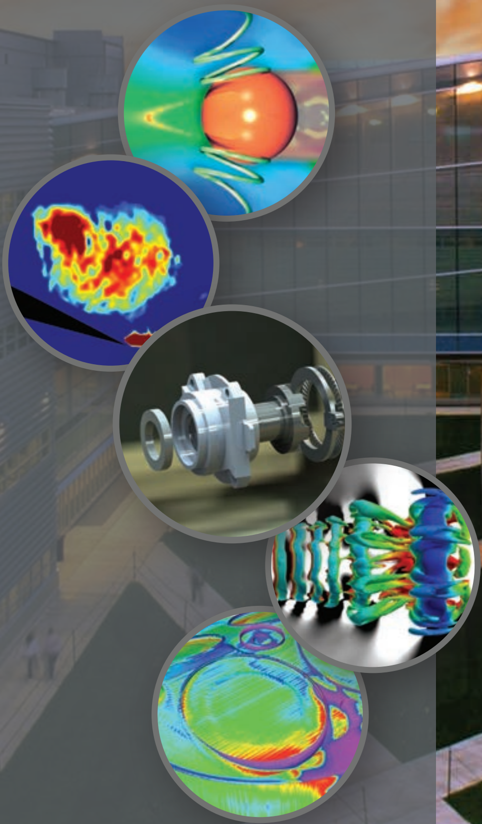
2015

RESEARCH NEWS

Department of Mechanical and Aerospace Engineering



IN THIS ISSUE

The Ohio State University

In contemplating the research accomplishments of our distinguished scholars over the past year, it comes as no surprise that in June 2015, Columbus, Ohio, was named the 2015 Intelligent Community of the Year by the Intelligent Community Forum (ICF), an international think tank headquartered in New York that studies the economic and social development of 21st century communities. Columbus was selected from more than 400 cities around the world following an evaluation process that included quantitative analysis of extensive data. Cities were judged on five indicators including innovation, knowledgeable workforce, broadband connectivity, digital inclusion, and marketing and advocacy.

Our faculty within the Department of Mechanical and Aerospace Engineering (MAE) at Ohio State are an integral part of this 21st century community, globally recognized for their research impact and scholarly achievements. They are innovators in engineering practice and leaders in their fields, sought after by industry, government and the broader community.

Perhaps most important, our faculty are dedicated teachers, equipping our graduates with a broader vision – and the lifelong skills to change the world.

In this issue of Research News, you will note how our faculty's research is addressing critical societal challenges that affect the quality of life, reflecting Ohio State's commitment as a land-grant research university and fulfilling our departmental mission of disseminating original knowledge and technology through the discovery of advanced solutions in mechanical, aerospace and nuclear engineering.

The MAE department's truly exceptional faculty continue explorations on their determined journey toward the generation of new knowledge, with far-reaching impact, for example, on cancer immunotherapy, environmental cleanups and magnetic control of heat and sound. *Simulation-driven discovery* in thermal transport at the nanoscale, enhancement of capability for automated modeling and simulation of problems with complex morphologies, and flow control in aerospace applications represent pioneering research across many disciplines. Our work with Chrysler in conducting novel experiments to understand in-cylinder heat transfer will enable design and operation of more knock-resistant, hence more fuel efficient spark-ignition engines. And, our faculty collaboration with The Simulation Innovation and Modeling Center (SIMCenter) for virtual simulation and modeling of product performance and manufacturing processes and development of new computer-aided engineering tools, is vital to regional, state and national economies to produce best-in-class products at competitive costs.

We proudly acknowledge Professor Bharat Bhushan for his leadership role on Capitol Hill as an American Society of Mechanical Engineers (ASME) Science and Technology Policy Fellow, informing the engineering profession on their ability to impact public policymaking. We congratulate Professor Blaine Lilly, elected to ASME Fellow status in 2015. Professor Rama Yedavalli and Associate Professor Jack McNamara, with their graduate students, received the 2015 Air Force Research Laboratory/Dayton Area Graduate Studies Institute Student-Faculty Research Fellowship, a significant honor. Our aerospace engineering research presented the third highest number of technical papers among 800 government, academic and private institutions in 40 countries at SciTech 2015, the largest aerospace conference in the world. And, Professor Datta Gaitonde and Rachelle Speth, PhD student, received ASME's Robert T. Knapp Award recognizing their outstanding paper. Professor Gaitonde was also named associate chair of our aerospace program, bringing his expertise to enhance our reputation. Finally, we congratulate faculty recently promoted including Raymond Cao, Manoj Srinivasan, Haijun Su and Shawn Midlam-Mohler and warmly welcome six top talents to our already impressive faculty ranks.

In summary, we recognize and celebrate all of our scholars who are embracing science, technology and innovation to solve important national and global problems, advancing engineering practice and paving the way for the brilliant students who will follow in the future.

AHMET SELAMET
Professor & Chair
Department of Mechanical and Aerospace Engineering

Scientists develop mesh that captures oil but lets water through

Bharat Bhushan, Ohio Eminent Scholar in Mechanical Systems (center), research assistant Dave Maharaj (left) and postdoctoral researcher Philip Brown (right) demonstrate new technology developed for separating oil from water. Photo by Jo McCulty, courtesy of The Ohio State University.

The unassuming piece of stainless steel mesh in a lab at The Ohio State University doesn't look like a very big deal, but it could make a big difference for future environmental cleanups.

Water passes through the mesh but oil doesn't, thanks to a nearly invisible oil-repelling coating on its surface. In tests, researchers mixed water with oil and poured the mixture onto the mesh. The water filtered through the mesh to land in a beaker below. The oil collected on top of the mesh and rolled off easily into a separate beaker when the mesh was tilted.

The mesh coating is among a suite of nature-inspired nanotechnologies under development at Ohio State and described in two papers in the journal *Nature Scientific Reports.* Potential applications range from cleaning oil spills to tracking oil deposits underground. "If you scale this up, you could potentially catch an oil spill with a net," said Bharat Bhushan, Ohio Eminent Scholar and Howard D. Winbigler Professor of Mechanical Engineering.

The work was partly inspired by lotus leaves, whose bumpy surfaces naturally repel water but not oil. To create a coating that did the opposite, Bhushan and postdoctoral researcher Philip Brown chose to cover a bumpy surface with a polymer embedded with molecules of surfactant – the stuff that gives cleaning power to soap and detergent. They sprayed a fine dusting of silica nanoparticles onto the stainless steel mesh to create a randomly bumpy surface, and layered the polymer and surfactant on top. "The silica, surfactant, polymer and stainless steel are all non-toxic and relatively inexpensive," said Brown. He estimated that a larger mesh net could be created for less than one dollar per square foot.

Because the coating is only a few hundred nanometers (billionths of a meter) thick, it is mostly undetectable. To the touch, the coated mesh doesn't feel any bumpier than uncoated mesh. The coated mesh is a little less shiny, though, because the coating is only 70 percent transparent.

The researchers chose silica in part because it is an ingredient in glass, and they wanted to explore this technology's potential for creating smudge-free glass coatings. At 70 percent transparency, the coating could work for certain automotive glass applications, such as mirrors, but not most windows or smartphone surfaces. "Our goal is to reach a transparency in the 90 percent range," Bhushan said. "In all our coatings, different combinations of ingredients in the layers yield different properties. The trick is to select the right layers." Certain combinations of layers yield nanoparticles that bind to oil instead of repelling it. Such particles could be used to detect oil underground or aid removal in the case of oil spills.

This work began more than 10 years ago, when Bhushan began building and patenting nano-structured coatings that mimic the texture of the lotus leaf. From there, he and his team have worked to amplify the effect and tailor it for different situations. "We've studied so many natural surfaces, from leaves to butterfly wings and shark skin, to understand how nature solves certain problems," Bhushan said. "Now we want to go beyond what nature does in order to solve new problems."

"Nature reaches a limit of what it can do," agreed Brown. "To repel synthetic materials like oils, we need to bring in another level of chemistry that nature doesn't have access to."

The research was partly funded by the American Chemical Society Petroleum Research Fund, the National Science Foundation and Dexerials Corporation, formerly a division of Sony Corp. in Japan.

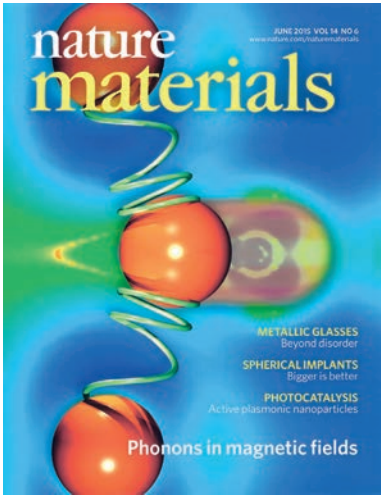
Landmark study proves that magnets can control heat and sound

Researchers at The Ohio State University have discovered how to control heat with a magnetic field.

In the June 2015 issue of the journal *Nature Materials,* they describe how a magnetic field roughly the size of a medical MRI reduced the amount of heat flowing through a semiconductor by 12 percent. The study is the first ever to prove that acoustic phonons – the elemental particles that transmit both heat and sound – have magnetic properties.

“This adds a new dimension to our understanding of acoustic waves,” said Joseph Heremans, Ohio Eminent Scholar and professor of Mechanical Engineering at Ohio State. “We’ve shown that we can steer heat magnetically. With a strong enough magnetic field, we should be able to steer sound waves, too.”

Heremans acknowledged that people might be surprised enough to learn that heat and sound have anything to do with each other, much less that either can be controlled by magnets. But both are expressions of the same form of energy, quantum mechanically speaking. So any force that controls one should control the other. “Essentially, heat is the vibration of atoms,” he explained. “Heat is conducted through materials by vibrations. The hotter a material is, the faster the atoms vibrate.” “Sound is the vibration of atoms, too,” he



continued. “It’s through vibrations that I talk to you, because my vocal chords compress the air and create vibrations that travel to you, and you pick them up in your ears as sound.”

The name “phonon” sounds a lot like “photon.” That’s because researchers consider them to be cousins: Photons are particles of light, and phonons are particles of heat and sound. But researchers have studied photons intensely for a hundred years – ever since Einstein discovered the photoelectric effect. Phonons haven’t received as much attention, and so not as much is known about them beyond their properties of heat and sound. This study shows that phonons also have magnetic properties. “We believe that these general properties are present in any solid,” said Hyungyu Jin, Ohio State postdoctoral researcher and lead author of the study.

The implication: In materials such as glass, stone, plastic – materials that are not conventionally magnetic – heat can be controlled magnetically, if you have a powerful enough magnet. The effect would go unnoticed in metals, which transmit so much heat via electrons that any heat carried by phonons is negligible by comparison. There won’t be practical applications of this discovery any time soon: 7-tesla magnets like the one used in the study don’t exist outside of hospitals and laboratories, and the semiconductor had to be chilled to -450 degrees Fahrenheit (-268 degrees Celsius), very close to absolute zero, to make the atoms in the material slow down enough for the phonons’ movements to be detectible, making the experiment even more difficult. Taking a thermal measurement at such a low temperature was tricky. Jin’s solution was to take a piece of the semiconductor indium antimonide and shape it into a lopsided tuning fork. One arm of the fork

Joseph Heremans, Ohio Eminent Scholar, holds an artist's rendering of a phonon heating solid material. Artist's rendering by Renee Ripley. Photo by Kevin Fitzsimons, courtesy of The Ohio State University.

This adds a new dimension to our understanding of acoustic waves. We've shown that we can steer heat magnetically. With a strong enough magnetic field, we should be able to steer sound waves, too.

— JOSEPH HEREMANS
Ohio Eminent Scholar

was 4 mm wide and the other 1 mm wide. He planted heaters at the base of the arms. In the experiment, Jin measured the temperature change in both arms of the tuning fork and subtracted one from the other, both with and without a 7-tesla magnetic field turned on.

In the absence of the magnetic field, the larger arm on the tuning fork transferred more heat than the smaller arm, just as the researchers expected. But in the presence of the magnetic field, heat flow through the larger arm slowed down by 12 percent.

In the larger arm, the freedom of movement worked against the phonons – they experienced more collisions. More phonons were knocked off course, and fewer – 12 percent fewer – passed through the material unscathed.

The phonons reacted to the magnetic field, so the particles must be sensitive to magnetism, the researchers concluded. Next, they plan to test whether they can deflect sound waves sideways with magnetic fields.

Co-authors on the study included Stephen Boona, a postdoctoral researcher in mechanical and aerospace engineering; and Roberto Myers, an associate professor of materials science and engineering, electrical and computer engineering and physics.

Funding for the study came from the U.S. Army Research Office, the U.S. Air Force Office of Scientific Research and the National Science Foundation (NSF), including funds from the NSF Materials Research Science and Engineering Center at Ohio State. Computing resources were provided by the Ohio Supercomputer Center.

Heat Transfer and Knock in Engines

Spark-Ignition (SI) engines powered 93 percent of light duty vehicles produced in North America in 2014, yet the ability to increase their efficiency through strategies such as boosting or raising the compression ratio is limited by knock. Knock, or the autoignition of the fuel and air mixture ahead of the flame front, is dictated by chemical kinetics and the rates of the reactions leading to autoignition are determined by the Boltzmann factor, which is exponentially dependent on the local gas temperature. The gas temperature is a function of both the heat release from combustion and the in-cylinder heat transfer. Therefore, to predict knock, it is necessary to accurately model the in-cylinder heat transfer process. Professor Ahmet Selamet and his team at The Ohio State University's Center for Automotive Research are conducting fundamental experimental and computational research to improve the understanding of in-cylinder heat transfer in order to enable the design and operation of more fuel efficient SI engines.

Figure 1. Heat flux microsensor surface.

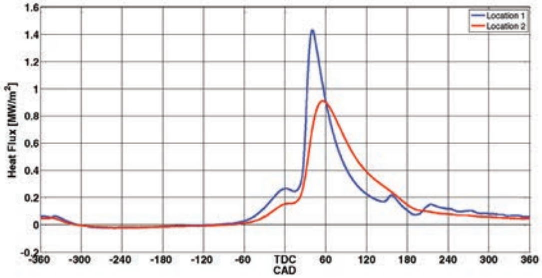


Figure 2. Heat flux measured at 2 different sensor locations (100 cycle average).

Using a novel experimental setup supported by FCA US LLC, time-resolved in-cylinder heat transfer measurements have been performed with a production Chrysler 2.0L I4 engine using Vatell Heat Flux Microsensors (HFMs) over a variety of operating conditions where knock is of greatest concern. The HFMs installed in the engine cylinder (Fig. 1) use thin-film thermopiles to measure heat transfer and temperature with a time constant of only 17 µs, allowing for the characterization of the temporal (Fig. 2) and spatial variation of heat transfer throughout the combustion chamber, while also shedding light on the cyclic variation of heat transfer. These data, coupled with time-resolved pressure measurements in the cylinder and throughout the engine's breathing system, facilitate a thorough analysis of engine performance, as well as the development and validation of a detailed three-dimensional Computational Fluid Dynamics (CFD) model of the engine in-cylinder/port processes.

Professor Ahmet Selamet and his team at The Ohio State University's Center for Automotive Research are conducting fundamental experimental and computational research to improve the understanding of in-cylinder heat transfer to enable the design and operation of more fuel efficient SI engines.

Modeling the engine cycle through CFD provides much needed insight into the in-cylinder flow physics and thermal boundary layer growth which ultimately drive heat transfer at the combustion chamber walls (Fig. 3). The CFD simulations are performed in CONVERGE capable of automatic mesh generation and adaptive mesh refinement in regions of sharp temperature and velocity gradients. A multi-zone chemical kinetics based solver is employed to model the heat release due to combustion. The Ohio Supercomputer Center has been generously providing the resources to meet the stringent demands of these computations.

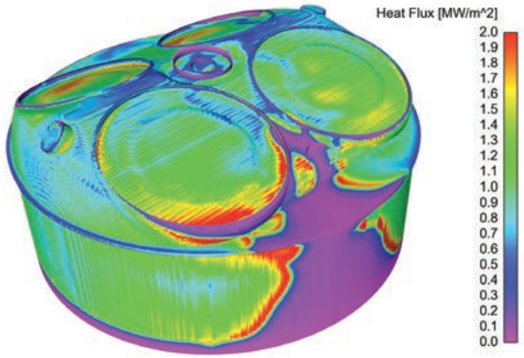


Figure 3. Predicted spatial variation of heat flux on combustion chamber walls at an instant.

The knowledge gained from the engine experiments and CFD simulations are being used to develop a new in-cylinder heat transfer correlation based on the fundamental principles of turbulence physics. This validated correlation, when implemented into quasi-one-dimensional engine simulation codes, will facilitate accurate predictions over a wide range of engine operating conditions, including in-cylinder gas temperatures, thereby leading to a reliable knock model for SI engines. ✣

Success of Flow Control in Aerospace Applications Using Small-Amplitude Perturbation-Based Actuation

Fluid flows are ubiquitous in many engineering applications, especially aerospace, as well as in nature. Over the past several decades, tremendous research effort has gone into the development and implementation of flow control techniques to improve the beneficial effects and/or reduce the detrimental effects of fluid flows. The nature of the flow control technique used in an application depends on several factors, including the flow physics, Mach number and Reynolds number.

Control techniques generally fall into one of two categories: passive or active. Passive control almost always involves geometric modifications; for example, vortex generators on the wing of an aircraft for flow separation control or chevrons on the exhaust nozzle of jet engine for noise mitigation. Passive control devices affect the flow, regardless of whether they produce a beneficial or detrimental effect, depending upon the flow/flight regime. Active flow control, on the other hand, involves energy or momentum addition to the flow in a regulated manner, and therefore can be turned 'on' or 'off' on command as needed, and thus it is more desirable. This saves energy and could avert any potential detrimental effects, but involves significant additional effort and cost.

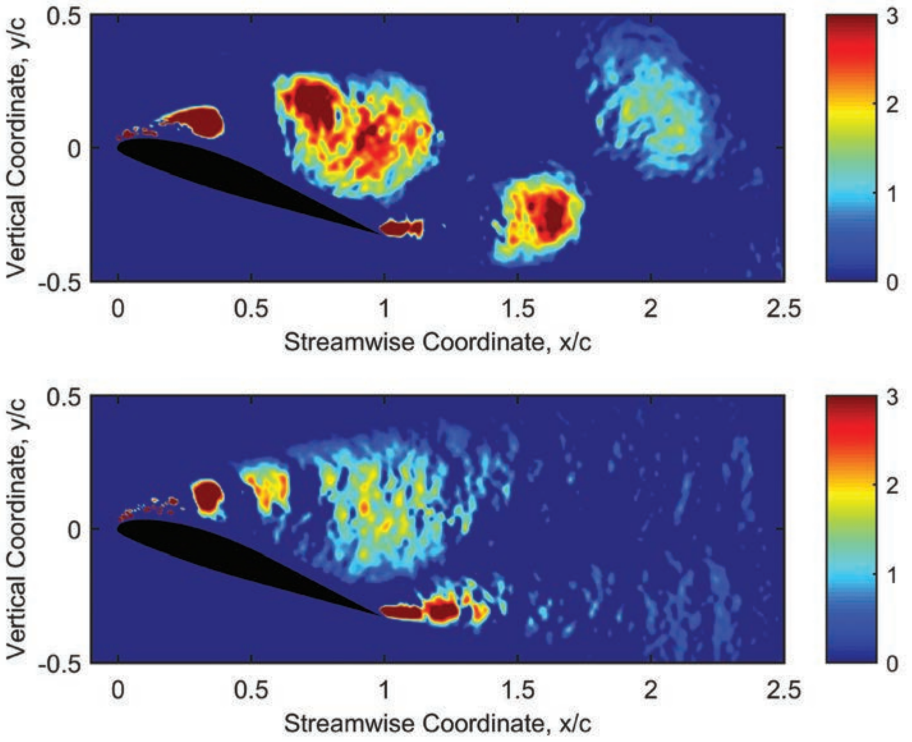
The actuators are at the heart of active flow control implementation and have been the weakest link in flow control technology development. Some of the desired attributes of actuators include: light weight, low profile, no moving parts, energy efficiency, durability, scalability, high amplitude, wide bandwidth and rapid response. Advanced plasma actuators possess many of these attributes and researchers at The Ohio State University have been pioneers in their development.

Over the past two decades, there has been considerable interest and research in the use of plasma actuators for flow control. The two primary mechanisms of plasma-based flow control include generation of a body force (i.e. momentum-based control) using either electrohydrodynamic or magnetohydrodynamic interactions, and thermal (or Joule) heating; primarily small-amplitude perturbation-based control. While the field is still evolving, there are currently several actuators at various stages of development and use. Momentum-based actuators have proven effective in low speed and low Reynolds number flows, which exclude many aerospace applications. On the other hand, perturbation-based control, which uses natural instabilities of the flow and thus requires small energy input, has shown tremendous success in many different aerospace applications over a large range of flow speeds and Reynolds numbers. Demonstrated applications include: subsonic or supersonic jets (for noise mitigation or observability), cavity flows (in landing gear or weapons bays), and flows over an aircraft wing or a rotorcraft blade (for lift and drag control). Several MAE faculty at Ohio State's Aerospace Research Center are at the forefront of flow control research and have made tremendous contributions to the field of flow control.

Several MAE faculty at Ohio State's Aerospace Research Center are at the forefront of flow control research and have made tremendous contributions to the field of flow control.

Several classes of flows in aerospace applications contain natural instabilities. Theoretical work in identifying such instabilities began in the late 1950s and significant experimental work in manipulation of these instabilities was carried out starting in the 1970s. However, the actuators were primarily based on acoustic drivers, which have wide bandwidth but limited amplitude and thus have limited effectiveness in aerospace applications. In order to expand the effective operational envelope, actuators were required with a wide bandwidth but also large amplitude.

We currently use two types of high amplitude and wide bandwidth plasma actuators in various projects sponsored by the Air Force Office of Scientific Research (AFOSR), Office of Naval Research (ONR), Army Research Office (ARO) and the Air Force Research Laboratory (AFRL): localized arc filament plasma actuators (LAFPAs) that have been developed at Ohio State and nanosecond dielectric barrier discharge (NS-DBD) plasma actuators. The LAFPAs are used when localized actuation is required and the second option when distributed actuation would be more effective. At right are two phase-locked images (obtained using particle image velocimetry) for controlled flow over an advanced Boeing VR-7 airfoil that could be used in an aircraft or rotorcraft. The flow responds to the control over a large range of normalized frequencies. In the top



Control of flow over a Boeing VR-7 airfoil: excited at a normalized natural shedding frequency of 0.6 (top); excited at a much higher normalized frequency of 3.45 (bottom).

image, the reduced frequency of excitation is near the natural shedding frequency of 0.6. In this case the control has synchronized the shedding of large-scale vortices from the leading and trailing edges of the airfoil. In the bottom image, the reduced frequency of excitation is 3.45 (nearly 6 times the natural shedding frequency), the structures are significantly smaller, and leading and trailing edge vortices are no longer synchronized. The measurements show that the lift to drag ratio for the two cases are similar and significantly increased in comparison with the uncontrolled case, but the coefficient of momentum is significantly lower in the high frequency excitation. This is a major benefit in many rotorcraft applications. ✣

Weak Induced Electric Fields Shown to Hinder Migration of Metastatic Cancer Cells

Migration of cells is important in many biomedical applications including embryonic development, wound healing and metastasis of cancer. Cells migrate in response to chemical, mechanical and electrical stimuli (galvanotaxis or electrotaxis). Certain molecules known as chemokines and growth factors promote cell migration, which is typically studied *in vitro* using assays (Boyden chamber or transmembrane assay and scratch assay). Electrotaxis is typically studied in planar culture plates by applying external electric fields (~1 V/cm – 10 V/cm) using electrodes connected to the medium containing the cells using agar salt bridges. Existing methods are susceptible to contamination and non-negligible Ohmic heating. Our researchers have developed novel methods to weaken induced electric fields (iEFs) in a non-contact manner in these traditional assays (***Scientific Reports 5***, 11005, 2015) using time-varying magnetic fields. By inducing electric fields as much as a million times smaller (~10^{-5} – 10^{-6} V/cm) than ever demonstrated before, migration of metastatic cancer cells is hindered even in the presence of a chemokine or growth factor. Our approach advances the state-of-the-art in applying electric fields to tissues and cells, which has remained largely unchanged over the past century. This method has widespread implications for manipulating cells *in vitro* or *in vivo,* and has the potential to extend to therapeutics in arresting metastasis, accelerating wound healing and driving differentiation of stem cells.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OPEN Non-contact method for directing electrotaxis

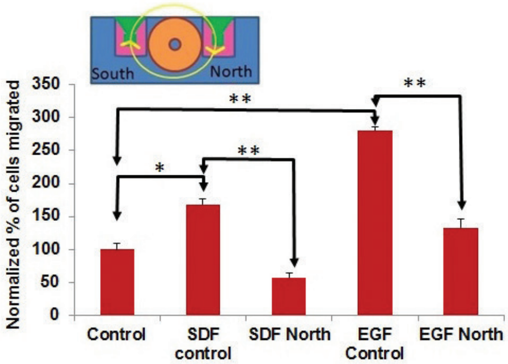
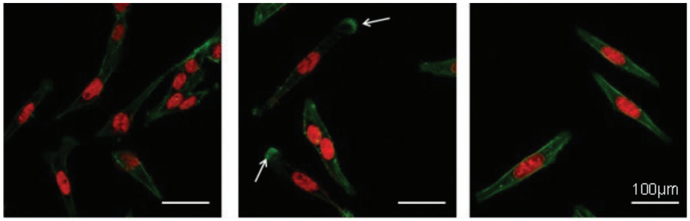


Fig. 1: Experimental results for highly metastatic breast cancer cells showing hindrance of their migration due to an induced electric field in a specific direction, even in the presence of a chemokine or growth factor. Statistical significance is denoted by '' ($0.01 \leq p < 0.05$) and '**' ($0.001 \leq p < 0.01$).*

Figure 1 illustrates results of migration experiments conducted on a highly metastatic breast cancer cell line (SCP2) using our modified Boyden chamber assay with an induced electric field, and in the presence of the chemokine SDF-1α (also known as the ligand CXCL12α, it is over-expressed in many malignant cancers including those of the breast, prostate, ovary, pancreas, colon and rectum) or EGF (epidermal growth factor). EGF is known to play a role in cell proliferation, apoptosis (programmed cell death) and tumorgenesis, and is also known to enhance cell migration and invasion. The normalized migration data (Fig. 1) indicate that cell migration, even in the presence of a chemokine or growth factor, is hindered when iEFs are applied primarily in a preferred direction.



SCP2 Control SCP2 EGF 1hr SCP2 EGF 1hr+induced E field

Fig. 2: (left panel) actin cytoskeleton in SCP2 cells in the absence of both EGF and iEF. (center panel) actin cytoskeleton with EGF alone. The white arrows indicate regions of polymerization of actin filaments signifying cellular movement or preparation for movement in response to the growth factor. (right panel) actin cytoskeleton with EGF and an iEF.

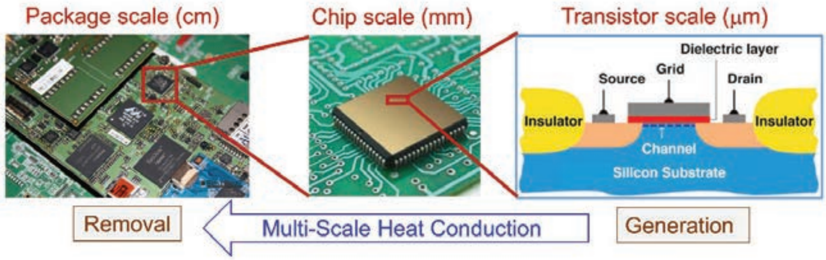
Figure 2 illustrates the actin cytoskeleton of SCP2 cells. In the control case (no iEF and no EGF), there is little polymerization of actin filaments and no discernible preferential direction of formation of filopodia (finger-like projections typically observed when cells begin to migrate). In contrast, in the presence of the growth factor EGF, polymerization of actin filaments can be observed at one end of some cells. In the presence of both an iEF and EGF, actin polymerization can be seen throughout the cells with no preferential direction and inhibition filopodia formation. These results suggest that the iEF is interfering with directional polymerization of actin filaments and with the electrostatic binding interactions between ligands (SDF-1α) and receptors (CXCR4), and growth factors (EGF) and their corresponding receptors (EGFR). This is a profound result as recent studies have shown that disruption of the SDF signaling pathway can prevent metastasis and improve patient outcomes when solid tumors are then treated with radiation or chemotherapy.

Our ongoing research collaborations collectively suggest that electrostatic interactions governing cell migration, cellular signaling, cell differentiation and activity of certain enzymes may all be manipulated using externally induced electric fields.

Our recently reported results (***Scientific Reports* 5,** 11005, 2015, and **PLOS one 9**(3), e89239, 2014) and ongoing research collaborations with Assistant Professors Jonathan Song and Shaurya Prakash in Mechanical Engineering, Professors Ramesh Ganju, Sashwati Roy, Chandan Sen and Rene Anand in the College of Medicine, and Professor Venkat Gopalan in Chemistry & Biochemistry collectively suggest that electrostatic interactions governing cell migration, cellular signaling, cell differentiation and activity of certain enzymes may all be manipulated using externally induced electric fields. ✣

***Scientific Reports** is an online, open access journal from the publishers of Nature. Read the full report at **http://www.nature.com/articles/srep11005**.*

Understanding Thermal Transport in Semiconductor Nanostructures



Hierarchy of length scales in thermal transport in semiconductor devices.

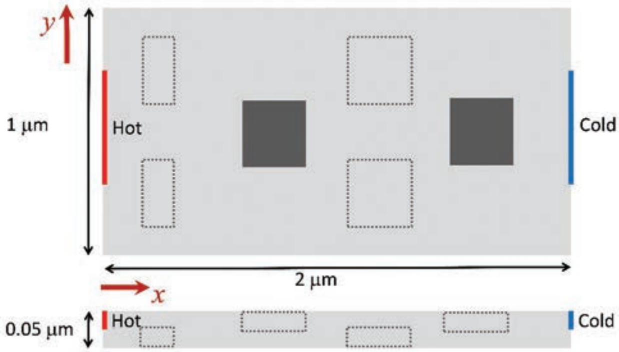
Today, high-end integrated circuits contain in excess of four billion transistors. The volumetric heat generation rate in such devices (~2.4 kW/cm^3) is comparable to that of nuclear fission. Overheating is the most common cause of device failure and thermal management is the biggest challenge for further miniaturization of electronic and optoelectronic devices.

Current thermal management strategies focus on removing heat at the macroscale (or package scale) as evidenced by the use of fans within our laptop or desktop computers. Unfortunately, the heat is not generated at this length scale, but rather, at the nanoscale (or transistor scale). Therefore, understanding thermal transport at the transistor scale is a prerequisite to designing smart thermal management strategies.

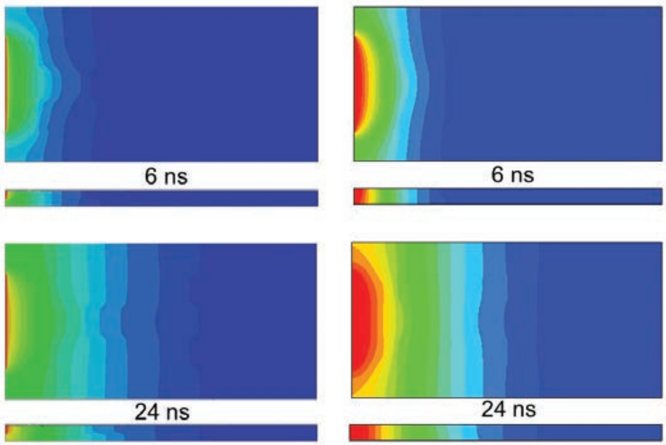
Experimental investigation of heat transport at the transistor scale is difficult. At the nanoscale, at best, one can measure the thermal conductance of thin films. For understanding beyond that, one must resort to fundamental physics-based models. Such models can predict the spatio-temporal evolution of temperature and heat flux within the device in question.

Modeling heat conduction at the nanoscale is challenging. The dominant carriers of energy in semiconductors are vibrational waves referred to as phonons. The average mean free path of phonons in most semiconductors – silicon, for example – is ~100 nm. In comparison, critical geometric features in modern-day transistors are ~10 nm, implying that the continuum assumption – and associated continuum laws for heat conduction – namely, the Fourier law – break down at these extreme length scales. One way to model non-equilibrium (non-continuum) heat conduction is to solve the Boltzmann Transport Equation (BTE) for phonons.

Unlike the four-dimensional partial differential equations encountered typically in classical transport phenomena, the BTE is a seven-dimensional partial differential equation. Its solution is extremely challenging both from a memory as well as computational time standpoint. Over the past two decades, Professor Sandip Mazumder and his group have developed algorithms for solution of the phonon BTE using both stochastic and deterministic methods. His seminal paper, co-authored by Professor Arun Majumdar of Stanford University, on solution of the BTE using the Monte Carlo method has received more than 300 citations. Advanced parallel algorithms for deterministic solution of the phonon BTE have also been recently developed by his group and continue to be explored. These algorithms enable simulation of non-equilibrium heat conduction in full three-dimensional heterostructures – computations that require solution of systems of equations with more than 10 billion unknowns. The work has been supported by the Department of Energy, the National Science Foundation (NSF) and the Ohio Supercomputer Center.



Schematic (plan and elevation) of a heterostructure with embedded Germanium blocks in a Silicon substrate.



Predicted spatio-temporal evolution of the temperature (Red = 400K, Blue = 300K) inside the heterostructure shown above via solution of the phonon BTE (left) and the Fourier law (right). The differences highlight non-equilibrium heat transport phenomena at these small scales.

The research is a prime example of how diverse disciplines (namely solid state physics), heat transfer, applied mathematics and computer science have intertwined to create a simulation platform that can significantly enhance our current understanding of thermal transport at the nanoscale. This is what the NSF refers to as simulation-driven discovery.

An Automated Computational Approach for the Treatment of Problems With Complex Geometries

The Finite Element Method (FEM) is one of the most widely used numerical techniques for the analysis and computational design of engineering structures and materials systems. Recent advances in computing power has enabled modeling problems with several hundred millions of degrees of freedom. Furthermore, a large body of research has been dedicated to the development of more accurate, more stable and faster algorithms for FEM simulations. Despite such advances, the labor cost associated with creating FEM models has not been considerably improved over past decades. This process involves two major tasks: (i) creating a computer aided design (CAD) drawing of the problem geometry, and (ii) creating a finite element mesh that matches (conforms to) the geometrical model boundaries and its materials interfaces. In the automotive and aerospace industries, these tasks often comprise 80 percent of the computational design process and only 20 percent of the time is spent on the simulation and post-processing.

The main focus of research in Professor Soheil Soghrati's group is on the development and implementation of new numerical techniques for the automated modeling of problems with complex morphologies. Such methodologies can significantly decrease the development time of the computational model, which reduces both the labor cost and the probability of human error during this process. Moreover, for problems such as heterogeneous and composite materials, the intricate microstructure of the problem can prohibit the straightforward application of the standard FEM. Even with the use of sophisticated commercial software packages, creating realistic microstructural models of such problems and discretizing them using appropriate finite element mesh could be extremely difficult or practically impossible in some cases.

The automation of the modeling process requires a combination of multiple disciplines of the computational science and high performance computing. The first step of this approach is to implement a more advanced numerical technique that obviates the burden of creating conforming finite element meshes. To accomplish this objective, Soghrati's team has recently developed a hierarchical interface-enriched FEM (HIFEM), which yields the same precision as the standard FEM but using simple structured grids that are completely independent of the problem morphology for discretizing the complex multi-phase problem. This is accomplished by adding special enrichment functions to the approximate field to simulate the discontinuous phenomena (e.g., stress discontinuities) emanating from mismatch between material properties. Figure 1 illustrates some of the modeling capabilities of the HIFEM in Soghrati's group.

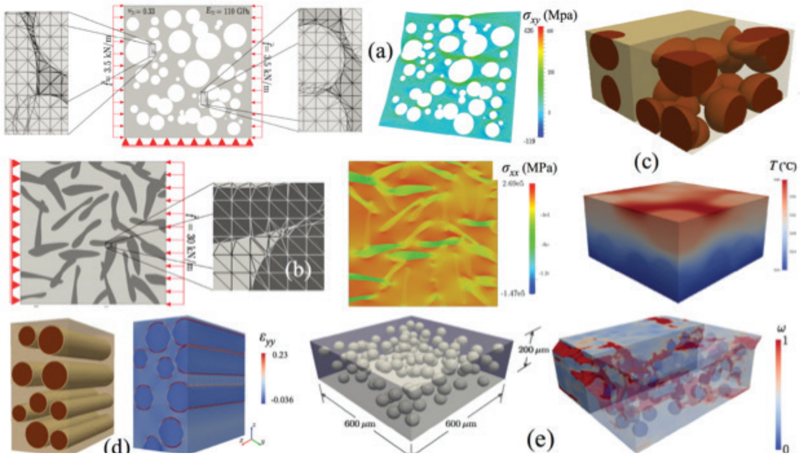


Figure 1: HIFEM simulation of the thermal and structural responses of problems discretized using simple structured girds: (a) stress concentrations in a porous titanium; (b) stress field in a random fiber composite; (c) thermal response of a particulate composite; (d) strain field in a ceramic matrix composite; (e) damage path in a heterogeneous adhesive (ω indicates extent of damage in the composite matrix).

The automated construction of HIFEM models requires the use of advanced computational geometry algorithms for determining the location of materials interfaces and evaluating the enrichment functions. Although this leads to a higher simulation time than that of a similar standard FEM analysis, this increase in the computational cost is negligible compared to the significant reduction in the time and labor cost associated with creating the FEM model. To automatically model heterogeneous materials with complex microstructures, Soghrati's group has also integrated the HIFEM solver with a new microstructure quantification algorithm. This algorithm uses morphological features of embedded particles extracted from a set of digital data such as micro-computed tomography (μCT) images to create realistic microstructural models of the material. Figure 2 illustrates the application of this method for creating multiple models of the representative volume element (RVE) of a heterogeneous adhesive with different volume fractions. The HIFEM simulation of the damage evolution in 2D and 3D models of this adhesive RVE are depicted in Figure 3.

The ultimate goal of this ongoing research is to further enhance the capability for automated modeling and simulation of problems with more than one billion degrees of freedom.

High performance computing is another key component of the automated modeling pipeline developed in Soghrati's group. For example, the large number of geometric calculations required for creating the HIFEM models shown in Figure 2 (>120 million degrees of freedom) cannot be treated efficiently without the parallel computing capacity. Furthermore, simulating the mechanical behavior (e.g., damage response) of such problems would be practically impossible on a single processor. Thus, Soghrati's team has developed a fully parallel computing paradigm for the automated treatment of such large-scale problems in multi-processor environments. This capability has been implemented to simulate the damage propagation in the adhesive RVE shown in Figure 3(b) using 360 processors and 2,160 MB of RAM. The ultimate goal of this ongoing research is to further enhance the capability for automated modeling and simulation of problems with more than one billion degrees of freedom.

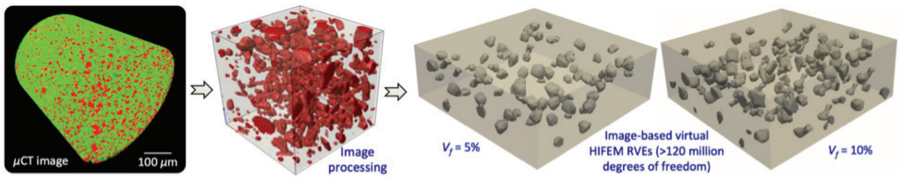


Figure 2: Application of the automated microstructure quantification algorithm for creating realistic HIFEM models of a heterogeneous adhesive based on the information extracted from micro-CT images.

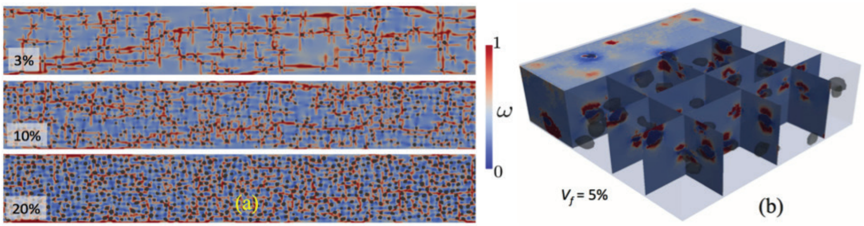


Figure 3: HIFEM simulations of damage evolution in (a) various 2D models and (b) 3D virtual models of a heterogeneous adhesive (ω indicates the extent of damage, 0: intact material, 1: fully damaged).

Ideas to Innovation – Taking the Lead

MAE faculty hosted four major international conferences in 2015, bringing together experts in biomechanics, dynamic walking and dynamic systems and control.

It is no coincidence that in the past six months alone, MAE faculty in various disciplines have taken leadership roles in hosting or co-hosting national and/or international conferences in Columbus, Ohio, bringing together brilliant minds from across the globe to confer on topics such as principles and concepts of legged locomotion; biomechanics, dynamic systems and control; and developments in the fields of engine and powertrain control and modeling.

“Collectively, it is an unusually high number of conferences for one department to host in one year,” said Ahmet Selamet, professor and chair. “That speaks to the overall strength of our department in a large number of fields.”

MAE’s faculty go beyond the classroom as experts in science and engineering, bringing real-world learning opportunities to our students and enhancing collaboration to bring innovation and discovery to critical research areas. Here are just a few examples:

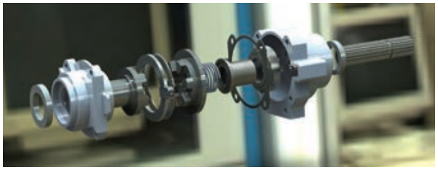
The Dynamic Walking Conference was held July 21-24, 2015 on the campus of The Ohio State University, hosted by Associate Professor Manoj Srinivasan. The conference focused on the fundamental principles underlying legged locomotion and other dynamic movements of animals and robots, bringing together international researchers from 10 countries who study human and animal locomotion, as well as those who design and build legged robots, prosthetic devices and exoskeletons. Srinivasan’s Movement Lab at Ohio State seeks to understand the basic principles behind such movement.

The Hyatt Regency in downtown Columbus, Ohio, was the location for **The 39th Annual Meeting of the American Society of Biomechanics (ASB)** on August 5-8, 2015, whose membership represents the broad interplay between mechanics and biological systems. MAE's Associate Professor Rob Siston served on the organizing committee of the four-day conference, attended by a record number of more than 930 ASB members. Associate Professor Ajit Chaudhari was the conference chair. Attendees toured several biomechanics labs on campus, and symposia by national leaders in the field of biomechanics were offered on topics such as "Changing the Landscape of Injury Prevention" and "Grand Challenges in Upper Limb Biomechanics." Major industry and exhibit sponsors included AMTI, OptiTrack, Qualisys, Motion Analysis, Vicon and Motekforce Link. The conference spotlight sponsor was Bertec, a local company headed by MAE's Faculty Emeritus Necip Berme.

Ohio State's Center for Automotive Research (CAR) and SIMCenter hosted the **International Federation of Automatic Control's (IFAC) E-COSM 2015 Conference** on August 23-26. Sponsored by GM, Honda and Cummins, E-COSM 2015 offered academic and industrial researchers and practitioners working in the automotive control sector an opportunity to meet and exchange ideas through a variety of organized workshops. Hosted by MAE Professor and Ford Motor Company Chair Giorgio Rizzoni, Assistant Professor Marcello Canova and Associate Clinical Professor Shawn Midlam-Mohler, the conference was held at The Blackwell Inn and Conference Center on the campus of Ohio State's Fisher College of Business, attended by more than 175 participants from around the world.

October 28-30, 2015 is the date for the **American Society of Mechanical Engineers (ASME) Dynamic Systems and Control (DSC) Conference** at the Hilton Hotel in downtown Columbus, hosted by Professor and Ford Motor Company Chair Giorgio Rizzoni, general chair; Professor Rama Yedavalli, program chair; Professor K. (Cheena) Srinivasan, exhibits and industry chair; and Assistant Professor Marcello Canova, students and young members chair. The DSC Conference is the showcase technical forum of the ASME Dynamic Systems and Control Division, providing an opportunity for dissemination and discussion of state-of-the-art dynamic systems and control research with a mechanical engineering focus. Sponsored by ASME, the conference includes a variety of sessions, workshops and exhibits. *Mechanical Engineering Magazine*, the award-winning monthly flagship publication of ASME, is the media sponsor.

Interdisciplinary Research-Introducing the SIMCenter



The SIMCenter may be one of the newest research centers on campus, but it's already tackling many computational simulation and modeling research projects and living up to the high standards set by Honda R&D Americas, Inc.

The Simulation Innovation and Modeling Center (SIMCenter), launched in early 2014 with a $5 million gift from Honda, has a mission of advancing computer-aided engineering techniques in research, design and manufacturing in industry with a focus on transportation. Located in Smith Laboratory at The Ohio State University, the SIMCenter combines expertise from several College of Engineering departments including mechanical, aerospace, electrical and industrial engineering, materials science, computer science and a unique partnership with the Ohio Supercomputer Center.

The SIMCenter evolved from Honda's need to respond to a quickly changing automotive industry. Shorter production times resulted in increased costs to build vehicle prototypes, so Honda's engineers looked for a way to eliminate expensive prototypes through computer simulation.

Noticing a shortage in the development of computer-aided engineering tools and the engineers who operate them, Honda looked to Ohio State. "Honda has a continual drive to increase the efficiency of its vehicle development process," said Allen Sheldon, manager and principal engineer with Honda's Strategic Research Division and liaison to Ohio State's SIMCenter. "At the same time, we're very committed to providing new and innovative vehicle designs for our customers."

Sheldon says a key mechanism in reaching both goals is to increase the application of advanced computer-aided engineering (CAE) tools during product development. The desire for rapid advancement in CAE tools inspired Honda to support expansion in this research area, collaborating with Ohio State. Thus, the SIMCenter was born.

Professor Rob Lee, director, and Associate Clinical Professor Shawn Midlam-Mohler, associate director, hand-picked staff and a team of researchers from various disciplines at the College of Engineering as advisors. Research focuses on six thrust areas: solid mechanics, fluid mechanics, optimization, digital manufacturing, multi-physics and system integration.

To provide the power necessary to run sophisticated software tools, the SIMCenter partnered with the Ohio Super-computing Center to harness high-speed networks using an infrastructure that emulates state-of-the-art networks present in industry, providing a real-world learning experience for students interested in pursuing careers in the transportation industry.

SIMCenter research is paving the way for lighter-weight vehicle structures and cleaner and more efficient engines, leveraging the power of simulation to improve quality and reduce costs. Teams of students, faculty and staff are working on engine models to predict the impact of design changes on efficiency without costly testing. Researchers are also investigating optimization techniques that will allow computer algorithms to automatically optimize component designs.

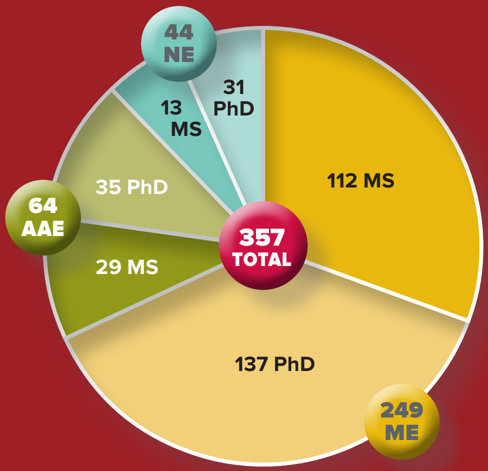
The SIMCenter is one of three industry-facing centers at Ohio State, including the Center for Automotive Research (CAR) and the Center for Design and Manufacturing Excellence (CDME), spanning the range of activities needed to take vehicles through the entire product lifecycle. SIMCenter's focus is on the application of CAE tools whose effective use is vital to regional, state and national economies to produce best-in-class products at competitive prices.

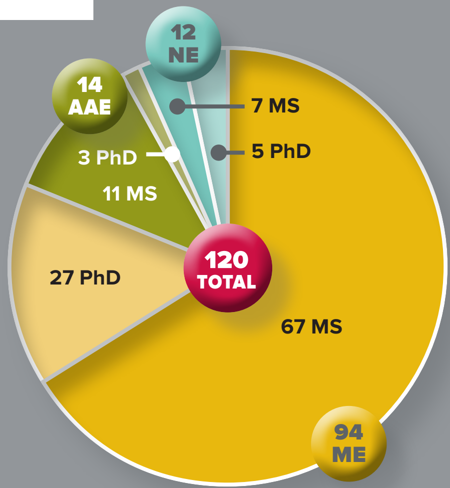
Sheldon and Honda welcome interest in the SIMCenter from others in the transportation industry. "The SIMCenter is rapidly becoming a major source of innovation in simulation and modeling of product performance and manufacturing process," Sheldon said. "By collaborating, we all advance faster and more efficiently."

AUTUMN SEMESTER 2015

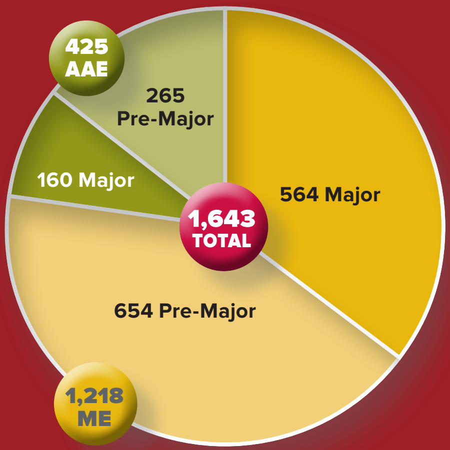
CURRENT STUDENTS | DEGREES GRANTED (SU14–SP15)

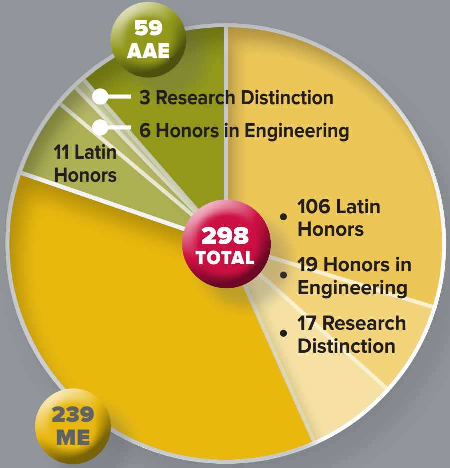
GRADUATE PROGRAM





UNDERGRADUATE PROGRAM





The Department of Mechanical and Aerospace Engineering enjoys an excellent academic reputation among peer programs, industry and government. At the forefront is the excellence of our scholars, several of whom have been recognized for their academic achievements in 2015.

Bhushan Influences Engineers to Engage in Public Policymaking in Washington

MAE's Professor Bharat Bhushan is leveraging his time on Capitol Hill as a Science and Technology Policy Fellow, part of the American Society of Mechanical Engineers (ASME) Congressional Fellows Program, to let the engineering and science profession know they can have an impact on public policymaking.

Bhushan, who served on the Republican staff of the Committee on Science, Space and Technology (SST) in the House of Representatives for one year, talks about his life-changing experience as a Congressional Fellow in an article, *"Laboratories of Policy,"* featured in the June 2015 issue of *Mechanical Engineering* magazine.

An Ohio Eminent Scholar and The Howard D. Winbigler Professor, Director of Nanoprobe Laboratory for Bio & Nanotechnology and Biomimetics, and Affiliated Faculty Member at The John Glenn School of Public Affairs, Bhushan is living proof that engineers can use their science and technology expertise to influence legislation by being champions for science policy. In Washington, he prepared the subcommittee for hearings on major bills, prepared hearing requests and assisted in the preparation of legislation, seeing some pieces of landmark legislation passed even in a difficult political climate, including the Frontiers in Innovative Research, Science and Technology Act to reauthorize funding for various science agencies and programs.

"Engineers cannot remain outside the political process," Bhushan said. "Their expertise is needed to ensure that technical policy is crafted to do the most good." ✣

Lilly Elected ASME Fellow

The Board of Governors of the ASME elected Associate Professor Blaine Lilly to ASME Fellow status. He is one of a select number of 3,350 Fellows awarded citations out of a total 137,000 ASME members.

Lilly has been teaching at The Ohio State University since 1994, and has been a member of the faculty in MAE and Integrated Systems Engineering since 1998. He holds four degrees from Ohio State; a BA in English, a BS and MS in Mechanical Engineering, and a PhD in Industrial and Systems Engineering and is a journeyman tool and die maker.

Lilly has been a driving force in engineering education in areas of design, manufacturing and product design over the past two decades. He has developed interdisciplinary curricula and extracurricular learning experiences, moving students from theory to practice, uniquely preparing them for success. He is currently a member of the University Senate for Ohio State's College of Engineering and is a member of The Ohio State University Council on Academic Affairs. ✣

Shaping the Future of Aerospace

Aerospace Engineering Research Highly Represented at SciTech 2015

Ohio State University researchers presented 40 technical papers at SciTech 2015, held last January in Kissimmee, Florida. The American Institute of Aeronautics and Astronautics (AIAA) SciTech 2015 is a compilation of 11 individual technical conferences focused on aerospace research and is the largest aerospace conference in the world.

The compilation includes 2,500 total presentations from approximately 800 government, academic and private institutions in 40 countries on the latest in aerospace research. Ohio State presented the third highest number of technical papers among all academic institutions and tied with NASA Ames for the fifth highest among all institutions behind NSAA Langley, Air Force Research Laboratories, Georgia Tech and Purdue.

According to Mo Samimy, John B. Nordholt Professor of Mechanical and Aerospace Engineering, University Distinguished Scholar and Director of the Aerospace Research Center, these impressive statistics clearly validate the strength of the program and show that Ohio State's aerospace research is cutting-edge. ✣

The Dayton Area Graduate Studies Institute

Yedavalli and McNamara Teams Receive 2015 AFRL/DAGSI Fellowship Award

Two teams of graduate students and faculty from MAE were awarded an Air Force Research Laboratory/Dayton Area Graduate Studies Institute (AFRL/DAGSI) Student-Faculty Research Fellowship: mechanical engineering graduate student Tim Seitz and Professor Rama Yedavalli; and Associate Professor Jack McNamara and aerospace engineering graduate student Marshall Levett.

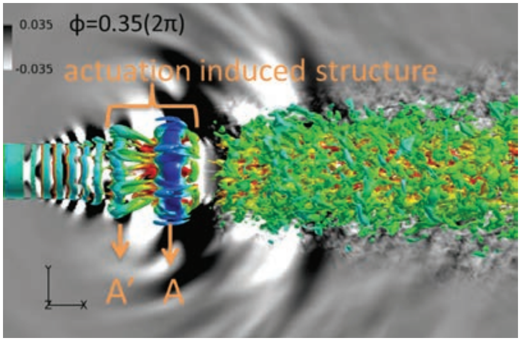
The goal of the McNamara/Levett team's research is to enable reusable hypersonic vehicle platforms by significantly decreasing the time-to-solution associated with long time record structural response and life simulation.

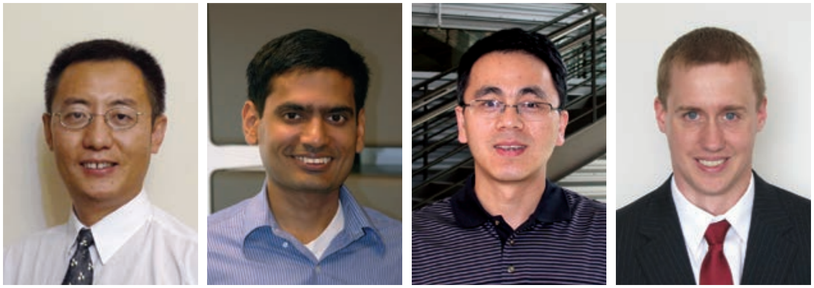
Essential to developing such a simulation capability is understanding and accounting for the strong interdependence between structural life and structural response over the operational history of a vehicle. Status quo approaches for reducing time-to-solution of expensive computations are the use of parallel computing via spatial domain decomposition or reduced order modeling. Neither can adequately address this issue.

The research addresses this problem by studying predictor-corrector schemes that enable parallel time marching on high performance computing architectures, distributing the workload required for an immense number of time iterations. The project is being carried out in collaboration with the AFRL/RQ Structural Sciences Center and the AFRL-University Collaborative Center in Structural Sciences.

The research of Professor Rama Yedavalli and graduate student Tim Seitz is based on the theme of integrating robust and/or adaptive controllers in the diagnostics and health management of turbine engines to improve engine efficiency and longevity over a wider range of engine operation envelope. The impact of the research will be to cut maintenance costs on the Air Force's fleet of planes from high performance fighters to reconnaissance and surveillance planes.

By making control design more finely tuned to engine dynamics and its health parameters, it is possible to better integrate control, diagnostics and health management of engines taking into account the degraded performance of aging engines and making it likely that existing planes will be able to have a more advanced control system retrofitted, thereby gaining the same benefits without having to purchase a new plane. The research will also directly benefit avionics companies in the State of Ohio. ✣





Pictured from left to right: Raymond Cao, Manoj Srinivasan, Haijun Su and Shawn Midlam-Mohler

Speth and Gaitonde Receive 2015 ASME Robert T. Knapp Award

Rachelle Speth, PhD student, and Professor Datta Gaitonde, MAE, received the ASME 2015 Robert T. Knapp Award recognizing their paper titled, *Near Field Pressure and Associated Coherent Structures of Excited Jets.* The award is presented for an outstanding original paper resulting directly from analytical or laboratory research.

Speth received her BS and MS degrees in aerospace engineering from Ohio State and is currently pursuing her PhD in aerospace engineering. Her research, supported by the Air Force Office of Scientific Research, concentrates on understanding and controlling large scale structures and noise created by high speed commercial and military jets.

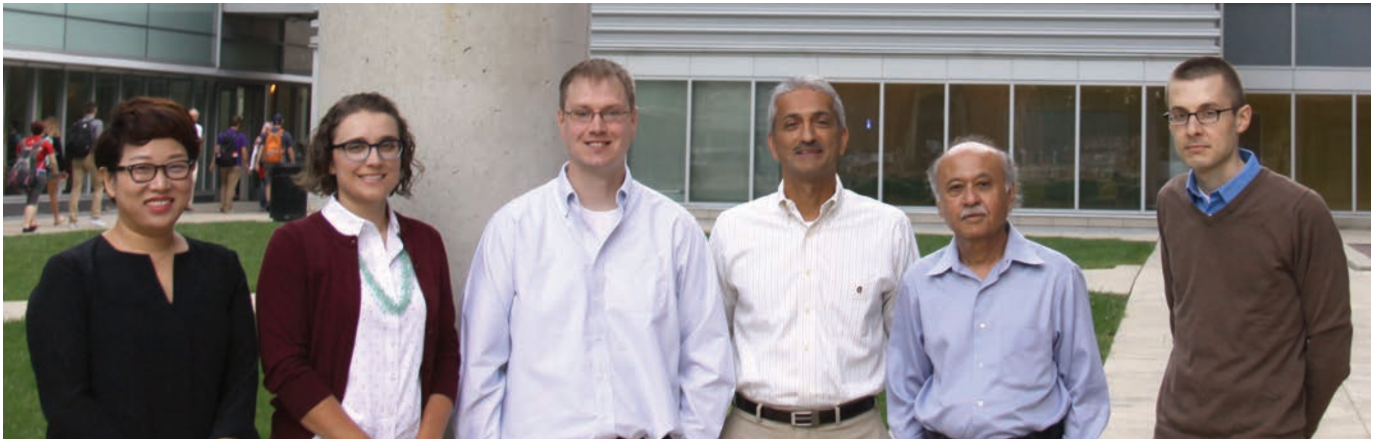
Professor Datta Gaitonde holds the John Glenn Chair and is an Ohio Research Scholar. He directs the High-Fidelity Computational Multi-Physics Lab (HFCMPL) whose focus is on jet noise, shock interactions, flow control and scramjet flowpaths. Gaitonde is deputy editor of the *American Institute of Aeronautics and Astronautics (AIAA) Journal*, and a Fellow of the Wright-Patterson Air Force Research Laboratory (AFRL), AIAA and ASME.

Congratulations to Promoted Faculty

In June, The Ohio State University Board of Trustees approved the well-deserved promotions of **Raymond Cao, Manoj Srinivasan** and **Haijun Su** to Associate Professor with Tenure, and **Shawn Midlam-Mohler** to Associate Clinical Professor.

Gaitonde Named Associate Chair, Aerospace Engineering Program

Professor **Datta Gaitonde** was named associate chair of our aerospace engineering program. Gaitonde is John Glenn Chair, an Ohio Research Scholar and director of the High-Fidelity Computational Multi-Physics Lab (HFCMPL).



Pictured from left to right: Dr. Hanna Cho, Annie Abell, Dr. Jason Dreyer, Dr. Farhang Pourboghrat, Dr. Jami J. Shah and Dr. Ryan L. Harne.

The Department of Mechanical and Aerospace Engineering continues to build on its research and educational strengths with our world-class faculty leading the way. In 2015, we welcomed six talented new faculty.

Annie Abell joins the department as assistant clinical professor. Her teaching interests will focus on Product Design Engineering and the overlap between engineering and design.

Hanna Cho joins MAE as assistant professor in Mechanical Engineering, where her research laboratory, the Micro/Nano Multiphysical Dynamics Laboratory, studies nonlinear dynamics in micro/nanomechanical systems.

Jason Dreyer, assistant clinical professor, previously served as a research scientist and primary researcher for externally sponsored research in MAE. He is currently involved in the development and implementation of the Senior Capstone Mechanical Engineering Laboratory.

Dr. Ryan L. Harne joins the department as assistant professor and director of the Laboratory of Sound and Vibration Research involved in integrating analytical and experimental investigations in mechanics, dynamics, vibrations, acoustics and waves.

Professor **Farhang Pourboghrat** has a joint appointment in the Integrated Systems Engineering Department and MAE, working closely with the Center for Design and Manufacturing Excellence. His research interests are in the multi-scale characterization of engineered materials and modeling of advanced forming processes.

Jami J. Shah joins MAE as professor of Mechanical Engineering and Honda Designated Chair where he will focus on new programs in digital design and manufacturing, and advanced simulation-based techniques for structural optimization.

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