

# MULTIPHYSICS SIMULATION

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## INTERACTIVE PRODUCT DEVELOPMENT

MULTIPHYSICS SIMULATION HELPS BRING  
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**PAGE 16**

# MULTIPHYSICS SIMULATION ILLUMINATES THE FUTURE

By **MICHAEL FORSTER, MANAGING DIRECTOR – PUBLICATIONS, IEEE**

**MULTIPHYSICS SIMULATION** is used to improve existing technologies — and create completely new ones. In terms of powertrain electrification, it is speeding up the design and development of electric vehicle motors. Volkswagen Kassel in Germany has developed an efficient modeling process for electric motors that balances both the electromagnetic and mechanical design requirements of this important engine component. By optimizing their development process, they can set their sights further down the road to new vehicle tech, like digitalization, autonomous driving, and electric drives.

Illinois Tool Works (ITW), the largest commercial food equipment company in the world, is using multiphysics simulation to optimize the design of a “smart” solid-state convection oven for the even and rapid heating of food.

Multiphysics simulation is also enabling engineers to investigate brand new ways to experience physical phenomena. Researchers at HARMAN International are designing audio infotainment systems for luxury vehicles and have even started experimenting with an interactive car-buying experience based in virtual reality.

A professor at Virginia Commonwealth University is using simulation applications to teach undergraduate students the building blocks of electromagnetics and is already thinking of ways to incorporate virtual or augmented reality into upcoming lesson plans.

From developing electromagnetics technology that helps the environment to inspiring the next generation of electrical engineers, multiphysics simulation is helping today’s companies and organizations visualize a brighter future for tomorrow.

I hope you enjoy reading the exciting and inspiring work featured in this special COMSOL report. ☺

## ON THE COVER:

Visualization of the sound field from a loudspeaker, augmented in a luxury car environment. Image is courtesy of HARMAN International.



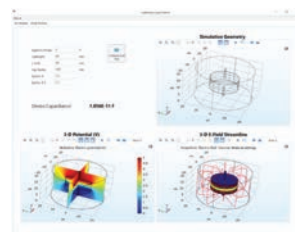
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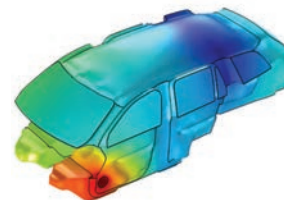
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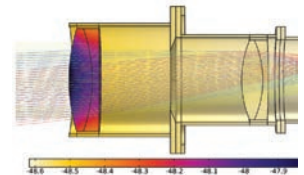
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# SIMULATION APPLICATIONS STREAMLINE THE DEVELOPMENT OF ELECTRIC VEHICLE MOTORS

*Volkswagen Kassel accelerates the design process for electric motors by building and distributing simulation applications that evaluate the strength of rotor laminations.*

By **THOMAS FORRISTER**

**AS MORE CONSUMERS EXPRESS** concern for the environment, electric vehicles are on track to outpace conventional internal combustion engine vehicles as the transportation mode of choice. In response to this growing demand, leading automakers are doing their part to pave the way for EVs, revving up the development of electric and hybrid motors alongside the manufacturers of combustion engines. One such automaker is Volkswagen, whose Kassel plant in Germany specializes in the development, planning, and production of electric drives. It has a production output of 150 electric and 300 hybrid drives daily.

As essential components in electric drives, rotors need to be tested for durability, since they must endure a very large number of revolutions at varying speed and torque during drive operation. However, evaluating the strength of rotor laminations is time-consuming. VW Kassel is automating this test process for rotors, as well as reducing development costs and increasing product quality, by building simulation applications with the COMSOL Multiphysics® software.

## » BALANCING ELECTROMAGNETIC AND MECHANICAL REQUIREMENTS

**IN 2015, VOLKSWAGEN** began developing a modular system to optimize EV design and make the manufacturing process more efficient, called the Modular Electrification Toolkit (MEB). The MEB accounts for the

torque, power, and speed for the main rear-wheel drive and for the optional front-wheel drive that is used in all-wheel drive versions (Figure 1). Among other requirements, such as the ratios for the axles, drive units, weight, and wheelbases, the design and placement of the high-voltage drive battery plays a major role in the overall MEB concept. While the MEB helps to optimize individual components and the system as a whole, balancing these requirements takes careful consideration on the part of the designer, especially when accounting for new technologies like digitalization, autonomous driving, and electric drives.

From the very beginning of the electric drive development process, there has been close cooperation between staff involved in design,

simulation, and testing at VW Kassel. First, the simulation experts review the performance specifications for an electric drive and use simulation to investigate how to best approach the design. For example, modeling the drive greatly reduces the number of variants, and distributing a simulation application based on this model enables the designers to then benchmark different variants and choose the best one.

This collaboration is vital and beneficial to all, as simulation cannot cover all of the real-world issues. Hence, the test process plays an important role in the development process. In addition, the experimental test procedure helps to improve the simulation models.

“In the development process of electrical machines, one has to fulfill

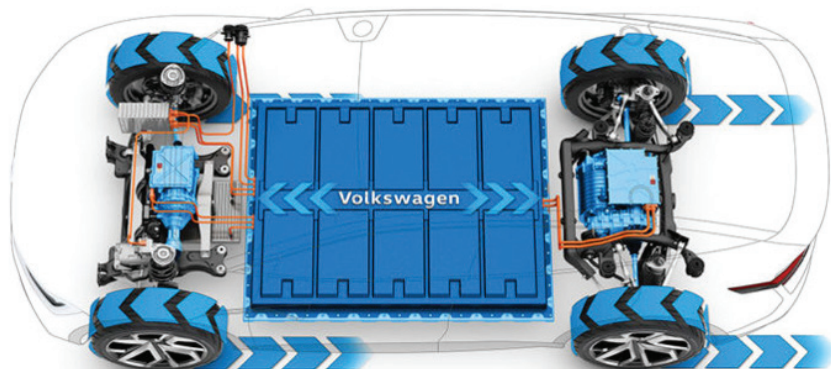


Figure 1. Schematic of the MEB, with the optional all-wheel drive (left, front of the vehicle) and the main drive (right, rear of the vehicle).



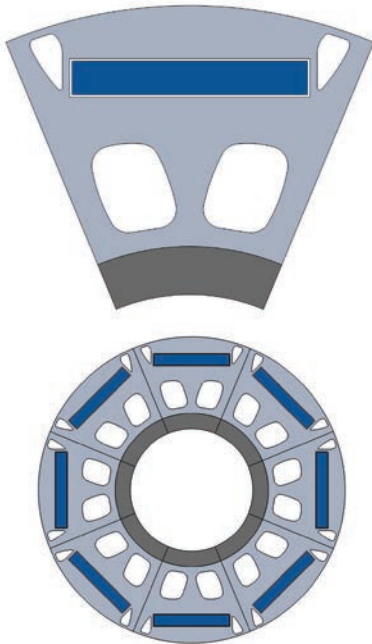


Figure 2. A typical rotor setup with the rotor plates, shaft, and magnet.

many requirements,” explains Dr. Steffen Rothe, simulation engineer of component development at VW Kassel. “On one hand, the machine has to match electrical requirements for the torque and power. On the other hand, the rotor has to possess a certain durability, where the centrifugal force is the major load for the rotor.”

Further, balancing dual requirements can be challenging, as they are sometimes at odds. For example, while it is better to use thin, weblike structures for the electromagnetic requirements, thicker structures are preferable for mechanical durability. It is important that these requirements are addressed early on in the development process. One way to do so efficiently is to simulate all of the load cases covering the requirements. “Simulation,” Rothe says, “plays a major role in accelerating the design process.”

“Many industrial simulation programs are designed as a black box, whereas COMSOL Multiphysics® is unique in its transparency. It

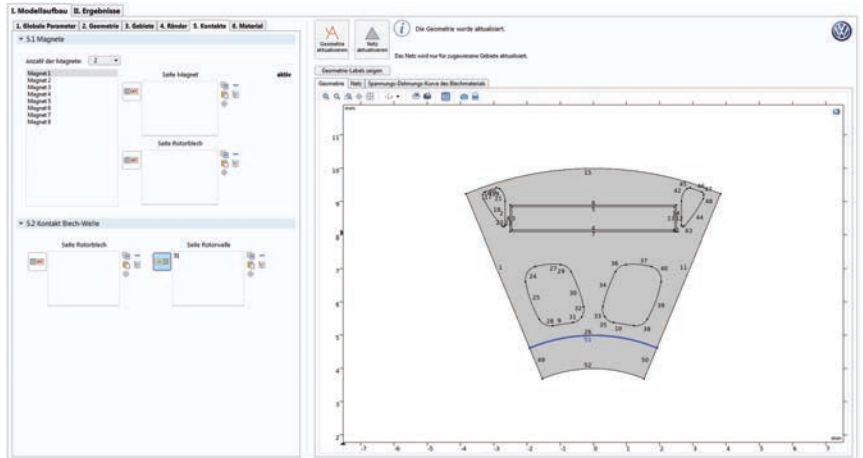


Figure 3. An example of the simulation application's user interface.

enables users to view and modify the implemented equations, or even add your own,” says Rothe. Furthermore the software is designed as a multiphysics tool from the beginning and enables users to simulate different physical fields simultaneously. Hence, the user can combine different physical fields to do something completely new.

However, analyzing complex physical problems such as these can be challenging, even for a simulation expert. The team needed a way to communicate with colleagues and enable nonexperts in mechanical simulations to test certain parameters. The designers were able to meet these needs by using the Application Builder, a built-in tool in COMSOL Multiphysics®, to create simulation applications that predict the stresses in a rotor.

### » IMPROVING EV PRODUCTION WITH SPECIALIZED APPLICATIONS

TO DESIGN AN APPLICATION for colleagues to evaluate the strength and durability of rotor laminations, simulation experts Marie Hermanns and Steffen Rothe

considered which part of the model could be automated, which model parameters were variable, and which results the application should show.

For a typical rotor setup (Figure 2), the simulation experts concluded that they could automate the load testing to include interference, temperature, and operating speed. These are parameters that colleagues in other departments would benefit from being able to change themselves. General variable parameters include geometry, area, interference, contacts, number of active magnets, and materials. These considerations helped Hermanns put together an intuitive user interface for the application (Figure 3) that colleagues could use to automate the calculations needed.

“The idea was to create an application for colleagues to enable an easy and fast way to benchmark different designs,” Hermanns says. “Additionally, one can create a tool for a specific problem with an intuitive user interface. In this case, the user does not have to learn the details

“Many industrial simulation programs are designed as a black box, whereas COMSOL Multiphysics® is unique in its transparency. It enables users to view and modify the implemented equations, or even add your own.”

—DR. STEFFEN ROTHE, VW KASSEL

of how the simulation works.”

### » STANDARDIZING DEVELOPMENT TO SERVE COMPANY AND CUSTOMER NEEDS

IN ADDITION TO AUTOMATING the development process among departments at VW Kassel, specialized simulation applications help the engineers standardize their

benchmarking process of rotor laminations.

The application shortens the time it takes to perform common tasks such as applying boundary conditions, materials, and loads, and is standardized and combined into a user interface. A further benefit is the automatically generated report, which includes a strength rating for laminated rotor sheet sections and helps to standardize the report summaries across teams (Figure 4).

Through the stress analysis of rotor laminations using simulation applications, engineers at VW Kassel are able to save time and money during the development process of electric drives. The applications also contribute to increasing product quality by helping simulation experts and nonexperts alike automate the lengthy model construction process and standardize models and results, shortening the distance it takes to get from model to concept available EV. ☺

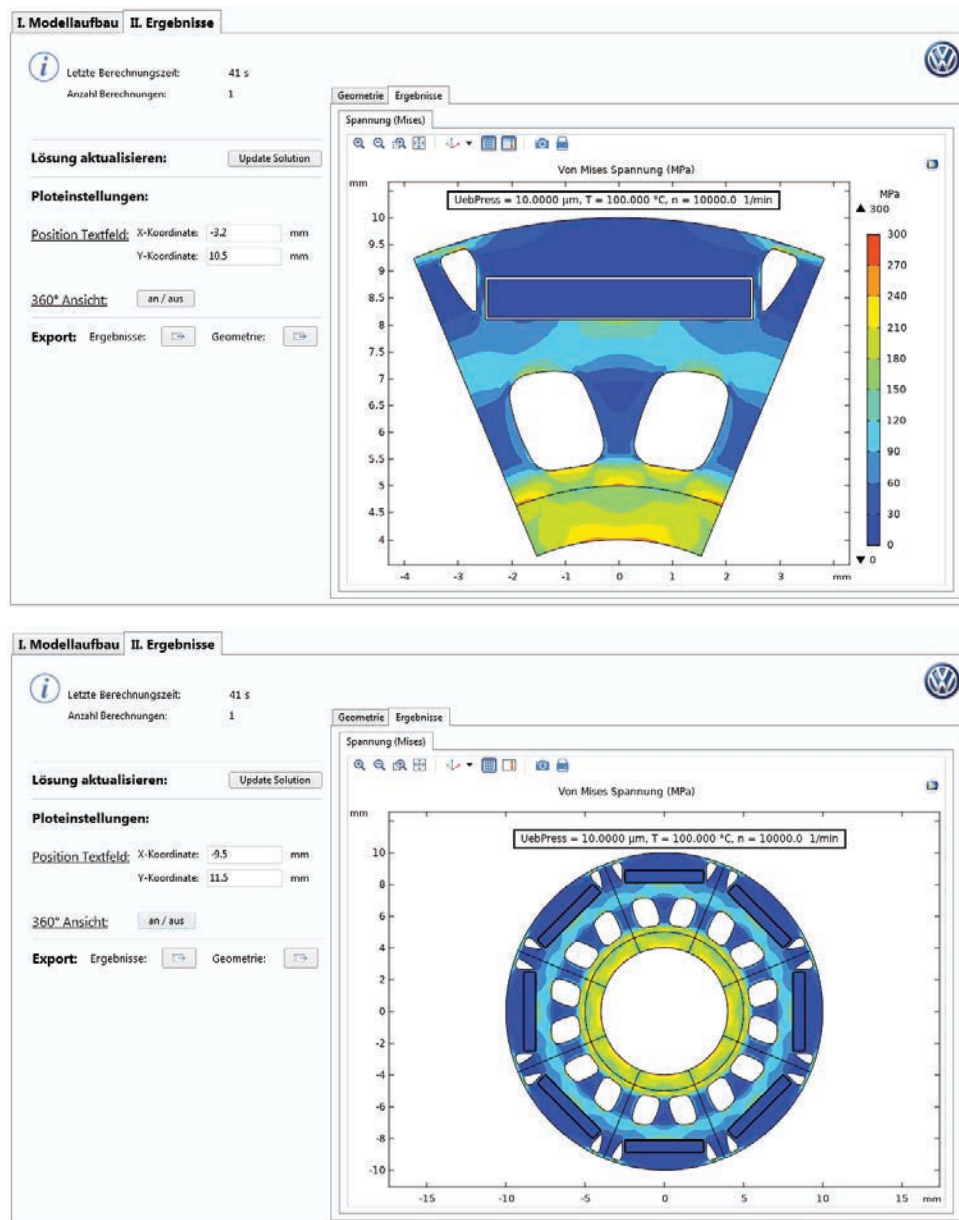


Figure 4. Standardized stress results for the rotor.



Top: Marie Hermanns (simulation engineer). Bottom: Steffen Rothe (simulation engineer).

# ABB DESIGNS OPTIMIZED INSTRUMENT TRANSFORMERS AND SENSORS WITH MULTIPHYSICS SIMULATION

*To protect and maintain power grids from system failure, ABB uses multiphysics simulation to design instrument transformers that can withstand very fast transient overvoltages and a split-core sensor for submersible underground vault applications.*

By **BRIANNE CHRISTOPHER**

**A POWER OUTAGE CAN LAST** a few hours, days, weeks — even months. No matter how long an outage lasts, it is a frustrating and disruptive experience. A blackout can even be dangerous when it occurs during extreme heat or cold. To ensure power grid stability, protection, and financial viability, ABB uses multiphysics simulation and applications to develop optimized electrical designs, particularly instrument transformers and sensors.

## » ENSURING POWER GRID PROTECTION WITH INSTRUMENT TRANSFORMERS

**INSTRUMENT TRANSFORMERS (ITs)** are specialized, highly accurate transformers that isolate, transform, or reduce high voltages and currents in order to maximize safety and usability. Uses of ITs include metering, monitoring, protection, and control of power systems. An IT is made up of a primary winding, which is connected to a high-voltage or high-current circuit, and a meter or relay, which connects to a low-voltage or low-current secondary circuit.

At ABB, current sensor designs (Figure 1) are based on the Rogowski

coil principle. A Rogowski coil consists of a uniformly wound coil with a nonmagnetic core, and the output voltage is proportional to the derivative of the primary current. Sensors that measure voltage in medium-voltage scenarios use resistive voltage dividers, while capacitive dividers, on the other hand, are used for voltage measurement and indication.

The IT and sensor (IT&S) industry has made significant developments in more recent years. Traditional ITs are based on standard technology and have been around for more than 100 years, mostly used in meters and relays. They are made up of a ferromagnetic circuit and are able to transfer power from the primary coil to the secondary coil, with an output of 1–5 amps or 120–240 volts.

Intelligent electronic devices (IED) use more advanced technology and have only been around for the past 20 years. Instead of ferromagnetic materials, these transformers are made up of solid-state components. Since they are unable to transfer power from primary to secondary coils, they have a low energy output. This makes them useful for many indoor and outdoor applications, such as air- and gas-insulated environments, line posts, and line-mounted transformers.

“IEDs are safer, more versatile, and have linear response for a wide range of input signals,” says Nirmal Paudel, consulting R&D engineer at ABB, adding that they are “compatible with today’s electronic devices and our level of usage.”

## » MULTIPLE CONSIDERATIONS FOR IT&S SIMULATION AND DESIGN

**WHEN DESIGNING AN IT**, multiphysics must be taken into account. In fact, Paudel calls this capability “critical.” A successful design should, of course, capture resistive and inductive heating, inductive and capacitive coupling, magnetic saturation, and magnetostriction. However, phenomena such as fluid flow, convective cooling, thermal expansion, external loads and circuits, noise and vibrations, and the skin effect also



Figure 1. An example of a sensor that uses the Rogowski coil principle.



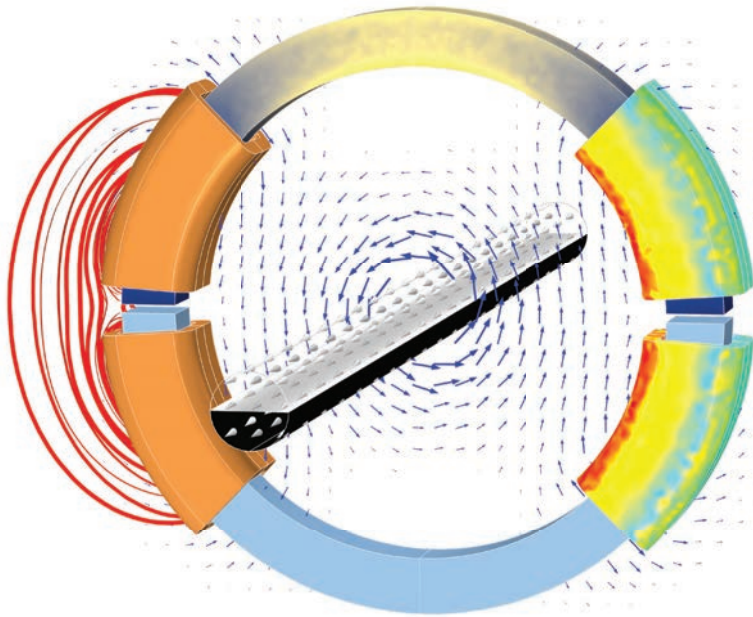


Figure 2. Multiple physics affect an instrument transformer design.

need to be considered (Figure 2).

To account for a wide range of physical effects, ABB uses the COMSOL Multiphysics® software. One example is the simulation of the IT's electric fields both caused by voids in the epoxy casting and during the basic impulse level (BIL). These results enable researchers to see how effective the insulation layers and dielectric materials are at protecting the device.

The software is also used to perform thermal analyses. In a line-line voltage transformer, simulation is used to calculate the core and resistive losses in both the primary and secondary coil windings. Another instance in which thermal modeling is used is to find the heat flux on the outer boundaries of the IT and the fixed temperature boundary on the baseplate. These results show the temperature rise and loss in the design, as well as provide a

look into the thermal curing process and mold flow of the epoxies.

A third example is structural analysis. The ABB team computes the stress level of the IT to optimize the geometry (Figure 3). They also look at the stress displacement levels of the devices and components in order to optimize them before 3D printing of prototypes for testing — or, more serious yet, mass production. Modeling is not only helpful for seeing the performance of the device in advance but also for determining its structural integrity.

#### » VERY FAST RESULTS FOR VERY FAST TRANSIENT PHENOMENA

**VERY FAST TRANSIENT (VFT) PHENOMENA** is an important factor to consider in power grid devices that involve switching, such as vacuum circuit breakers. When switching causes VFT, it can stress the insulation system and cause internal resonances in the primary winding of a transformer. The distribution of the transient overvoltage, when it becomes highly nonlinear, leads to internal failure. There is a higher incidence for VFT overvoltage (VFTO) near renewable energy sources, such as wind power, because of the new grid generation, loads, line characteristics, and increase in switching. VFTO steepness (i.e., how quickly the

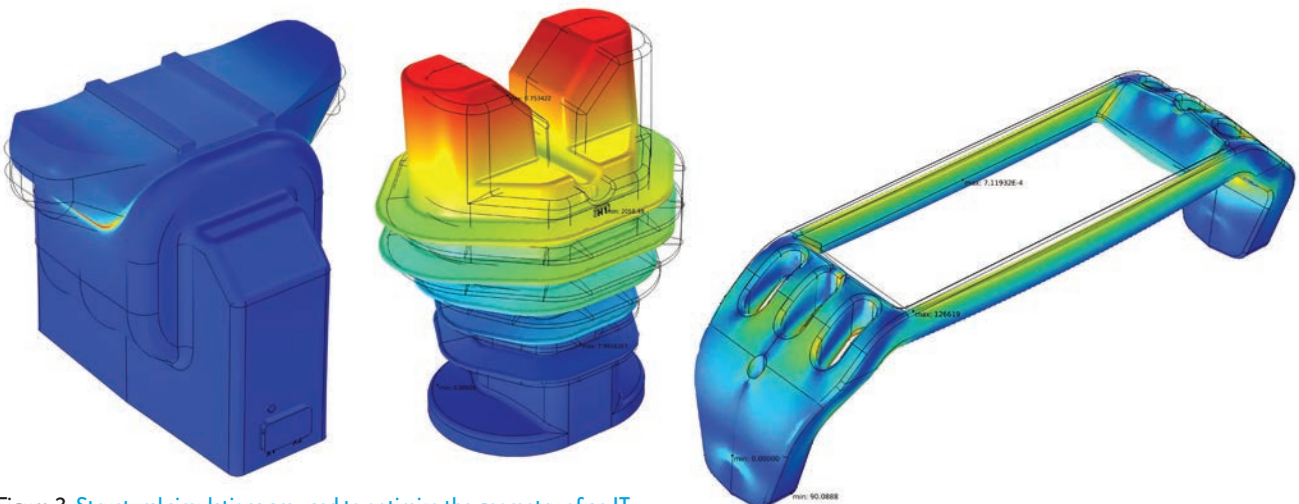


Figure 3. Structural simulations are used to optimize the geometry of an IT.

overvoltage is distributed) can be up to three MV/microsecs, which is much steeper than lightning! (Note that steepness is just as damaging to insulation systems as magnitude.)

Typical design approaches to IT&S do not yield results that are sufficient at withstanding VFTO. This is because these designs require extensive modeling of the high-frequency voltage distribution in the winding, for which no software models existed — until now. ABB, in collaboration with Hochschule für Technik (University of Applied Sciences) in Rapperswil, created a tool to model this behavior and understand voltage distribution in an IT turn by turn. The results? New design methods and a new dry type of insulation that can resist the negative effects of VFTO.

#### » DESIGNING A SPLIT-CORE CURRENT TRANSFORMER FOR UNDERGROUND SWITCHING

SPLIT-CORE DESIGN IS AN IMPORTANT feature for transformers because it enables power grid maintenance without any disruptions. ABB set out to design a split-core current transformer (sensor) that allows high-accuracy current measurement while the switching is done by other devices and the need for switching is evaluated by IED based on signals from the sensor. The sensor is waterproof and submersible so that it can be used underground. (Underground power lines are becoming the industry standard because they are less likely to be affected by high winds or severe weather, especially in cities.) This split-core sensor comes with its own set of design challenges, including its shape, size, and weight as well as

“When a device such as an IT or split-core current sensor can survive in all conditions, everyone benefits.

—NIRMAL PAUDEL, ABB

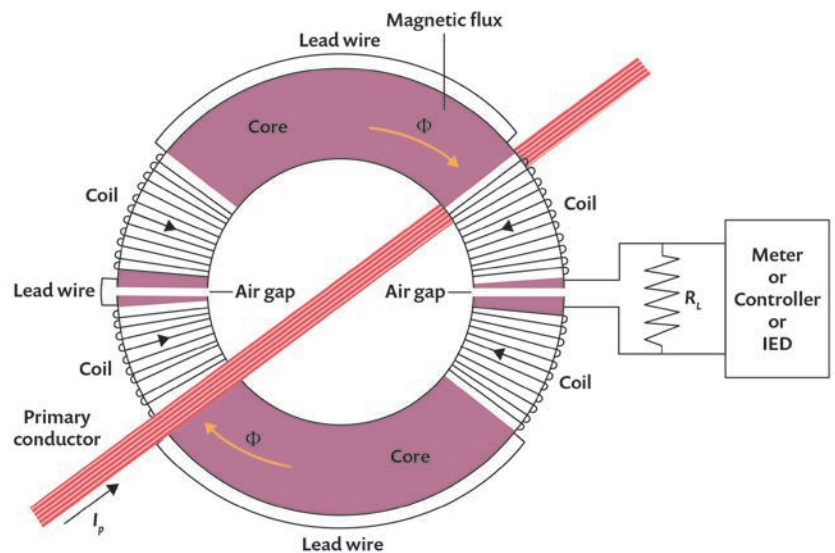


Figure 4. Schematic of a split-core current transformer model.

the winding turns, core shape, and core size (Figure 4). Besides that, there is the risk of current crosstalk, depending on the configuration of the device. Lastly, the sensor needs to conform to industry standards before it can even be tested for production and use. “All kinds of IEEE and IEC standards must be met before the test lab,” says Paudel.

The ABB team turned to the software yet again in order to optimize the split-core current sensor design before prototyping. Paudel has been using it for a long time and enjoys its “ease of use, and the fact that it has the same interface for multiple physics and is easy to couple with other physics.” The COMSOL software includes built-in settings for implementing Maxwell–Ampère’s law and an interface to solve for the magnetic fields in the frequency domain (Figure 5). By using geometric symmetry, the ABB team only has to model one-fourth of the coil, saving time, effort, and computational resources. A special coil modeling feature enables the team to set up the primary coil as a solid conductor and the secondary coil as a homogenized

multiturn coil. A boundary condition describes the area where the tangential component of the magnetic field and surface current density is zero as a perfect magnetic conductor, and the external boundaries are set to be magnetic insulators. Solver features enable the team to easily adjust the settings between solid and homogenized conductors, and solid conductors versus wires.

#### » SIMULATION APPLICATIONS OFFER QUICK CALCULATIONS

ONE TIME-CONSUMING ASPECT of IT&S design is the conversion between a nonlinear magnetic B-H curve (DC magnetization) and equivalent AC effective H-B curve. ABB used an example application from the Application Library to perform these calculations. After finding the effective H-B curve with the application, they used the value to model the magnetic core of the split-core current sensor. They found that the magnetic permeability is almost linear throughout the entire core because of the decrease in magnetic flux density. Based on these results, the team concluded that



homogenous anisotropic conductivity and permeability should be used.

Looking at the magnetic flux and current density results of the simulation, the ABB team found that the flux level for their design is very small, which is ideal for their medium-voltage use case. In addition, the group noticed something interesting: Usually, when the number of turns on the secondary coil is increased, the open-circuit voltage also increases (as it did for one of their studies, from 130 to 196 V). However, when the load is connected across the coil, the voltage does not always increase, and sometimes even decreases instead.

One of the final analyses that ABB completed for this project was looking at the three-phase crosstalk for different configurations for the split-core current transformer design. They found that the crosstalk differed depending on whether the secondary coils were placed closer to or farther away from the transformer's air gaps.

» **FINAL PRODUCT: OPTIMIZED DESIGNS AND ENHANCED DEVELOPMENT PROCESSES**

ABB'S FINAL DESIGN ITERATION, the Submersible Split-Core Sensor, met the standards set out by IEEE and IEC (Figure 6). When asked about their future plans, Paudel mentions that his team is working on developing a tool to advance the analysis of VFTO and transformers, decreasing the timeline of the analysis process from weeks to days. The tool will rely primarily on MATLAB® but may offer an integration with the COMSOL® software via the LiveLink™ for MATLAB® interfacing product. The plans for this new tool show that ABB is just as dedicated to optimizing their workflow and processes as they are to the end results. They work hard to optimize devices that increase power grid accessibility. As Paudel says, when a device such as an IT or split-core current sensor can survive in all conditions, “everyone benefits.” ©

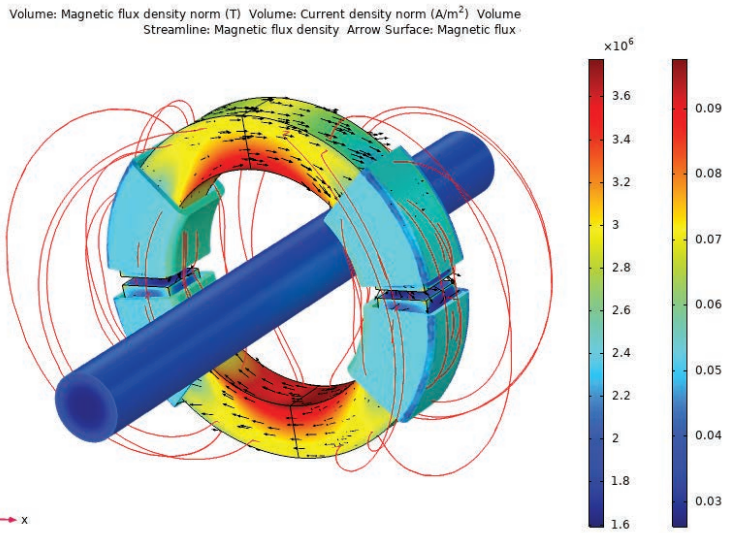


Figure 5. The magnetic flux and current density of the split-core transformer.

“ [I enjoy COMSOL’s] ease of use, and the fact that it has the same interface for multiple physics and is easy to couple with other physics.”

—NIRMAL PAUDEL, ABB



Figure 6. The submersible split-core sensor.



The ABB team, from left to right: Vivek Siddharth, Steve Shaw, David Raschka, and Nirmal Paudel.

# ILLUMINATING THE PHYSICS BEHIND ELECTROMAGNETICS CONCEPTS WITH SIMULATION APPLICATIONS

*Electrical engineering students at Virginia Commonwealth University are able to visualize electromagnetic fields using simulation applications — for a better learning experience and successful future.*

By **BRIANNE CHRISTOPHER**

**NATE KINSEY RECALLS HIS FIRST UNDERGRADUATE COURSE IN ELECTROMAGNETICS...** It was tough. “A lot of smart people remember their electromagnetics course as the first course they experience where things do not work without a lot of effort,” he says. “It was eye-opening.”

Fortunately, the experience did not leave him discouraged: Kinsey went on to pursue a master’s degree from the University of Missouri Columbia and a PhD from Purdue, both in electrical engineering. He is currently researching integrated photonics and nonlinear optics while teaching undergraduate engineering students at Virginia Commonwealth University.

Kinsey used his experience in that first electrical engineering course as an impetus for introducing his students to simulation. The way he sees it, the key to student success in such a challenging course is the ability to actually visualize and gain intuition for the problems. However, it is not as easy as it sounds.

## » HELPING ELECTRICAL ENGINEERING STUDENTS VISUALIZE THE INVISIBLE

**ELECTROMAGNETICS COURSES INVOLVE RIGOROUS MATHEMATICAL FORMULAS**, 3D vector calculus, and more — plus, these topics converge for the first time in a student’s career, compounding the challenge. Because of this, many students get stuck in the complex mathematical formulas and equations without getting a clear picture of the actual problem they are trying to solve, which Kinsey believes is integral to their success.

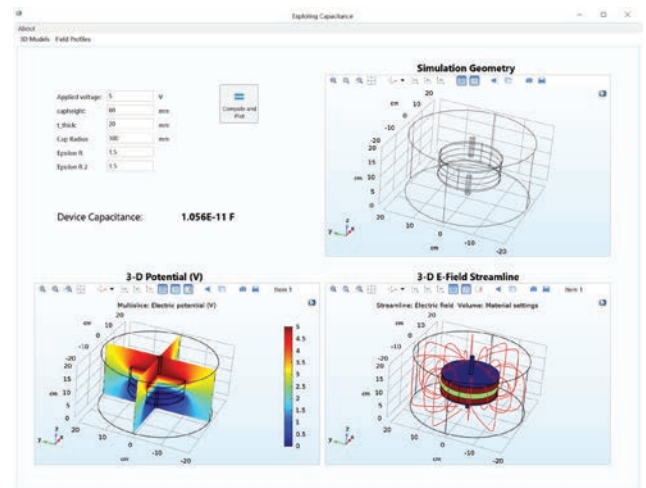


Figure 1. A simulation application that students can use to study the fringe fields in capacitors.

In fact, Kinsey has observed that the current generation of students struggle to create a picture of an object or problem in their mind’s eye. What this technology-immersed generation *is* great at, however, is recalling the image once they *do* have a visualization in their mind. They just need assistance getting there.

In terms of electromagnetics, students have a poor understanding of what the EM fields around their phones or a cell tower actually look like because they cannot see or interact with it; they seem abstract. To a point, Kinsey uses water

waves and acoustics waves as a stand-in for electromagnetic waves, because the former are much easier to visualize and relate to, helping students to gain intuition for the effects and physics the math is trying to describe. The problem is that these waves do not accurately represent 3D electromagnetics problems.

“Students need 3D visualizations to see real-world electromagnetics problems, like a magnetic field around a dipole,” explains Kinsey. He illustrates these concepts on the board (so the field around the dipole looks like either a circle

“COMSOL exploits the ability to visualize electromagnetic fields, rotate them, scale them, and interact with them; such as to see how fields curve around a dipole. This can be difficult to accurately convey by drawing on the board.”

—NATE KINSEY, VIRGINIA COMMONWEALTH UNIVERSITY

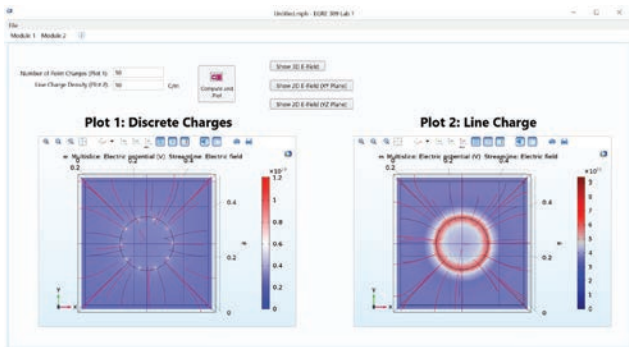


Figure 2. A simulation application for electromagnetics students to compute discrete and continuous charges.

or figure eight depending upon the viewing angle), but drawings can only accomplish so much. “Some students will get it,” Kinsey says, “while others struggle.” This is where simulation comes in. “COMSOL exploits the ability to visualize electromagnetic fields, rotate them, scale them, and interact with them; such as to see how fields curve around a dipole. This can be difficult to accurately convey by drawing on the board,” says Kinsey.

### » ENABLING STUDENT SUCCESS WITH THE HELP OF ELECTROMAGNETICS SIMULATION APPLICATIONS

ALTHOUGH FOUNDED IN THEORETICAL CONCEPTS, Nate Kinsey believes that the addition of laboratories and simulation tools greatly enhances the student experience. In 2017, he helped redesign the electrical engineering curriculum at

Virginia Commonwealth University in an attempt to bolster student success.

To do so, Kinsey added simulation applications built in the COMSOL Multiphysics® software to the course curriculum. “Applications enable students to see and interact with a phenomenon themselves, and at their own pace,” he says. Since Kinsey’s curriculum already had to cover a large amount of material, he did not want to add the task of learning a new simulation software onto his students’ plates. Instead, teaching assistants in his class build and package applications based on the concepts being taught and upload them to the university’s instance of COMSOL Server™, where students can access and run the applications for their assignments.

“We give them five to

seven parameters to play around with, enough to be interesting but not enough to bog them down in details,” says Kinsey (Figures 1–3). Moreover, simulation labs are carefully designed, as prescribing too much of a process or giving too much instruction inhibits the students’ critical thinking skills. Instead, students are provided with an application and asked open-ended questions, such as: “Using the application, show me that the electric field of a sphere falls off as  $1/r^2$ ” (Figures 4–5). By not telling students to set specific numbers or parameters, they “actually have to think,” he explains. This approach gets them to ask themselves: “What more do I need to measure? What parameters do I need to sweep? How can I justify my answer?” If students get an answer wrong or do not find the information they need, Kinsey says it is a good experience for them to have to try again and grow from their mistakes.

Kinsey’s electrical engineering course is designed as a two-week tandem cycle of simulation lab and hands-on experiment bolstered through lectures and recitation. During the first week, students explore key topics from lecture through numerical simulation, and in the second week of the cycle they perform the actual experiments, which are designed to show that the concepts are not just fancy numerical tricks but real physical effects.

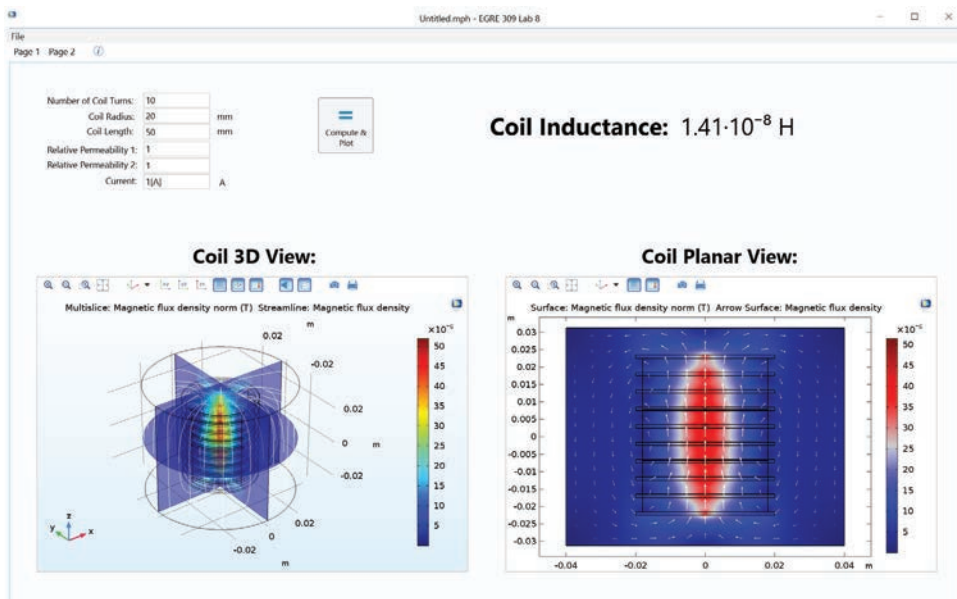


Figure 3. An application for computing coil inductance and fringe fields, with settings for adjusting the coil geometry and other set parameters.



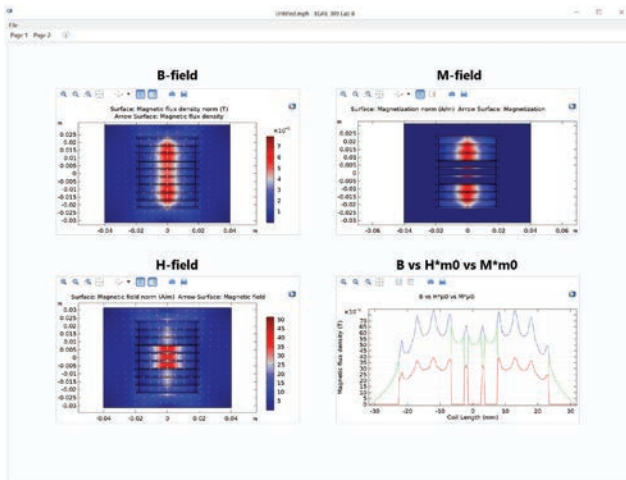


Figure 4. Results of a simulation application that students can use to solve for magnetic fields and magnetization.

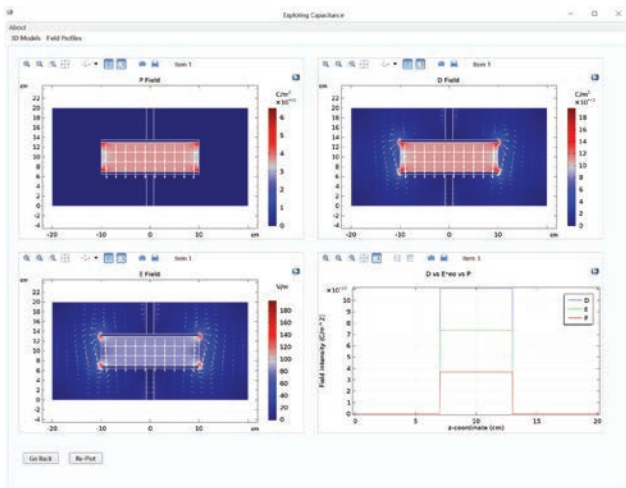


Figure 5. Simulation results of an application that calculates electric fields in dielectrics.

Here, students compare their measurements to the simulation results and discuss how things differ, as well as potential reasons why.

As with any shakeup to an educational institution, simulation applications took some time to get right and become popular. At first, Kinsey struggled to get the right mix of difficulty versus freedom in the simulation

assignments. Also, some of the students noticed that their simulations were taking a long time to solve. Kinsey saw this as a good learning opportunity to show the trade-off between accuracy and speed in simulation software — a valuable lesson for tomorrow’s engineers.

### »» PREPARING THE NEXT GENERATION OF ELECTRICAL ENGINEERS

**UNDERGRADUATE STUDENTS IN ELECTRICAL ENGINEERING** at VCU get three main takeaways from Nate Kinsey’s course. First of all, he hopes that his students are able to develop an intuition for how electric charges affect other electric charges without getting discouraged by the difficulty of the problems. “Electromagnetics is very very easy to make very very complicated,” says Kinsey. “At the heart, all you are trying to do is find forces between charges — it is as simple, but as difficult, as that.”

Second, Kinsey wants his students to leave his class as agile critical thinkers who are able to address tangential, real-world problems. This involves thinking about the rules of electromagnetics without memorizing them. For example, instead of being able to spout Gauss’ law from the top of their heads, he wants his students to ask themselves: “What does Gauss’ law tell me and what does it really mean?”

The third goal that Kinsey has for his students is that they can recognize the convergence of areas in electromagnetics on a higher level, such as how math and physics come together. For example, a student might be able to solve a line integral with no problem, but ask them to calculate the potential difference from point A to point B and they get confused, even though the problems essentially require the same mathematical steps. By moving beyond a “copy-paste” line of

thinking, students will be able to see mathematical formulas as tools. “It is like learning how to use a hammer,” says Kinsey. “You start by practicing just hitting a bunch of nails, but at some point you have to move beyond that and build something.”

### »» THE FUTURE OF ELECTROMAGNETICS ENGINEERING COURSES AT VCU

**ALWAYS LOOKING FOR NEW AND BETTER WAYS** to immerse his students in learning, Nate Kinsey has big dreams to someday incorporate virtual or augmented reality (VR, AR) into his engineering curriculum. AR or VR would be a path to give students a more tactile experience of common engineering scenarios, allowing them to basically go inside the problem and truly immerse themselves into EM fields, capacitors, and dielectrics. “It will be interesting to see how some of these emerging technologies become more cost effective in terms of teaching students, and how simulation plays into that,” Kinsey says. ©



Assistant Professor Nate Kinsey, Dept. Electrical & Computer Engineering, Virginia Commonwealth University.

# ITW USES MULTIPHYSICS SIMULATION TO COOK UP SMART MICROWAVE OVEN DESIGNS

*Engineers at ITW use multiphysics simulation and applications to analyze smart appliance designs, improving the tools kitchen professionals need to cook food faster and more evenly with solid-state, convection heating capabilities.*

By **THOMAS FORRISTER**

**WHAT MAKES AN ELECTRONIC DEVICE “smart”?** Connectivity, certainly, is a large factor, and it is now commonplace to seamlessly switch from a phone or tablet to a computer using Bluetooth, wireless internet, or 4G LTE and 5G protocols. Another sign that earns the smart (and sometimes artificial intelligence) label is a device’s computing capabilities, which help us more easily perform everyday tasks. Take the smart home concept, for example. Thanks to the broader software capabilities of many devices, consumers are now able to automate their lives and save energy costs by using robot vacuum cleaners and adjusting lighting and heating settings on a timer.

Inside the kitchen, appliances such as refrigerators, dishwashers, and microwave ovens with smart features are becoming part of daily life. Smart appliances also have a place in *professional* kitchens. By designing cutting-edge smart appliances for these professional spaces, Illinois Tool Works (ITW) Food Equipment Group, the world’s largest commercial food equipment company, is revolutionizing the way chefs cook, manage their time during service, and build menus.

## » GENERATING MICROWAVES WITH SOLID-STATE TECHNOLOGY

**ITW PROVIDES INDUSTRIAL APPLIANCE PRODUCTS** ranging from drink service refrigeration to hot holding equipment, and uses the COMSOL Multiphysics® software to build and distribute simulation applications, improving manufacturing processes and designs. One of their latest commercial offerings, IBEX (Figure 1), is a microwave and convection oven that is designed for the professional kitchen. The IBEX product includes a number of smart features and changes the way food is cooked by heating food differently than other smart combination ovens.

RF technology provides consistent performance during

the varied load conditions required for cooking. Engineers at ITW are harnessing the power of RF energy with a solid-state RF power amplifier and receiver, which directs the energy in a smarter, more uniform, and more efficient way than with a traditional magnetron — depending on the type of food or how much food it is heating. This technology achieves the quality of a combination oven, but with a rapid-cook oven time.

The targeted heating

capabilities help automate tasks for chefs and other kitchen staff. Aside from the efficiency of solid-state heating, the IBEX oven is able to use algorithms to help professionals program recipes and custom menus, as well as perform common functions as they go about their work. No smart device would be complete without the connectivity factor: The IBEX has a USB port to easily expand menus via upload or transfer.

Adding smart features helps kitchen professionals, but what about tools that aid in designing the equipment? “When trying to optimize food heating with microwave/RF energy, simulations can be used to gain an approximate understanding of what to expect,” says Christopher Hopper, sr. RF systems engineer at ITW. “Using simulation to get an idea of the heating patterns available in a solid-state oven allows for a more informed experimental setup.”

He adds that the team also saves on food and labor costs, because there



Figure 1. The IBEX solid-state microwave/convection oven by ITW.

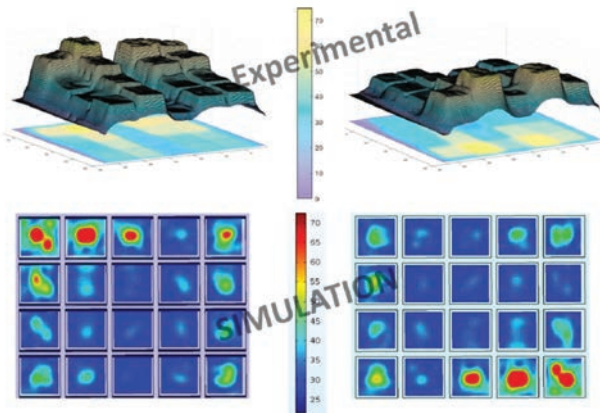


Figure 2. The improved uniformity when combining different heating patterns.

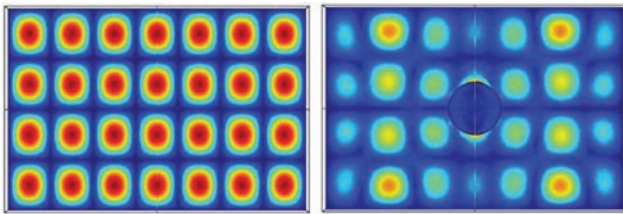


Figure 3. Electric field pattern comparison for loaded and unloaded cavity modes within a microwave oven.

are virtually no trial-and-error runs of an experiment — they can do it all ahead of time to find the optimal design for both the appliance and the related experiments.

### » WORKING SMART WITH A COMBINATION OF SIMULATION AND EXPERIMENTS

**SETTING UP EXPERIMENTS** by first using the COMSOL® software and add-on RF Module helps Hopper and his team study varying loads, uniformity, hot spots in the food, and more. Then they take advantage of LiveLink™ for MATLAB® to reduce computational time by combining parametric sweeps with complex postprocessing. Hopper finds this interfacing capability especially beneficial, as he uses the MATLAB® software extensively.

One of their important experiments considers the efficiency of the solid-state RF IBEX design. Hopper and his team were interested in how well the oven can maintain a high efficiency for different food containers that have varied volumes and load distribution, so they used simulation to help them test the containers and identify where there was room for uniformity improvement. A cubic arrangement of thin layers and an array of cylinder-shaped loads were compared. For each type of container, the solid-state oven could maintain highly efficient energy delivery to the load.

Current rapid-cook ovens on the market are unable to adjust parameters such as phase, frequency, and output power, which leads to large swings in efficiency when the

load volume, distribution, and number of items change. Alternatively, the effectiveness of convection or combi ovens depends on the surface area of the load, so increasing the number of items does not necessarily lead to an increase in time required for cooking or reheating. In contrast, the IBEX oven's efficiency stays high for a multitude of load configurations, thus combining the quality of a combi/convection oven with the speed of commercial rapid-cook ovens.

However, simply having the ability to control frequency, phase, and output power is not enough to maintain highly efficient energy delivery. Instead, they relied on the closed-loop feedback system to evaluate opportunities for improving cooking configurations. Closed-loops, as opposed to open-loop-type ovens, allow the device to learn the initial conditions, apply specialized heating configurations, and adapt to the changing physical properties of the load during cooking. By using closed loops as a form of control, engineers can feed the system's generated output back into the system. By comparing the actual output with the desired output, they can design this type of system to automatically sense and monitor the difference in output via an error signal, and thus change the loads, food properties, and other conditions to improve the cooking process.

Using feedback from the

cavity/load system, they are able to run tests to see that cooking configurations can be combined to improve uniformity and consistent energy delivery (Figure 2) while using less nominal power to achieve the same result.

From there, the team can continue to refine tests and confirm and understand the simulation results. "COMSOL Multiphysics® allows our team to perform accurate coupled electromagnetics and thermal simulations of food materials, or loads," says Hopper. "The properties of these loads change with temperature and frequency, and we have found that the software can account for these changes and provide good approximations for the heating pattern, electromagnetic field magnitude, and power loss density."

For example, when they create simulations of loaded and unloaded cavity modes, the team can see where hot spots are most likely to be located (Figure 3). Evaluating likely heating patterns and potential cavity and cookware absorption using simulation can assist them in structuring their experiments in which thermal and electromagnetic data will be collected using multiple frequencies (Figure 4). Furthermore, they can be sure that the simulation results are accurate by creating an intentional temperature difference between foods like bread and eggs.



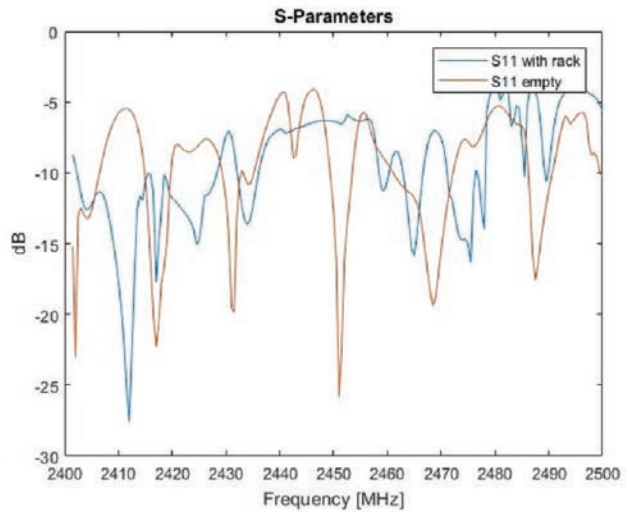
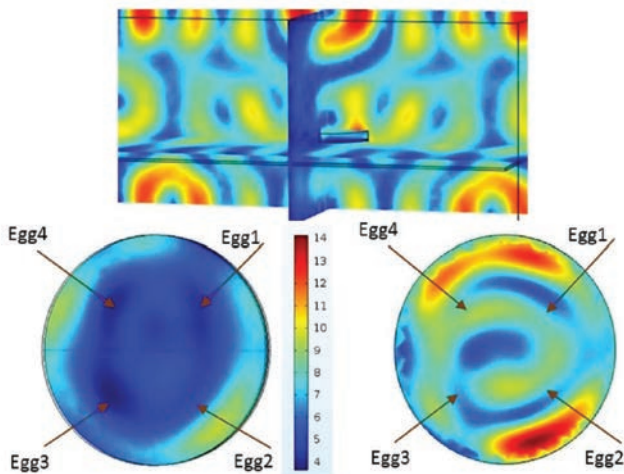


Figure 4. Left: The probe placement in the oven and eggs for collecting thermal and electromagnetic data. Right: S-parameters for an oven with and without a rack.

### » THE MORE COOKS IN THE SMART APPLIANCE DESIGN KITCHEN, THE BETTER

IN ADDITION TO MORE complex simulations, Hopper creates simulation applications so that colleagues are able to interact with the design by changing parameters such as frequency or phase response, temperature and time (in terms of recipe creation), sample size and location effects, dielectric properties, and more.

There are many advantages to deploying applications within an organization. “When working in a diverse team with different skill levels and backgrounds, I have found that tailoring applications to a person’s interests and job duties lightens the workload on the simulation experts,” says Hopper.

He also sees building simulation applications as an opportunity to educate others. In fact, some of the applications of the IBEX oven (Figure 5) have

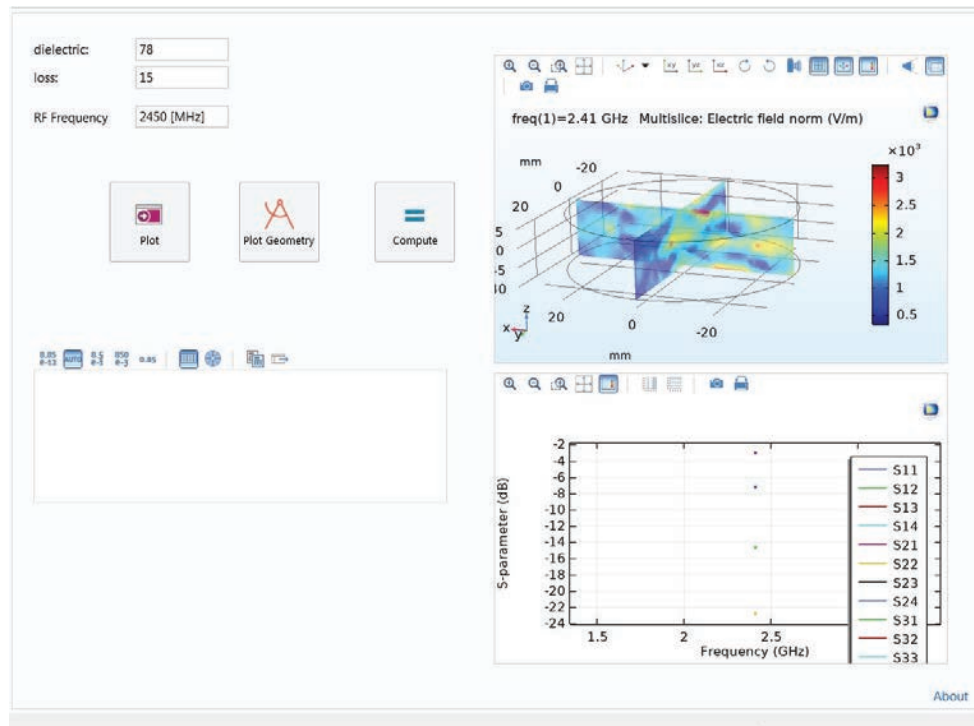


Figure 5. User interface for an IBEX oven simulation application.

been created specifically to introduce new team members and interns to the basics of wave interference, dielectric and loss factor dependencies, and RF heating.

Solid-state cooking devices present many promising advancements in the culinary arts, with targeted food heating being just one of them. By continuing to use important ingredients like simulation, applications, and postprocessing tools, engineers and manufacturers in the food equipment industry can design more efficient and reliable smart appliances for both professional and home kitchens. ☺

# SIMULATION APPLICATIONS HELP SHAPE THE DESIGN OF CAR AUDIO SYSTEMS

*Experts at HARMAN are building and distributing simulation applications to develop audio systems for cars that surpass customer expectations, improving their internal workflow in the process.*

By **THOMAS FORRISTER**

**TODAY'S LUXURY CAR MARKET** is entering uncharted territory in its ability to meet customer preferences. Vehicles are designed to offer the ultimate driving and riding experience: massaging seats; heated steering wheels; stylish interiors; roomy cabins; and, of course, electronic entertainment. Over the past decade, the importance of the audio and multimedia system in cars has grown significantly, because the car has become an elemental component of many end consumers' lifestyles. Research suggests that the car is the number one place where people listen to music, while their expectation is to get the same high-quality listening experience they are accustomed to from their home audio system. However, designing such car audio systems presents some challenges.

From a system-engineering point of view, the various hard and soft surfaces that characterize the interior design, providing style and comfort, often interfere with sound, as reflections or sound absorption might occur. The even bigger challenge, though, is that the consumer expects new applications, new features, and new listening experiences in a car to be released in a similar frequency as that of new features becoming available for smartphones. The development cycles for consumer electronics (sometimes not even six months) are much shorter than for a car (five to six years). HARMAN International, a subsidiary of Samsung Electronics Co. Ltd, uses simulation software and builds applications that improve workflows, speed up product development, and help push the boundaries of what is possible for in-car audio technology.

## » PROVIDING A PERSONALIZED IN-VEHICLE AUDIO EXPERIENCE

**EVERY DAY, CONSUMERS SPEND** a lot of time in their cars, commuting to work or driving around in urban areas. For many, the car is not just a means of transportation for getting from point A to B. They want to enjoy their ride to the fullest, getting a sense of freedom, adventure, and even escaping for a moment from their everyday routine.

To create this experience, a seamless integration between the consumer's devices and the vehicle is important, as well as the in-vehicle technologies. For instance, the different car displays, applications, and the audio system must work together in harmony. "Today's consumers are demanding personalized solutions and experiences at home, on the go, and also in the car," says François Malbos, principal engineer at

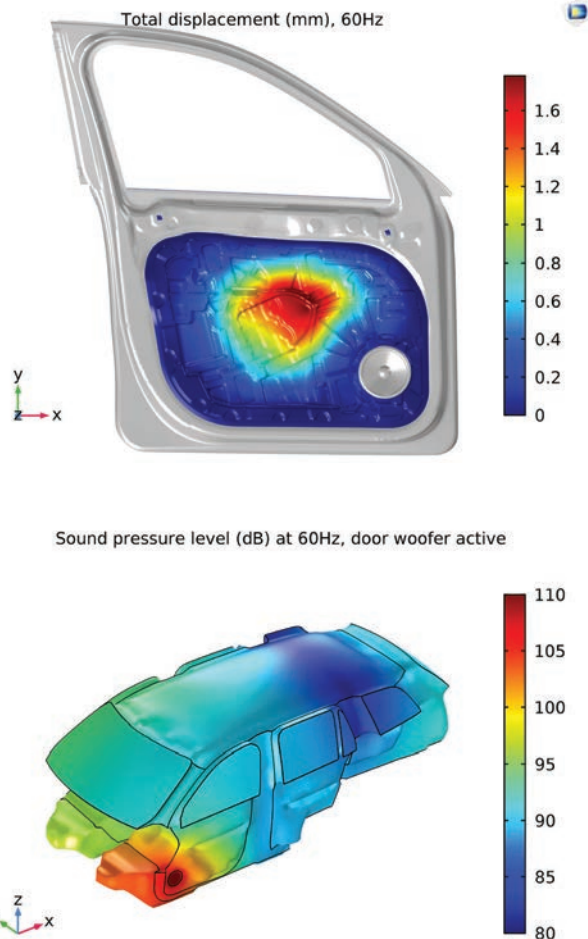


Figure 1. Top: Door stiffness analysis. Bottom: Car cabin simulation for different speaker placements.

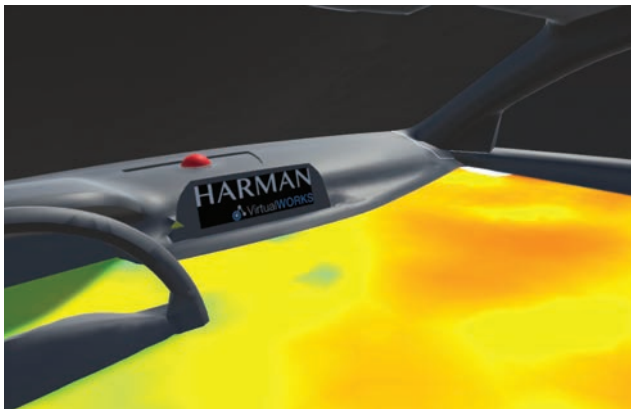
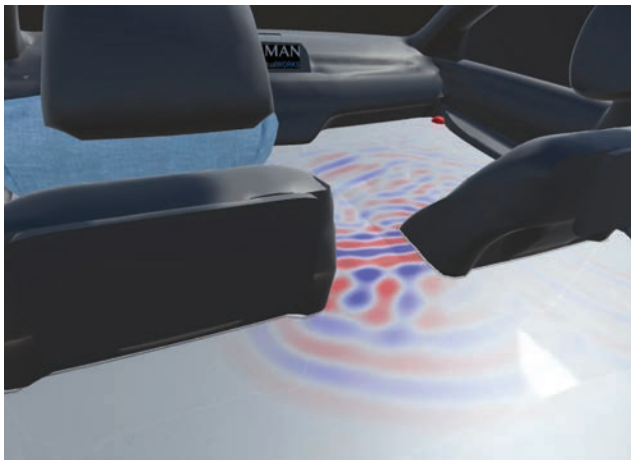


Figure 2. Acoustic sound field of the back seat (top) and right front speaker (bottom), augmented in the car environment.

HARMAN. “A luxury vehicle offers more technology, more speakers, and more sophisticated audio capabilities. On midrange vehicles, personalized features are more limited, and there might be less technology integrated. The larger and more capable the system is, the more complex and sophisticated it gets, so the interfaces must be simple and intuitive to use but also scalable.”

It was not too long ago that a vehicle’s value was measured by its mechanical performance and driving dynamics. With the emerging popularity of shared mobility and in-vehicle technology, value is now being measured by experience-per-mile. With more than seven decades at the forefront of introducing breakthrough developments in the audio industry, HARMAN is driving this shift to the experiences-per-mile paradigm, taking a consumer-centric approach in offering personalized audio experiences. One example is HARMAN’s Virtual Venues technology, which acoustically transports the listener into world-famous music venues — concert halls, stadiums, a cozy jazz club, or a sound studio — by reproducing the sound of this

particular venue based on its acoustic fingerprint. HARMAN’s Premium Communication Solutions, to name another example, leverages the latest advancements in smart audio and acoustic signal processing to personalize the sonic environment and provide clear, frustration-free communication for all vehicle occupants — whether it is with a voice assistant, someone on the other end of a phone call, or between passengers. Enhanced voice command capabilities also increase traffic safety by allowing drivers to keep their eyes on the road and their hands at the wheel when using their telephone or infotainment screens.

To balance the broad range of personalized features being built into luxury vehicles, the team of acoustics and simulation experts at HARMAN accounts for different components, acoustics, and unique configurations early on in the design system process (Figure 1). One way that these engineers “think outside the cabin” is by designing a car around the audio system, not the other way around. This helps the team adapt to customization requests at a moment’s notice. There are also several factors influencing the acoustics of a car cabin; for example, the choice of trim level, which often involves changes in the interior design or different materials being used. The tuning of the system has

to compensate for such changes in the design to not compromise the sound quality. Aspects like the stiffness of a car door can change the car’s acoustics, so the engineers would need to factor in extra bells and whistles.

The sensitivity of these audio system designs increases the complexity of product development, benchmarking of automotive solutions, and quality assurance processes. “Fortunately, HARMAN is uniquely poised to address these design challenges head-on. We can develop everything in house, from the initial design to the manufacturing stages, so that our systems are unique to market,” says Michael Strauss, senior manager of virtual product development (VPD) at HARMAN.

To facilitate their workflow, HARMAN uses the COMSOL Multiphysics® software to accelerate design and production processes, predict and validate in-cabin test results, and ultimately enhance their designs.

**» THE ROADMAP TO ENHANCED AUDIO SYSTEMS INCLUDES SIMULATION APPLICATIONS**

**SIMULATION PLAYS A LARGE ROLE** in product development at HARMAN, with the ultimate goal to perform fully virtual developments for transducers, packaging, car cabins, binaural playback, and more. Currently, the



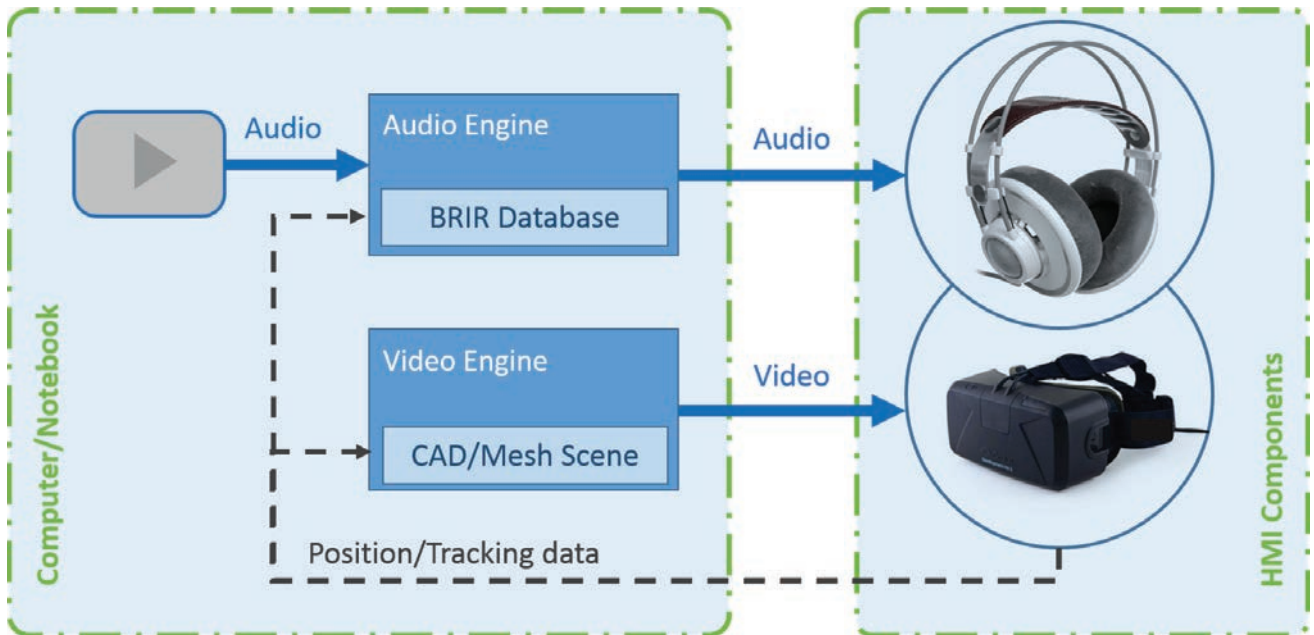


Figure 3. The VR setup at HARMAN.

VPD team combines physical experiments with numerical modeling. Moving forward, more *in situ* listening tests will be replaced with virtual tests. When virtually developing an audio system using COMSOL Multiphysics®, the HARMAN engineers can quickly make adjustments based on the different components and unique configurations of the cars being worked on. Furthermore, the results from physical car cabin tests can be compared to simulation results (Figure 2).

HARMAN has also explored ways to turn their models into digital twins and simulation applications. “All models are sensitive to changes in boundary conditions, and each simulation result is different in terms of defining interfaces between simulation and physics,” says Michal Bogdanski, project leader in VPD at HARMAN. “With an app or digital twin, we do not have to worry about it as much because we can ‘lock’ certain boundary conditions. Those parameters are crucial for physics definitions and cannot be changed by the app user. Such an approach ensures that the results are in line with the measurements.”

HARMAN simulation reference models are nowadays evaluated and proven during daily work. The VPD team established a simulation workflow to offer numerical support at any stage of a development project. With Industry 4.0 in mind, one of the objectives is to introduce simulation support and simulation applications into the legacy workflow and eventually transform it into a VPD workflow. With this application, users and simulation experts alike can work together

companywide to make design changes much earlier in the process than before. To further accelerate their workflow, Malbos created a roadmap concept that helped HARMAN design a toolbox that any application user can access. This makes the use of applications better suited for long-term resource planning. “It has really improved our workflow. Not everyone can work at the same time, so the app concept helps keep track of the project status and drive it forward with the support of a global, cross-functional team,” says Malbos. “Moreover, the app benefits other team members that are not necessarily fluent simulation experts,” Strauss adds. “This helps in two ways, as on the one hand, the designer’s workflow will become more

“Not everyone can work at the same time, so the app concept helps. It frees up resources so that the users have what they need and the simulation experts can focus on more advanced modeling. With apps, we can create a consolidated set of tools that is accessible to domain experts in my branch.”

—FRANÇOIS MALBOS, SENIOR ACOUSTICS ENGINEER, HARMAN

efficient and they will gain more insight into the product features. On the other hand, simulation experts can lift off some of their routine tasks and focus on more time- and resource-demanding projects.”

The applications are constantly being improved based on feedback from the different user groups that help identify potential bugs, or make recommendations and suggestions on how they want to use the application. To provide the most value to the user groups, suggestions are discussed on a regular basis and then selected and implemented by the team.

Building trust in the capability of virtual simulations is another important part of application democratization. Each application user needs validated material parameters, accessible and high-quality data, and a balance of both innovative solutions and a quick delivery of results required for most of the processes. Furthermore, for advanced simulations, there needs to be accurate rendition and validation as well as communication so that the users understand the measurements.

“To help build trust and transparency with users, every app comes with a validation document. When you buy a pit microphone, for example, you get a sheet with specs. This validation doc is comparable to that,” says Strauss. “The user can find a PDF and compare measurements with the app or twin.”

Using COMSOL Server™, the VPD team put together a library of validated applications that other engineers can use to predict loudspeaker performance with a wide variety of configurations and under different conditions. The transducer engineering department at HARMAN was the first to use applications, but other departments, like acoustics engineering, became interested soon after. “Acceptance is growing,” says Strauss.

Democratizing simulation via applications frees up resources — allowing the VPD team’s simulation experts to focus on other projects, like virtual reality.

### » HARMAN VIRTUALWORKS MAKES WAY FOR VIRTUAL REALITY

**HARMAN VIRTUALWORKS**, one of HARMAN’s audio development tools, has been recently expanded to include the HARMAN VirtualWORKS VR (Virtual Reality) Experience. With the interactive VR capability, customers get the same auditory experience as if they were sitting in an actual car. This is a critical advantage in the system design

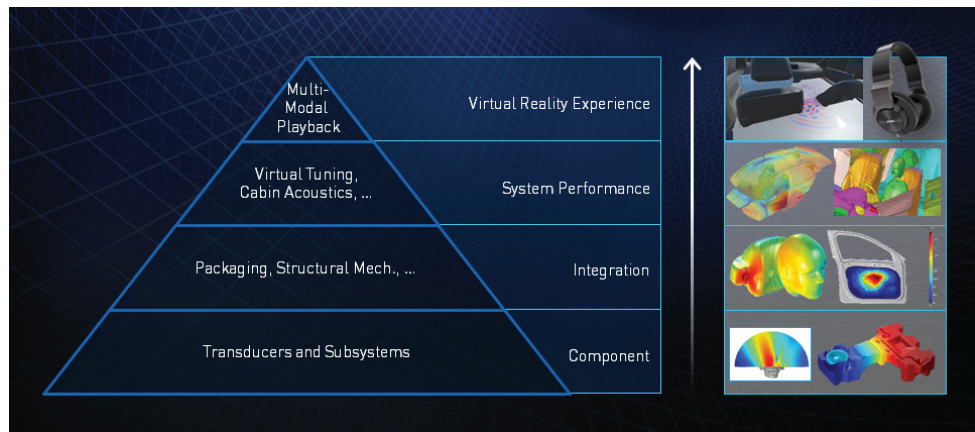


Figure 4. The numerical simulation workflow at HARMAN VirtualWORKS.

process together with the carmaker, as nonexperts could experience the performance of an audio system in a specific car without having to build a physical prototype.

“VirtualWORKS VR gives the user a chance to test the system and sound field of the cabin,” says Bogdanski. “With a VR setup and glasses, customers can ride in the car and see and hear how the audio system performs. It helps, for example, OEM interior designers to understand that their idea to maybe shape the interior differently has a certain effect on the sound performance.”

Strauss adds: “In particular, for the decision-making process internally but also with the OEM executives, it is sometimes hard to convince key stakeholders with numbers only. VirtualWORKS VR is a great instrument to illustrate and demo how the system would perform considering relevant factors and given a certain setup. And that is, like the apps

concept, another strong driver for achieving digital transformation of product development processes.”

With the head-mounted display of the VR setup, audio cues make the listening experience visible through 3D movement and high-resolution graphics. This augmented reality gives users an in-car experience and helps them, for example, visualize the acoustic sound field of speakers for different configurations (Figures 3).

New products and technologies for luxury vehicles need to be both innovative and mature, yet they also need to keep up with the growing demand for personalization. HARMAN drives development for car audio systems forward by incorporating advanced tools into their engineering workflow that help them optimize designs (Figure 4). In the near future, they may be able to go fully virtual in their development cycle before ever building a prototype. ©

# UNDERSTANDING BRILLOUIN OPTOMECHANICAL INTERACTION WITH MULTIPHYSICS MODELING

Researchers from the University of Campinas and Corning use electromagnetics and solid mechanics analysis to investigate a different kind of coupling: how photoelasticity and moving boundary effects work together to enhance or suppress Brillouin scattering in waveguides, optical fibers, and other nanophotonic structures.

By **BRIANNE CHRISTOPHER**

**OPTICAL WAVEGUIDES HAVE CHANGED** a lot since the 1970s. The waveguides were larger then, and scientists had just discovered that, especially for optical fibers, photoelastic effects were important in a design. With the introduction of the field of optomechanics, the moving boundaries of the waveguides also needed to be taken into account. Researchers realized that there was a complex interplay between both effects that could be tweaked to either increase or downplay Brillouin scattering effects in a design. Brillouin scattering is the interaction between light and the material waves in a medium, named after Léon Brillouin. A research group from the University of Campinas and Corning has been using multiphysics simulation to investigate this coupled effect and how it can be used to optimize nanophotonic structures.

## » A TALE OF TWO EFFECTS

**BRILLOUIN OPTOMECHANICAL INTERACTION** involves a coupling between two effects. First, there is the moving boundary

effect, in which just the boundary or geometry of the device is considered. In general, the moving boundary effect comes into play, for instance, when making a waveguide thinner. The photoelastic effect, on the other hand, considers the materials involved. Here, it is the refractive index in the waveguide that is modified due to elastic strain in the material.

Think about the design of a tapered optical fiber. Every time you perturb

the geometry, it affects the Brillouin optomechanical scattering occurring in the design. This is the moving boundary effect. The photoelastic effect considers the materials of which the fiber is made, which also affects the interaction.

## » TO ENHANCE OR SUPPRESS: THAT IS THE QUESTION

**WHEN ACCOUNTING FOR BRILLOUIN SCATTERING** in an optomechanical design, you often want to either enhance or suppress the effect. For example, in a regular optical fiber, Brillouin scattering is an impairment in communication systems that causes a lot of light to scatter backward instead of propagate forward. This could mean that little to no light travels through the fiber from its input source. Examples where this is an important design consideration include regular fibers and accelerometers (Figure 1).

So, when would you want to enhance Brillouin scattering effects? One example is on integrated waveguides. For instance, you can manipulate the mechanical interactions in these waveguides to create a narrow-bandwidth laser, or use Brillouin scattering to specify frequencies and wavelength channels for an exceptionally accurate filter.

At the Photonics Research Center in the University of Campinas and Corning Research & Development Corporation, professors Gustavo Wiederhecker, Paulo

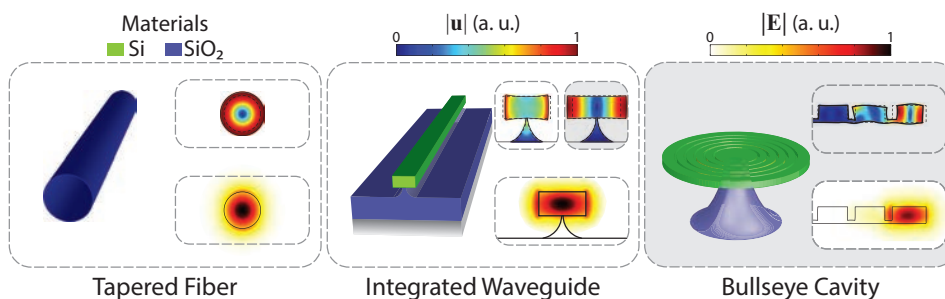


Figure 1. A COMSOL Multiphysics® model of Brillouin scattering in a nanophotonic structure, including a tapered fiber (left), integrated waveguide (center), and bulls-eye cavity (right).



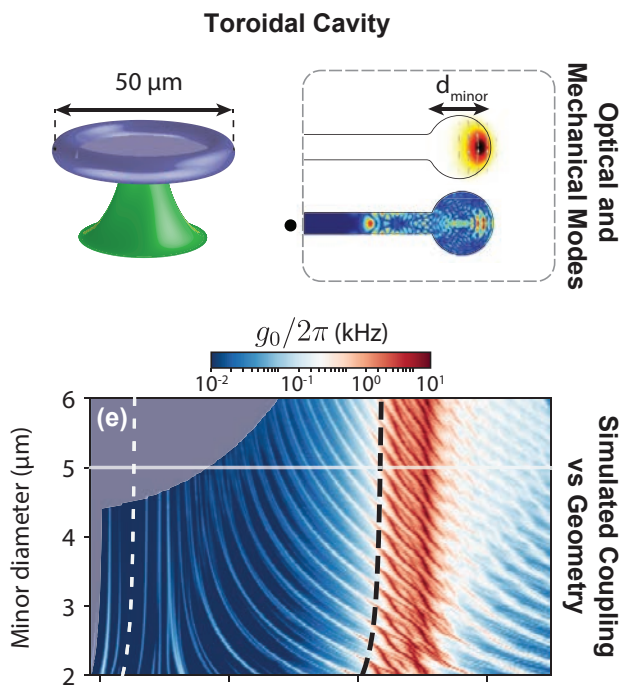


Figure 2. Top: A full example of the use of COMSOL Multiphysics. A model for the toroidal cavity is used to simulate both the optical and mechanical modes. Bottom: The coupling between these two modes is then simulated for a series of different geometries.

Dainese, and Thiago Alegre aimed to understand the coupling between boundaries and materials that causes Brillouin optomechanical interaction. One of their main goals was to understand the coupling of the photoelastic effect and moving boundary effect in nanophotonic structures to set up more effective (or, in some cases, ineffective) couplings, depending on whether the device calls for enhanced or suppressed Brillouin scattering.

### » MULTIPHYSICS SIMULATION OF BRILLOUIN OPTOMECHANICS

**HOW DID THE TEAM** from the University of Campinas gain a deeper understanding of this complex interplay? One way is through the use of multiphysics simulation. The team used the COMSOL Multiphysics® software to model the coupling of photoelastic and moving boundary effects, and the resulting Brillouin scattering, in nanophotonic structures. They started with 2D simulations that are both easy to simulate and good observatory examples. “2D models are very quick to solve,” says Alegre. They started with simple examples, like a single silica rod, and integrated both electromagnetics and solid mechanics physics into their analyses — eventually building up to fully integrated nanophotonic structures (Figure 2). The team then used their simulation results to calculate the overlap

integrals between optical and mechanical fields, one of the main aspects of Brillouin scattering. “Once you have access to these integrals, you can understand and plot optomechanical integrands, which is very helpful,” says Alegre. “COMSOL Multiphysics® is one of the only software [products] that gives us access to this type of analysis.”

The University of Campinas team found a few features of the COMSOL® software particularly useful, the first being the multiphysics capabilities. Solving for both photoelastic and moving boundary effects in the same study makes it easy to integrate them, compared to solving for one physics, exporting the results, going back and solving for the other, and so on.

Another helpful tool is the user interface (UI) in general. “Using the interface in COMSOL® is very nice,” says Alegre, adding that after running a simulation, “right away, we have the relevant coupling coefficient right in the user interface.”

“Using the interface in COMSOL® is very nice. Right away, we have the relevant coupling coefficient right in the user interface.”

—THIAGO ALEGRE,  
UNIVERSITY OF  
CAMPINAS

The team also enjoys that postprocessing features are available directly in the UI. “With any other software, you have to write postprocessing code along with all of the integrals,” says Alegre. COMSOL Multiphysics, on the other hand, includes postprocessing as part of the modeling workflow.

### » GUIDING LIGHT TOWARD FUTURE RESEARCH

**AS FOR FUTURE RESEARCH**, the University of Campinas team plans to explore the effect of different materials on the optomechanical coupling as well as look into the hybrid integration of materials in nanophotonics. They also plan to investigate different geometries for the design of better waveguides, seeking good candidates for Brillouin scattering devices.

In addition, as the home base of their research is an academic institution, the team is also thinking about how to inspire and involve the next generation of nanophotonics researchers, namely, their students. To do so, the team created a data repository to go along with their Brillouin scattering project, “Brillouin optomechanics in nanophonic structures,” APL Photonics 4, 071101 (2019). The repository includes their models and codes, which students can use to change the geometry of a waveguide or cavity. By seeing Brillouin optomechanical interaction in real time, students can potentially develop some bright ideas of their own. ©

# OPTIMIZING A GIS FOR HIGH-VOLTAGE DISTRIBUTION WITH MULTIPHYSICS SIMULATION

*Using the COMSOL Multiphysics® simulation software, Pinggao Group accelerated the development of a gas-insulated, metal-enclosed switchgear (GIS) and significantly reduced the development cost. Further, they built a simulation application that has streamlined the collaboration of cross-functional teams in the organization.*

By **YUHANG QIN** with **DR. BO ZHANG**



Figure 1. 1100-kV GIS. Image courtesy of Pinggao Group.

**INCREASING DEMANDS FOR POWER ENERGY** have expanded the size of the electric power grid, requiring more electrical equipment to be used. Transformer substations are an important part of the power system, which has a direct impact on people's everyday life. This substation's main function is to transform the voltage as well as to receive and distribute the electrical energy. To minimize power losses in transmission lines, power plants use a transformer substation to raise the voltage before sending it over long distances. When it reaches its destination, the voltage must be reduced at another transformer substation before distribution to ensure the safety of consumers.

A traditional transformer substation includes a large

number of electrical components, which are arranged in different rooms according to their functions. Since air is used as the insulating medium, components in the substation are placed far apart from each other to ensure that the clearance space meets the insulation requirements.

Therefore, a very large footprint is required for this kind of power substation. In addition, many components in the substation are exposed to the harsh environment, which incurs a heavy maintenance workload.

The gas-insulated, metal-enclosed switchgear (GIS, shown in Figure 1), a modern type of high-voltage distribution device, could help address these issues. With an enhanced design and special insulation gas, the GIS compactly integrates all of the components in the substation except transformers. Compared to traditional substations, the GIS has many advantages, such as a smaller ecological footprint, reduced overall size, higher reliability, and fewer maintenance requirements, making it widely used in recent years.

Although a GIS is generally more reliable than a conventional substation, the electric charges accumulated on the surfaces of solid insulation parts, such as the rods, may lead to insulation failure after long-term operations and cause severe safety issues. However, all of the components are enclosed inside of the system, so it is very difficult to allocate and repair the malfunction of the GIS, which makes the fault invisible. Pinggao Group, a subsidiary of the State Grid Corporation of China, is using multiphysics simulation to investigate possible solutions in order to develop an efficient, stable, and reliable GIS.

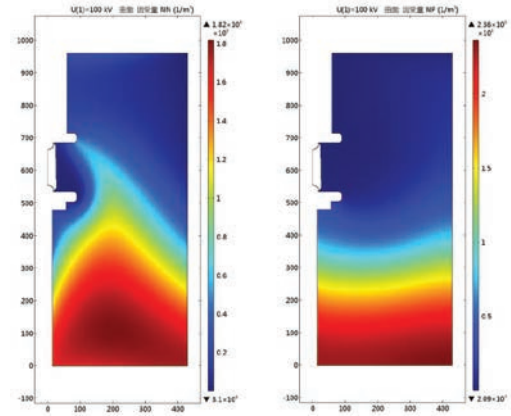
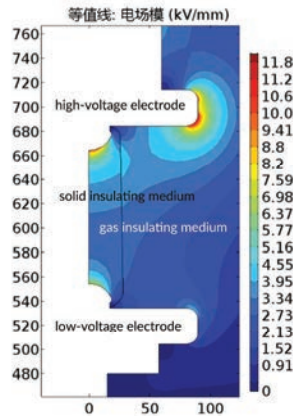
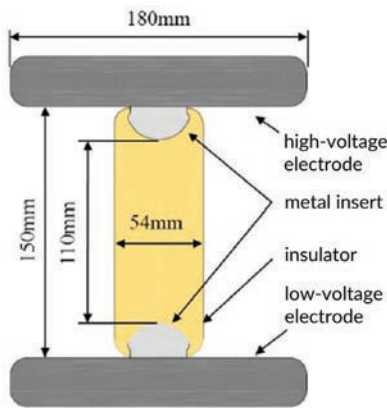


Figure 2. Left: Cross-sectional view of the geometry for the GIS insulation system component. Right: DC electric field distribution in the insulator and its surroundings when 100 kV is applied.

Figure 3. The distribution of the negative (left) and positive (right) ions on the GIS insulation system component.

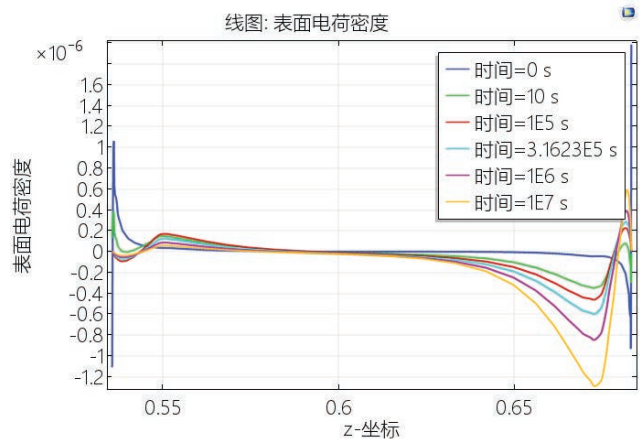
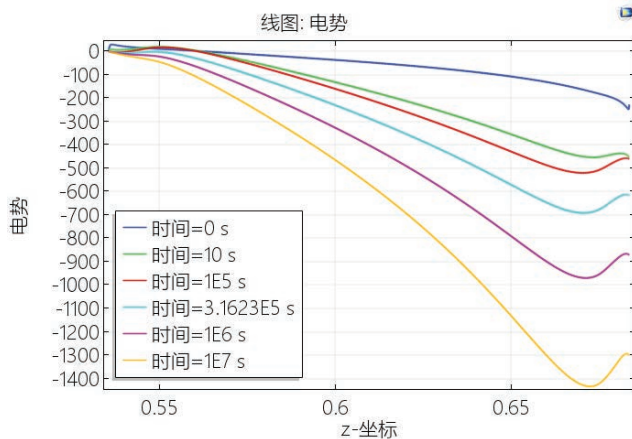


Figure 4. Surface potential (left) and charge density (right) of the insulator as a function of time.

## » ANALYZING GIS INSULATION FAILURE

A GIS IS MUCH SMALLER than traditional substations due to its better insulation. All components of the system are enclosed in a grounded metal shell that is filled with sulfur hexafluoride ( $\text{SF}_6$ ), a synthetic inert gas, for insulation. The reason for using this gas is that its insulation and arc-extinguishing capabilities are much higher than air. Therefore, the distance between components inside the GIS can be significantly reduced.

“Using COMSOL®, [we can] solve for potential issues faster with fewer iterations and significantly reduce the testing cost.”

—BO ZHANG, SENIOR ENGINEER, PINGGAO GROUP

When a GIS runs for a long time, electric charges will accumulate at the interface between the insulation gas and solid insulation parts. Once the electric charge reaches a certain level, high voltages will build up and break down the gas insulation between different parts. An electric discharge also releases along the surface of the solid insulator. After a partial discharge, the ionized insulating gas and metal parts will produce

decomposed particles, resulting in the failure of the insulation components.

Insulation failure is a common issue, restricting the engineering uses of the GIS. This mechanism of failure is a complex problem related to the coupling of multiple physical phenomena, including electromagnetics, heat transfer, and structural mechanics. In addition, using experiments to investigate this problem is both difficult and costly,



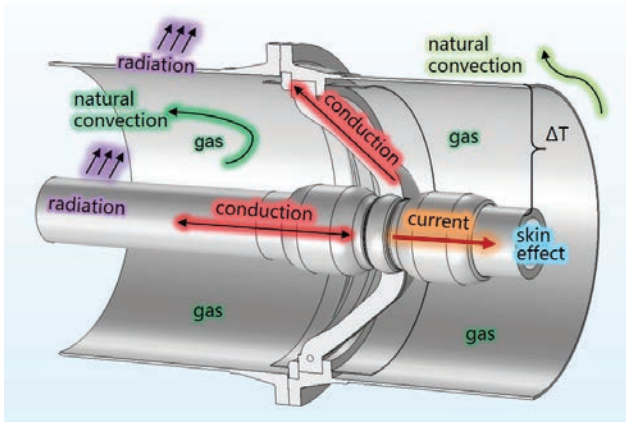


Figure 5. Schematic of the heat transfer of the bus in the GIS design.

since building a GIS prototype is very expensive and several experiments are needed to discover the real cause of the problem. To quickly diagnose potential issues and reduce the cost of tests, engineers at Pinggao Group used the software to analyze the insulation failure of GIS equipment. Dr. Bo Zhang, senior engineer at Pinggao Group, explains: “Using COMSOL®, [we can] solve for potential issues faster with fewer iterations and significantly reduce the testing cost. For example, in our 1100-kV bushing test, reducing one test could save us 1.5 million USD.”

The engineers in Pinggao Group created a numerical

model, calculating the electric field distribution of the gas-solid insulation system in the GIS design under DC voltage as well as the surface charge accumulation. The model consists of a high-voltage electrode, low-voltage electrode, insulator, and metal insert (Figure 2, left). These components are surrounded by SF<sub>6</sub> gas with the absolute pressure at 0.4 MPa, and 100 kV is applied on the high-voltage electrode. The electric field distribution is obtained, as shown in Figure 2 (right).

The charge density of the solid insulating medium depends on the dielectric constant and conductivity of the material. The conductivity in the gas region is highly nonlinear because positive and negative ions will

drift in the gas under the electric field and diffuse due to the concentration gradient. An electric charge will accumulate at the gas-solid interface, where the conductivity and dielectric constant is discontinuous. The change in the ion distribution will further cause the distortion of the original electric field and thus make the insulator weaker under the DC electric field.

Dr. Zhang and his team simulated the concentration distribution of the positive and negative ions in the insulator (Figure 3). They also obtained the particle concentration distribution at different intervals within the gas region and the nonuniform spatial distribution of the gas conductivity, which is helpful for improving the insulation effect of the system.

Based on the results of the conductivity simulation, the engineers determined the surface potential and surface charge as a function of applied pressure (Figure 4). It can be seen that the charge accumulation increases over time, and it reaches a steady state after approximately 10<sup>7</sup> seconds (about 3000 hours).

To improve the insulation design of the GIS, the engineers also investigated the factors that might affect the production rate and distribution of the gas ions (such as the volume of the solid insulation) as well as the polarity and distribution of the surface-accumulated charge. Based on the simulation results,



Figure 6. Simulation application for analyzing the GIS bus temperature rise.

“The simulation application greatly enhances the inheritance of experience and knowledge sharing. Now, the whole organization can benefit from the advantages provided by simulation analysis.”

—BO ZHANG, SENIOR ENGINEER, PINGGAO GROUP

Dr. Zhang and his team were able to optimize the geometry and material properties of the insulators, verify the design changes to reduce the electric field in a certain region, and minimize the accumulation of the surface charge.

#### » OPTIMIZING A GIS DESIGN USING MULTIPHYSICS SIMULATION

TEMPERATURE CONTROL is another important issue that needs to be accounted for when optimizing a GIS. During the operation of GIS equipment, a substantial amount of Joule heat is generated when the electric current flows through the bus (a simple barrier used for further insulation), which causes the internal temperature to rise and may lead to the failure of various internal components due to overheating. Therefore, controlling the temperature rise and heat dissipation of the bus is an effective way to improve GIS equipment performance.

Dr. Zhang and the engineering team created a multiphysics model in the software to analyze the temperature variation of the bus in the GIS, shown in Figure 5. The model calculates

the heat dissipation through different ways of heat transfer, such as conduction, convection, and radiation. The steady state of the internal temperature distribution of the equipment is estimated according to the resistive heating and the heat dissipation of the equipment.

The simulation results of the temperature rise helped the development team to accurately estimate the temperature rise of the product while designing the GIS. In addition, they were able to optimize various design parameters, such as the material type, product size, and structural layout, in order to avoid various overheating faults that might be caused by the temperature rise of the equipment.

#### » ORGANIZATIONAL BENEFITS OF SIMULATION APPLICATIONS

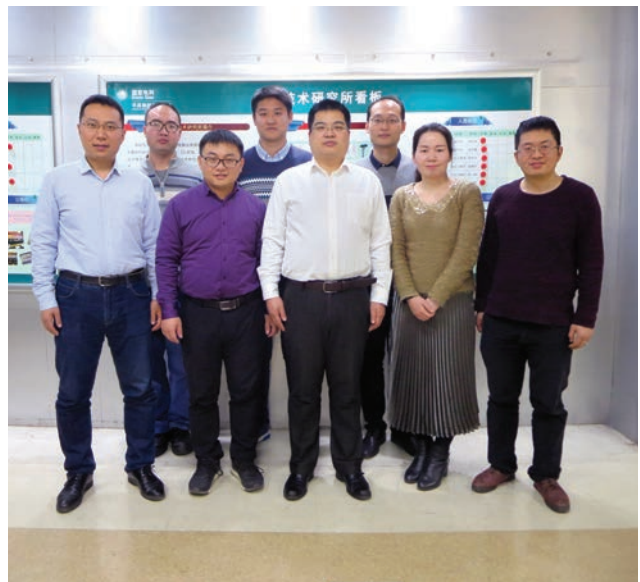
THE DESIGNERS OF GIS products at Pinggao often need to change design parameters in the development process. They used to have to go to the simulation engineers on the development team to test their ideas, even to change simple parameters. The simulation engineer then has to

adjust the parameters of the underlying model for each requirement, which results in a lot of repetitive work and project delays.

To allow more people in the organization to benefit from simulation, the engineers at Pinggao Group used the Application Builder in the COMSOL® software to quickly convert the GIS temperature rise model into a simulation application, shown in Figure 6. Therefore, all product designers can conveniently calculate the power and temperature variations by simply typing in parameters in the application and optimize the product based on the simulation results. Product designers, design engineers, and operation staff at Pinggao Group can now develop and maintain the GIS on a common platform with this

easy-to-use application. The accessibility of simulation makes it easier for different departments within the organization to collaborate with each other. “The simulation application greatly enhances the inheritance of experience and knowledge sharing. Now, the whole organization can benefit from the advantages provided by simulation analysis,” Dr. Zhang explains.

Pinggao Group is currently developing the high-voltage switchgear simulation application based on cloud computing. The simulation team hopes to help product designers develop GIS products with better performance by conducting an in-depth investigation of high-voltage switchgears with multiphysics simulation. ©



The simulation team at Pinggao Group Technology Center, from left to right: Hao Zhang, Gang Wang, Zhijun Wang, Yapei Liu, Yujing Guo, Bo Zhang, Xiangyu Hao, and Yongqi Yao.

# STRUCTURAL-THERMAL-OPTICAL PERFORMANCE ANALYSIS: THE QUINTESSENTIAL MULTIPHYSICS MODEL

*Performing a structural-thermal-optical performance (STOP) analysis presents unique challenges that can be addressed in COMSOL Multiphysics®, as this model of a Petzval lens exemplifies.*

By **CHRISTOPHER BOUCHER**

**NUMERICAL SIMULATION HAS** become an indispensable tool for the design, optimization, and diagnostics of optical systems. A high-fidelity computational model can greatly cut down the amount of time and effort spent on prototyping and related experimental work.

The task of setting up a high-fidelity model becomes more challenging for cameras, telescopes, spectrometers, and similar devices operating in extreme environments. This challenge is perhaps most daunting for optical systems on spacecraft. The environment of space can subject equipment to extreme temperature gradients, from the cold vacuum of space itself to the overwhelming heat of the Sun, and everything in between.

Changes in temperature directly affect the performance of an optical system because most real-world materials have temperature-dependent refractive indices. In addition, thermal stresses combine with other applied loads to cause deformations that can further degrade performance. Here, we will explore some of the unique challenges of using simulation software for coupled structural-thermal-optical performance analysis, or simply STOP analysis.

## » A SIMPLE PETZVAL LENS SYSTEM

**LET US FIRST CONSIDER** a Petzval lens system at uniform temperature and with no applied forces. The Petzval lens consists of front and rear lens groups followed by a field-flattening lens. Collimated rays propagate from the left (green) toward an image plane at the right (red) (Figure 1).

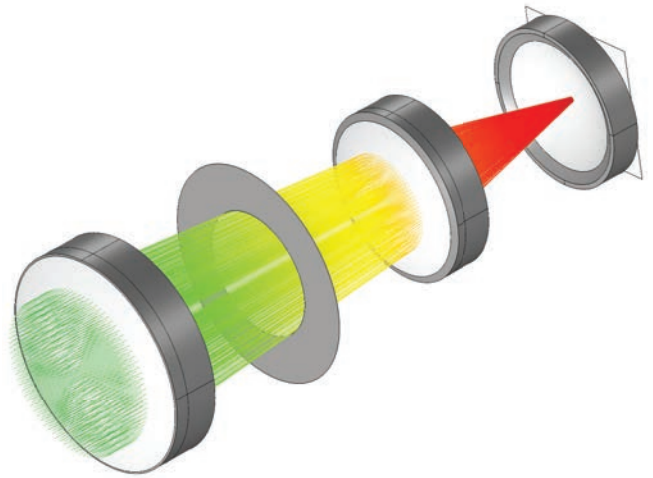


Figure 1. Ray diagram of a Petzval lens.

Also shown are the image plane and an aperture stop between the lens groups.

Now suppose we take this simple lens system and insert it into a real-world assembly with stresses and temperature gradients. To perform an accurate STOP analysis, we must not only model the lenses themselves but also the surrounding apparatus. This requires us to consider the following questions:

- How are the lenses mounted?
- What are the boundary conditions for the structural analysis?
- What are the boundary conditions on temperature?

To demonstrate this workflow, we modified the previous Petzval lens geometry by mounting the lenses in a barrel inside a thermovacuum chamber, which aims to mimic the environment of space by regulating both pressure and temperature. A diagram showing a cross section of the lenses, barrel,

mount, and chamber is shown in Figure 2. Such a chamber might be used to test a camera or telescope at a low temperature in a controlled laboratory environment before launching it into space.

The entire barrel is contained within the thermal shroud boundaries (1) which are, in this example, held at a low fixed temperature of  $-50^{\circ}\text{C}$ , perhaps by pumping a liquefied gas through the walls. Radiation then enters the thermal shroud through an exterior vacuum window (2) and additional thermal window (3). This extra thermal window is in place to help regulate the temperature gradient in the lenses. The ambient surroundings outside the thermal shroud are at the laboratory temperature of  $25^{\circ}\text{C}$ .

Also shown are the lens groups (4, 5, and 6); the image plane (7); barrel (8); and a rigid support (9) where the displacement is assumed to be zero. The quantities being



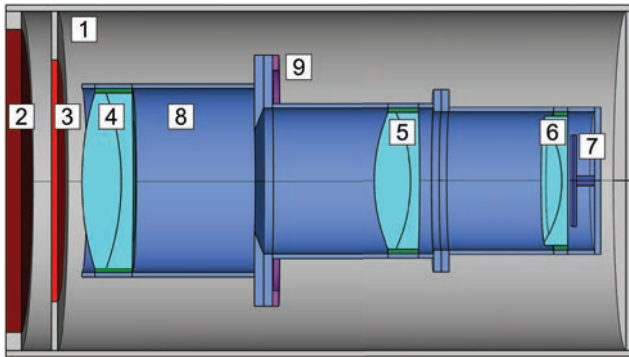


Figure 2. Schematic of the Petzval lens assembly with added barrel and thermovacuum chamber.

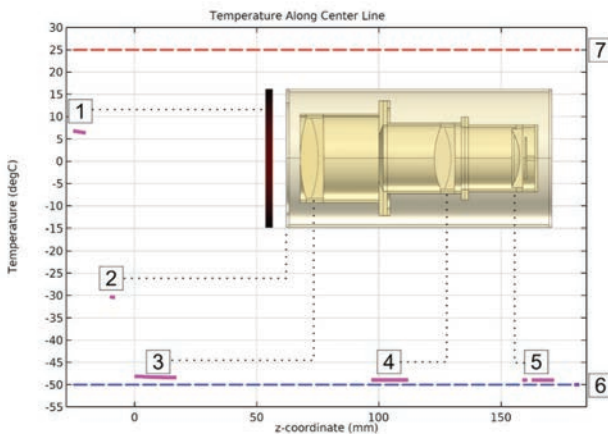


Figure 3. The temperature in a cross section of the lenses, barrel, and thermal shroud.

solved for include the temperature throughout the lenses, barrel, and windows; the structural displacement in the lenses and barrel; and the ray paths through the system.

### » STOP ANALYSIS REQUIRES A COMBINATION OF NUMERICAL METHODS

FROM A MATHEMATICAL POINT OF VIEW, STOP analysis is uniquely challenging because the structural and thermal models require a different type of numerical approach compared to the optical model. The most robust and flexible approach to structural and thermal simulation is the finite element method (FEM). This method involves representing the geometry as a number of discrete numerical cells, or elements, and then approximating the strain and temperature in each element as piecewise functions defined on that element.

The optical performance is best predicted using a ray tracing approach. This is because FEM implementations of optical simulation usually require a mesh fine enough to resolve individual wavelengths, and this requirement is not practical for optical frequencies.

If the structural and thermal simulations are performed on a discretized representation of the geometry using FEM, and the optical simulation uses a ray tracing approach, how do we factor in the effect of structural deformation and temperature change on the optical performance? The COMSOL Multiphysics simulation software provides a seamless integration of these different numerical methods within an all-encompassing user interface, which also includes tools for geometry setup, meshing, solvers, postprocessing, and much more. As of COMSOL Multiphysics® version 5.4, there are dedicated tools for coupled STOP analysis and several examples.

### » ASSUMPTIONS FOR THERMAL SIMULATION

THE RADIATION ENTERING through the vacuum window and thermal window has a broad spectral range. At the optical frequencies, we assume that light gets refracted by the lens; but in the infrared regime, we assume that the lenses are opaque, meaning that they absorb the incoming radiation and then reemit it diffusely in all directions. Therefore, the radiation entering the chamber actually requires two different modeling approaches to be used in tandem. In the optical regime, we use ray tracing to observe the focusing behavior, while in the infrared regime, we model the thermal radiation in tandem with conductive transport through the

lenses and barrel assembly.

Using multiphysics simulation, the most accurate way to model thermal radiation (assuming ideal diffuse surfaces) is with the radiosity method. Thus the thermal model combines the radiosity method to model surface-to-surface radiation with the finite element method to model conductive transport through solid bodies. There is no convective transport to worry about because the lenses and barrel are in a vacuum.

### » RAY TRACING IN A DEFORMED GEOMETRY

THE RAY TRACING ALGORITHM automatically accounts for thermo-optic dispersion and optical stress. The rays interact with a mesh representation of the boundaries in a geometry rather than their analytic representation, and this makes it very convenient to model reflection and refraction by a deformed geometry, because the displacement field in each boundary element is known from the FEM simulation. In other words, the same mesh is used to assign degrees of freedom in a FEM calculation of the structural displacement and temperature, and to query the position and normal direction at ray-boundary interactions.

To account for thermo-optic dispersion, the rays can query the temperature field at any location within a lens. This temperature and the ray's vacuum wavelength are used to compute the refractive

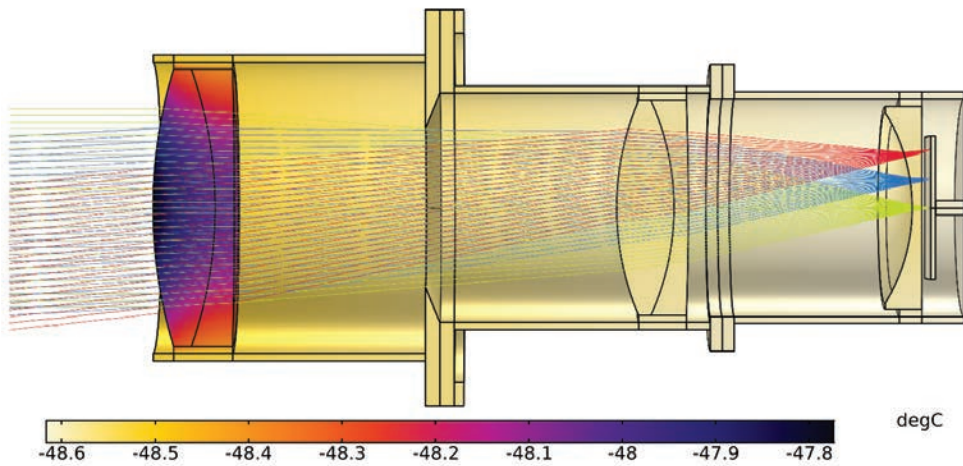


Figure 4. Ray diagram of the heated Petzval lens assembly and barrel for three field angles.

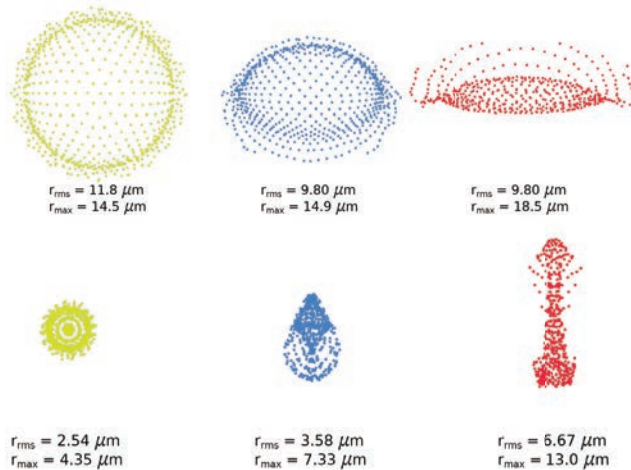


Figure 5. Spot diagrams for the Petzval lens system in the thermovacuum chamber (top) and at room temperature (bottom).

index encountered by each ray.

Altogether, multiphysics modeling enables us to simultaneously do the following:

- Model conductive heat transfer and structural deformation using FEM,
- Model radiative heat transfer between diffuse gray bodies using the radiosity method, and
- Trace light rays through the heated and deformed lens system.

### » THERMAL SIMULATION RESULTS

THE RESULTS OF THE thermal model demonstrate the importance of using an additional thermal window to regulate temperature in the Petzval lens assembly. Figure 3 shows the temperature in a cross section of the lenses, barrel, and

thermal shroud. Because the temperature change within the barrel is rather hard to see, the temperature is also plotted as a 1D graph along the center line of the assembly.

The outer window of the vacuum chamber (1) is the warmest because it is exposed to radiative heat transfer by the ambient surroundings (7). The thermal window (2) is about  $-30^{\circ}\text{C}$ , much colder than the surroundings but still significantly warmer than the thermal shroud (6). The lens groups (3, 4, and 5) are all within  $2^{\circ}\text{C}$  of the thermal shroud.

This aptly demonstrates the need for a thermal window; without it, the temperature difference among the lens groups might be as high as  $20^{\circ}\text{C}$ , rather than  $2^{\circ}\text{C}$ , leading to significantly greater thermal stress. This is similar to the rationale behind using double-pane windows for room insulation.

### » RAY TRACING RESULTS

#### RAYS WERE TRACED

through the thermally deformed system for three different field angles. The trajectories are shown in Figure 4; the temperature field in the lenses and barrel is also shown.

A convenient way to compare the optical performance in this thermovacuum chamber and at room temperature ( $20^{\circ}\text{C}$ ) is by creating spot diagrams, which show the distribution of rays in the image plane. Spot diagrams for each of the three field angles are shown in Figure 5.

From the spot diagrams, it is more obvious that the temperature change has a significant effect on optical performance; not only are the spots visibly different, but their root mean square (RMS) spot sizes differ significantly.

### » LOOKING FORWARD

#### USING MULTIPHYSICS

SIMULATION, we are able to conduct a coupled STOP analysis within a single, self-contained simulation software package. Furthermore, the means for deploying numerical models to a larger user base have improved rapidly in recent years. The democratization of simulation, together with the ease-of-use of modern STOP analysis tools, suggests that the use of simulation in optical design will only become more essential and more widespread in the future. ©

# LIGHTING THE WAY FOR IMPROVED SYNCHROTRON VACUUM CHAMBERS AT RADIASOFT

*RadiaSoft and Argonne National Laboratory are working together to enhance the brightness in synchrotrons. They created a user-friendly simulation tool to streamline the design of synchrotron vacuum chambers, advancing particle accelerator research in the process.*

By **BRIDGET PAULUS**

A **SYNCHROTRON LIGHT SOURCE** is a type of particle accelerator used for scientific research across a wide variety of disciplines. A beam of electrons is accelerated to an extremely high (ultrarelativistic) speed using an accelerator chain composed of a linear accelerator (LINAC) and a circular booster synchrotron. Once injected into the storage ring, the beam is directed in a circular orbit by powerful magnets, causing the release of X-ray radiation tangential to the curved trajectory of the electrons. The energy lost to the radiation must be restored each revolution with radiofrequency cavities placed along the ring. Many beamlines branch off from the synchrotron, each containing a unique sequence of optical elements that modify the X-rays in accordance with the requirements of a given experiment and sample.

The radiation from synchrotrons enables scientists to peer into different materials and chemical processes, acting as a “super microscope”. For instance, synchrotrons can be used to examine the internal structure of crystals, nondestructively test archaeological findings (like ancient pottery), and study complex proteins. However, while the research may vary, one requirement is the same in every case: The beam needs to be as intense as possible.

To foster more advanced research, many facilities are planning to enhance the brightness of synchrotron beams, and the Advanced Photon Source (Figure 1) at Argonne National Laboratory (ANL) is no exception. However, accomplishing this task is quite challenging. Nicholas Goldring of RadiaSoft LLC, a company that designs particle accelerators using simulation, describes the process of improving an accelerator as an “inherently multiphysics problem,” since the device involves vacuum science, magnetic fields, heat, and particle motion. Even optimizing individual parts can be difficult. For instance, the vacuum chambers, which the electron beam travels through, involve

complex phenomena that all interact with and affect each other, making for a long and complex development process.

To create a design tool for vacuum chambers that can account for all of their effects, RadiaSoft and ANL teamed up, with support from the United States Department of Energy. Using

the COMSOL® software, the group developed a comprehensive multiphysics model of a synchrotron vacuum chamber. Adding another step to their modeling workflow, the researchers created an easy-to-use graphical interface for the model, a simulation application, which they distribute to particle accelerator facilities around the world.

## » MODELING THE MULTIPHYSICS OF VACUUM CHAMBERS

### VACUUM CHAMBERS

(Figure 2) are critical to a particle accelerator’s effectiveness. According to Goldring, the chambers must maintain a pressure in the nanotorr region to let the electron beam propagate unimpeded. Higher pressure means there are too many gas particles, which causes scattering and leads to beam loss. Accurately

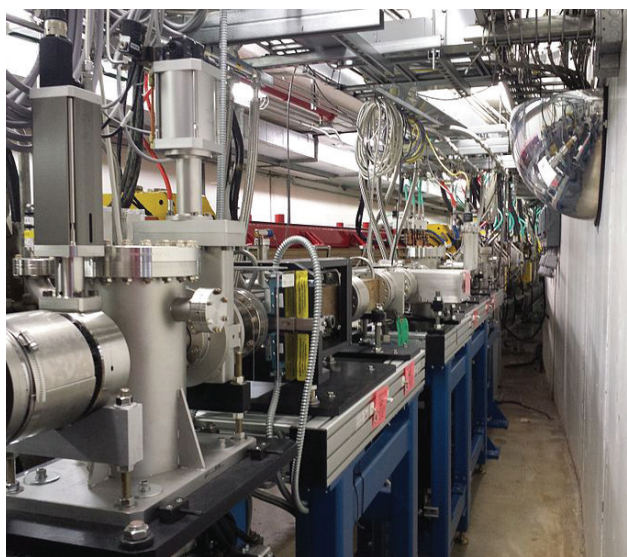


Figure 1. The Advanced Photon Source (APS), a synchrotron at Argonne National Laboratory.



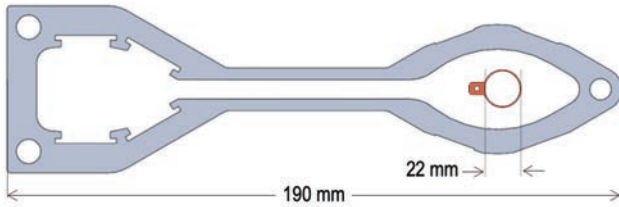


Figure 2. Cross section of a 2D axisymmetric vacuum chamber geometry. This design is used for the APS and needs to be downsized from 190 mm to 22 mm for an upgrade.

accounting for these scenarios and effects like high temperatures, synchrotron radiation, outgassing, and desorption can get complicated — especially when all of these phenomena affect each other.

To develop vacuum chambers, particle accelerator engineers often rely on simulation software. However, Goldring pointed out that the traditional tools are highly specialized and typically simulate only one physical process. Plus, since these software packages also tend to have very little (if any) documentation, there is a steep learning curve for actually using them, creating a siloed work environment: One engineer excels in running ray tracing analyses, another specializes in gas flow and pressure calculations, and so on. Each engineer tests specific changes in the design, passing the results back and forth for every iteration.

For a streamlined process, RadiaSoft turned to COMSOL Multiphysics® and the add-on Ray Optics Module and Molecular Flow Module. “COMSOL drew our interest due to its multiphysics capabilities. It can solve all of the important calculations that a vacuum engineer will need to perform in a simpler manner,” says Goldring. He added that obscure and complex simulations can be done more easily and all in one place.

Goldring says that compared to other software, COMSOL Multiphysics offers additional benefits, including better data analysis tools, solver types, and more. “What is nice about COMSOL is that we can model multiple gas species at a time,” says Goldring about molecular flow simulations.

Standard accelerator simulation software can typically only simulate one species at a time. Plus, it is possible to replicate the functionality of other specialized software in COMSOL and get results that are just as accurate. Goldring compared results from a variety of models to analogous models created with software dedicated to free molecular flow in vacuum chambers and found good agreement between the two.

### » THE POWER OF PARTICLE ACCELERATOR SIMULATION APPLICATIONS

RADIASOFT AND ANL used the Application Builder in COMSOL Multiphysics to add a user-friendly interface to their vacuum chamber model, making it easier to analyze how the propagation of synchrotron radiation affects the design. By creating an application, “people do not have to go into the model itself to figure out how to set up the ray tracing, which is complicated,” says Goldring. Instead, they can just define where the beam starts and what the magnets look like;

import a CAD geometry; and find the pressure, temperature, and more.

The simulation application (Figure 3) solves a true multiphysics problem: analyzing the propagation of synchrotron radiation using ray optics simulation, then observing the effect of outgassing on the vacuum chamber pressure as X-rays hit the chamber walls.

Application users can define parameters such as the electron beam source, the beam’s energy and arc length, and the strength of the dipole magnets. After the user clicks Compute, the application visualizes the rays’ path and power as well as the temperature in the chamber. For particle accelerator engineers, these results provide valuable insight into the radiation power distribution of the high-energy beam at different points, enabling them to examine how the distribution changes as the beam travels within the synchrotron.

The application can also be used to determine the amount of desorption from the walls of a vacuum chamber. (Figure 4) In the chamber, the high-energy particle beam produces synchrotron radiation that hits the chamber walls, causing gas molecules to be kicked out, thus altering the pressure within the vacuum. However, maintaining the vacuum pressure is critical to the lifetime of the beam. To avoid disabling the beam, it is important to know just how much gas leaves the walls to enter the chamber.

The simulation application (Figure 4) makes this calculation simple, determining the desorbed gas for various

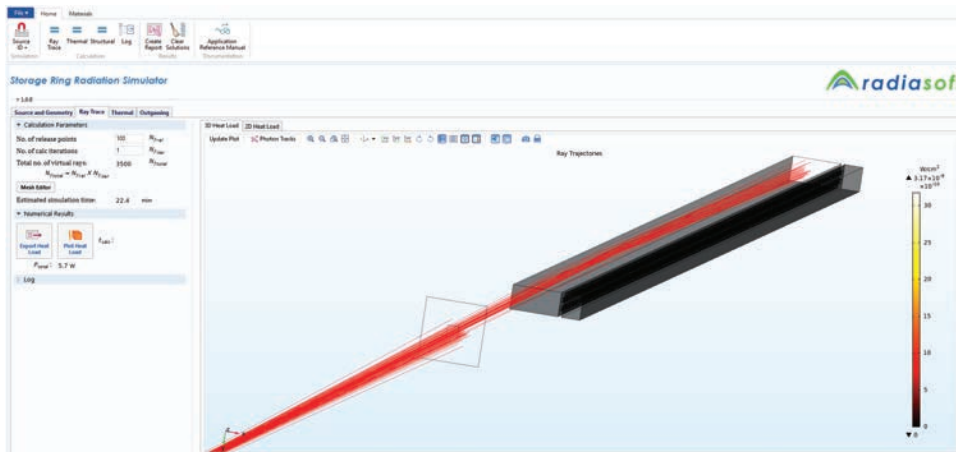


Figure 3. Simulation application of synchrotron radiation ray tracing in a vacuum chamber.

species by combining a ray tracing simulation with equations that convert the photon flux density into the accumulated number of rays on the wall. This incident energy flux is then used to set boundary conditions in a free molecular flow simulation to predict the density and pressure of outgassed molecules in the chamber. As Goldring says: “The tool lets people import the flux profile and then autocomputes how much gas gets out according to that and material properties.” Simulation applications can also include multiple gas species simultaneously.

**» PROMOTING COLLABORATION AND GETTING FEEDBACK**

**AFTER BUILDING A SIMULATION APPLICATION,** Goldring distributed it to other people involved in the project using the COMSOL Server™ product (Figure 5). According to Paula Messamer of RadiaSoft, creating and deploying an application can make the design process for vacuum chambers much more collaborative and efficient. “The application allows people with lower levels of expertise to get answers to questions without going back to the engineer who created the code and without having to go through the steep learning curve,” she says, adding: “Essentially, it is like a calculator.”

Deploying applications also allows RadiaSoft to get feedback from those in the field, enabling them to customize the application’s

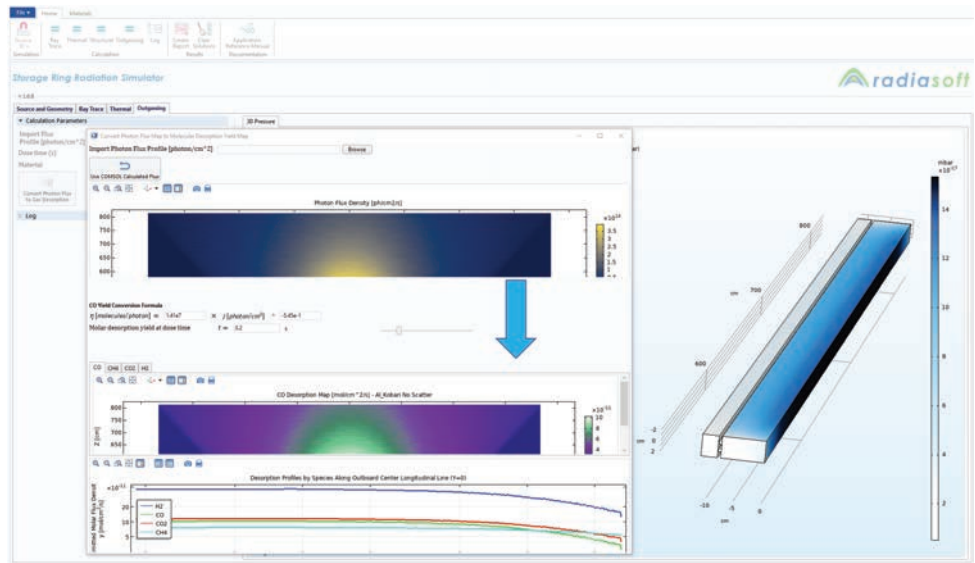


Figure 4. Simulation application for calculating gas desorption and pressure.

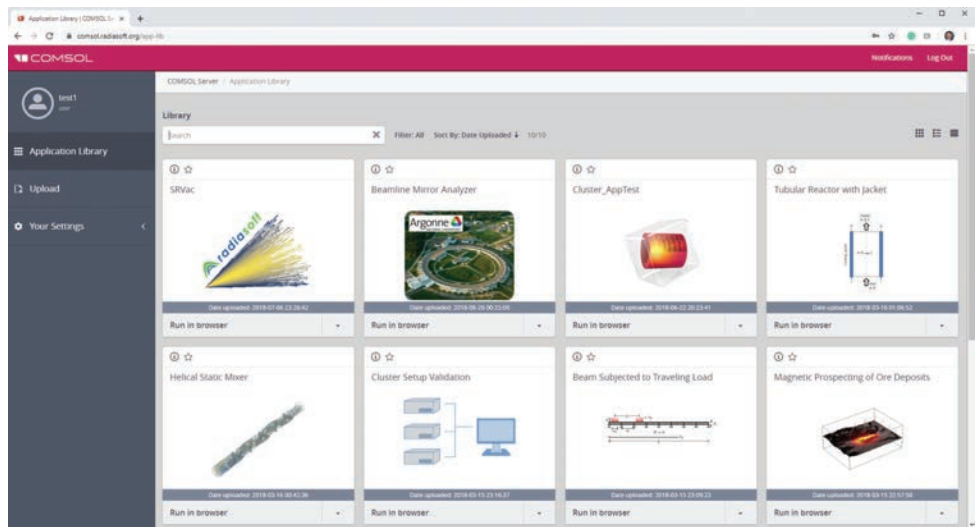


Figure 5. RadiaSoft’s applications in their instance of COMSOL Server™.

interface to meet the needs of users. Goldring mentions that the application is not only being tested by those at ANL but also at other particle accelerator facilities around the world.

**» PLANS FOR FURTHER IMPROVING THE VACUUM CHAMBER SIMULATION APPLICATION**

**IN THE FUTURE,** Goldring

plans to improve the application to include import functionality of arbitrary geometries, which would make it even easier for users to test and optimize different vacuum chamber designs. Further, RadiaSoft wants to generalize the application to accommodate different types of existing and future particle accelerators.

By deploying simulation applications, the teams at RadiaSoft and ANL are giving engineers a specialized tool for improving vacuum chambers, enabling a more efficient design and optimization process. This, in turn, allows for better-performing particle accelerators while facilitating further cutting-edge research and imaging. ©

# MOVING THE CELLULAR MARKET TOWARD 5G WITH COMSOL MULTIPHYSICS®

By ERIC GEBHARD, VICE PRESIDENT, SIGNAL MICROWAVE

**THE TRANSITION FROM 4G LTE TO 5G** in the cellular industry is demanding a new way of looking at designs. The size of electromechanical components in 4G LTE were typically made as small as reasonably possible to reduce the size, power, and weight — and otherwise make systems more efficient. With these size and RF requirements, a certain level of manufacturing tolerances and material choices were acceptable.

4G LTE has a maximum frequency of around 6 GHz. 5G has jumped the frequencies into the 40-GHz and 70-GHz ranges. In 4G LTE at 6 GHz, the wavelength in air is approximately 1.97 inches. For 5G at 40 GHz, the corresponding wavelength is 0.30 inches, and at 70 GHz, the wavelength is 0.17 inches. The 6-GHz wavelength of 1.97 inches is over 10 times the 70 GHz wavelength of 0.17 inches.

This requires engineers to approach designs with the understanding that sizes need to be reduced. To understand the scope of the reduction in size, an analysis of all electromechanical components in a system needs to be done.

Standard	Frequency	Wavelength in Air
4G LTE	6 GHz	1.97 in
5G	40 GHz	0.30 in
5G	70 GHz	0.17 in

Some of the questions that need to be asked include:

- How small does the size need to be?
- How tight do the tolerances need to be?

- Will my current material choices be sufficient?

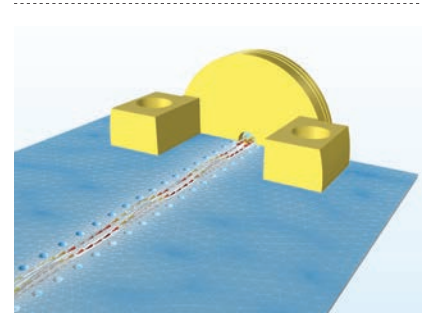
Simulation is a tool in which these questions can be explored without the costly process of making components and testing them. 5G is driving the use of simulation as a learning tool — even before product design occurs.

The rule of thumb for component design is: If the component is smaller than 10% of the wavelength, it can be simply modeled as a lumped element. With 4G LTE systems, a component as small as 0.197 inches (10% of the 6-GHz wavelength) can be treated as a DC lumped element in a circuit. With the move to 5G, anything larger than 0.030 inches for 40-GHz systems and 0.017 inches for 70-GHz systems must be modeled as an RF component. As a result, components must be made smaller and with tighter tolerances than before to meet performance requirements.

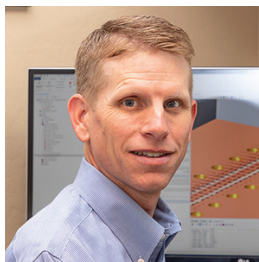
Simulation tools such as COMSOL Multiphysics® help engineers understand how to handle the higher frequencies required with the implementation of 5G. Starting out by developing simple models where various sizes, tolerances, and materials are evaluated, engineers can begin to understand how these

items interact and how changes to these items will affect performance. This is the first step toward building a database of knowledge that can be used in designing bigger and more complicated components and devices. As these parts get further developed, more physics (such as heat flow and mechanical stress) can be added to the model to further understand how the design will work in the real world.

The move from 4G LTE to 5G is a major challenge that will require a greater understanding of how all of the aspects of the design will affect its performance. COMSOL Multiphysics® is an excellent tool to learn and understand how to make the move to 5G. ☺



A test connector modeled in COMSOL Multiphysics®.



**ERIC GEBHARD** received his BS in engineering from Arizona State University in 1995. He has worked for over 20 years in various engineering and management positions in both the aerospace and RF industries, with the last 10 years working on RF connector designs and RF simulation using the COMSOL Multiphysics® software. Currently, he is the vice president of Signal Microwave.