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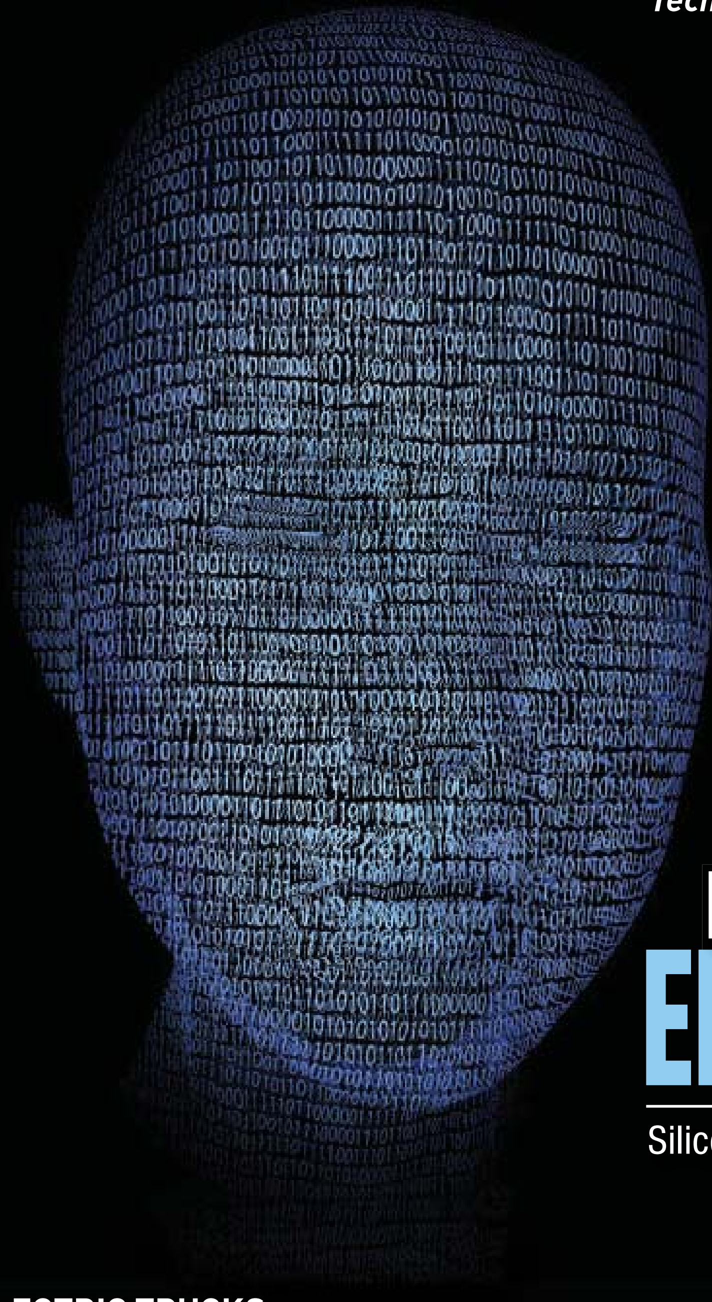
Technology that moves the world



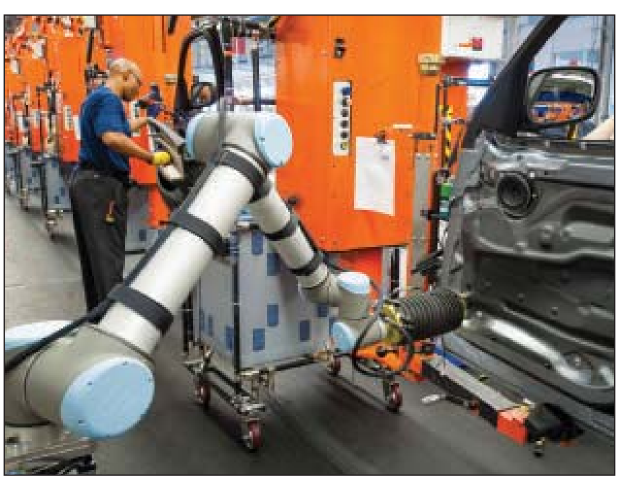
Not Enough ENGINEERS

Silicon Valley struggles to recruit talent with digital skills.

Image: ASME.org

DRONES JOIN THE FIGHT AGAINST ZIKA

ROBOTS ARE USUALLY THOUGHT OF AS A HIGH-TECH solution to first-world problems, like building cars, vacuuming floors, or delivering pizzas. But developing countries have, arguably, bigger problems, and it turns out that robots have a place in solving some of them. Take the fight against the Zika virus. WeRobotics, a company based in Switzerland and Delaware, aims to democratize the technology and get robots working for those in the greatest need.



ROBOTIC CO-WORKERS DO THE HEAVY LIFTING

At BMW, robots and humans work together within set zones and without fences or dividers, to save wear and tear on human muscles.

For these articles and other content, visit asme.org.

SCHOOLS AND FLOCKS INSPIRE WIND TURBINE DESIGN

A RESEARCHER AT STANFORD BELIEVES that the kind of flowing motion birds in flocks and fish in schools summon might just be applicable to the world of wind turbines.

Image: ASME.org

VOICING A TECH REVOLUTION AT ARIZONA STATE

ARIZONA STATE UNIVERSITY'S FULTON SCHOOLS of Engineering and Amazon's Alexa team are partnering to stay at the forefront of voice-activated technology. The institutions share a belief that society is on the brink of an age when advanced voice technology will soon be ubiquitous and that voice is the next serious revolution in information technology science.

NEXT MONTH ON ASME.ORG

ROBOT TEACHERS TRANSFORM EDUCATION

Robot and artificial intelligence-based teachers have been increasingly finding their way into classrooms, augmenting human educators and serving as stand-alone teachers themselves. What's next for this segment and what does it mean for students?

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Give me the place to stand, and I shall move the earth
—Archimedes

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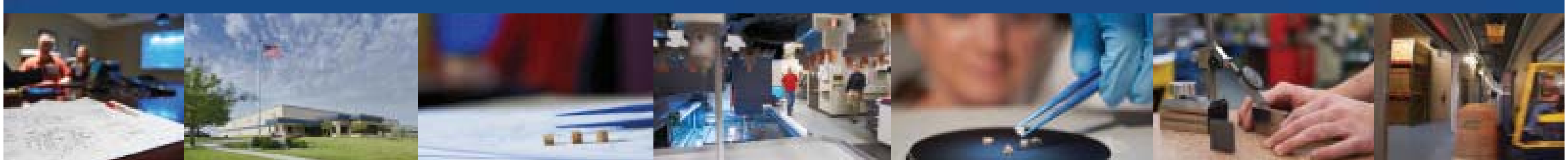

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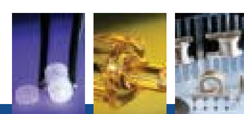

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John G. Falcioni
Editor-in-Chief

THOMAS LOUGHLIN
FAREWELL, FRIEND

There are times when the 500 or so words on this page aren't nearly enough to express all I want to convey. This is one of those times.

After nine years as ASME's 13th Executive Director, and 25 years with the organization overall, Thomas G. Loughlin's last day as the staff lead for ASME was December 1, 2017. ASME's former Associate Executive Director, Phil Hamilton, returns to ASME as the interim Executive Director until the Board of Governors' search for a permanent replacement is completed later this year.

I've known Tom since pretty much the day he started at ASME, so I've had a unique perch on which to see his and ASME's development through those years. You can imagine that in the past quarter century both he and I have gone through many, respective, professional and personal changes.

Seeing Tom rise through the ranks from director of membership to become Executive Director of ASME, and also become a respected and forward-thinking leader in the non-profit, association world, has been inspiring.

Tom has also been an agent of change. The industry-focused roadmap Tom and the Board of Governors have laid down for ASME—along with the introduction of an integrated operating plan—will help the organization grow even more relevant in the years to come. ASME now approaches business opportunities far more differently than it ever has before. Its internal tools are more robust; staff is stronger; and its reputation has grown.

ASME has a bright future, thanks to Tom's stewardship. That future, which includes greater engagement with industry, with members, and with customers and other stakeholders in and outside of the United States, will be Tom's enduring legacy.

In an interview with Tom I conducted for my July 2008 editorial, on his appointment to Executive Director, he spoke of his goals to create a stronger strategic approach to the ASME digital environment, including the web as well as digital content acquisition and delivery. The growth of ASME.org, of ASME's Digital Collection, and the growing digital pathway of ASME's Standards and Certification programs are examples of the progress Tom envisioned.

He also imagined that, by 2018, a virtual network of organizations and individuals strategically partnered to benefit humankind would be established. Today, the ASME-driven EngineeringForChange.org represents a strong platform for galvanizing the international engineering workforce to improve the quality of life of underserved communities around the world.

For his work, and his unwavering dedication to ASME, we owe Tom Loughlin a great deal of thanks. It has been my professional and personal privilege to work with him for all these years. **ME**

FEEDBACK

What role should ASME play in society during the next decade? Email me.

falcionij@asme.org

NOVEMBER 2017

Reader Joselson writes that the magazine shows a bias toward fossil fuels.

« One reader points out the competition between electricity and fuels, while another suggests design in the universe is obvious.

FOSSIL FOCUS

To the Editor: In his November 2017 feature "Rekindling the Spark," John Kosowatz cites a report that claims "most of the environmental impacts generated by [internal combustion engine vehicles] are localized to the combustion of gasoline in the engine, but the [battery electric vehicles] manufacturing process 'generates a much more widely dispersed and damaging set of environmental impacts.' "

While it is true that the environmental impacts of manufacturing batteries for BEVs are not insignificant and need to be addressed, it is simply untrue that the environmental impacts of internal combustion engines come from the direct burning of gasoline. This analysis leaves out the extraction, transportation, and processing of oil into gasoline, a very environmentally costly process.

In addition it seems to ignore the potential for enormous environmental disasters from oil spills and pipeline leaks, which have the potential to unleash countless barrels of crude and processed oil into the environment.

The article shows a clear and unapologetic bias towards the continued and unabated use of gasoline and fossil fuels in general, over the development of the cleaner technologies that are required to safeguard the environment and stop the advance of climate change.

Usually when I read *Mechanical Engineering* I am engaged and interested in the topics and methods presented. The bias in this article prevented me from doing that.

Adam Joselson, *Cleveland, Ohio*

EV ISSUES

To the Editor: The race between electric and internal combustion engines may be determined by fuels, not engine technology: electricity on the one hand versus fossil fuels, biofuels, hydrogen, or ammonia. That includes considering the hourly to seasonal ability to store low-carbon biofuels, hydrogen, or ammonia.

The other consideration is that cold climates degrade battery performance as well as create a large demand for passenger compartment heat—not a challenge for internal combustion engines.

Battery enthusiasm comes from California—with the climate for batteries. The question may be how far they will go outside their comfort zone.

Charles Forsberg, *Cambridge, Mass.*

SOMETHING INSTEAD OF NOTHING

To the Editor: The ongoing debate between evolution and creationism tends to obscure basic issues of origins and design. Scientific literature crediting evolution routinely acknowledges superior engineering in nature, yet no one has any inkling of how a purposeless, careless, mindless, and lifeless universe could give rise to such—time is immaterial (and also no agent).

Computer code like "the evolutionary feature of the Solver optimizer" referenced by E.R. Jeffreys (Letters, September 2017) is no solution. Both Excel and its Solver add-on, not to mention the computer and its operating system, are purposefully engineered, thus an example of intelligent design.

Probabilities presume the dice, the thrower, and the throw. What of the birth of our "just right for life" material universe? Whence the singularity? Why is there something rather than nothing? Evolutionary theories, though presumptuously dependent, especially fail here, as the fundamental questions are metaphysical.

As an engineer, I must remain firmly skeptical of all such sleight of hand. The only available examples always point to intelligence behind any intelligible design. We all see the awe-inspiring design throughout the natural world.

No wonder many of us, like Matt Highstreet (Letters, June 2017), reasonably credit an awesome, transcendent engineer behind it all.

C.R. Norris, *Memphis*

FEEDBACK Send us your letters and comments via hard copy or e-mail memag@asme.org (subject line "Letters and Comments"). Please include full name, address, and phone number. We reserve the right to edit for clarity, style, and length. We regret that unpublished letters cannot be acknowledged or returned.

GETTING A GRIP

SOFT ROBOT GRIPPER IS CAPABLE OF HANDLING, MANIPULATING FRAGILE OBJECTS.

The old set-up line, "How many robots does it take to screw in a light bulb?" has a new answer, thanks to a team of engineers at the University of California, San Diego.

The team has created a robotic gripper capable of picking up and manipulating fragile objects. Unlike previous grippers, it can twist objects, sense them, and build models of what it manipulates, enabling it to operate in low light or with poor visibility. The robot's embedded tactile sensing can discern an object's shape to complement its other sensing modes.

The gripper contains three fingers, each consisting of three soft, flexible pneumatic chambers that move when air pressure is applied, enabling the manipulation of objects it holds. Each finger is covered with a skin made from silicone rubber with embedded sensors comprised of conducting carbon nanotubes. The rubber is rolled up, sealed, and slipped onto the fingers for a skinlike covering.

"Many other soft robotic grippers exist, but ours is unique because of its exclusive use of soft materials for the fingers, the ability to twist objects, and the sensing layer to both help with control of the hand and to allow modeling of the objects it handles," said Michael T.

A gripping mechanism developed at the University of California, San Diego can attach to a common robotic arm.
Image: UCSD

Tolley, a roboticist at the Jacobs School of Engineering who led the engineering team that presented the device at the International Conference on Intelligent Robots in September 2017. Tolley said the device mimics what happens when someone reaches into their pocket and feels around for their keys.

In fact, the main goal for the project was to design a soft robot that could achieve complete motions and the "integration of the embedded sensing abilities for feedback control and integration."

"We chose a three-chambered design because it enabled us to cover a hemispherical workspace," Tolley said. "We went through many iterations on the geometry and the soft material. Sensor integration is a particular challenge, as our sensors must be distributed over the actuators as opposed to the discrete joints of traditional robots, leading to challenges with fabrication, integration, and durability."

The gripper has enough dexterity to grasp a standard light bulb without shattering it.
Image: UCSD

Testing the gripper on a Fetch Robotics arm, the team was able to demonstrate that device could pick up, manipulate, and model items as varied as light bulbs and screwdrivers. Indeed, one gripper deployed by one robot can apply just enough force and dexterity to tighten and loosen a light bulb.

"We believe this type of gripper would be useful for agricultural applications such as picking fruit, and for robots capable of direct interaction with humans [such as] home assistance robots," Tolley said. **ME**

NEIL COHEN is a writer based in Ramsey, N.J.

Domino's and Ford have collaborated to gauge customers' reaction to getting their pizzas delivered by a self-driving car.
Image: Domino's

DOMINO'S, FORD TEST-DRIVE AUTOMATED PIZZA DELIVERY

It may be labor-saving for the restaurant, but pizza delivery of the future may require more exertion from customers than the existing pizza-guy method.

"The majority of our questions are about the last 50 feet of the delivery experience," said Russell Weiner, president of Domino's, which has teamed up with Ford on a pilot program that delivers pizza using self-driving cars.

"For instance," Weiner said, "how will customers react to coming outside to get their food? We need to make sure the interface is clear and simple. We need to understand if a customer's experience is different if the car is parked in the driveway versus next to the curb. All of our testing research is focused on our goal to someday make deliveries with self-driving vehicles as seamless and customer-friendly as possible."

To test customer reactions to fetching orders from self-driven pizza delivery vehicles, randomly selected Domino's customers in Ann Arbor, Mich., over several weeks starting in September received their food from a Ford Fusion Hybrid Autonomous Research Vehicle. (The car was only a simulated self-driving vehicle, as it was manually driven by a Ford safety engineer and staffed with researchers.) The customers tracked the delivery through GPS and received text messages guiding them on how to retrieve their pizza from inside the car using a unique code to unlock a prototype container fabricated by local partner Roush Enterprises.

Domino's has made a name for itself over the years for its pizza-delivery gimmicks. In addition to simulated self-driving vehicles, the chain has also deployed robots and drones.

Ford and Domino's conducted preliminary testing of the delivery process using the vehicle in self-driving mode at M City, the simulated urban environment on the University of Michigan's campus. **ME**

A SUSTAINABLE, POWER-PRODUCING TEXTILE

A piece of fabric woven with special strands of material that harvest electricity from the sun and motion. *Photo: Georgia Tech*

Georgia Institute of Technology researchers have leveraged work in both triboelectricity and solar energy to develop a wearable textile composed of two fabrics, one that gets energy from sunshine and one that draws electricity from mechanical motion.

"[It's] a novel solution with a collection of compelling features [that], for the first time, is presented as a sustainable power source for wearable electronics," said Zhong Lin Wang, professor in the Georgia Tech School of Materials Science and Engineering and a pioneer in nanoscience and nanotechnology.

A textile that generates electrical power from absorbed solar irradiance and mechanical motion could be an important step toward next-generation wearable electronics, he added. The textile could power smartphones and other portable electronics.

Although known to produce energy and a field of study for many years, triboelectricity— the production of electrical charge from friction caused by different materials coming in contact —was largely discounted as an energy source because it was considered unpredictable and not well understood.

About five years ago, Wang and his research team discovered that the triboelectric effect could be harnessed for power generation. While working on piezoelectric generators, the output from one piezoelectric device was much larger than expected.

The researchers traced the cause of the higher output to incorrect assembly that allowed two polymer surfaces to rub together. Further research by the group resulted in the invention of a triboelectric nanogenerator that was key to being able to reliably convert an electrical charge into current.

A bracelet made from the fabric.
Image: Georgia Tech

In a triboelectric generator two dissimilar materials, one an electron donor and the other an electron acceptor, are used. When the materials are in contact with each other, electrons flow from one material to the other. If the sheets are then separated, one sheet holds an electrical charge. Then if an electrical load is connected to two electrodes placed at the outer edges of the two surfaces, a small current will flow to equalize the charges. By continuously repeating the process, current can be produced.

The separate photovoltaic fabric for harvesting solar energy consists of wire-shaped photoanodes fabricated by depositing two layers of semiconductor over copper-coated polymer fiber.

The textile base is made of inexpensive polymers into which the solar and triboelectric parts are woven. "This approach enables the power textile to be easily integrated with other functional fibers or electronic devices to form a flexible, self-powered system," Wang said.

The resulting textile is versatile and can be customized into various shapes and sizes and woven together with cotton or wool fabric. It can also be used as a coating on existing fabric products.

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MOTOR AND GEARBOX COMBINES IN E-BIKE

The German automotive manufacturing company Continental has developed new electric bike drive systems that combine the motor and gearing into one efficient unit.

Continental, in collaboration with German bicycle maker Cycle Union, will launch an e-bike line powered by the pioneering drive systems later this year. Cycle Union has been pursuing a long-term goal of integrating batteries into the frames of all its future e-bike models. The company has invested heavily in a product line in which the central element of each frame consists of a single molding manufactured via gravity casting.

One of the new models, the Revolution, runs on a motor with a fully integrated stepless automatic transmission. Along with advantages in maintenance and servicing, the all-in-one drive unit makes for easier maneuvering because it is mounted in a single unit at the bottom bracket axle position, lowering and centering the bike's center of gravity.

The 48V drive unit found in the other model, the Prime, can be used with conventionally geared e-bikes via a single unified frame adapter.

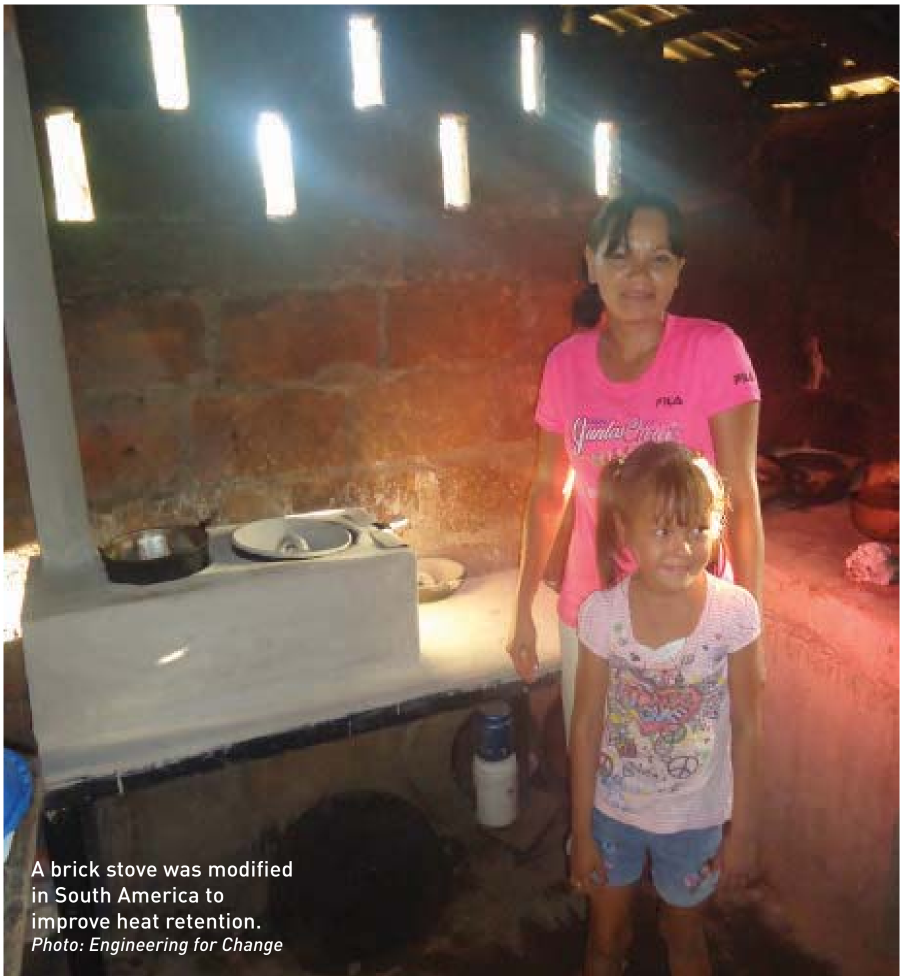
The new drive systems are compatible with both the Continental belt drive system and traditional chains, and each produce a maximum torque of 70 Nm. The battery has a capacity of 600 Wh. **ME**

The 48V Revolution is the world's first 48V e-bike motor with an integrated stepless automatic transmission in an all-in-one drive unit.
Image: Continental AG

"What we're now able to do with these new kinds of digital factories is make things in small quantities where you get the same kind of quality you get in the large thing but at the same low cost. It also leads to mass customization and that's dramatically different."

Carl Bass, *CEO emeritus of Autodesk, quoted by Boston radio station WBUR on November 3, 2017.*

CHANGING COOKSTOVE DESIGN BASED ON THE CULTURE



A brick stove was modified in South America to improve heat retention.
Photo: Engineering for Change

Stove design flourishes where the needs of a culture butt against constraints of the environment, financial resources, and distribution systems. Thousands of variations in clean stove designs have been manufactured and sold in the world's impoverished and underserved communities. Some work as intended, other do not. Research, rigorous testing, and new performance standards under development now are revealing which stove designs and kitchen configurations can reduce emissions, fuel consumption, and expenses. But even the most efficient stove will not work as advertised if it does not fit into the cook's cultural context.

Two maxims that global development engineers often use are these: No need to reinvent the wheel, and technology alone won't solve a problem. One organization has manifested both to create four new stove designs for Latin American kitchens. Samaritan's Purse Canada, the Canadian arm of the international Christian humanitarian aid organization, avoided reinventing wheels by starting with African and other established stoves as the base for their models. Then, acknowledging that the technology alone is not the solution, the design team adapted the stoves to the unique requirements of cooks in Nicaragua, Costa Rica, Peru, and Bolivia. The adaption required research, cultural understanding, and co-design with the users to create a better product.

The Samaritan's Purse team began work in the Central American country of Nicaragua in 2015, then moved on to South America, before returning to Central America to design stoves in Costa Rica.

In South America, the designers worked in Peru and Bolivia modifying a brick stove that was already in use in the region. They added a metal lid to improve heat retention and made cosmetic improvements, said Carolina Zuleta-Sanchez, a project manager for Samaritan's Purse Canada in Latin America and the Caribbean.

The team then took their experience with them northward to Costa Rica. They found that the South American brick ovens were not as well liked in Central America.

"They prefer a design that is not attached to the house, but one that they can build and bring," Zuleta-Sanchez said.

Rather than asking the cooks to change their work, the team searched for stoves that might be a better fit in Central American cultures. They settled on an ACE stove design that is distributed in Sub-Saharan African countries and modified it in tandem with the people who will cook on it.

"We considered a wide variety of models used around the world and then created a localized version based on best practices, available resources, and input from the community," said Zuleta-Sanchez. "Each of the partners involve the beneficiaries during the stove construction and installation. Peru and Bolivia need to do it in each of the houses. Nicaragua and Costa Rica have more flexibility to invite beneficiaries to the factory. There the beneficiaries can help with the construction and transportation of the stove to their houses." **ME**

ROB GOODIER is managing editor at Engineering for Change. For more articles on global development visit www.engineeringforchange.org.

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POWER-PRODUCING TEXTILE

The researchers are encouraged that production and assembly costs for the textile are low, and the process is environmentally friendly and likely to be suitable for large-scale manufacturing. They also believe the textile can be adapted for applications such as curtains and tents, although the size now is limited to the equivalent of A4 paper because of the capability of the weaving machine.

Testing on a small piece of the textile has shown that the combination of sunlight and such common mechanical motion as human fidgeting or flapping in the wind has delivered sufficient power for directly charging a commercial cell phone or continuously powering an electronic watch. Testing also showed there is good performance in the temperature range that human beings tolerate.

Long-term durability is still an open question, although current experimental data does not suggest a drop in electrical output under what would be considered normal use.

The team does know that electrical output of the textile is gradually reduced when relative humidity rises from 10 percent to 90 percent, but it is believed that it could withstand rain if properly protected. Additionally, if the textile does get wet, performance can be recovered when the device dries.

In a paper published in *Nature Energy*, the team wrote, "Developing lightweight, flexible, foldable and sustainable power sources with simple transport and storage remains a challenge and an urgent need for the advancement of next-generation wearable electronics. Searching for renewable energy resources that are not detrimental to the environment is one of the most urgent challenges to the sustainable development of human civilization." ME

NANCY S. GIGES is an independent writer. For more articles on sustainable power visit ASME.org.

"CONNECTED TOYS ARE BECOMING INCREASINGLY popular, but as our investigation shows, anyone considering buying one should apply a level of caution."

Alex Neill, managing director of home products and services at the British consumer advocacy group Which?, as quoted by the Guardian on November 14, 2017. The group found security flaws in many internet-enabled toys.

NOT TAKEN FOR A RIDE

Some companies have seen technological innovation as the key **to profitable ride sharing.**

Ride sharing services such as Uber are becoming increasingly popular and the patent activity surrounding the industry is actively reported in the news. Some of those patents face a validity challenge: since the 2014 Supreme Court decision in *Alice Corp. v. CLS Bank International*, business method patents are almost impossible to procure or defend and even many software patents have been found invalid by the courts and by the U.S. Patents and Trademark Office.

A few of Uber's pending patent applications have been rejected by the patent office in light of the *Alice Corp*. ruling.

But the concept of ride sharing services has spawned technology patents that are more defensible.

Before ride sharing there was car sharing. Patent No. 3,624,608 (1971) features cars activated via a card. The user goes to a parking lot, inserts his card into a reader to unlock a car, drives it, and afterwards returns the vehicle to the same or a different parking lot. The driver is automatically billed for the mileage by a "central processing unit."

Today, many bicycle-sharing schemes use the same basic concept.

A 1982 patent pertains to customers requesting rides from drivers who operate their own vehicles. Since the patent was filed decades before the widespread availability of cell phones, it described a network of electronic terminals where riders could specify the number of passengers, the pick-up location, the pick-up time, and the destination.

A "central coordinating station computer" would process the requests, send them to the fleet of private vehicle owners who would bid on the rides, select the winning bid based on how close the driver is to the rider, and automatically charge the rider the fare.

The inventor, Robert W. Behnke, was a transportation expert, and his patent, No. 4,360,875, is cited 191 times by later patents. Those citations may be an indication that this was a seminal ride-sharing patent.

With Patent No. 5,604,676 (1997), Lucent disclosed a system that provided GPS capabilities to ride sharing. And Patent No. 6,356,838 (2002) added a feature where the driver is automatically provided with the most efficient route to the rider's location. In this patent, the driver's cell phone receives information about the rider's location, cell phone number, and other pertinent data.

General Motors reportedly licensed this patent from Sidecar—a now defunct ride sharing company. That's a common strategy, buying up older but still valid patents from individuals or defunct companies to use as a sword or a shield in court.

Uber and its rival, Lyft, have both been sued for patent infringement, and have filed for a number of patents. In addition, Uber has purchased patents from Lucent, Microsoft, and others.

The next technological breakthrough for ride sharing will be autonomous cars, which will negate the need for drivers altogether. For example, Lyft and Waymo, LLC (the driverless car division of Google) are now reportedly working together. Uber has its own research partnerships.

Uber today is valued at more than $50 billon, and if it can cut labor costs, it will likely be worth much more in the future. ME

"THAT'S A COMMON STRATEGY, BUYING UP OLDER BUT STILL VALID PATENTS FROM INDIVIDUALS OR DEFUNCT COMPANIES TO USE AS A SWORD OR A SHIELD IN COURT."

KIRK TESKA is the author of *Patent Project Management* and *Patent Savvy for Managers*, is an adjunct law professor at Suffolk University Law School, and is the managing partner of Iandiorio Teska & Coleman, LLP, an intellectual property law firm in Waltham, Mass.

QUICK-SWITCH WINDOW GOES DARK

Venetian blinds have a certain film noir appeal, but few household fixtures are more of a pain. They are unwieldy and impossible to clean. The less evocative roll-up shade's better, but not much.

Stanford University researchers have developed a window that may one day end this domestic frustration.

The prototype pane, about 4 square inches, blocks light through the movement of a copper solution over a sheet of indium tin oxide modified with platinum nanoparticles. When transparent, the window is clear and allows about 80 percent of surrounding natural light to pass through. When dark, the transmission of light drops to below 5 percent. It only takes about 30 seconds to change from transparent to dark or vice versa.

Existing smart windows are made of materials, such as tungsten oxide, that change color when charged with electricity. But these materials tend to be expensive, have a blue tint and can take more than 20 minutes to dim. They also become less opaque over time.

Materials science and engineering professor Michael McGehee, who has an undergraduate degree in physics, hit upon the idea in collaboration with chemist Christopher Barile, a former Stanford postdoc student and now a University of Nevada professor. "I had the concept of plating metal and using it to block light," McGehee said, "and Chris got all the chemistry to work."

McGehee said the window technology can improve lighting in rooms, automobiles, even sunglasses, and has the potential to save about 20 percent in heating and cooling costs.

The researchers have filed a patent and entered into discussions with glass manufacturers and other potential partners. Developed commercially, McGehee said, the windows could operate with a switch, knob, or by automation. The thicker the metal, the more light will be blocked, he explained. Tinting will be determined by controlling the amount of plating.

Making larger windows switch quickly presents a challenge in future development because there can be a voltage drop across a large transparent electrode. The researchers switched the windows on and off more than 5,000 times and saw no degradation in the transmission of light, but further testing is needed in real-world conditions to gauge the effect of things like high temperature and prolonged exposure to sunlight. ME

WHERE DOES A U.S. NAVY AVIATOR go after flying combat missions over Afghanistan? For Capt. Mark Bruington, it was time to return to his roots as a physics major and head up the Naval Research Laboratory, the research and development arm for the Navy and Marine Corps. At NRL, Bruington oversaw the work of 1,500 engineers and scientists who are developing new technologies for American sailors and Marines. We spoke to Bruington shortly before his retirement last year.

Q&A CAPT. MARK BRUINGTON

ME: From your position at the command of NRL, you've seen a lot of cutting edge technology. Will new technology change the culture of the armed services? Or change the way they operate?

M.B: I like to think even though we're steeped in tradition, young people can adapt quickly. So I am less worried about how the Navy's culture, which has served us well for 230-plus years, is going to change and more interested in seeing how our naval personnel will adapt to this rapidly, exponentially changing world.

I see the Big Data, machine learning, quantum sensing, quantum computing—those are going to rapidly change not just the Navy but our society. But I am also really excited about turning what is today a sailor's or Marine's uniform into a bandage or radio or a sensor—or even a cloaking device. Something as simple and mundane as a uniform or body armor could have a whole host of new, repurposed capabilities.

ME: Was there a bit of a culture clash when you took command of a lab full of scientist and engineers?

M.B: After being a physics student in the 1980s and then being in the military for 20 years, I wasn't on the cutting edge of physics anymore. So I learned a lot. But I have put things in context for our researchers. I was able to tell them what the environment was like aboard ship, what it was like to land on an aircraft carrier at night, to see what saltwater corrosion does and how fast it works, what it is like to be a sailor who is fatigued at the end of a very long shift and has to interact with a computer system.

ME: When you were flying combat missions over Afghanistan, was there ever a piece of technology that you wish you had when you were in the air?

M.B: I am amazed by how little I knew about the NRL technology that was in the fighter. It had been there, but it had a defense contractor's name on the box. I didn't realize how much a defense research lab was the initial incubator of those ideas, trying them out and then working with industry to get in on a plane or ship and in the hands of a war fighter.

ME: But was there any specific thing?

M.B: It wasn't a specific piece of hardware, but it was more the refresh cycle. When you are in the fleet, there is a lag between when someone says, "This is a capability we could one day produce," and actually having it and using it in combat. That gestation period was something I noticed. So it's not any one technology I wish I had, it's more the ability to refresh the things that are in the field today. I understand the system now, but I am frustrated that we can't do things in a more rapid fashion. ME

ME: A lot of defense spending is conducted through grants. What does the Department of Defense get by having its own lab?

M.B: When we use government employees to solve government problems, the intellectual property is ours. We gain the full insight and use of that intellectual property. So we get the basic, first-principle fundamental science and engineering, understanding how best to use that to solve Navy and Marine Corps needs, and then have the exclusive rights to it because it was formulated here.

ME: Are there things that are not licensed and patented because they are too secret to release?

M.B: On an unclassified line? Yes. There is a large portion of our portfolio that is in the classified realm. We are performing research for government agencies that have unique needs.

JEFFREY WINTERS

A SODIUM-BASED BATTERY ALTERNATIVE

The projected growth in renewable energy has also led to the forecasted need for battery farms to store power and provide electricity on dark nights when the air is still. While lithium ion batteries are the top choice for performance, lithium itself is rare and costly.

Stanford University researchers believe they have developed a battery chemistry that could serve as an alternative to lithium at a substantially lower cost. Chemical engineer Zhenan Bao and her collaborators have created a sodium ion battery costing less than 80 percent than that of a lithium ion battery, with the same storage capacity. The team's findings were published in a recent *Nature Energy* paper.

The sodium-based electrode has a chemical makeup common to all salts: a positively charged ion—in this case, sodium—joined to a negatively charged ion. In table salt, chloride is the positive partner, but in the Stanford battery, a sodium ion binds to an organic compound known as myo-inositol.

Originally, according to Lee, the compound stored, at maximum, only two sodium electrons per unit—not good enough to compete with the energy density of the lithium ion battery cathode. But as reported in the journal, the team examined exactly how the sodium ions attach and detach from the cathode and found a way to double the number of ions that can latch on.

"Our new cathode comprised of carbon, oxygen, and sodium, has a comparable energy density to a conventional lithium cathode, and so it can be a desirable option in building an ion battery to replace Li-based technology for grid-scale application," said Min Ah Lee, postdoctoral scholar and author on the paper.

"Currently, our full-cell energy density is limited by the anode with a relatively high operating potential, so we are working on making a better anode to have comparable full-cell energy density in the near future," she added.

The cost difference between lithium and sodium is stark—about $15,000 a ton to mine and refine lithium versus just $150 a ton for the ubiquitous sodium-based electrode material. When cost-per-storage is factored in, the team's models offer promise. ME

MEREDITH STETTNER is a writer based in Jersey City, N.J.

Models of bubble formation in 2-phase cooling show how to boost efficiency by a factor of 10.
Photo: United Technology Research Center

NEW MODELS FOR SIMULATION

GOOD MODELS ARE ESSENTIAL FOR good engineering. This month, we look at two ways in which their capabilities are expanding. On one hand, their increasing speed and realism allows researchers to create structures that achieve unprecedented cooling. On the other, we discover a way to scan large structures without using a tripod.

DRAMATIC COOLING

THE LAB Thermal & Fluid Sciences Dept., United Technologies Research Center, Hartford, Conn. Maid Yazdani, staff research scientist.

OBJECTIVE Develop fundamental thermal and fluid flow technologies for United Technologies' Carrier air conditioners and Pratt & Whitney turbofan engines.

DEVELOPMENT A model that uses fundamental physics to predict structures that can boost the efficiency of two-phase cooling by a factor of 10.

A new simulation model of two-phase cooling enables Miad Yazdani to design small structures on heat transfer surfaces that can boost cooling efficiency by a factor of 10 in a field where incremental gains are the norm.

"The only way to achieve disruptive and radical improvements is to delve into the fundamental physical processes of cooling," Yazdani, a staff research scientist at United Technologies Research Center, said.

Two-phase cooling boils coolant to carry away more heat than liquid coolant alone. UTRC hopes to apply the technology to its Carrier air conditioners and cooling systems for hot electronics.

In commercial air conditioners, there are only a few degrees difference between the temperature of the heated surface and the coolant. Yazdani's model predicts the size and shape of micron-scale shapes on the cooling surface that best encourage the formation of vaporized bubbles of liquid coolant. He hopes the designs will help Carrier build smaller, more efficient chillers.

Military and power electronics run hundreds of degrees hotter than air conditioners, and engineers often submerse them in cold, fast-moving refrigerant to keep them cool. Adding nanostructures or nanowires to the cooling surface increases the surface area and potential nucleation sites where bubbles can vaporize, reducing demands on the coolant system.

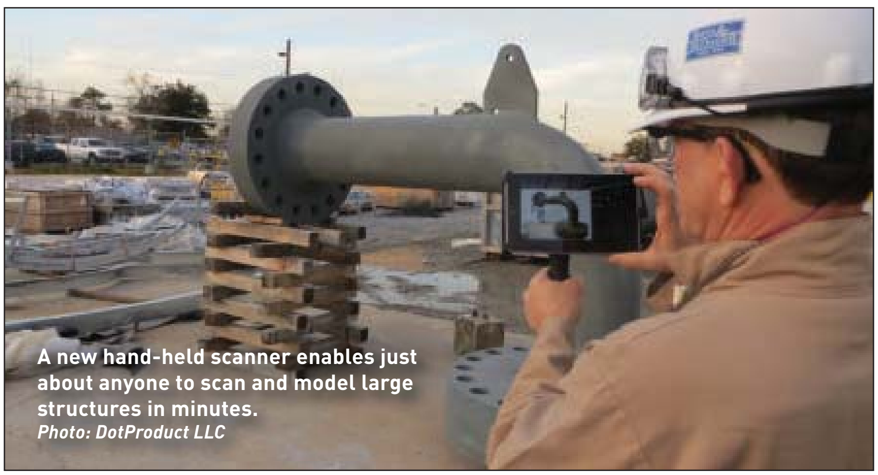
The model bridges the gap between nanoscale and macroscale behaviors to optimize the shape, size, and location of surface features. It models nanoscale bubble formation statistically rather than deterministically, so it can simulate large surfaces without drawing lots of computing power. It then uses a proprietary algorithm to communicate those results to a conventional CFD model of large-scale flows and heat transfer.

Yazdani describes the model as "predictive, not post-dictive." That means he cannot tune it. Instead, the underlying physics either works or it doesn't.

When a micro-structured surface failed to match predictions, Yazdani scanned it with computed tomography and imported the resulting scan into CAD. Tests on the as-built structure closely matched predictions.

In addition to exploring manufacturable and exotic geometries, Yazdani is also addressing such issues as corrosion, scaling, and chemical interactions.

"Our goal is to simulate the way the system would run in real life," he said. ME



A new hand-held scanner enables just about anyone to scan and model large structures in minutes.
Photo: DotProduct LLC

OUTDOOR SCANNING

THE LAB DotProduct LLC, Boston, Mass. Rafael Spring, chief technology officer; Brian Ahern, CEO.

OBJECTIVE Create simpler ways to scan large structures that take advantage of new scanning and automatic positioning technologies.

DEVELOPMENT A hand-held laser scanner that can capture a production line or large structure and output a CAD model automatically, simply by walking around.

Complex models are growing easier to build, thanks to the widespread availability of easy-to-use scanners. Scanners capture part geometry by mapping it with a laser and turning the resulting cloud of points into a usable CAD model.

Scanners are an especially powerful way to capture complex systems, like manufacturing lines or offshore oil rigs. Instead of drawing each structure laboriously by hand, engineers scan structures and import them into their CAD system. They can use the resulting model to compare "as-designed" to "as-built," see if that new robot will fit into a line, or animate their models of existing equipment to see how harmoniously they will work with new machinery.

Once, those large scans took professionals and large equipment days to complete. Today, tripod-mounted units that do 360-degree scans automatically.

DotProduct's DPI-8X 3D scanner goes further. Strapped to a consumer gaming tablet, it lets users scan large structures while walking around them and aiming the scanner the way they would a video camera. The scanner takes 30 pictures, or frames, per second and stitches them together to provide a full picture of the site.

The device is the brainchild of Rafael Spring. He founded Enkin, an augmented reality app for Android phones. After Google acquired the business in 2008, he worked on Google's Glass, Goggles, and Tango augmented and virtual reality programs. He founded DotProduct in 2011 to build scanners that leveraged consumer AR/VR technologies.

DPI-8X 3D works much like gamer vision sensors, Tom Graves, the company's chief marketer, said. For each frame, the device emits an infrared grid of thousands of dots and measures their distance from the scanner by the time needed to sense their reflection.

DotProduct's software superimposes this 3-D map over a photograph taken by the scanner's camera. It then inspects the features where three frames intersect to see how they have changed, and uses this to compute the position of the scanner in 3-D space. Knowing the position of the scanner enables it to build a 3-D map of the world around it.

The device's resolution is only 1-2 millimeters, not fine enough for reengineering small parts, but it costs only $5,000 and prices are likely to fall, Graves said. ME

ALAN S. BROWN

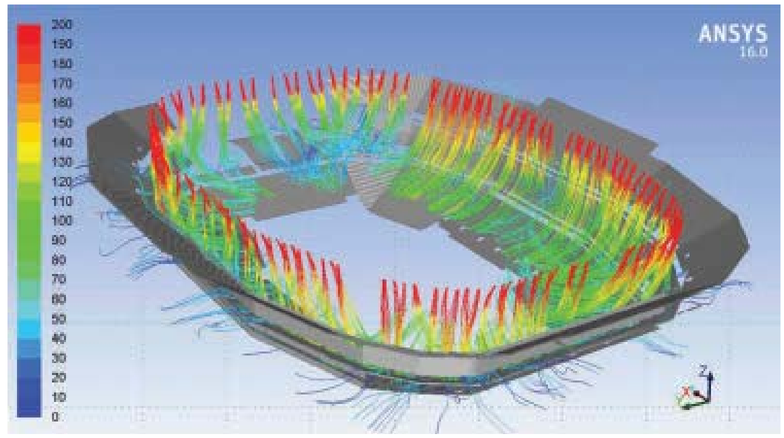
SIMULATION KEEPS NEW DOME COOL

Mercedes-Benz Stadium, the new home of the Atlanta Falcons football team, features a dome that retracts like the iris of a camera lens. When it works, at least—for the stadium's debut, a preseason game in August, the mechanical systems had not been completed. Add 75,000 fans to an enclosed building in Atlanta's summertime heat, and it could have made for a sweltering game.

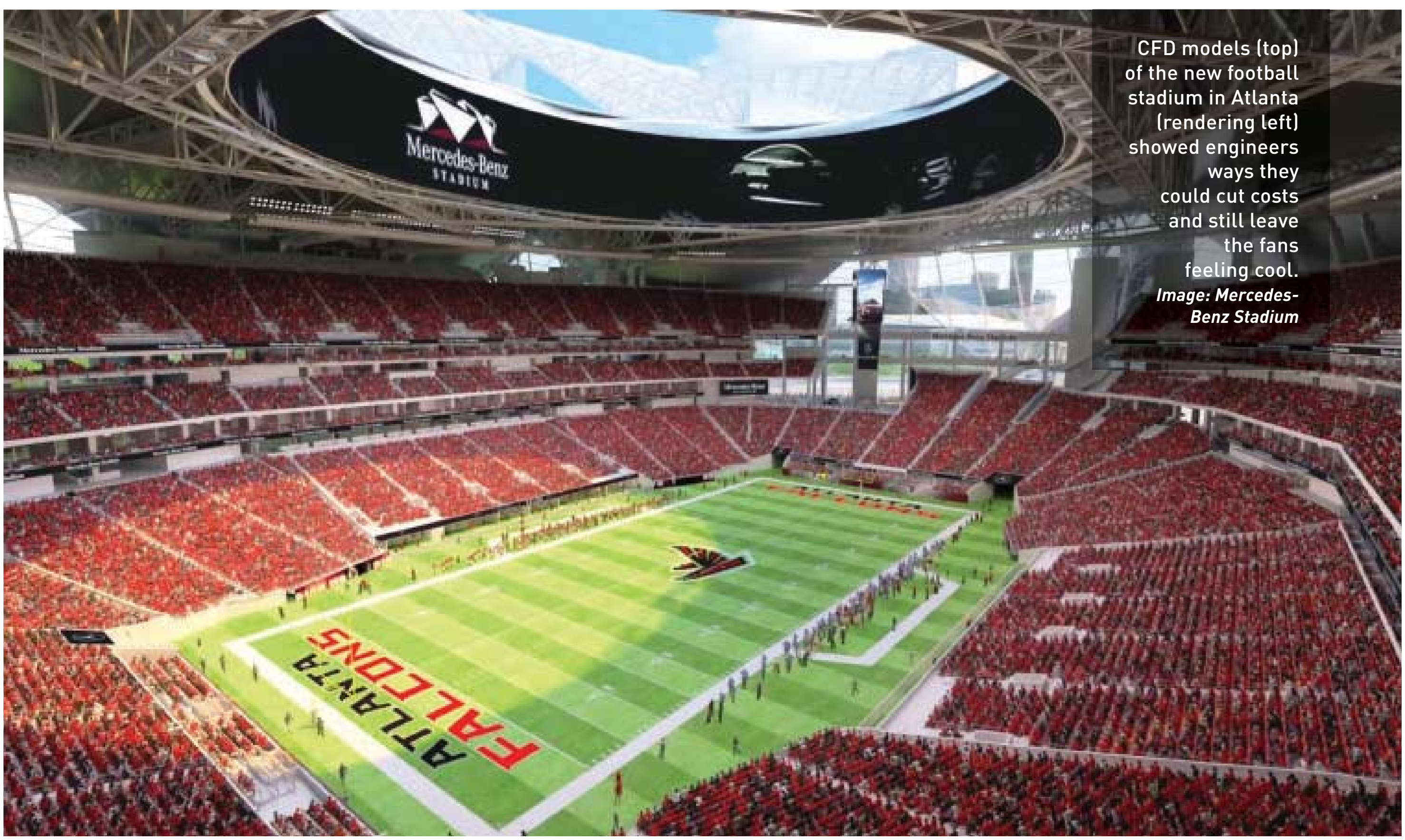
Fortunately, the fans and the teams stayed cool and comfortable thanks to an HVAC system fine-tuned by complex simulations relying on computational fluid dynamics (CFD).

"CFD offers us a way of predicting flow in systems that are atypical," said Chris Skoug of Southland Engineering, a mechanical, electrical, and plumbing design company. "Over time our industry has developed very good test data and a methodology for water running through a pipe and air coming out of ductwork inside normal shapes, if you will—in an office, operating room, or commonly occupied space with conventional geometry. But the thing about stadiums is that each one is unique."

CFD modeling is used by engineers designing everything from high-end aerospace applications down to the water spray patterns inside a dishwasher. For its stadium work, Southland employed



ANSYS Fluent software to analyze the flow field and temperature distribution, as well as the thermal and load stresses with corresponding deflections in structure. Finite element analysis, a computerized method for predicting how a material reacts to real-world forces, vibration, heat, fluid flow, and other physical effects, was applied to a model that divided the stadium into a mesh of around 120 million polyhedrons. The resulting colorful



CFD models (top) of the new football stadium in Atlanta (rendering left) showed engineers ways they could cut costs and still leave the fans feeling cool. *Image: Mercedes-Benz Stadium* graphic simulations depicted onscreen the most constructible and energy-efficient ventilation scenarios, taking into account such tiny details as the heat given off by spectators in the 75,000-seat arena.

With the simulation in hand, Southland engineers proposed a redesign of the 2 million-square-foot stadium that saved $800 million in labor and 500 tons of ductwork. The analysis determined that a ring of ducting would suffice for the dome's retractable roof, replacing the previously conceived crisscross design.

That ring-shaped ductwork design was put to the test in the preseason game and passed with flying colors.

One great advantage of CFD, particularly when dealing with unusual geometry, is its ability to predict the flow of fluids in a nonlinear manner that is counterintuitive, otherwise landing engineers' gut feelings about building specs way off the mark, which results in costly and time-consuming overdesign.

"CFD gives us a competitive advantage in validating our design," Scroug said. "It's driven by cost, but the performance can't be compromised." ME

MEREDITH NELSON is a writer based in New York City.

BIG NUMBER

26,150

NUMBER OF VEHICLES DELIVERED BY TESLA MOTORS IN THE THIRD QUARTER OF 2017

TESLA MOTORS is a high-profile automaker, but its production is minuscule compared to companies such as Ford, Toyota, or Volkswagen. Production is growing, however. The company announced in October that it had delivered 26,150 vehicles between July and September 2017, a 4.5 increase over its delivers for the same quarter in 2017. Of those vehicles, 220 were of the new, mass market Model 3, which has been troubled by production hiccups in the face of strong demand.

For more on electric vehicles, see Trending on page 28.

KOREAN SHIPYARDS, STEEL MILLS AT ODDS

The Korea Offshore and Shipbuilding Association urged the country's top steel producers to cut the prices of steel plates used for shipbuilding.

The association claimed in September that its member local shipyards are struggling with falling prices for their products and increased competition.

South Korea is home to three of the top four shipbuilding companies in the world: Hyundai Heavy Industries, STX Groups, and DSME. Three other South Korea are in the global top ten.

According to the Yonhap News Agency, South Korea's major shipbuilders and steelmakers have had difficult discussions about the setting steel prices that would be acceptable to both sides.

Steel producers, including POSCO and Hyundai Steel Co., have demanded that the steel plate prices be increased in tandem with a rise in the price of iron ore.

The shipbuilding association claimed that the price of iron ore has fluctuated in 2017, but had declined for the two years before that. It also claimed that an increase in the price of steel would make shipbuilding in Korea unprofitable.

In recent years, Korean shipbuilders have suffered from a decline in new orders and outright cancellations of existing orders, as a downturn in global trade and oil prices cut the demand for newly built ships. The country's top three shipyards suffered a combined operating loss of $7.53 billion in 2015.

Typically, thick steel plates account for roughly 20 percent of shipbuilding costs. ME

PRINTER COMBINES FIVE DIFFERENT TECHNOLOGIES

Buy a 3-D printer. Bring it home and use it to print out another 3-D printer. Return the original printer to the store the next day and get your money back.

Danny Rau and five other Virginia Tech grads have taken a tiny step toward making that joke a reality. Their Dream Machine combines five different 3-D printing technologies—filament extrusion, paste extrusion, vat photopolymerization, binder jetting, and material jetting—in one modular platform that lets users incorporate new printing technologies and swap between heated, reflective, and other types of build plates.

"What's super innovative about it is the modular build plate that allows you to switch plates depending whether your process is based on powder, resin, or extrusion," Rau said. "We have three different build plates, and the toolhead has five different processes on it, so we can mix and match."

That flexibility makes it possible to create complex objects that might include electrical wires, solid thermoplastic bodies, and flexible elastomeric segments. By combining photopolymerization and paste extrusion processes, for example, the student team was able to print a device with an embedded circuit board, a feat that would have taken several discrete processes in the past.

Aside from the multiple printing types, the Dream Machine also features a method of modular construction that will allow it to continue to grow and incorporate new technologies as they become available.

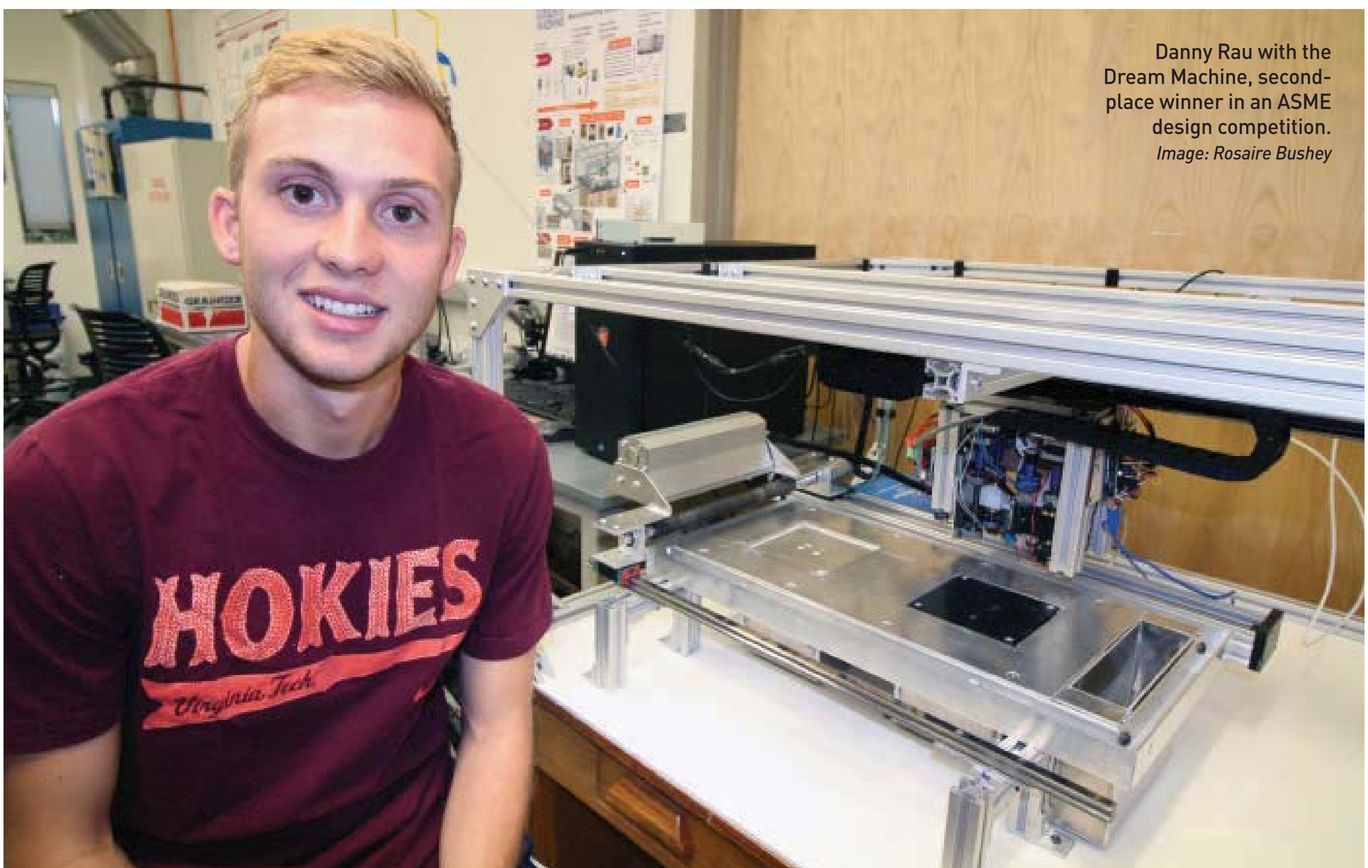
The printer, a senior design project, earned Rau and his former classmates second place in an ASME-sponsored design contest, part of this year's Manufacturing Science and Engineering Conference held at the University of Southern California.

"The thing that challenged us was the scope," said Rau, now a graduate student at Virginia Tech's DREAMS Lab. "We had to make five different printers, test them, and tune each one before integrating it into one system. I still don't know how we got it done."

Having presented the printer at conferences, impressing academics and industry reps alike, the young inventors have nothing but dreams of their own.

"If you look at the things you use every day, they are a combination of different materials," Rau said. "We're moving toward creating components. Now that we have the machine built, I'll spend my next year working on my master's and showing what this machine is capable of and the different parts it can make." **ME**

MEREDITH NELSON is a writer based in New York City.



Danny Rau with the Dream Machine, second-place winner in an ASME design competition.
Image: Rosaire Bushey

HITTING A TORPEDO WITH A TORPEDO

We are accustomed to smart bombs that are dropped from planes and guided to their target, but during the Cold War, Soviet engineers developed a torpedo that could hunt down its prey without human assistance.

Their smart torpedo used upward-looking sonar to detect a ship's wake, zigzagging from one side of the wake to the other until it reached the target. A ship in the crosshairs can't take evasive action because wherever it goes, its wake follows.

Now researchers at Penn State's Applied Research Laboratory have developed a means to stop the relentless smart torpedo.

When a sensor array towed behind the ship detects an incoming threat, sailors can launch a Countermeasure Anti-Torpedo Torpedo, or CAT, which is designed to find and destroy a wake-homing torpedo.

"It goes out with its own sensors, searches, determines its own targeting, and makes decisions on how to maneuver," said retired Navy officer Gary Watson, one of the project's managers. "The level of technology in the vehicle, nose-to-tail, is light years ahead of other torpedoes in our fleet. This is probably the smartest torpedo that's ever been produced."

"THIS IS PROBABLY THE SMARTEST TORPEDO THAT'S EVER BEEN PRODUCED."
GARY WATSON, PROJECT MANAGER

The Penn State's lab produced the CAT in about two years—full steam for a defense project.

The engineers at the lab cut development time by doing all their design and testing through simulation. That made it possible to design all the sections of the torpedo—each carrying different components such as the power supply or navigational instruments—in parallel, instead of the usual path of working on one system at a time.

When a section was ready for testing, the simulation filled in the missing pieces. The process not only cut development time, but the cost was about a half to a third of the cost of its predecessors.

The system is now being deployed on U.S. Navy ships, including the supercarrier USS *George H.W. Bush*. ME

A Navy contractor inspects a portion of the anti-torpedo torpedo system aboard the USS *George H.W. Bush*. *Photo: Tony D. Curtis/U.S. Navy*

PROGRESS IN MACHINE-SHOP PRACTICE

L. C. MORROW, CHAIRMAN OF THE MACHINE-SHOP PRACTICE DIVISION EXECUTIVE COMMITTEE

An engineer's view of industrial machinery.

LOOKING BACK

The Society was keeping abreast of factory-floor developments when this article first appeared in January 1928.

Most of the progress in machine-shop practice is indicated by the changes in machine tools. The first machine-tool exposition sponsored by the National Machine Tool Builders' Association, held in Cleveland in September, was therefore an index of such progress.

It thoroughly impressed the users of machine tools as to the extent and the solidarity of the machine-tool industry, and doubtless served to convince the machine-tool builder anew of the importance of his industry to civilization.

Progress in machine-shop practice can be shown best by a consideration of the details of changes in design of machine tools.

The demand of the machine user for greater strength, greater rigidity, and constantly higher speeds of production has been met by the builder with increase in weight, strengthening of critical sections, and a substitution of sturdier materials, especially in the more universal use of heat-treated alloy steels. Though the removal of great volume of metal is not of necessity a part of modern high-production methods, the ability of a machine to do so is, in a measure, a test of its capacity to withstand the shocks of high-pressure work without lowering its standard of accuracy and precision.

Anti-friction bearings have been incorporated extensively into the design of machine tools on rotating shafts, and in some cases on spindles, particularly on the spindles of drilling and grinding machines. Even on milling machines their use is quite common. At least one lathe builder uses them regularly on the spindle, and another supplies them as optional equipment. No standard practice in the application of anti-friction bearings has appeared. Some builders use only ball bearings, others only roller bearings, still others use both. On many machines the plain bearing has practically disappeared.

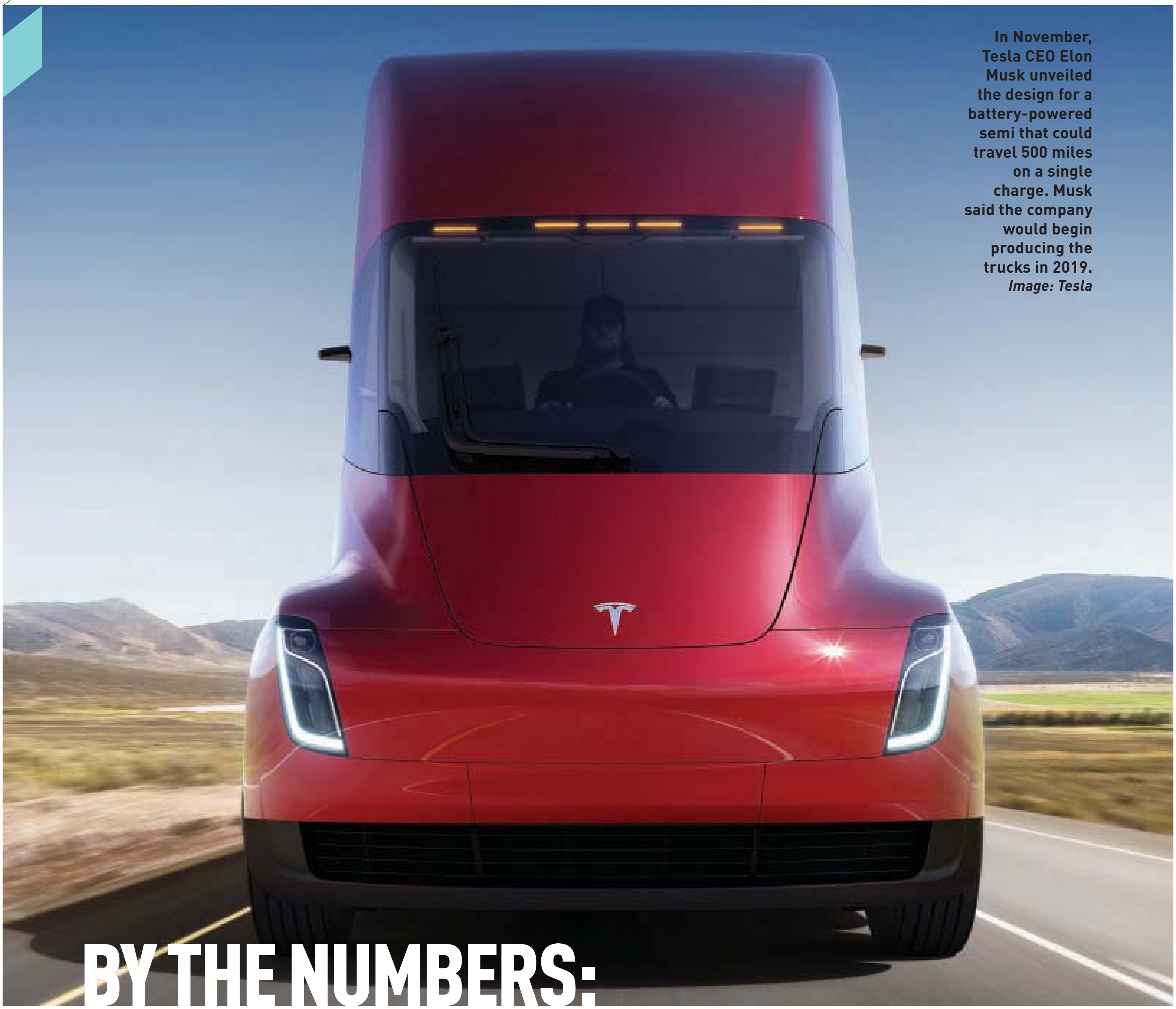
It is becoming more common practice to connect the rotor shaft of the electric motor direct to the first driving shaft of the machine through some form of compensating coupling. In many of the machines having movements of adjustment in several directions a corresponding number of motors is used, each motor driving the particular unit upon which it is mounted without reference to or connection with the other parts of the machine.

In spite of the growth of the method of driving through direct connection of motor to driving shaft, the method of transmitting power by means of a short belt or some form of silent chain remains the most popular. It permits considerable latitude in the matter of speed ratios, works well upon even very short center distances, and operates without noise. A check-up of half of the machines at the machine-tool exposition showed that approximately 57 percent were so driven. Another drive suitable for short center distances, and finding favor, is the multiple V-belt type. There are now several applications, and the indications are that its use will increase. ME

SLICED BREAD

The 1930s sliced bread revolution is mostly associated with Wonder Bread's marketing and popularity—by 1933, bakeries sold more sliced than unsliced bread. But the road to universal convenience began quite humbly. Iowa native Otto Frederick Rohwedder, who held a degree in optics, hatched the idea in 1912. During a brief career as a jeweler, he spent his spare time inventing machines, including one that used pins to slice loaves of bread automatically and wrap them for freshness. Despite his design blueprints being destroyed in the factory where he planned to build, he persisted. After many unsuccessful prototypes, Rohwedder got a break when pop-up toasters went mainstream in 1926 and he filed for a patent. The Chillicothe Baking Company in Missouri bought Rohwedder's machine and sold the first loaf commercially on July 7, 1928. Customers loved the product—called Kleen Maid Sliced Bread—declaring it the best thing since....

Otto Rohwedder's bread-slicing machine. *Image: Wikimedia*



In November, Tesla CEO Elon Musk unveiled the design for a battery-powered semi that could travel 500 miles on a single charge. Musk said the company would begin producing the trucks in 2019. *Image: Tesla*

BY THE NUMBERS: WILL TRUCKING GO ELECTRIC?

According to a new report, fleet owners may quickly adopt EVs for medium-haul routes.

The sounds and smells of the trucking industry are as much a part of American mythology as the jangle of the cowboy's spurs or the belch of coal smoke from a steam locomotive. For decades, diesel-powered semi-trailer tractors have pulled loads at high speed from coast to coast, providing not only the fodder for music and movies, but also the backbone of the just-in-time retail economy.

Trucking may remain economically important for decades to come, but according to a report late last year from McKinsey and Company, the diesel-powered tractor is in line for an overhaul. Much more quickly than most people might expect, the commercial vehicle sector will switch from internal combustion engines to battery-electric vehicles for many use cases.

The report says that, unlike consumers who often decide which passenger car or truck to buy based on emotion and faulty logic, fleet owners "place greater emphasis on economic calculations and reflect a greater sensitivity to regulation." When the total cost of ownership—encompassing not only the initial purchase price but also operating and maintenance costs—becomes lower for electric trucks than for diesels, fleets will switch over relatively quickly.

In some scenarios McKinsey looked at, that tipping point will come within ten years in local and regional cargo markets worldwide and before 2031 for even long-haul trucking.

But in some instances, the total cost of ownership makes electric trucks an economical choice today.

The report highlighted the regional light-duty delivery market in Europe, where fuel costs are higher than in the United States. "While most industry players focus on last-mile and urban-delivery solutions, the regional hub-and-spoke distribution approach is more advantageous," the report stated. "Vehicles in this use case could share passenger-car components and infrastructure to accelerate adoption." Light-duty regional electric delivery trucks would carry such items as groceries or flowers and be more stripped down and less capable than conventional diesel trucks. Even so, a battery range of about 70 miles would enable several deliveries per charge, and partial top-offs per day would keep the truck on the road.

Designing vehicles and business models around the capabilities of electric powertrains—capabilities that differ from those of diesel trucks—will enable battery-electric trucks to penetrate the market more quickly. It may be some time before we get a semi-trailer tractor capable of hauling containers coast to coast, but well before then, the McKinsey report declares, electric trucks will have become common enough to rewrite at least part of the mythology of the highway. ME

JEFFREY WINTERS

TYPICAL USE CASES COULD SPARK THE ELECTRIFICATION OF TRUCKS

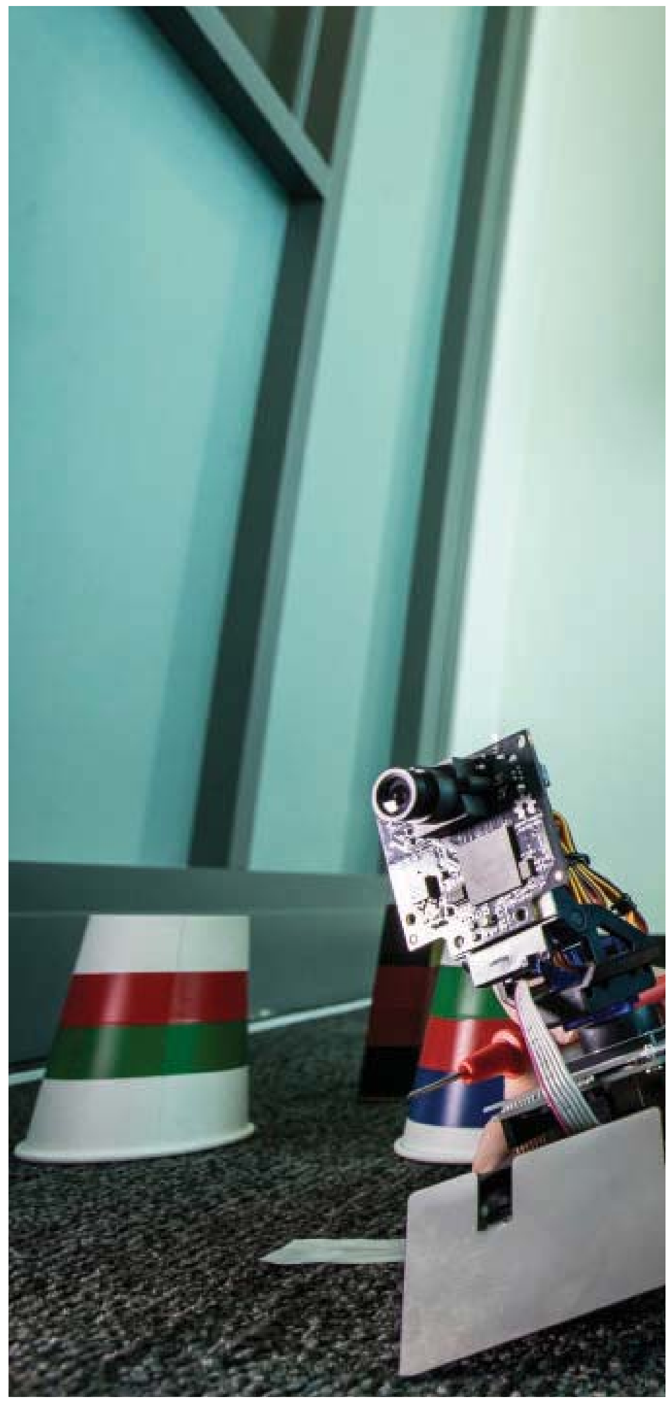
APPLICATION SEGMENT	SEGMENT PERSPECTIVE	EXAMPLE USE CASES	DATE OF TOTAL COST PARITY
Regional light-duty truck hub-and-spoke delivery	First truck segment to reach total-cost-of-ownership (TCO) parity, lowest entry barrier for battery electric vehicles	Regional grocery delivery for shops and restaurants	2017
Urban light-duty truck stop-and-go delivery	Second truck segment to reach TCO parity due to low share of battery cost	Urban last-mile distribution with central hub and many stops	2017-2021
Regional medium-duty truck hub-and-spoke delivery	Third segment to reach TCO parity due to balanced capital and operating expenditure	Grocery store chain with logistics center for several branches	2017-2023
Urban heavy-duty city bus	In China and US, buses have a lower share of battery cost in total capital expenditure than do trucks	Typical city bus or school bus with dozens of stops	2020-2023
Long-haul heavy-duty truck point to point	Parity for average users around 2030, due to large battery need, but up to 7 years earlier in beneficial use cases	International or continental freight logistics	2023-2031

Date of parity depends on region; Europe shown.
Source: McKinsey Center for Future Mobility.

Does Silicon Valley Have Enough Mech

The internet of things promises a world of digitally connected physical objects. But do tech firms have enough mechanical engineering talent to make it happen?

By Kayt Sukel



For those with the right skills, Silicon Valley has developed a system that can catapult the career of a couch-surfing coder to new heights, making him or her wealthy and perhaps even nerd-famous in the process. The model is simple: invest in startups with a handful of employees, avoid physical assets, and sell their final code across the internet. While many firms fail, others, like Google, Facebook, and Netflix, have changed their industries—and our lives—forever.

It's hard to disagree with renowned Silicon Valley entrepreneur Marc Andreessen, whose oft-cited 2011 *Wall Street Journal* essay argued that software is eating the world. Nor is it hard to miss how Silicon Valley's economic model offers few opportunities for mechanical engineers, the people trained to design physical machines and their components.

Until now.

A new digital revolution is upon us. In fact, Andreessen, Nostradamus-like fashion, foretold it. In the same essay that explained how software was eating conventional entertainment and retail alive, he predicted that it would start consuming the physical world. Now, seven years later, the most stubbornly physical of industry verticals—think agriculture, manufacturing, and construction—are getting their own virtual makeover through the internet of things (IoT).

anical Engineers?

Frederick Fourie of Microsoft combines programming, internet of things sensors, and mechanical parts to build a robot at a hackathon.
Photo: Microsoft

IoT, at its simplest, is not so much a technology as a model of connection. It makes it possible for just about any physical device—from a car or HVAC system to warehouse shelves or sensors—to connect to the internet and other devices. This makes it possible for users to remotely unlock the front door or collect critical data from a wind farm.

"IoT is not some technology fad," said Alfonso Velosa, an IoT analyst at the tech consulting firm Gartner. It goes beyond using a smartphone app to control the thermostat or dim the lights. Today, emerging networks of connected things are also becoming more important in industries ranging from healthcare to logistics.

"We are now seeing business leaders, across the world, wanting to implement IoT projects so they can make business transformations or get the data they need to make better business decisions," he said. "The conversation over the last few years has gone from, 'What is IoT?' to 'How can I make this work for my business?' "

In fact, Gartner estimates that the world will be home to over 26 billion connected devices in the next few years. The emerging rule of thumb is, anything that can be connected, will be connected. And as those connections grow richer, they promise to upend human and corporate behavior in ways that are every bit as surprising as the changes caused by the internet and smartphone technology.

As this revolution unfolds, it raises some very important questions. If the IoT seeks to control physical things that require an understanding of engineering principles—force, stress, and thermodynamics, for example—how will that change the role of mechanical engineers? And does Silicon Valley have enough skilled MEs to keep up with the IoT boom?

The Right Stuff, the Right Skills

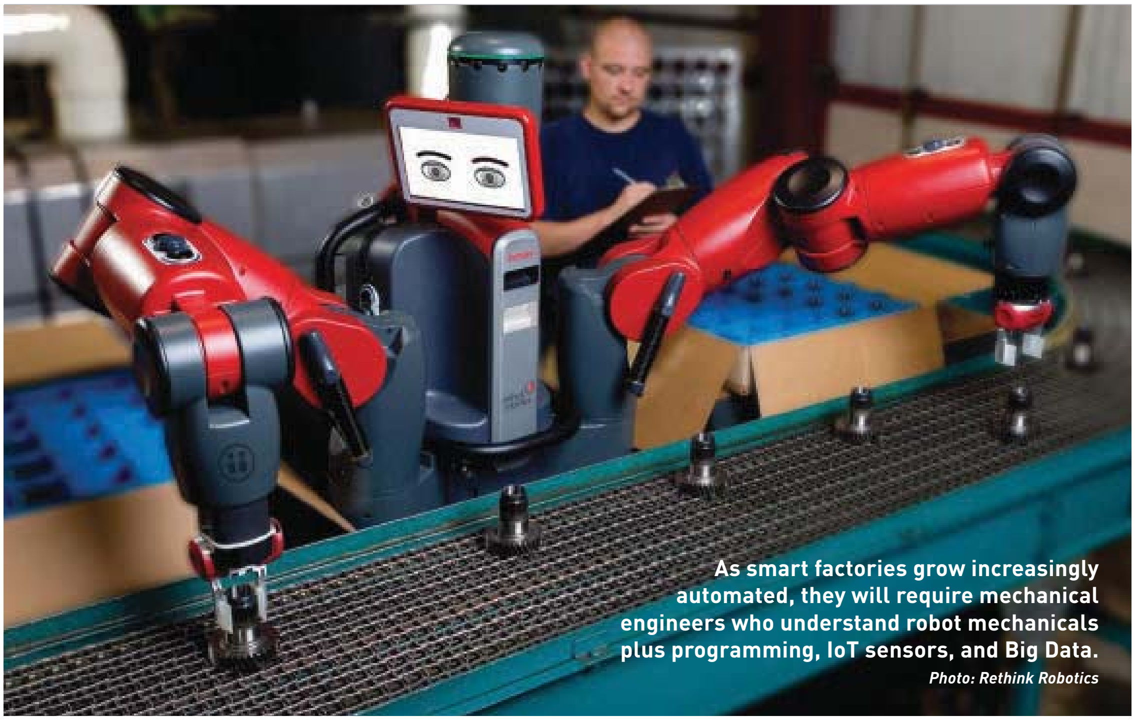
Companies will need employees who successfully straddle the line between information technology (IT) and engineering skills, said Ram Ramasamy, consulting manager for digital industrials at consultant Frost & Sullivan. He expects IoT demand to rise 11 to 14 percent annually over the next five years.

"We are going to see a convergence of sensors, assets, algorithms, cloud, and information and data needs," Ramasamy said. Hence, someone who has experience with industrial assets and mechanical engineering as well as IT skills will be the most sought after.

"There is a supply-demand issue right now. For so long, the world has had a single stream focus. You were either IT or operational technology (OT). We're now at a juncture where IT/OT convergence is driving change in skill set requirements. Companies want people who can do both," he said.

Those people are not easy to find. IT managers are reporting that hiring has gotten harder over the past year, said Rich Pearson, a senior vice president of marketing for UpWork, a global platform that helps businesses find freelance talent. While technical positions are always hard

Smart homes connect many devices that were once exclusively mechanical, such as HVAC, fans, appliances, power systems, and even window shades to the internet.



As smart factories grow increasingly automated, they will require mechanical engineers who understand robot mechanicals plus programming, IoT sensors, and Big Data.
Photo: Rethink Robotics

to fill, those that require IoT skills are especially difficult.

When Pearson ticks off employer needs, they include the usual computer science/IT skills, such as machine learning, web programming, and geographic information systems. Yet, they also include such mechanical engineering standbys as AutoCAD and Arduino software and hardware used to sense and control physical objects.

"We track the demand for different skills and, from an IoT perspective, we're trying to find freelancers as fast as we can to fill these jobs," Pearson said. "As long as the business world and the distribution models for products continue to evolve as quickly as they have done, we're going to see continued demand for engineers."

Those mechanical engineers, however, will have to bring something a little more than just traditional skills to the table, said William Oget, vice president of engineering for Prodea, a global IoT services operator.

"We're at the point where almost everyone needs some kind of understanding of software engineering," Oget said. "Perhaps everyone is a bit of an overstatement—but it's a must for engineers. Today, if you have a blind spot around IoT, if you have a blind spot around the cloud, if you have a blind spot around coding or data, you will be at a disadvantage especially since the efforts of mechanical engineers and software engineers will need to dovetail throughout the timeline of any IoT project."

Clearly, Silicon Valley needs a different type of mechanical engineer, one who is fluent in forces, thermodynamics, and process control—and also data science, informatics, and some basic IoT application programming.

"I call this new generation of engineers, 'digital engineers,' " Ramasamy said. "Codification of processes to make IoT faster, smarter, and simpler will be their defining role in the industries of the future."

Building Tomorrow's Engineer

Are today's mechanical engineering students learning the skills they need in order to become tomorrow's digital engineers? They should be, said Jonathan Cagan, co-director of Carnegie Mellon University's Integrated Innovation Institute in Pittsburgh. To compete for a job in the future, MEs must broaden their idea of what a mechanical engineer does.

Every engineer needs a basic set of IoT skills, and not just to send the right data to the internet, Cagan argued. They need to understand how accessing IoT data after it is processed will change how we design and build mechanical

Silicon Valley is looking at hackathons for engineers who understand how to build mechanical devices that work in an interconnected IoT world.

products to interact with one another and with humans.

"Today's mechanical engineer needs to understand how to design these things, and also how connectivity works, the advantages of connectivity, and how things need to function in a collaborative system," Cagan said.

Most university mechanical engineering programs require at least some basic programming. Yet Anthony Rueda, who is pursuing a master's degree in mechanical engineering at Carnegie Mellon after graduating with a B.A. in electrical and computer engineering, wonders if it is enough.

"The integration between mechanical engineering and computer science is at the forefront of Silicon Valley, no doubt," Rueda said. "And that may be why you don't see many mechanical engineers finding jobs there. There aren't enough mechanical engineers with a strong enough programming background."

Paul Steif, associate head of the mechanical engineering department at Carnegie Mellon, said the department is always adding courses to reflect new workplace demands, and to fill in perceived gaps in their students' education. They have already added some IoT courses.

"Last year, for example, we added a course in the internet of robotic things," Steif said. "We recognize there is opportunity here—a new area where students want to gain skills—and we are trying to meet that opportunity. We are definitely seeing that the whole connection between electronics, mechanical engineering, and computational processing is becoming more and more central to today's work. Being able to integrate the mechanical side—the actuators, sensors, and old-fashioned mechanical things—with the processing and computation is becoming more and more important."

IoT knowledge is also working its ways into traditional courses as well. At the University of California, Berkeley, in the heart of Silicon Valley, mechanical engineering professor Francesco Borrelli has been modifying his process control class to fit today's requirements.

"I can't teach the same class I taught five years ago," Borrelli said. "The field of IoT is evolving—but there is definitely a kind of skill profile that IoT companies are looking for.

"Mechanical engineers who work in this area will have to be comfortable with some programming. They will have to analyze and work with data. And, you know, not everything that is connected should be connected. Since it's the engineers that understand the mechanical design, they need to be able to help make a use case of why something should even be on the internet in the first place."

Borrelli's point on the field's rapid evolution is important. While most experts agree that IoT will be increasingly important in the future, it has not quite reached the anticipated feeding frenzy status. One reason, Gartner's Velosa said, is because companies are having such difficulty finding the right people to staff current projects. He expects that 75 percent of IoT projects will take up to twice as long as planned through 2018.

That skills shortage is a global problem, Velosa said. "I see more capabilities in North America because educational institutions are now realizing the importance of IoT. Yet IoT is not about some abstracted model of a physical asset. You have to understand the physical asset—how it works and how it is used. High levels of abstraction can only take you so far. We need more people who can work in that physical space."

Prodea's Oget, whose firm recently acquired another IoT company, agrees. So where is he looking for more mechanical engineers?

"Anywhere we can find them," he joked.

"The top universities are mostly great," Oget said. "But I'd love to see more flexible, innovative programs where there are partnerships between universities and companies and students are working on IoT internships and bringing that knowledge back to the classroom," he said.

Prodea, like many other companies, still recruits engineers through job sites and at job fairs and technical opportunity conferences at the top universities. It fills immediate needs through freelancer work platforms.

Until the market fully matures, and companies know exactly what skills they will need from tomorrow's mechanical engineers, Oget has a piece of unorthodox advice: participate in hackathons.

Hackathons are sprint-like design events where computer geeks collaborate intensively to create usable—and perhaps even commercially viable—software. Once the sole province of computer science majors, hackathons now embrace autonomous robots, smart homes and cities, driverless cars, and other IoT standbys.

These festivals provide many opportunities for mechanical engineers to show off their practical IoT skills. They are a boon for students just entering the job market, and also established engineers who are looking to expand and showcase their IoT capabilities.

"Go to these kind of events, show your skills, have fun, meet people," Oget said. "Go to an accelerator, to a crowd-funding meet-up, to places where new ideas and start-ups are discussed. You may discover a company that would have never been able to explain why they need you and your skills, but will realize they need you once they see you in action."

Those companies are surfing the IoT wave. After decades of ignoring hardware, Silicon Valley is rediscovering its physical assets. It may not know exactly what skills it needs now or will need in the future as IoT evolves, but it is ready to start talking to mechanical engineers.

"It's clear that Silicon Valley does not have enough mechanical engineers," Velosa said. "It does not have enough people who understand how these interconnected physical things work in the real world.

"Right now, we are at the beginning of what will be a ten- or twenty-year journey. We barely understand how these things that we are connecting work, how or why or where they should connect to one another, how we can or should use the data we collect from them. But we are learning as we go.

"There are a broad range of challenges. But within those challenges, there are also a huge set of opportunities, not just for mechanical engineers but for the other professional fields that can help us address them," Velosa said. **ME**

KAYT SUKEL is the author of *The Art of Risk* and covers science and technology from outside Houston.

It took engineers and computer scientists to design NASA's virtual reality glasses.
Photo: NASA

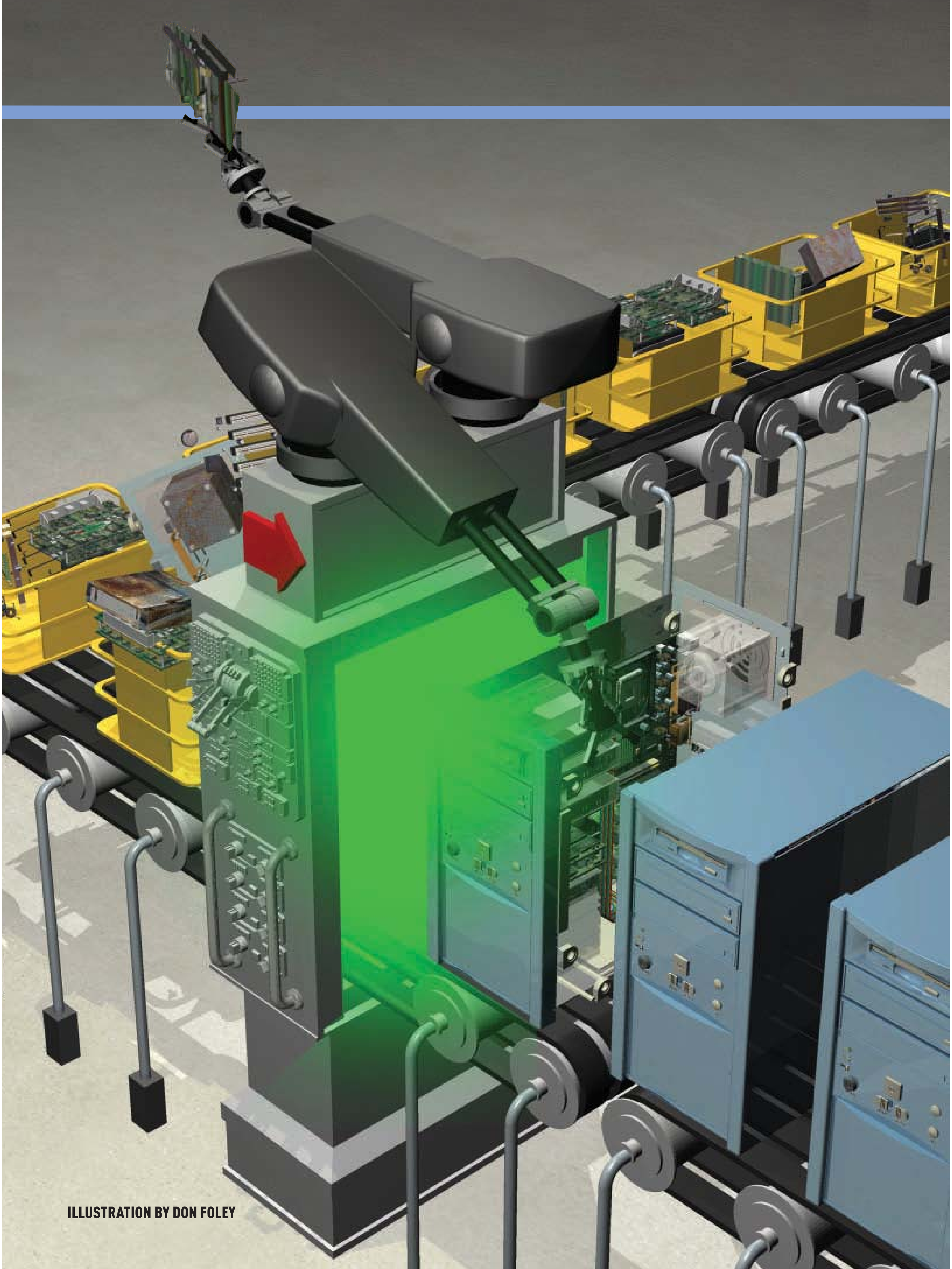


ILLUSTRATION BY DON FOLEY

MINIMAL SOLUTIONS

Manufacturers are working with researchers to develop ways to make products using less material and energy.

BY R.P. SIEGEL

Xerox's Webster manufacturing facility outside Rochester, N.Y., produces 24-foot long high-speed, high-resolution printers that sell for upward of half a million dollars. The process involves highly skilled union labor. These printers are the kind of products that most people can't imagine being made profitably in the United States anymore. But Xerox has a secret weapon that make the economics work: remanufacturing.

A vast majority of Xerox printers are leased, so the company retains ownership and responsibility for the machines throughout their life cycles. The company spent over $1 billion developing its iGen series of production printers based on a platform architecture and design intended to support remanufacturing.

Old iGen3 models coming off leases are returned to the factory to be converted into iGen4 and iGen5 machines. Remanufactured equipment is sold at the same price as brand-new, under the same terms and conditions and the same total satisfaction guarantee, even though it is less costly to produce a remanufactured printer than a new one.

According to Kevin Kelley, plant manager at the facility, "There's an exchange that occurs when the customer trades in the old model and gets the latest and greatest version and we then transform the old machine into a new one."

Xerox has been doing "reman" in one form or another since the 1960s. This has worked out well from every perspective including cost, quality, safety, and customer satisfaction.

Walking down the assembly line, Kelley pointed out how the returned "cores," as they are called, are stripped down to the frames, which are cleaned, inspected, and repainted. Internal modules are dispatched for various types of processing, which could include anything from cleaning, testing, various levels of refurbishing and updating, or recycling, with a significant portion being eventually fed back into the line and "model mixed" along with new-build products.

Manufacturers looking to make American factories more competitive with foreign-based facilities are finding opportunities through re-engineering long-held wasteful practices. To a large degree the U.S. economy is a linear one, where raw materials are dug or drilled from the ground, processed into feedstocks, and then turned into products. Those products generally have a brief life, are tossed out—usually into landfills where they are never seen again—and the cycle starts over again. Substantial energy is consumed at each step, particularly in the production of raw material.

The system was designed at a time when energy was cheap, alternatives few, and awareness of environmental considerations missing. None of that is true today, and the World Economic Forum estimates waste could cost $25 trillion between now and 2050.

REMANUFACTURING, WHICH CAN REDUCE that waste stream considerably, employs 180,000 people in the United States and is valued as a $43 billion industry, according to 2012 Department of Commerce data. Today it is in the $100 billion range once the military is factored in, said Nabil Nasr, chair of the Sustainable Manufacturing Innovation Alliance at the Rochester Institute of Technology.

"But the intensity is only 2 percent," Nasr said. "If you could double that to 4 percent, we're looking at quite a few new jobs.

"A lot of people think of recycling and remanufacturing as dirty and boring," Nasr continued. "It's a green field for innovation because so much has to be rethought. We've been doing things without thinking about the environmental impact. There is tremendous room for innovation."

The concepts underlying circular economics and the awareness of the energy embodied in products have been around for some time, but the size and complexity of the supply chains involved have made it a challenge to study in a rigorous and comprehensive way.

To learn more about these concepts and how to apply them to real-world manufacturing, the U.S. Energy and Commerce departments, along with the National Institute of Standards and Technology, established the REMADE Institute in 2017. REMADE is a backronym for "reducing embodied-energy and decreasing emissions" and is chartered to "reduce life-cycle energy consumption and carbon emissions associated with industrial-scale materials production and processing." The institute coordinates activity among universities, private companies, industry trade associations, and seven national laboratories.

REMADE aims to develop technology enablers to accomplish such goals as reducing primary feedstock consumption in manufacturing by 30 percent, reducing energy demand of secondary material processing by 30 percent, and achieving a 25 percent improvement in embodied energy efficiency of materials such as metals, polymers, fibers, and electronic waste.

As part of a multi-pronged approach, Pradeep Rohatgi, professor of materials science and engineering at the University of Wisconsin-Milwaukee, is leading an effort at REMADE to examine manufacturing processes. Drawing on his experience in India developing low-energy manufacturing systems such as solar furnaces, Rohatgi is focusing on reducing energy.

Bringing in embedded energy as a criterion for material selection, he said, will have a major impact on the design process, energy consumption, and the environment. "It will likely also trigger some fundamental advances in materials science," he said.

> "Can we design products in a way that allows us to more easily recover materials?"
>
> —MAGDI AZER, Illinois Applied Research Institute

Adding embedded energy to more traditional criteria such as strength, weight, stiffness, durability, and cost, expands the scope of any life-cycle analysis applied to products and could very well tip the balance in favor of a new material over another that had traditionally been used.

For instance, automakers have started making substantial portions of their vehicles, such as the Ford F-150 pickup and the Audi A8, from aluminum rather than steel. That switch to aluminum improves life-cycle energy use because the metal is lighter than steel, improving fuel economy. But from an embedded energy perspective, an even better choice would be recycled aluminum, as that requires 95 percent less electricity per ton to produce than raw aluminum.

Another approach for reducing embodied energy in aluminum production, Rohatgi said, is to replace a portion of the metal with filler materials, such as fly ash.

A worker at Xerox's Webster manufacturing facility refurbishes a high-end printer. These remanufactured machines sell for the same price and on the same terms as new ones.
Image: Xerox

The move to building automobile bodies from aluminum improves both life-cycle energy use and fuel economy.
Image: Audi

Casting is another area of opportunity. Today, castings yield only 40 to 50 percent of the material poured. Advanced models, combined with experimental results, can more accurately predict shrinkage and provide specific surface finishes, eliminating the need for secondary operations such as grinding, polishing, or machining as well as reducing flash and dross. This approach, known as near net shaping, can also be applied to ceramics, composites, and plastics in addition to metals.

With embedded energy as the measuring stick, it is also possible to find manufacturing processes that produce very low life-cycle energy costs using carbon fiber composites or high-strength steels. The use of plant-based materials should also be considered, Rohatgi said.

In order to economically recover reusable materials from the waste stream, advanced separation techniques are needed. According to Eric Peterson, an inorganic chemist at Idaho National Laboratory in Idaho Falls, recycling of polymers is hampered by the tendency of mixed plastics to deteriorate when melted together. The recycling efforts at REMADE are investigating how mechanical separation followed by a chemical process can extract valuable polymers cleanly from a mixed stream. One of the institute's industry partners—a company that shreds automobiles for scrap—has been looking for exactly such a solution to allow it to recover and utilize much of the plastic found in today's cars.

Another research group at the University of Utah has developed a new method for separating metals. Electrodynamic sorting, a hybrid approach utilizing magnetics and eddy currents, can separate stainless steel from aluminum alloys. Peterson hopes that efforts like that will help enable the sorting of nonmagnetic alloys for recycling.

Refurbishing worn products is another approach to retain the energy already embedded in it to reduce the cost of manufacturing. Michael Thurston of the Golisano Institute for Sustainability at the Rochester Institute of Technology, said his group was looking at materials that could withstand powerful, heavy surface cleaning, and whether that sort of process would make it more economical to clean nuts and bolts rather than replacing them.

Thurston's team has also developed the capability to restore parts through additive processes. A flame-sprayed polymer coating and high pressure cold sprays have enabled researchers to build up material thickness for dimensional restoration on mechanical parts that have experienced wear or corrosion or cracking, allowing them to be reused. The hope is that this sort of additive restoration could be done for a fraction of the economic and energy cost of fabricating new parts.

Researchers also recognize that in addition to these manufacturing technologies, supply chain management and industrial design are key disciplines for reducing the embedded energy in products and increasing the amount of manufactured parts that can be recycled. Magdi Azer, associate director for manufacturing science at the Illinois Applied Research Institute and REMADE's chief technology officer, asked, "Can we design [products] in a way that allows us to more easily recover materials?"

Companies that lease products rather than sell them outright have a decided advantage in understanding the life-cycle cost of their products.

> "If you're a company that's only manufacturing a product, you're only doing half your job."
>
> —NABIL NASR, Sustainable Manufacturing Innovation Alliance

XEROX TRACKS the performance of machines in the field through remote diagnostics, which enables the company to quickly identify any trends that occur. Robust information systems allow technicians to look up a serial number and see a machine's entire history, including its prior incarnations before remanufacture. Signature analysis stations, which test electromechanical components to determine whether they had sufficient life remaining to be safely sent back out into the field, are being replaced by a combination of remote monitoring and big data analysis.

Thanks to a shift toward circular economic thinking, Xerox has been able to drive down costs in its U.S. facilities, enabling the company to resist the temptation to move work to countries with lower labor costs.

During a tour of the Webster plant, Kelley (who has since left the company to begin a job with the Sustainable Manufacturing Innovation Alliance) pointed out one line where the product had been outsourced to a contract manufacturer in Mexico. The company gave the workers in the upstate New York plant the opportunity to see if they could produce the same product at a competitive price.

"We're kind of costly up here," Kelley said, "so we need to be a little smarter in how we do things. This is one area where we are really leveraging remanufacturing." After the cost of shipping the cores down to Mexico and the completed products back up north was figured in, the company decided to bring the work back in-house.

Another innovation that Xerox has been using in the remanufacturing process is CO_2 cleaning. Liquid carbon dioxide is pumped through a pelletizer machine, picking up rice-size grains and spraying them under pressure at machine parts to gently strip away dirt. Unlike solvents or water, which must be carefully disposed once used for cleaning, the liquid CO_2 sublimates into a gas under normal pressure and can be collected by a fume hood for recycling.

In a sense, the idea of a product being a fixed and static thing—representing an endpoint once it has been produced—is no longer a given. Instead, Xerox and scattered research labs of the REMADE Institute have provided a vision of a product being an amalgamation of parts and materials that are in perpetual flux that we might use for various periods of time and then return like library books where they can be redistributed.

"If you're a company that's only manufacturing a product," Nasr said, "you're only doing half your job."

That might not sound as exciting or sexy as designing the next electric car or smartphone, but it is fundamental to the proposition that we can continue to build products for generations to come, because that can only happen if we learn to do it sustainably. **ME**

R.P. SIEGEL is a technology writer based in Rochester, N.Y.

David Camarillo coupled sensors to mouthguards to provide the clearest picture yet of the rotational accelerations that cause concussions.
Photo: Saul Bromberger and Sandra Hoover

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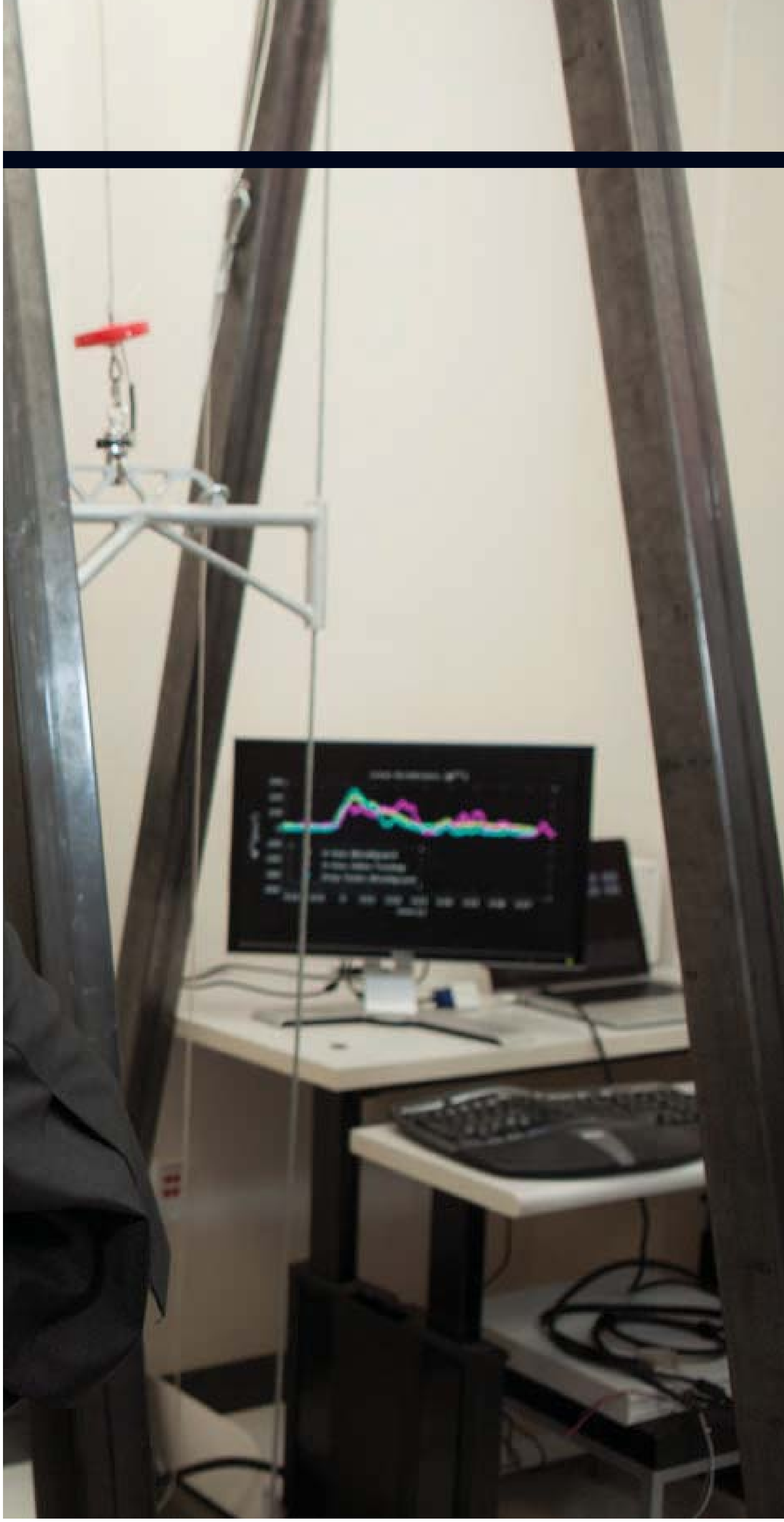
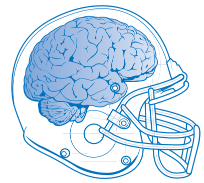


IMPACT

A new way of measuring the forces that cause head injuries could change how engineers protect professional and weekend athletes.

JAMES G. SKAKOON



MOST FOOTBALL FANS HAVE SEEN a player dragged off the field after a shot to the head as an announcer says, "He really got his bell rung." That makes it sound as if his brain was clanging back and forth in his skull like the clapper in a bell.

However, that image is entirely wrong. In 1943, British physicist A. H. S. Holbourn argued that the brain is not loose enough to rattle against the skull. Instead, using math and a gelatin model of the brain, Holbourn showed that shear strains caused by rotation were the likely culprit for most concussions.

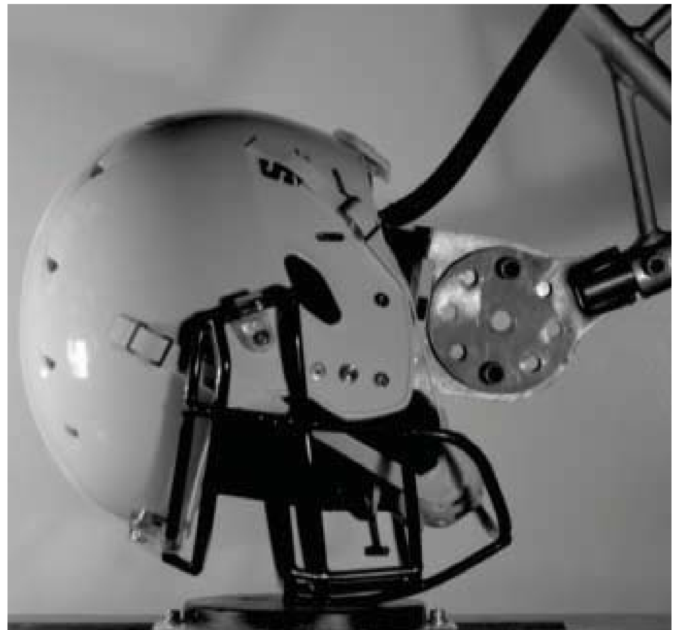
But how? While most engineers and physicians eventually came around to Holbourn's point of view, they had a difficult time measuring rotation of the head accurately. As a result, they could not explain or model exactly how rotation damaged the brain or how they might prevent it.

That has changed, thanks to an innovative methodology developed by researchers at Stanford University. The team, led by bioengineering professor David Camarillo, has not only collected more accurate data, but has used it to develop models that provide critical insights into mechanisms that cause concussions and ways we might protect against them.

MOUTHGUARDS

In the past, most researchers mounted sensors, mostly accelerometers, either on helmets or directly onto the skin. Unfortunately, those sensors did not couple tightly with the cranium, so the data could be off by a factor of two or more. Moreover, they only recorded linear acceleration, ignoring rotation.

Camarillo, who played football at Princeton University, realized he could overcome those limitations by embedding



Camarillo, a former football player, uses sensors to measure forces affecting the brain. *Images: Stanford News/ Kurt Hickman*

sensors in the athletic mouthguards used by football players, who are prone to head injuries. These protective devices, developed in his CamLab laboratory, fit snugly over the teeth of the upper jaw. By embedding both accelerometers and gyroscopes within the mouth guards, the laboratory tracked all six degrees of freedom and slashed data errors to 10 percent or less.

The sensors include a triaxial accelerometer and a triaxial gyroscope to measure rotation, said Lyndia Wu, a CamLab doctoral candidate. They enable engineers to record motion in three linear and three rotational directions. The sensors resemble those found in smartphones, but have much higher dynamic ranges (up to 100 g for the accelerometers).

"Wearable sensors that collect inertial data can register high-acceleration events on the field that are not head impacts," Wu said. So to filter out unwanted data, like a player tossing a mouthguard to the ground or chewing on it, CamLab researchers added infrared position sensors to the mouthguard, and created data-processing algorithms that discarded irrelevant events.

To outfit players on the Stanford football team with the new mouthguards, the investigators first obtained a dental mold from each athlete's upper teeth. Then they used it to form a base layer of molded plastic, fastened the sensors and electronics to that layer, and covered them with a second layer of thermoplastic.

"It's more or less like a regular mouthguard, with only a little bit of added bulkiness," Wu said.

"If you make a device that's custom fit to [each athlete's] teeth, it snaps in and holds tightly," Camarillo added.

Since the upper teeth are firmly coupled to the bones of the cranium, the mouthguards can provide data accurate enough for the lab to use in finite element models to describe what is happening inside the brain.

ANATOMY LESSONS

Holbourn originally argued that linear acceleration would create only hydrostatic pressure, rather than displacement, and would not damage the brain. This is because the brain is highly hydrated, so it behaves much like a liquid and is incompressible. Moreover, it is suspended in cerebrospinal fluid, which fills all voids inside the rigid cranium that surrounds it completely, so the brain has no room to move.

"The best analogy for what is going on is a snow globe," said Fidel Hernandez, a recent CamLab doctoral graduate. "If you move the globe in a straight line, even really quickly, the water and flakes inside won't move."

Neither will the brain. "There's actually no evidence of that," Hernandez said. "You don't get a lot of brain movement, because it has nowhere to go."

Yet even a slight rotation will agitate a snow globe's flakes due to the shear manifested in the fluid. In engineering terms, Hernandez said, the brain has a very high bulk modulus and a very low shear modulus; it resists compression because of the former, but changes shape readily when rotation causes shear.

Hernandez and the team needed to measure both translation and rotation to understand the mechanics of a concussion. Using the instrumented mouthguards, CamLab collected a library of head impact events from the Stanford football team. While most produced no concussions, two did. In one case, a player lost consciousness right after impact.

Hernandez found this event differed greatly from other impacts. The player lost consciousness after rapid coronal rotation, where his head moved from near one shoulder to the other.

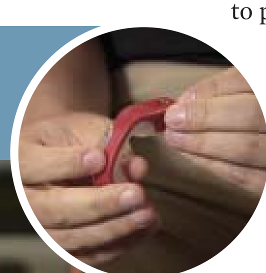
Hernandez input the incident's kinematics data into a finite element analysis model of the brain developed by the KTH Royal Institute of Technology in Sweden. This enabled him to simulate how different structures within the brain responded to the impact, he said.

Hernandez focused on one structure, the corpus callosum, a bundle of nerve fibers connecting the brain's right and left hemispheres.

"It stands to reason that if this structure were damaged, it would produce many of the symptoms that we associate with concussion, like loss of balance and impaired depth perception," Hernandez said.

But the corpus callosum lies deep within the brain, so how would the force of an impact reach it?

Customized mouthguards couple tightly to the skull, to measure forces accurately.
Images: Stanford News/Kurt Hickman



According to Camarillo, most of the brain is like Jell-O, gooey and almost soupy. Yet some structures within the brain are much stiffer. This led him to hypothesize that injuries could occur at the interface between tissues that have very different material properties. Stiffer structures could provide a pathway for energy to penetrate the brain.

Hernandez's computer simulation showed that the falx cerebri appears to be the culprit. It is a rigid vertical sheet that separates the brain's two lobes. It lies right above the corpus callosum and extends upward, attaching to the skull at the very top. It conducts impact energy from the skull deep into the brain, where it oscillates and induces strain in the corpus callosum, Hernandez said.

"We found the strain in the corpus callosum [that the injured athlete] experienced was far larger than for any of the subconcussive impacts we had recorded," Hernandez said. He believes that this mechanism is one likely cause of chronic traumatic encephalopathy, or CTE, a debilitating illness suffered by many professional athletes.

FIELD GOALS

Camarillo wants to use these findings to prevent head injuries, and his interest is personal. Besides playing football at Princeton, but has been injured twice in bicycling accidents despite wearing a helmet.

"You can see some of my motivation," he said.

He argues that today's sports helmets are designed to prevent skull fractures and can save lives. Yet they clearly do not prevent mild traumatic brain injuries like the concussions that can lead to CTE and other maladies.

Although his lab has tested helmets, improved evaluation methods, and helped redefine industry standards, Camarillo's focus is on developing sensing technology.

"Getting good measurements has turned out to be much trickier than you would think," Camarillo said. But his lab has been able to make the first-ever measurements of head rotation during concussions. Now he hopes other researchers will use the lab's methodology to build a database of head injuries.

That would be a giant step toward reducing sports-related concussions. "Until we understand the mechanics of an injury, how do we know the kind of helmet we should be designing? Or if the next one is better than the last?" Camarillo said. **ME**

JAMES G. SKAKOON is a retired mechanical design engineer in St. Paul, Minn., and a frequent contributor.

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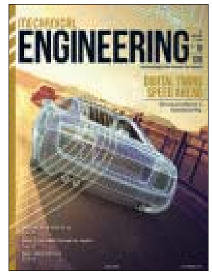

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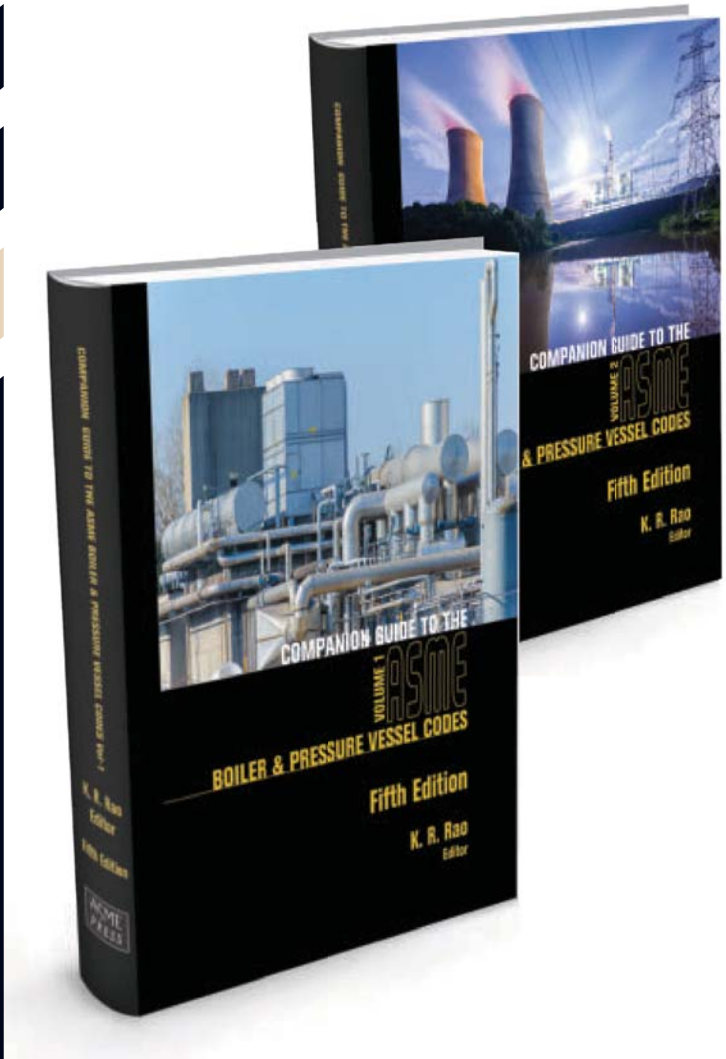


FEATURED

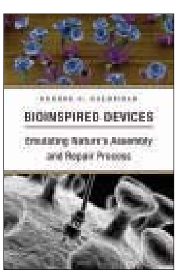
COMPANION GUIDE TO THE ASME BOILER & PRESSURE VESSEL CODE, VOLS. 1 AND 2, FIFTH EDITION

K.R. RAO, EDITOR

ASME Press Books,
Two Park Avenue, New York, NY 10016. 2018.

This fully updated and revised fifth edition of the classic reference work is current to the latest ASME BPV Code release. It is available in a convenient two-volume format that focuses on all twelve sections of the ASME Code, as well as the relevant piping codes. The 51 authors who have contributed to the guide's 40 chapters have updated the text, tables, and figures of the previous edition to be in line with the 2015 Code and topics pertinent to the 2017 B&PV Code, bringing the insight and knowledge of these experts in updating the previous edition. In his introduction, Rao gives a special acknowledgement to the newly added authors, who have provided additional perspective. Some chapters have been entirely rewritten, Rao writes, making this new guide more than a perfunctory update.

TWO-VOLUME SET: 1,800 PAGES. $629; $499 ASME MEMBER.
ISBN: 978-0-7918-6129-5

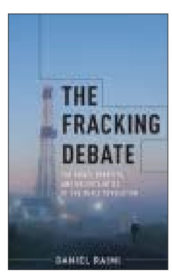


BIOINSPIRED DEVICES: EMULATING NATURE'S ASSEMBLY AND REPAIR PROCESS

Eugene C. Goldfield
Harvard University Press,
79 Garden Street, Cambridge,
MA 02138. 2018.

Robots are the ultimate mechanical devices, but most still have a biological inspiration, whether it is the welding arm reaching down on the assembly line or the long wings of the military drone aircraft. Goldfield presents the natural inspirations for many of these robotic adaptations, including eyes, ears, and nervous systems as well as legs and wings. Even animals are made of component parts, he writes, which are organized and coordinated into functioning beings. Until technologists fully understand and harness such emergent properties at every level—from cells and molecules all the way to organs—they will struggle at integrating robotic systems with living creatures.

480 PAGES. $45. ISBN: 978-0-6749-6794-6



THE FRACKING DEBATE: THE RISKS, BENEFITS, AND UNCERTAINTIES OF THE SHALE REVOLUTION

Daniel Raimi
Columbia University Press,
61 West 62 Street,
New York, NY 10023. 2017.

The low oil prices that the world has enjoyed in the past few years have been due in large part to the unconventional petroleum process known conventionally as fracking. Raimi, who teaches energy policy at the University of Michigan, addresses many of the questions commonly asked about the technology, which has labored under fears concerning polluted water supplies, swarms of earthquakes, and industrial machinery overrunning the countryside. Raimi worked to bring stories from communities directly affected by shale oil drilling and strove for balance, but with an issue so fraught with emotion, many people will see balance as an unnecessary concession.

280 PAGES. $30. ISBN: 978-0-2311-8486-1

COMSOL NEWS

SPECIAL EDITION **ACOUSTICS**

Computational Acoustics Provides Early Insight and Predictive Ability in the Design Process

When we discuss acoustics, the first images that might come to mind are of a loud subwoofer or a concert hall with all of its sound baffles. But there are many more acoustics applications that we come into contact with everyday. Acoustics is a multidisciplinary science requiring engineers to resort to all of their ingenuity and the most powerful mathematical modeling tools to create products that satisfy many customers' requirements.

This special edition of *COMSOL News* celebrates designers, engineers, and researchers working in the field of acoustics. As you will see by reading their stories, the common denominator is a passion for high-fidelity multiphysics modeling, flexibility, and the ability to share their work with colleagues and customers through simulation apps.

From virtual product development to NVH performance, acoustic cloaking, and feedback reduction, I'm sure you will feel inspired from reading about the many ways computational acoustics drives the solution of practical problems and the design of innovative products.

Enjoy your reading!

Valerio Marra
Marketing Director
COMSOL, Inc.

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COMSOL NEWS

Special Edition
Acoustics

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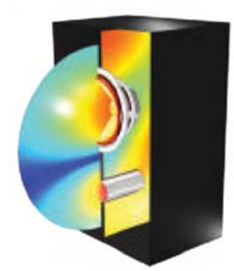

ON THE COVER

Adventure-touring motorcycle Mahindra Mojo. Image credit: Mahindra Two Wheelers Ltd.

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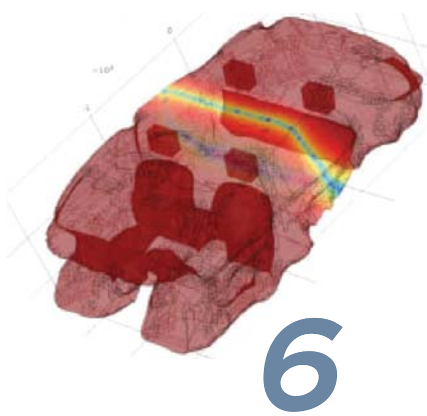
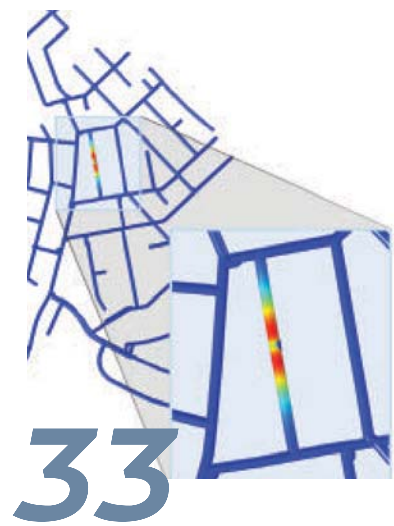
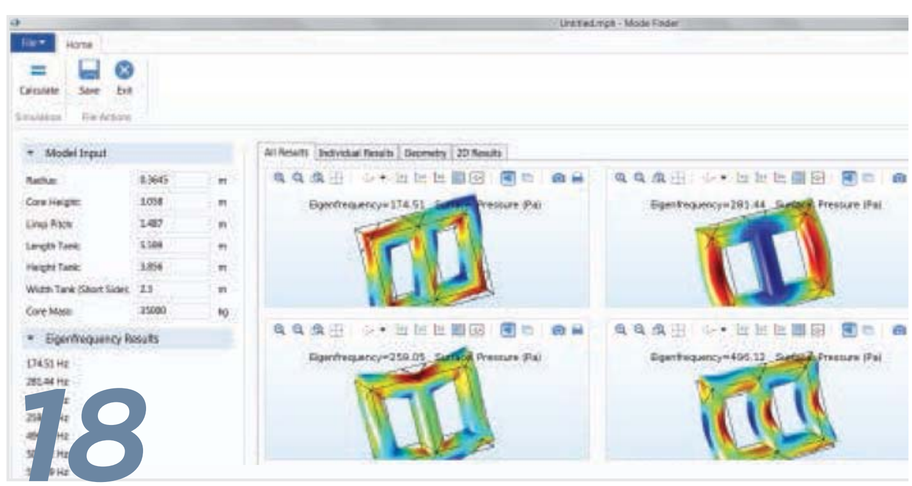
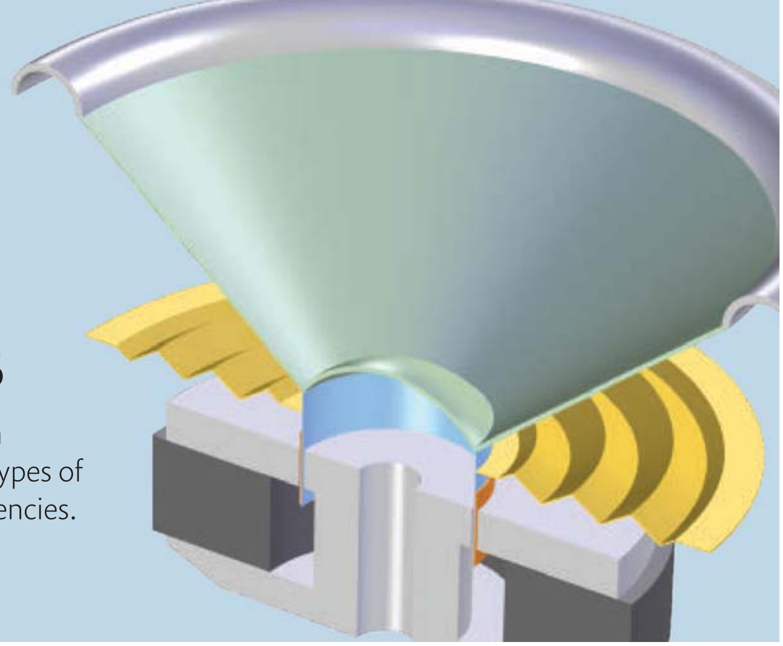






MAKING THE CASE FOR ACOUSTIC MODELING AND SIMULATION APPS



Acoustic phenomena are multiphysics in nature. When building a model, engineers must account for several types of physics and their coupling at different scales and frequencies.

by MADS J. HERRING JENSEN

With increasingly complex systems and tighter project deadlines, acoustical engineers are turning to numerical simulation software to get the job done. By using computational tools, design tasks can be accelerated and the need for costly and time-consuming physical prototypes can be reduced. Acoustics simulation also increases the understanding of a design, leading to better informed decisions and higher-quality products.

To reap the benefits, what capabilities are important in acoustics simulation? Applications often include the reproduction, propagation, and reception of sound signals under diverse conditions. This includes not only the interaction of the sound signal with structures, porous materials, and flow, but also modeling the transducers involved in the generation and detection of the sound signals. All these are multiphysics problems by nature that acousticians have to consider for the efficient development of new products and technologies. This places a critical requirement on the modeling software in terms of the ability to couple physics effects relevant to the full system.

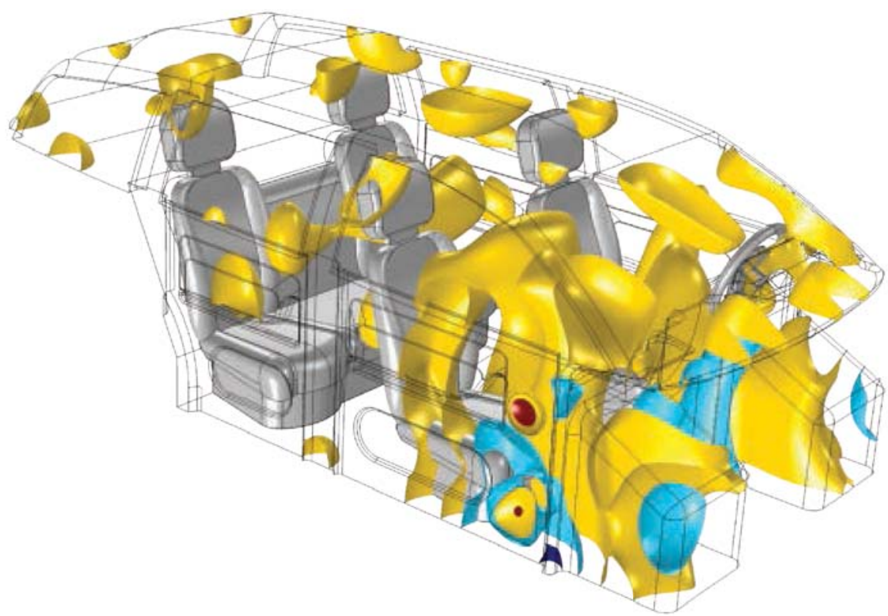


FIGURE 1. Acoustics simulation of a sedan interior including sound sources at the typical loudspeaker locations. Results show the total acoustic pressure field inside the cabin.

⇨ CURRENT TECHNOLOGICAL CHALLENGES IN ACOUSTICS

Sound quality is a trending topic in many industries. This concerns the reproduction of sound inside, for example, car cabins (Figure 1) or the output from the exhaust and muffler systems. Other examples include the performance and optimization of headphones and loudspeakers or the speaker system of mobile devices. In all of these cases, a detailed understanding of both sound propagation and transducer behavior is necessary to optimize the systems. Clever digital signal processing is not enough anymore to make systems behave and "sound good". For example, to improve the performance of hearing aids using adaptive feedback canceling, a coupling of a miniature loudspeaker vibroacoustics model with an acoustic and solid mechanics finite element (FE) model is needed for producing accurate simulation results.

In the loudspeaker industry, a standard driver design has reached the limit of where improvements can be done by simple trial-and-error testing (Figure 2). Optimization requires detailed numerical analysis. Miniature loudspeaker systems are now driven at such high sound pressure levels that distortion and attenuation due to nonlinearities are introduced. The same nonlinearities also play a significant role in liners in aerospace applications.

Another example involving a multiphysics coupling — electrostatics, structural membranes, and thermoviscous acoustics — is the modeling of condenser microphones. The physics are tightly coupled and all necessary for a correct prediction of the microphone sensitivity.

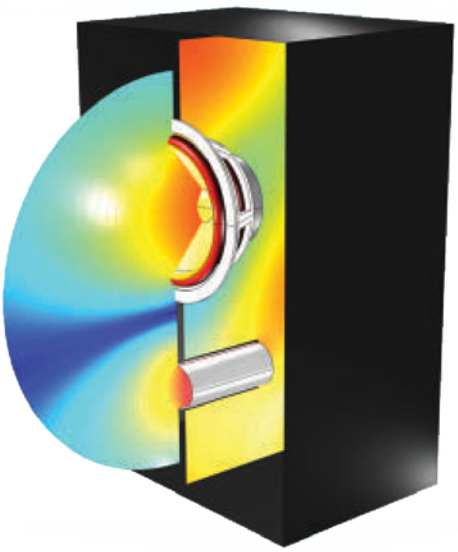


FIGURE 2. Simulation results showing the sound pressure distribution in a loudspeaker driver enclosure.

⇨ COMSOL MULTIPHYSICS AND THE ACOUSTICS MODULE

The Acoustics Module, an add-on product to the COMSOL Multiphysics® software, is ideally suited for modeling the many decades of frequencies involved in acoustics, ranging from infrasound to ultrasound, as well as the multiscale nature of acoustics when dealing with, among others, thermoviscous loss mechanisms or aeroacoustics. The acoustic simulation capabilities of the software include built-in easy-to-use multiphysics couplings between the different physics, which are set up seamlessly in the same modeling environment, while the Acoustics Module adds many specialized formulations of the governing equations of acoustics.

⇨ ACOUSTICS SIMULATION APPS

To tackle the acoustic challenges faced by many in the industry, users without previous simulation software experience can run apps specifically tailored for them and their needs with predefined inputs and desired outputs. This is possible using apps created with the Application Builder available in COMSOL Multiphysics. Simulation apps are multiphysics models wrapped in a custom user interface. With this tool, specialists can package a complex simulation and allow users to change design parameters and analyze results autonomously with respect to industry standards and customer requirements.

Thanks to a local installation of the COMSOL Server™ product, apps can be easily deployed to colleagues and customers throughout an organization and worldwide. Users can connect via the COMSOL Client or a major web browser. It has never been easier for simulation specialists to model acoustic devices with such high fidelity and let their colleagues benefit from their work. ❖

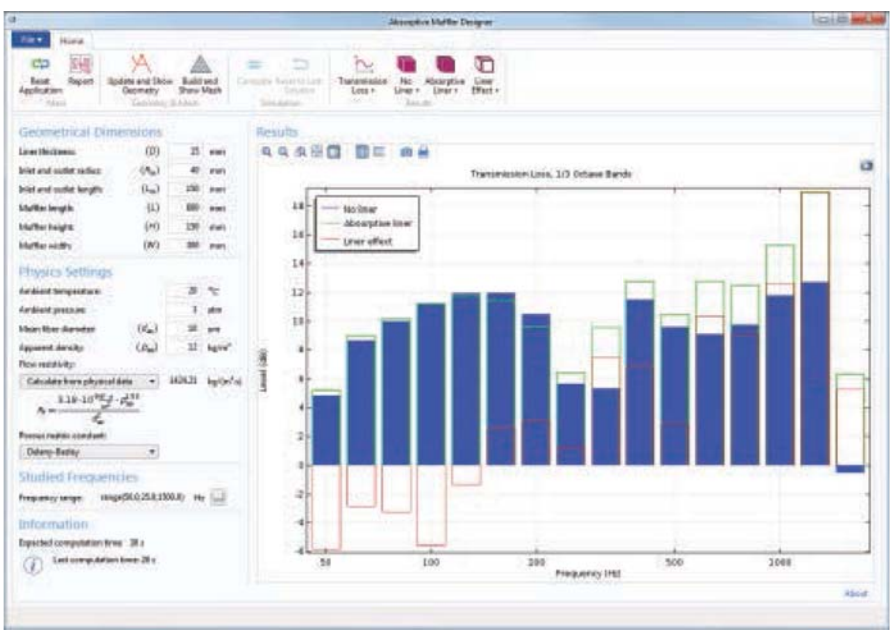


FIGURE 3. This example app is based on a model in COMSOL Multiphysics® of an absorptive muffler. The user may change the geometric design of the muffler, the ambient temperature and pressure, and material properties in order to evaluate the resulting acoustic behavior.

PHYSICS INTERFACES AVAILABLE IN THE ACOUSTICS MODULE

Pressure Acoustics: The sound field is described by acoustic variations around the ambient static pressure. Porous and fibrous materials, narrow structures, and bulk absorption behavior are modeled. Perfectly matched layers (PMLs) are available to truncate unbounded domains.

Acoustic-Structure Interaction: Models phenomena where the fluid's pressure causes a load on the solid domain and the structural acceleration affects the fluid domain across the fluid-solid boundary. Piezoelectric material, elastic and poroelastic waves, and pipe acoustics are included.

Aeroacoustics: Solves the one-way interaction of a background fluid flow with an acoustic field.

Thermoviscous Acoustics: Accurately models acoustics in geometries with small dimensions where the effect of the viscous and thermal boundary layer near the walls is important.

Ultrasound: Solves large transient linear acoustic problems containing many wavelengths in a stationary background flow field.

Geometrical Acoustics: Models acoustics in the high-frequency limit where the wavelength is significantly smaller than the characteristic geometrical features.

RESOURCES

- **COMSOL Blog**
- **COMSOL Video Gallery**
- **COMSOL Application Gallery**

VIRTUALLY TUNING AN AUTOMOTIVE AUDIO SYSTEM

Experts at HARMAN are using physical experiments in conjunction with mathematical modeling and numerical simulation to improve the development process for the latest vehicle infotainment technology.

by JENNIFER HAND

FIGURE 1. Loudspeaker positioning in the vehicle interior.

Today's vehicles offer dazzling electronic entertainment possibilities, from smartphone connectivity to interactive displays and video screens. HARMAN is the market leader in these connected car setups, equipping more than 80% of the world's luxury cars with premium audio systems.

Each vehicle model requires a unique configuration, and HARMAN's team of acoustic and simulation specialists ensure that different components and car acoustics are accounted for in their design process. Details such as the ideal placement and orientation of speakers, speaker packaging, and driver enclosure geometry such as car doors all influence the sound quality.

The team uses physical experiments in conjunction with numerical analysis to accelerate product development by virtually "tuning" their systems before ever creating a live prototype. This saves time on physical testing, and allows virtual tests to replace in situ listening, so that the team can design their products even before the final car designs are complete.

"We may become involved very early in the car development process, when a vehicle designer has not yet decided what is required from the audio system," explains Michael Strauss, Senior Manager of Virtual Product Development and Tools (VPD) at HARMAN. "Or we may only have basic details such as size and volume of the car cabin. Yet frequently we need to present a concept within a few days, creating a tricky challenge to meet our clients' requirements and deliver high-quality systems."

⇨ SIMULATION AND EXPERIMENTS TEAM UP FOR CUSTOMER SATISFACTION

To provide customers with a response that is both quick and accurate, engineers at HARMAN turn to mathematical modeling in COMSOL Multiphysics® software. "We needed capabilities for mechanical, acoustic, and electrical simulations in one integrated environment, and we wanted a program that would free up the time and effort spent on creating and updating our own tools," says François Malbos, Principal Acoustics Engineer, at HARMAN.

"The multiphysics approach is one of the most important parts of the virtual product development process," says Michał Bogdanski, Simulation Engineer and Leader of the Project at HARMAN. "We can explore how the acoustic behavior of a loudspeaker relates to any part of a vehicle structure — for example the stiffness of a door — and then provide door design guidelines to our customer."

In one case, they both measured and simulated the sound pressure levels generated by a loudspeaker in the cabin of a Mercedes-Benz ML car (Figure 1) in order to validate their numerical models and later use them to optimize acoustic equipment. "Car cabin simulations are among the most challenging to run because they cover many different areas of physics," explains Strauss. Fortunately, COMSOL® software offers options to couple together the acoustic, mechanical, and electrical effects throughout the system.

To support companywide engineering efforts, Strauss' team established a library of validated models and known solutions that allows for performance predictions of a wide variety of loudspeaker configurations. "We are able to offer everything from a high level trend analysis to a detailed design examining the performance of a subsystem," he continues.

> "We needed capabilities for mechanical, acoustic, and electrical simulations in one integrated environment, and we wanted a program that would free up the time and effort spent on creating and updating our own tools."

⇨ ANALYZING VEHICLE LOUDSPEAKER

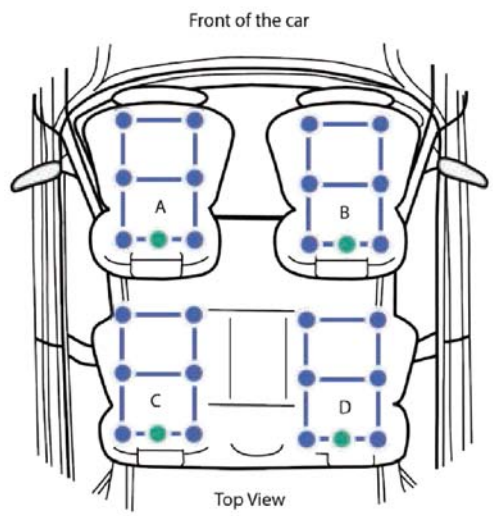


FIGURE 2. Left, top view of the microphone arrays positioned in the four different locations.

FIGURE 3. HARMAN's 3D scan of the car cabin.

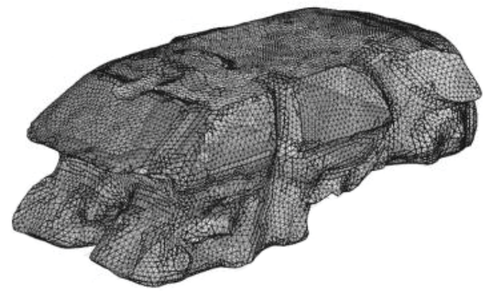


FIGURE 4. Surface mesh of the car cabin.

PERFORMANCE

In one study, engineers at HARMAN used COMSOL to create a simulation of a car cabin's sound system in order to optimize the speaker acoustics, specifically for low-frequency soundwaves. They then designed a series of tests to validate the model. Once validated, the model would allow the HARMAN team to deduce the best loudspeaker setup for a given car.

In validation tests, a loudspeaker was mounted on a rigid enclosure near the driver's seat of the car. Four sets of microphone arrays throughout the cabin served to measure the average sound pressure levels at each location (see Figure 2).

For frequencies below 1 kHz, the loudspeaker was represented as a rigid flat piston tied to a simplified lumped parameter model (LPM) taking into account the voltage at the voice coil terminals and the stiffness of the suspension and speaker membrane surface. The geometry was generated from a manual 3D scan (see Figure 3). Using a postprocessing algorithm implemented in MATLAB® software and an add-on product to COMSOL® called LiveLink for MATLAB® that creates a bidirectional link between the two programs, the team converted the point cloud created by the scan into a surface mesh of the car cabin (see Figure 4) and created an optimized mesh for studying acoustic pressure waves.

The simulation analyzed the interaction of the sound waves generated by a speaker with the different materials of the windshield, floor, seats, headrests, steering wheel, and other sections such as the roof, doors, and instrument panels, each of which have different absorption properties.

⇨ OPTIMIZING THE ACOUSTIC MODEL

In addition to accounting for many different materials, the team also defined speaker membrane motion and acceleration based on the volume of the enclosure using the Livelink™ for MATLAB® and developed special MATLAB® scripts to simplify the preprocessing and postprocessing activities.

"Everything is fully optimized and automatic so that we do not have to calculate the acceleration for each case; when one simulation finishes, the next launches," explains Michal Bogdanski. "This ensures that the whole process is easy and error-free; we simply let the scripts run."

The team also optimized the frequency-dependent absorption coefficients necessary to achieve a strong

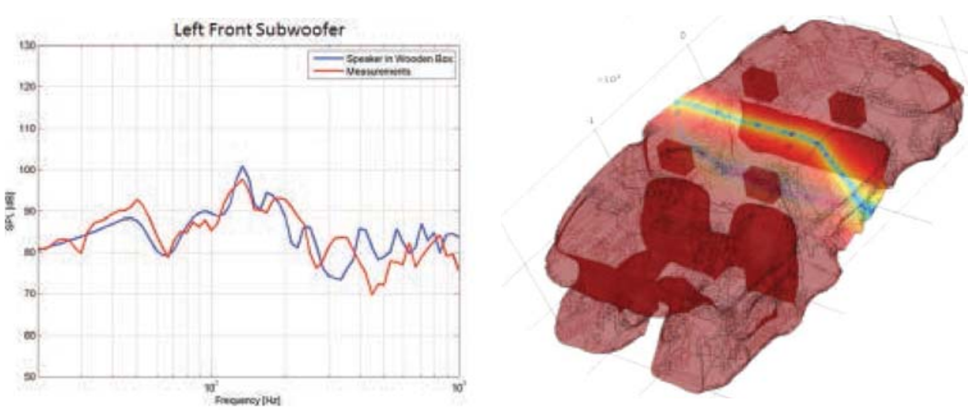


FIGURE 5. Sound pressure levels for one microphone array (left) and throughout the cabin (right).

correlation between the measured and simulated sound pressures. The analysis then provided the sound pressure levels emanating from each microphone array (see Figure 5).

⇨ OBJECTIVE AND SUBJECTIVE EVALUATIONS IN THE DRIVER'S SEAT

Using their validated simulations, HARMAN is able to begin developing a sound system even as a vehicle is still being designed. The accurate prediction of the sound pressure field throughout the car cabin allows for optimization of audio system performance. Equalizers and psychoacoustic effects are also included in their tuning algorithm, allowing for design modifications without the need for a physical prototype.

Auralization, or the production of sound from virtually computed acoustics, is of interest in the pursuit of a top-notch sound system. Using a high end headphone, Engineers at HARMAN have developed a playback system that allows, for listening, evaluation, and comparison of audio systems comprising subwoofers, midranges, and tweeters. "All based on simulation results and signal processing," says Malbos.

> "Using simulation Harman engineers will be able to assess, optimize, predict and subjectively evaluate the performance of a proposed sound system, even though it does not actually exist yet."

HARMAN engineers include the effects of the human head, torso and ear canals on acoustics in predicting Binaural Impulse Responses (BRIR), or how ears receive a sound. To capture the full 3D sound, BRIR are computed at various head positions in the azimuth plane. The playback system uses a head position tracker to perfectly reproduce the sound experience as the listener would experience it, e.g. in the driver's seat.

Figure 6 depicts the mesh created using COMSOL® software that was used in predicting the BRIR. Figure 7 shows a comparison between predicted and simulated BRIR.

Auralization is not without its challenges. Auralization quality, a measure that is inherently subjective, must compare to real-world listening. As such, subjective measurements are made to ensure the quality of the listening experience.

At HARMAN, the ability to assess an audio system based purely on simulation has increased the quality of product and speed of product development. It also has improved customer responsiveness, and lowered the cost of design amendments, fostering a sense of design freedom among the engineers.

"The beauty of simulation is that a systems engineer can sit at a desk, put headphones on and begin to tune a system without the car," Says Strauss. "Using simulation Harman engineers will be able to assess, optimize, predict and subjectively evaluate the performance of a proposed sound system, even though it does not actually exist yet." ❖

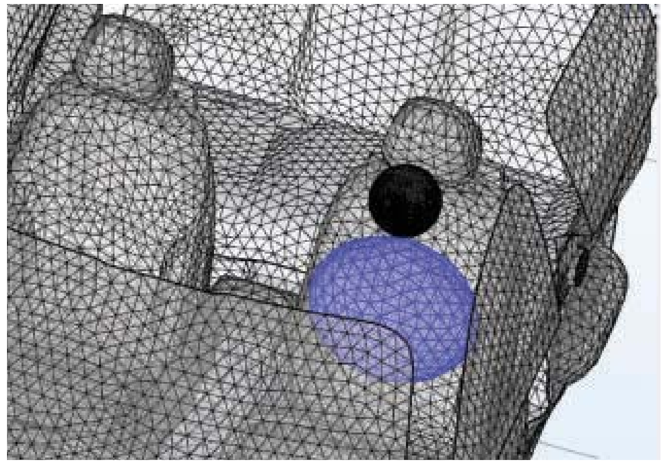


FIGURE 6. Mesh created using COMSOL® used for the prediction of binaural impulse responses, or how ears receive a sound.

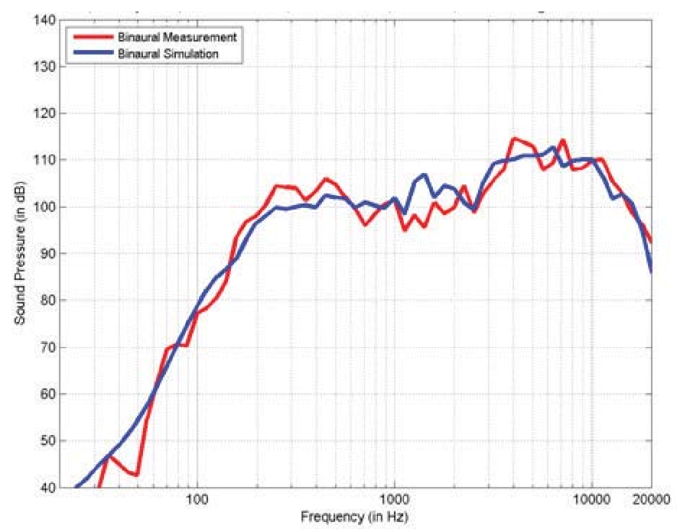


FIGURE 7. Comparison of measured and simulated BRIR in the frequency domain.

The HARMAN VPD team consists of Maruthi Srinivasarao Reddy, Michał Bogdanski, Michael Strauss, Ninranjan Ambati, and François Malbos.

Precision Performance: The Pursuit of Perfect Measurement

Researchers at Brüel & Kjær are using simulation to achieve new levels of precision and accuracy for their industrial and measurement-grade microphones and transducers.

by VALERIO MARRA

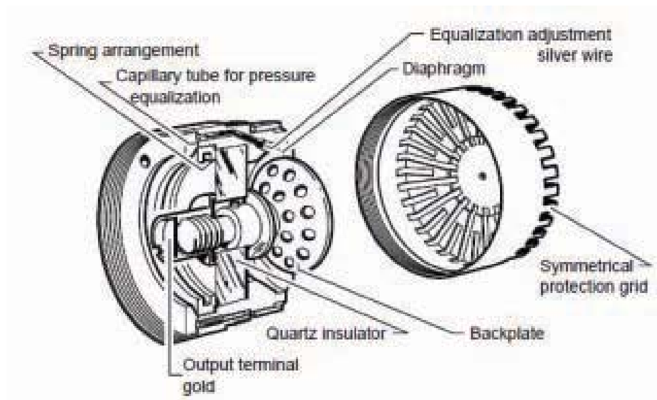


FIGURE 1. Left: Photo of a 4134 microphone including the protective grid mounted above the diaphragm. Right: Sectional view of a typical microphone cartridge showing its main components.

There will never be a perfect measurement taken or an infallible instrument created. While we may implicitly trust the measurements we take, no measurement will ever be flawless, as our instruments do not define what they measure. Instead, they react to surrounding phenomena and interpret this data against an imperfect representation of an absolute standard.

Therefore, all instruments have a degree of acceptable error—an allowable amount that measurements can differ without negating their usability. The challenge is to design instruments with an error range that is both known and consistent, even over extended periods of time.

Brüel & Kjær A/S has been a leader in the field of sound and vibration measurement and analysis for over 40 years. Their customers include Airbus, Boeing, Ferrari, Bosch, Honeywell, Caterpillar, Ford, Toyota, Volvo, Rolls-Royce, Lockheed Martin, and NASA, just to name a few.

Because industry sound and vibration challenges are diverse—from traffic and airport noise to car engine vibration, wind turbine noise, and production quality control, Brüel & Kjær must design microphones and accelerometers that meet a variety of different measurement standards. In order to meet these requirements, the company's R&D process includes simulation as a way to verify the precision and accuracy of their devices and test new and innovative designs.

⇨ DESIGNING AND MANUFACTURING ACCURATE MICROPHONES

Brüel & Kjær develops and produces condenser microphones covering frequencies from infrasound to ultrasound, and levels from below the hearing threshold to the highest sound pressure in normal atmospheric conditions. The range includes working standard and laboratory standard microphones, as well as dedicated microphones for special applications. Consistency and reliability is a key parameter in the development of all of Brüel & Kjær's microphones.

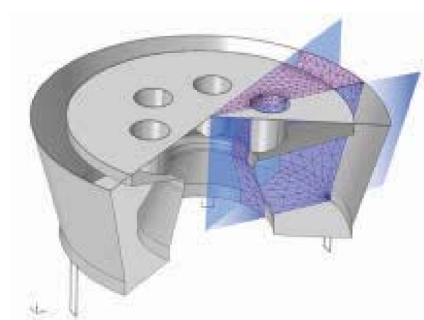


FIGURE 2. Geometry plot of the 4134 condenser microphone. The figure shows the mesh used in the reduced sector geometry, representing 1/12 of the total geometry.

"We use simulation to develop condenser microphones and to ensure that they meet relevant International Electrical Commission (IEC) and International Organization for Standardization (ISO) standards," says Erling Olsen, development engineer in Brüel & Kjær's Microphone Research and Development department. "Simulation is used as part of our R&D process, together with other tools, all so that we know that our microphones will perform reliably under a wide range of conditions. For example, we know precisely the influence of static pressure, temperature and humidity, and the effect of other factors for all of our microphones—parameters that would have been very difficult to measure were it not for our use of simulation."

The Brüel & Kjær Type 4134 condenser microphone shown in Figure 1 is an old microphone that has been subject to many theoretical and practical investigations over time. Therefore, the 4134 microphone has been used as a prototype for developing multiphysics models of Brüel & Kjær condenser microphones. To analyze the microphone's performance, Olsen's simulations include the movement of the diaphragm, the electromechanical interactions of the membrane deformations with electrical signal generation, the resonance frequency, and the viscous and thermal acoustic losses occurring in the microphone's internal cavities.

⇨ MICROPHONE MODELING

When sound enters a microphone, sound pressure waves induce deformations in the diaphragm, which are measured as electrical signals. These electrical signals are then converted into sound decibels. "Modeling a microphone involves solving a moving mesh and tightly coupled mechanical, electrical, and acoustic problems—something that could not be done without multiphysics," says Olsen. "The models need to be very detailed because in most cases, large aspect ratios (due to the shape of the microphone cartridges) and small dimensions cause thermal and viscous losses to play an important role in the microphone's performance."

The model can also be used to predict the interactions that occur between the backplate and diaphragm. Among other things, this influences the directional characteristics of the microphone. "We used the simulation to analyze the bending pattern of the diaphragm," says Olsen. For simulations such as thermal stress and resonance frequency, model symmetry was used to reduce calculation time (see Figure 2). The reduced model was also used to analyze the sound pressure level in the microphone for sounds that are at a normal incidence to the microphone diaphragm (see Figure 3). However, when sound enters the microphone with non-normal incidence, the membrane is subjected to a nonsymmetrical boundary condition. This requires a simulation that considers the entire geometry in order to accurately capture the bending of the membrane (see Figure 4).

Simulation was also used to determine the influence of the air vent in the microphone for measuring low-frequency sounds. "We modeled the microphone with the vent either exposed to the external sound field, outside the field (unexposed), or without a vent," says Olsen. "While the latter would not be done in practice, it allowed us to determine the interaction between the vent configuration and the input resistance results for different low-frequency behaviors. This is one of the most important things about simulation: We can make changes to the parameters of a model that move away from already manufactured devices, allowing us to test other designs and explore the limits of a device (see Figure 5)."

With simulation as part of the R&D process, Olsen and his colleagues are able not only to design and test some of Brüel & Kjær's core products, but devices can also be created based on a specific customer's requirements.

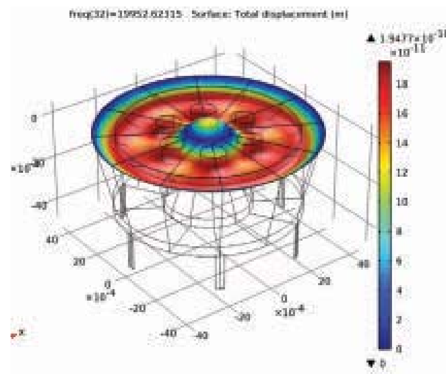


FIGURE 3. Representation of the sound pressure level below the diaphragm for normal incidence, calculated using the sector geometry. The membrane deformation is evaluated at f = 20 kHz.

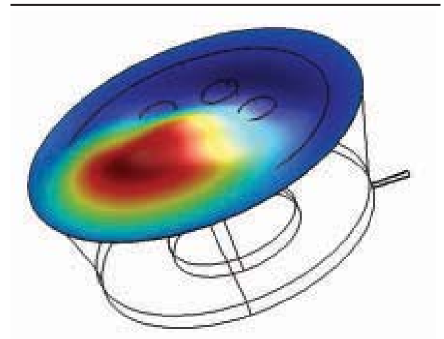


FIGURE 4. Simulation results showing the membrane deformation calculated for non-normal incidence at 25 kHz. Since the deformation is asymmetrical, this is calculated using the full 3D model.

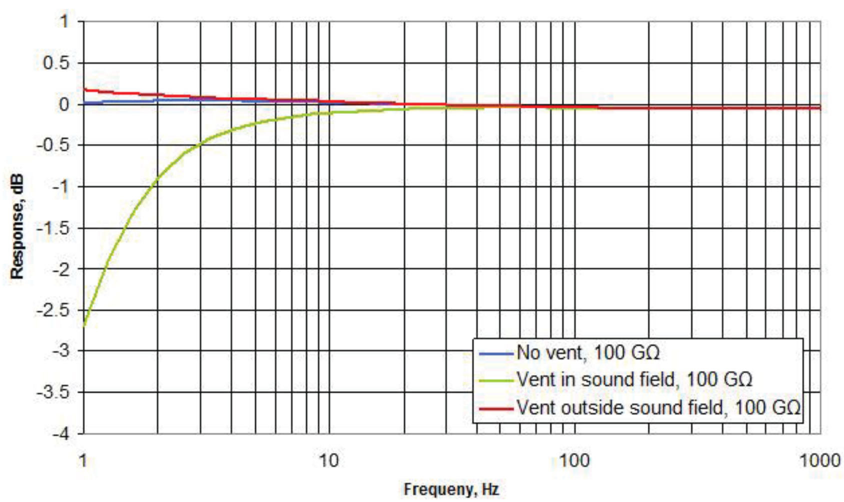


FIGURE 5. In the no-vent configuration, the sensitivity increase is due to the fact that the sound field becomes purely isothermal inside the microphone at very low frequencies. In the vent outside the sound field configuration, the curve initially follows the no-vent curve, but sensitivity increases further as the vent becomes a pressure release on the back of the diaphragm.

"With simulation, we can pin-point approaches for making specific improvements based on a customer's needs. Although microphone acoustics are very hard to measure through testing alone, after validating our simulations against a physical model for a certain configuration, we are able to use the simulation to analyze other configurations and environments on a case-by-case basis."

⇨ VIBRATION TRANSDUCER MODELING

Søren Andresen, a development engineer with Brüel & Kjær, also uses simulation to design and test vibration transducer designs.

"One of the complications with designing transducers for vibration analysis is the harsh environments that these devices need to be able to withstand," says Andresen. "Our goal was to design a device that has so much built-in resistance that it can withstand extremely harsh environments."

Most mechanical systems tend to have their resonance frequencies confined to within a relatively narrow range, typically between 10 and 1000 Hz. One of the most important aspects of transducer design is that the device does not resonate at the same frequency as the vibrations to be measured, as this would interfere with the measured results. Figure 6 shows the mechanical displacement of a suspended vibration transducer, as well as a plot of the resonance frequency for the device.

"We want the transducer to have a flat response and no resonance frequency for the desired vibration range being measured," says Andresen. "We used COMSOL to experiment with different designs in order to determine the combination of materials and geometry that produces a flat profile (no resonance) for a certain design. This is the region in which the transducer will be used."

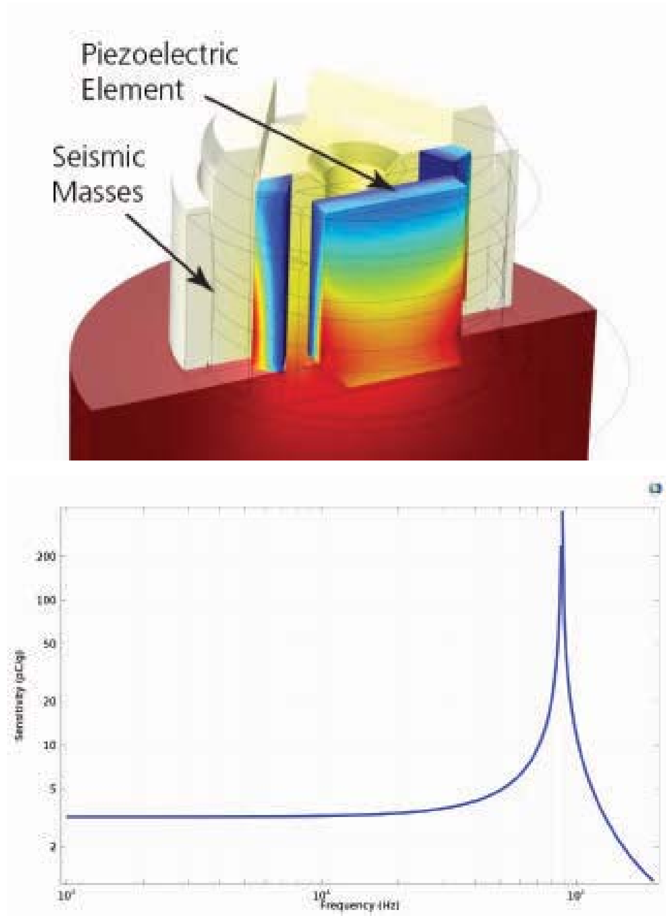


FIGURE 6. Simulation results of a suspended piezoelectric vibration transducer. Top: Mechanical deformation and electrical field in the piezoelectric sensing element and seismic masses. Bottom: Frequency-response plot showing the first resonance of the transducer at around 90 kHz. This device should only be used to measure objects at frequencies well below 90 kHz.

When designing the transducer, a low-pass filter, or mechanical filter, can be used to cut away the undesired signal caused by the transducer resonance, if any. These filters consist of a medium, typically rubber, bonded between two mounting discs, which is then fixed between the transducer and the mounting surface.

"As a rule of thumb, we set the upper frequency limit to one-third of the transducer's resonance frequency, so that we know that vibration components measured at the upper frequency limit will be in error by no more than 10 to 12%," says Andresen.

⇨ AS ACCURATE AND PRECISE AS POSSIBLE

While it may not be possible to design a perfect transducer or take an infallible measurement, simulation brings research and design teams closer than ever before by allowing them to quickly and efficiently test new design solutions for many different operating scenarios.

"In order to stay ahead of the competition, we need knowledge that is unique," says Andresen. "Simulation provides us with this, as we can make adjustments and take virtual measurements that we couldn't otherwise determine experimentally, allowing us to test out and optimize innovative new designs." ❖

"With simulation, we can pin-point approaches for making specific improvements based on a customer's needs."

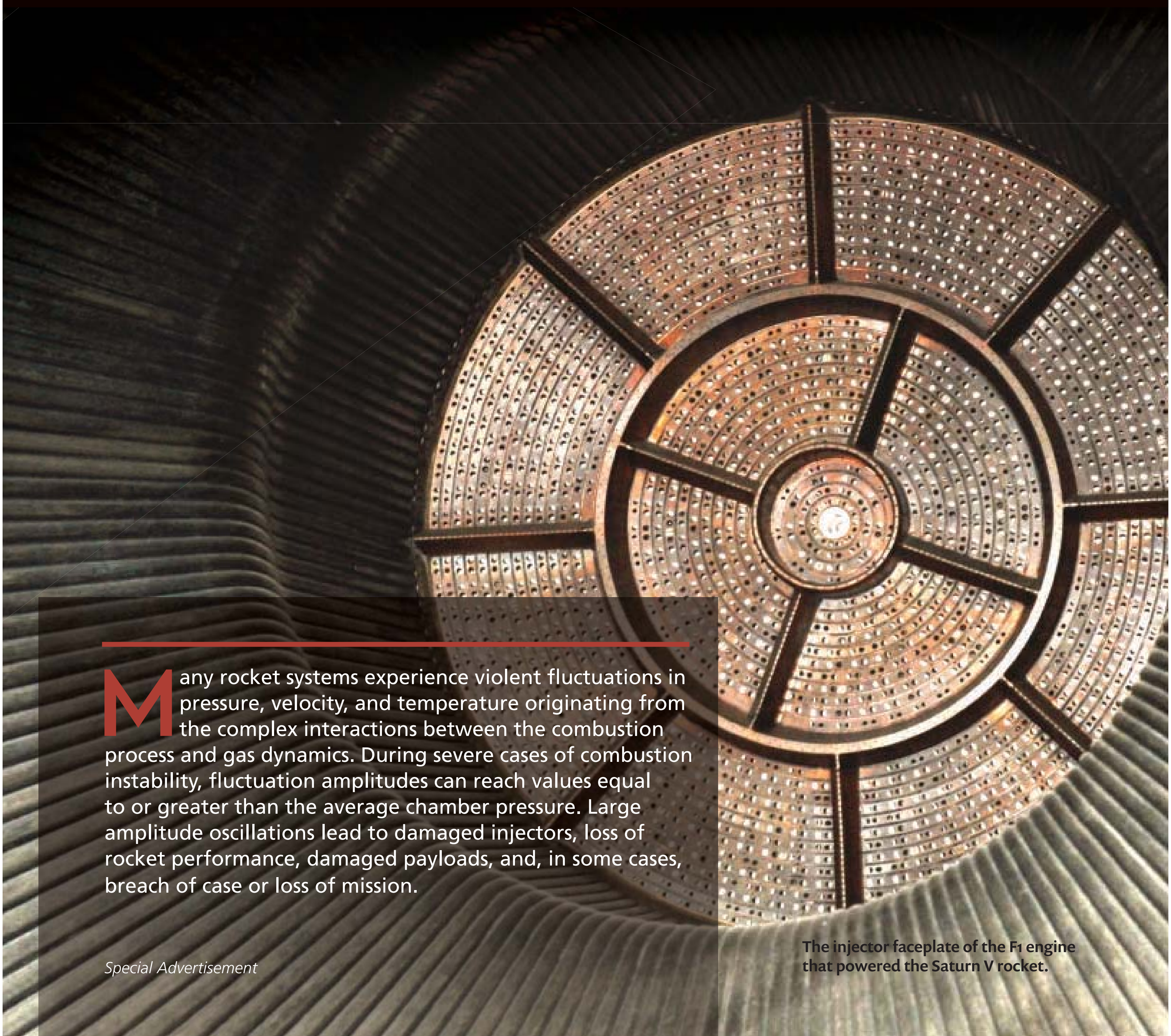
— ERLING OLSEN, DEVELOPMENT ENGINEER AT BRÜEL & KJÆR

NASA, USA

MULTIPHYSICS SOFTWARE MODELS MEAN FLOW-AUGMENTED ACOUSTICS IN ROCKET SYSTEMS

Combustion instability in solid rocket motors and liquid engines is a complication that continues to challenge designers and engineers. The adoption of a higher-fidelity modeling approach supported by multiphysics analysis provides greater insight and predictive ability.

by SEAN R. FISCHBACH



Many rocket systems experience violent fluctuations in pressure, velocity, and temperature originating from the complex interactions between the combustion process and gas dynamics. During severe cases of combustion instability, fluctuation amplitudes can reach values equal to or greater than the average chamber pressure. Large amplitude oscillations lead to damaged injectors, loss of rocket performance, damaged payloads, and, in some cases, breach of case or loss of mission.

The injector faceplate of the F1 engine that powered the Saturn V rocket.

Historic difficulties in modeling and predicting combustion instability have reduced most instances of rocket systems experiencing instability to a costly fix through testing (see Figure 1), or to scrapping of the system entirely.

> "A more complete depiction of combustion instability oscillations is achieved when a global energy-based assessment is used."

During the early development of rocket propulsion technology scientists and engineers were cued to the underlying physics at play through the measurement of vibrating test stands, observation of fluctuating exhaust plumes, and, most notably, the audible tones accompanying instabilities. These observations lead the pioneers of combustion instability research to focus their modeling efforts on the acoustic waves inside combustion chambers.

This focus on acoustics is quite logical given that the measured frequency of oscillation often closely matches the normal acoustic modes of the combustion chamber. But this narrow focus misses contributions made by rotational and thermal waves that are a direct result of, or closely coupled with, the acoustic wave. A more complete depiction of combustion instability oscillations is achieved when a global energy-based assessment is used.

Recent advances in energy-based modeling of combustion instabilities require an accurate determination of acoustic frequencies and mode shapes. Of particular interest are the acoustic mean flow interactions within the converging section of a rocket nozzle, where gradients of pressure, density, and velocity become large. The expulsion of unsteady energy through the nozzle of a rocket is identified as the predominate source of acoustic damping for most rocket systems.

Recently, an approach to address nozzle damping with mean flow effects was implemented by French[2]. This new approach extends the work originated by Sigman and Zinn[3] by solving the acoustic velocity potential equation (AVPE) formulated by perturbing the Euler equations[4].

Determining eigenvalues of the AVPE, where ψ is the complex acoustic potential, λ the complex eigenvalues, c the speed of sound, and M the Mach vector,

$$\nabla^2\psi - \left(\frac{\lambda}{c}\right)^2 \psi - \boldsymbol{M}\cdot[\boldsymbol{M}\cdot\nabla(\nabla\psi)] - 2\left(\frac{\lambda\boldsymbol{M}}{c} + \boldsymbol{M}\cdot\nabla\boldsymbol{M}\right)\cdot \nabla\psi - 2\lambda\psi\left[\boldsymbol{M}\cdot\nabla\left(\frac{1}{c}\right)\right] = 0$$

is considerably more complex than the traditionally used pressure-based wave equation,

$$\nabla\cdot\left(-\frac{1}{\rho}\nabla p\right) + \frac{1}{\rho c^2}\frac{\partial^2 p}{\partial t^2} = 0$$

and requires numerical approximations of the chamber flow field and eigenvalues.

⇨ MODELING CHAMBER GAS DYNAMICS

The latest theoretical models for oscillatory disturbances in high-speed flows require a precise determination of the chamber acoustic eigenmodes. But first, a simulation of the mean flow properties of the combustion chamber must be performed.

COMSOL Multiphysics® software provides a numerical platform for conveniently and accurately simulating both the chamber gas dynamics and internal acoustics. This finite element software package provides many predefined physics along with a generalized mathematics interface.

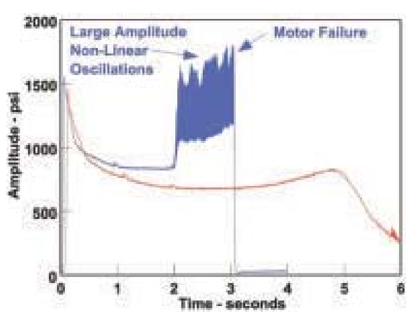


FIGURE 1. Pressure trace of a stable (red) and unstable (blue) solid rocket motor[1].

The present study employs the COMSOL finite element framework to model the steady flow-field parameters of a generic liquid engine using the High Mach Number Laminar Flow physics interface, which makes use of the fully compressible Navier-Stokes equations for an ideal gas together with conservation of energy and mass equations.

In order to account for the injection of hot gas due to the burning propellant, the injector face plate is modeled with a uniform inward flow of combusted propellant gas (see Figure 2). All other solid boundaries are modeled with the slip boundary condition, and the exit plane is modeled with the hybrid outflow condition, which means that both subsonic and supersonic flows are supported.

Results from the mean flow analysis are reviewed to ensure a valid and converged solution. Mean flow parameters such as pressure, density, velocity, and speed of sound are needed to model the AVPE. The values of the mean flow in the converging section of the nozzle, near the sonic choke plane, are of considerable interest. The sonic plane, where the Mach number is equal to 1, creates an acoustic barrier in the flow. In order to create an accurate geometry for the acoustic analysis, the sonic plane (pictured in magenta in Figure 3) is extracted from the mean flow analysis.

⇨ MODELING CHAMBER ACOUSTICS

The Coefficient Form PDE (Partial Differential Equation) mathematics interface of COMSOL Multiphysics is used to determine the complex eigenvalues of the AVPE. Mean flow terms in the AVPE are supplied by the solution from the mean flow analysis. Gas dynamics within the combustion chamber play a key role in defining the boundary conditions for the acoustic analysis. Within the converging and diverging section of the rocket nozzle, gradients of chamber pressure, velocity, and density grow theoretically infinite at the sonic plane where the Mach number is equal to 1. Downstream of the sonic plane, acoustic disturbances are convected with the mean flow at speeds greater than

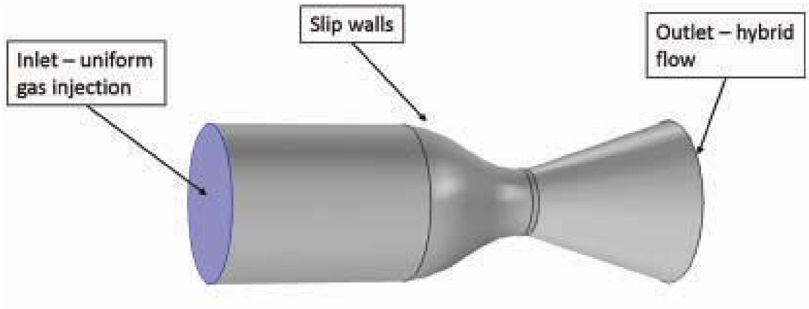


FIGURE 2. Simulated liquid engine geometry with boundary conditions.

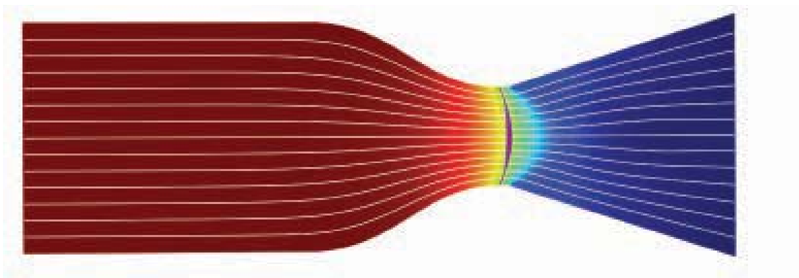


FIGURE 3. Velocity streamlines plotted over chamber pressure. The Mach 1 surface is plotted in magenta.

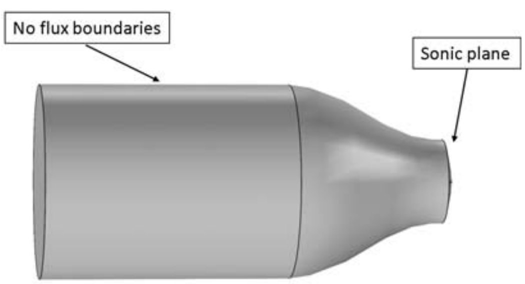


FIGURE 4. Acoustic analysis geometry with boundary conditions.

the speed of sound.
This condition prevents disturbances downstream of the sonic plane from propagating back upstream. The diverging section of the nozzle is acoustically silent and does not affect the chamber acoustics. The simulation geometry is truncated at the nozzle sonic line, where a zero flux boundary condition is self-satisfying (see Figure 4). The remaining boundaries are modeled with a zero flux boundary condition, assuming zero acoustic absorption on all surfaces.

The eigenvalue analysis produces complex eigenmodes and eigenvalues representing each acoustic mode and its complex conjugate. The real part of the complex eigenvalue represents the temporal damping of the acoustic mode, with the imaginary part defining the frequency of oscillation. The complex eigenvectors represent the spatial amplitude and phasing of the acoustic wave.

Comparing the acoustic mode shapes derived using the classic homogeneous wave equation (Helmholtz equation) to those derived using the AVPE demonstrates the benefits of higher-fidelity models that correctly represent the underlying physics (see Figure 5). Inclusion of mean flow terms in the AVPE accurately models the phase shift caused by the steady gas flow. Phasing is extremely important since combustion instability models make use of temporal and spatial integration of the acoustic eigenvectors.

Utilizing COMSOL Multiphysics to simulate the rocket gas dynamics and acoustic eigenmodes provides a more accurate mode shape over previous techniques. The higher-fidelity acoustic representation is easily incorporated into combustion instability models to give rocket designers and engineers greater predictive capabilities. The inclusion of damping devices, such as baffles, or changes in operating conditions, can now be more accurately modeled before testing.

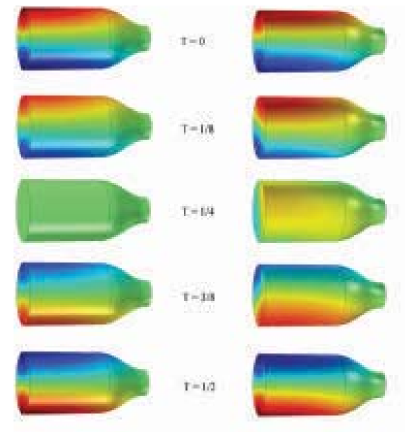


FIGURE 5. Comparison of the first tangential eigenmode calculated using the classic homogeneous wave equation (left), and the AVPE (right) of a half period (T) of oscillation.

⇨ CONTINUED WORK

A more complete depiction of combustion instability includes rotational oscillations and thermal oscillations in conjunction with chamber acoustics. Rotational oscillations occur as a direct result of the acoustic oscillation, where thermal waves can also be present in the absence of acoustic fluctuation. Continued work using COMSOL Multiphysics will focus on solving the viscous rotational wave that accompanies all acoustic oscillations. ❖

This article was written by Sean R. Fischbach, Marshall Space Flight Center/ Jacobs ESSSA Group, MSFC, Huntsville, AL.

REFERENCES

1. F. S. Bloomshield, *Lessons Learned in Solid Rocket Combustion Instability*, 43rd AIAA Joint Propulsion Conference, AIAA-2007-5803, Cincinnati, OH, July 2007.
2. J. C. French, *Nozzle Acoustic Dynamics and Stability Modeling*, Vol. 27, Journal of Propulsion and Power, 2011.
3. R. K. Sigman and B. T. Zinn, *A Finite Element Approach for Predicting Nozzle Admittances*, Vol. 88, Journal of Sound and Vibration, 1983, pp. 117-131.
4. L. M. B. C. Campos, *On 36 Forms of the Acoustic Wave Equation in Potential Flows and Inhomogeneous Media*, Vol. 60, Applied Mechanics Reviews, 2007, pp. 149-171.

BEHIND THE RUMBLE AND ROAR OF MAHINDRA MOTORCYCLES

Mahindra Two Wheelers used multiphysics simulation to meet engine noise regulatory requirements in its high-end luxury motorcycles while maintaining customers' satisfaction.

by **VALERIO MARRA**

Mahindra Two Wheelers builds a wide range of scooters and motorcycles for the Indian market. Thanks to the adoption of numerical simulation tools early in the development cycle, drivers and passengers can enjoy great performance and mileage, along with a superior ride experience on tough Indian roads. Mahindra used multiphysics simulation to study the NVH (noise, vibration, and harshness) performance of the engine, intake, and exhaust systems of their motorcycles.

The knowledge gained from numerical simulation studies enabled their engineers to improve the structural design of their motorcycle engine and achieve desired noise levels. "COMSOL software helped us to significantly reduce the number of design iterations that we had to go through, thereby saving time," said Niket Bhatia, deputy manager R&D, Mahindra.

⇨ ACHIEVING OPTIMAL NOISE LEVELS

In an engine, there are many sources of noise, including the intake and combustion processes, pistons, gears, valve train, and exhaust systems. Combustion noise is due to structural vibrations caused by a rapid pressure rise within the cylinders.

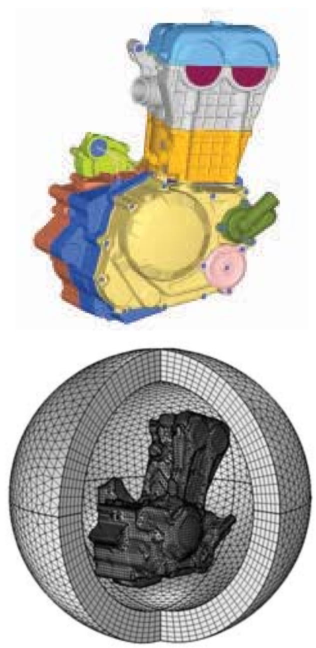


FIGURE 1. Top: engine CAD geometry. Bottom: meshed 3D model enclosed in a perfectly matched layer (PML).

These vibrations continue from the powertrain to the engine casings through bearings, radiating noise.

Acoustics analysis solely through physical testing can be an expensive and time-consuming process. The team at Mahindra decided to complement physical testing with acoustics modeling to analyze how the engine's structure might encourage noise radiation. The research goal was to find the parts of the engine that generate the most noise and come up with changes to the structure that could reduce it.

Using the COMSOL Multiphysics® software, the researchers performed an acoustic-radiation analysis of a single-cylinder internal combustion (IC) engine under combustion load. The engineers enclosed the engine skin in a computational domain surrounded by a perfectly matched layer (PML).

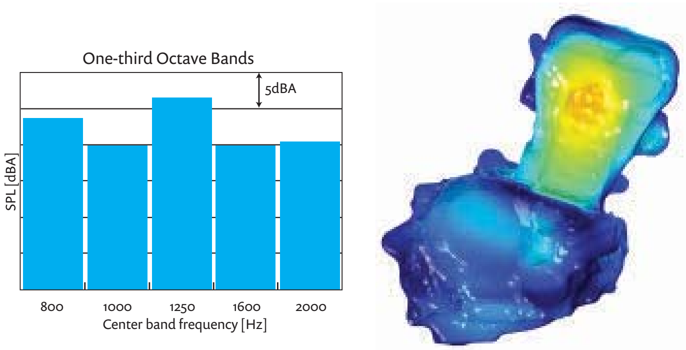


FIGURE 2. Left: One-third octave band plot. Right: 3D surface plot of the sound pressure level (SPL) simulation results.

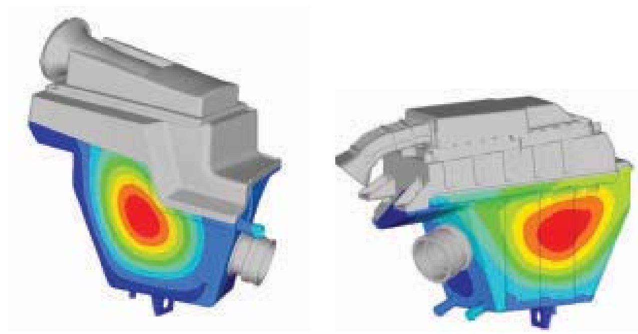


FIGURE 3. Air filter structure. Left: Original design. Right: Modified design, featuring ribs to improve the ATF.

PML's dampens the outgoing waves with little or no reflections (Figure 1). This allows for accurate results while reducing the size of the computational domain.

The team decided to focus their analysis in the 800 Hz -2000 Hz frequency range, as physical experiments indicated that the motorcycle's engine noise radiation under combustion load was dominant in that region of the acoustic spectrum. This choice allowed the team to save computational resources and better understand what areas radiate the most noise.

Based on this analysis, the sound pressure level (SPL) was studied and modifications, such as increasing rib height and wall thickness and strengthening the mounting location, were made to the cylinder head and block (Figure 2). By adjusting these parameters, reduction in SPL was achieved at the targeted frequency range.

⇨ REDUCING INTAKE STRUCTURAL NOISE

Both intake and exhaust noise are major contributors to pass-by-noise. Noise radiating from the air filter structure, usually made of plastic, is one of the major contributors to intake noise. An acoustic transfer function (ATF) analysis was carried out for the plastic air filter walls. The air filter structure was modified by providing ribs to improve the ATF (Figure 3). This helped in reducing the structural noise of the air filter (Figure 4).

⇨ ANALYZING TRANSMISSION LOSS TO IMPROVE MUFFLER SOUND

Regulatory requirements are always competing with customer demands for louder 'rumbling' from the muffler, as it is perceived as an important indicator of the motorcycle's power. Within the constraint of pass-by-noise, the challenge for Mahindra engineers was to increase the 'rumble' sound from their muffler at low frequencies while reducing the sound level for higher frequencies.

While attenuation of engine exhaust noise is the primary function of the muffler, factors such as the ability to provide low back pressure and meet pass-by-noise regulations also need to be considered. The performance of a muffler in an automotive exhaust system is characterized by three parameters: transmission loss, insertion loss, and radiated noise levels. Transmission loss is considered the most important parameter, and it is determined solely by the muffler design and is independent of the pressure source. The challenge for the team at Mahindra was to predict the transmission loss for a motorcycle muffler and then optimize the loss to desired levels for a certain frequency range.

A muffler of a single cylinder motorcycle engine was considered for the analysis. Transmission loss analysis of the muffler was carried out using COMSOL Multiphysics. With the Acoustics Module, boundary conditions such as continuity and sound hard wall were applied at appropriate locations.

Perforations in pipes were defined by giving porosity details for the perforated area using a built-in transfer impedance model. The inputs required for analysis were the area porosity, baffle and pipe thickness, and diameter of holes. For porous materials such as glass wool, flow resistivity was defined with a poroacoustic model available in the software. Unit pressure was given as input at the inlet and a plane wave radiation condition was applied to both inlet and outlet boundaries.

Based on the results, the muffler design was modified by increasing the pipe length inside the muffler. With the modified muffler, the team achieved reduced transmission loss at low frequencies (Figure 5). As a result, the desired outcome of increased noise levels at

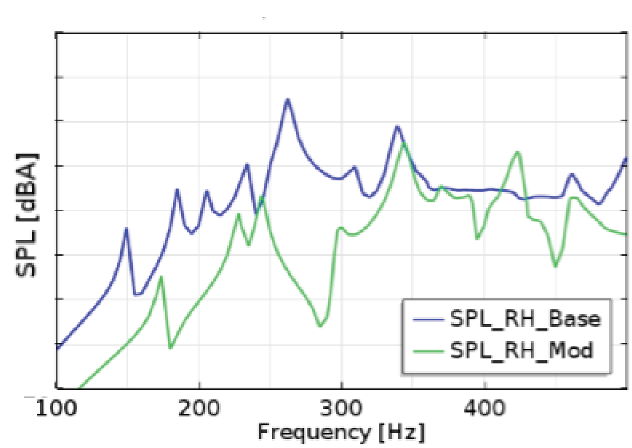


FIGURE 4. Simulation results show a reduction in the structural noise for the modified air filter design.

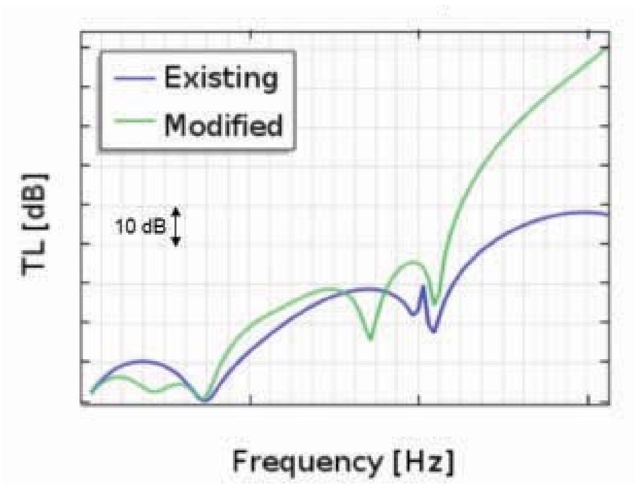


FIGURE 5. Transmission loss (TL) comparison between different designs. The modified design is characterized by reduced transmission loss at low frequencies and increased transmission loss at high frequencies. The modified design achieved the sought after 'rumbling' noise while meeting regulations.

low frequencies, or the 'rumbling' noise, was achieved.

⇨ OPTIMIZATION EARLY IN THE DESIGN CYCLE LEADS TO COST AND TIME SAVINGS

"I personally really liked the software's flexibility and available tools like the COMSOL API," said Ulhas Mohite, manager of R&D, Mahindra. "It allowed us to carry out process automation using Java code which, while dealing with acoustic analysis for example, enabled us to use different meshes for different frequency steps to find the right compromise between simulation accuracy and computational time. It also enabled us to automatically export desired outputs such as surface SPL plots and far-field SPL data in the middle of the simulation run. This helped save a lot of time with respect to manual postprocessing and exporting the data."

Mohite also found the Application Builder tool available in COMSOL extremely useful. "We created a simulation app (Figure 6) using the Application Builder to compare analysis output files and plot the SPL data, which was a great time saver."

Analysis results proved to be very closely correlated with physical experiment data. With simulation, the engineers at Mahindra were able to take corrective actions by carrying out structural modifications based on analysis results early in the design stage. This helped reduce both time and cost involved in product development. "When supported with experiments, these simulations lead us in the right direction to find an efficient solution to motorcycle noise issues," concluded Bhatia. ❖

"We created a simulation app using the Application Builder to compare analysis output files and plot the SPL data, which was a great time saver.

— ULHAS MOHITE, R&D MANAGER, MAHINDRA

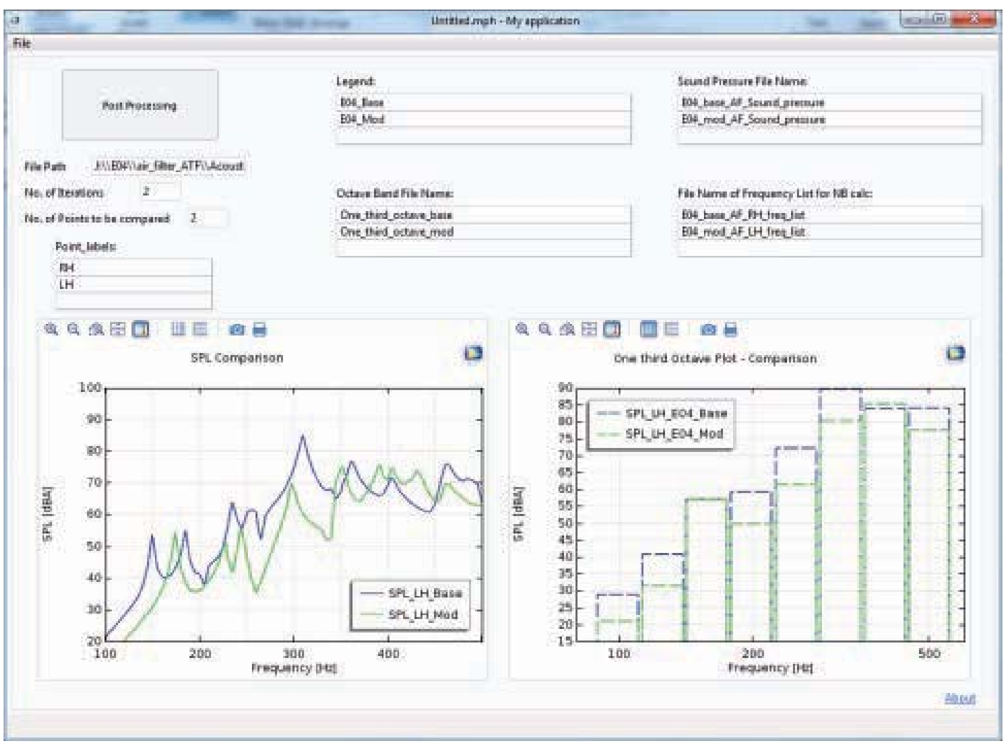


FIGURE 6. With the Application Builder, Mahindra engineers created an easy-to-use simulation app that is used to compare analysis files and plot sound pressure level (SPL) data.

REFERENCES

1. Mohite, U., Bhatia, N., and Bhavsar, P., "An Approach for Prediction of Motorcycle Engine Noise under Combustion Load," SAE Technical Paper 2015-01-2244, 2015, doi:10.4271/2015-01-2244.

2. Reducing Motorcycle Engine Noise with Acoustics Modeling, COMSOL Blog

FROM SPREADSHEETS TO MULTIPHYSICS APPLICATIONS, ABB CONTINUES TO POWER UP THE TRANSFORMER INDUSTRY

Companies developing new and improved power transformer equipment incur costs for prototyping and testing as they work to reduce transformer hum. At ABB, a team of engineers develops multiphysics simulations and custom-built applications to offer insight into their designs.

by LEXI CARVER

For everything from cooking to charging our phones, we rely every day on the electrical grid that powers buildings like homes, businesses, and schools. This complex network includes stations generating electric power, high-voltage transmission lines that carry electricity across large distances, distribution lines that deliver power to individual homes and neighborhoods, and the related hardware used for power flow control and protection.

Among this equipment are power transformers for increasing and decreasing voltage levels in power lines that carry alternating current (see Figure 1). Power transfer with higher voltages results in lower losses and so is more desirable for transporting power long distances. However, such high voltage levels would pose a safety hazard at either end of the lines, so transformers are used to increase voltage levels at the power feed-in point and decrease them close to neighborhoods and buildings.

But transformers come with noise, often manifested as a faint humming or buzzing that can be heard when walking nearby. Although it is impossible to completely silence them, regulations require adherence to safe sound levels, and good product design can minimize

FIGURE 1. Photo of transformer equipment for high-voltage power lines.

these acoustic effects.

One of the biggest manufacturers of transformers used around the world, ABB (headquartered in Zürich, Switzerland), has used numerical analyses and computational applications in order to predict and minimize the noise levels in their transformers. Through the COMSOL Multiphysics® simulation software and its Application Builder, they have run virtual design checks, tested different configurations, and deployed their simulation results through customized user interfaces built around their models.

➩ SILENCING SOUND FROM SEVERAL SOURCES

Transformer noise often comes from several sources, such as vibrations in the transformer core or auxiliary fans and pumps used in the cooling system. Each of these sources needs to be addressed differently to reduce noise.

ABB's transformers comprise a metal core with coils of wire wound around different sections, an enclosure or tank to protect these components, and an insulating oil inside the tank (see Figure 2, top). Passing alternating current through the windings of one coil creates a magnetic flux that induces current in an adjacent coil. The voltage adjustment is achieved through different numbers of coil turns.

Because the core is made of steel, a magnetostrictive material, these magnetic fluxes — which alternate direction — cause mechanical strains. This generates vibrations from the quick growing and shrinking of the metal. These vibrations travel to the tank walls through the oil and the clamping points that hold the inner core in place, creating an audible hum known as core noise (see Figure 2, bottom).

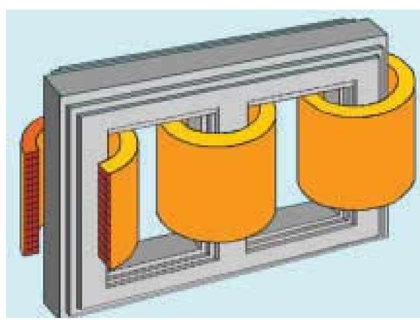
In addition to the core noise, the alternating current in the coil produces Lorentz forces in the individual windings, causing vibrations known as load noise that add to the mechanical energy transferred to the tank.

With these multiple sources of noise and the interconnected electromagnetic, acoustic, and mechanical factors at play, engineers at the ABB Corporate Research Center (ABB CRC) in Västerås, Sweden needed to understand the inner workings of their transformers in order to optimize their designs for minimal transformer hum.

➩ COUPLING ACOUSTIC, MECHANICAL, AND ELECTROMAGNETIC EFFECTS ALL IN ONE

"We chose to work with COMSOL Multiphysics because it allows us to easily couple a number of different physics," said Mustafa Kavasoglu, scientist at ABB CRC. "Since this project required us to model electromagnetics, acoustics, and mechanics, COMSOL® software was the best option out there to solve for these three physics in one single environment."

Kavasoglu; Dr. Anders Daneryd, principal scientist; and Dr. Romain



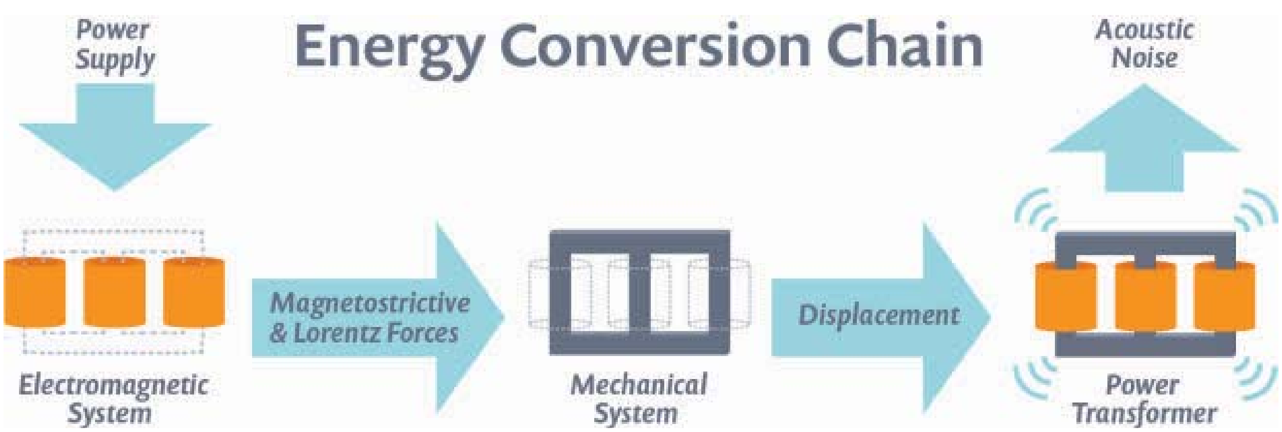


FIGURE 2. Top left: CAD model of the active part of a three-phase transformer with windings mounted around the core. Top right: The active part of a power transformer that is placed in a tank filled with oil. Bottom: The energy conversion chain for core noise and load noise generation (magnetostriction in the core and Lorentz forces in windings).

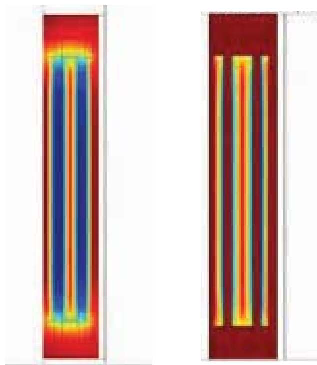


FIGURE 3. Simulation results showing the magnetic flux density (left) and Lorentz forces (right) in the transformer coil windings.

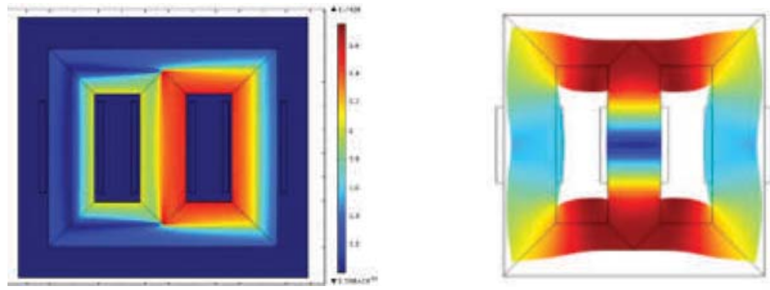


FIGURE 4. Left: COMSOL® software results showing levels of magnetic flux in the steel. Right: Results showing the resonance of the core. Deformations are exaggerated for visibility.

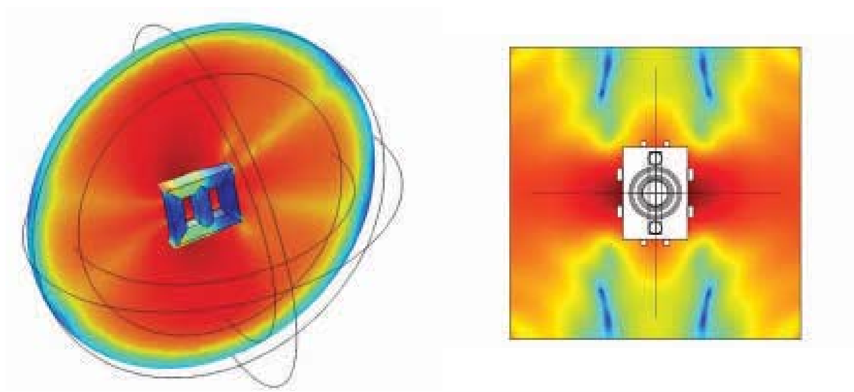


FIGURE 5. Results of the acoustic analysis showing the sound pressure field around the core (left) and around the transformer (right).

Haettel, principal engineer, form the ABB CRC team working with transformer acoustics. Their objective was to create a series of simulations and computational apps to calculate magnetic flux generated in the transformer core and windings (see Figure 3, left), Lorentz forces in the windings (see Figure 3, right), mechanical displacements caused by the magnetostrictive strains, and the resulting pressure levels of acoustic waves propagating through the tank.

They work closely with the Business Unit ABB Transformers, often relying on the experience and expertise of Dr. Christoph Ploetner, a recognized professional in the field of power transformers, to ensure that they satisfy business needs and requirements.

One simulation models the noise emanating from the core due to magnetostriction. The team began with an electromagnetic model to predict the magnetic fields induced by the alternating current, and then the magnetostrictive strains in the steel.

Their geometry setup included the steel core, windings, and an outer domain representing the tank. "We obtained the displacement from the magnetostrictive strains, then calculated the resonance for different frequencies using a modal analysis," said Kavasoglu (see Figure 4). "Resonances are easily excited by the magnetostrictive strains and cause high vibration amplification at these frequencies."

They were then able to predict the sound waves moving through the oil and calculate the resulting vibrations of the tank, implying sound radiation into the surrounding environment (see Figure 5).

They also simulated the displacements of the coil windings that cause load noise and determined the surface pressure on the tank walls due to the resulting sound field (see Figure 6).

Including parametric studies that illustrated the complex relationships between design parameters (such as tank thickness and material properties) and the resulting transformer hum made it possible to adjust the geometry and setup of the core, windings, and tank to minimize the noise.

⇨ SPREADING SIMULATION CAPABILITIES THROUGHOUT ABB

The CRC team continues to use the COMSOL software to not only improve their understanding and their models, but to extend their knowledge to the rest of ABB's designers and to the business unit. Using the Application Builder in COMSOL Multiphysics, they have begun creating apps from their multiphysics models, which can be easily customized to suit the needs of each department.

"We've also been using the COMSOL Server™ license to distribute our app to other offices for testing, which makes it easy to share it. This worldwide license is great; with a global organization, we expect users in our other locations around the world to benefit from these apps."

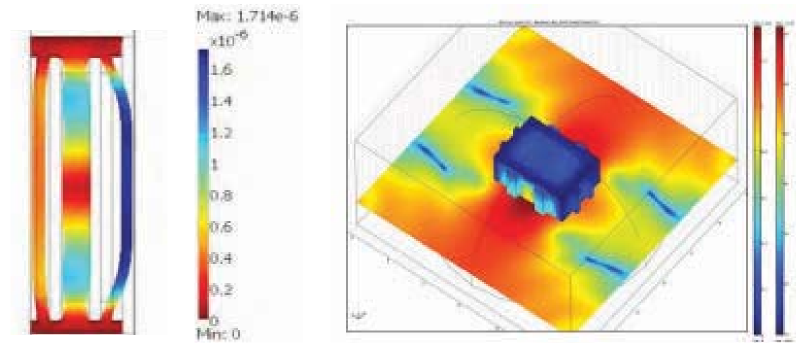


FIGURE 6. Left: Simulation results showing the displacement of the windings. Deformations are exaggerated for visibility. Right: Results showing the sound pressure levels outside the tank and the displacement of the walls.

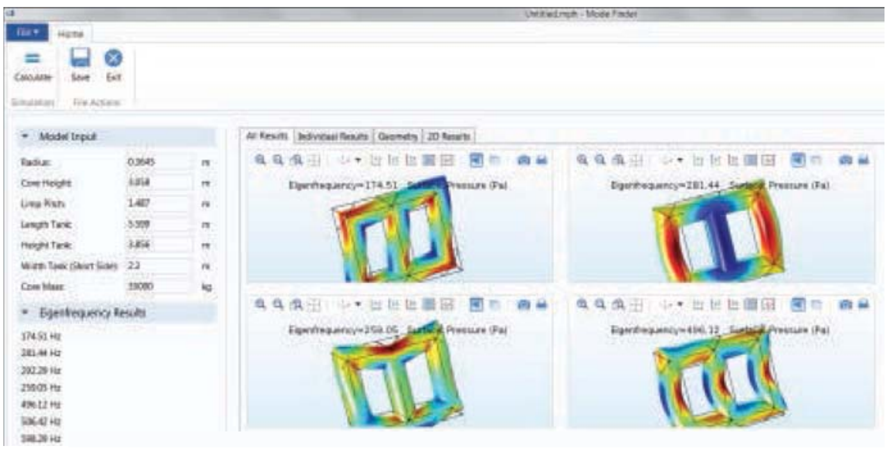


FIGURE 7. Cropped screenshot of the first simulation app created for calculating eigenfrequencies of the transformer core. At left, a tab in the app shows the model inputs; at right, results are shown for the calculated eigenfrequencies. Deformations are exaggerated for visibility.

These simulation applications simplify testing and verification for the designers and R&D engineers: "The designers have been using tools based on statistics and empirical models. We are filling the gaps by deploying simulation apps. The Application Builder allowed us to give them access to finite element analysis through a user interface without them needing to learn finite element theory," Haettel explained.

One application (see Figure 7) calculates the specific eigenfrequencies of the transformer core that can imply noise-related issues due to frequencies that fall within the audible range. This app includes both the physics model developed in the COMSOL® software and custom methods written in Java® code, programmed within the Application Builder.

"Our designers use standard spreadsheets that work well for the transformers they build frequently. But when new designs or different dimensions are introduced, they may run into problems with this approach, like error outputs showing less accurate data for noise levels. This can become quite costly if additional measures to reduce noise are required on the completed transformer," Haettel continued.

"Besides the cost aspect, there is the time aspect. The new app will make the designers' job easier and more efficient by using the precision of an FEA code."

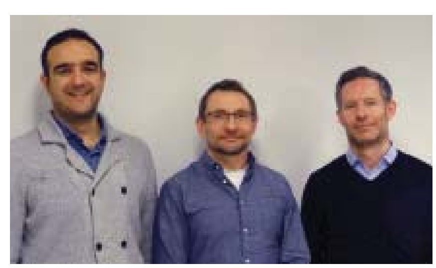
The custom application adds a level of convenience by letting users check how certain combinations of geometry, material properties, and other design parameters will affect the resulting transformer hum. "We've been deliberate about selecting which parameters we provide access to — focusing on the ones that are most important," Kavasoglu added.

With the wide range of industrial applications for which ABB designs transformers, this flexibility is immensely helpful for their design and virtual testing process. "ABB produces transformers for every industrial need. At the moment we're focusing on AC large power transformers commonly used by power companies that transmit and distribute electricity throughout cities," he explained.

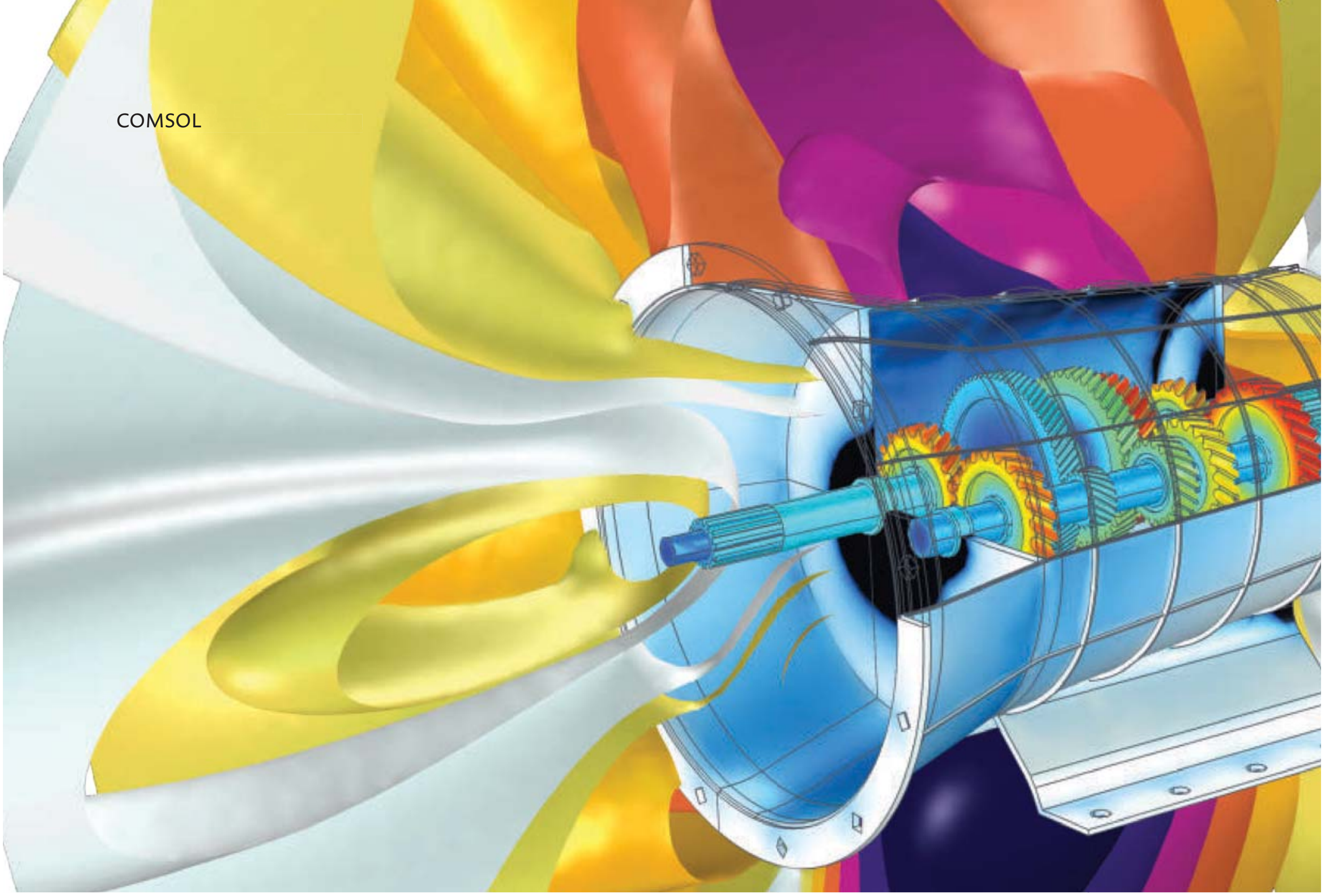
"But the work we're doing can be translated to any type of transformer, and of course if we receive a specific request, we adapt the app to that need. This allows us to easily do additional development work. The Application Builder has made the transfer of knowledge and technology much easier.

"We've also been using the COMSOL Server™ license to distribute our app to other offices for testing, which makes it easy to share it. This worldwide license is great; with a global organization, we expect users in our other locations around the world to benefit from these apps." With a local installation of COMSOL Server, simulation specialists can manage and deploy their apps, making them accessible through a client or web browser.

The team is focusing on a second application that will calculate load noise. Once deployed to the business unit, this application will further remove the burden of tedious calculations, allowing designers and sales engineers to run more virtual tests without needing to work with a detailed model, and enable ABB to more quickly and easily produce the world's best transformers. ❖



Left to Right: Mustafa Kavasoglu, Romain Haettel, and Anders Daneryd of ABB CRC.



MODELING VIBRATION AND NOISE IN A GEARBOX

Predicting the noise radiation from a dynamic system like a gearbox provides designers with insight early in the design process.

by **PAWAN SOAMI**

A gearbox, used to transfer power from the engine to the wheels, radiates noise for two reasons. First, the gears, which transmit power from one shaft to another, exert undesired lateral and axial forces on bearings and the housing. Second, the flexibility of the different components of the gearbox, including bearings and housing, can result in vibration.

In a gearbox, varying gear mesh stiffness causes sustained vibration that is transmitted to its housing, which in turn vibrates and transmits energy to the surrounding fluid; gearbox oil, for example; resulting in the radiation of acoustic waves. In order to accurately model and simulate this coupled phenomena, a contact analysis, multibody dynamics analysis, and acoustic analysis should be performed.

The gearbox considered in this analysis has a drive shaft connected to the counter shaft and five pairs of helical gears (Figure 1). The gears are different sizes but are made of the same material: a structural steel.

⇨ CONTACT ANALYSIS OF THE GEAR MESH

The mesh of gears, which is assumed to be elastic, is a source of sustained vibration. As such, the stiffness of the gears must be evaluated at different positions. As gear teeth deform during operation, a stationary parametric analysis is performed to determine the stiffness variation over a gear mesh cycle. A penalty contact method is used and constraints are defined to account for the twisting of gears leading to contact forces.

Simulation results showing the distribution of von Mises stress in a gear pair indicate high stress values at contact points as well as at roots of the teeth (Figure 2). Using simulation, it is possible to see the variation of gear mesh stiffness with shaft rotation, as shown in Figure 2.

⇨ MULTIBODY ANALYSIS OF SHAFTS, GEARS, AND HOUSING

The multibody analysis is performed in the time domain for one full revolution of the drive shaft using the gear mesh stiffness predicted by the contact analysis. This analysis is needed to compute the dynamics of gears and the resulting vibrations of the housing. In this case, the analysis is performed at an engine speed of 5000 rpm and output torque of 2000 N·m. The shafts and gears are assumed to be rigid except for the gear mesh, for which the stiffness is taken from the previous contact analysis. The housing is comprised of steel and is considered elastic.

The von Mises stress distribution in the housing due to the forces transmitted by the drive shaft and the counter shaft can be seen in Figure 3. The normal acceleration of the vibrating housing, which is responsible for the noise radiation, is also shown in Figure 3.

Figure 4 shows the time history and frequency spectrum of the normal acceleration at the top of the housing. The dominant frequencies at which the housing is vibrating are between 1500 Hz and 2000 Hz. The housing deformation is shown in Figure 5.

⇨ ACOUSTIC ANALYSIS OF NOISE RADIATING FROM THE HOUSING

The normal acceleration experienced by the housing and predicted by the multibody analysis is used as the noise source in the acoustic analysis. The simulation, performed in the frequency domain, predicts the sound pressure level outside the gearbox. As the normal

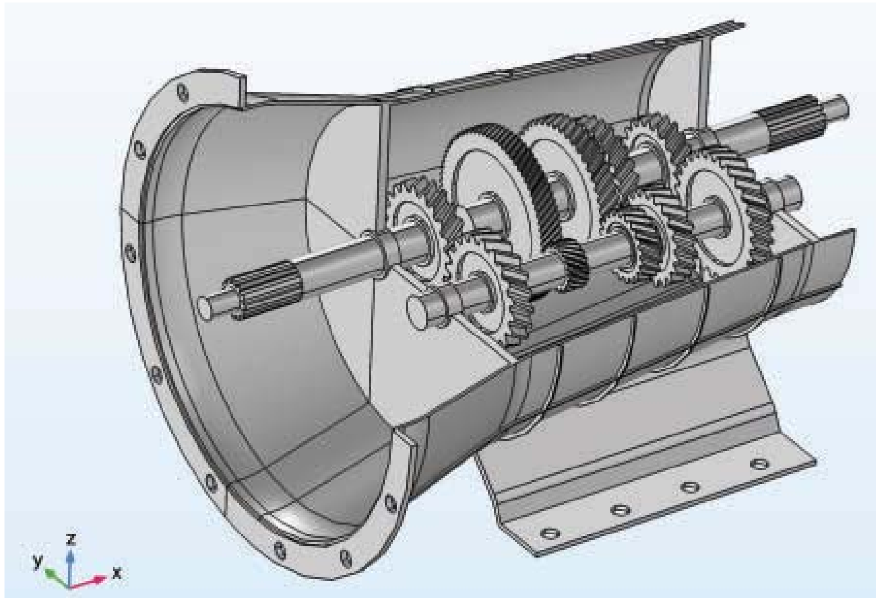


FIGURE 1. Model geometry of a 5-speed synchromesh gearbox for a manual transmission vehicle. Only selected parts of the gearbox considered in the multibody analysis are depicted.

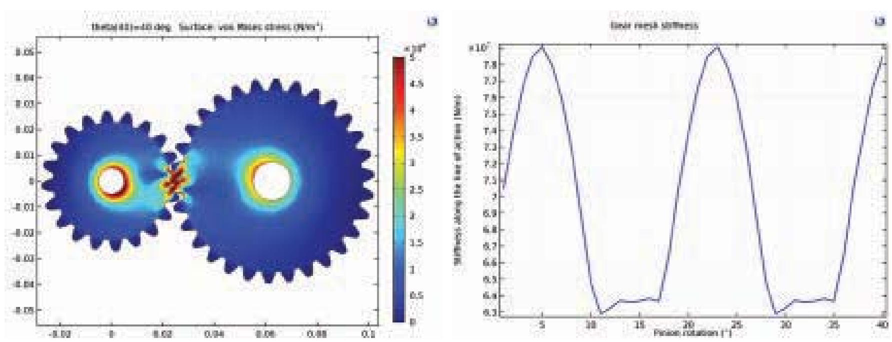


FIGURE 2. Left: von Mises stress distribution in a gear pair. Right: Variation of gear mesh stiffness with shaft rotation.

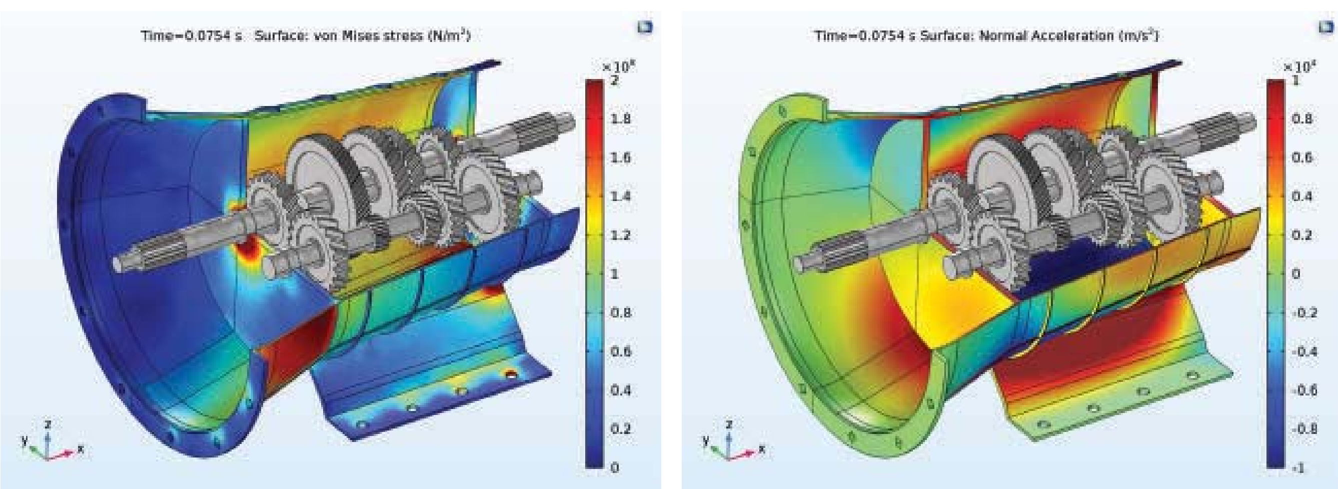


FIGURE 3. Left: von Mises stress distribution in the housing. Right: Normal acceleration of the housing.

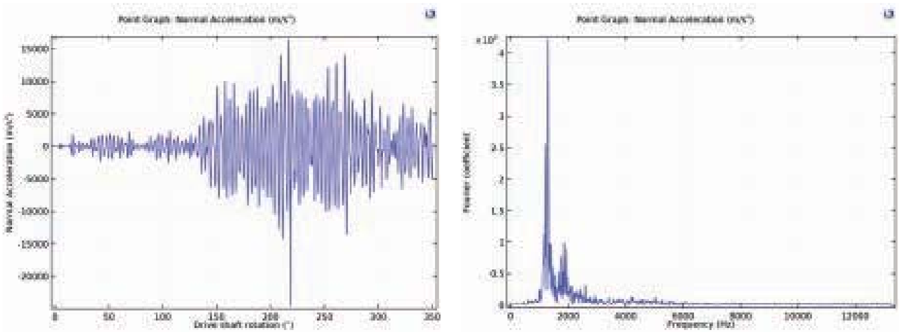


FIGURE 4. Normal acceleration at the top of the housing. Left: Time history. Right: Frequency spectrum.

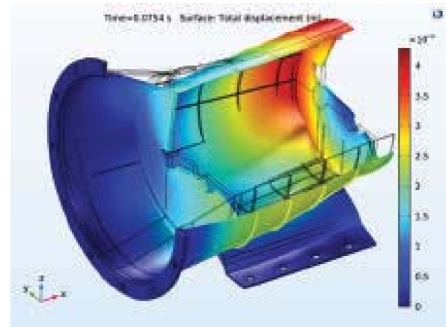


FIGURE 5. Housing deformation magnified 200 times.

acceleration values are in the time domain, a forward FFT (fast Fourier transform) is used to convert them to the frequency domain. An air domain encloses the gearbox where the acoustic pressure is computed (Figure 6). To reduce the size of the computational domain without affecting the accuracy of the results, a spherical wave radiation condition is applied on the exterior boundaries of the air domain to allow outgoing acoustic waves to leave the modeling domain with minimal reflections.

The sound pressure level (SPL) on the housing surface and in the near field are shown in Figure 7. SPL can also be plotted in the far-field, as shown in Figure 8. Far-field plots in different planes and at a distance of 1 m give an idea of the dominant directions of noise radiation at the selected frequency.

⇨ CONCLUDING REMARKS

For simulating the vibration and noise generated, a multibody-acoustic interaction modeling approach is adopted. This technique can be used early in the design process of the gearbox, thus improving the design in such a way that the noise radiation is minimized for different operating conditions. ❖

RESOURCES

- Using Software For Gearbox Noise Prediction, Auto Tech Review, June 2017
- How to Model Gearbox Vibration and Noise in COMSOL Multiphysics®, COMSOL Blog
- Modeling Vibration and Noise in a Gearbox, COMSOL Application Gallery

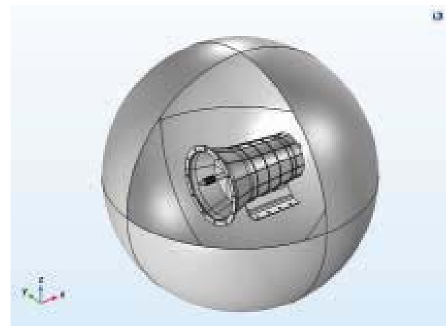


FIGURE 6. Air domain enclosing the gearbox used for the acoustic analysis.

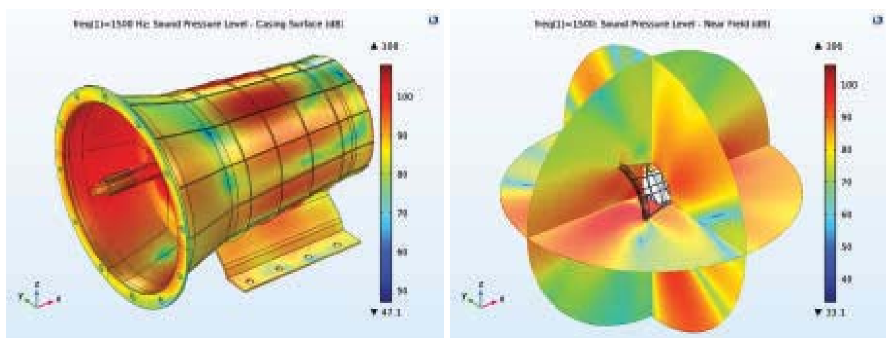


FIGURE 7. Sound pressure level at 1500 Hz. Left: Housing surface. Right: Near-field region.

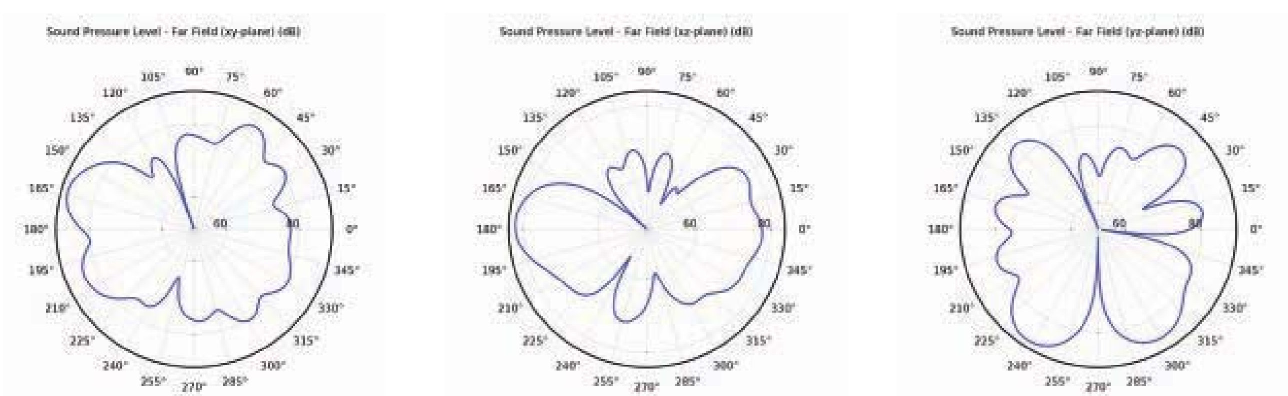


FIGURE 8. Far-field SPL (dB) in the x-y, x-z, and y-z planes, respectively, at a distance of 1 m at 1500 Hz.

Manipulate and Control Sound: How Mathematical Modeling Supports Cutting-Edge Acoustic Metamaterials Research

From consumer audio to ultrasound imaging, the implications of research into metamaterial structures for acoustic cloaking are far-reaching and fascinating. Researchers are using mathematical modeling to design acoustic metamaterials by combining transformation acoustics and highly anisotropic structures.

by GEMMA CHURCH AND VALERIO MARRA

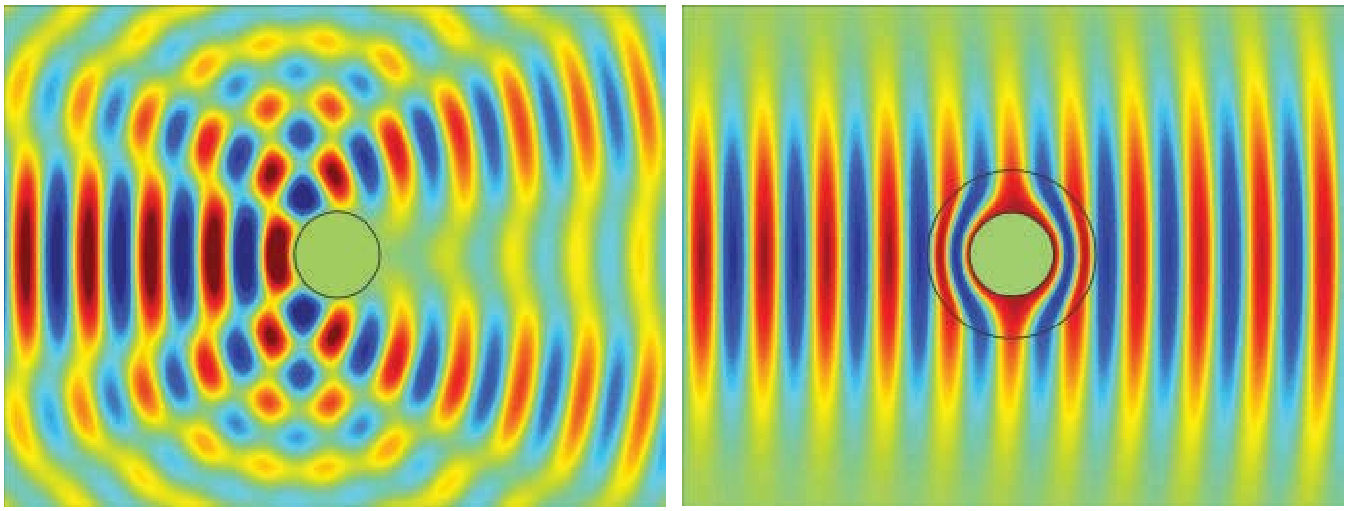


FIGURE 1. Controlling acoustic wave scattering from an object. Left: The scattering of a wave incident from the left from a rigid object is obvious: the reflection is quasi-specular, the shadow is deep, and a portion of wave power is spread in all directions. Right: Surrounding the same object with an ideal cloaking shell shows the absence of both reflection and shadow, while power is transmitted around the metamaterial object with virtually no losses.

Metamaterials are Man-made, specially fabricated materials featuring properties never found in nature, such as zero or even negative refractive index. The result is the creation of cutting-edge designs and functionality, such as superlenses and sound absorbers. Recent research efforts have turned to the arbitrary manipulation of sound waves using metamaterial devices, including making an object acoustically invisible.

The research has been a success. Using little more than a few perforated sheets of plastic and a staggering amount of mathematical modeling and numerical simulation work, engineers at Duke University have demonstrated the world's first 3D acoustic cloak. The device bends sound waves smoothly around an object, fills in the shadow and gives the impression the waves went straight through the surrounding air.

Acoustic invisibility is just one aspect of the broad concept of transformation acoustics, in which carefully designed materials can deform or control sound waves in almost arbitrary ways. From sci-fi to mundane, there are many possible applications of this technological breakthrough.

⇨ DESIGNING SILENT METAMATERIALS

Duke University, alongside MIT, University of California, Berkeley, Rutgers University, and the University of Texas at Austin, forms part of a five-year research program sponsored by the US Office of Naval Research to develop new concepts for acoustic metamaterials with effective material parameters that can be fabricated in the real world.

Steve Cummer, professor of electrical and computer engineering at Duke University, said: "Mathematical models are the starting point. The acoustic metamaterial designs are optimized through numerical simulations, which we then translate into modern fabrication techniques and experimentally test."

> "COMSOL makes it so easy and relatively straightforward to manipulate the material properties and the underlying dynamic equations."
>
> — STEVE CUMMER, ELECTRICAL AND COMPUTER ENGINEERING DEPARTMENT, DUKE UNIVERSITY

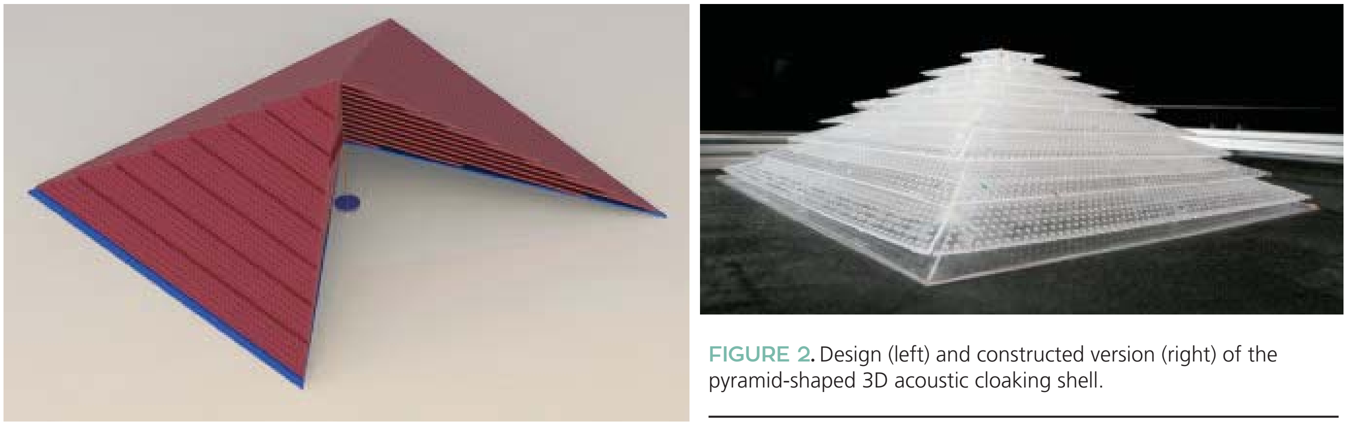


FIGURE 2. Design (left) and constructed version (right) of the pyramid-shaped 3D acoustic cloaking shell.

One focus of the group's current research efforts is on developing acoustic metamaterial structures that can be used in water-based environments, including the human body, to arbitrarily transform and control incoming sound waves. Acoustic cloaking structures (Figure 1) have proven a useful testbed for demonstrating the arbitrary control enabled by transformation acoustics. Designing for aqueous environments represents a shift in metamaterial research, which has evolved from electromagnetic cloaking and transformation optics, to acoustic cloaking and transformations in 2D and then 3D structures in air.

COMSOL Multiphysics® software has been a vital commodity at every stage of the research, going back to the very early days of electromagnetic cloaking. Cummer said: "In the first paper where we showed simulations of electromagnetic cloaking using real electromagnetic material parameters, we used COMSOL® software specifically because it was one of the only electromagnetic software tools that had the ability to accommodate arbitrarily anisotropic electromagnetic material parameters."

To attack the acoustics problem, the researchers began with deriving the needed material properties. Cummer explained: "To arbitrarily control sound using transformation acoustics, we first apply a coordinate transformation to describe how you would like to bend or twist or deform the sound field in a particular device. Once you've defined that coordinate transformation, then you can derive the effective material parameters you need to create that particular deformation of the sound field."

That resulting set of material parameters is almost always anisotropic, which means the material properties behave differently in different directions. To handle this the researchers needed to be able to change the equations representing the physics being simulated. "COMSOL makes it so easy and relatively straightforward to manipulate the material properties and the underlying dynamic equations. This was really important because we could add that one extra twist of the anisotropy to the model and start simulating some of the designs that we were exploring within the transformation acoustics approach," Cummer added.

The resulting real-world designs have been very successful and their performance matched the simulations "astonishingly well", according to Cummer. "The gold standard in metamaterials publications these days, to show whether a structure works the way you want it to and produces the physics you want it to, is to take a measurement of the full sound field produced by the acoustic metamaterial and compare that to the simulation," he added.

COMSOL Multiphysics® software is able to consistently achieve such agreement, even when human error has tried to derail the research. In an earlier project, a 2D acoustic cloaking shell featuring a series of tiny holes was

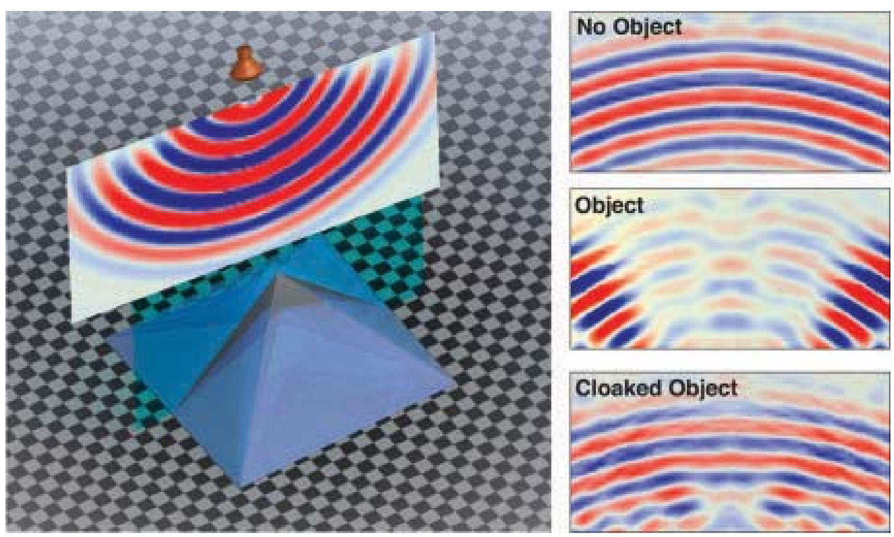


FIGURE 3. (left) To test the metamaterial shell, a sound pulse is launched in three different configurations and the reflected sound pulse is measured with a scanned microphone. (right) The reflected acoustic pulse from the test object is dramatically different than that with no object. When the cloaking shell is placed on the object, the reflected pulse is almost identical to that with no object, demonstrating its invisibility to sound.

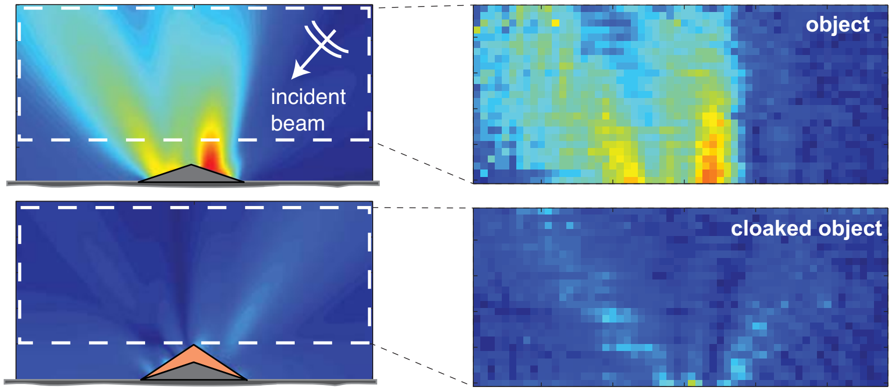


FIGURE 4. The good agreement between simulations (left) and measurements (right) of the scattered acoustic fields not only shows the degree of acoustic cloaking of the object, but confirms that COMSOL accurately predicts the performance of the fabricated device.

designed and built, but the experiments did not match the simulations. The team was flummoxed and could not see any viable reason for the discrepancy. They suddenly realized that holes in the structure were the wrong size due to a mix up during its construction.

Cummer said: "The efficiency of COMSOL has been pretty critical in our work because we can do numerical simulations of both the idealized parameters and then of the full structure that we would actually build, to confirm that they behave the same way."

⇨ FABRICATING AND TESTING AN ACOUSTIC METAMATERIAL

The design of a 3D acoustic cloaking shell employed the same basic perforated plate structure in a pyramidal shape (Figure 2) under which an object could be hidden from sound waves. The structure may at first appear to be relatively simple in its design, but many factors are balanced to achieve the desired acoustic transformation, including the hole diameter, the spacing between the plates, and the angle of the plates. All of these parameters combine to give just the right amount of acoustic anisotropy to make the structure work.

This pyramid structure was the world's first 3D acoustic cloak, and laboratory measurements confirmed that it is capable of rerouting sound waves to create the impression that both the cloak and anything beneath it are not there (Figure 3). The device works in all three dimensions, no matter which direction the sound is coming from or where the observer is located, and holds potential for future applications such as sonar avoidance and architectural acoustics.

Given the necessary thickness of the acoustic metamaterial shell, the latter is the more plausible option, where such acoustic cloaking devices could be used to optimize the sound in a concert hall or dampen it in a noisy restaurant environment, for example. Cummer said: "The cloaking material is not just magic paint you can spray onto something. Generally speaking, that's not the way that these kind of ideas can be deployed in practice."

Beyond the design stage, modeling and simulation have been used to predict the quantitative performance of metamaterial shells like this, including a detailed analysis of the scattering from a 2D cloaking shell implementation (Figure 4). Not only does this show how much the scattered field is reduced by the shell, but COMSOL accurately predicts the amount of scattering reduction given design tradeoffs made in the fabrication of the acoustic metamaterial.

⇨ FROM AIR TO WATER, DIFFERENT MEDIUM, NEW CHALLENGES

Attention has now shifted to getting acoustic metamaterials to work in an aqueous environment, such as underwater or inside the human body. Multiphysics modeling is used as the primary design tool to first map the previously designed structures and run simulations in order to test how they will perform in water. The move from air to water is more difficult than it seems.

The problem is that the mechanical properties of air are dramatically different from those of water. Cummer explained: "That's why in air we can get away with building acoustic metamaterials in plastic, or whatever solid is convenient, as the solid can act essentially as a perfectly rigid structure to control the sound field flow. It doesn't really matter what it is made of."

But the mass density and compressional stiffness of water are not so different from solid materials. "When sound waves hit a solid structure in water, the mechanical properties of that solid start to matter a lot. We need to come up with new techniques in the design phase to be able to control how that sound wave energy interacts with the solid so that we can maintain the properties we want," he added.

"The ability to easily merge acoustics and structural mechanics is essential, especially when we're dealing with structures in water where we can't ignore the mechanical responses of the solid material that we're using to build the metamaterial. In airborne acoustics, we can get away with treating the solid as a material that is infinitely rigid, which is easy and computationally efficient, but for the water-based material it is essential to be able to consider fluid-structure interaction, which is easy with COMSOL."

The leap from research into commercially viable acoustic metamaterial structures is far from simple and means such structures must be able to be fabricated reliably and repeatably. Cummer concluded: "The next step to creating any acoustic metamaterial is that it is able to hit specific quantitative metrics. That means we have a more complicated design process, but that's exactly what COMSOL is designed to do. [It allows] much more design iteration and clever use of optimization to identify degrees of freedom in the design that can be manipulated to then hit those specific numerical targets. That's definitely the key going forward in transitioning these ideas from proof of concept demonstrations to something that's actually practical and deployable in the real world." ❖

NGI, NORWAY

Shake, Rattle, and Roll

Norwegian researchers are tracking how low-frequency sound waves travel within buildings so that they can recommend design adjustments to alleviate annoying vibrations.

by JENNIFER HAND

Anyone who has slept near an airport will know the sensation — an early morning flight wakes you from sleep, not only because the engine is noisy but also because everything around you seems to be shaking. Likewise, people living near wind turbines, military sites, or hospitals with helicopter landing pads often complain that windows rattle and everyday objects buzz when there is external noise. More puzzling for them is the fact that even when they can discern no sound, they may still notice irritating vibrations.

If the response of the sound is 20 vibrations per second (20 Hz) or less, it is described as infrasound, meaning that the original sound is not usually audible to the human ear. The effects, however, are very easy to detect. As waves hit windows, spread to the floor, and affect internal walls, they induce a noticeable indoor vibration. Low-frequency sound waves are notorious for their potential to create annoying disturbances.

➩ LOW-FREQUENCY SOUND WAVES IN BUILDINGS

Noise is part of modern life and there are formal standards that use sound pressure level measurements to recognize high-frequency sound waves at levels of sensitivity, intrusion, and danger for humans. According to Finn Løvholt of the Norwegian Geotechnical Institute (NGI), the generation of building vibration due to infrasound is an area of research that has not been explored extensively. For this reason, NGI, an international center for research and consulting within the geosciences, has been running investigative programs for several years on behalf of the Norwegian Defence Estate Agency.

"Low-frequency sound encounters less absorption as it travels through the air than higher-frequency sound, so it persists for longer distances. The amount of sound transmitted from the outside to the inside of buildings is greater. We are interested in what happens at the threshold of hearing," explains Løvholt. "We want to understand how sounds from external sources interact with buildings and generate vibration that is perceived by people. We can then recommend countermeasures to prevent vibration and may be able to propose standard units that recognize the need to account for the 'annoyance' factor."

> "We have never achieved this level of agreement with real-life testing before and it is all down to how we were able to model the different structural elements in COMSOL Multiphysics."
>
> — FINN LØVHOLT, NGI

➩ SIMULATING THE SPREAD OF SOUND WAVES

Løvholt and his colleagues decided to create a computer model that would allow them to pick apart the mechanism of low-frequency sound waves hitting and penetrating a building. They used the COMSOL Multiphysics® software to simulate a wooden structure with two rooms separated by a wall (see Figure 1, top), closely mimicking the laboratory experiment setup. Within the model, they assigned a loudspeaker to one room, a microphone to the other, and placed various probes around the structure in order to monitor sound pressure levels and vibrations. Every component was carefully modeled,

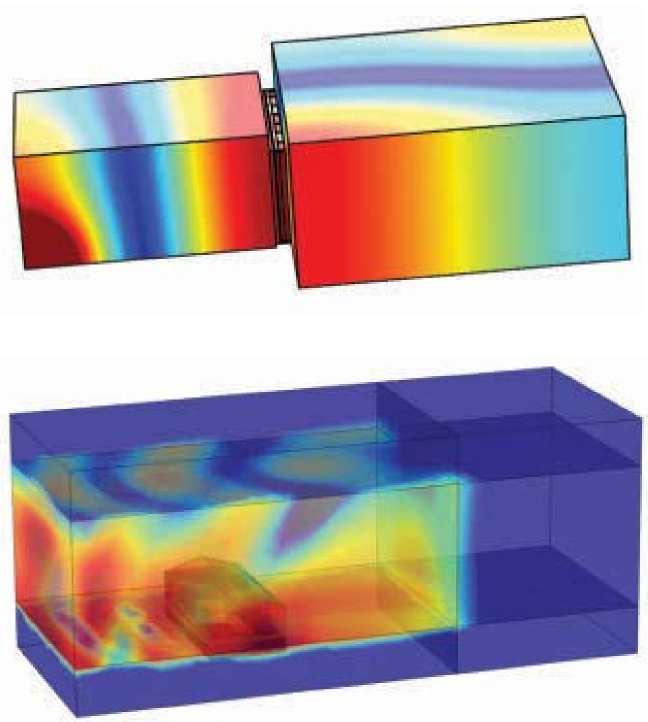


FIGURE 1. Top: Simulated sound pressure in a laboratory with two chambers divided by a wall. A loudspeaker is placed in the room on the left-hand side. The simulations show that the acoustic resonances within each room affect the sound insulation. Bottom: Simulated low-frequency sound originating from outside, around, and inside a building. In both cases, the colors indicate the variation in the sound pressure within the rooms and the wall cavities.

including the steel frame, the air cavity and studs in the wall, the windows, the plywood sheet, and the plasterboard. "Each element has a resonance that depends on the wavelength of the sound wave and the pressure distribution. For example, there is high pressure in the speaker room and lower pressure in the microphone room, and the resonance of a wall will depend on its length, thickness, and stiffness," explains Løvholt.

The team also had to recognize compound resonances created when two components are joined, such as two pieces of timber that are screwed together. "The advantage of COMSOL Multiphysics is that it allows us to enter all the parameters we need to monitor. In particular, it enables us to couple physics, so we can, for example, look at the acoustics of open-air sound interacting with indoor structural dynamics. The coupling works both ways so we can identify feedback. This coupling is crucial for our analysis because sound waves can generate a huge range and variety of resonances. The model really allows us to see these."

The NGI team then validated their simulation with laboratory testing of low-frequency sounds as they were transmitted through a wooden construction with two rooms. Løvholt explains that the motion of the wall and the sound pressure level are the main quantities measured and results show very close correlation to the COMSOL Multiphysics model (see Figure 2). "The response of the real wall is very clear and the model mimics it almost perfectly. This is the most spectacular aspect."

The model shows that the transmission of sound within a building is governed by the way in which low-frequency waves interact with the fundamental modes of the building components, the dimensions of the room, and the way in which air leaks from the building envelope. Vibrations in ceilings and walls seem to be the dominant source of low-frequency indoor sound, with floor vibration driven by sound pressure inside the room.

⇨ CHEAPER AND QUICKER THAN PHYSICAL TESTING

"We now have a tool to predict sound and vibration at low frequencies," Løvholt says. "We can use it to design and test mitigation measures such as the lamination of windows and the stiffening of walls — if a wall or window moves less, sound transfers less. In addition, the model shows us the influence small details have on the system; for example, how the screw connection between studs and plasterboards can reduce the effect of a countermeasure, as they actually reduce the overall stiffness of the structure."

The next stage for the team is full-scale field tests on a real house in an area of Norway that is exposed to aircraft noise. Meanwhile, the team will continue to use and develop the model. "We have never achieved this level of agreement with real-life testing before and it is all down to how we were able to model the different structural elements in COMSOL Multiphysics," concludes Løvholt. "The model enables us to make decisions and assign countermeasures. This is much cheaper and quicker than physical testing. The model may then be expanded to simulate the sound propagation and vibration in an entire building" (see Figure 1, bottom). ❖

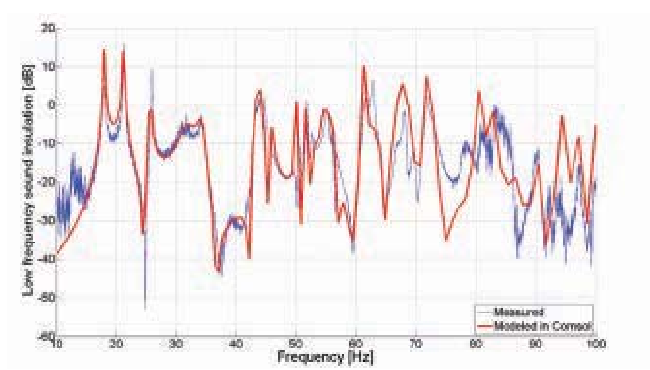


FIGURE 2. The model accurately captures the location of the resonances as well as the level within a few decibels. As the frequency increases, more modes in smaller and smaller structures will get excited. This shows as the increasing difference between the measurements and the model results.

On the Cutting Edge of Hearing Aid Research

Engineers at Knowles bring the hearing aid industry together to fight feedback with multiphysics simulation.

by **GARY DAGASTINE**

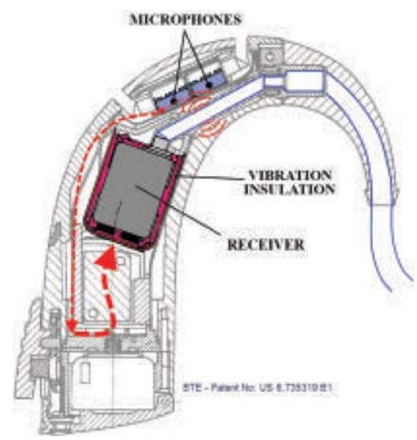


FIGURE 1. A typical BTE hearing aid includes microphones, vibration insulation, and a receiver, among other components. The tight spacing of these components invites troublesome acoustic and mechanical feedback. (Image credit: Knowles Corp.)

In the United States, nearly 20% of the population is reportedly hearing impaired — although that figure could be higher because many people are reluctant to admit they have a hearing problem. Those who are treated rely on miniature and discreet hearing aid devices to improve their hearing, hence their quality of life. Significant R&D effort is required to bring a hearing instrument from a prototype stage to a marketable hearing aid device.

Engineers face daily technical challenges in hearing aid design. Feedback is a major issue that leads to high-pitched squealing or whistling, and limits the amount of gain the aid can provide. "Feedback usually occurs when a hearing aid's microphone picks up sound or vibration inadvertently diverted from what's being channeled into the ear canal and sends it back through the amplifier, creating undesirable oscillations," explains Brenno Varanda, a senior electroacoustic engineer at Knowles Corp. in Itasca, IL.

"For many of Knowles' customers, designing a new hearing aid is a costly, time-intensive process that could take anywhere from 2 to 6 years to complete," Varanda explains. Accurate modeling helps designers select speakers, refine vibration isolation mounts, and package components to reduce the amount of speaker energy that is fed back to the microphone. The industry is in dire need of simple transducer models that will expedite that process, and provide more effective options to consumers. Complete models of speakers and microphones are quite complex, and incorporate many factors that are not necessary for feedback control. "While understanding the electromagnetic, mechanical, and acoustic physics of our transducers is important to transducer designers at Knowles, all of that complexity is not necessarily useful for our customers." Varanda says.

As a global leader and market supplier of hearing aid transducers, intelligent audio, and specialty acoustic components Knowles took a multilateral initiative to develop transducer vibroacoustic models that are easy to implement and compatible with its hearing health customers. The models are intended to help hearing aid designs graduate from a prototype stage to a final product in a more efficient manner without having to sacrifice accuracy.

⇨ HEARING AID DESIGN AND FEEDBACK

When designing hearing aids two major conflicting requirements must be accounted for by engineers. They must be compact and unobtrusive, yet still capable of providing a powerful sound output to overcome the user's hearing loss. The user is far more likely to wear a hearing aid if they are discreet and lightweight. This makes solving the feedback issue more challenging. "A common design challenge is to cram all the hardware components into the smallest space possible without causing feedback instability," Varanda continues.

A typical small behind-the-ear (BTE) hearing aid comprises microphones to convert ambient sounds into electrical signals, a digital signal processor and amplifier to process and boost the electrical signals, and a tiny loudspeaker, also known as a receiver (Figure 1). The receiver, or speaker, "receives" amplified electrical signals and converts them into acoustic energy, or sound, which is then channeled into the ear canal through a tube or an ear mold.

The receiver contains an electromagnetically controlled lever, known as the reed, connected to a diaphragm which generates sound through its oscillating motion. The internal electromechanical forces also generate reaction forces which transmit vibrations through the hearing aid package, creating sound that is picked up by the microphone. This signal in turn is magnified by the amplifier and returned again to the receiver, causing feedback. This path is shown in Figure 1.

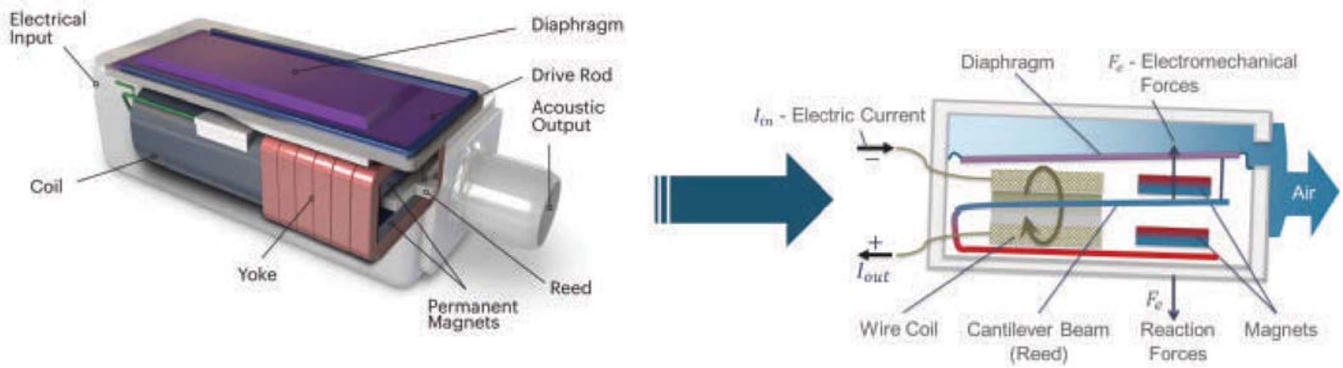


FIGURE 2. A receiver, a key hearing aid component, contains a tiny loudspeaker with an electromagnetically controlled diaphragm that generates sound. Internal electromagnetic forces cause structural vibration that results in mechanical feedback.

FIGURE 3. Hardware and schematic of the experimental setup.

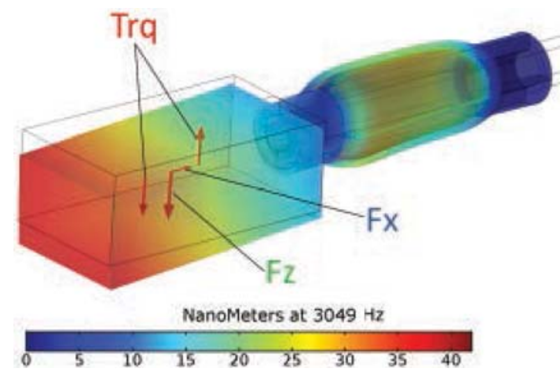


FIGURE 4. Simulation force and displacement results at 3 kHz of the receiver and silicone tube attachment.

⇨ THE "BLACK BOX" MODEL

The receiver's only function is to convert the amplified voltage signal from the microphone into sound. While the construction appears simple, the process is rather complex (Figure 2). The electrical signal is first converted to a magnetic signal, then to a mechanical signal, and finally into an acoustic signal. Each of these steps has its own frequency-dependent characteristics. Understanding the combined effects of all the internal components is vital to the ability of effectively designing receivers for all different hearing aid platforms. Engineers at Knowles have been using complex circuit-equivalents to model all of their internal electrical-magnetic-mechanical-acoustic effects since the 1960s.

Accurately modeling the full complexity of a receiver requires a dauntingly large and complex multi-physics finite element model, making it impractical for fast and efficient hearing aid design. This issue was overcome when Dr. Daniel Warren, a hearing health industry expert in receiver and microphone research, introduced a 'black box' model in 2013. The design uses a minimum amount of simple circuit elements to capture the essential electroacoustic transfer function between voltage and output sound pressure level for balanced armature receivers, while leaving out factors that are unimportant to feedback control.

A key step to simplifying the model was when Warren and Varanda demonstrated that the simplified electroacoustic circuit could be converted into a powerful vibroacoustic model while adding very little complexity to the model. "The conversion is achieved by probing a section of the 'black box' circuit where the voltage across inductors is directly proportional to the internal mechanical forces responsible for structural vibration," Warren explains.

The "black box" and vibroacoustic models needed to be tested and validated against realistic acoustic and mechanical attachments to the receiver before designers could start using them for product designs. A worldwide collaboration between Knowles and its hearing health customers got started in 2014 to validate the models using the COMSOL Multiphysics® software and industry standard tests.

⇨ WORKING TOGETHER ON VALIDATION

To validate the models, engineers needed to measure the acoustic output and vibration forces at the same time, using a structure that could be easily modeled in FEA. Like common hearing aid tests, this test involved connecting a receiver to a short section of tubing leading to an enclosed cavity with a two cubic centimeter (2 cc) volume, which is a standardized ear canal acoustic load as shown in Figure 3. The acoustic pressure inside the cavity is measured with a laboratory-grade microphone. To help verify the robustness of the model, the receiver was also measured using a complex tubing assembly similar to a BTE hearing instrument. The long tubing in this design varies in diameter, and is long enough to support multiple acoustic resonances. At the same time the acoustic output was being measured, the receiver's structural motion was captured by a laser vibrometer. Both translational and rotational motion were measured by observing the motion at multiple points on the surface of the receiver housing.

Warren and Varanda collaborated with several Knowles customers to perform the measurements described above. With the help of COMSOL Multiphysics, they were able to implement the simplified vibroacoustic circuit model into a simulated replica of the test setup described above. The simulation couples the mechanical interaction between the motion of the receiver and the silicone tubing attachment, thermoviscous losses within the various tubing cross sections, and acoustic pressure loads inside the cavity and tubing with the internal electro-magnetic-acoustic effects in the "black box" receiver model.

The COMSOL model revealed the dependence of the output pressure and mechanical forces on the applied voltage, frequency, and material properties. Figure 4 shows the displacement results from the simulation at 3 kHz and the reaction forces coupled to the receiver.

When Varanda compared the results of simulations with the physical measurements, they showed excellent agreement (Figure 5). The forces acting on the diaphragm and the reed are acoustically dependent on the output sound pressure. However, the coupling between the forces acting on the diaphragm with the structural reaction forces proves to be, as expected, directly proportional.

> "With multiphysics simulation hearing-aid designers now have the capability to reduce feedback and improve overall performance better, faster, and more economically than before, which will lead to better options for people who are hearing impaired."

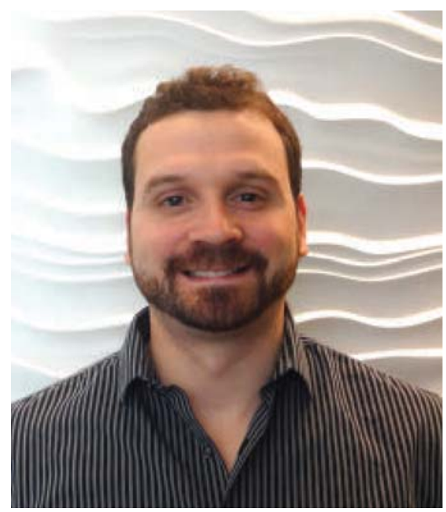
⇨ SPREADING THE KNOWLEDGE

Knowles shares their model to empower engineers at other hearing aid companies to solve their own system feedback troubles. With a complete representation of the acoustic, mechanical, and electromagnetic behavior inside the hardware, designers are well set up to virtually optimize their products.

"COMSOL is one of the few modeling and simulation tools that can easily couple the lumped 'black box' receiver circuit with acoustics and solid mechanics," says Varanda. "Until now, verifying and optimizing hearing aid designs has been as much art as science. We will be very happy to see new hearing instruments designs that have benefitted from these models."

By joining forces, the intercompany effort has made it easier for everyone in the hearing health industry. "Ultimately, hearing aid designers don't want to get bogged down with complex transducer models and time-consuming simulations. They simply want focus on their own design and to swap transducers in and out to see how everything will work together," he adds. "This COMSOL model enables them to do this. The behavior of hundreds of transducers can be easily compared for one hearing aid package."

Hearing aid designers now have the capability to reduce feedback and improve overall performance better, faster and more economically than before, which will lead to options for people who are hearing impaired. ❖



Brenno Varanda, senior electroacoustic engineer, Knowles Corp.

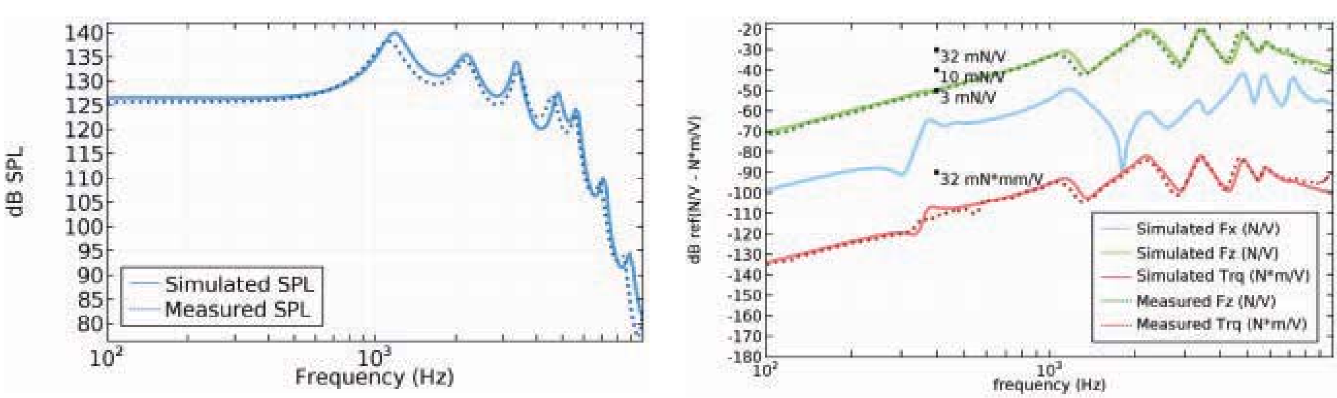


FIGURE 5. Left: Measured (dotted line) vs. simulated (solid line) sound pressure level inside a 2-cc coupler. Right: Measured (dotted line) vs. simulated (solid line) forces and torque acting on the receiver.

ECHOLOGICS, CANADA

MULTIPHYSICS ANALYSIS ADVANCES WATER MAIN LEAK DETECTION

Predicting the speed of sound is important for accurately locating leaks in buried pipes such as water mains. Echologics Engineering has implemented a finite element simulation framework to model acoustic behavior in pipes and estimate variations in the speed of sound.

by VALERIO MARRA

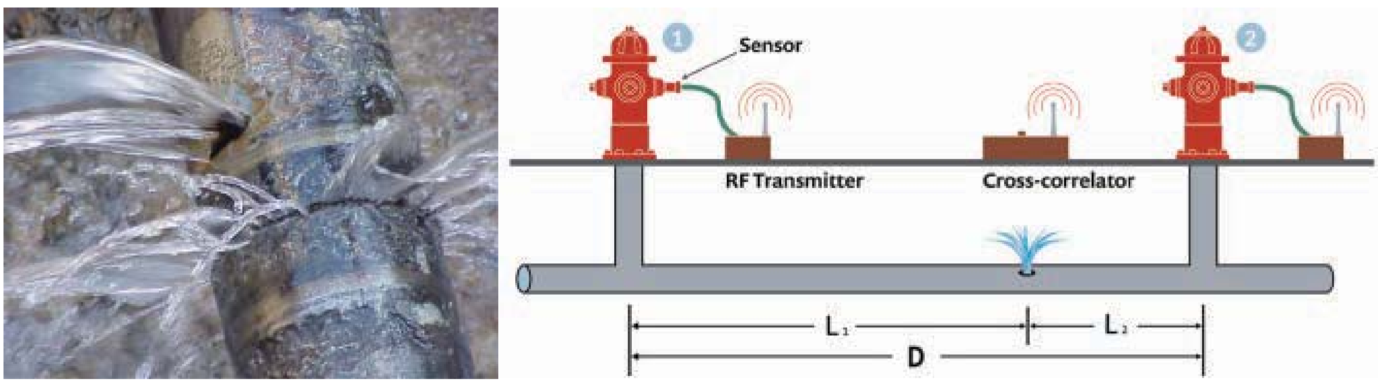


FIGURE 1. Left: Leaky pipe under investigation. Right: Schematic of leak detection setup. A leak is bracketed by two sensors whose distance is D. The leak sound propagates in both directions and a correlator measures the time it takes to reach each sensor. Based on the speed of sound in the pipes, the exact leak location can be found.

Fresh, clean water is a precious commodity that municipalities cannot afford to waste in underground pipe leaks. As pipe infrastructure ages, finding leaks becomes more difficult. As water grows in value, finding leaks becomes more critical.

That is where the Toronto-based company Echologics, a division of Mueller Canada, Ltd., with its unique acoustic technology for noninvasive leak detection, enters the picture. "Leaks make noise," explained Sebastien Perrier, R&D acoustical scientist at Echologics. Perrier is a mechanical engineer who specializes in acoustics and vibrations, the coupling of structures, as well as signal processing. "The pipes talk and, if you listen, they'll tell you where leaks are located," he said.

Echologics measures the time-of-flight of the sound using a correlation function and acoustic sensors set on the pipes or fire hydrants. If a leak occurs somewhere between two sensors, the leak is detected and the correlation result is used to determine the time difference the leak noise takes to reach each sensor. This provides the distance from the leak to each sensor once the speed of sound is known in the pipes under investigation (Figure 1).

A leading innovator of acoustic systems for water infrastructure, Echologics designs technologies that exploit this correlation to find leaks and to continuously monitor pipes for leaks. Examples of Echologics products include the LeakFinderST™ leak noise correlator (Figure 2) and the EchoShore®-DX pipeline monitoring system (Figure 3). Echologics correlators allow field specialists to investigate leaks in a variety of pipes using transmitters, sensors, and a user interface that can be set up on a standard laptop. This acoustic technology can detect even very small leaks in the early stages of formation, saving municipalities' money and pipe damage since they monitor leaks as they grow and are able to take action quickly.

The technology powering Echologics' products requires a precise understanding of the speed of sound in different types of pipes. It is material dependent, proportional to the stiffness of the pipe, and influenced by the pipe geometry. "The key was developing technology sensitive enough to make leak detection possible in PVC pipes," explained Perrier. Plastic has high attenuation and dampening compared with metal. Even trickier is the fact that older water systems originally made with cast iron pipes are being repaired — in individual segments — with plastic.

Keeping the sophisticated acoustic correlation algorithms up to date and accurate is one of Perrier's

FIGURE 2. The LeakFinderST™ correlator is a compact, intuitive leak noise correlator.

FIGURE 3. The EchoShore®-DX System turns existing fire hydrants into smart leak detection technology.

responsibilities. He must understand the physics involved at a fundamental level in order to optimize and develop next-generation solutions for buried pipe infrastructure. To help him speed up the design process and share his findings with other departments, Perrier creates computational acoustic models and builds simulation apps based on them.

⇨ CATCHING LEAKS BEFORE THEY CAUSE FAILURES

How does numerical simulation help predict acoustic wave propagation in pipes? The pipe network analysis can be complex and time consuming. One may want to understand the sound propagation and vibration response from a single pipe perspective or from an entire network. Therefore, the complexity of the model and the time it takes to run the analysis can change considerably depending on the level of details needed for the physics involved in the model to be accurate.

Making sure that the sound propagation speed is accurate for each pipe segment is at the heart of the problem that Perrier solved at the early stage of the design process. He then adopted multiphysics simulation to give him faster access to the values relevant to his work. In a pipe networks analysis, multiphysics couplings between acoustics, flow, and structural mechanics are needed.

In Perrier's work, there are multiple uses for simulation. Such as being able to understand slight margins of error and fine-tune the technology. Exploring material and geometry parameters for a pipe network through acoustics simulation reveals predictions for different scenarios. The acoustics simulation exhibits the presence of signal noise when the sensors' distance varies, or indicates that a plastic repair must have occurred that wasn't included in the test. Perrier's simulation also predicts the pressure in a pipe network as the acoustic wave travels to the sensor, as well as mechanical damping accounting for sections of different materials, offering a way to visualize the problem (Figure 4).

⇨ ROUTINE USE AND SIMULATION APPS

With routine use of the computational model, Perrier saw the advantage in building a custom simulation app. Based on his COMSOL Multiphysics® software analysis and using built-in tools in the software, he created his own app that combines acoustic-structure interaction, pipe acoustics, and time-dependent and frequency studies (Figure 5). The app allows the user to vary geometry and material properties in multiple runs, and analyze a pipe segment or an entire network.

Using the app a user can define a water main network by specifying segment lengths, number of segments, and pipe characteristics. Speed of sound is computed by selecting material properties from a predetermined list, such as cast iron or plastic. The simulation then incorporates the results from field measurements, which a user would manually enter based on correlations to predict leak locations.

Turning the multiphysics model into a simulation app is convenient for

> "By building simulation apps I can share a complex model with colleagues and make it accessible anywhere."
>
> — SEBASTIEN PERRIER, R&D ACOUSTICAL SCIENTIST, ECHOLOGICS

interacting with others in the company. "By building simulation apps I can share a complex model with colleagues and make it accessible anywhere," Perrier said. Simulation apps can be password protected and deployed with a local installation of the COMSOL Server™ product, making it possible to quickly push app updates and maintain confidentiality.

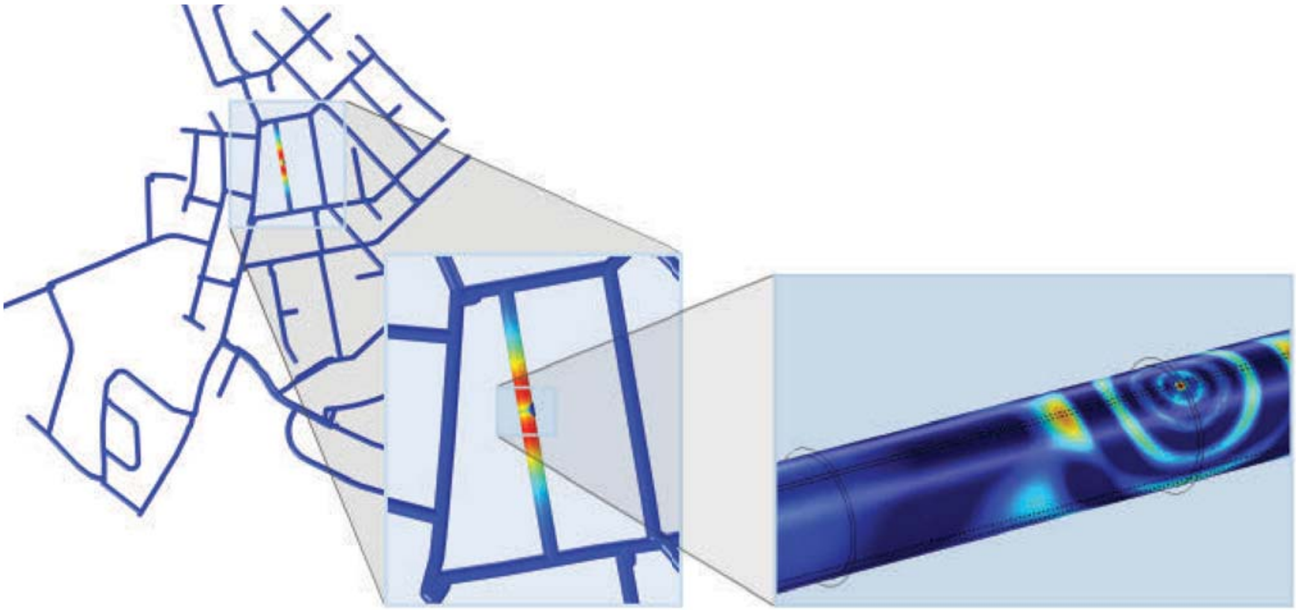


FIGURE 4. Sound propagation analysis of a leak noise in a pipe network. The plot shows the acoustic pressure in the area surrounding the leak.

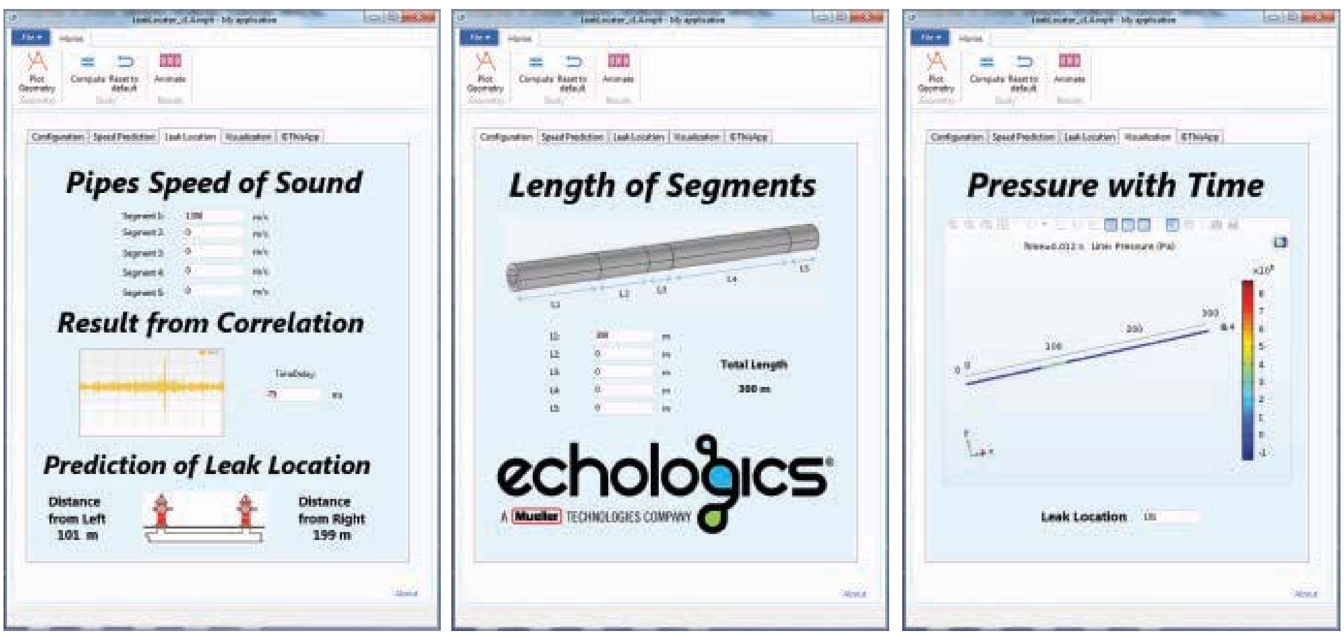


FIGURE 5. An easy-to-use interface guides a user to predict an accurate leak location by defining geometry and pipe characteristics. The app calculates the speed of sound in the pipe and allows the user to visualize, with an animation, the sound propagation from the leak location, while hiding the complex calculations for acoustic-structure interaction and location prediction.

This was a key attribute for him, noting that much of what he does is confidential. He created the app so it could be run by field engineers' on-site.

He expects that the app will be broadly used within Echologics. The key is for Echologics field engineers to be able to quickly and accurately find leaks without having a detailed understanding of the mechanics or mathematics behind the simulation. A powerful tool, in Perrier's vision, is a simulation that visualizes the propagation of sound and lets users see whether the speed of sound is decreasing or increasing when the geometry or material properties change. ❖

Sebastien Perrier, R&D acoustical scientist at Echologics.

Music to Your Ears: New Transducers Meet Electrostatic Headphones

An audio technology startup delivers new manufacturable transducers for high-end electrostatic headphones and reduces low-end roll-off.

by **JENNIFER HAND**

Serious hi-fi enthusiasts get excited about the musical experience delivered by electrostatic headphones. Producing a natural, airy sound, they provide greater clarity, less distortion, and extended bandwidth when compared to other types of headphones where high resolution audio sources are involved.

Most electrostatic speakers apply an electric charge on a thin elastic membrane situated between two conductive plates. The charged membrane moves in direct response to the electrical input, generating the sound waves that our ears and brain interpret as music, and moving us to joy and tears.

Despite their high quality and accurate audio reproduction, electrostatic speakers can be prohibitively expensive, sometimes fragile, and until recently, were handmade because of mechanical precision requirements. Seeing a need for affordable, high-quality headphones that could be manufactured more easily, Warwick Audio Technologies Limited (WAT) designed the High-Precision Electrostatic Laminate (HPEL) transducer, a patented technology based on an ultrathin diaphragm and a single conductive plate instead of a pair. With its origins at Warwick University in the UK, WAT has developed a lightweight laminate membrane only 0.7 mm thick that is perfectly suited for electrostatic headphones.

The new HPELs are lightweight thin-film structures manufactured through a continuous roll process. "The technology we've developed is unique," explains Martin Roberts, CEO of WAT. "The HPEL transducer is made up of a metallized polypropylene film, a polymer spacer with hexagonal cells, and a conductive mesh" (Figure 1).

In the typical setup, direct current (DC) bias voltage is applied to the elastic membrane and alternating current (AC) drive signal to the surrounding plates. WAT's one-sided speaker involves both the DC bias and the AC drive signal applied to the elastic membrane, with a single wire mesh (plate) positioned opposite the membrane as a ground plane.

The fabrication method makes it possible to reproduce the transducers at a significantly lower cost than traditional electrostatic speakers. This means that for the first time, electrostatics may be considered a commercially viable high-res audio option across a wide range of device types and market segments.

> "We went from making multiple prototypes by hand each week to simply dialing up a new one in the software. In addition to settling on a final design we're very happy with, it is now easy for us to customize our transducers for clients' custom requirements."
>
> — MARTIN ROBERTS, CEO, WAT

⇨ SIMULATING ACOUSTIC PLAYBACK

To develop a transducer like this, which can be easily manufactured and inexpensive without compromising sound quality, the WAT team thoroughly investigated the influence of many design elements before settling on a final version. "We had developed numerous prototypes that clearly performed. The big issue was that we were not entirely sure how varying individual material and design parameters affected the transducer's performance," Roberts says.

The dynamics of the HPEL are dependent on the extremely complex interplay between membrane tension, AC signal level, speaker geometry, elastic and dielectric material properties, thermoacoustic losses, and the added mass effects of the air next to the open side of the membrane. The designers wanted to improve bass performance by reducing low-end roll-off, minimizing distortion, and maximizing the sound pressure level for a given electrical input. But they discovered that small changes to any component greatly affected the acoustic output.

Although WAT had significant mechanical, electrical, and acoustic expertise, they had no in-house simulation capability to help them understand this interplay. In order to perform a virtual optimization of the

FIGURE 1. Top to bottom: WAT's HPEL transducers; single laminate, assembled, and exploded views of a finished HPEL transducer. All laminates are made in the UK.

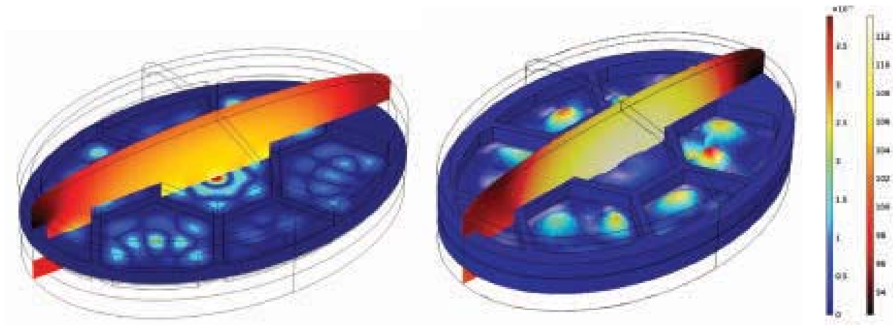


FIGURE 2. Simulation plot showing the sound pressure level (thermal color surface) in dB and the displacement of the membrane (rainbow color surface) in mm from a fully coupled acoustics-MEMS model solved in the frequency domain. Left: solution at 5,000 Hz. Right: solution at 5,250 Hz.

HPEL transducer design they enlisted the help of Xi Engineering, a COMSOL Certified Consultant that specializes in computational modeling, design recommendations, and solving noise and vibration problems in machinery and other technology.

Dr. Brett Marmo, technical director of Xi Engineering, oversaw the development of the COMSOL Multiphysics® software models they used to analyze the behavior of the HPEL. The software allowed Xi Engineering to model nonlinear effects that would arise with amendments to the HPEL's asymmetrical design.

"We kept the early model simple, focusing on specifics that influence sound quality, for example keeping the first harmonic as low as possible to understand the acoustic-structure interaction and the HPEL's performance at low frequency," Marmo explains, describing their preliminary tests. "Our model showed how applied voltage affects signal levels, which helped us understand sound distortion for an initial case."

Because the transducer is one-sided, the electrostatic force varies with the position of the vibrating membrane, decreasing with the square of the distance between the membrane and the mesh. Once they understood the resulting nonlinear distortion and were able to predict its effects, the WAT engineers could then cancel any related distortions electrically.

⇨ PERFECTING THE HPEL TRANSDUCER DESIGN

In a more extensive simulation that involved a structural-MEMS-acoustic coupling, he examined the impact of adjusting parameters like the size of the hexagonal cells in the wire mesh, thickness of the wires, membrane tension, spacing between membrane and mesh, and material properties of each component. Marmo and his colleagues also studied the effects of different DC biases, which are often responsible for distortion at low frequencies, and looked at conductivity along the plate to discern whether voltages were higher in one area than another. They then used COMSOL to study the thermoacoustic losses and model the displacement of the membrane for different frequencies (Figure 2).

"We found that this type of simulation was the only accurate way to truly model planar electrostatic transducers," Marmo continues. "For this case, lumped parameter modeling can characterize limited aspects of performance, such as low-frequency amplitude response. One parameter might be excellent but there may be significant distortion created elsewhere. Multiphysics modeling encompasses all dimensions that affect our perception of sound, such as the time-domain response and nonlinear distortion."

The simulations made it possible for the engineers at WAT to tweak design parameters in order to optimize overall performance. Ultimately, they were able to predict what was causing spikes in the frequency response and smooth out the signal for better fidelity.

"This represented a huge cost and time benefit for us," says Roberts. "We went from making multiple prototypes by hand each week to simply dialing up a new one in the software. In addition to settling on a final design we're very happy with, it is now easy for us to customize our transducers for clients' individual requirements."

Marmo's team compared each model with physical measurements provided by the WAT design team. "The simulation results were astoundingly close to the physical measurements," comments Dan Anagnos, CTO at WAT. "That was probably the most exciting aspect, seeing the simulation come to life and knowing it was giving us an accurate picture of how the speaker would perform."

⇨ FREEDOM AND FLEXIBILITY WITH A SIMULATION APP

With simulation results verified and validated and WAT satisfied with their design, the next step was for Xi Engineering to put WAT in control of further modeling. The Application Builder available in COMSOL software enabled Marmo's team to build an app from their simulation and host it online.

The app's interface allows users to change certain inputs to test changes to a number of parameters, such as the DC bias, AC signal level, frequency range and resolution, material properties, speaker size, wire mesh shape and size, and spacer placement (Figure 3). The original model setup is not accessible from the app; instead, it allows users to run further tests without needing to learn the software.

"Providing WAT with a simulation app removed the need for them to purchase the software or appoint an experienced user," Marmo says. "Simulation apps put our customers in charge, so they don't have to come back to us for small changes and they can test exactly what they want. It also frees us to explore new challenges, rather than working on variations of the same problem." Xi Engineering expects to use computational apps more and more in the course of its work for other customers.

WAT is doing the same, sharing the app with their own customers — companies wanting to find the HPEL transducer best suited to their particular headphone designs. "The team at Xi Engineering have been superb. They have deep expertise and helped to unpack the complexity of our product," adds Roberts. "The intuitive app that Xi developed for us is an additional bonus. Without revealing any intellectual property we can give our own clients access to our design through the app, so they can test and incorporate the technology into their own high-end headphones." ❖

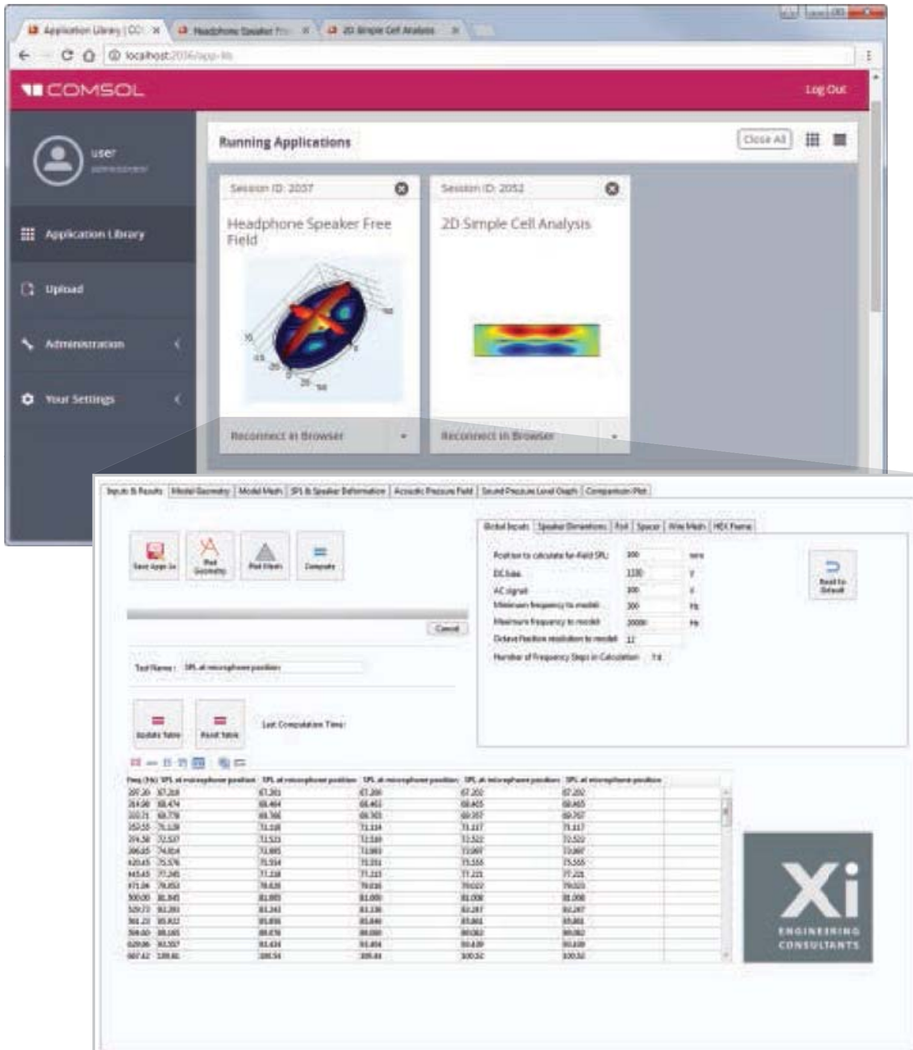


FIGURE 3. Foreground: The app developed by Xi Engineering allows engineers to vary parameters related to frequency, electrical input, speaker dimensions, and properties of the membrane, spacer, and wire mesh. Results give the sound pressure levels for different cases, membrane displacement, frequency response to different DC biases, and a comparison of the simulated design against experimental results. Background: The app is shared through the COMSOL Server™ product and accessible from a web browser or a COMSOL Client for Windows® operating system.

Left: Brett Marmo, technical director at Xi Engineering.
Center: Martin Roberts, CEO, Warwick Audio Technology.
Right: Dan Anagnos, CTO, Warwick Audio Technology.

Simulating the World Through the Lens of Multiphysics

Real-world applications are inherently multiphysics and should be treated as such.

by **ED FONTES**

What is unique to the COMSOL® software is the way in which the software receives user input and generates a mathematical model, consisting of differential equations, to describe physics phenomena. Any CAE software today is based on predefined numerical models, which are approximations of differential equations. These approximations are necessary as, in most cases, the relevant differential equations cannot be solved analytically, that is — an exact solution cannot be determined. Instead, different types of discretization, such as finite differences, finite volumes, and finite elements methods, among others, are used to approximate the relevant differential equations. It is difficult to add phenomena and descriptions of variables and multiphysics couplings to a numerical model if they are not considered in the differential equations from the beginning. COMSOL differs from other software in that a full mathematical model is generated on the fly, based on the user input, before the discretization is created when the user clicks the Solve button. This core technology allows users to create their own expressions and multiphysics couplings by using the names of variables and coordinates and by directly typing the mathematical expressions in the user interface. In traditional software, descriptions that are not built-in must be done at the numerical level, and after the discretization has happened, using user-defined subroutines, which may be inaccurate and/or difficult to produce.

COMSOL has an intuitive interface through which the user can input arbitrary mathematical expressions describing material properties, loads, sources, sinks, and multiphysics couplings. This is kind of a paradox, since math is usually perceived as difficult — but our software truly makes it possible to swiftly build extremely complex mathematical models. The mathematical modeling capabilities of COMSOL are transparent, easy-to-use, and highly adaptable to the specific needs of the user.

Researchers and scientists may have a deep understanding and an intuition about a process or phenomena in their field of expertise; in most cases, without being experts in mathematical modeling. It is important that this understanding and intuition is also utilized when building models and running simulations, since this results in more accurate models and better designs. For this reason, COMSOL provides the Application Builder for creating apps with custom-made user interfaces for specific purposes. The apps allow for both experts and nonexperts in mathematical modeling to validate models and also to benefit from these when optimizing and developing new processes and designs.

One example of this is from Mahindra Two Wheelers (featured on page 15). They use simulations to study the noise and vibration performance of engine, intake, and exhaust systems of motorcycles. Ulhas Mohite, manager of R&D at Mahindra, informed us that "they created a simulation app using the Application Builder in the COMSOL Multiphysics® software to compare analysis output files and plot the sound pressure level data, which was a great time saver." In this case, they solved an acoustic problem and simultaneously used the app to compare and analyze simulation data.

Users have been surprising us with their creative designs and uses for apps that we could not have predicted — studying their work and analyzing their feedback have been crucial in the launch of many new software features. All the development that we have made, and will make, to the software aims at facilitating the adoption of accurate numerical simulations at an early stage in order to understand physics phenomena and optimize designs better and faster. The core design of our software reflects our philosophy of studying real-world phenomena through the high-fidelity lens of multiphysics models and simulations. ❖

How Computational Acoustics Benefits from Multiphysics

by **NAGI ELABBASI, VERYST ENGINEERING**

The field of acoustics is quite diverse and so is the need for computational tools supporting it. Acoustic simulation is very common in applications like automotive noise control, room acoustics, loudspeakers, miniature speakers, musical instruments, acoustic sensors and actuators, and nondestructive testing. It provides engineers valuable and timely design insights that help optimize their products and evaluate new design concepts. At Veryst Engineering, we find a growing interest in acoustic simulation — especially in applications involving medical devices and MEMS sensors.

The formulations suitable for computational acoustics vary significantly for some of the applications listed above. In many cases, the acoustic problem cannot be solved in isolation from other physics; mainly structural, fluid, electric, heat transfer, and porous media. This multiphysics coupling between acoustics and other phenomena typically becomes more significant the smaller the devices get.

What I currently find exciting about this field is the growing number of acoustic applications I see, especially in two influential areas: medical devices and wearable technology.

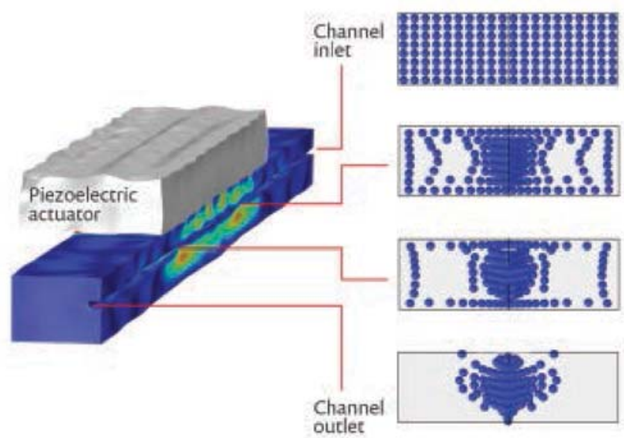
We recently worked on a multiphysics acoustic simulation problem within the medical device industry: a lab-on-a-chip device for bodily fluids focusing using acoustophoresis. This method involves the motion of particles resulting from an oscillatory acoustic field and is used for applications including fluid wash, fluid separation, and acoustic levitation. This particular model involves pressure acoustics, solid mechanics,

"What I currently find exciting is the growing number of acoustic applications, especially in two influential areas: medical devices and wearable technology."

electric field, fluid flow, and particle tracing. Geometry and particle properties used in this example model are taken from available literature. The figure shows the particle distribution across the channel, demonstrating effective particle focusing toward the channel center. The computational model helps designers select the dimensions, materials, operating frequency, and flow rate of the device.

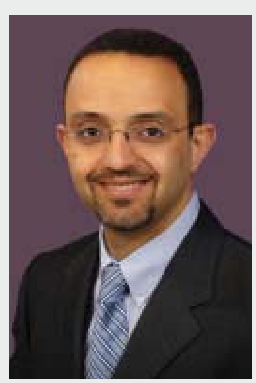
Two challenges we often face with acoustic simulations, not too different from other physics, are obtaining accurate material properties and model validation. In my experience, damping is one of the hardest properties to accurately evaluate in acoustic problems. If an acoustic actuator operates close to a resonant frequency, and it frequently does, the effect of damping on the results is significant. If the device also involves polymeric components, which they frequently do, that damping is most likely frequency dependent. A single damping measure provided by the manufacturer, such as Q factor or loss factor, is simply not enough for an accurate analysis. More material testing and device level testing are frequently needed.

To overcome these challenges and more, we are beginning to develop more simulation apps for clients. Using the Application Builder available in the COMSOL Multiphysics® software, we are able to build applications with an intuitive user interface that is fully customizable based on each client's needs. We hope that these apps will give nonanalysts direct access to the benefits of computational acoustics through a simple user interface. Customers will be able to experiment with parameters or suggest design iterations based on their specific skill set. The field of acoustics has evolved greatly thanks to the power of multiphysics simulation, and we look forward to seeing the expansion of this area through the deployment of simulation apps.



Acoustophoretic particle focusing in a microchannel simulated using the COMSOL Multiphysics® software. Deformation and von Mises stress are also shown.

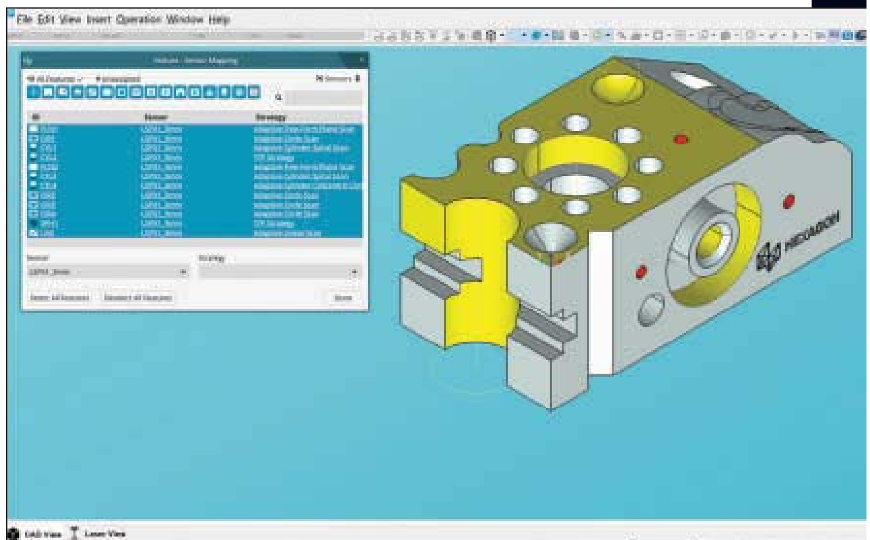
ABOUT THE AUTHOR



Dr. Nagi Elabbasi is a principal engineer at Veryst Engineering, LLC, and his main area of expertise is modeling multiphysics systems. He has extensive experience in simulating structural mechanics, CFD, heat transfer, acoustics, and coupled systems, and in finite element software development. He holds a PhD in mechanical engineering from the University of Toronto. To learn more about the consulting, testing, and training services offered at Veryst, visit veryst.com/mechanical-engineering-services.

MARBLE AND STONE FABRICATION

HEXAGON MANUFACTURING INTELLIGENCE, NORTH KINGSTOWN, R.I.



THIS DATA-DRIVEN PRODUCTION SOLUTION INTEGRATES the portable ROMER Absolute Arm 73 series with Alphacam Stone software to accelerate precise stone fabrication. Alphacam Stone, a CAM software package developed by Vero Software, is an all-purpose metrology system delivered by the ROMER 73 series PCMM (portable coordinate measurement machine) for stone-cutting craftsmen who need to scan and reverse engineer existing parts. The scanning process captures intricately detailed part surfaces and converts point clouds into usable data for machining processes with speed and accuracy. The integrated RS3 laser scanner is designed to capture data from almost any object surface.

DRAWING

SMARTDRAW, SAN DIEGO, CALIF.

SmartDraw 2017, with SmartDraw Cloud, enables users to create visuals from any platform, including PC, Mac, and mobile devices. More than 700 new templates for infographics and presentations were added to the upgraded version, along with new floor-plan and CAD features such as scaling and AutoCAD import, Visio import (including stencils) and export, new administrative controls for site licenses, and sharing with embeddable widgets for your blogs and websites. With full Google integration, users can insert diagrams into Google Docs and Sheets. Other highlights are versioning for SmartDraw cloud documents; improved electrical engineering linking behavior and network design content; and cloud improvements including ungrouping of complex symbols and Asian character support.

VISUALIZATION APP

THEOREM SOLUTIONS, STAFFORDSHIRE, U.K.

This visualization application for the mixed-reality Microsoft HoloLens can be downloaded from the Microsoft app store for a free 90-day trial. It lets users visualize and experience engineering and manufacturing design data in an environment that combines the real world with high-quality holographic representations. By upgrading to the full subscription license, users can load their own CAD and PLM data to be automatically optimized for use in the Microsoft HoloLens. Theorem's server then streams the data to the device, where it comes to life in the "Visualization Experience," giving users complete freedom of movement to view, manipulate, and interrogate their 3-D data, all controlled by hand gestures and voice commands.

EASY 3-D PRINTING

STRATASYS, EDEN PRAIRIE, MINN.

GrabCad Print's Offline Mode Part 2 enables users installing for the first time to skip the login if they don't have an internet connection and give trays custom names from the tray preview in the Project Panel. Jobs will inherit the name when you click print. All jobs sent with version 1.5 will include a preview of the tray in the Schedule View job details, both online and in the desktop app. You can disable this in System Preferences > Privacy. Among many other upgrades to the previous version, box select in Model View makes it easy to change the print settings of any model all at once and the View Controls are now conveniently at the top of the viewer.

1-D ANALYSIS

SIGMETRIX, MCKINNEY, TEXAS

EZtol is a 1-D analysis tool that lets designers and engineers quickly understand the impact of part and assembly variation on the fit and performance of their products. It outperforms the more robust 3-D analysis tools when engineers use hand calculations or spreadsheets to conduct tolerance stack-up analyses, because unless they are specifically considering more complex interactions like the rotation of surfaces, their calculations may not fully account for all the variation that can occur in the critical functional requirements. EZtol not only performs these 1-D stack-up analyses far more efficiently than manual methods, it detects scenarios where 1-D treatment is insufficient and adds a caution symbol and note to the results row indicating that the calculated 1-D results may be underestimating the actual variation the design will have during production.

SUBMISSIONS

Submit electronic files of new products and images by e-mail to **memag@asme.org**. Use subject line "New Products." *ME* does not test or endorse the products described here.

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SPLIT HUB CLAMPS

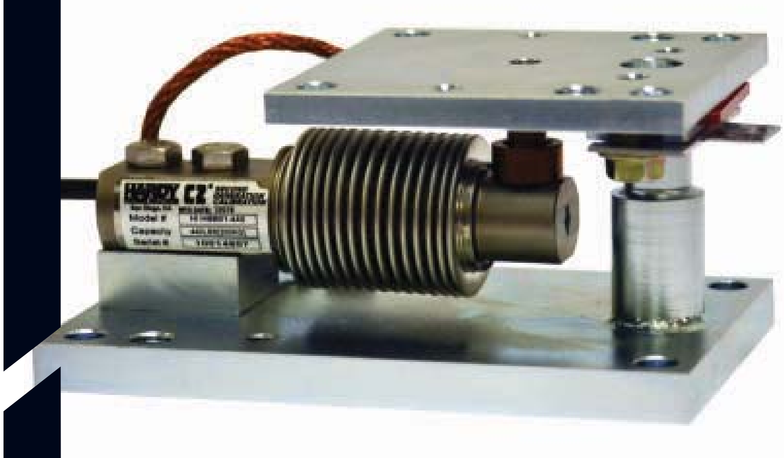
STAFFORD MANUFACTURING, WILMINGTON, MASS.

Custom-designed split hub clamps from the Stafford Manufacturing Corp. can be manufactured to OEM specifications for use with hollow shaft motors, encoders, and gearboxes. They are available in one- and two-piece clamp-style designs machined from a variety of materials with special features such as wider slots, stress relief holes, and balancing flats. Suitable for both stationary and rotary applications, these split hub clamps are non-marring and can be manufactured to precise OEM design requirements. Easy to adjust, they can be machined from aluminum, steel, stainless steel, brass, titanium, and other alloys.

LOW-CAPACITY BEAM SENSOR

HARDY PROCESS SOLUTIONS, SAN DIEGO, CALIF.

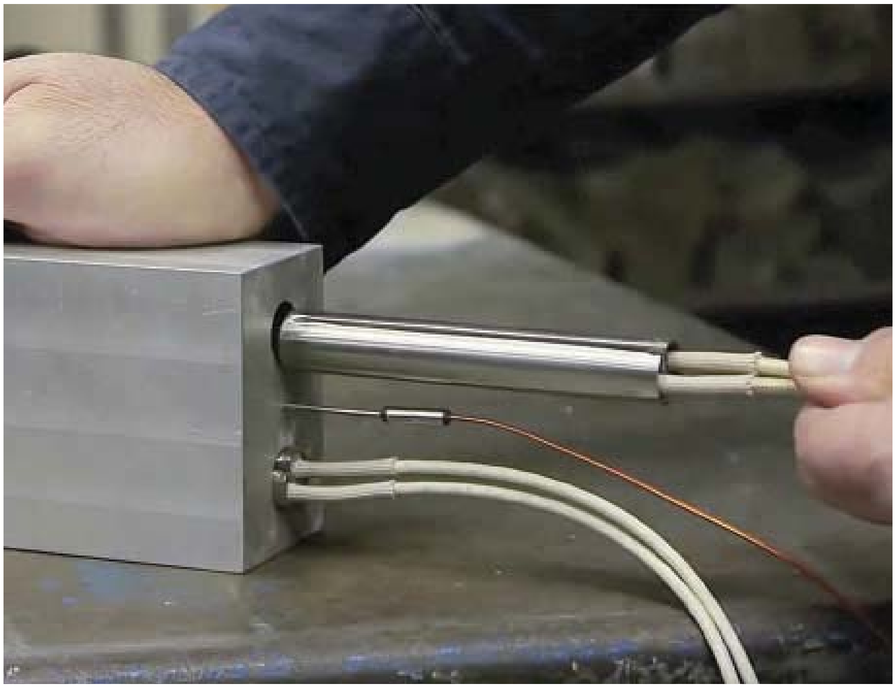
Hardy expanded its OneMount line to include a model designed for small hoppers, tank weighing systems, and bagging machines, as well as other dynamic low-capacity applications such as checkweighing and conveyor scales. The Hardy OneMount with Advantage beam sensors enable a vessel or hopper to be installed, bolted, and welded using the mount itself, without installation accessories. Integral spacers carry the full-rated capacity without the load cells installed, eliminating the need for expensive dummy load cells or welding fixtures typically used to avoid damaging the load sensor during the welding process. The 360-degree checking mechanism enables load points to be installed in any direction.



CLEANING TINY PARTS

EXAIR, CINCINNATI

EXAIR's Model 1004SS, M4 NPT back-blow air nozzle was designed to deliver the smallest, most effective airflow for blowing debris and liquids from small pipes or hoses inside diameters, channels, bores, holes, internal threads, and other internal part features. An array of holes provides a forceful, 360-degree airflow to clear out coolant, chips, and light oils following machining processes. This nozzle also prevents blowing chips further into a part, tube, or pipe and eliminates any safety hazard created by blowing debris out the far end of a pipe or tube. The air nozzle thread is M4x0.5 and manufactured with a small profile. It fits inside openings as small as 0.25 in. (6.3 mm) and is effective on diameters up to 1 in. (25.4 mm).



CARTRIDGE HEATERS

DALTON ELECTIC HEATING, IPSWICH, MASS.

Watt-Flex cartridge heaters are warranted removable from bores by their manufacturer because their unique split-sheath design prevents warping, the primary cause of bore seizure for conventional cartridge heaters. The split-sheath construction allows the Watt-Flex heater to expand bilaterally when energized for maximum metal-to-metal contact with the bore and maximized heat transfer (conduction) to the surrounding metal. Because of their continuous coil construction, the heaters have no sections to burn out and cause warping of the heaters in the bore. Instead they provide a uniform temperature profile along the entire sheath. The heaters also have no ceramic cores. This, along with proprietary manufacturing techniques, allows compaction of the high-grade magnesium oxide to near-maximum density around the heater coil for greater dielectric strength.

BIN HANDLING

KARDEX REMSTAR, WESTBROOK, MAINE

Part of the company's LR 35 Vertical Buffer Module, this bin handling solution retrieves goods in no time, making it a good fit for spare part and MRO inventory, which can be expensive. Geared toward medium-size businesses and wholesalers with 24-hour service and overnight delivery, companies especially benefit when they have to stock a high number of slower-moving SKUs that must be picked quickly and accurately. It occupies less space and consumes much less energy than a mini-load system. The LR 35 can perform up to 500 order lines an hour per picking station while occupying just 60 percent of the space.

BEARING PROTECTION RINGS

TRANE SUPPLY, MECHANIC FALLS, MAINE

Trane Supply now offers AEGIS bearing protection rings through its nationwide network of service centers. AEGIS universal shaft grounding ring kits (AEGIS uKITs) are designed to be installed on virtually any brand motor and fit the usable shaft diameter for easy selection and installation by motor frame size. AEGIS shaft grounding rings protect the bearings of motors controlled by variable frequency drives (VFDs or inverters) from damaging VFD-induced shaft voltage discharges. VFDs, an effective tool for designers to improve the energy efficiency of HVAC systems, enable motors to run at less than full speed, a cost-effective means of matching heating/cooling capacity to a changing load, reducing energy costs.

CLAMPING SYSTEM

SCHUNK, MORRISVILLE, N.C.

The VERO-S clamping system is designed for use with even the smallest machine tables. Its quick-change pallet system delivers fast and precise resetting for workpieces, clamping devices, and other equipment on 3-, 4-, or 5-axis machining centers. Workpieces can be directly clamped and machined from five sides without restricting accessibility. This is done by screwing the clamping pins of the pallet system directly into the workpiece. The components are quickly exchanged in the machine, positioned, fixed, and clamped all in one step with a repeat accuracy of less than 0.005 mm. The clamping height of the workpieces can be adjusted with module height extensions, so the machine spindle can reach all five sides of the workpiece without any special tools.

VOLTAGE TRANSDUCER

NK TECHNOLOGIES, SAN JOSE, CALIF.

The company's VTU-DIN Series is a high-performance true RMS transducer for sensing voltage in single, three-phase, or DC installations. It measures 0-15 to 0-600 V with an industry-standard output proportional to connected voltage in AC circuits with sinusoidal or non-sinusoidal (variable frequency) applications or DC circuits. Standard outputs make the VTU-DIN reliable and easy to use with existing controllers, data loggers, and SCADA equipment. It is housed in a space-saving 35-mm-wide, easy-to-install DIN rail-mounting enclosure. The series features 0- to 5-kHz measurement for situations where the power supplied is non-sinusoidal (such as VFD applications), poor quality installations, or other electrically harsh or challenging environments. It effectively detects a wide range of damaging conditions, including below-normal/brownout, phase loss, and over-voltage conditions.

DIGITAL MICROSCOPE

KEYENCE, ITASCA, ILL.

The VHX-5000 digital microscope is simple to use, but a powerful measurement tool for a variety of applications. By eliminating the need for focus adjustments, it greatly speeds up the measurement of hard-facing alloys used in welding such as the cobalt-based Stellite, which is used in the oil and gas, food processing, dental, aerospace, and any industry requiring supertough, heat- and corrosion-resistant materials. With the push of a button, an optimized view of the target is produced in as little as one second. It has a depth of field 20 times greater than traditional microscopes, with high-resolution optics and software that captures and optimizes images automatically. It features numerous functions such as wide area stitching, 3-D depth of field display and measurement, edge detection, and more.

TEMPERATURE TRANSMITTER PROBES

AUTOMATIONDIRECT, CUMMING, GA.

The company's XTP series of temperature transmitter probes combines a precision RTD sensing element and transmitter electronics in a single stainless steel probe. Offered in three preconfigured temperature-measuring ranges, the ready-to-use probes come in four standard insertion lengths (30, 50, 100, or 150 mm) and two integral male NPT thread sizes (1/4-inch or 1/2-inch) that allow direct mounting to the process or thermowells, eliminating the need for separate probe mounting or adapter fittings. An M12 quick-disconnect enables a connection to the loop-powered 4-20 mA output signal that provides a linear representation of measured temperature compatible with PLCs, SCADA systems, and digital panel meters.

3-D MOLDED INTERCONNECT DEVICES

MULTIPLE DIMENSIONS, BRÜGG, SWITZERLAND

The company said its 3-D molded interconnect devices are a welcome addition to conventional printed circuit boards and particularly well suited to Industry 4.0 applications. First employed for the challenges of spatial antenna construction, as well as for expanding frequency ranges, integration densities, and available installation spaces for high-frequency applications, MIDs are particularly well-suited for smoke detectors. Plastic MIDs combine electrical and mechanical functions in a single component. This makes it possible to use the housing and other molded inner structures as an interconnect device, sometimes eliminating the need for a PCB. MIDs are also useful for 3-D antennas in frequency ranges exceeding 6 GHz, reliable for Bluetooth, LTE, or Wi-Fi applications.

POSITIONS OPEN

University of California, Santa Barbara The Department of Mechanical Engineering at the University of California, Santa Barbara invites applications for a full-time faculty position in Mechanical Engineering, with particular emphasis on the area of controls and dynamics at the Assistant Professor level. The Department is especially interested in candidates who can contribute to the diversity and excellence of the academic community through research, teaching, and service. Applications received by December 15, 2017 will be given priority consideration. For full details about the positions and to apply, visit http://apptrkr.com/1108958 The University of California is an Equal Opportunity/Affirmative Action Employer and all qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity, national origin, disability status, protected veteran status, or any other characteristic protected by law.

Emerging Acquisitions LLC, dba Bulk Handling Systems, seeks to hire a Chinese Market Sales Engineer to work in Eugene, Oregon and to provide technical support for sales of conveyance systems, optical sorting technologies, and other waste handling systems; confer with customers to assess needs and determine system requirements; prepare and deliver technical presentations. If interested mail resume to: Bulk Handling Systems 3592 West 5th Avenue, Eugene, OR 97402 Attn: Ron Britt

College of
ENGINEERING
UNIVERSITY OF HAWAIʻI AT MĀNOA

Assistant Professor (Mechanics: Autonomous Systems)

Position Number: 0083205. **Hiring Unit:** College of Engineering – Mechanical Engineering **Location:** Manoa. **Closing Date:** Continuous – application review begins February 1, 2018. **Salary Information:** Commensurate with qualifications and experience. **Monthly Type:** 9 Month. **Tenure Track:** Tenure. **Full Time/Part Time:** Full Time. **Temporary/Permanent:** Permanent. **Funding:** General Funds

Other Conditions

University of Hawaiʻi at Mānoa (UHM), College of Engineering (COE), Department of Mechanical Engineering, invites applications for a full-time, general funds, tenure-track, Assistant Professor position, pending position clearance and availability of funds, in the area of Mechanics: Autonomous Systems to begin on August 1, 2018 or as soon thereafter as possible.

The University of Hawaiʻi is a Carnegie R1 (i.e., highest research activity) doctoral university with is recognized as a Land Grant, Sea Grant, Space Grant, and Sun Grant university. The Department offers B.S., M.S., and Ph.D. degrees in mechanical engineering, and its undergraduate program is ABET accredited.

The Department has active research programs in robotics, UAS, AUV, ocean and space science & exploration, control systems, dynamical systems, multidisciplinary design analysis and optimization, biomedical engineering, biotechnology, renewable energy systems & sustainability, nanotechnology, corrosion, boiling and two-phase flow, microscale heat transfer, and high-performance computing. For more information on the Department, please visit www.me.hawaii.edu.

The applicants should identify potential collaboration(s) with one or more of the following units: Ocean Resource Engineering (ORE), Hawaii Space Flight Laboratory (HSFL), and Hawaii Institute of Geophysics & Planetology (HIGP). For more information on college research themes, please visit www.eng.hawaii.edu.

Duties and Responsibilities: To conduct assigned mechanical engineering undergraduate and graduate courses and seminars including courses in the area of mechanics; To develop an extramurally funded research program that results in publication in leading scholarly journals; To supervise independent study activities; To serve as an academic adviser to students; To serve on Departmental, College, and University committees; To render service to the professional or lay community that is relevant to the individual's academic specialty; To participate in curriculum development activities including the development of curricular materials and special instructional methods; To serve on thesis committees for advanced degree candidates; To present research work in leading scholarly conferences; and To perform related tasks as assigned.

Minimum Qualifications: An earned Ph.D. in Mechanical Engineering or closely related field (particularly in mechanics and autonomous systems) from a college or university of recognized standing (All-But-Dissertation, ABD, cases will be considered, but dissertation must be filed before start of employment); Coursework and/or research experience in mechanics; Demonstrated ability as a teacher; Demonstrated scholarly achievement; and Ability to communicate effectively with others.

Desirable Qualifications: Experience in emerging research areas and cross-disciplinary activities. Expertise and experience in autonomous systems with emphasis on one or more of the following topics: optimization, control systems, system design, systems integration, sensing, decision making, AI, big data analysis, machine learning, mission planning, internet of things, navigation, motion planning, AUVs and other autonomous vehicles, and relevance to Hawaiʻi.

To Apply: Applicants should follow the instructions at the following website to electronically submit their materials: https://apply.eng.hawaii.edu/apply/apply.php?pool_id=me83205b. The applicant should submit a cover letter specifying the position and the research area; a statement on research interests, activities, and plans; a statement on teaching philosophy, interests, and plans; a curriculum vitae detailing research and teaching accomplishments; copies of up to 4 relevant publications; official transcripts (copies/web versions acceptable, however official transcripts will be required upon hire); and the names, addresses, e-mail, and telephone numbers of 4 professional references (for short listed applicants, the committee will solicit letters of recommendation from these professional references).

Inquiries Dr. Marcelo Kobayashi (Professor and Chair) marcelok@hawaii.edu.

The University of Hawaiʻi is an equal opportunity/affirmative action institution and is committed to a policy of nondiscrimination on the basis of race, sex, gender identity and expression, age, religion, color, national origin, ancestry, citizenship, disability, genetic information, marital status, breastfeeding, income assignment for child support, arrest and court record (except as permissible under State law), sexual orientation, domestic or sexual violence victim status, national guard absence, or status as a covered veteran. Employment is contingent on satisfying employment eligibility verification requirements of the Immigration Reform and Control Act of 1986; reference checks of previous employers; and for certain positions, criminal history record checks. In accordance with the Jeanne Clery Disclosure of Campus Security Policy and Campus Crime Statistics Act, annual campus crime statistics for the University of Hawaii may be viewed at: http://ope.ed.gov/security/, or a paper copy may be obtained upon request from the respective UH Campus Security or Administrative Services Office.

UT DALLAS

THE UNIVERSITY OF TEXAS AT DALLAS

The Erik Jonsson School of Engineering and Computer Science

EXPERIMENTAL FLUID MECHANICS

FACULTY POSITION

The Erik Jonsson School of Engineering and Computer Science at The University of Texas at Dallas (UTD) invites applications for a faculty position in Mechanical Engineering at the rank of Assistant or Associate Professor.

Candidates must have a commitment to undergraduate and graduate education and strong potential to develop an externally funded research program. Candidates for the position at the Associate Professor level must have records of scholarly and professional achievements.

Applications will be considered in the general area of experimental fluid mechanics with applications to environmental flows. Domains of interest include, but are not limited to, wind engineering, wind energy, urban flows, and natural hazards. Preference will be given to an experimentalist that can support and advance research efforts in model validation and uncertainty quantification for the analysis, design and control of engineered systems involving complex fluid flows.

The Department of Mechanical Engineering is among the fastest growing programs at UTD. The department offers ABET-accredited BS, as well as MS and PhD degree programs in mechanical engineering. The department was founded in 2008 and currently has 1185 students enrolled, including 196 graduate students. There are 27 tenured-system faculty members and 7 teaching faculty members.

The junior faculty are highly decorated and include three NSF CAREER awardees, five Young Investigator Program awardees from DoD, and one awardee of the NIH Director's Program. In 2018, the department will be housed in a brand new building with 200,000 square feet for teaching and research.

The research conducted by graduate students and faculty is focused on problems of global significance with regional impact in medicine, energy, and nanotechnology. The department is home to an NSF Industry/University Cooperative Research Center in Wind Energy. An atmospheric boundary layer wind tunnel has been completed with unique characteristics, such as test section with 30-m length, 2.8-m width, 2.1-m height, and maximum velocity of 34 m/s. Several measurements systems are already available, such as stereo PIV, hot-wire anemometry, multi-hole pressure probes, and force balances. It is expected that the successful candidate will make use of this facility for teaching and research.

In addition to Mechanical Engineering, the Erik Jonsson School is home to the Departments of Bioengineering, Electrical Engineering, Computer Science, Materials Science & Engineering, and Systems Engineering, and has interdisciplinary degree programs in Computer Engineering and Software Engineering. Opportunities for interdisciplinary research and industry-university collaboration are outstanding.

Review of applicants will begin immediately and will continue until the position is filled. Indication of gender and ethnicity for affirmative action statistical purposes is requested as part of the application.

To apply for this position, applicants should submit (a) their current curriculum vitae, (b) letters of research and teaching interests, and (c) letters of recommendation from three academic or professional references via the on-line application form available at **http://jobs.utdallas.edu/postings/9146**. Additional references may be requested if deemed necessary.

The University of Texas at Dallas is an Equal Opportunity/ Affirmative Action employer and strongly encourages applications from candidates who would enhance the diversity of the University's faculty and administration.

THE UNIVERSITY OF MEMPHIS.

Tenure-Track Faculty Positions in Mechanical Engineering

The Department of Mechanical Engineering at The University of Memphis invites applications for a tenure-track Assistant/Associate Professor beginning August 2018. Appointment at the rank of Associate Professor will be considered for exceptionally qualified candidates. Duties include teaching undergraduate and graduate courses in mechanical engineering, obtaining research funding from external sponsors, supervising graduate students, and providing professional service. Applicants must have an earned doctoral degree in mechanical engineering or a related field, or earn the degree within the first semester of hire. Candidates in all areas related to advanced manufacturing (e.g., additive manufacturing, design for manufacturability, and sustainable manufacturing) will be considered and are expected to collaborate on multi-disciplinary research.

The University of Memphis is the largest public university and engineering program in western Tennessee and has an enrollment of about 22,000 students. The Herff College of Engineering at The University of Memphis is nationally ranked in both its undergraduate and graduate programs. Over the next few years, several hires are expected in the Department of Mechanical Engineering. The Department has identified advanced manufacturing and sustainable energy as its priority areas, and future hires are expected to be in these areas. The Herff College of Engineering is in the process of establishing an Advanced Manufacturing Center of Excellence with the associated equipment and infrastructure, and candidates who can be an integral part of this center will be preferred for this position. Additional information about the College and the Department can be found at http://memphis.edu/herff/.

The Department has 12 tenured/tenure-track faculty positions and an enrollment of about 375 students pursuing B.S., M.S. and Ph.D. degrees. Additional faculty hires are expected to meet the student growth, as total enrollment in the Herff College has increased by 30% over the last four years. Future faculty hires will be targeted towards individuals who can build strong externally-funded research programs, participate in inter-disciplinary research, grow the departmental masters and doctoral programs, and establish themselves as outstanding educators.

The city of Memphis is an attractive location in Tennessee, and is world-renowned for its music, food, and hospitality. Memphis is home to three Fortune 500 companies (FedEx, International Paper, and AutoZone) and has a strong presence in health, biomedical devices, transportation, automotive, aero-propulsion and entertainment industries. The Herff College has many partnerships with local industry for both research and education applications.

Applications are to be submitted via https://workforum.memphis.edu. Click on the faculty box to find the posting for the Assistant/Associate Professor position. Applications must include a teaching and research plan, a comprehensive curriculum vitae, and the full names and contact information (business address, phone number(s), and e-mail address) of three professional references. The committee will begin screening applications on January 16, 2018, and will continue until the position is filled.

THE OHIO STATE UNIVERSITY
COLLEGE OF ENGINEERING

Applied Mechanics – Tenure-Track Faculty Position
Department of Mechanical and Aerospace Engineering
College of Engineering

Position Overview: The Department of Mechanical and Aerospace Engineering at The Ohio State University invites applications for a tenure-track faculty position at the Assistant Professor level in the broad disciplinary area of applied mechanics. We welcome applicants from all backgrounds related to applied mechanics.

Experience Requirements: Applicants must have earned a doctoral degree in mechanical engineering or a related discipline by the start date and should have demonstrated record of excellence in research. The new faculty member is expected to develop and maintain a nationally recognized and externally funded research program at the forefront of their field, collaborate across disciplines, teach and supervise students at the undergraduate and graduate levels, develop and teach courses in their area of expertise, and participate in service to the university.

Application Instructions: To be considered, please submit your application electronically via Academic Jobs Online: **https://academicjobsonline.org/ajo/jobs/10310**.

The Ohio State University College of Engineering is strongly committed to promoting diversity and inclusion in all areas including scholarship, instruction and outreach. In the cover letter, describe experiences, current interests or activities, and/or future goals that promote a climate that values diversity and inclusion in one or more of these areas.

Review of applications will begin on **December 1, 2017** and continue until the position is filled.

The Ohio State University is an equal opportunity employer. All qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation or identity, national origin, disability status, or protected veteran status.

Requires the successful completion of a background check.

The University of Akron

Assistant/Associate Professor of Polymer Engineering

The Department of Polymer Engineering at The University of Akron seeks to fill a tenure-track faculty position in Advanced Manufacturing at the Assistant/Associate Professor rank beginning in August 2018.

The ideal candidate will develop an internationally-recognized research program in advanced manufacturing involving polymeric materials and devices, potentially including characterization and modeling. Areas of interest include, but are not limited to: translating new materials structure/process/property relations into advanced manufacturing breakthroughs; integrating new materials into advanced manufacturing processes that provide a value-add for emerging technologies; enhancing the efficiency of manufacturing processes; developing inline control-loop metrologies to enhance quality and materials utilization; and developing disruptive technologies that significantly enhance existing manufacturing processes or provide the fundamental basis for the creation of new manufacturing processes. In addition to building an externally funded research program, the successful applicant will be expected to direct graduate and undergraduate student research in their area of expertise; teach graduate and undergraduate classes; and contribute to the functioning of the department, college, and university through service on committees, centers, and outreach activities.

Qualifications:

- PhD in polymer engineering, chemical engineering, mechanical engineering, industrial engineering, or a related field
- Record of research accomplishments, as emonstrated by relevant peer-reviewed publications and/or patents
- Ability to teach and mentor graduate and undergraduate students
- Strong communication and teamwork skills
- Commitment to an interdisciplinary collaborative approach to research that facilitates innovation, creativity and translation of ideas to practice is expected of the ideal candidate

The successful candidate will be well-placed to leverage large existing university investments in polymers and advanced manufacturing, including the National Polymer Innovation Center (NPIC, http://www.uakron.edu/cpspe/about-us/buildings-npic.dot), the National Center for Education and Research on Corrosion and Materials Performance (NCERCAMP https://www.uakron.edu/corrosion/ncercamp/), and The Biomimicry Research Innovation Center (BRIC, http://uabiomimicry.org/), and will cultivate and enhance relationships with the more than 2400 companies that work with polymers in Northeast Ohio.

The University of Akron, with 22,000 students, has a world-class history in polymer science and polymer engineering dating back to 1909. The Department of Polymer Engineering currently has 10 full time faculty and approximately 150 full time graduate students.

For complete details and to apply visit:
uakron.edu/jobs Job ID # 9819

Applicants must complete an on-line application and attach a cover letter along with a curriculum vitae, a description of research plans and a statement of teaching philosophy and contact information for at least three professional references. Review of applications will begin December 1st and continue until the position is filled.

The University of Akron is an equal education and employment institution. It is the policy of this institution that there shall be no unlawful discrimination against any individual in employment or in its programs or activities at The University of Akron because of race, color, religion, sex, age, national or ethnic origin, sexual orientation, gender identity, disability, genetic information, military status or status as a veteran. The University is also committed to the principles of affirmative action and acts in accordance with state and federal laws.

LSU

Two Tenure-Track Positions

Department of Mechanical Engineering
College of Engineering

The Department of Mechanical and Industrial Engineering (MIE) at The Louisiana State University (LSU) continues its significant growth of faculty. The Department is currently seeking excellent applicants to fill two tenure-track positions in Mechanical Engineering.

The College of Engineering (CoE) at LSU is undergoing unprecedented growth, which includes a new engineering complex. The CoE encourages interdisciplinary research including, but not limited to, Advanced Manufacturing and Materials, Energy, and BioTechnology. Depending on their background, new hires will have the opportunity to leverage the resources and collaborative environments of the CoE, the recently NSF-funded ($20M/5 yrs.) Consortium for Innovation in Manufacturing and Materials, the National Center for Advanced Manufacturing (**http://ncam.eng.lsu.edu/**), the Center for Computation and Technology (**https://www.cct.lsu.edu/**), the Institute for Advanced Materials, and partnerships with IBM and ANSYS.

The MIE Department realizes Mechanical and Industrial Engineering education, research and scholarship. It aspires to advance professional frontiers within a creative, multidisciplinary and diverse atmosphere that promotes discovery, creativity and innovation. It is the largest of seven departments in the CoE and is currently home to 26 Mechanical Engineering Faculty, 8 Industrial Engineering Faculty, and a vibrant undergraduate and graduate student body. The faculty conduct funded research across a broad spectrum of traditional and emerging areas. The Department offers separate B.S., M.S., and Ph.D. degree programs in Mechanical Engineering, and B.S., M.S. degree programs in Industrial Engineering. More information can be found at: **http://lsu.edu/eng/mie**.

Duties of the positions include undergraduate and graduate level teaching and providing associated service; initiating and sustaining independent, externally-funded research leveraging their specialty area, and supervising graduate students. Successful candidates are expected to develop substantive collaborations across departmental and college boundaries, engage industry and develop activities supporting the State's economic development efforts.

Successful candidates will possess a Ph.D. in Engineering or a related scientific field (ABD candidates will be considered if degree will be obtained by August 2018), with at least one degree in Mechanical Engineering. Please see position descriptions online for additional information regarding qualifications.

For more information and to apply, please visit
https://lsu.wd1.myworkdayjobs.com/en-US/LSU.

An offer of employment is contingent on a satisfactory pre-employment background check. Applications will be accepted until the positions are filled and those received before February 1, 2018 will be guaranteed full consideration.

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College of ENGINEERING
UNIVERSITY OF HAWAIʻI AT MĀNOA

Title: Assistant Professor (Thermofluids: Biological and/or Biomedical Applications)

Position Number: 0082374. **Hiring Unit:** College of Engineering – Mechanical Engineering. **Location:** Manoa. **Closing Date:** Continuous – application review begins February 1, 2018. **Salary Information:** Commensurate with qualifications and experience. **Monthly Type:** 9 Month. **Tenure Track:** Tenure. **Full Time/Part Time:** Full Time. **Temporary/Permanent:** Permanent. **Funding:** General Funds

Other Conditions: University of Hawaiʻi at Mānoa (UHM), College of Engineering (COE), Department of Mechanical Engineering, invites applications for a full-time, general funds, tenure-track, Assistant Professor position, pending position clearance and availability of funds, to begin on August 1, 2018, or as soon thereafter as possible.

The University of Hawaiʻi is a Carnegie R1 (i.e., highest research activity) doctoral university, which is recognized as a Land Grant, Sea Grant, Space Grant, and Sun Grant university. The Department offers B.S., M.S., and Ph.D. degrees in mechanical engineering, and its undergraduate program is ABET accredited. The Department has active research programs in biomedical engineering, boiling and two-phase flow, microscale heat transfer, microfluidics, CFD, acoustics, multidisciplinary design analysis and optimization, space and ocean science & exploration, robotics, UAS, AUV, control systems, dynamical systems, nanotechnology, corrosion, and high-performance computing. For more information on the Department, please visit **www.me.hawaii.edu.**

Duties and Responsibilities: To conduct assigned mechanical engineering undergraduate and graduate courses and seminars including courses in the area of thermofluids; To develop an externally funded research program that results in publications in leading scholarly journals; To present research work in leading scholarly conferences; To supervise independent study activities; To serve as an academic adviser to students; To serve on Departmental, College, and University committees; To render service to the professional or lay community that is relevant to the individual's academic specialty; To participate in curriculum development activities including the development of curricular materials and special instructional methods; To participate on committees in charge of candidates for advanced degrees; and
To perform related tasks as assigned.

Minimum Qualifications: A doctorate in Mechanical Engineering or a closely related field (particularly in thermofluids) from a college or university of recognized standing (All-But-Dissertation, ABD, cases will be considered, but dissertation must be filed before start of employment); Coursework and/or research experience in thermofluids; Demonstrated ability as a teacher; Demonstrated scholarly achievement; and Ability to communicate effectively with others.

Desirable Qualifications
Experience in emerging research areas and cross-disciplinary activities.

To Apply: Applicants should follow the instructions at the following website to electronically submit their materials: **https://apply.eng.hawaii.edu/apply/apply.php?pool_id=me82374**. The applicant should submit a cover letter specifying the position and the research area; a statement on research interests, activities, and plans; a statement on teaching philosophy, interests, and plans; a curriculum vitae detailing research and teaching accomplishments; copies of up to four relevant publications; official transcripts (copies/web versions acceptable, however official transcripts will be required upon hire); and the names, addresses, e-mail, and telephone numbers of at least four professional references (for short listed applicants, the committee will solicit letters of recommendation from these professional references).

Inquiries: Dr. Marcelo H. Kobayashi, Professor and Chair, **marcelok@hawaii.edu.**
The University of Hawaiʻi is an equal opportunity/affirmative action institution and is committed to a policy of nondiscrimination on the basis of race, sex, gender identity and expression, age, religion, color, national origin, ancestry, citizenship, disability, genetic information, marital status, breastfeeding, income assignment for child support, arrest and court record (except as permissible under State law), sexual orientation, domestic or sexual violence victim status, national guard absence, or status as a covered veteran. Employment is contingent on satisfying employment eligibility verification requirements of the Immigration Reform and Control Act of 1986; reference checks of previous employers; and for certain positions, criminal history record checks.

In accordance with the Jeanne Clery Disclosure of Campus Security Policy and Campus Crime Statistics Act, annual campus crime statistics for the University of Hawaii may be viewed at: http://ope.ed.gov/security/, or a paper copy may be obtained upon request from the respective UH Campus Security or Administrative Services Office.

Samueli School of Engineering University of California, Irvine
Tenure-Track Assistant/Associate Professor Faculty Positions

In response to a hiring initiative associated with a UC Irvine program to advance and sustain the standing of major university centers, the Advanced Power and Energy Program at the University of California, Irvine (UC Irvine) is interested in receiving applications from faculty candidates in power generation and energy conversion associated with:

1. **Chemical processes** in combustion systems.
   https://recruit.ap.uci.edu/apply/JPF04357

2. **Advanced electrochemical conversion and energy storage** in fuel cell systems.
   https://recruit.ap.uci.edu/apply/JPF04356

Chemical Processes are integral to power generation and transportation systems that involve the transformation of the energy chemically bound in an energy carrier or fuel. In heat engines, the preparation of the fuel/air mixture, including atomization and evaporation in the case of liquid fuels, chemical kinetics and mixing govern both the heat release in the oxidation of a fuel as well as the formation and removal of pollutant species both within the combustion process as well as in after-treatment systems. Methods to recover and use exhaust heat also involve complex chemical processes. In the production of practical fuels, contaminant removal from renewable fuels, and processing of fuels to make desired products, chemical processes are the cornerstone to system design, control and performance optimization. The successful applicant is expected to contribute to the leadership of the *UCI Combustion Laboratory*, and conduct transdisciplinary collaborative research with faculty in combustion, fuel cell technology, transportation studies, and air and water resources. The appointment is expected in either the Department of Mechanical and Aerospace Engineering, or the Department of Chemical Engineering and Materials Science.

Advanced Electrochemical Conversion and Energy Storage are integral to fuel cells and related electrochemical conversion devices and systems (e.g., electrolyzers, batteries, flow batteries) that have unique features essential to achieving sustainable energy in the future. Dispatchable power and energy storage with zero criteria pollutant and greenhouse gas emissions are possible with fuel cell and related electrochemical conversion systems and technologies which can be applied in concert with intermittent renewable power sources to enable energy sustainability. Clean and efficient delivery of power and energy resources requires more than the isolated improvement or optimization of individual components; rather, integrated electrochemical and energy storage systems must be advanced in the context of larger energy infrastructure and systems and societal demand and renewable power dynamics. The successful applicant is expected to contribute to the leadership of the *National Fuel Cell Research Center*, and conduct transdisciplinary collaborative research with faculty in fuel cell technology, combustion, transportation studies, air and water resources, power electronics, and hydrometeorology. The appointment is expected in either the Department of Mechanical and Aerospace Engineering, or the Department of Chemical Engineering and Materials Science.

Applicants are expected to have a doctoral degree from an accredited university in a relevant science or engineering discipline. Successful candidates will be expected to develop a vigorous externally funded research program, maintain a strong publication record, advise students, provide outstanding teaching at the undergraduate and graduate levels, and contribute their leadership and innovative thinking towards an excellent science and engineering program within the department. Successful candidates will also be expected to contribute towards a campus-wide initiative to create more field-based (off-campus) student learning opportunities with the goal of increasing the number of students (especially underrepresented minority students) pursuing graduate degrees in related programs.

Applications should include a cover letter, a description of research, teaching and service interests, including ability to contribute to departmental and interdisciplinary programs, a curriculum vitae, and the names and contact information of at least five references. References will not be contacted until later stages of consideration, in consultation with the candidate. A separate statement that addresses past and/or potential contributions to diversity, equity and inclusion must also be included in the application materials.

Applications must be received by January 31, 2018 to receive full consideration.

The Advanced Power and Energy Program was established in 2000 to address the generation of power, the transport and storage of energy, and the utilization of energy in both stationary and mobile (transportation) applications. While the Program is based in the Samueli School of Engineering with faculty from mechanical, civil, chemical, and electrical engineering, the transdisciplinary nature of APEP encompasses faculty from the social, physical, earth systems, and business sciences as well. The Program includes the *National Fuel Cell Research Center* (established in 1998 by the U.S. Department of Energy and the California Energy Commission) and the *UCI Combustion Laboratory* (established in 1970 with a focus on continuous combustion and spray systems).

The University of California, Irvine is part of the premier public university system in the world. UCI is a member of the Association of American Universities (AAU), is ranked as a top ten public university by U.S. News and World Report, and was identified by the New York Times as No. 1 among U.S. universities that do the most for low-income students. UCI is located in Orange County, 4 miles from the Pacific Ocean and 45 miles south of Los Angeles. Irvine is one of the safest communities in the U.S. and offers a very pleasant year-round climate, numerous recreational and cultural opportunities, and one of the highest-ranked public school systems in the nation.

The University of California, Irvine is an Equal Opportunity/Affirmative Action Employer advancing inclusive excellence. All qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity, national origin, disability, age, protected veteran status, or other protected categories covered by the UC nondiscrimination policy. A recipient of an NSF ADVANCE award for gender equity, UCI is responsive to the needs of dual career couples, supports work-life balance through an array of family-friendly policies, and is dedicated to broadening participation in higher education.

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RECRUITMENT

THE OHIO STATE UNIVERSITY
COLLEGE OF ENGINEERING

Robotics – Tenure-Track Faculty Position
Department of Mechanical and Aerospace Engineering
College of Engineering

The Department of Mechanical and Aerospace Engineering at The Ohio State University invites applications from outstanding individuals for a tenure track faculty position with primary focus on robotics. The anticipated start date is August 2018, but the search will continue until the position is filled. Though candidates are primarily sought at the assistant professor level, exceptionally qualified applicants at the associate professor level may be considered.

Qualifications:

An earned doctorate in mechanical engineering, electrical engineering, or an appropriate related field is required. We seek candidates with demonstrated ability to conduct research at the highest level, and with a commitment to outstanding teaching and mentoring of students. The successful candidate will be expected to attract funding to develop and sustain active sponsored research programs, teach core undergraduate and/or graduate courses, and develop new graduate courses related to their research expertise. Screening of applicants will begin on December 1, 2017 and will continue until the position is filled. Interested candidates should provide complete curriculum vitae, separate 2-3 page statements of research and teaching goals, and the names and postal/email addresses of four references at: **https://academicjobsonline.org/ajo/jobs/10284**

The Ohio State University is an equal opportunity employer. All qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation or identity, national origin, disability status, or protected veteran status.

Requires the successful completion of a background check.

ASME's 136th President Charla Wise spoke about the Society's goals during the President's Luncheon at the IMECE 2017. *Image: ASME*

ASME PRESIDENT CHARLA WISE ADDRESSES THE SOCIETY'S PATH

ASME has embarked upon a path to become the "go-to" engineering organization to address technology-related challenges, declared ASME President **Charla Wise** during her speech at the President's Luncheon at the ASME 2017 International Mechanical Engineering Congress and Exposition on Nov. 6 in Tampa, Fla. Wise laid out the issues the Society is working on— including leadership, collaboration, and engagement—to help assure that it reaches that goal.

On the subject of leadership, Wise recounted the story of an ASME member and former Roe Scholarship recipient, who described her experience as an ASME member as one that made it possible for her to transform from an introverted student into an engineer serving a leadership role on a major technology company's advanced technical leadership team. She still finds time to mentor and teach undergraduate and graduate students, Wise said.

During her speech at the luncheon, Wise noted that ASME sought input from both inside and outside the Society to determine what it meant to be a go-to organization.

"She is giving back, in service and in heart, to build up for others the professional home that ASME volunteers and members helped her create for herself," Wise said.

As an example of collaboration between Society groups and members making ASME "greater than the sum of its parts," Wise pointed to the success of this year's E-Fest Asia Pacific. More than 1,000 students attended the festival, which was organized by more than 250 ASME volunteers.

Another success story, Wise noted, was a collaboration between ASME Engineering Education and Standards & Certification departments, and volunteers from more than 25 institutions and experts in key standards areas to develop a series of standards-education modules for university curricula.

In order for ASME to achieve its goals, ASME has engaged not only its own leaders, volunteers, and members; it has also sought input from engineers, academics, and government professionals outside the Society to define what constituted such an organization, Wise said.

Among the key discoveries were that while ASME still draws new members, its recognition by engineers under 35 needs to increase. In addition, remaining "agile and flexible" must be a primary concern in planning ASME programs.

"Ten years from now, I hope that there is no hesitation when we think of ASME, we think of it as the go-to organization," Wise said. "But until then, every step we take should bolster our role as a thought leader and an essential resource for innovative technology development. But I have every reason to be encouraged that we are making the right connections and reaching the next generation." ME

IMECE KEYNOTE SPEAKER CHUCK HULL DWELLS ON 3-D PRINTED ORGANS

During his keynote address at the ASME 2017 International Mechanical Engineering Congress and Exposition in Tampa earlier this month, **Chuck Hull**, the co-founder of 3D Systems, discussed what he believes is an important frontier for advanced manufacturing: regenerative medicine.

"The idea is to print something that will help the body heal itself," Hull, who is considered the inventor of 3-D printing, told the crowd of more than 700 engineers attending the event on Nov. 6. "This really combines this wonderful growing field of biotechnology with 3-D printing."

Looking ahead, Hull spoke enthusiastically about saving lives.

"There are about 31,000 lung transplants a year in the United States," Hull said. "The waiting list is about four times that. There is a huge unmet need beyond that. There are about 900,000 deaths in the United States alone from organ impairment. If we could figure out how to manufacture these organs, it would be a huge benefit to the society."

Chuck Hull delivered the Opening Keynote presentation at the IMECE 2017 . *Image: ASME*

Hull said researchers are about six years away from clinical trials with a bioprinted lung. He described steps such as using microscanning to improve our understanding of how organs work; studying the collagen scaffolds that physically support cells; learning to 3-D print scaffolds with collagen-based materials, using printers with a resolution two orders of magnitude higher than what is available today; and growing billions of organ cells. ME

BEJAN'S WORK RECOGNIZED WITH BENJAMIN FRANKLIN MEDAL

ASME Honorary Member and Fellow **Adrian Bejan**, the J.A. Jones Professor of Mechanical Engineering at Duke University, was named the recipient of the 2018 Benjamin Franklin Medal in Mechanical Engineering. Bejan, who also received ASME's 2017 Ralph Coats Roe Medal at the Honors Assembly on Nov. 6, was recognized with the Benjamin Franklin Medal for "his pioneering interdisciplinary contributions in thermodynamics and convection heat transfer that have improved the performance of engineering systems, and for constructal theory, which predicts natural design and its evolution in engineering, scientific, and social systems."

Bejan joined seven others who received the prestigious Franklin Institute Awards this year. They join a long list of innovators whose revolutionary discoveries have significantly transformed our world. These scientists and engineers have made enormous strides in their fields, improving the lives of billions of people across the world. ME

ASME WORKSHOP EXPLORES TECHNOLOGY DEVELOPMENT GOALS

ASME President-Elect Said Jahanmir introduces the panelists at the ASME Congressional Briefing. *Image: Paul Cleri*

ASME explored technology development in gas turbine industrial sectors at a workshop and congressional briefing the Society convened in Washington, D.C. The event also focused on how public-private partnerships such as Manufacturing USA enable manufacturers to create jobs and achieve technology goals, while also supporting overall U.S. public policy priorities in energy, transportation, and national security.

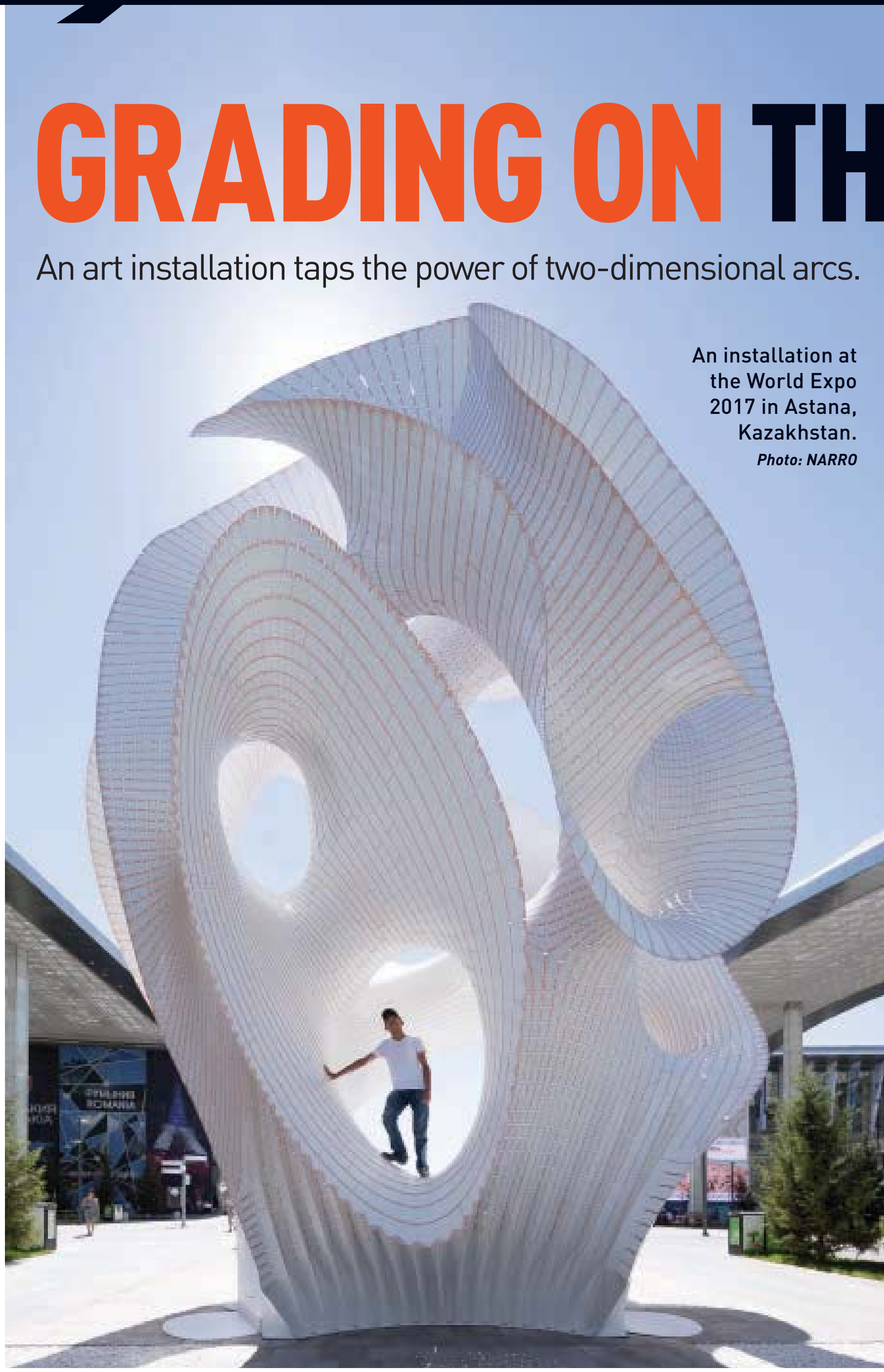
ASME's two-day event, Realizing Gas Turbine Performance Goals through Advanced Manufacturing, was held Oct. 17 and 18 at the Rayburn House Office Building. It brought together leaders from a wide variety of industrial sectors and related organizations, including the Gas Turbine Association, the Consortium for Advanced Production and Engineering of Gas Turbines and Rotating Machinery, the Department of Energy, the National Institute of Standards and Technology, the National Aeronautics and Space Administration, the Air Force Research Laboratory, and other leaders in research organizations across industry and academia.

The House Manufacturing Caucus, led by U.S. Representatives **Tom Reed** (N.Y.) and **Tim Ryan** (Ohio), and the House Natural Gas Caucus, chaired by U.S. Representatives **Glenn "G.T." Thompson** (Pa.), **Gene Green** (Tex.), **Tom Reed** (N.Y.), and **Jim Costa** (Calif.), also provided support in sponsoring the briefing.

The opening keynote featured **Brett Lambert**, formerly Deputy Assistant Secretary of Defense for Manufacturing and Industrial Base Policy and now vice president of corporate strategy for Northrop Grumman, who discussed his experiences at the U.S. Department of Defense, where he worked to establish the first site for the National Network for Manufacturing Innovation (now called Manufacturing USA). ME

GRADING ON THE CURVE

An art installation taps the power of two-dimensional arcs.



An installation at the World Expo 2017 in Astana, Kazakhstan. *Photo: NARRO*

Buildings have traditionally been made of flat planes and simple curves. But a team of Brooklyn-based architects have demonstrated that warping material across two dimensions can provide enough strength to cut down on material use.

Minima|Maxima was an installation at the World Expo 2017 in Astana, Kazakhstan, made from complex, three-ply, curved aluminum sheets supporting one another, reaching 43 feet into the sky. The sheets are made of components called structural stripes that were invented by French architect Marc Fornes, using a digital fabrication method in which thousands of sub-elements are fastened together to form an ultrathin continuous surface.

The surface is only 6-mm thick, about the same as three stacked nickels. An egg at the same scale would have a shell some 2 inches thick.

"The entire structure relies on the fact that it is curved into two directions, not on the material," said Fornes, from his THEVERYMANY studio in Brooklyn.

Computer-assisted design tools enabled architects to explore more complex curves. But in 2004, when Fornes graduated with a master's in architecture and urbanism from the Design Research Lab of the Architectural Association in London, architects were still having trouble designing curved structures. Fornes taught himself coding and developed the stripes as a way to enable this structural process. The composite stripes are positioned perpendicularly from one another, creating an anistropic composite material (its structural properties depend on direction) from an isotropic material, such as aluminum (the properties are mostly the same in all directions).

Minima|Maxima rests on a pleated base that takes the dead load and rigidifies the edge. The aluminum sandwich is made of three flat layers—two white enveloping one pink. Because the layers support each other as they assume curvature and gain height, no columns or temporary scaffolding are needed.

The same dual curvature that provides its structural integrity splits, merges, and recombines, incorporating elements that enable visitors to walk through the structure.

"People are used to living in a box," Fornes said. "We might have seen those curved elements in a biology book or a marine environment, but we never entered one. I think people engage it because it is very organic, and then there is the curiosity of how it is actually standing. And it is white, which makes it very abstract and surreal."

The 10-architect studio is working on other projects, from an eight-floor façade to pavilions to parking lots. For his part, Fornes is still toying with how to build with curves.

"It's more than a question for me," Fornes said. "It's a fascination." **ME**

MEREDITH NELSON is a writer based in New York City.

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ASME

SETTING THE STANDARD

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