansion of silicon anodes, we design, fabricate, and test two types of Si anode cantilevers with bimorph actuation: (1) double-unimorph configuration and (2) double-side-coated-anode configuration. Both bimorph configurations exhibit deflections in two directions and store energy. A 1D shape optimization is used to explain the varied charge distribution along the length for a LIB actuator and thereby the effect of distance between electrodes in charging.



Experiment setup: A transparent battery chamber made of polypropylene is fabricated, provided with NMC cathodes, and filled with electrolyte. The relationship between state of charge and deformation of electrodes is measured using current integration and high-resolution photogrammetry, respectively.

Articulated Tensegrity Structures for Space Applications



Sponsor: US Government

Student: Kaila Roffman, Ph.D. December 2022 (expected)

Summary: Spacecraft having extended configurations must be stowed for launch compactly, with final stiffness adequate to maintain shape and stability under dynamic disturbances. Tensegrity structures are of interest for their potential to provide novel deployable structures (booms, arrays) for space applications, as well as articulated structures that can be reconfigured and adjusted during mission operation. Research issues include tendon actuation; metrology, precision and control; and reachable states.

Artificial Intelligence and Machine Learning

Group Leader: Daning Huang
Assistant professor of aerospace engineering

Group Leader: Karl Reichard
Associate research professor of acoustics

Group Summary

The mission of the Artificial Intelligence (AI) and Machine Learning (ML) Technical Group is to explore and leverage applications of AI and ML in all areas of acoustics and vibration. The overarching goal of the group is to solve traditionally challenging problems in acoustics and vibration, particularly involving sensing, prediction, estimation, and control, in realistic industrial scenarios. The methodology of AI and ML ranges from the conventional supervised and unsupervised learning, to the more sophisticated operator-theoretic and information-theoretic methods, and to active, transferrable and explainable learning.

Research Topics

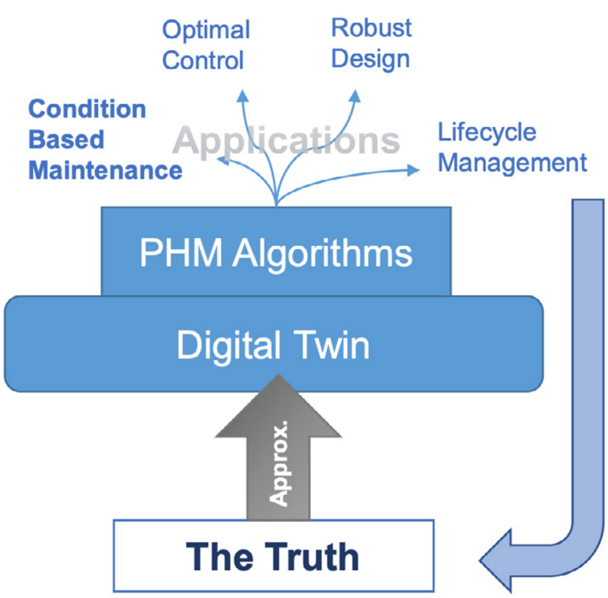
- Reduced-order modeling of multidisciplinary dynamical systems
- Data-augmented design and optimization of complex mechanical systems
- Feature engineering and extraction, representation, and mining of big measurement data sets
- Multi-fidelity multi-variate information fusion and predictive inference
- Data-driven predictive analytics and decision making
- Classification and pattern recognition

Below are some highlights of this group's recent work.

On Mitigating the Opacity of Digital Twins

Principal investigator: Gregory Banyay

Summary: Digital twins, or variants thereof, are becoming ubiquitous across many disciplines of engineering computational modeling and simulation. Despite the increased use of this concept, industrial practitioners and academic researchers alike lack consensus as to what exactly constitutes a digital twin, much less how one might quantify associated uncertainties to support the verification, validation, and ultimately credibility assessment thereof. Furthermore, the complexities involved in modeling structural vibration and acoustics can exacerbate the epistemic uncertainties of this opaque portrait. We therefore posit that use of goal structured notation in the context of a credibility assessment framework provides one viable means by which key stakeholders in both the development and deployment of digital twins can collectively work towards increased clarity. One can expect that achieving greater clarity for requirements of digital twins, particularly those of phenomenological relevance to structural dynamics and acoustics, computational, experimental, and operational disciplines can more optimally combine to achieve desired engineering outcomes.



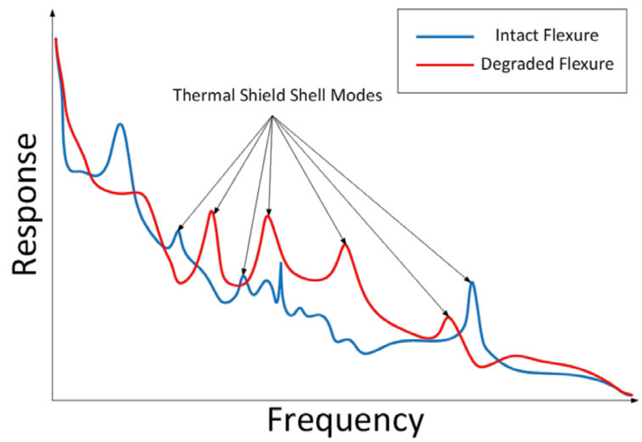


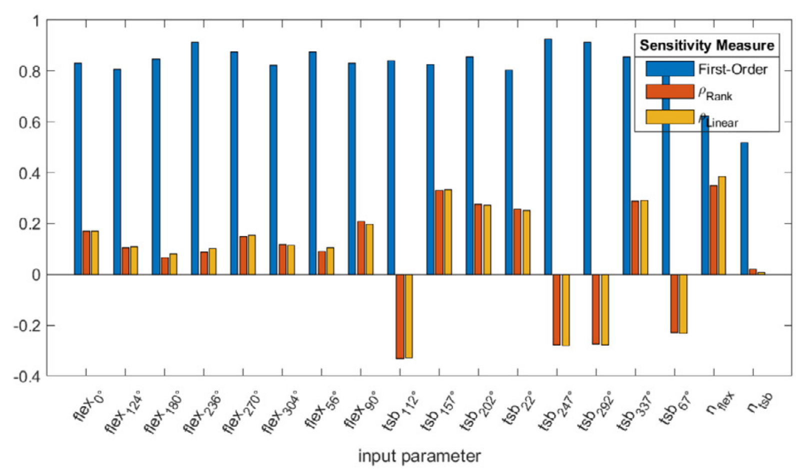
Illustration of Thermal Shield Flexure Degradation on Response Spectra

Mechanics Informed Neutron Noise Monitoring to Perform Remote Condition Assessment for Reactor Vessel Internals

Sponsor: Westinghouse Electric Company

Principal investigator: Gregory Banyay

Summary: Use of neutron noise analysis in pressurized water reactors to detect and diagnose degradation represents the practice of proactive structural health monitoring for reactor vessel internals. Recent enhancements to this remote condition monitoring and diagnostic computational framework quantify the sensitivity of the structural dynamics to different degradation scenarios. This methodology leverages benchmarked computational structural mechanics models and machine learning methods to enhance interpretability of neutron noise measurement results. The novelty of the methodology lies not in the particular technologies and algorithms but in our amalgamation into a holistic computational framework for structural health monitoring. Recent experience revealed successful deployment of this methodology to proactively diagnose different degradation scenarios, thus enabling prognostic asset management for reactor structures.



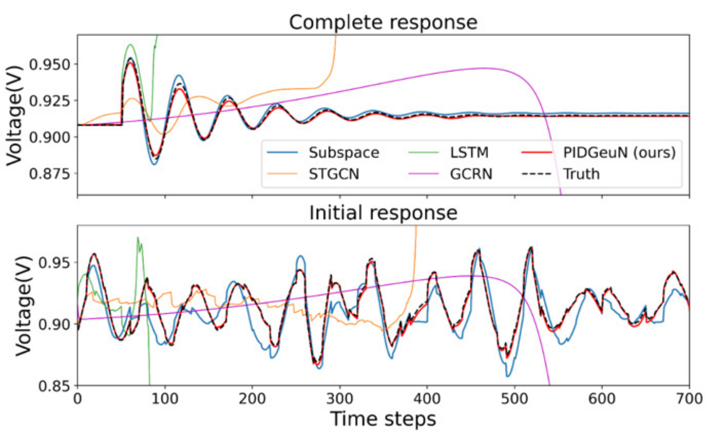
Typical Sensitivity of Mode Frequency to Finite Element Model Parameters Simulating Thermal Shield Flexure and Bolt Degradation

PIDGeuN: Graph Neural Network-Enabled Transient Dynamics Prediction of Networked Systems Through Partial Field Measurements

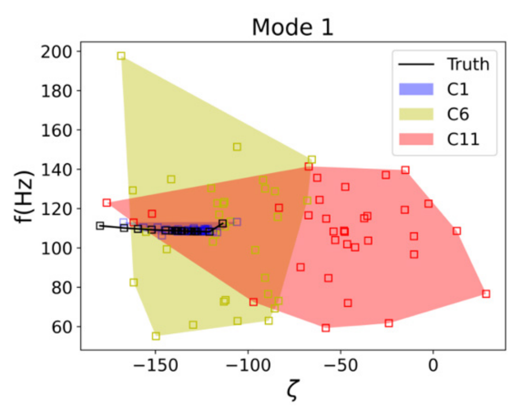
Principal investigator: Daning Huang, assistant professor of aerospace engineering

Student: Yin Yu (Ph.D., Aerospace Engineering)

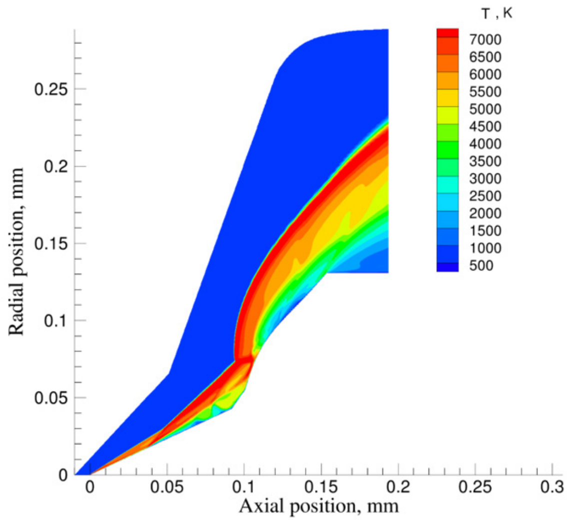
Summary: A Physics-Informed Dynamic Graph Neural Network (PIDGeuN) is presented to accurately, efficiently and robustly predict the nonlinear transient dynamics of an unstructured, interconnected system in the presence of disturbances. The graph-based architecture of PIDGeuN provides a natural representation of the topology of the system connectivity, i.e., its graph structure. Using only the state information that is practically measurable, PIDGeuN employs a time delay embedding formulation to fully reproduce the system dynamics, avoiding the dependency of conventional methods on internal dynamic states such as controllers. Based on a judiciously designed message passing mechanism, the PIDGeuN incorporates two physics-informed techniques to improve its prediction performance, including a physics-data-infusion approach to determining the inter-dependencies between the nodes of the system, and a loss term to respect the known physical law, e.g., conservation of eneryg, to ensure the feasibility of the model prediction. Extensive tests show that PIDGeuN can provide accurate and robust prediction of transient dynamics for an interconnected system over a long-term time period, with demonstrations on networked microgrids of power system. Therefore, the PIDGeuN offers a potent tool for the modeling of large-scale dynamical responses on graph, with potential applications to predictive or preventive control in real time applications for the stable and resilient operations of interconnected systems.



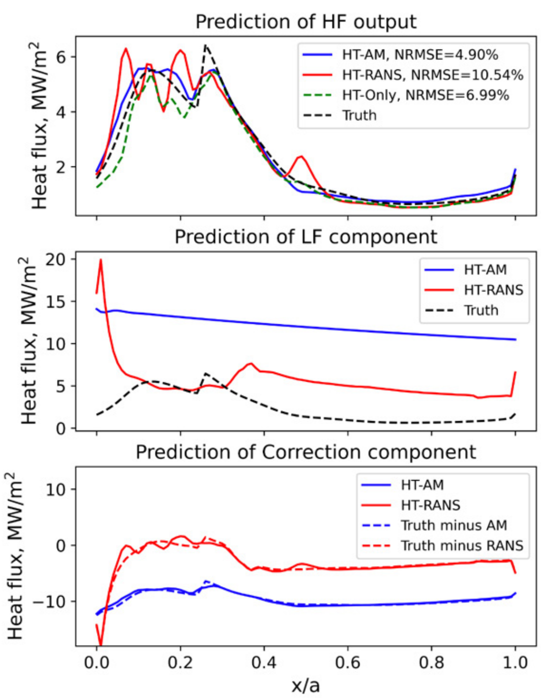
Benchmark of PIDGeuN against other popular non-graph and graph-based time series prediction methods; showing excellent stability and accuracy over long time horizon prediction.



Convergence study of the PIDGeuN architecture, showing that as the level of inter-node communication increases (C11-C6-C1), the frequencies (f) and damping ratios (ζ) of each node converge to the truth.



Top: Illustration of a high-temperature flow field, significantly distorted due to surface deformation, which leads to undesirable concentrated aerothermal loads.



Right: Illustration of a "common sense" that datasets of higher fidelities (HT-RANS) do not always improve single-fidelity predictions (HT) or inferior fidelity datasets (HT-AM); a geodesic distance metric is developed to quantify the suitability of multi-fidelity datasets.

Study of Fluid-Thermal-Structural Interaction in High-Temperature High-Speed Flow using Multi-Fidelity Multi-Variate Surrogates

Principal investigators: Daning Huang; Kyle Hanquist (University of Arizona)

Student: Aravinth Sadagopan (Ph.D., Aerospace Engineering)

Summary: This study investigates the impact of the high-temperature effect, especially the real gas effect and chemical reactions, on the fluid-thermal-structural interaction of a double wedge configuration in hypersonic flow. The multi-fidelity multi-variate Gaussian process regression (M2GPR) method for problems with high-dimensional outputs was developed to create an aerothermal surrogate model. The model achieves a balance between model accuracy and computational cost of sample generation, using the combination of a few high-fidelity samples and many low-fidelity samples. It achieved six orders of magnitude in the reduction of computational cost. The numerical examples show that, using the M2GPR formulation, the required number of high-fidelity samples may be reduced by over 80% while maintaining an accuracy comparable to the high-fidelity computational fluid dynamics solvers. In addition, a geodesic-distance-based metric is developed to inform the choice of high-dimensional datasets of different fidelities for the M2GPR surrogate with improved accuracy. Finally, the aerothermal surrogate was applied to study the impact of the high-temperature effect on the aerothermoelastic response of a hypersonic skin panel, emphasizing the necessity of the accurate characterization of the localized heat flux for reasonable assessment of the response of a compliant structure in high-speed high-temperature flowfield.

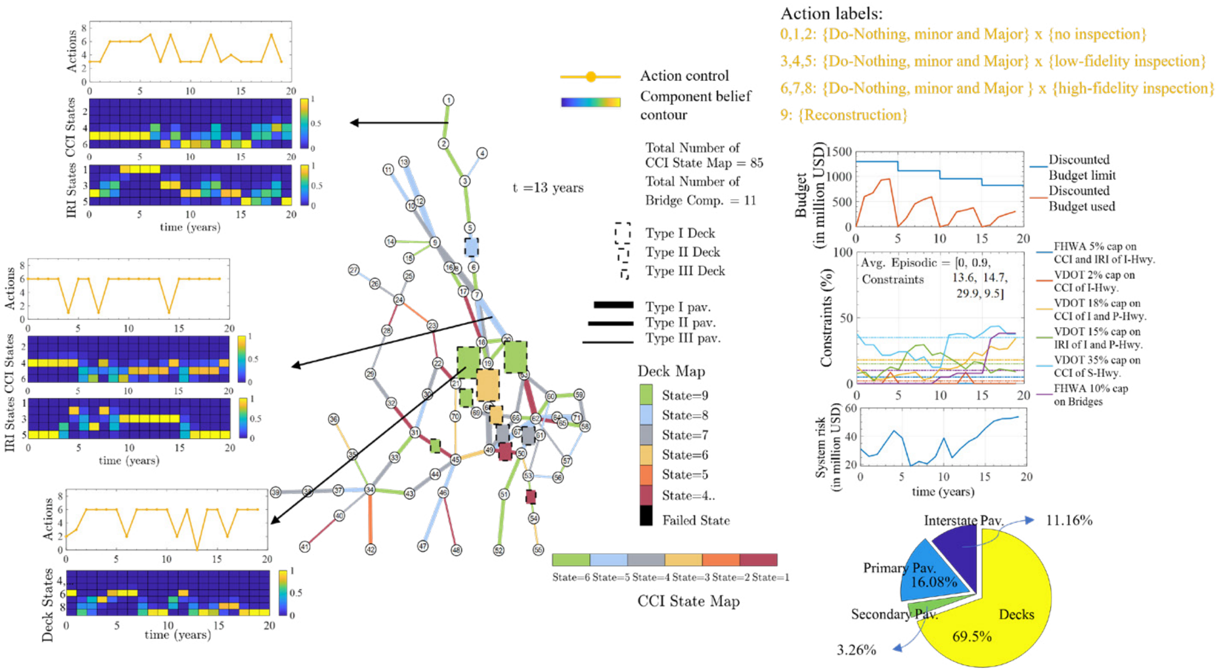


Figure shows a snapshot of a 20-year-cycle realization for a transportation network in Virginia with 85 pavement components and 11 bridges. Yellow line plots show the component inspection and maintenance actions taken over time, and the contour plots depict the belief state evolution in time. The plots on the right side represent budget utilization, performance constraints, and system risk over time, along with a pie chart of total cost distribution among the different asset types.

Deep Reinforcement Learning-Based Decision Making and Control under Uncertainty

Sponsor: National Science Foundation, U.S. DOT

Principal investigator: Kostas Papakonstantinou

Student: Mohammad Saifullah (Ph.D., Civil and Environmental Engineering)

Summary: A multi-agent deep reinforcement learning decision framework has been developed, supporting versatile plans for optimal stochastic control of deteriorating large-scale engineering systems that operate under (i) incomplete real-time information, (ii) system model unavailability, (iii) uncertain action outcomes, (iv) resource limitations and various other constraints. Relevant systems include, but are not limited to, transportation networks, aircraft fleets, industrial machines, energy generation systems, and so on. The life-cycle management of such engineering systems is a significant and challenging endeavor requiring appropriate sequential inspection and maintenance decisions to reduce risks (failure or downtime) and costs under various uncertainties and constraints. Static age- or condition-based maintenance methods and risk-based or periodic inspection plans are currently being mostly used for this class of optimization problems. Such solutions suffer however from sub-optimality, the inability to efficiently consider uncertain data in the solution process, and scalability issues, due to the exponential increase of state and action spaces with the number of components/units. To address all these issues, the optimization is cast in a constrained Partially Observable Markov Decision Processes (POMDPs) framework, which provides a comprehensive mathematical approach for stochastic sequential decision-making settings under observation uncertainty and limited resources. To address exceedingly large state and action spaces, an original Deep Decentralized Multi-agent Actor-Critic (DDMAC) method with Centralized Training and Decentralized Execution (CTDE) is suggested, termed as DDMAC-CTDE. Compared to traditional and currently used practices, the developed AI technique significantly outperforms its counterparts in a variety of cases, applications, and problem settings.

Biomedical Acoustics

Group Summary

The mission of the Biomedical Acoustics Technical Group is to understand and apply acoustics towards improving human health. The group joined Center for Acoustics and Vibration (CAV) in fall of 2017. The group has grown and consists of 13 faculty members and approximately 15 students. Research interests include advanced image processing, ultrasound imaging and therapeutics, photoacoustic imaging, shear wave elastography, drug delivery, and more! Some highlights for 2021-2022 include:

- Acoustics graduate students Eric Rokni and Ferdousi Rawnaque winning their respective divisions of the Penn State College of Engineering Research Symposium in April 2022;
- Sujata Khandare receiving her PhD in Biomedical Engineering for her thesis entitled, ""
- Dr. Raj Kothapalli's work developing transparent ultrasound transducers for cell stimulation with low intensity pulsed ultrasound making the front page of Lab on a Chip Journal.

Group Leader: Julianna Simon
Assistant professor of acoustics and biomedical engineering

Additionally, we hosted 2 CAV seminars given by Dr. Mehdi Kiani of Penn State and Dr. John Cormack from the University of Pittsburgh.

Below are some highlights of this group's recent work.

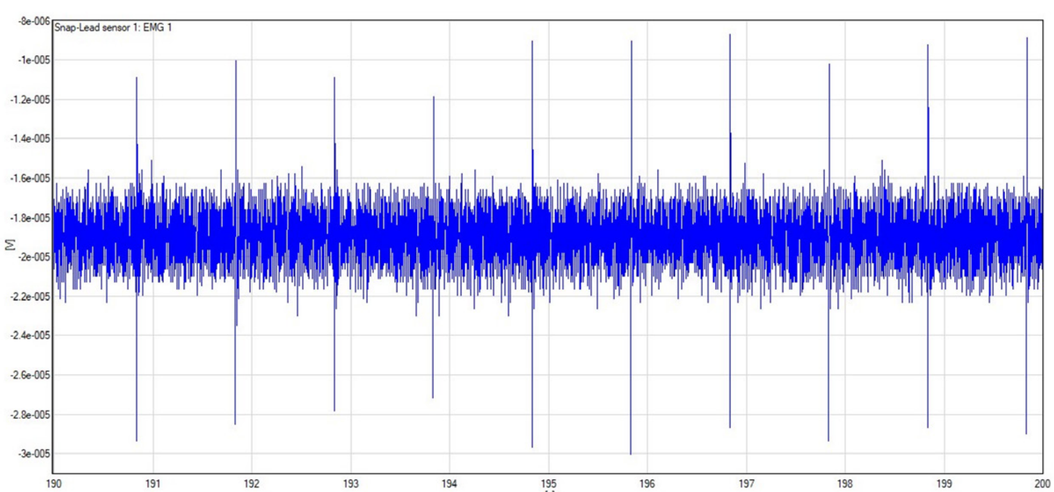
Developing Novel Rehabilitation to Combat Low Back Pain: A Focused Ultrasound Intervention for Muscle Activation

Sponsor: 2021-2022 Penn State College of Engineering Multidisciplinary Seed Grant Program

Principal investigator: M. Vidt; **Co-principal investigator:** J. Simon

Students: Jacob Elliott (PhD Student, Acoustics), Zoe Moore (PhD Student, Biomedical Engineering)

Summary: Chronic low back pain is highly prevalent, expensive to treat, and disabling for patients. While exercise is known to be effective at strengthening spine stabilizing muscles, no specific exercise has shown superiority and patient compliance is low. In this project, we are developing focused ultrasound to activate muscles. We have recently found that ultrasound can produce a response in the electromyography signal as shown in the figure below.



Example EMG signal from bovine muscle (700mV amplitude, 10ms PL, 1 Hz PRF, 1.1 MHz)

Ultrasound to Diagnose and Treat Heterotopic Ossification

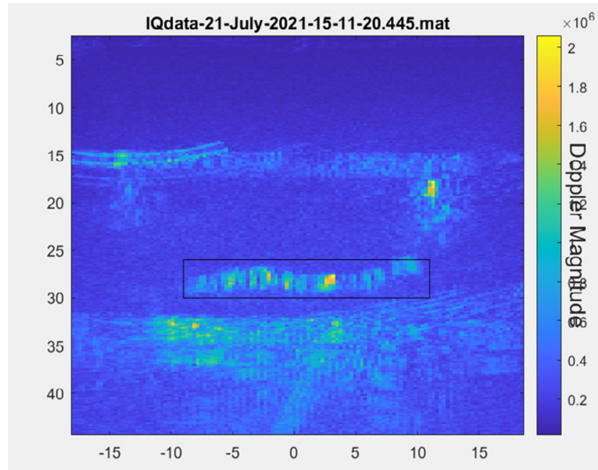
Sponsor: Congressionally Directed Medical Research Program – Peer Reviewed Medical Research Program

Principal investigator: J. Simon

Co-investigator: D. Hayes

Students: Lucas Ruge-Jones (MS Student, Acoustics), Lisa Bernstein (PhD Candidate, Biomedical Engineering), Fea Morgan-Curtis (PhD Student, Acoustics)

Summary: Heterotopic ossification (HO), or the presence of bone in soft tissues where bone does not normally exist, occurs in over half of musculoskeletal blast injuries. HO has also been found to occur in up to 90% of patients after surgical musculoskeletal injury. Using the color Doppler ultrasound twinkling artifact, we have found that we can detect very early forms of mineralization in cell samples (see figure below) and in mice with HO. Treatment of HO with ultrasound is ongoing.



Processed in-phase quadrature data from the research ultrasound system showing a strong signal from the surface of a collagen scaffold containing ossified human stem cells. This signal indicates we can detect early mineralization in Heterotopic Ossification.

Histotripsy for Collagenous Tissues: A Novel Therapeutic Approach to Tendon Injury

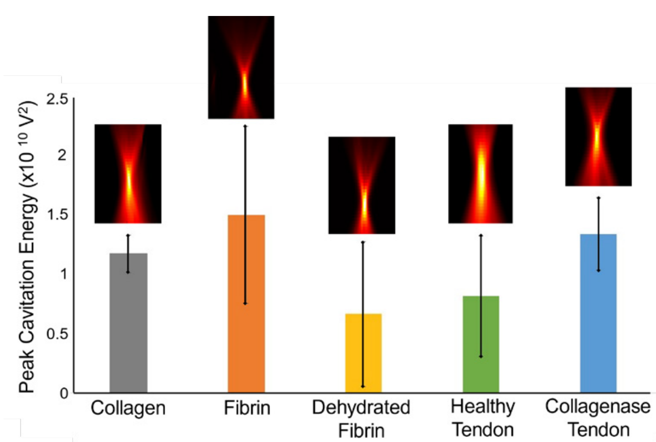
Sponsor: National Institutes of Health

Principal investigator: J. Simon

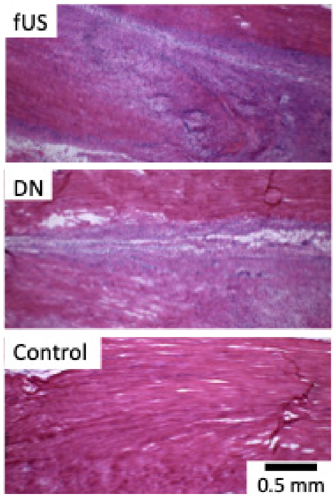
Co-investigator: M. Vidt

Students: Molly Smallcomb (PhD Candidate, Acoustics), Sujata Khandare (PhD in May 2022, Biomedical Engineering), Jacob Elliott (PhD Student, Acoustics)

Summary: Tendinopathy is common and costly to society. Conservative treatments, like dry needling, are invasive and produce mixed success rates. Histotripsy, or the fractionation of tissue into its submicron components with high intensity focused ultrasound (HIFU), has been successfully implemented in most soft tissues; however, highly collagenous tissues, like tendon, have been difficult to fractionate. We have made dehydrated fibrin hydrogels that better mimic the acoustic properties of tendon to allow us to improve our understanding of the bubble dynamics in tendon. We have also been testing focused ultrasound treatment of tendon and have found HIFU parameters that cause minor disruption of healthy tendons through to full fractionation of tendinopathic tendons. These focused ultrasound treatments performed as well or better than the conventional dry needling.



Plot of passive cavitation imaging (PCI) maxima versus hydrogel composition and healthy and tendinopathic tendons. Inserts show 2x3.5 cm representative PCI images for each hydrogel/tendon.



Histology images showing the effects of focused ultrasound (fUS) and dry needling (DN) compared to control tendons 1 week after intervention. The healing response looks similar when comparing fUS to DN.

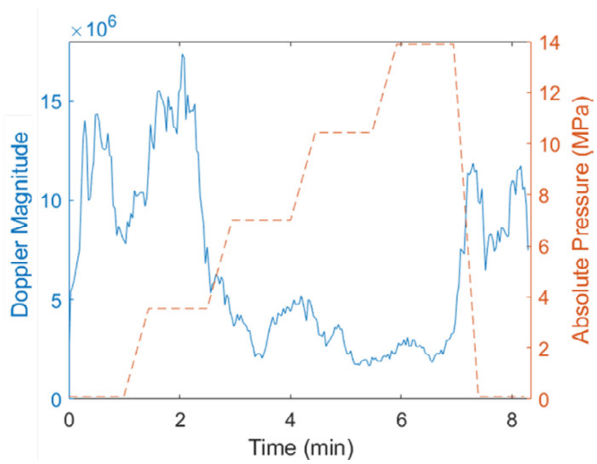
CAREER: Evaluation The Distribution of Bubble Nuclei for Acoustic Cavitation in Tissues

Sponsor: National Science Foundation

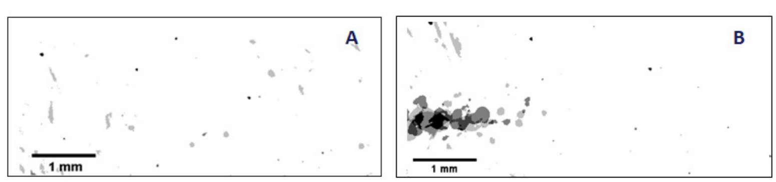
Principal investigator: J. Simon

Students: Eric Rokni (PhD Candidate, Acoustics), Ferdousi Rawnaque (PhD Student, Acoustics) Lucas Ruge-Jones (MS Student, Acoustics), Lisa Bernstein (PhD Candidate, Biomedical Engineering), Fea Morgan-Curtis (PhD Student, Acoustics)

Summary: Bubbles are a concern in every ultrasound application, including fetal imaging. While significant research has been conducted in water to understand what constitutes a bubble nuclei for acoustic cavitation, these results don't directly translate to the complex structures of biological tissues. We also don't know how the distribution of bubble nuclei in tissues change in diseases such as pathological biomineralization. So far in this research, we have shown that bubbles are present in microcracks and crevices on mineralization grown in the lab through the Doppler ultrasound twinkling artifact. We have also shown that as the stiffness increases in tissue-mimicking hydrogels, acoustic cavitation decreases. The addition of impurities the size of proteins to hydrogels also reduces the cavitation threshold.



As the ambient hydrostatic pressure increases around a submerged cholesterol crystal, the Doppler magnitude, or twinkling, decreases. When the pressure is reduced, the Doppler magnitude increases. These results suggest bubbles may be stabilized in crevices on the surface of the cholesterol crystal.



Binarized high-speed images overlaid for 3 tissue-mimicking hydrogels. As the gel stiffness increases from 2.55 GPa to 2.67 GPa (measured at 1 MHz), acoustic cavitation and shock scattering becomes less consistent for the same applied acoustic pulse.

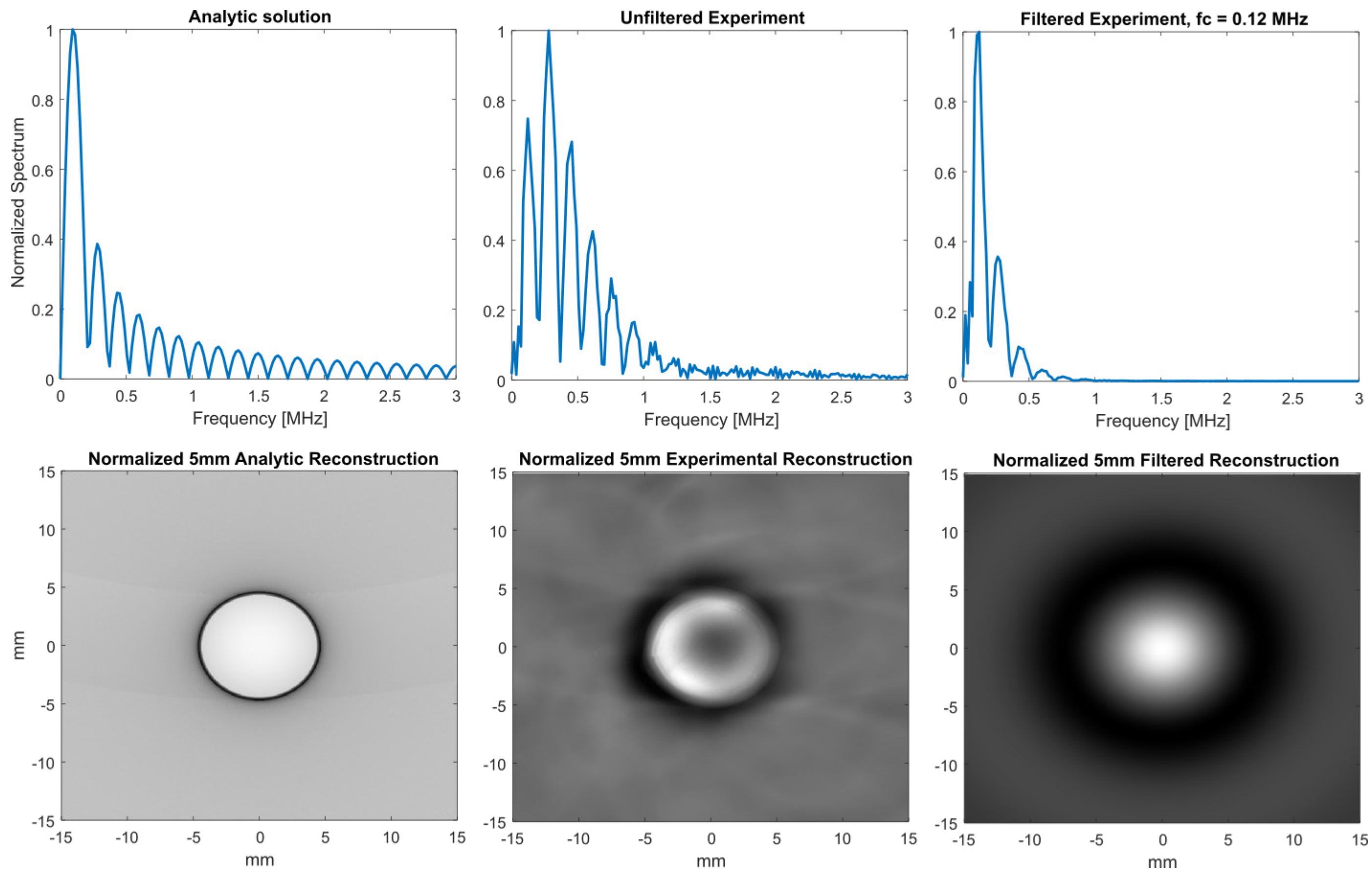
Low Frequency Signals in Photoacoustic Imaging

Affiliation: PSU graduate program in Acoustics

Principal investigator: Dr. Yun Jing

Student: Paul Klippel, pursuing a Ph.D.

Summary: As a part of the SIMBA lab we have been working closely with a partner lab at Duke University to emphasize the importance of low frequency signals in Photoacoustic Imaging (PAI), particularly for their use in functional and molecular imaging. This work has proven to be exceptionally effective in helping restore the broadband signal characteristics that are normally filtered out by the transducer response of the system or by direct filtering pre-reconstruction. Directly comparing the linear spectra of the analytical solution of a homogeneously heated sphere to the spectra of experimental data for the same size sphere and then filtering the experimental data, we have shown that the characteristic shape of that spectrum can be restored. Additionally, we are working to further accelerate our reconstruction method by implementing parallel processing on the GPU.

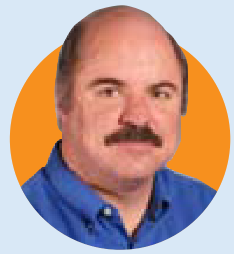


Flow-Induced Noise

Group Summary

The focus of the Flow-Induced Noise Technical Group is the basic understanding and control of acoustic noise and structural vibration generated by fluid flow. The engineering challenges cover a very wide range of fluid/acoustic phenomena involving atmospheric acoustic media and the noise created by compressible fluid flow, as well as liquid acoustic media and the associated noise and vibration generated by essentially incompressible flows. Progress in developing models and supporting experimental data bases permits the description of possible noise control methods that can be evaluated analytically or numerically, and then with confidence, prototype apparati may be evaluated in the laboratory.

Below are some highlights of this group's recent work.



Group Leader: Michael Krane
Associate research professor in aerospace engineering

Glottal Jet Aerodynamics

Sponsor: NIH NIH 5R01DC005642-14

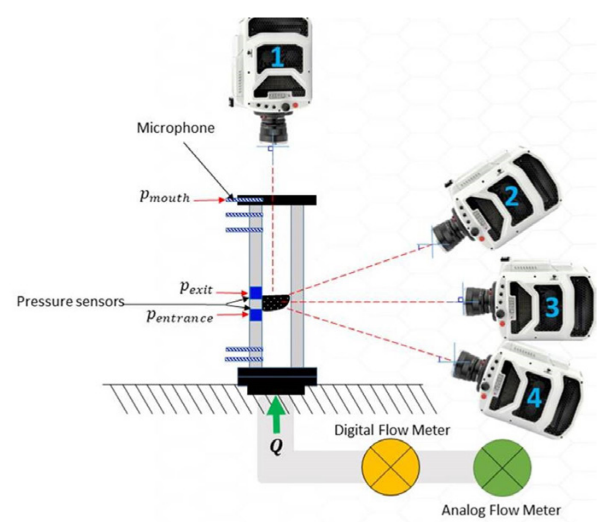
Principal investigator: Michael Krane (PSU Applied Res. Lab.)

Collaborators: Jeff Harris, Adam Nickels, Rommel Pabon, David DeVilbiss (*ARL Penn State*); Michael McPhail , Stephanie Zacharias (*Mayo Clinic*); Lucy Zhang (*Rensselaer Polytechnic Inst.*); Timothy Wei (*Northwestern Univ.*); Daryush Mehta, Robert Hillman (*Massachusetts General Hospital*); Sid Khosla (*Univ. of Cincinnati Med. School*)

Students: Paul Trczinski (*PSU Mechanical Engr.*), Feimi Yu (*RPI Mech. Eng.*), Abigail Howarth (*UNL Mech. Eng.*), Dylan Rogers (*UNL Mech. Eng.*), Hunter Ringenberg (*UNL Mech. Eng.*), Nathan Wei (*Caltech Aeronautics*), John Kershner (*Lehigh Mechanical Engr.*)

Summary: The project uses a combination of reduced-order modeling, aeroacoustic-aeroelastic computer simulation, and benchtop model measurements to address current open questions regarding the physics of human phonation, and to translate these findings into improved clinical measures. Current focus areas: (a) energy utilization and voice efficiency, (b) the relationship between glottal jet fluctuations and cycle-to-cycle variations in voice, and (c) the development of measurements suitable for computational model validation.

For the first study, a control volume analysis of the vocal system has yielded new definitions of voice efficiency for the voice source in the larynx, and the transmission in the vocal tract. The standard voice efficiency measure characterizes the system as a whole, and thus can't distinguish between these two effects. The new efficiency measures have been characterized using computer simulation, and in benchtop experiments.



The second study used time-resolved PIV and pressure measurements in a scaled-up model, with water as the working fluid. These measurements were used to determine the features of laryngeal flow that contribute most to vocal fold drag, the source of voiced sound. Cycle-to-cycle variations in vocal fold drag were shown to correlate to fluctuations in glottal jet direction.

The third study has involved spinning up the capability to perform simultaneous measurements of acoustic and aerodynamic pressure, vocal fold wall motion using Digital Image Correlation, and glottal jet flow using Particle Image Velocimetry, and working with simulation specialists to integrate these measurements into a procedure to interactively assess their aeroelastic-aeroacoustic computational models of phonation.

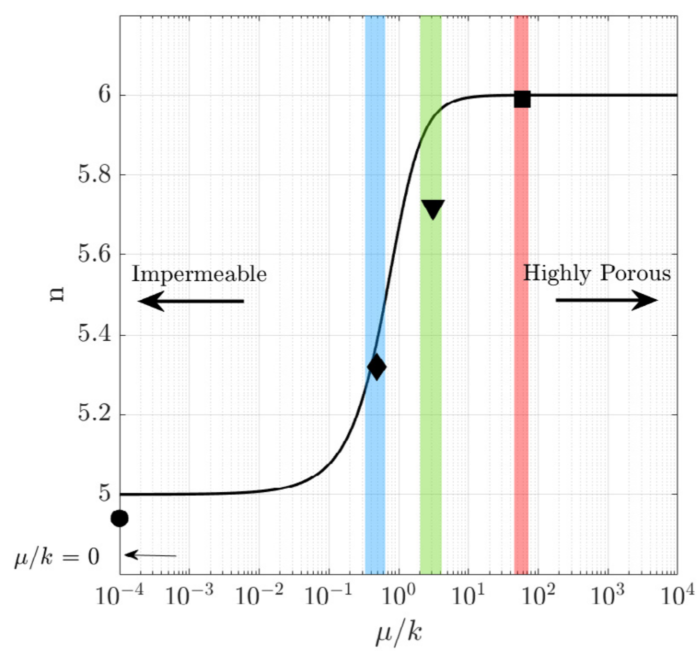
Aerodynamic-Aeroacoustic Performance of Poroelastic Wings, Inspired by the Silent Plumage of Owls

Sponsor: NSF CBET-1804445/ CBET-1805692

Co-Principal investigators: Michael Krane (PSU Applied Res. Lab.), Justin Jaworski (Lehigh Univ.)

Students: Zachary Yoas (MS, PSU BioE 2021), Huansheng Chen (PhD, 2022, Lehigh Mech. Eng.), Mitchell Swann (PSU Acoustics)

Summary: Inspired by the wing structure thought to underlie quiet owl flight, this project studies the effect of wing porosity on trailing edge noise. Project is collaboration with Lehigh University, who performs the theoretical side of study, while experiments are performed at PSU ARL. In this study, trailing edge noise is abstracted to its fundamental features, namely, the convection of a vortical eddy past the edge of a non-compact plate. In this study, we examine the effect of plate porosity on the level and directivity of sound radiated by the convection of a vortex ring past the edge of a flat plate. Plate porosity is thought to affect trailing edge sound radiation by altering the nearfield of the edge – as plate porosity increases, the nearfield flow is more able to load the edge force, as in the case of a compact edge. Relative to an impermeable plate, this alteration of the nearfield modifies the radiated sound by attenuating sound levels, and by transitioning directivity from a cardioid to a dipole pattern. Measurements to date show that sound levels changes as predicted by theory, while directivity is affected strongly by even the smallest porosity.



(Top) Sound power scaling law $\Pi \sim U^n$ exponent, n, vs porosity parameter $\frac{\mu}{k}$. (Bottom) directivity for different values of $\frac{\mu}{k}$. Lines are theoretical prediction, symbols denote measurements.

Vibrations of a High-Aspect-Ratio, Multi-Element Wing

Sponsor: NASA

Co-Principal investigators: Robert Campbell (PSU Applied Res. Lab.), Michael Jonson (PSU Applied Res. Lab.)

Student: Auriane Bottai (PSU Aerospace Engr.)

Summary: A full-scale finite element model of a high aspect ratio, back swept, slotted-natural-laminar-flow wing is used to: 1) study the uncoupled and coupled modes of the two elements of the wing; 2) investigate the effects of connection stiffness and number of connections on the coupled modes. The two elements are attached via constraint equations and springs or connectors, using a component mode synthesis approach. The wing model includes the aerodynamic skins as well as internal structural elements. The analysis shows that increasing the stiffness of the springs can couple the two wings such that the low order modes resemble those of a conventional wing. Out-of-plane modes are the most compliant modes with coupling. Torsional modes become mixed bending/torsional modes, with the aft element undergoing most of the deformation. In-plane bending modes appear to evolve to mixed in-plane /out-of-plane/ torsion modes with more connectors or higher stiffness.

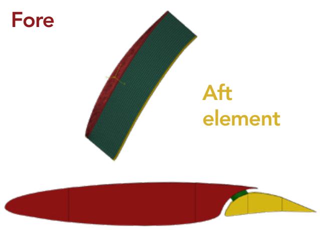
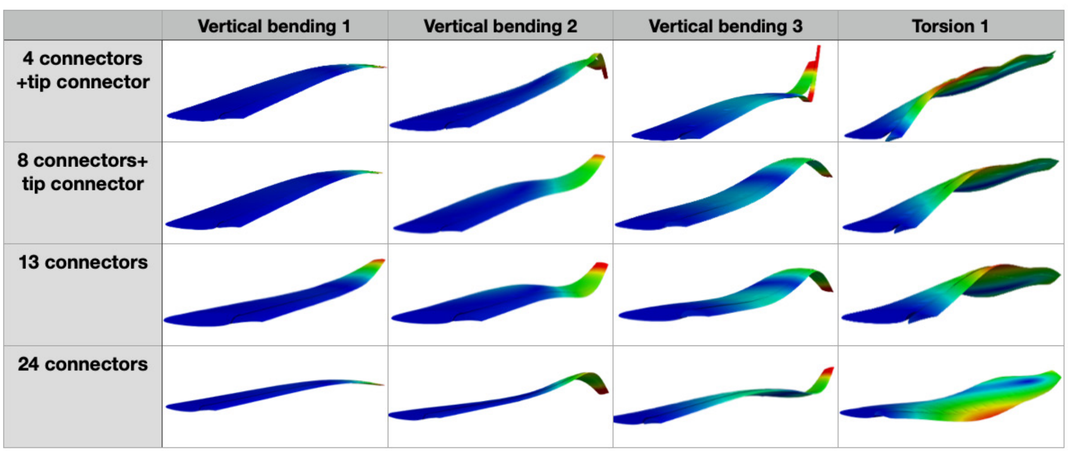


Figure 1: SNLF wing profile and its connector (enlarged)



Mode frequencies [Hz]	Vertical bending 1	Vertical bending 2	Vertical bending 3	Torsion 1
5 connectors	2.21	8.11	9.16	10.66
9 connectors	2.21	8.49	9.55	11.55
13 connectors	2.21	8.62	9.65	11.64
24 connectors	2.22	8.75	9.81	11.74

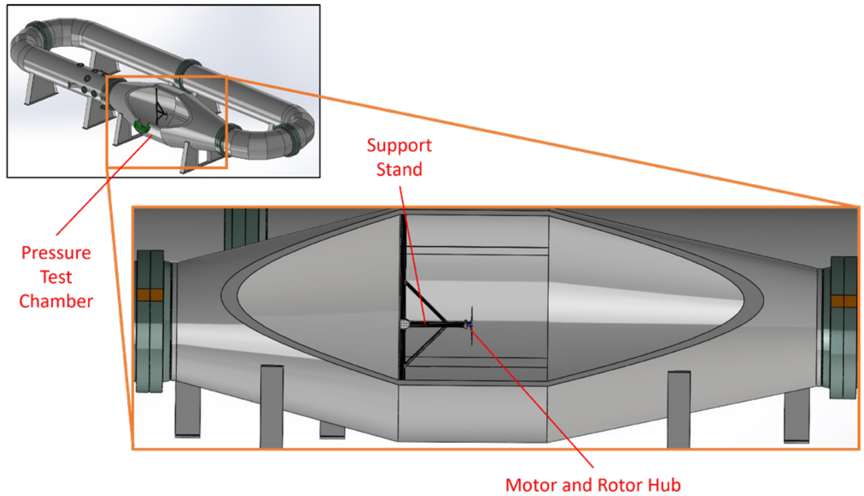
Figure 2: Comparison of the mode shapes and frequencies of the first vertical bending and torsional modes of the SNLF wing with aerodynamic connectors

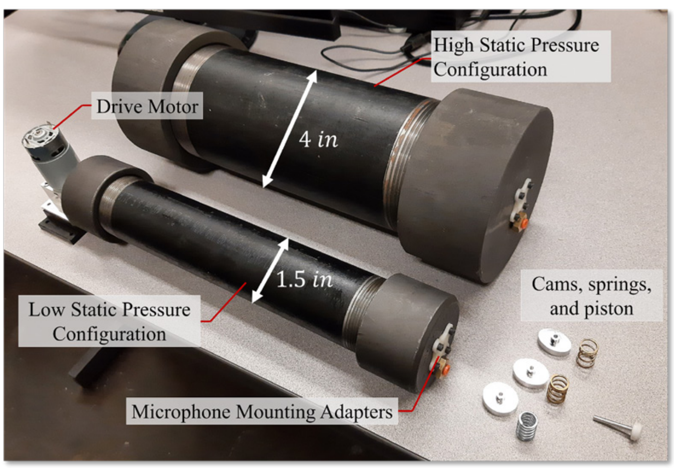
Title: Scaling for Interactional Aerodynamics and Acoustics of Multirotor Systems

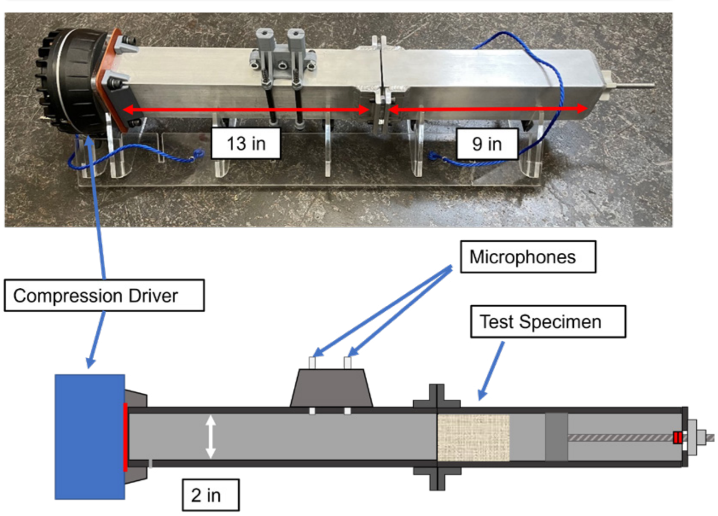
Sponsor: U.S. Army Vertical Lift Research Center Program (VLRCOE)

Co-Principal investigators: Mark A. Miller (PSU Aerospace Engr.), Eric Greenwood (PSU Aerospace Engr.), Jose Palacios (PSU Aerospace Engr.)

Summary: Full-scale experimental aeroacoustic measurements are often impractical due to the prohibitive expense associated with full-size testing and large facilities capable of far-field acoustic measurements. Although small-scale models can provide useful acoustic data, this scaling is limited by the inability to achieve the equivalent aerodynamic conditions at smaller scale. However, testing models under hyperbaric conditions (i.e. where the background static pressure is increased) does allow for aerodynamic similarity on small models.







While promising, microphones and anechoic materials used in acoustic experiments are not explicitly designed to be used under increased background pressures and so their performance must be verified. To characterize the response of condenser microphones at elevated pressures, a pistonphone style calibrator was developed to operate over a range of pressures. Various internal volumes and piston stroke lengths are used to achieve predictable sound pressure levels over a range of static pressures from atmospheric up to 100 bar. Likewise, for anechoic materials, an impedance tube was developed to evaluate material response under a similar range of conditions. Initial evaluation and testing of these systems for a range of background pressures is currently underway. Following this work, development of a high-pressure anechoic testing chamber is planned which will enable simultaneous measurements of the full-scale aerodynamic performance and acoustics for a variety of electric Vertical Take-Off and Landing (eVTOL) rotors using small-scale models. This information can then be used to guide design decisions such as rotor and fuselage placement on the resulting performance and far-field sound levels.

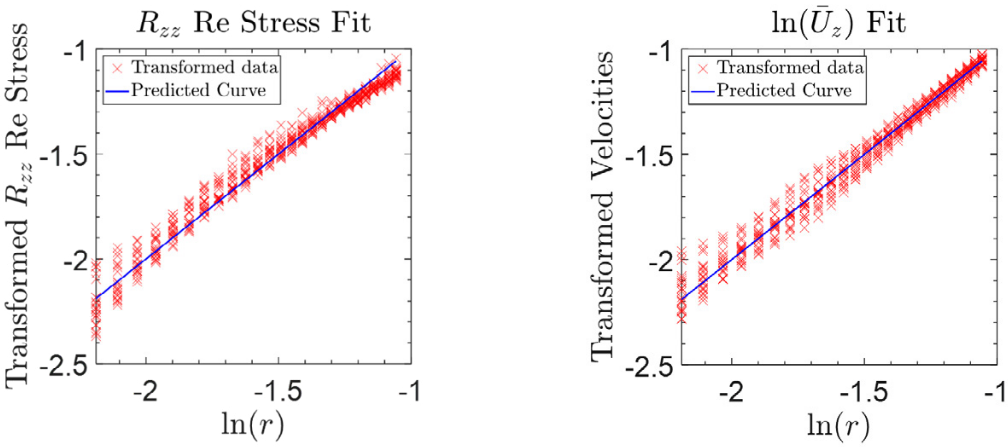


Figure: Scaling law parameters fits for experimental pipe flow data for Reynolds stress (left) and mean velocity profile (right), in the streamwise flow direction

Development of Empirically-Driven Axisymmetric Turbulence Models Using a Symmetry-Based Approach

Sponsor: ARL Walker Fellowship

Advisors: Dr. Michael Jonson, Dr. Zachary Berger, Dr. Ryan Murray

Student: Jeremy Pannebaker

Summary: This research analyzes a high Reynolds number, axisymmetric, turbulent pipe flow for the purpose of developing a turbulence model that describes the mean velocity and two-point correlation statistics. The work utilizes analytical and experimental methods in the form of Lie theory and planar PIV to construct mathematical models for the chosen statistics. Lie theory is a classical method of solving differential equations by using symmetries that are inherent in the equations under analysis. This work analyzes the Reynolds-averaged Euler equations to identify a family of scaling solutions for the mean velocities and two-point correlations of a turbulent, cylindrical pipe flow. Using the scaling solutions, the theoretical findings are tested experimentally by collecting and analyzing planar PIV data from the core region of a fully-developed, axisymmetric, turbulent pipe. The Lie theory analysis results in various scaling parameters being manifested in the scaling solutions, so curves are fit to the experimental data using a nonlinear least squares approach to quantify the parameters. Through this process, sufficient curve fits to the experimental data could be achieved for the mean streamwise velocity and axial direction Reynolds stress, however, the scaling parameters do not agree across the chosen statistics. Theoretically, the scaling parameters are expected to be universal for all statistics. This work also evaluates the Reynolds stress because it is a special case of the two-point correlation equations and serves as a check of the theory before proceeding into the more complex two-point correlation fittings with spatial separations. Future work will aim at finding universal scaling parameters and curve fitting the two-point correlations with spatial separations. In the current literature, to date, there has not been any work that identified symmetry solutions for two-point correlations and used experimental data to validate the results in this manner.

Propagation and Radiation

Group Summary

The mission of the Propagation and Radiation Technical Group is to develop a new understanding of how sound is generated, propagated, and perceived in realistic environments, to translate this understanding into techniques for making decisions about the use and control of sound, for making inferences about sources and the environment, and to apply this understanding to the design of devices and systems. Propagation and radiation studies closely tie in with transduction techniques, noise impact on the public, sound quality assessment, and 3D spatial audio.

Penn State has continued to participate in the Federal Aviation Administration (FAA) Center of Excellence in Alternative Jet Fuels and the Environment. As part of the Aviation Sustainability CENTer (ASCENT), 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 understanding and providing new technologies for FAA's current noise tools, particularly in improving the propagation modeling for noise around airports. Further work has centered on improving our understanding of sonic boom impacts from future supersonic aircraft.

Group Leader: Vic Sparrow
United Technologies Corporation Professor of Acoustics

Below are some highlights of this group's recent work.

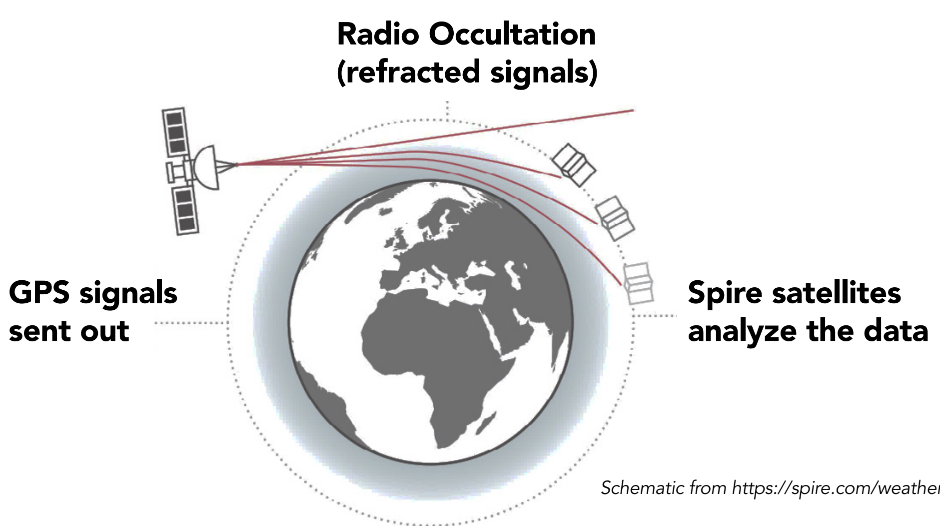
Using Satellite Data to Better Predict Aircraft Noise Around Airports

Sponsor: FAA

Principal investigator: Victor W. Sparrow, United Technologies Corporation Professor of Acoustics

Students: Harshal Patankar, doctoral candidate in acoustics, and Emma Shaw, M.S. candidate in acoustics

Summary: As part of Penn State's collaboration with Georgia Tech on ASCENT Project 62 "Noise Model Validation of AEDT" Penn State is using high resolution meteorological data around airports, including three-dimensional temperature and humidity as a function of time. The new high-fidelity weather data is being provided by Spire Global (spire.com), a company that has many low-earth orbiting satellites. By analyzing standard GPS signals refracted by the atmosphere, Spire Global is able to provide highly detailed meteorological maps with resolution much better than existing techniques. Current capabilities include providing this data on an hourly basis on a 1 km by 1 km grid for every 500 m of altitude. This is allowing Penn State to understand the propagation of aircraft noise through a complex 3-dimensional and time-dependent atmosphere around airports. One aim of the project is for the research team to utilize the high-fidelity weather data in FAA's Aviation Environmental Decision Tool (AEDT) to make better noise predictions with greater accuracy.



Schematic from https://spire.com/weather/

Supporting supersonic en-route noise standards development

Sponsor: FAA

Principal investigator: Victor W. Sparrow, United Technologies Corporation Professor of Acoustics

Student: Joshua Kapcsos, doctoral candidate in acoustics

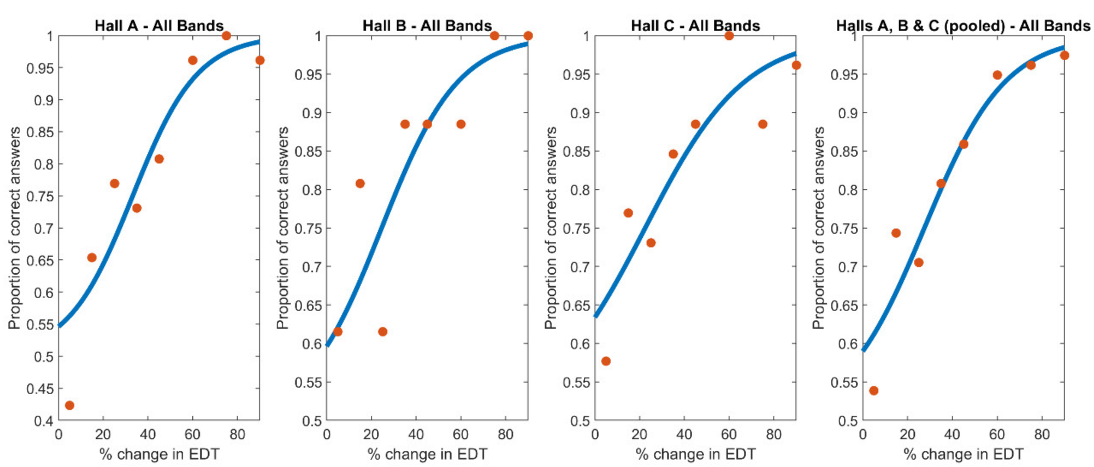
Summary: Penn State is assisting FAA by leading ASCENT Project 57 "Support for supersonic aircraft en-route noise efforts in ICAO CAEP." ICAO is the International Civil Aviation Organization, a specialized agency of the United Nations. CAEP is ICAO's Committee on Aviation Environmental Protection. There are efforts underway in CAEP's Working Group 1 (Noise) to develop standards that could be used to certify the en-route noise (sonic boom) from future supersonic civilian aircraft. Penn State is supporting this effort by making predictions of sonic boom time pressure waveforms, called signatures, as those sounds pass through the turbulence in the atmospheric boundary layer. The atmospheric boundary layer can cause distortions in the signatures which can be perceived upon hearing them. In addition Project 57 is exploring the role of secondary sonic booms which can be perceived as low-frequency, rumbly noises which can appear at substantial distances from the primary sonic boom carpet. The industrial partners assisting in Project 57 include Boom, Exosonic, and Gulfstream, and we thank them for their support.

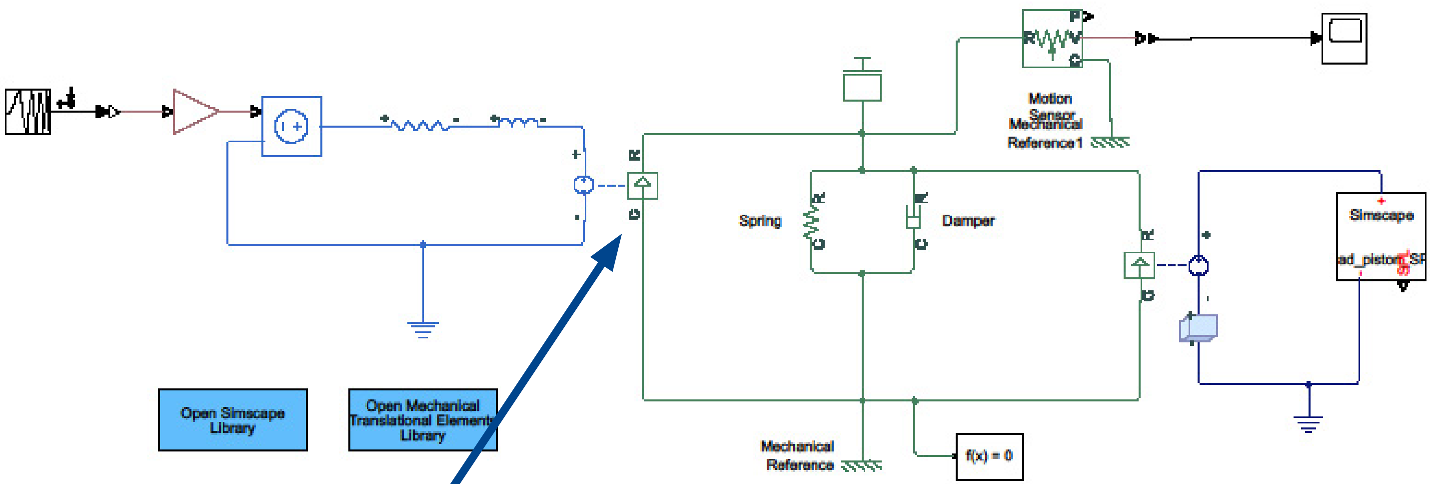
Just Noticeable Difference of Early Decay Time (EDT)

Principal investigator: Michelle Vigeant, Associate Professor of Acoustics and Architectural Engineering

Student: Fernando del Solar, doctoral candidate in acoustics

Summary: Several perceptual attributes contribute to the perception of the acoustics in a concert hall. One of the most important is the perception of reverberance, the perception of sound lingering in a space. This perception is quantified using the metric of early decay time (EDT), however, the just noticeable difference (JND) of EDT has not been established. This quantity is necessary to know if significant perceptual differences will arise as a result of design decisions for new halls or when comparing existing spaces. There have been past studies on the JND of reverberation time, but work has shown that EDT is a much better predictor of reverberance. A subjective study was conducted wherein 30 participants listened to sets of stimuli based on measured room impulse responses of three North American concert halls that were varied in terms of EDT. The stimuli were presented in the AUralization and Reproduction of Acoustic Sound-fields (AURAS) facility at Penn State, which is a 30.2 loudspeaker array housed in an anechoic chamber. The spatial sound fields were reproduced using the method of third-order Ambisonics. The EDT JND was found to be approximately 28% of the EDT value when broadband changes in EDT were made ranging from 5% to 95%. The EDT JND results for each of the three halls and the overall result using a combined data set are shown below.





$$F = B\ell(x)i \qquad V = B\ell(x)v$$

where

$$B\ell = B\ell_0 + B\ell_1 x + B\ell_2 x^2 + B\ell_3 x^3 + B\ell_4 x^4$$

Realistic Modeling of Moving Coil Loudspeakers

Principal investigator: Stephen C. Thompson, Research Professor of Acoustics

Summary: Small signal linear models of moving coil loudspeaker performance using the methods developed by Thiele and Small a half century ago remain the most often used models today. While those methods are a good starting point, practical speaker systems are seldom used with truly small driving signals. Deviation from small signal behavior is often seen when driving commercial speakers to only several per cent of their rated maximum drive level. The Simscape physical modeling methods that are included in the Matlab/Simulink software system provide a provide a way to include

1. Nonlinear magnetic force factor as a function of cone displacement $B\ell(x)$.
2. Nonlinear mechanical restoring force as a function of cone displacement $k(x)$.
3. Semi-inductive electrical impedance caused by eddy currents.
4. Nonlinearity caused by signal coupling to the magnetic circuit.
5. Thermoviscous loss in enclosures and acoustic transmission paths

These and other practical features of design and implementation can be included in the Simscape models. The example of including the nonlinear $B\ell(x)$ is shown in the figure. Anecdotal evidence from discussions with Acoustics Program alumni working in industry indicate that these simulations agree well with prototype hardware.

Rotorcraft Acoustics and Dynamics

Group Summary

Group Leader: Edward Smith
Professor of aerospace engineering

The Penn State's Center for Acoustics and Vibration (CAV) Rotorcraft Acoustics and Dynamics Technical Group continues to be at the core of our Vertical Lift Research Center. Penn State is home to one of only three National Rotorcraft Technology Center Vertical Lift Research Centers of Excellence (VLRCOE) in the country. In the summer of 2021, our center was successfully renewed for another five years. As part of our new program, we started eleven new research projects. The center currently supports more than 40 full-time graduate students and involves more than 20 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 growing suite of research tasks, and reduced exterior noise signatures is a high priority. We have experienced substantial growth in programs focused on advanced eVTOL air mobility vehicles, and high speed rotorcraft vehicles. Our various research projects are presently supported by the U.S. Army, U.S. Navy, NASA, FAA, USAF, 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, novel anti-icing systems, variable speed rotors, structural health monitoring, and rotor loads control/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 facilities have also been recently developed for acoustic testing small scale rotor models (single and coaxial configurations) in an anechoic environment. An outdoor acoustic flight test array capability has also been brought online.

Our annual Rotorcraft Technology Short Course will be offered for the 54th consecutive year on Aug. 8-12. Topics in the comprehensive course include rotorcraft aerodynamics, dynamics, acoustics, composite structures, flight controls and propulsion. For more information, please visit rotary-wing.outreach.psu.edu/. The 2022 course will be taught in an in-person format.

Below are some highlights of this group's recent work.

Efficient Modeling of Interaction Noise for UAM Vehicles

Sponsor: National Institute of Aerospace / NASA Revolutionary Vertical Lift Technology Project

Principal investigator: Eric Greenwood, assistant professor of aerospace engineering

Student: Robert F. Rau

Summary: The goal of this project is to develop a proof-of-concept method of modeling the unsteady loading noise caused by the aerodynamic interactions between the rotors of multirotor Advanced Air Mobility (AAM)—formerly termed Urban Air Mobility (UAM)—vehicles. A computationally efficient multirotor wake model called MuRoSim has been developed by using an advanced three-dimensional actuator disk model to inform the convention of the rotor wake, allowing the coupled wake geometry of multirotor systems to be predicted at much lower computational cost than conventional free vortex wake methods. This analysis has been coupled with the PSU-WOPWOP acoustic propagation code to allow noise predictions of multirotor systems to be made at the conceptual design stage.

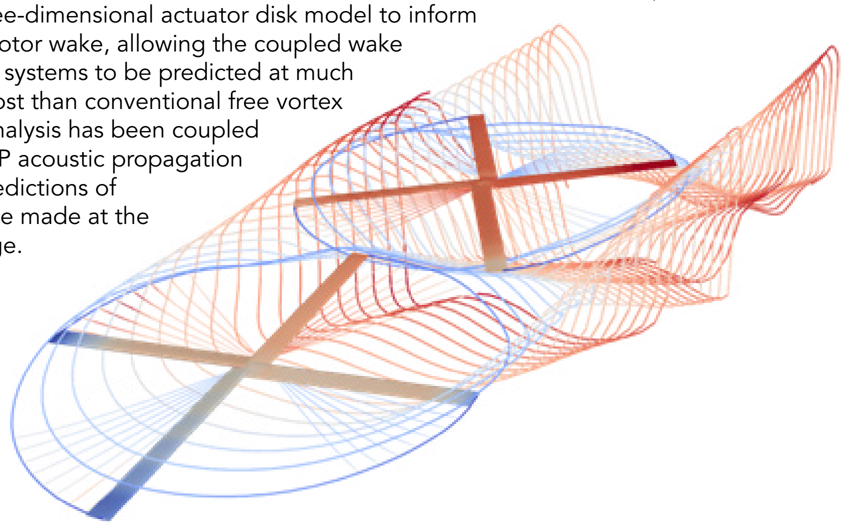


Figure: Predicted wake geometry for a notional tandem rotor system.

Efficient Modeling of Interaction Noise for UAM Vehicles

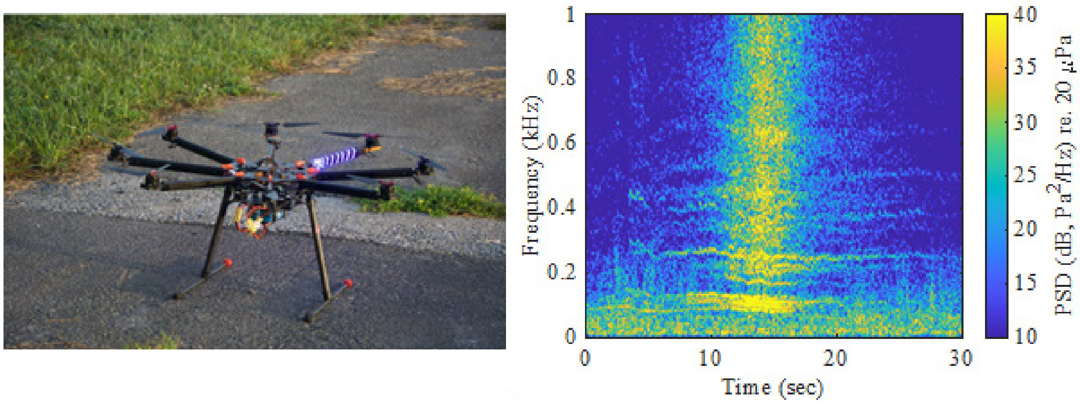
Sponsor: Federal Aviation Administration

Principal investigators: Eric Greenwood, Assistant Professor of Aerospace Engineering, Kenneth S. Brentner, Professor of Aerospace Engineering, Eric N. Johnson, Professor of Aerospace Engineering

Students: N. Blaise Konzel, Joel S. Rachaprolu, Keon Wong Hur, and Vítor T. Valente

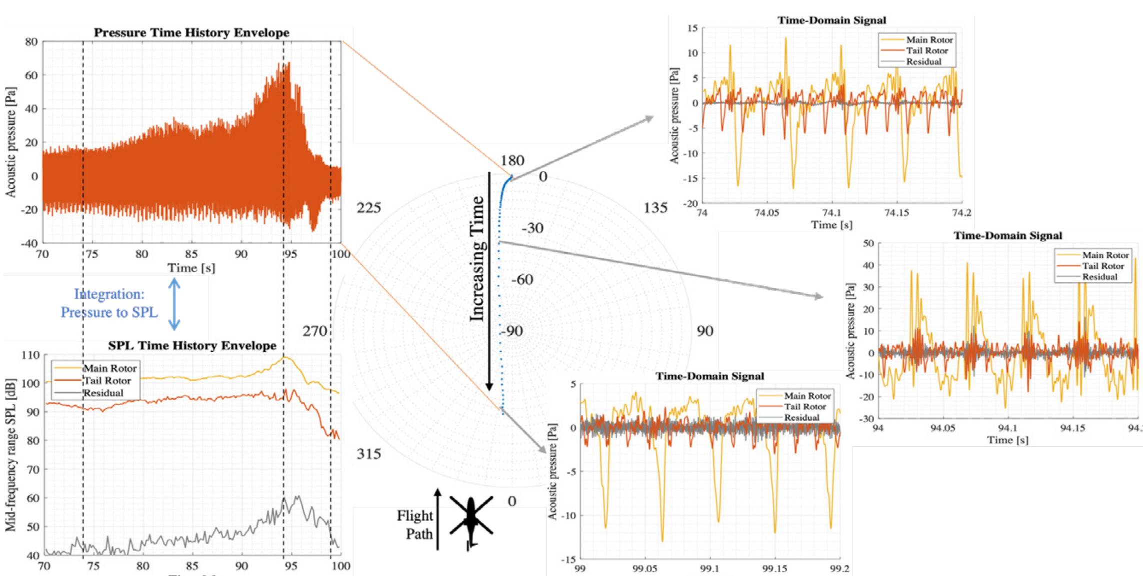
Summary: The goal of this project is to develop measurement and data processing techniques for the repeatable characterization of noise for unconventional aircraft, such as Unmanned Aerial System (UAS) and Urban Air Mobility (UAM) vehicles. Outdoor noise measurements of UAS and UAM vehicles pose unique challenges relative to conventional aircraft due to the use of distributed electric propulsion which is likely to increase the variability of noise during a flyover. Under this project, noise outdoor noise measurements have been conducted for a variety of multirotor UAS using large arrays of inverted ground plane microphones. Over 100 test points have been collected for the Tarot X8 octocopter for a variety of level flight, hover, ascending, and descending flight conditions. A large number of repeated test points were collected under varying ambient environment conditions to assess the repeatability of noise measurements for this class of vehicle.

Figure:: Flyover Noise Spectrogram for the Tarot X8 Octocopter



Another goal of this project is to develop rotor noise source separation techniques for multirotor aircraft, with the aim of reducing the variability of the acoustic characterization. A source separation method was developed that combines a time-domain de-Dopplerization approach with the Vold-Kalman order tracking filter. This method was applied to noise measurements of an instrumented Bell 430 helicopter collected by NASA, Bell Helicopter, and the US Army in 2011. The source separation approach was shown to accurately extract noise radiated by the main rotor, the tail rotor, and broadband noise, even when the source is nonstationary, such as noise caused by Blade-Vortex Interaction during maneuvering flight. A large reconfigurable research UAS, representative of proposed package delivery platforms, has recently been constructed. The rotors of this UAS are instrumented with encoders, allowing the source separation technique to be applied to acoustic data collected for this vehicle.

Figure: Helicopter Noise Source Separation for a Maneuvering Helicopter



Testing of Fluidic Flexible Matrix Composites (F2mc) Damped Vibration Absorber for Stiff In-Plane Hingeless Rotorcraft Blades

Sponsor: U.S. Army VLRCOE (2016-2022)

Principal investigators: Edward Smith, professor of aerospace engineering, R. Bill, H. DeSmidt (Univ of Tennessee)

Student: Randy Redfield, MS, mechanical engineering

Summary: A detailed physics-based design analysis of various transmission components – gears, bearings, shafts, and housing has led to manufacturing of a Pericyclic Drive prototype for 50 HP and 5000 RPM nominal input. NASA's, APG ARL's, and Penn State ARL's experience is being leveraged for assembly and testing. Conduct low-power tests to evaluate backlash and oil churning. Conduct high power tests at APG ARL VIPER test rig. Following this, gear noise, vibration modes will be predicted, and an optimal torque range will be evaluated for each load case. The results from the experiment will be then used to validate the mechanical design as well as the noise and vibration analysis. Develop and exercise an optimization methodology to achieve higher efficiency, reliability, and reduced weight will be the final step. With all components procured and any required reworks finished the assembly procedure and all components have been checked for accurateness compared to the drawings. The process of assembling, procurement of fasteners and O-rings, and creation of a detailed assembly procedure, has been completed at the Penn State ARL. Preparations have begun for the transition of the pericyclic drive into the VIPER rig located at the APG ARL lab in order to undergo powered testing.

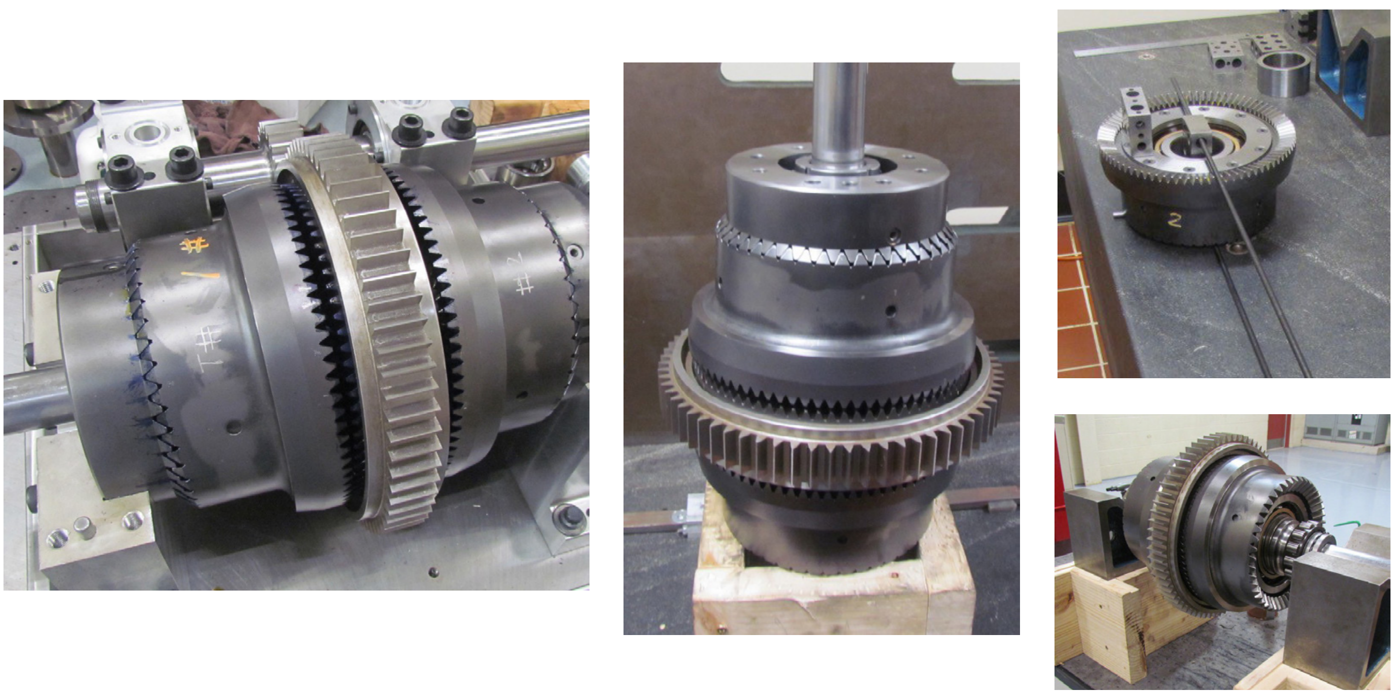


Figure: Prototype Assembled 25-50 HP Pericyclic Transmission on Test Bench

Acoustic Emission Damage Detection for Bonded Metal-Elastomer Components

Principal investigators: Edward Smith, professor of aerospace engineering, Clark Moose, Penn State ARL

Student: Daniel Jaep, MS, mechanical engineering

Summary: The objective of this research is to determine the feasibility of using AE for bonded elastomeric fault detection and develop a test methodology for recently manufactured components. Fully synched load, elongation, and AE data were collected for this purpose. Patterns between the various AE parameters and mechanical behavior were studied in order to determine failure indicators for these bonded materials. Energy per hit, hit amplitude, and hit rate were generally the AE parameters that best indicated certain mechanical phenomena. When a bonded component was cycled to the same load, fewer and lower amplitude hits were typically seen, indicative of the stress softening Mullin's effect. Conversely, prior to cohesive failure AE signals were higher in amplitude and energy in the seconds precipitating the loss of load carrying capability. Results show that AE, while difficult for rubbery materials, is capable of indicating faults and failure in bonded elastomer components. Finite element analysis (FEA) was also utilized to aid in the determination of testing methodology. Specifically, FEA was used for determining the optimal placement of AE transducers for any given geometry due to the ability to model any geometry and reduce the number of physical tests that needed to be conducted. Simulations were used to determine the most sensitive sensor location for a variety of distinct AE source locations. Results comparing the average peak value and Q-factor for a frequency response of each 'pseudo-sensor' location on the finite element model guided how transducers would be placed on physical components to evaluate the greatest amount of material in the least amount of time possible.

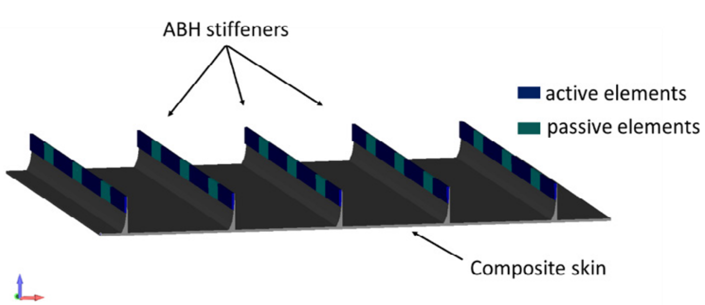
Advanced Damping System for Broadband Vibration and Interior Noise Control of Composite Airframes of Transport Rotorcraft

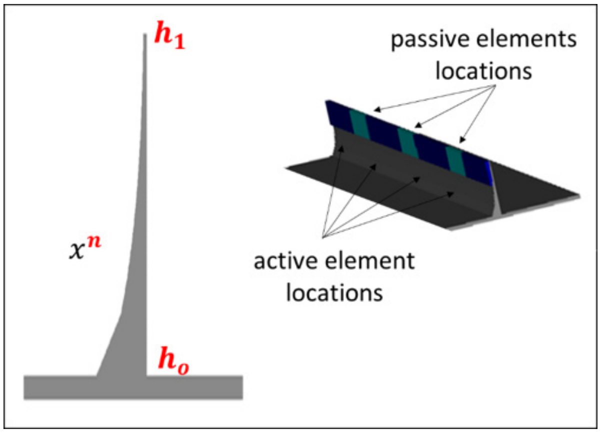
Sponsor: Office of Naval Research

Principal investigators: Ed Smith, Prof. of Aerospace Engineering, Micah Shepherd (PSU ARL), Ben Beck (PSU ARL), Chuck Bakis, Prof of Engineering Mechanics

Students: Anna Moorhouse (MS, Acoustics), Avery Brown (PhD Engineering Mechanics)

Summary: The objective of this new program is to develop modeling, optimization tools, and manufacturing methods to determine the trade-off in the strength, mass and damping performance of a novel stiffened composite panel concept with an acoustic black hole shaped stiffener cross-section and hybrid active/passive damping elements.





Structural Vibration and Acoustics

Group Summary

The Structural Vibration and Acoustics Technical Group investigates how structures vibrate and radiate sound. We develop novel methods to analyze, measure, and control structural vibrations and radiated noise.

Below are some highlights of this group's recent work.

Group Leader: Steve Hambric
Research professor in the Penn State Applied Research Laboratory and acoustics

Optimization of structural-acoustical shaped concrete slabs in buildings

Principal investigator: Nathan Brown, assistant professor of architectural engineering

Co-principal investigator: Micah Shepherd, assistant research professor in the Penn State Applied Research Laboratory

Student: Jonathan Broyles, PhD Candidate, Architectural Engineering

Summary: With advancements in digital design tools, architects and engineers have developed novel building components that can reduce embodied carbon in structures. However, these optimized structures can neglect secondary design objectives such as acoustics during the computational process. This research investigates the relationship between structural and acoustic performance for shaped concrete slabs with curved, non-standard geometry. Design space exploration techniques including optimization are applied to find structural-acoustic trends and identify the high-performance shaped slabs at varying acoustic performance levels. To support simulation-based design optimization, we have explored modified metrics for sound transmission that more effectively capture the acoustic performance, and we have analyzed physical samples to validate the computational models. More can be read about the project here:

https://www.psu.edu/news/engineering/story/balancing-sustainability-safety-and-comfort-engineered-floor-slabs/

https://happyvalleyindustry.com/engineering-research-reimagines-concrete-floors-to-advance-construction-innovation/

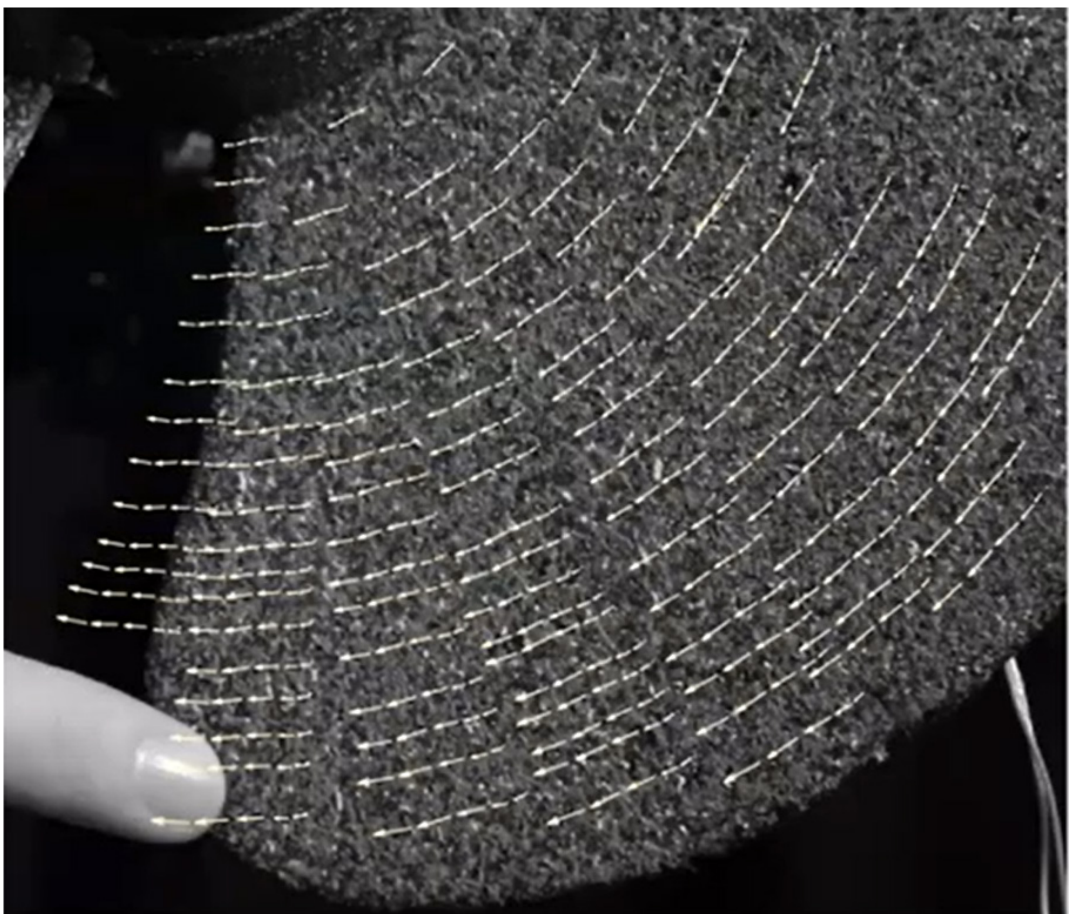
Phase-Based Optical Flow for Vibrations Measurements and Force Reconstruction

Principal investigator: Tyler Dare

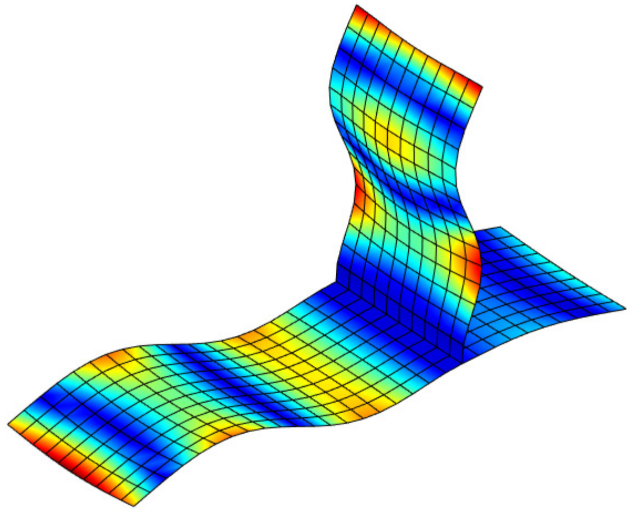
Student: Sean Collier

Summary: Digital images have become ubiquitous in vibration measurement for their full-field and spatially-dense nature, particularly through the use of correlation methods like digital image correlation. Much like cross-correlation for time series, these techniques are based on the idea of relating two similar signals (i.e., similar regions between two images) through some phase shift to extract displacements, or the spatial "delay." This concept can be extended further, resulting in techniques such as phase-based optical flow (PBOF) to capture smaller and more localized vibrations of interest. Though far less common, PBOF has been shown to outperform correlation methods and also provides the ability to visually magnify motion in video—a feature particularly useful in applications like structural or biomedical health monitoring. Applications to force reconstruction are currently being explored.

See a recording of Sean Collier's CAV presentation on this work at https://www.youtube.com/watch?v=wE5j9E-EBtU



Pixel Pushing allows for an intuitive, succint, and efficient approach for handling combinations of large motions and vibrations, such as both bulk rotation and bending waves in a fan blade.

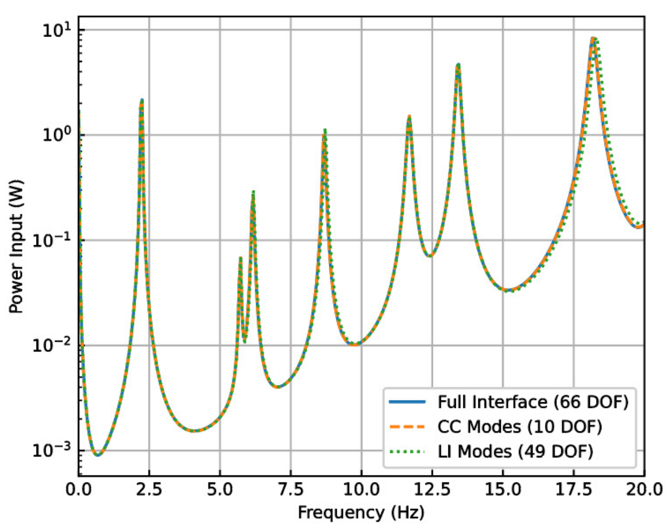


Power Flow through Reduced Substructure Interfaces

Principal investigators: Kyle Myers, Assistant Research Professor, Applied Research Lab and Robert Campbell, Associate Research Professor, Applied Research Lab

Student: Jonathan Young, doctoral candidate in mechanical engineering

Summary: Power transmission between substructures can be used to analyze the vibratory response of a complex structure. Dynamic substructuring methods exist to reduce the size of a numerical model by expressing the internal dynamics of the structure by a set of normal modes of vibration. However, if there are many degrees of freedom on the interfaces that join two substructures, the calculation of power flow can become computationally expensive. Instead, the number of degrees of freedom can be reduced by means of eigenanalysis along the coupling interfaces. Two sets of interface modes are considered, characteristic constraint (CC) and local interface (LI), and both allow for quick and accurate computation of power flow between structures, while minimizing the number of degrees of freedom that need to be retained on the model.



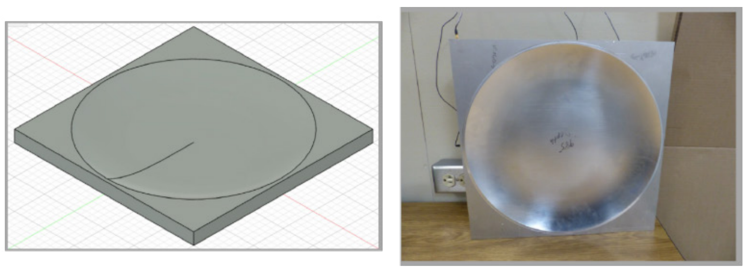
Acoustic Black hole Evaluation for Reduced Radiation Efficiency

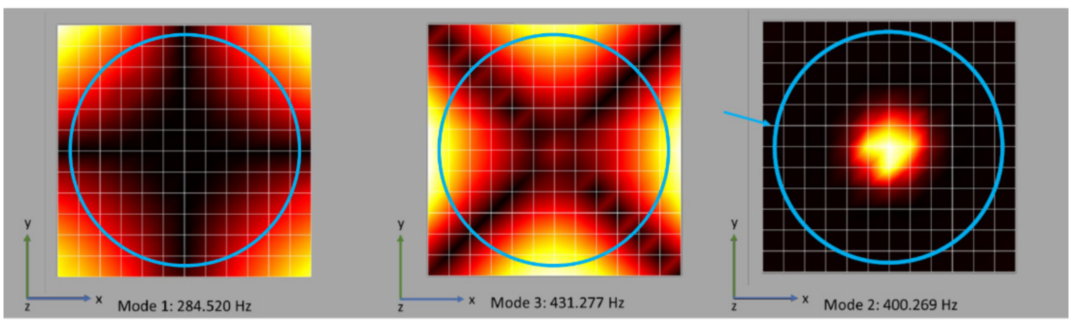
Sponsor: Fluor Marine Propulsion, LLC

Principal investigators: Micah Shepherd, assistant research professor in acoustics and Amanda Hanford, assistant research professor

Student: Emily Stimson, MS candidate in acoustics

Summary: Acoustic black hole (ABH) technology will be expanded to exploit its ability to the reduce radiation efficiency when embedded in a structure. Design guidance will be developed which utilizes the ABH parameters and locations to create a meta-structure plate which exhibits reduced radiation efficiency when compared to standard plate. To demonstrate, prototype panels will be fabricated and tested. The modes will be compared according to their global and local characteristics.





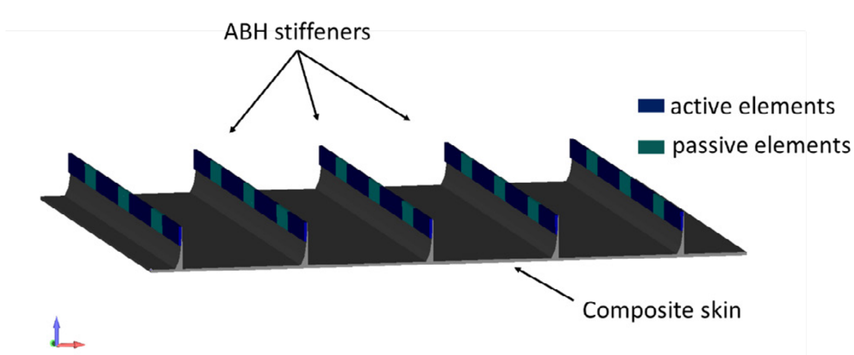
Advanced Damping System for Broadband Vibration and Interior Noise Control of Composite Airframes on Transport Rotorcraft

Sponsor: Office of Naval Research

Principal investigators: Micah Shepherd, associate research professor in acoustics and Ben Beck, associate research professor and Chuck Bakis, professor of engineering mechanics and Ed Smith, professor of aerospace engineering

Student: Anna Moorhouse, MS candidate in acoustics

Summary: The object of this research is to determine the trade-off in the stiffening, mass and damping performance of an ABH-stiffened composite panel. The stiffener cross-section will be an ABH shape with damping elements near the tip with the design parameters determined using formal, multi-objective optimization. Additionally, a combined active/passive damping system will be investigated to achieve the best broadband reduction of the meta-structure.



Optimization and Uncertainty Quantification Using Substructured Models

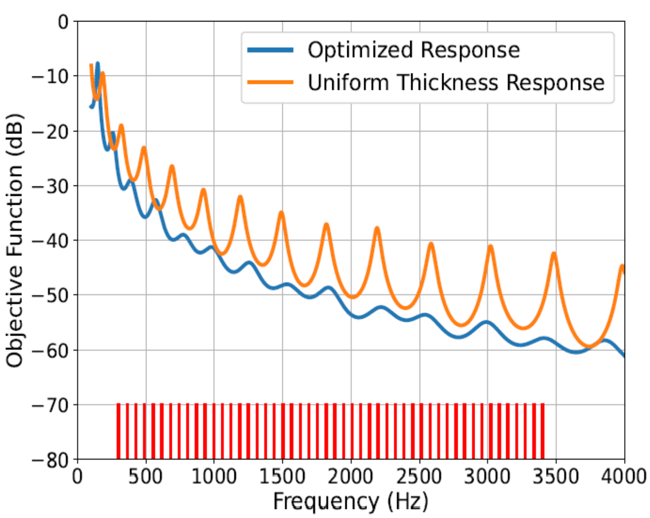
Sponsor: Office of Naval Research

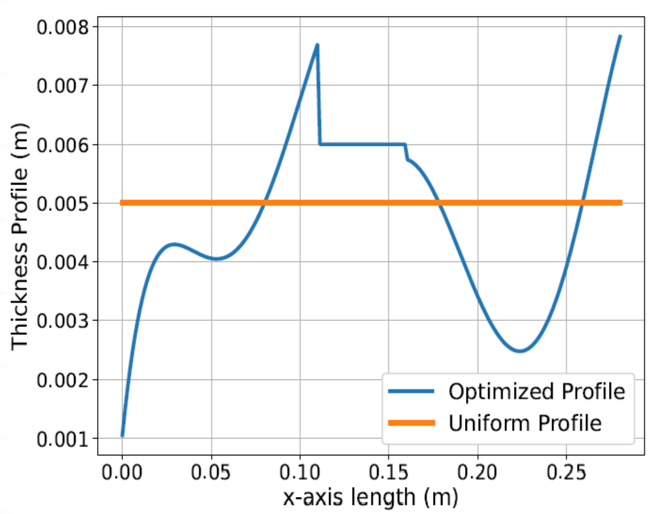
Research Advisors: Andrew S. Wixom, assistant research professor in the Penn State Applied Research Laboratory; Micah Shepherd, assistant research professor in the Penn State Applied Research Laboratory and acoustics

Principal investigators: Amanda Hanford, assistant research professor in the Penn State Applied Research Laboratory, mechanical engineering and acoustics

Student: Matthew B. Luu, doctoral student in acoustics

Summary: The concept of *substructuring* – that is, computing the overall response of a structure by first determining the behavior of one or more or its components – has been around for several decades and remains popular even today. Substructuring can greatly reduce the computation time necessary to analyze any particular design due to its reduction of the degrees of freedom (DOFs) for each component leading to a much smaller model overall. In this project, we aim to leverage these reduced analysis times to allow for optimization studies that would otherwise be infeasible using traditional modeling strategies. One early result is as follows where the thickness profile of a notional beam structure is optimized in order to reduce broadband vibration transmitted to a region of interest, using a substructuring strategy based on primal-coupled spectral elements.

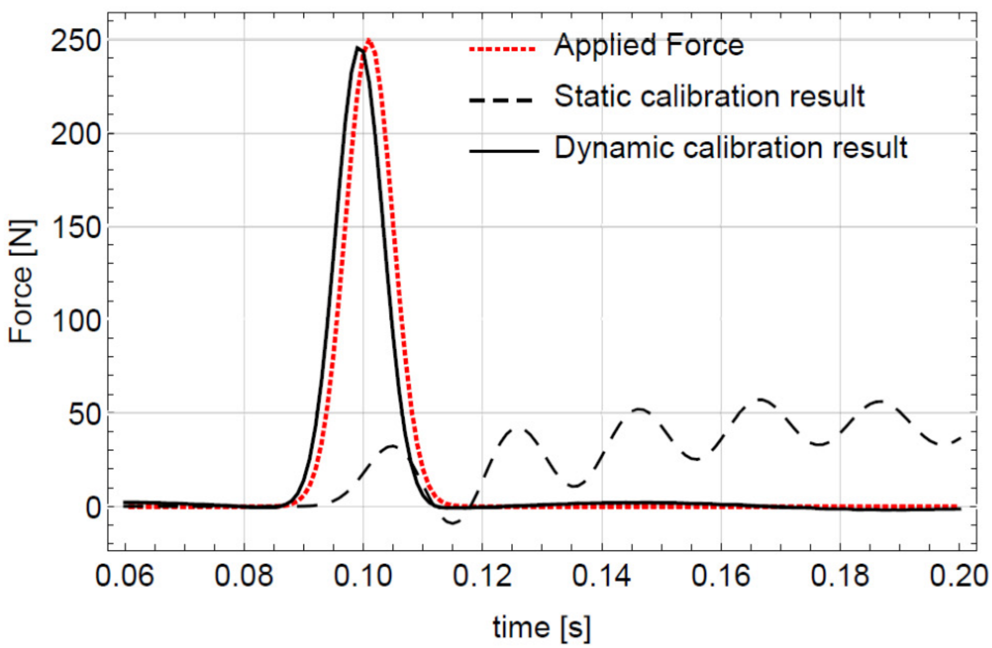


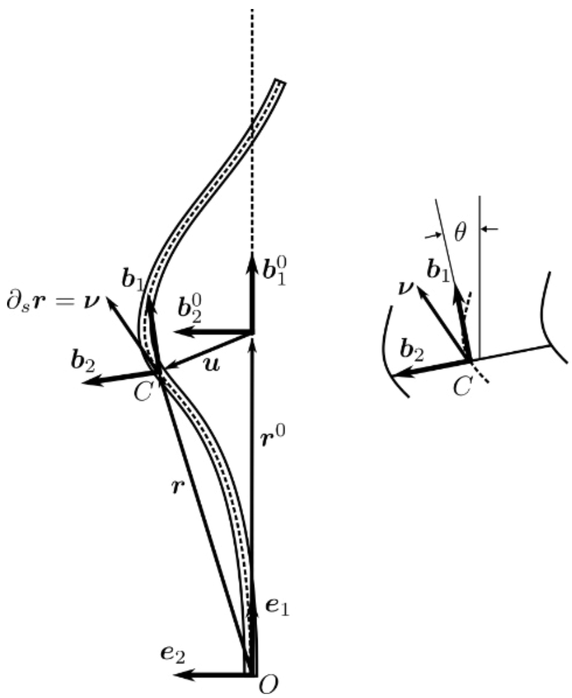


Methodology for Improved Dynamic Force Measurements

Principal investigator: Nicholas Vlajic, assistant research professor in the Penn State Applied Research Laboratory

Summary: Force balances used in wind tunnel ground test facilities to determine forces and moments acting on a test article are typically calibrated statically, but are often used to make dynamic measurements. The additional structural components (e.g., test article and sting) can change the response of these devices and lead to errors when using the static sensitivity to measure dynamic quantities. A recently accepted paper in the Journal of Aircraft written by researchers from Penn State ARL, NASA Langley Research Center, and the National Institute of Standards and Technology provides a guide that can be used to improve these dynamic measurements. The procedure outlined in the paper starts by documenting design considerations that can be used in the initial experimental design, then focuses on different analysis techniques that can be implemented with varying degrees of difficulty. The intent of this paper is to raise awareness of dynamic measurement challenges in the aerospace community and to provide a guide to enable more accurate dynamic force measurements.



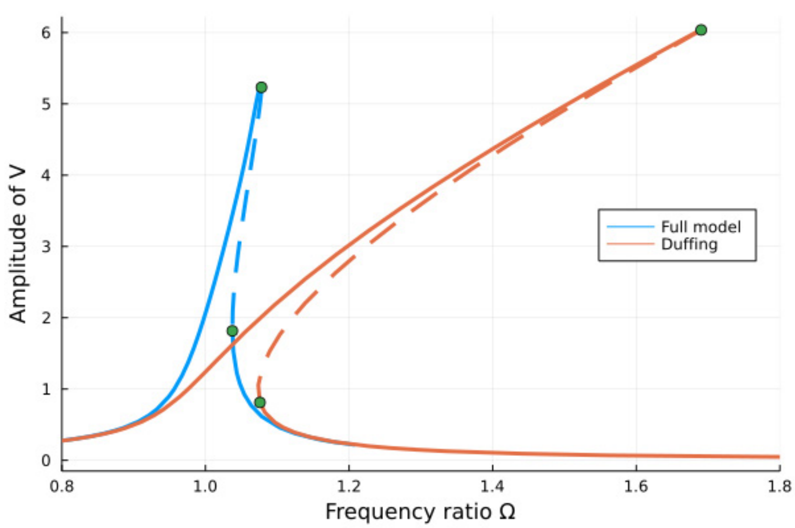


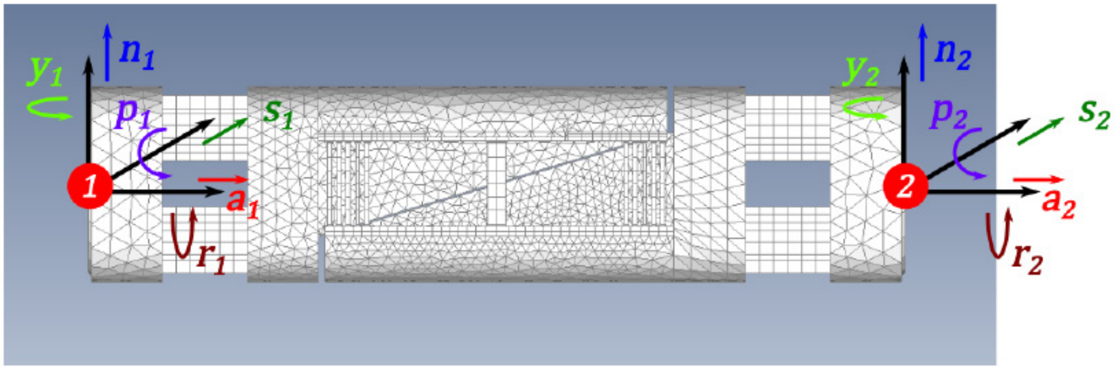
Large-Amplitude Vibrations of a Slender Cantilevered Beam

Principal investigators: Nicholas Vlajic, assistant research professor in the Penn State Applied Research Laboratory, Timothy Fitzgerald, associate professor of Mechanical Engineering at Gonzaga University

Student: Fisher Ng, undergraduate student Gonzaga University

Summary: The dynamics of slender cantilevered beams have recently seen a renewed interest with applications such as wind-energy capture systems that exploit vortex-induced vibrations of these structures. Recently, a geometrically exact beam model (also known as Cosserat theory) was developed to understand the nonlinear dynamics of cantilevered beams undergoing large-amplitude deformation, specifically, amplitudes that can be as large as 30% of the total length of the beam. The dynamics of these structures were studied using a numerical continuation technique to map out the stable and unstable solutions of the cantilever's periodic response. The nonlinear inertia terms are shown to have a softening-type effect, while the nonlinear curvature terms create a stiffening-type effect. The net result is a beam that behaves nearly linear, which is in consonance with prior studies. The geometrically exact beam formulation will be coupled with a reduced-order fluid model to study the vortex-induced vibrations of these structures in future work.





Reduced-Order Modelling in Aerospace Wind Tunnel Applications

Sponsor: Walker Graduate Fellowship Program

Principal investigator: Nicholas Vlajic, assistant research professor in the Penn State Applied Research Laboratory

Student: Zachary Jones, doctoral student in acoustics

Summary: Wind tunnel measurement systems are complex assemblies that typically consist of a test article, strain gage force balance, and sting. Often times, these measurements systems are assembled in a wind tunnel facility and the natural frequencies and mode shapes are then experimentally determined. Predicting the dynamics apriori is a powerful tool as it can be used to identify problematic operating conditions before testing takes place. However, finite element models of these assemblies are time consuming to construct given the different length scales needed for the larger sting and test article components down to the intricate features of the force balance. We have developed a reduced-order model of this measurement system that is able to accurately capture the first six natural frequencies and mode shapes. The effects of structural changes (e.g., altering mass and stiffness) can be observed on the reduced-order model before implementing changes in more time-consuming finite element models. Moreover, this reduced-order model may be an effective tool for predicting test conditions that lead to undesirable resonant behaviors such as pitch-buffeting.

Systems and Structures Health Management

Group Leader: Cliff Lissenden
Professor of engineering science and mechanics and acoustics

Group Leader: Karl Reichard
Associate research professor in the Penn State Applied Research Laboratory

Group Summary

The mission of the Systems and Structures Health Management Technical Group is to develop new methodologies and technologies to manage the life cycle of systems and structures. This includes the full range of material state awareness, health and usage monitoring, and condition-based maintenance, to support both autonomic and conventional operations with logistics informed by reliable useful life prediction.

The underlying goal of the group is to maximize safety, minimize life cycle cost and increase capability. Key areas being investigated include: sensor systems, signal processing, pattern recognition, reasoning techniques, and modeling of damage progression to failure.

Below are some highlights of this group's recent work.

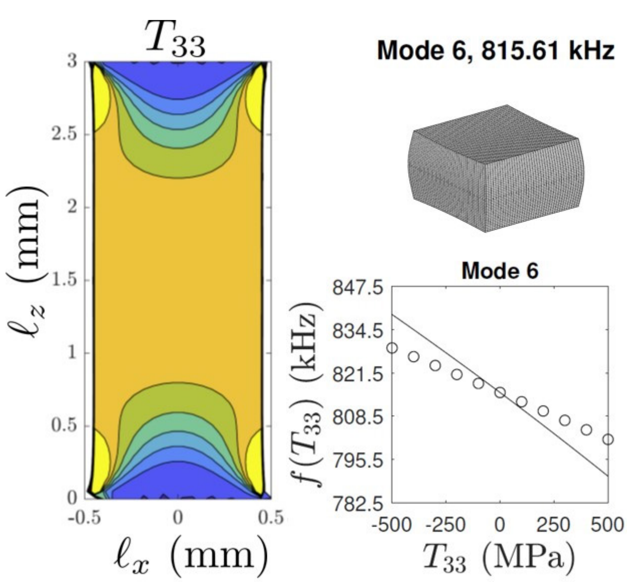
Residual Stress Influence on the Free Vibrations of Elastic Solids

Sponsor: U.S. Air Force Research Laboratory

Principal investigator: Christopher Kube, assistant professor of engineering science and mechanics and acoustics

Student: Jared Gillespie, graduate student in engineering science and mechanics

Summary: The presence of an initial or residual stress existing in a solid is usually neglected when considering its vibratory response. While the volume average residual stress field and tractions at the boundaries must satisfy equilibrium, the distribution of residual stress within the volume can have a strong influence on the structure's resonance frequencies. In this work, the team developed a micromechanical model to introduce stress-dependent effective elastic properties into the traditional variational model that governs the resonance behavior of elastic solids. Figure 1 shows that a realistic residual stress field with a dominant stress component T_{33} is predicted to change the resonance frequency significantly for a rectangular parallelepiped sample. While this work is supporting the use of resonance behavior for quality control of AM sample, the results are applicable to general vibratory structures.



A nonuniform but realistic residual stress distribution with dominant T33 component is shown to have a significant influence on the resonance frequency of a rectangular parallelepiped sample.

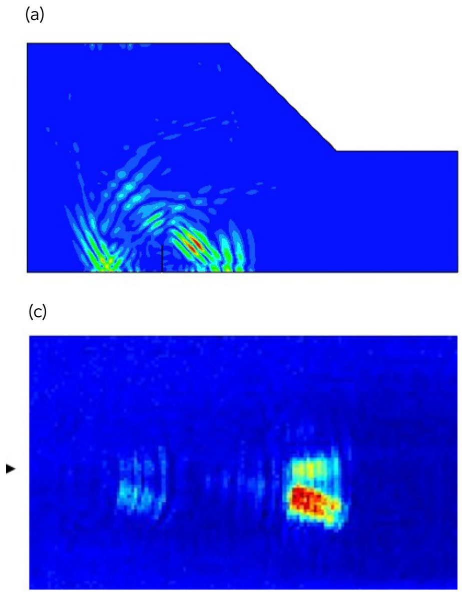
Computational Modeling of Vertical Crack Scattering

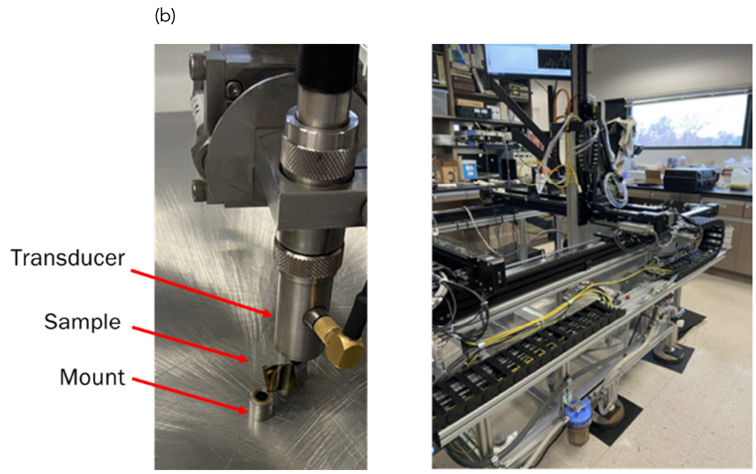
Sponsor: Intel Corp.

Principal investigator: Andrea P. Argüelles, assistant professor of engineering science and mechanics and acoustics

Student: Lauren Katch, doctoral student in engineering science and mechanics

Summary: Semiconductors are susceptible to micro-sized cracking during manufacturing. These cracks can be vertical and undetectable using traditional scanning acoustic microscopy methods. We are researching oblique incidence pulse echo methods that rely on shear wave scattering for detection. Currently, we are developing a combined modeling and experimental approach (see Figure 2) that optimizes detection and sizing of vertical cracks.





(a) Scattering of an angled shear wave from a vertical crack in a silicon sample modeled in Abaqus; (b) experimental setup for testing of silicon wafers, and (c) C-scan image of shear wave reflection from verticals cracks in silicon wafer.

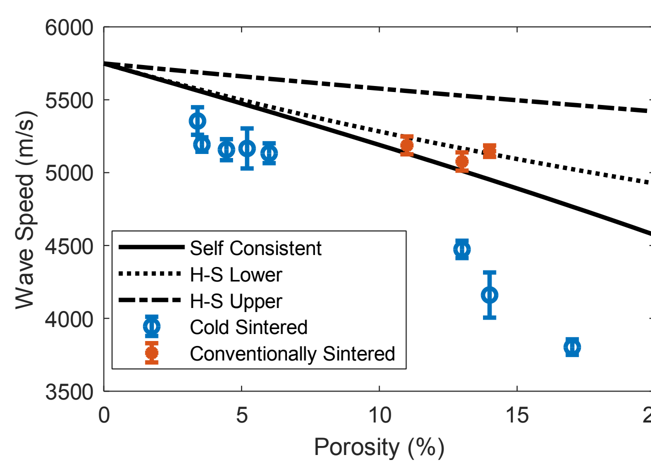
Acoustic Characterization of Cold Sintered Components

Sponsor: Center for Dielectrics and Piezoelectrics, Penn State

Principal investigators: Andrea P. Argüelles, assistant professor of engineering science and mechanics and acoustics; Susan Trolier-McKinstry, Evan Pugh Professor and Steward S. Flashchen Professor of Materials Science and Engineering and professor of electrical engineering

Students: Elizabeth Trautman, Shruti Gupta

Summary: The cold sintering process (CSP) is a low temperature processing technique used to synthesize ceramics and composites. In some CSP parts, density gradients arise due to pressure gradients in the die, inhomogeneities in the temperature, and/or heterogeneous distribution of the flux. Relative density measurements alone cannot distinguish between small, isolated pores and larger defects, which encourages the development of new techniques to identify the homogeneity of cold sintered parts. This work focuses on the ex situ ultrasonic characterization of cold sintered samples. The preliminary results in Figure 3 demonstrate significant differences in the response of cold vs. conventionally sintered ceramic samples.



Porosity dependent wave speeds for cold and conventionally sintered ZnO samples, where the data points correspond to the mean wave speed for each sample and the error bars are the standard deviation. The lines represent analytical estimates of the porosity dependence based on Hashin-Shtrikman and self-consistent averaging.

Nonlinear Laser Ultrasonics for Reduced Variability in Additive Manufacturing

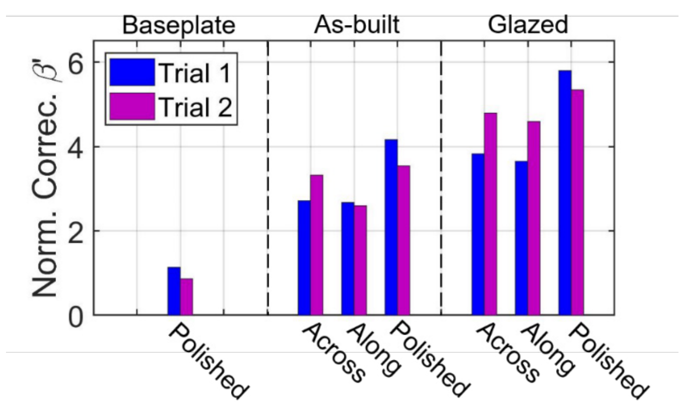
Sponsor: Penn State Vertical Lift Research Center of Excellence (U.S. Army, U.S. Navy, NASA)

Principal investigators: Cliff Lissenden, professor of engineering science and mechanics and acoustics; Ted Reutzel, associate research professor in the Penn State Applied Research Laboratory, engineering science and mechanics, and mechanical engineering

Students: Chaitanya Bakre and Gerald Boddie graduated with PhD and MS respectively in ESM

Summary: Laser ultrasonics is an attractive NDT tool for harsh environments (such as AM in-situ NDT) that require rapid scanning of a surface because it is noncontact; only the laser beam itself touches the surface. We monitor the top layer of an AM 'build' with laser ultrasonics before the next layer is deposited. When a pulsed laser beam irradiates a material surface, it is partially absorbed into a very thin layer of the surface, and as a result, extremely fast heating and cooling occur. This causes rapid variation in the thermal stress on the surface, which leads to the generation of ultrasonic waves. Of these waves, the (Rayleigh) surface wave has the highest amplitude and is confined to propagate along the surface, i.e., within a depth of about one wavelength. Thus, surface waves are the most suitable for monitoring a newly deposited AM layer. We generate surface waves with a Q-switched Nd:YAG pulsed laser and receive it with a laser interferometer. The pair of lasers scan the newly deposited layer and linear features of the received wave will be used to determine elastic modulus and identify gross defects such as lack of fusion and pores that would constitute rejection of the part. Identification of such defects during the deposition process may enable re-melting and repair before subsequent deposition layers effectively bury the defect. Additionally, after the part is completed these defects would be internal and thus much more difficult to identify. Likewise, harmonic generation from finite amplitude surface waves have the potential to provide information about the microstructure that is not available from linear ultrasound features.

We integrated the laser ultrasound system with the directed energy deposition AM chamber and receive linear and nonlinear Rayleigh wave signals. The fourth integration of the laser ultrasound system with the AM chamber was redesigned to enable shorter propagation distances between the wave generation and reception points. This greatly improved the signal-to-noise ratio in the presence of significant surface roughness. Interrupted build-monitoring was performed for Ti-6-4 and Inconel 718 deposition. Both a narrow-band slit mask and a broadband cylindrical lens were used to pattern the pulsed laser beam onto the AM surface providing a diverse dataset for AM materials processed with different parameters (resulting in different porosities) as well as local flaws. Perhaps the most striking result is the difference in wave distortion (resulting in second harmonic generation) between AM processed Ti-6-4 and reference wrought Ti-6-4.



Despite directed energy deposition additively manufactured Ti-6Al-4V surfaces being rough (Pa ~25-50 μm), surface waves can be generated by an angle-beam transducer and received by a laser interferometer. The microstructures of wrought and additively manufactured material are much different and have much different ultrasonic nonlinearity. Normalized attenuation-corrected relative nonlinearity parameters for baseplate, as-built, and glazed specimens are shown. The relative ultrasonic nonlinearity parameter of the AM material is 3-6 times larger than the wrought material.

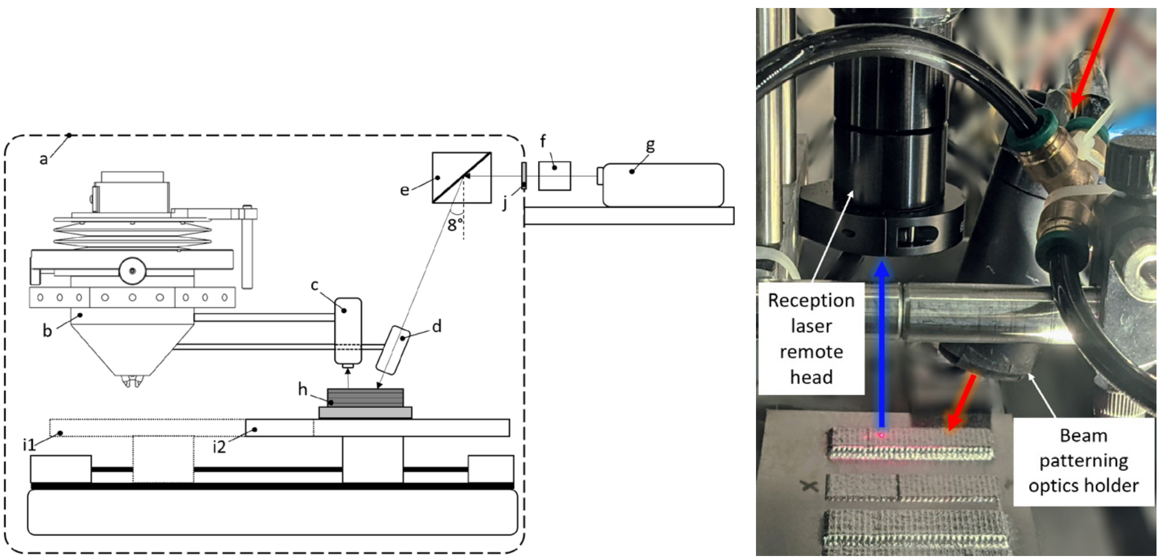
Mixing Elastic Waves to Nondestructively Characterize Microstructure during Additive Manufacturing of Metals

Sponsor: National Science Foundation

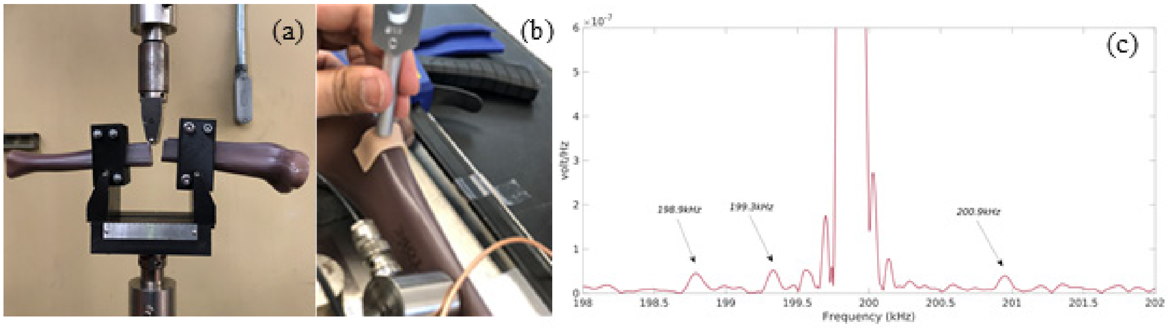
Principal investigators: Cliff Lissenden, professor of engineering science and mechanics and acoustics; Abdalla Nassar, associate research professor in the Penn State Applied Research Laboratory, engineering science and mechanics, and mechanical engineering

Students: Chaitanya Bakre and Gerald Boddie graduated with PhD and MS respectively in ESM

Summary: We researched ultrasonic Rayleigh waves for process monitoring in a directed energy deposition additive manufacturing (DED-AM) chamber. Potentially, linear features of the surface waves are indicative of defects (discontinuities) and local linear elastic properties, while nonlinear features of the surface waves are indicative of microstructural characteristics that affect strength, fatigue, and fracture properties. Specifically, we are investigating the capabilities of laser ultrasonics to generate and receive Rayleigh waves propagating along the surface of the build in situ.



Schematic of the integrated system: a – the DED chamber, b – deposition head, c –reception laser head mounted on an XY stage (not shown), d – beam patterning optics holder, e – mirror, f – beam expander, g – generation laser head, h – AM specimen, i1 – DED stage at the deposition position, i2 – DED stage at LU testing position, j – glass window. Photograph of reception laser head, beam patterning optics holder, and AM specimen.



The overall vibro-acoustic setup and analysis; (a) fatigue fracture created in diaphyseal region of tibia, (b) holding tuning fork on tibial tuberosity, (c) resulting frequency spectrum showing sidebands created by 512 Hz tuning fork.

Ultrasonic Guided Waves as a Diagnostic Tool to Evaluate Fragility Fractures

Principal investigators: Michael Aynardi, staff physician of orthopaedics at the Milton S. Hershey Medical Center; Greg Lewis, assistant professor of orthopaedics and rehabilitation; Cliff Lissenden, professor of engineering science and mechanics and acoustics; and Parisa Shokouhi, associate professor in engineering science and mechanics and acoustics

Students: Anurup Guha and Tyler Duane graduated with PhD and MS respectively in ESM

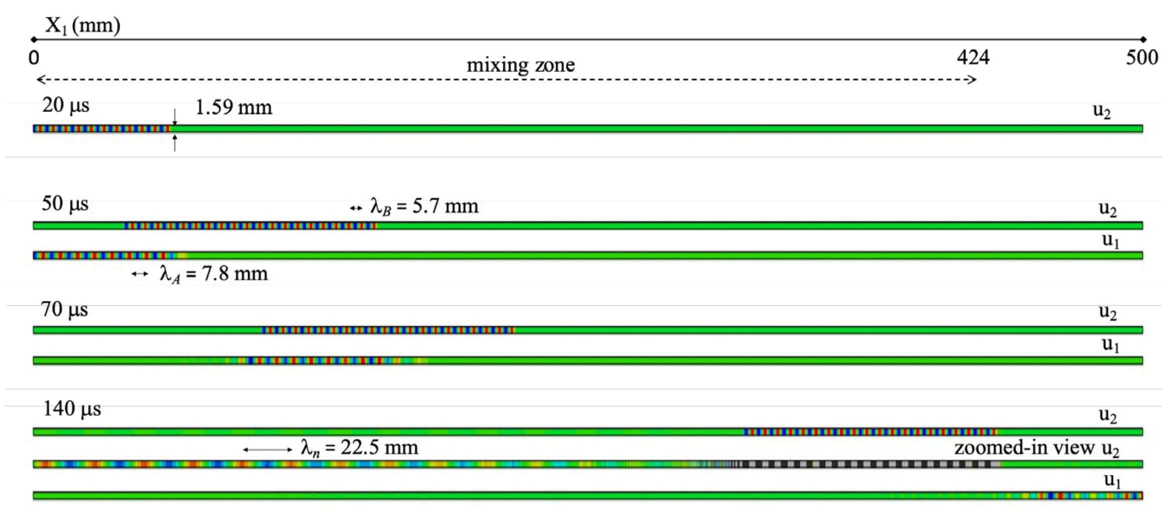
Summary: Ultrasonic Guided waves are mechanical waves which propagate in thin-walled structures. They are inherently sensitive to the material and geometric properties of the medium in which they propagate. In the last couple of decades, considerable amount of work has been done in utilizing the benefits of ultrasonic guided waves towards characterizing long bone health (such as shin bone, femur). Although, a majority of these investigations rely heavily on plate and shell approximations used to model long bones, and as a result they come short of realizing the true nature of the propagating ultrasonic guided wave modes in heterogeneous long bones over a long propagation range within the bone shaft. Much of the reason for such approximations is the complexity in the material behavior of long bones, their heterogeneous geometrical features, and the presence of soft tissue and bone marrow on the outside and inside of the bone shaft. Focusing on shin bone as the primary waveguide of interest, my work uses real bone geometry extracted from high-definition CT-scan and anisotropic material behavior to numerically characterize the ultrasonic guided wave modes in shin bone shaft. The know-how from the numerical studies is then used to experimentally investigate ultrasonic guided waves in synthetic bone samples. I demonstrate a sensitive excitation and reception mechanism for ultrasonic guided waves in long bones which can help in better management of long bone health and give an idea of a unique method to identify fractures in shin bone shaft which can help to diagnose hair-line fractures. The findings from this work will help in better understanding of the influence of material and geometric complexities of a shin bone on propagating ultrasound, develop long range guided wave generation and reception strategies, and help in identification of stress fractures which are otherwise hidden in an X-ray scan.

Nonlinear ultrasonic guided waves for nondestructive evaluation

Principal investigator: Cliff Lissenden

Student: Anurup Guha

Summary: Guided wave mixing leverages mutual wave interactions to provide sensitive diagnostics of material degradation in plates and pipes and an early warning upon which maintenance decisions can be based. In some cases, the material to be interrogated may be otherwise inaccessible for nondestructive evaluation. The distortion of the waveform in nonlinear ultrasonics is typically quite small, often making it difficult to distinguish from nonlinearities in the sensing system. Mutual wave interactions are preferred to wave self-interactions in this respect because they can be designed to occur away from frequencies corrupted by sensing system nonlinearity. Furthermore, primary waves that generate secondary waves having a different polarity also provide a means to separate the material nonlinearity from the sensing system nonlinearity. Finite element simulations of wave mixing using a hyperelastic material model are conducted as a precursor to laboratory experiments in order to establish realistic expectations. In one case shear-horizontal waves are mixed with co-directional symmetric Lamb waves to generate back-propagating shear-horizontal waves at the difference frequency. In the second case counter-propagating shear-horizontal waves mix to generate secondary standing waves at the cutoff frequency of the S1 Lamb wave mode. In both cases the results indicate that the larger the wave mixing zone, the more measurable is the amplitude of the secondary waves. These results will be used to design experiments that demonstrate the utility of these novel wave interactions.



Nonlinear finite element simulation of wave mixing in aluminum plate. Waves A (Lamb wave mode) and Waves B (SH wave mode) generated at left edge propagate to the right. Their mutual interaction (shown at 70 μs) generates a back-propagating SH wave at the difference frequency (shown at 140 μs) making it possible to send and receive at the same position.

Illuminating Key Mechanistic Feedbacks Among Transport, Seismic, and Frictional Properties of Fractured Rock

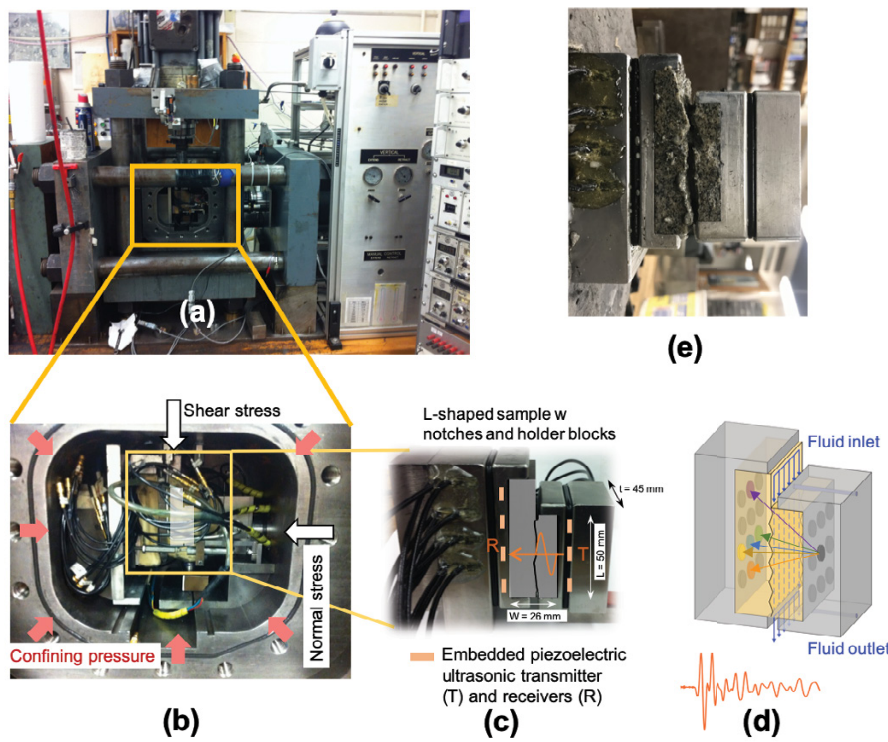
Funding: Department of Energy – Office of Basic Energy Sciences (awarded in 2020)

Principal investigators: Parisa Shokouhi, Jacques Rivière, Chris Marone, and Derek Elsworth

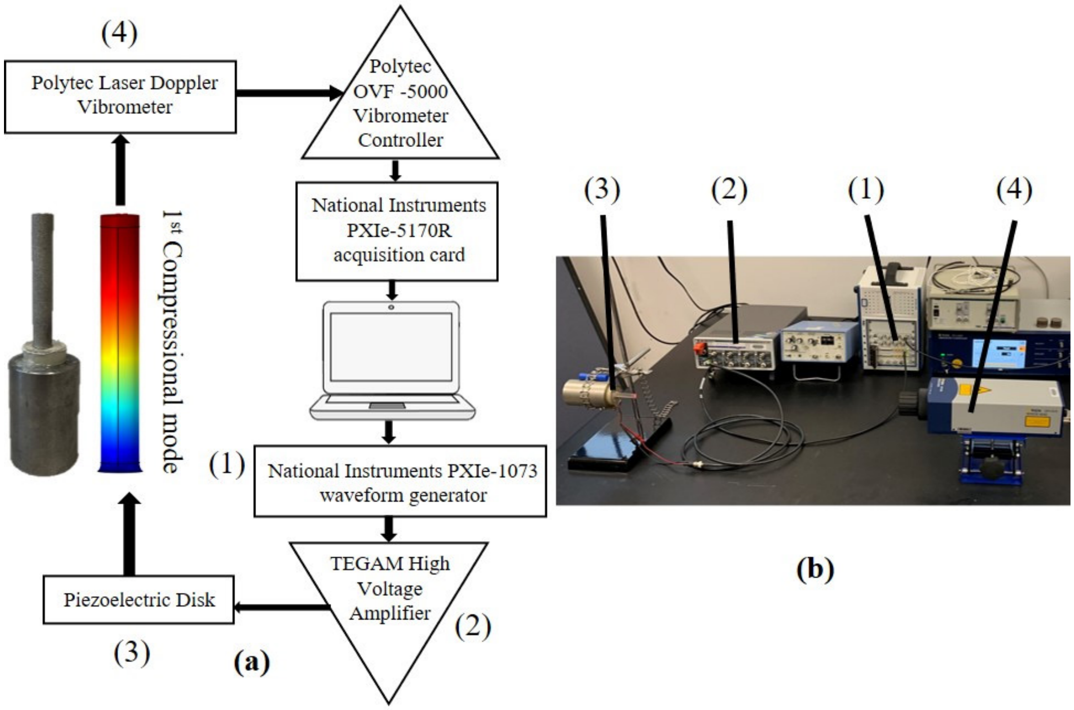
Students: Clay Wood (PhD, Geosciences), Prabhakaran Manogharan (PhD, ESM)

Post-doc: Samson Marty, postdoctoral scholar in geosciences

Summary: The project goal is understanding the fundamental mechanisms that govern fluid flow, friction, and elastic properties of fractured rock. Specifically, we conduct experiments (see Figure 7) to: (I) decouple the influence of fracture aperture distribution and roughness from unclogging on the elastic and flow properties, explore these behaviors for (II) shear-reactivation of fractures, and develop complex analyses that: (III) assimilate these data, illuminate key mechanistic feedbacks and address upscaling of our results to field scale. The work addresses societally-relevant issues such as induced seismicity, probes frontier scientific problems related to nonlinear elasticity and the coupling between transport and elastodynamic properties and utilizes machine learning techniques to maximally illuminate correlations from the mechanism-rich geophysical data. Our proposed plan includes unusually well-controlled lab experiments to measure friction and flow. We are using new techniques including synchrotron X-ray computed tomography of fracture properties and plan to combine 4D microstructural and ultrasonic imaging of fractures under dynamic stressing to probe causative mechanisms linking permeability and stiffness. The primary elements of this project include: 1) active and passive ultrasonic measurements to determine the elastodynamic response of fractured samples and simulated faults, 2) permeability studies of fractured samples subject to elastic loading and inelastic deformation, 3) measurement of friction constitutive properties under steady state shear and during stick-slip sliding, and 4) physics-based and data-driven modeling to predict hydraulic properties and controls on induced seismicity. The laboratory program includes a subset of simple tests with isolated measurement of one variable, but the majority of our work will focus on coupled processes as revealed by simultaneous monitoring of the evolution of elastodynamic properties, permeability, and friction constitutive behavior during elastic loading and inelastic deformation. We follow a systematic approach by studying both intact rock and comparing it to well-characterized fractures (with and without infilling) under a range of stress and saturation conditions. The role of microstructure and shear fabric will be illuminated by our laboratory data and also by studies that involve synchrotron X-ray imaging. Our research will provide a new understanding of coupling between poromechanical and acoustic properties of rock and new insights into the evolution of rock properties and seismic hazards associated with energy production and the injection of fluids in deep reservoirs.



(a) The biaxial loading apparatus in Penn State's Rock Mechanics lab including (b) a pressure vessel to apply triaxial stress to the sample. (c) The L-shaped sample is sandwiched between two holder blocks with embedded piezoelectric transducers. (d) The experimental setup allows simultaneous measurements of flow and multi-channel ultrasonic data. (e) Picture of an in-situ fractured sample of Westerly Granite.



Experimental setup: (a) diagram and (b) testing components.

Ultrasonic Measurements of Additively Manufactured (AM) Materials

Funding: Triad National Security, LLC (Los Alamos National Lab/Department of Energy)

Principle investigator: Parisa Shokouhi, associate professor of engineering science and mechanics and acoustics

Students: Colin Williams (MS, ESM), Evan Bozek (MS, ESM), Zach Martinez (BS, ESM)

Summary: The goal of this project is to devise new ultrasonics based methods for AM part qualification. We test a series of AM samples and their wrought counterparts with various linear (velocity and attenuation) and nonlinear ultrasonic testing methods (nonlinear ultrasound spectroscopy and second harmonic generation) as shown in Figure 8. The samples undergo various heat treatments and are characterized independently using X-ray micro-CT, ESM and other characterization methods. The outcome will be microstructure-property linkage through linear and nonlinear ultrasonic parameters.

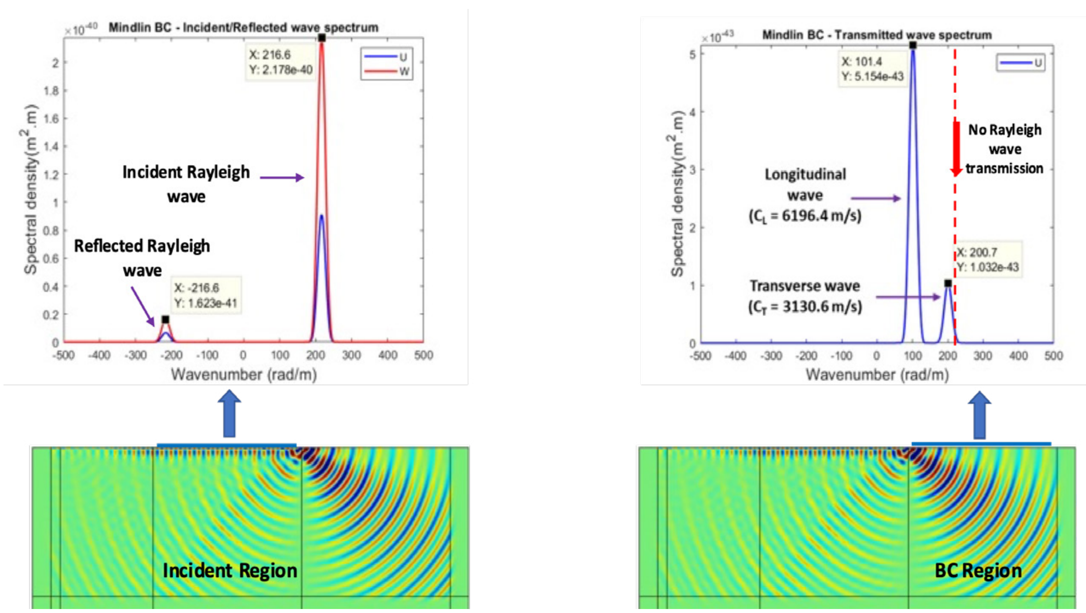
A Meta-Surface to Control Surface Wave Propagation

Sponsor: National Science Foundation

Principal investigators: Parisa Shokouhi, associate professor of engineering science and mechanics and acoustics; Mary Frecker, Riess Chair of Engineering, director of the Penn State Center for Biodevices, and professor of mechanical engineering and biomedical engineering; and Cliff Lissenden, professor of engineering science and mechanics and acoustics

Students: Daniel Giraldo Guzman, Lalith Pillarisetti, Eric Sullivan, Jeremy Keirn, Sashank Sridhar

Summary: Our research objective is to control the motion of Rayleigh surface waves through modifying the surface along which the waves propagate i.e., by purposefully changing the boundary conditions on the surface in order to promote desirable reflections and mode conversions as shown in Figure 9. One way to impose the necessary BCs for a given range of frequencies is to place an assembly of resonators on the surface at sub-wavelength spacing. Such resonant meta-surfaces are typically designed through a parametric study of the dispersion curves and tuning the resonance frequencies for a periodic unit cell. Our proposed method takes the view that BCs are the key to providing the desired control. This new approach suggests a systematic strategy for creating a meta-surface, a departure from the commonly used parametric process. The fundamental knowledge gained in this research will have potential applications across length scales. Examples include, but are not limited to, design of next-generation miniature surface acoustic wave (SAW) filters, narrow-band actuators and sensors, vibration isolating barriers as well as seismic and explosive shields for vulnerable structures or even towns.



The wavenumber spectrum along the surface indicates that no Rayleigh waves are transmitted past where the change in boundary conditions occurs; i.e., the Mindlin BCs cause mode conversion to longitudinal and transverse waves and some reflection of the incident Rayleigh waves.

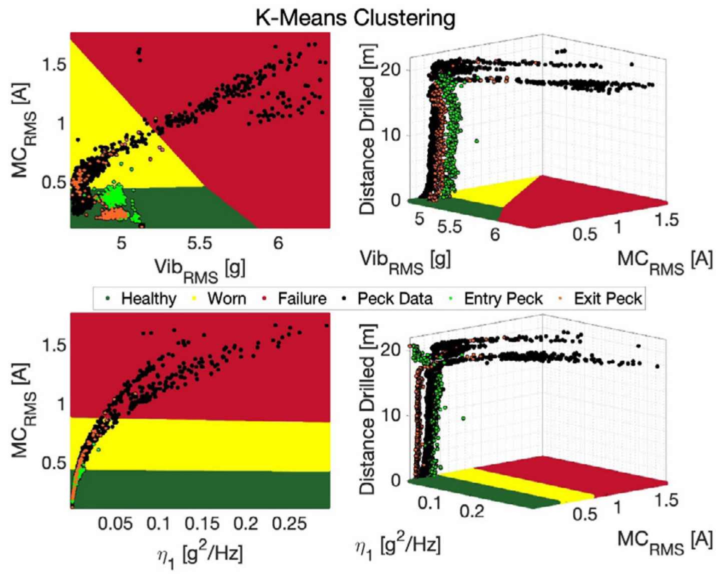
Machine Tool and Bearing Failure Analysis

Sponsor: Office of Naval Research ManTech Program

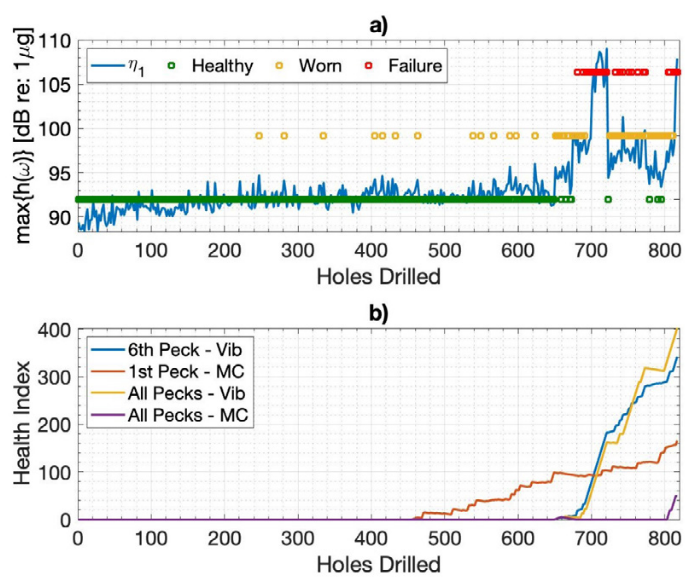
Principal investigators: Jeff Banks, Matt Rigdon, Karl Reichard

Students: Trent Furlong, Nick Carder

Summary: The orthogonal Hilbert-Huang transform (OHHT) is a recent improvement to the relatively new Hilbert-Huang transform (HHT) that is significantly more computationally efficient—compared to other improved HHT algorithms—and reduces the amount of energy leakage caused by non-orthogonal intrinsic mode functions. The HHT and its derivatives are being explored in CBM applications due to its adaptive nature in analyzing nonlinear and non-stationary phenomena, which is characteristic of machining induced vibrations. It has also shown promise in diagnosing machine tool wear from motor current signals compared to commonly used techniques such as wavelet analysis. A condition indicator, based on the OHHT were able to classify the health of a given machine component. An artificial neural network (ANN) for classifying the health of a given part was initially trained on a bearing dataset with success consistent with similar analyses in the literature. The same ANN was modified through transfer learning for use on a drilling dataset and showed similar success in predicting tool wear. These results strengthen the claim that the OHHT is applicable for general CBM applications.



Comparison of k-means clustering results using the RMS spindle motor current and the a) vibration RMS and b) η_1 from the vibration. The plots on the right contain the same information plotted over time.



a) Values of η_1 for the z-axis vibration data and the ANN predictions using the single peck model. b) Health index results for single peck and single hole models for the vibration and motor current data.

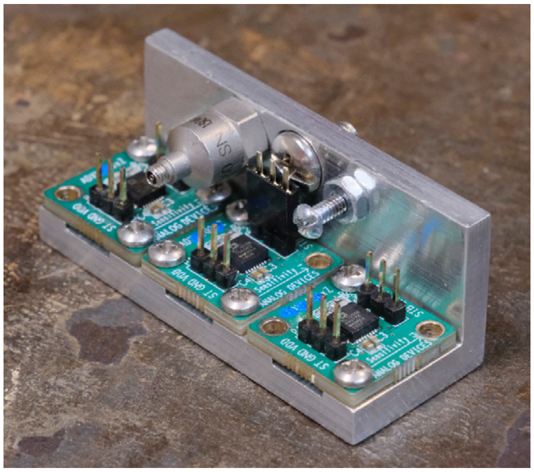
Fault Detection in a Physically Redundant MEMS Accelerometer Array

Sponsor: Office of Naval Research

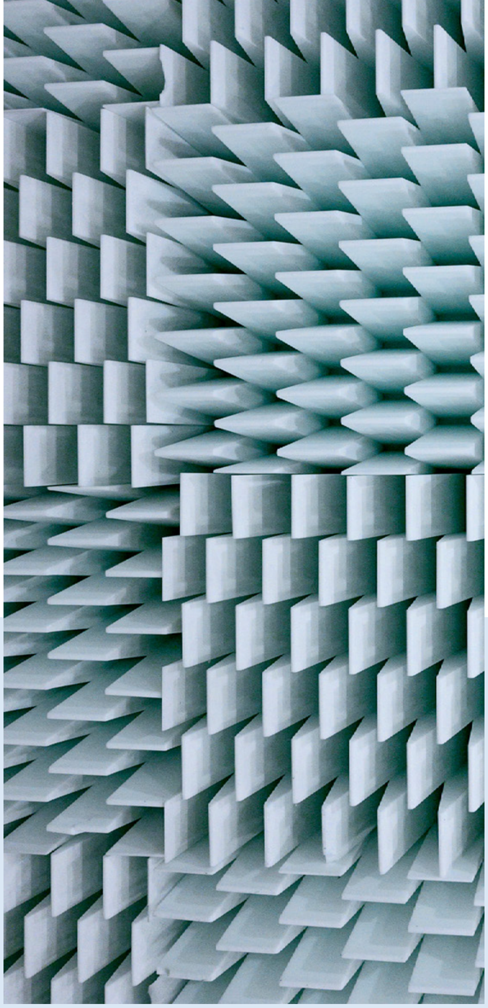
Principal investigator: Karl Reichard

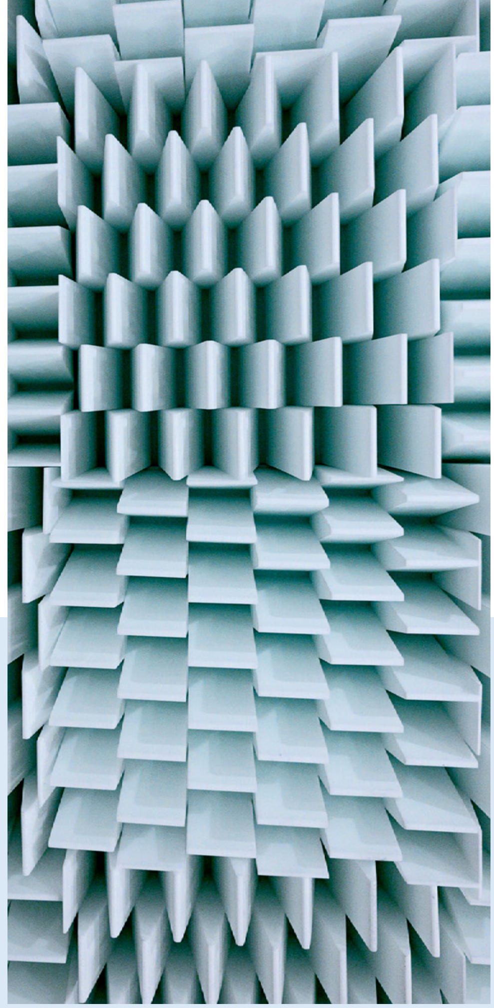
Student: Dan Watson

Summary: The latest generation micro-electro-mechanical system (MEMS) accelerometers offer high bandwidth and low noise floors previously limited to piezoelectric transducer (PZT) based sensors. These relatively low cost MEMS sensors drastically expand the financially practical applications for high frequency, vibration based, prognostic health management (PHM). This project is exploring the use of MEMS accelerometers in the detection of scuffing where and examining the use of redundant, co-located sensors to improve fault detection performance and overall sensor reliability. The research has demonstrated that single sensor faults can be detected using majority voting and computationally efficient cross-correlation calculations. Testing shows that the ADXL1005z evaluation boards are suitable for use with a common power supply with minimal impact to sensor output independence. Theoretical results for synthesized signals show that waveforms dominated by random noise or impulsive events produce sharp correlation peaks that are conducive to sensor fault detection. Analysis of real world datasets confirm the applicability of correlation for sensor fault detection. The physically redundant MEMS accelerometer array was used to collect impulse data and motor vibration data in healthy and faulted conditions. Results from array testing confirm that cross-correlation can be used to identify a single faulty sensor in an array of three physically redundant sensors. Ongoing work includes detection of individual sensor sensitivity drift and installing the physically redundant MEMS accelerometer array on tribology test equipment to detect the initiation of scuffing wear.



MEMS sensor and reference PZT accelerometer mounted on test fixture.





CAV Contact Info

Dr. Stephen A. Hambric
Research professor in acoustics
sah19@psu.edu

Dr. Cliff Lissenden
Professor of engineering science and mechanics
lissenden@psu.edu

www.cav.psu.edu

Diane Bierly
Editorial assistant in engineering science and mechanics
212 Earth and Engineering Sciences Building
814-863-6491 // dkb11@psu.edu

Kelly Driftmier
Workshop and corporate sponsor liaison
225 Penn State Conference Center
814-865-9202 // kmd5315@psu.edu

PennState College of Engineering

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