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COMSOL NEWS

THE MULTIPHYSICS SIMULATION MAGAZINE

Immersive Audio for Virtual Reality

Optimizing a speaker for the gold standard in gaming headsets

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The Power of Virtual Experiments

In early 2020, the world seemed to move to a virtual space nearly overnight: Everything from classroom lectures and industry conferences to birthday parties and holiday celebrations was suddenly held via video chat. Although this came as a big adjustment for many, scientists, researchers, and engineers have been successfully conducting virtual experiments and prototypes using simulation software long before COVID-19 was a household term.

The engineers featured in this year's edition of *COMSOL News* are harnessing the power of virtual experiments and numerical modeling to develop new processes, devices, and techniques. In this issue, you will meet acoustics engineers who teamed up with a video game developer to make a virtual reality headset that sounds as real as it feels. You will get a look at a simulation app that can be used to predict the outcome of an additive manufacturing process for a rocket engine component — right on the manufacturing room floor. You will read about researchers who developed a new way to model semisolid flow batteries as well as an environmentally friendly anode-baking process. You will also see how designers developed an efficient and reliable way to film and broadcast live sporting events and optimized a testing chamber for high-speed communications systems.

COMSOL users from around the world shared their stories with us, and now we are looking forward to sharing their expertise, insight, and innovative ideas with you.

Enjoy!

Brianne Christopher
COMSOL, Inc.

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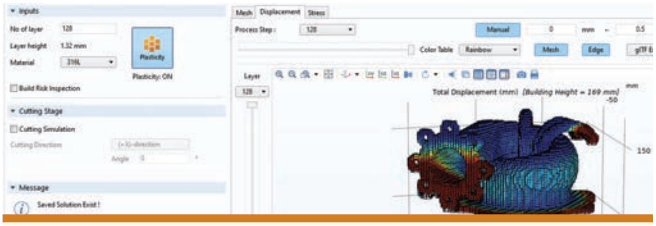

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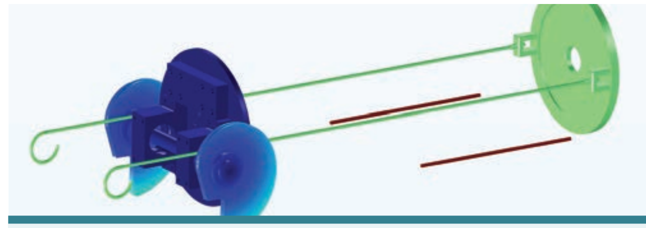


DESIGN OPTIMIZATION

RESEARCH SPOTLIGHT

GUEST EDITORIAL

Industrial Technology Research Institute (ITRI), Taiwan

MAKING PREDICTIONS IN ADDITIVE MANUFACTURING WITH SIMULATION APPS

Engineers at the Industrial Technology Research Institute built a simulation app that can be used to predict the performance of laser powder bed fusion, an additive manufacturing process. The app saves time and money during the additive manufacturing process for a 3D printed injector for hybrid rocket engines at Taiwan Innovative Space.

by **BRIANNE CHRISTOPHER**

The Industrial Technology Research Institute (ITRI) in Taiwan provides 3D printing original design manufacturing (ODM), redesign, and simulation services to the Taiwan Innovative Space (TiSPACE). At ITRI, the 3D printing process for a fuel injector component used in TiSPACE hybrid rocket engines begins with a note of optimism: The laser melts and fuses the first layer of powder onto the build plate, the recoater spreads the next layer of powder across the first layer, and the laser melts and fuses the layers. The build continues, layer after layer, without issue. Suddenly, the recoater jams. Heat from the laser caused a temperature gradient in the material, which led to deformation in the layers and, eventually, the jammed recoater. The entire process terminates.

The engineers try again. This time, the build is completed, but the end result is an injector with deformations that make it unusable. The group tries a third time. And a fourth.

The engineers realize that they need to optimize the parameters of the entire process to ensure a successful build, but the trial-and-error approach is leading to wasted time, efforts, and costs...

» AN INTUITIVE AND COST-EFFECTIVE ADDITIVE MANUFACTURING PROCESS

Laser powder bed fusion (LPBF) is a type of additive manufacturing (AM) in which a laser melts and fuses powder together. LPBF is also a catch-all term that describes processes like selective laser melting (SLM), selective laser sintering (SLS), and direct metal laser sintering (DMLS), to name a few. During LPBF, a thin layer of material, usually about 30–50 μm, is spread over a build platform. A laser fuses the first layer of the model, and then a roller or recoater spreads the next layer of powder across the first layer. More layers of powder are spread on and fused until the complete part or component has been built. (In a variation of the process, an electron beam is used instead of a laser and the build takes place in vacuum.)

LPBF enables manufacturers to make complex shapes, due in part to the high resolution of the laser. Another benefit of this type of AM is that unused powder from one build can be incorporated back into the machine and used to make something else, which makes AM more cost effective than some other types of manufacturing processes that waste material. Because of these benefits, LPBF is used in various types of manufacturing, including in the aerospace, automotive, and medical industries. It is also common in dental applications and jewelry making.

However, LPBF comes with its own set of challenges. For one, the process involves highly localized laser heating, which results in a large thermal gradient in the material. This gradient can induce residual thermal stress and deformation in the layers as the part is being printed. If this residual deformation becomes excessive, it can cause the recoater component of the machine to jam, which terminates the entire manufacturing process. If the machinery jams and terminates the build, the process has to

FIGURE 1 The 3DP injector component.

be restarted, which wastes money and time. Another risk is that the finished part can also be deformed, sometimes beyond the end user's acceptability limits.

» USING LPBF TO MANUFACTURE A ROCKET ENGINE COMPONENT

ITRI studies the LPBF process in an effort to balance its cost and time constraints with well-made finished products. Researchers from the AM System Innovation Department, Laser and Additive Manufacturing Technology Center (LAMC), ITRI, including engineers Wai-Kwuen Choong and Tsung-Wen Tsai, and manager Steven Lin, optimize the LPBF process for manufacturing a 3D-printed (3DP) injector component for TiSPACE hybrid rocket engines (Figure 1). The 3DP injector is designed by TiSPACE to enhance the mixing efficiency of the engine's hybrid propellants and utilize the fluid-dynamics-optimized design. ITRI further improved the design using design for additive manufacturing (DFAM) techniques. As Wai-Kwuen Choong says, "The complex internal flow channel and consolidated component features of this part make it an excellent demonstration for LPBF technology."

The design challenges associated with LPBF are important to consider when manufacturing the injector. In a part of this size, generally about 110 mm x 110 mm x 170 mm, the accumulation of thermal stress is unavoidable and can lead to a large deformation in the *z* direction, the axial direction of the injector. This deformation can — and has — caused the recoater to jam and the system to terminate. By optimizing the LPBF process to avoid deformation, ITRI and TiSPACE can reduce the wasted time and costs that result from terminated builds.

» PREDICTING FUTURE OUTCOMES WITH MECHANICAL MODELING

Typically, the outcome of the LPBF process is predicted using simplified rules of thumb and trial-and-error methods. One example is the 45° rule, a simple and commonly accepted rule in the field of additive manufacturing in which a design should avoid containing angles over 45° of overhangs, or else it is not a good candidate for 3D printing. This is because the layer to be printed will stick out too much compared to the layer underneath, and the new layer will not have enough structural support from below. This rule does not account for complex and intricate designs like that of the 3DP injector, and so trial and error can quickly eat into the time and costs of a manufacturing project. Instead, ITRI uses simulation to predict the residual stress and deformation of the manufactured part (Figure 2). To do so, they turn to the COMSOL Multiphysics® software.

To predict how thermal gradients would cause stress and deformation in the injector design, the team implemented the inherent strain method in their preliminary simulations. This method was first established to quickly predict residual stresses and deformation in welding problems, but is increasingly being used to solve metal additive manufacturing

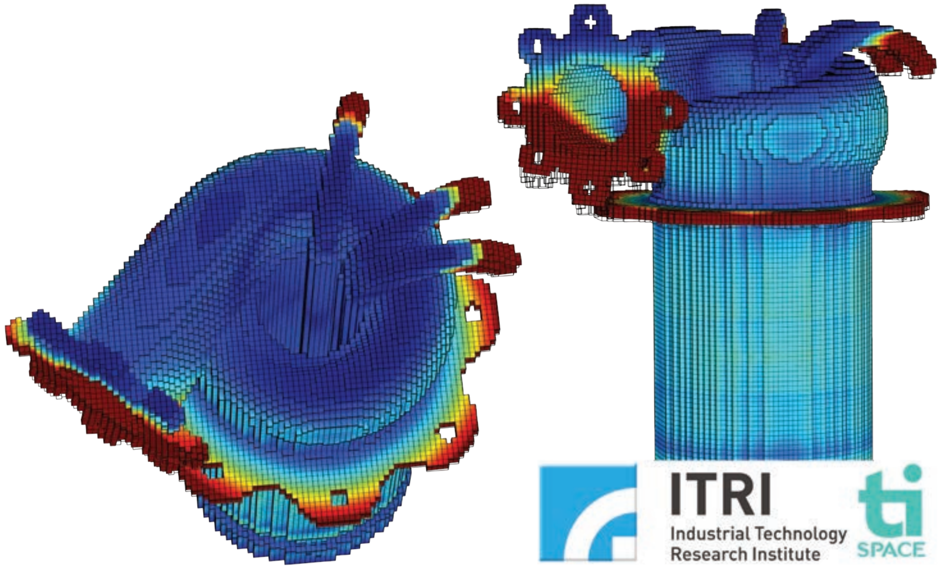


FIGURE 2 Simulation of the 3DP injector's LPBF manufacturing process.

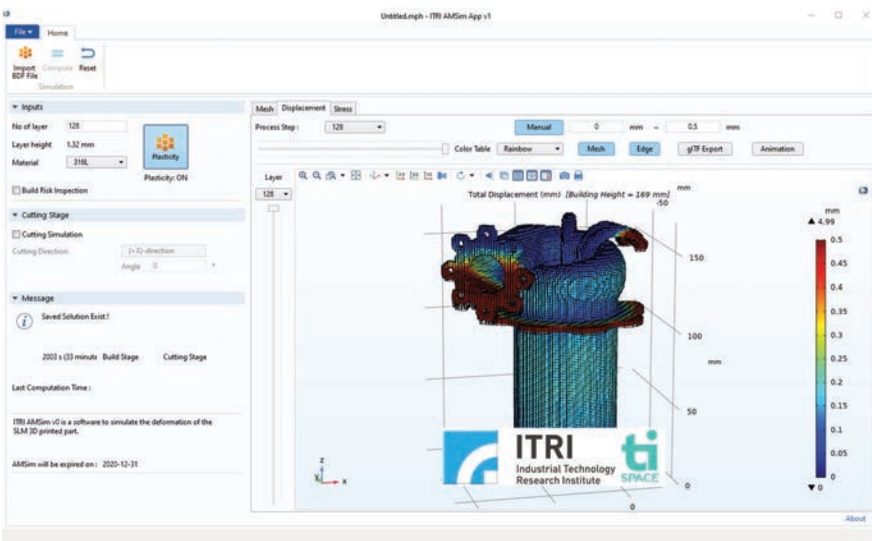


FIGURE 3 The ITRI AMSIM app.

problems as well.

The team used the *Solid Mechanics* interface in the Structural Mechanics Module to perform a thermomechanical analysis. Doing so, they could estimate the residual stress and deformation in the manufactured part. Specialized for additive manufacturing, the *Activation* feature in the COMSOL® software was perfect for modeling the repeating, layer-by-layer addition and fusion involved in LPBF. They also used the Optimization Module to optimize the part orientation and support structure of the component during the build.

INTRODUCING THE ITRI AMSIM APP TO THE MANUFACTURING WORKFLOW

The ITRI team used simulation to successfully predict stress and deformation outcomes during the LPBF process, but there was still an issue: The AM system manufacturing engineers who deploy the LPBF process are not typically familiar with simulation. Hiring a simulation specialist to do so would only add to the time and cost of the project. What to do?

The team built a simulation app (Figure 3) with an intuitive user interface and specialized inputs and outputs from their LPBF model, naming it the ITRI AMSIM app. Apps can be built from existing models in COMSOL Multiphysics® using the built-in Application Builder. The simulation app enables process engineers to predict and assess the build characteristics for an optimized manufacturing process. It includes inputs for an STL file, an elastic or elastoplastic model (available with the Nonlinear Structural Materials Module), and the choice to enable or disable the cutting process simulation or base plate removal. It also includes a choice of five different powder materials, including Ti 6Al-4V, a titanium alloy; MP1, a CoCrMo alloy; PH1 and 316L, types of stainless steel; and AlSi10Mg, an aluminum alloy. The app's outputs are the results the process engineers need on the floor, such as the displacement and residual stress distribution during the building stage and after cutting.

The app's inputs are based on experimental calibration, which the ITRI team performed via different scanning strategies to extract the correct inherent strain vector. This vector, or the components of this vector, changes depending on the powder material and laser parameters, such as laser power, beam size, scanning speed, hatch size, and more.

The app was compiled to a standalone executable using COMSOL Compiler™. The compiled application was distributed to the process engineers and it can be run without a COMSOL Multiphysics® or COMSOL Server™ license. In fact, the ITRI team licensed the app at their own discretion, offering it to the intended users on a three-month trial basis.

When asked about the benefits of using simulation apps for the combined project between ITRI and TiSPACE, Choong echoed the benefits for saving time and money, adding that it is "all about the cost issue."

SAVING TIME AND COSTS WITH APPS

The simulation app enabled the team to predict a high-risk region of the component and add additional support to the design, resulting in a successful build. Running through the physical AM process to test the part build takes about a week, while the app simulation takes under an hour. The total time spent on testing the process decreased by 75%. This is also much more efficient than the testing process before building and deploying AMSIM: The build for the 3DP injector at TiSPACE was started and terminated four times using trial-and-error methods. Each time, the process failed when either the recoater jammed or the part itself broke.

Calculating the labor, machine, and material costs of those trials with the cost of running the simulation app further reduced costs, this time by 83.3%.

And finally, the time it takes to obtain the outcome of the AM process for the 3DP injector, when comparing the simulation to the real manufacturing process, is reduced by a whopping 99%.

FUTURE PLANS FOR APP ENHANCEMENTS

The ITRI team plans to improve AMSIM, which has already undergone three iterations, with new features for material calibration, as well as functionality to detect recoater interference, simulate support structures, and more. They hope that adding more advanced but user-friendly features to the app will make it even more time and cost effective than it already is, further boosting the return on investments for the entry-level users in the AM industry by shortening the learning curve.

With the ITRI AMSIM app, an accurate preview of the 3D printing process, and failure-free production, is getting closer to reality.

Tectonic Audio Labs, Washington, USA

DESIGNING THE GOLD STANDARD OF IMMERSIVE AUDIO FOR VIRTUAL REALITY GAMING

by **JULIA ABRAMS**

Tectonic Audio Labs created a state-of-the-art balanced mode radiator speaker using electromagnetics, mechanical, and acoustics simulation. The speaker was implemented into a virtual reality (VR) headset for Valve Corporation and is now regarded as the gold standard for VR audio.

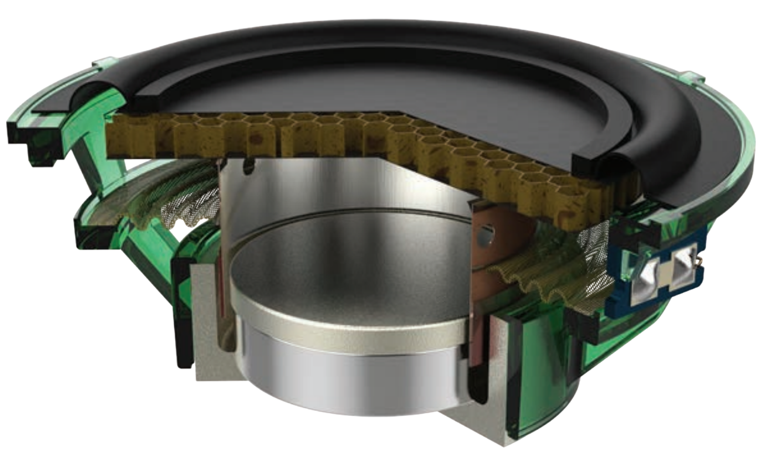


FIGURE 1 Cutaway view of the BMR speaker.

Virtual reality is meant to immerse the user in the virtual world as much as possible by making it feel as real as can be. When virtual reality is done right, you could visit a historical site from your couch, experience a habitat from eons past at a museum, or explore Mars or the Moon from the comfort of your living room.

The gaming industry is making great strides in VR development, but one challenge that game developers have encountered is how to effectively obtain suspension of disbelief in the virtual world.

Whether you are using VR to study an asteroid approaching Earth or playing a game where you have to fire missiles at it, the more immersive the experience, the better. Other entertainment fields, like literature and film, face the same challenge of suspension of disbelief, but there's something exclusive to VR: audio immersion.

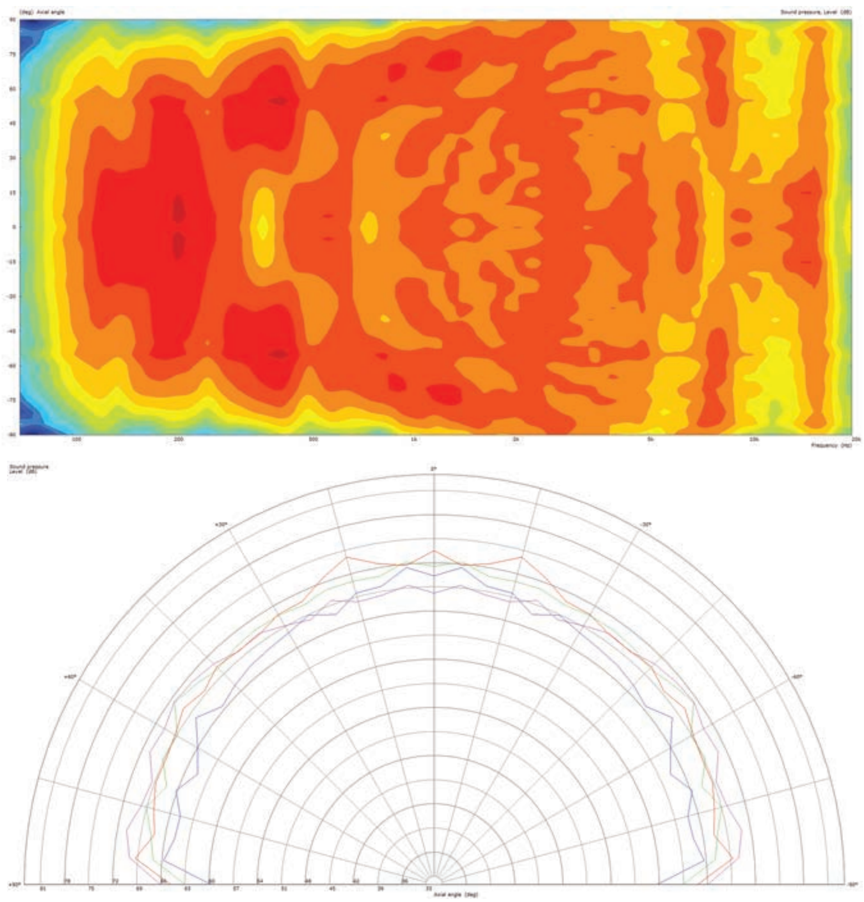


FIGURE 2 Directivity and polar plots for the BMR speaker analysis.

» ACHIEVING AUDIO IMMERSION IN THE VALVE INDEX® HEADSET

Valve Corporation, a leading developer in the gaming industry creating games, gaming platforms, and gaming hardware, sought to develop the Valve Index® VR headset that could provide suspension of disbelief. To do so, Valve engineer Emily Ridgway and her team had to figure out how to create an immersive audio experience.

While playing video games, people often wear stereo headphones to determine where the sound is coming from relative to their character in the game. If the source is to the left of the character, the player will hear the sound through the left headphone speaker, and vice versa. The Valve team decided against using traditional headphones, because headphones are designed to isolate sound, cancel noise, and exaggerate frequency responses — not to create audio immersion. Ridgway was concerned that the very physical design of headphones could counteract audio immersion. For one, headphones put sound directly into the ear canal, so the sound can feel imagined (known as an internalized auditory source), coming from within the person's head, or otherwise "not real". Also, headphones can be physically uncomfortable, and this discomfort can draw a user out of the gaming experience. Some people opt for loudspeakers instead of headphones. While loudspeakers mitigate some of these issues, they come with their own problems. The sound of a loudspeaker is affected by the geometry and acoustics of the real room. Another reason is that they have a "sweet spot" that the player would need to stay in for best sound quality, but when people experience VR, they tend to move around.

Ridgway's solution? A pair of ultra-near-field, full-range, off-ear (extra-aural) headphones.

Ridgway and her team went through several types of audio speakers for the headset. None quite fit their goals; none, that is, until they found Tectonic Audio Lab's balanced mode radiator (BMR) speakers. Ridgway "immediately noticed several positive benefits," she wrote in a blog post. "They reduced coloration due to speaker mispositioning, were almost within range of our weight target, had great frequency response in high-mid ranges (important for binaural simulations), and were much thinner than traditional speaker drivers." Valve teamed up with Tectonic Audio Labs to harness these benefits and design custom speakers for their VR headset.

» WHAT IS BMR SPEAKER TECHNOLOGY?

In traditional speakers, audio is generated by a cone diaphragm moving pistonically. This movement transfers energy along the axis of movement and creates sound. BMR speakers are different in that they are utilizing bending waves: waves that are moving perpendicular to the propagation direction. This means that they have more interaction with the surrounding air, so they are able to transfer more energy. Higher frequencies can be difficult for traditional speakers to handle, as they can cause the traditional diaphragm to ripple or bend, also known as cone breakup. The subsequent peaks and troughs decrease audio quality and increase placement sensitivity. While most speakers try to avoid bending waves, BMR embraces them.

"We embrace the bending modes and want them to occur. We can control where they occur, and it's those bending modes that preserve the off-axis output. We're using resonance breakup to our advantage," said Tim Whitwell, vice president of engineering at Tectonic Audio. "In many ways, BMR goes against the thinking of traditional acoustic engineering."

BMR technology is able to exploit this high-frequency rippling through the optimization of several characteristics, such as material selection and mass loading. Through this exploitation of the bending modes, and the superposition of both the bending and piston modes, sound is evenly propagated in the BMR speaker.

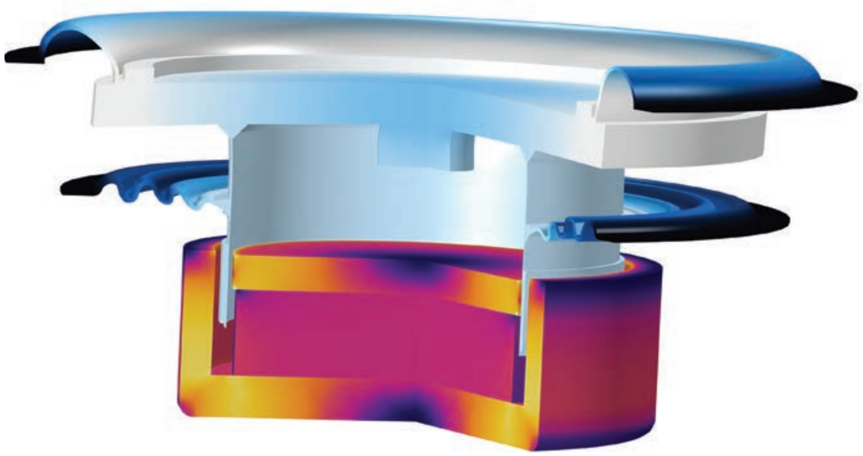


FIGURE 3 Fully coupled BMR model.

» CREATING THE GOLD STANDARD

The team at Tectonic Audio Labs got to work on the audio speakers for the Valve Index® VR headset. "For us, the starting point is to analyze the modal structure of the diaphragm," Whitwell said. "What's really important for us with the BMR is to make sure that the modal behavior begins right when the pistonic behavior begins beaming." Once beaming is about to begin, the bending modal behavior begins, which "fills in" the off-axis output that the beaming neglects.

In order to optimize this behavior, the Tectonic team first had to figure out where in the disc bending modal behavior occurs and how many bending modes occur across the bandwidth. They used the COMSOL Multiphysics® software to perform an eigenfrequency analysis of this behavior. From there, the team was able to control the bending modes through optimizing the thickness and material of the disc. By making sure this behavior occurs precisely where and when they want it to occur, Tectonic Audio is able to preserve the speaker's wide directivity output throughout the range.

Tectonic also analyzed the motor design, performing an electromagnetics analysis to optimize the voice coil. "You can add many turns to your voice coil wire to increase your conversion of electromagnetic to mechanical energy, but your weight goes up, and so you have competing constraints there," Whitwell explained. "All of that optimization we do within COMSOL®."

The mechanical and electromagnetics models were processed and optimized separately.

Tectonic Audio Lab's next step was to bring the two together for a coupled analysis. Because nearly everything in the model is axisymmetric, they were able to model the coupling in a 2D axisymmetric space, saving computational resources. The diaphragm material is the exception. "The diaphragm material itself is actually orthotropic; it has different stiffnesses in different directions," Whitwell said, "The *Solid Mechanics* interface in COMSOL Multiphysics® lets us model the orthotropic nature of the material within the 2D axisymmetric space, which is really fantastic."

After the team developed the fully coupled model, they introduced other elements, like the spider suspension, which centers the coil and controls its movement. At the same time, they continued optimizing the fully coupled model to ensure that the diaphragm's behavior would be balanced — which is the key to the BMR technology, allowing it to work properly in the Valve Index® VR headset and provide a great experience for different users.

Once the speakers are fully dialed in, the suspension is the next focus, and its geometry is analyzed in a nonlinear study. "We deform the suspension geometry up and down, to see how the stiffness of those components changes with displacement," Whitwell said. "And again, there's a lot of optimization required there." Whitwell emphasized that this optimization was particularly important in this project. "Any noise in the drive unit or distortions would be very, very obvious to the listener." After the suspension is fully optimized, it goes back into the coupled model.

"We make sure that everything is still giving us the performance we desire," Whitwell said, "And then we can go and build a prototype."

"You can add many turns to your voice coil wire to increase your conversion of electromagnetic to mechanical energy, but your weight goes up, and so you have competing constraints there. All of that optimization we do within COMSOL®."

— TIM WHITWELL, VICE PRESIDENT OF ENGINEERING AT TECTONIC AUDIO LABS

» THE "KING" OF VR HEADSETS

After Tectonic Audio Lab's design optimization and prototyping were successful, Valve Corporation was able to bring their headset to market. Since then, it has earned many, many positive reviews.

One example is a beloved and popular YouTube channel called *Linus Tech Tips*, run by the titular Linus. Video topics range from explaining if more RAM makes your computer faster to reviewing recently released wireless keyboards, and even building a PC tower case out of cardboard. And, of course, they review different VR headsets.

In August 2019, Linus uploaded a video called "Maybe VR isn't dead after all..." in which he reviewed the Valve Index® Headset. He was initially ambivalent to the speakers, but after a day of using the headset, Linus was impressed.

"Credit to the speakers," he said, somewhat incredulously. "They actually sound shockingly good!" Linus spends the rest of the video going over the headset's specifications.

At the end of the video, Linus holds up the Valve Index® Headset and looks directly into the camera, saying "This is absolutely the king of VR gaming headsets." ◎

Raychem RPG, India

IMPROVING OVERHEAD EQUIPMENT DEVICES FOR A NEW ERA OF RAILWAY TRANSPORTATION

As part of the Indian government's plan to revitalize the country's railway system, researchers at Raychem RPG designed an autotensioning device and modular cantilever for catenary and contact lines using structural modeling and optimization.

by **ADITI KARANDIKAR**

The railway network is the backbone of the Indian transportation system, connecting remote villages and towns with metropolitan cities across the country. Recent government initiatives aim to revamp and modernize the entire network by 2030, and the past couple of years have already brought many changes to the rail system. From a technological perspective, we can expect two notable changes to Indian railways: the introduction of electric and solar-powered trains and an increase in the operating speeds of trains from 100 km/h to 160–220 km/h. To support these plans, suitable modifications must be made to the existing infrastructure and components, such as the overhead equipment (OHE), including catenary and contact lines, as well as pantograph assemblies.

Raychem RPG, a pioneer in innovative energy solutions for various sectors, has a dedicated team working on products that can meet the challenging requirements of the evolving railway network. The team of scientists and researchers, led by Mr. Ishant Jain, has improved the designs of autotensioning devices (ATD) and modular cantilevers (MC), two of the most critical components of the railway's overhead equipment, using multiphysics simulation.

» PROTECTING RAILWAY OHE LINES WITH AUTOTENSIONING DEVICES AND MODULAR CANTILEVERS

In an electric rail system, power is supplied by overhead lines that run along the entire length of the railway track. This power is transferred to the train by means of the pantograph, which is a current collector mounted on top of the locomotive. The ATD (Figure 1, left) provides a mechanism for automatic tensioning and serves as a termination point for the contact lines. Tensioning is needed on the contact lines due to the variation in their lengths: Contact lines are primarily made from copper-based alloys, which are prone to expansion and contraction due to variations in atmospheric temperature. The conductors of overhead lines are installed with a very specific tension value. This tension is variable over time and is closely dependent on the ambient temperature. The absence of tensioning causes the overhead lines to sag or tighten, leading to pantograph entanglement or snapping of the overhead equipment (OHE) lines.

> “Structural optimization of the modular cantilever assembly with COMSOL® has enabled Raychem to secure four patents for our different designs."
>
> — ISHANT JAIN, RAYCHEM RPG

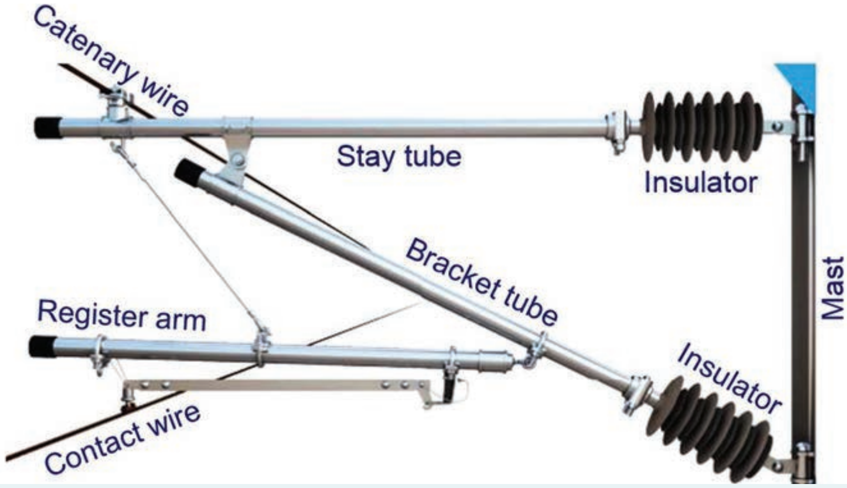


FIGURE 1 Autotensioning device (left) and diagram of the modular cantilever assembly (right).

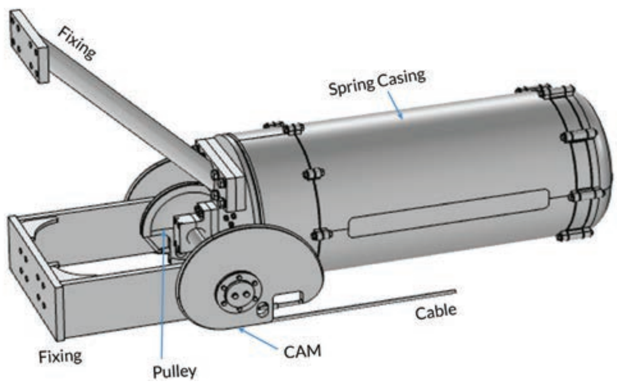


FIGURE 2 Geometry of the ATD.

Similarly, overhead MCs are designed to support the assembly of overhead power transmission wires — i.e., catenary (1000/1200 kgf tension), contact (1000/1200 kgf tension), and droppers — to transfer the overall bending, transverse, and vertical loads to the mast via insulators (Figure 1, right). The quintessential cantilever is lightweight and robust enough to support the current-carrying assembly with train speeds up to 250 km/h. In addition to these functional requirements, ease of maintenance, transportation, handling, and aesthetics also need to be considered.

» DESIGN CHALLENGES FOR RAILWAY COMPONENTS

To ensure the safety of rail passengers at high speeds, the ATD has stringent design requirements. To determine the correctness and efficiency of an ATD design experimentally, a pull-out test is performed. A large experimental setup is required for such a test, which is not practically feasible at all times. The team at Raychem RPG, working out of the Raychem Innovation Centre (RIC), was tasked with designing an ATD that is both light in weight and highly sensitive to temperature fluctuations, while providing ease of service, assembly, and maintenance.

In addition, the MCs that can be imported from European and American markets are bulky and include many ancillary components. As part of the "Make in India" initiative of the Indian government, the Raychem team's objective was to come up with a novel design to eliminate these ancillary components while ensuring structural integrity by efficiently using material, which ultimately saves costs and reduces weight.

To achieve both design goals, the Raychem team used TRIZ, a theory for coming up with innovative solutions to problems, for generating and conceptualizing various ideas. They then turned to the COMSOL Multiphysics® software for optimization and design validation as per the railway's standards.

» STAYING ON TRACK: PERFORMING ANALYSES WITH COMSOL MULTIPHYSICS®

Using COMSOL Multiphysics® and its add-on modules, the Raychem team structurally optimized the individual components of the ATD, while also performing a multibody analysis to study the coupled motion of these components for a system-level analysis. The team first imported a typical assembly (Figure 2) and then applied the appropriate boundary conditions to account for the effects of dynamic loading. They performed a study to find the tension in the outer cable along with the variation in spring force.

The results of the analysis (Figure 3) represent the cable displacement and tension. It can be clearly seen that the tension remains unchanged, which accomplishes one of the objectives of the project.

For the modular cantilever, an initial model was imported into COMSOL Multiphysics®. While analyzing the cantilever model, the team quickly realized that the MC was rather bulky and the stresses were distributed unevenly. They then performed a structural optimization of the design and carried out a multivariable optimization, where the minimization of total strain energy is set as an objective function along with the minimization of total mass criteria.

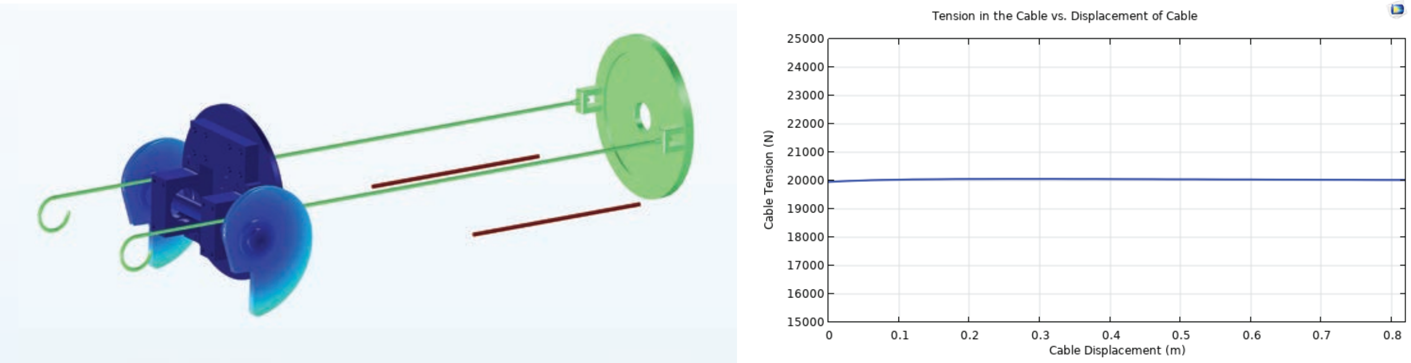


FIGURE 3 Cable displacement on the applying load (left) and tension in the cable (right).

Using topology optimization, the system's mass was reduced by 75% compared to the initial geometry (Figure 4, top) — without violating the design specifications. A 3D model was then created using the optimization study and later subjected to both static and dynamic structural loading (Figure 4, bottom) to emulate the impact of a train moving at 250 km/h.

» RIDING FORWARD: HOW STRUCTURAL ANALYSES AND OPTIMIZATION HELPED THE RAYCHEM TEAM

Using the observations from the simulation analyses, the entire ATD assembly was completely redesigned to incorporate a foldable design with a 50% reduction in the assembly size. Moreover, Jain's team also replaced the metallic spring with a polymer spring, which was designed using the Nonlinear Structural Materials Module, an add-on to the Structural Mechanics Module and COMSOL Multiphysics®. All of these design changes led to an 80% decrease in the weight of the entire assembly. "With the help of the structural and multibody analyses we performed on the ATD, we were able to reduce the number of components from 20 in the earlier design to just 8," says Jain.

Further, a simulation model was established to optimize the conventional overhead modular cantilever with the help of topology optimization in COMSOL Multiphysics®. The resulting model was used to create a simplified design concept and was later subjected to a detailed structural analysis in terms of strength and vibration modes to verify the optimized results. Simulation was instrumental in reducing the design complexity, with the number of components reduced from 12 to 5 and the weight reduced by approximately 33%. Out of the two designs proposed, the Indian Railways Board has already accepted one design while the other is in the approval stage. According to Jain: "Structural optimization of the modular cantilever assembly with COMSOL® has enabled Raychem to secure four patents for our different designs."

In June 2020, the Raychem team received the Golden Peacock Innovative Product Award (GPIPSA), Engineering Sector, for their foldable design of the modular cantilever system.

» THE TRACK AHEAD: FUTURE PLANS AT RAYCHEM

With the modifications expected in the Indian railway infrastructure over the next decade, the team at Raychem Innovation Centre is now using COMSOL Multiphysics® to develop more new OHE products for the Indian Railways. In addition to projects in the energy utility and oil & gas sectors, the railway system is now another specialized area for which Raychem RPG will continue to provide innovative solutions with the power of multiphysics simulation. ◎

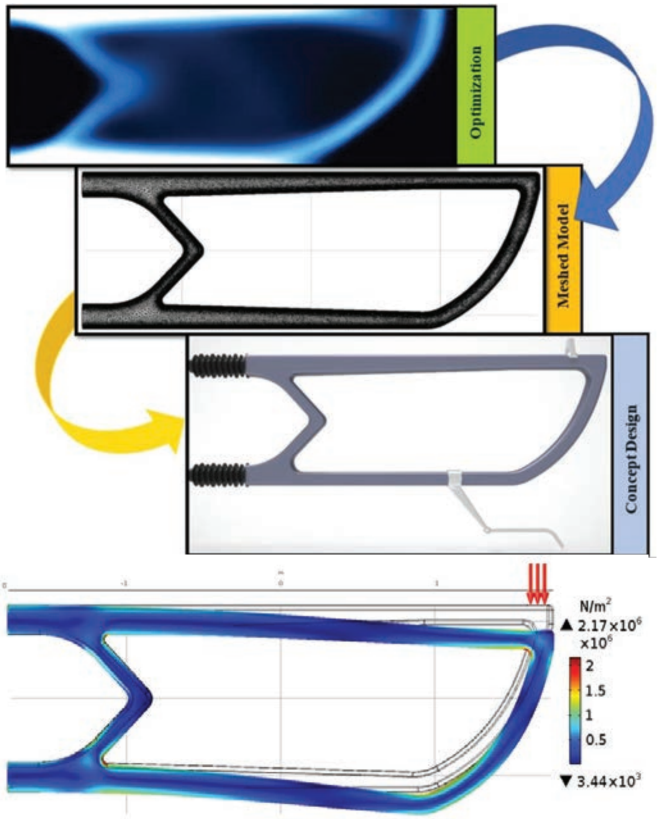


FIGURE 4 Cantilever design optimization (top) and loading test of the optimized model (bottom).

ACKNOWLEDGEMENTS

Ishant Jain would like to acknowledge the following persons for their assistance in the research described in this article: Ganesh Bhoye, Nitin Pandey, Raghav Upasani, and Hamza Saiger.

Flemish Research Institute for Technology (VITO), Belgium

DEVELOPING A NOVEL BATTERY MODEL TO ANSWER CLASSICAL CHEMISTRY QUESTIONS

Researchers at the Flemish Institute for Technical Research (VITO/EnergyVille) and KU Leuven developed a pseudo-three-dimensional model of a semisolid flow battery to find reliable answers to their design questions, such as how flow rate affects particle discharge and how cell voltage changes during the discharge process.

by **BRIANNE CHRISTOPHER**

The development of any process, component, or device involves some level of trial and error — nothing is perfect the first time. When it comes to the modeling approach itself, the same sentiment applies. Take, for instance, the modeling of a semisolid flow battery (SSFB), an innovative type of flow battery that is similar to the vanadium redox flow battery (VRFB), but involves a liquid electrolyte that carries solid particles. Up until recently, literature pertaining to SSFBs was sparse.

Kudakwashe Chayambuka, currently a PhD researcher copromoted by Grietus Mulder at the Energy Technology unit at the Flemish Institute for Technical Research (VITO/EnergyVille), along with Xochitl Dominguez, senior scientist at VITO, and Professor Jan Fransaer of the Catholic University of Leuven, set out to address this research gap in SSFB modeling.

Early research into SSFB systems used models that considered diffusion and convection as transport mechanisms occurring within the active particles. The problem? This assumption is both physically and conceptually wrong. "These models assume convective flow when the charge is contained inside flowing particles," says Chayambuka. "The equations of the original model do not hold up, and are not physical," says Fransaer, calling the model "fishy."

"We attempted to model the proper physics," continues Chayambuka. In this case, "proper physics" refers to the fact that molecular diffusion is the only transport mechanism occurring inside the solid active particles of an SSFB. Their bulk movement is not related to this molecular transport mechanism. The team developed a novel way to model an SSFB that could accurately account for its behavior and surrounding physics.

» BATTLE OF THE BATTERIES

Flow batteries are able to separate (and independently scale up) their power generation and energy storage capacity. So what makes a semisolid flow battery (Figure 1) so special? "SSFBs are very interesting, and very difficult to realize. There's no limit to the amount of energy that can be stored," says Fransaer. This type of battery is beneficial in many applications due to its high volumetric energy density. In fact, they offer 10 times the storage capacity in volume of existing vanadium redox flow batteries (VRFBs).

When based on the same materials as Li-ion batteries, SSFBs provide the highest energy density theoretically, but there are some drawbacks, including a high cost to make and an increased risk of toxicity. SSFBs made with a nickel-metal-hydride (NiMH) material include an aqueous electrolyte of potassium hydroxide to sidestep these issues.

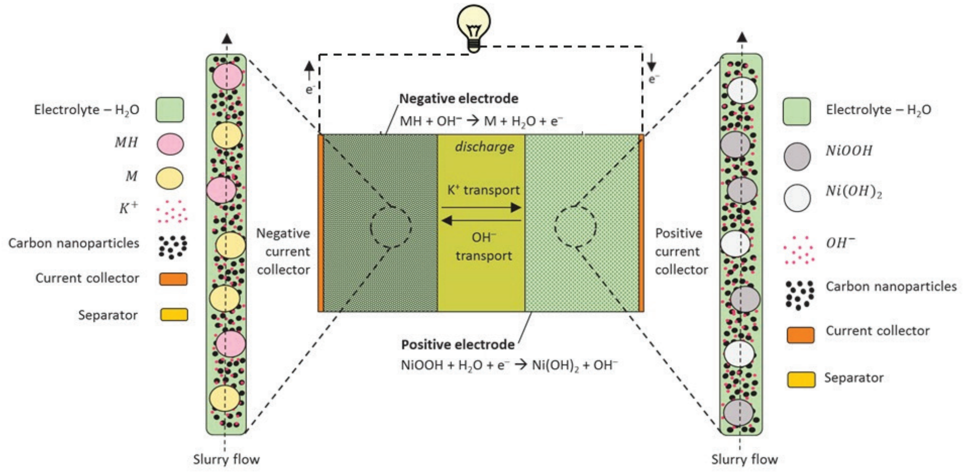


FIGURE 1 A schematic of a semisolid flow battery.

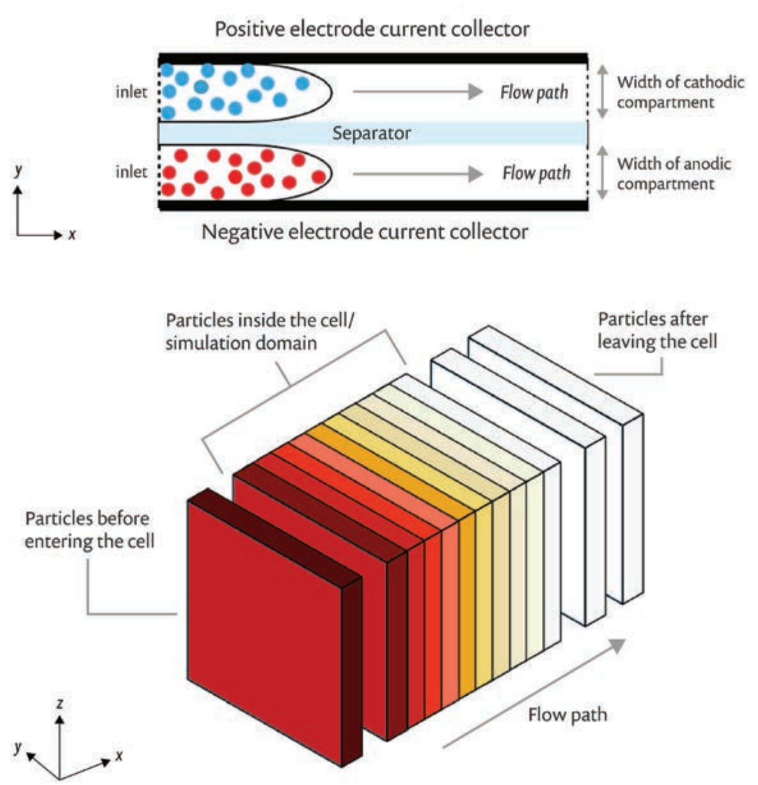


FIGURE 2 The P3D model of the SSFB.

No matter the type of SSFB, there is a major design challenge to address: Researchers need an electrochemical model that accurately describes the kinetic and transport processes occurring within the design. That is where the research group — and their novel modeling approach — come into play.

» BATTERY MODELING: NOW IN PSEUDO 3D

The researchers realized that to successfully model SSFBs, they needed to be able to correctly account for the interactions between macroscale and microscale domains, as well as multiple physical processes, simultaneously.

"SSFBs are very complex systems compared to other batteries. For instance, you need the right viscosity for the slurries," says Dominguez. "To predict what's happening, you need to model it. Experiments would take too much time and be too complex."

The group found that the COMSOL Multiphysics® software offers the multiphysics and multiscale capabilities their research calls for. In addition, the accurate and efficient electrochemical modeling that is possible in the COMSOL® software facilitates the optimization and scaling up of NiMH SSFB systems.

"Simulations like this are really only possible with COMSOL," says Mulder.

Aside from the need for both multiphysics and multiscale modeling, SSFBs present another unique modeling challenge. Because of the active particles involved in the battery, the model needs to include particle tracing. However, you cannot couple a hydrodynamics analysis with a full particle-tracing approach, because the two studies are not compatible. The researchers tackled this problem in a two-step approach. First, they modeled the electrode movement of a nonflowing SSFB system in 2D (Figure 2). The 2D model acted as a first approximation where they could select optimized parameters, such as the concentrated and dilute solution theories for the electrolyte, material balance in the solid active particles, current balance, reaction rate, and model geometry.

Next, the researchers extended the 2D model into the pseudo 3D (P3D) model for flowing SSFB systems. "We wanted to make a nearly particle tracing model that includes physics discretized in the time domain; then stop and solve, update the position of the particles, and start again to generate proper results," says Chayambuka. "We needed a P3D geometry to model the entire flow of the battery." To do so, the team determined all of the dependent variables in separate domains as well as the associated variables that needed to be made available in the different geometries at their corresponding coordinates. "The extrusion operator feature in COMSOL Multiphysics made it simple to link the 2D and 3D domains," he says. The extrusion coupling functionality also enabled them to map the variables between separate geometries at every time step in the simulation.

Using the P3D model, the team was able to account for hydrodynamic effects in the SSFB, such as transport in the electrolyte through the Navier–

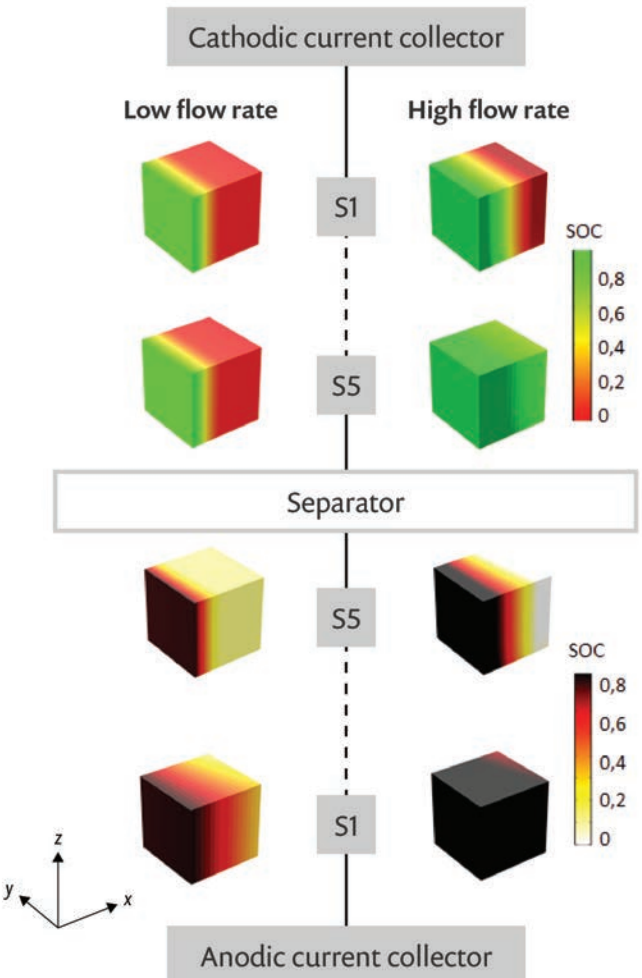


FIGURE 3 Comparison of low-flow-rate and high-flow-rate SOC distributions in a P3D NiMH SSFB model.

> **"To predict what's happening, you need to model it. Experiments would take too much time and be too complex."**
>
> — XOCHITL DOMINGUEZ, SENIOR SCIENTIST AT VITO

Stokes equations for incompressible Newtonian fluid, as well as the transport in the solid phases, including the hydrogen intercalation process modeled by pure diffusion. The team solved the time-dependent diffusion equation inside the active particles using partial differential equations (PDEs).

The researchers also found the LiveLink™ *for* MATLAB® interfacing product particularly helpful. Before introducing LiveLink™ *for* MATLAB® into their modeling workflow, the researchers did not have an automated P3D process. This meant that they had to repeatedly run the simulation, change the particle position, and then start all over again. This process was fine when they were initially starting the project, but the group soon found that it was taking a long time to find the results they needed — and this method was also more prone to errors. When they later introduced the LiveLink™ functionality into their process, Chayambuka says "it became so much easier to generate results, and we do not have to be behind a computer the whole time."

» FLOW RATE, STATE-OF-CHARGE, AND ENERGY OUTPUT

Through the results of the 2D model, the researchers found that not all of the SSFB's available charge is evenly exhausted. In fact, the extent of each particle's discharge depends on its position. The P3D model showed the researchers how the flow rate of the battery affects particle discharge, an important factor for analyzing the battery cells' dynamic behavior.

The team found that at high flow rates, the cell voltage remains mostly stable. As the discharge current increases, the voltage difference between the initial and steady-state voltage increases. For low flow rates, the voltage differences between the initial and steady-state stages are more pronounced (Figure 3). By understanding how flow rate affects the dynamic behavior of cells, they can design SSFBs for different flow rates and predict the steady state for given sets of initial conditions.

One of the most exciting aspects of the project is that this is the first time the flow-rate behavior of an SSFB has been shown in a model. Further, experimental SSFBs are showing similar transient profiles to those found in COMSOL Multiphysics, demonstrating the validity of the P3D model for this type of research.

» CHARGING UP THE FUTURE OF BATTERY RESEARCH

Through the P3D model, the research team demonstrated a novel way to model SSFB behavior. With this model, they were able to visualize the relationship between hydrodynamic and electrochemical phenomena, providing a new way to explore the design of different types of batteries. Next steps include introducing phase change effects in the model materials, introducing non-Newtonian behavior and validating the simulated flow field with experiments using carbon-water suspensions with the same rheological behavior as the electrolytes.

"Our hope is to apply this model to other types of flow batteries and test other chemistries, which would be interesting," says Chayambuka. Further, "this kind of model can be extrapolated to other systems, because they use the same principles," says Dominguez. One example she gives is the particle-based system of wastewater treatment.

The group hopes that by continuing their work, they will be able to realize an experimental system to validate the SSFB model, which would generate more interest and funding so that they can look into more ways of modeling energy losses and optimized conditions. Improved battery designs, and a better understanding of how they work, can improve how battery manufacturers store energy and generate power. ◎

COMSOL, Massachusetts, USA

THE VITAL ROLE OF SIMULATION FOR VIRTUAL EMI AND EMC TEST ENVIRONMENTS

5G, the internet of things, and high-speed wireless communication all require the deployment of microwave and millimeter-wave devices and systems that are optimized for performance. To ensure the operation of these systems and avoid EMI and EMC, designers can turn to virtual test platforms through simulation software.

by **JIYOUN MUNN**

Before deploying microwave and millimeter-wave devices and systems within 5G, the internet of things, and high-speed wireless communication, it is essential to predict their performance. This need has increased the demand for virtual test platforms through simulation software.

High carrier and system bus frequencies are necessary for high-data-rate communication between multiple devices present in such systems. However, increased operational frequencies may induce undesirable and troublesome electromagnetic compatibility (EMC) and electromagnetic interference (EMI) issues, especially when communication is congested. Moreover, the impact from other physics is no longer negligible in mmWave devices. Multiphysics phenomena, such as structural deformation caused by heat expansion, need to be a part of the design consideration as well. Fortunately, a wide range of EMC and EMI scenarios can be virtually emulated and tested without having to elaborately adapt test configurations to real-world environments.

Using electromagnetics simulation software for evaluating device functionality reduces time and costs during the development and production cycle. Virtual evaluations can be performed prior to fabrication, test, and manufacture and are an important component in reliable quality control processes.

The goal of simulation is to describe the real world as

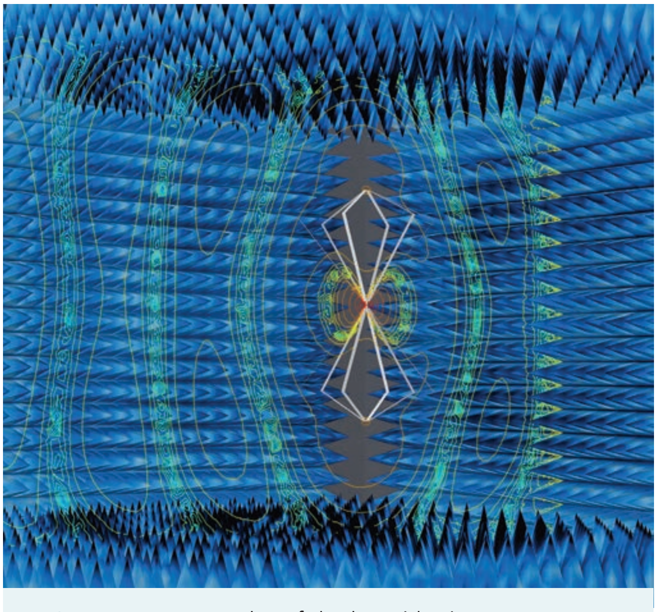


FIGURE 1 Contour plot of the logarithmic field distribution of a biconical antenna in a fully anechoic chamber.

Original work published in Interference Technology, August, 2020, reprinted with courtesy of Lectrix®.

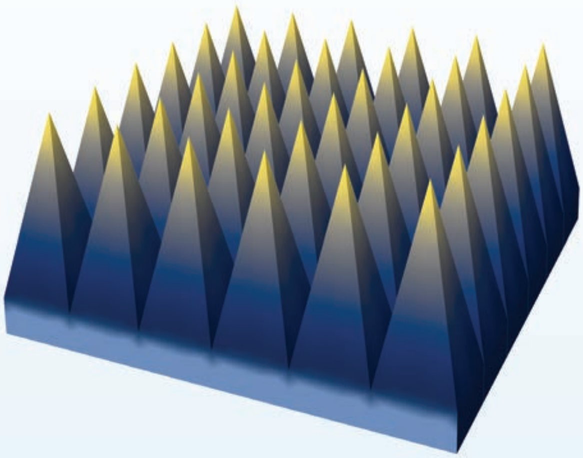


FIGURE 2 Microwave absorber simulation using Floquet periodic boundary conditions.

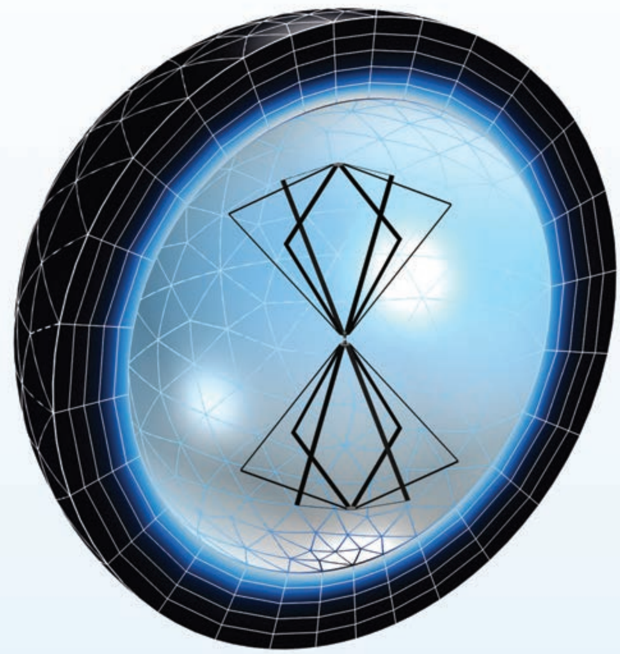


FIGURE 3 Biconical antenna enclosed by a perfectly matched layer (PML). The PML at the front is removed from view to show the interior.

closely as possible on the computer by using proven physics equations. Ideally, the numerical model is used to mimic multiple physical phenomena representing a great variety of operational conditions, which is hard to realize in a lab environment. Accurately analyzing real-world designs and conditions comes at a cost. The more complex the analysis, the more computational resources are needed. Therefore, engineering judgment is used for excluding unnecessary parts from the analysis and for configuring the simulation settings to ensure efficient computations.

» VIRTUAL EMC/ EMI TESTING

When evaluating EMI and EMC performance of radiating devices, test engineers often perform measurements in a fully anechoic chamber. Simulation tools are used to set up a numerical environment that can reproduce such tests virtually (Figure 1) by using, for example, the finite element method (FEM). For instance, the pyramidal absorbers that are attached to the anechoic chamber walls contain lossy conductive carbon particles. The absorbers attenuate the incident electromagnetic waves gradually with only small amounts of unwanted reflections. For efficiency, instead of modeling the full-sized wall of absorbers, the simulation uses only a single pyramidal unit cell with periodic boundary conditions (Figure 2). This is an efficient way of estimating the performance of the complete set of absorbers to make sure the reflectivity is at a minimum. Even if the model consists of just a single unit cell, the periodic boundary conditions make it equivalent to an infinite array of pyramidal absorbers. The effective homogeneous material properties obtained from the unit cell simulation are then used for the entire anechoic chamber wall.

To validate the virtual version of the anechoic chamber, a wideband biconical antenna is placed inside the anechoic chamber. The performance of the antenna (for example, far-field radiation patterns and S-parameters) is computed to validate that there is no degradation of performance due to the incomplete absorber characterization.

» MEMORY-LEAN COMPUTATIONAL TECHNIQUES

Although the real-world representation of the antenna inside the fully anechoic chamber in the simulation is visually quite appealing, as shown in Figure 1, its computational cost is unnecessarily high. The simulation can be made much faster and more efficient in terms of memory usage by using a numerical technique that is equivalent to the anechoic chamber walls. Such techniques involve using perfectly matched layer (PML) and absorbing boundary condition features. To efficiently study the near and far fields and other antenna parameters, it is sufficient to place the same biconical antenna in a much smaller surrounding air domain enclosed by a perfectly matched layer (Figure 3).

In order to simulate a large system efficiently, it is crucial to choose proper numerical boundary conditions. In addition, eliminating design details that are deemed to have negligible impact on the results, just keeping the relevant components, can make further efficiency gains. By using PMLs, a large system can be simulated and not limited to just device-level modeling.

In Figure 4, the electric field transmitted from a fictitious radiating device on the rear windshield of a car is studied to see the radiated emission effect over the cable harness inside. The PML covers the upper half-space, absorbs all outgoing waves, and ensures that reflected waves do not bounce back onto the car. Meanwhile, the bottom ground and the car body generate reflection and multipath fading effects on the cable

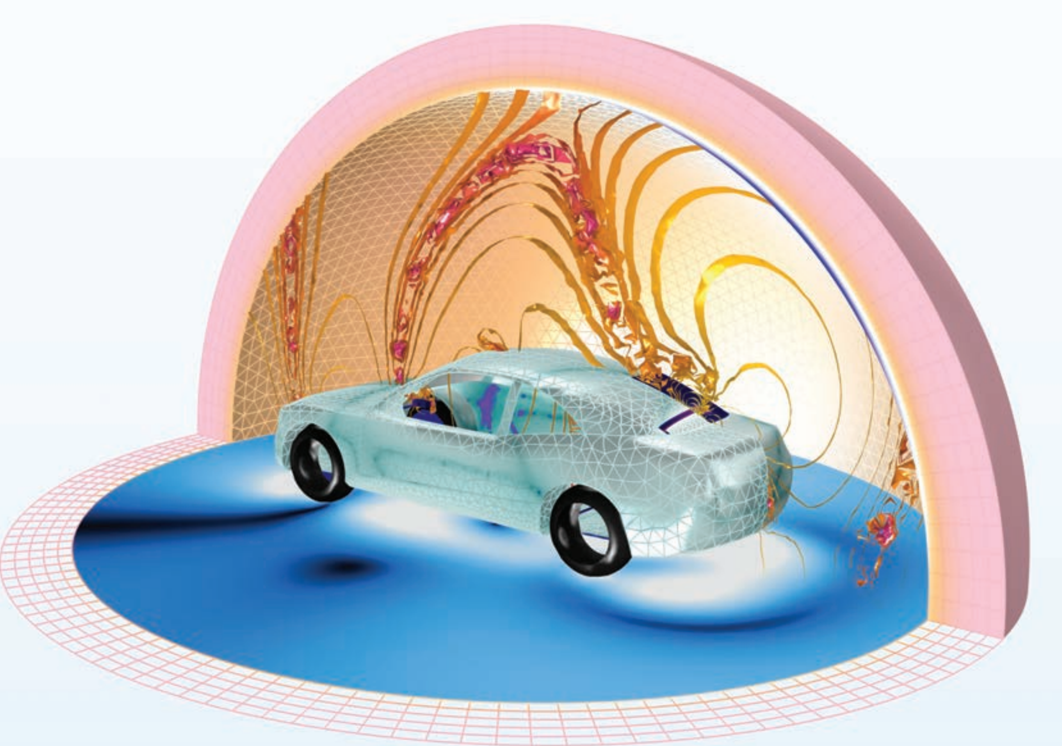


FIGURE 4 Impact on a cable harness by the radiation from the rear windshield in the FM radio frequency band.

harness. The electromagnetic waves coupled to the cable are a source for unwanted conducted emission as well. In a real car system, it would be hard to access and relocate the source and victims for the EMI/EMC test. However, by using simulation, it is possible to analyze arbitrary configurations. In this way, by not being limited by physical testing, engineers can produce more robust system designs.

» NUMERICAL METHODS FOR IOT DESIGN SOLUTIONS

By using simulation, one can estimate the actual performance of devices for IoT applications when they are deployed in a real environment. IoT devices may be placed in a living room, a garage, or other spaces in a house. The electrical size of the problem in terms of the number of spanned wavelengths can easily exceed what can be addressed by so-called full-wave numerical methods. Full-wave methods include the finite element method (FEM), the finite difference time domain (FDTD) method, and the method of moments (MoM). There are alternative computational electromagnetics approaches available for approximating the performance of IoT devices without sacrificing too much accuracy. In addition, such approximate methods can produce useful results while still using limited computational resources. One such approach is the method of ray tracing. Figure 5 shows multiscale simulation capabilities when ray tracing is employed together with FEM. The part of the simulation that uses FEM analyzes a small simulation domain surrounding the antenna of a wireless router that includes a truncated surrounding air domain. Rays are launched from the antenna location, and their initial strength is proportional to the directional intensity of the 3D far-field radiation pattern of the antenna. The antenna coverage inside a media room (Figure 5) can be approximated quickly without long simulation times or excessive memory usage. This multiscale electromagnetics modeling technique is a great alternative for overcoming the limitations of traditional computation methods for large EMI and EMC problems.

Simply combining existing computational methods can overcome the limitations of traditional numerical analysis. Two such situations are when you need to produce wideband results with high-frequency resolution or when you need to analyze signal integrity and time-domain reflectometry (TDR) for a large device. Such simulations can be very time consuming. However, in both cases, the computational performance can be greatly boosted by conducting a fast Fourier transform (FFT), either from the time domain to the frequency domain or the other way around. For example, you can first perform a transient analysis and then run a time-to-frequency FFT to achieve a wideband S-parameter and far-field calculation in the frequency domain. Alternatively, you can first perform a frequency sweep and then run a frequency-to-time FFT for a time-domain bandpass impulse response. This is useful for time-domain reflectometry analysis, such as identifying a defective part of a transmission line, which results in impedance mismatch and signal quality degradation.

» BRINGING ELECTROMAGNETICS SIMULATION ORGANIZATION-WIDE

Simulation provides virtual analysis platforms for a wide range of test scenarios. However, learning how to use electromagnetics simulation software may not be the best use of time for everyone in an organization. Limited training and access to simulation software may restrict usage of electromagnetics simulation tools to a small set of expert users. Completed numerical EMI and EMC test models may frequently need new input parameters in order to adjust to a real-world test environment's variations. The need for updating boundary conditions, mesh, and postprocessing settings outside of the

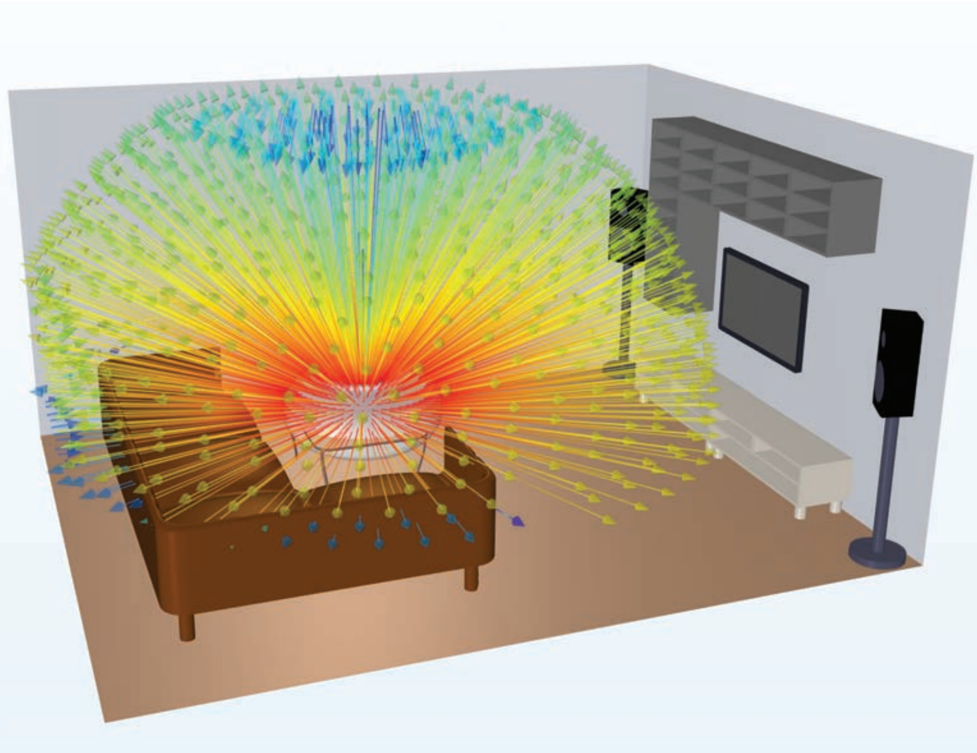


FIGURE 5 Multiscale electromagnetics simulation example. It combines the conventional finite element method for antenna analysis and ray tracing for describing indoor communication.

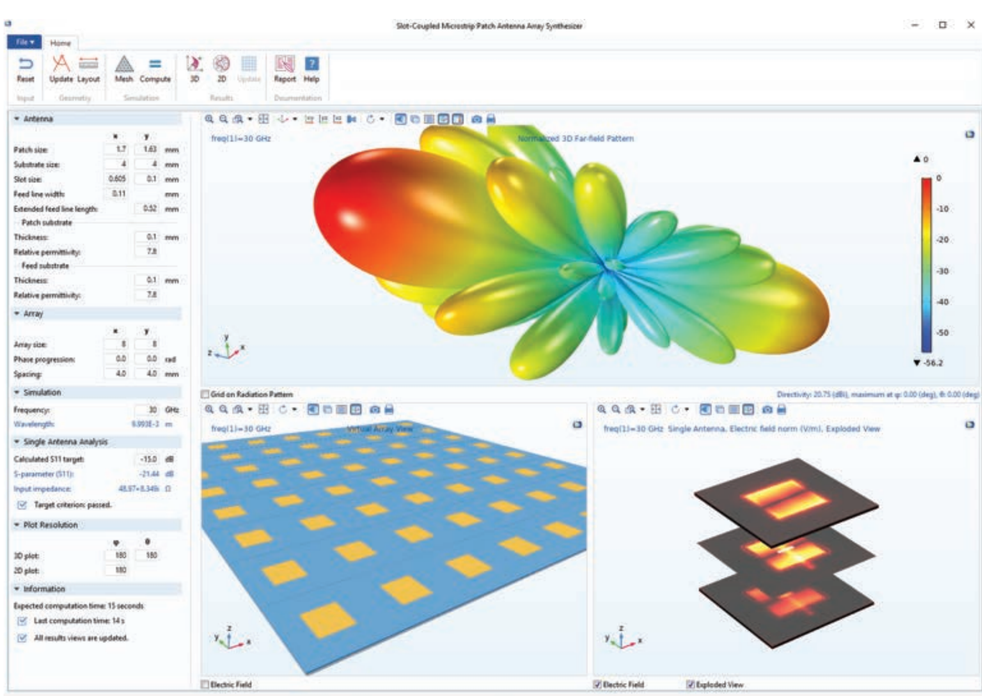


FIGURE 6 Simulation app for quickly estimating the far-field pattern of a phased array antenna using a full-wave single antenna simulation and array factor.

simulation group can cause unexpected delays in the development cycle. The good news is that simulation software has evolved to accommodate specialists who are not dedicated simulation engineers. The simulation models can be converted to easy-to-use apps (Figure 6). An app has a straightforward, specialized user interface (UI) and can be deployed to colleagues and customers through existing web browsers or as a standalone executable file. Such standalone apps do not require purchasing extra software licenses and can run regardless of the operating system. A large number of people involved in EMI test projects can easily access the virtual test kit provided by an app and optimize the product without learning how to use the software behind the curtain.

» EVOLVING SIMULATION TOOLS FOR AN EVOLVING 5G AND IOT WORLD

The variety of simulation tools that support multiple numerical methods within electromagnetics helps engineers and researchers not only to design conventional devices, such as filters, couplers, antennas, and waveguide structures, but also to test EMI and EMC problems in applications for 5G, IoT, and wireless communication. Conventional electromagnetics analyses can be extended to include multiple physical effects using multiphysics simulation. The simulation software industry is also evolving to meet the demands of the fast-paced market for emerging high-speed communication technologies and help more people benefit from simulation. ◎

Bluetest, Sweden

OPTIMIZING WIRELESS TEST SYSTEMS AND ANTENNAS FOR HIGH-SPEED COMMUNICATION

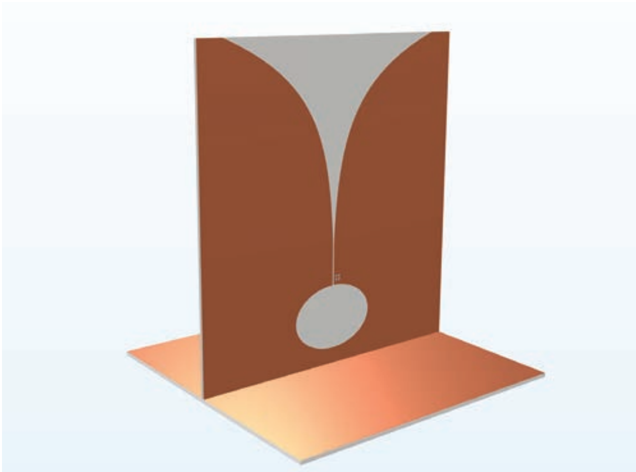
by **RACHEL KEATLEY**

Bluetest, a pioneer in wireless test solutions, designs reverberation systems used to measure the performance of wireless devices and wideband antennas. They use RF simulation to streamline their development cycle of design, fabrication, testing, and validation — enhancing high-speed wireless communication in the process.

FIGURE 1 An example of one of Bluetest's reverberation test systems, known as the RTS65. Bluetest currently has five different RTS on the market.

Every year, consumers are dazzled by the latest smartphones and wireless devices that hit the market. Before these upgraded gadgets reach the shelves, there is an extensive design and testing process that goes into developing them. Antennas, a paramount component of wireless devices, are consistently updated in order to keep up with advancing technology, such as 5G and the internet of things (IoT). They are expected to have greater bandwidth, meet safety regulations, and be small enough to fit into microdesigns.

To help engineers working with wireless equipment, Bluetest, a



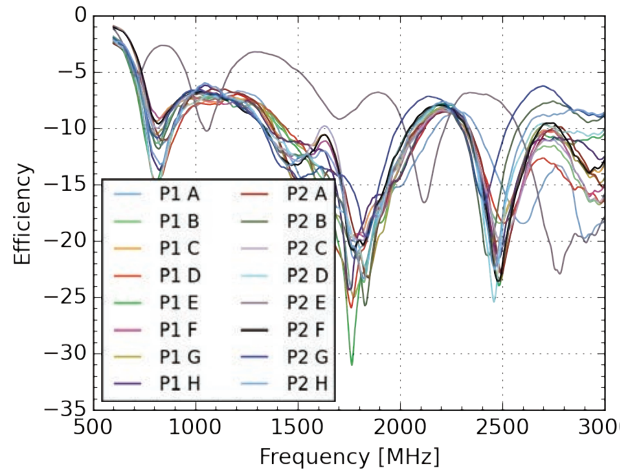


FIGURE 2 Bluetest's first prototype of a Vivaldi antenna, simulated in COMSOL Multiphysics®. The S-parameter plot (right) shows the impedance matching characteristics up to 3 GHz.

company based in Gothenburg, Sweden, has developed easy-to-use reverberation test systems (RTS) that measure the performance of wireless devices and antennas. Today, Bluetest is a market leader in over-the-air, multiple-input-multiple-output (MIMO) testing. Robert Rehammar, chief technology officer (CTO) at Bluetest, uses simulation to ensure that the components of Bluetest's RTS designs are optimized for performance.

» FROM STARTUP TO WORLDWIDE POWERHOUSE IN WIRELESS TEST SOLUTIONS

Since the early 1940s, antenna performance has been tested in anechoic chambers, microwave-absorbing rooms. In this type of chamber, an antenna is rotated, and its radiated intensity is measured in different directions. The data gained from this testing method is relatively easy to interpret, but anechoic chambers tend to be expensive, and their large size makes them unwieldy. In the 1960s, a different type of chamber was developed — the reverberation chamber — which was originally used for electromagnetic compatibility (EMC) testing. Unlike anechoic chambers, reverberation chambers reflect electromagnetic waves (or sound for the acoustic equivalent) instead of absorbing it. "You can generate very high field intensities inside this kind of chamber, which is a great feature for testing immunity and how sensitive a device is when it gets radiated with high-power electromagnetic fields," said Rehammar.

In the late 1990s, people learned that reverberation chambers can also be used to test certain antenna parameters. For example, a small antenna's most important property is its efficiency, or the quotient between the power you put into the antenna compared to how much power is actually radiated (typically measured in dB). "What was realized is that you can measure antenna efficiency in reverberation chambers, and it turned out that for a small antenna, you can do it very fast and accurately," said Rehammar.

Toward the beginning of the reverberation testing system's popularity, Per-Simon Kildal, a professor of antenna systems at Chalmers University of Technology in Sweden, started a research project on reverberation chambers and their ability to analyze antennas. After studying these chambers, Kildal was inspired to start a company based on his findings — as a result, Bluetest was born. For several years, Bluetest was a small research startup, but in 2010, the company grew significantly. Around this time, 4G, or the fourth generation of mobile systems (also known as LTE), was introduced, along with MIMO. As a result, said Rehammar, "A lot of very complicated questions popped up, like: 'How are we going to test the performance of these systems?'"

Luckily for Bluetest, it turned out that using reverberation chambers for 4G and MIMO testing is highly efficient because it is fast, affordable, and accurate. "Today, essentially all mobile phone vendors in the world use Bluetest equipment to test their antenna and radio performance," said Rehammar.

> "Today, essentially all mobile phone vendors in the world use Bluetest equipment to test their antenna and radio performance."
>
> — ROBERT REHAMMAR, CHIEF TECHNOLOGY OFFICER AT BLUETEST

» MEASURING ANTENNA PERFORMANCE

Bluetest's reverberation systems (Figure 1) perform passive and active tests to determine whether or not a device is optimized. Passive tests predominantly measure antenna efficiency, while active tests measure the total radiated power and total isotropic sensitivity in the device under test's (DUT) transmitter and receiver, respectively. During active tests, the transmitter and receiver in the DUT are powered on. Active measurements help give an overview of how the DUT performs as a whole. Both tests help ensure that the device, such as a mobile phone, meets regulations and customer requirements.

All of Bluetest's reverberation test systems and products are designed and produced at their main office in Gothenburg. The RTS contains a wide variety of components, such as walls

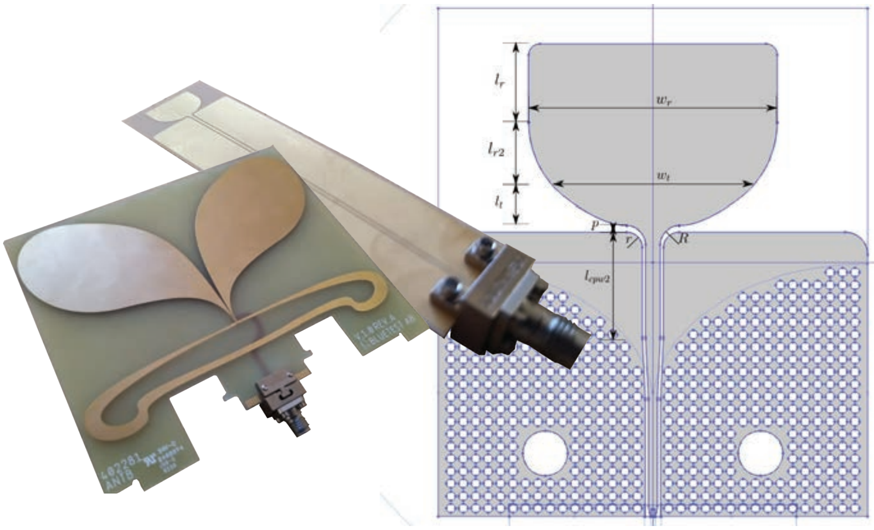


FIGURE 3 Fabricated antennas designed using COMSOL Multiphysics®.

made of reflective material, a reference antenna, four to sixteen measurement antennas with different polarizations, mode stirrers, RF interfaces, and more. When the production process is complete, the system is packaged in a large wooden cradle and sent to customers around the world. "One of the neat things about the reverberation test systems is that, despite that they are quite large when compared to a computer or a measurement instrument, for an over-the-air test system, they are very small," said Rehammar.

» DESIGN, FABRICATION, TEST, VALIDATION

Bluetest is in the process of designing new technology to use in their reverberation test systems for millimeter-wave (mmWave) applications, including the 5G mmWave band, where the center frequency is an order of magnitude higher than that of conventional microwave applications. High-speed communication relies on a wide bandwidth, which is provided by a high carrier frequency. One of the most popular antenna designs for wideband applications is the Vivaldi antenna — a tapered slot antenna. "When it comes to antennas, we need to be able to test anything from the low cellular bands around 650 MHz up to over 40 GHz," said Rehammar.

The wavelength in millimeter-wave device designs is much smaller than the microwave wavelength, and any minor physical distortion due to thermal-structural effects or fabrication tolerance error would undesirably impact its performance. Therefore, it is critical to validate the performance of such devices using simulation. Bluetest used the COMSOL Multiphysics® software and add-on RF Module to optimize their antenna and circuit designs, including the Vivaldi antenna.

The first prototype of the Vivaldi antenna design was modeled in FR4 substrate (a composite material made up of woven fiber glass and epoxy resin) with a thickness of 1.6 mm. Simulating the first iteration of this antenna allowed Rehammar and his team to see that there were a few issues relating to its mounting, size, stability, and efficiency while operating at low frequencies. Thanks to these findings, they were able to simulate an improved Vivaldi antenna by implementing Bézier curves into their model (Figure 2).

Bluetest also simulated, designed, and tested the efficiency of a wideband monopole antenna for ultrawideband operating from 6 GHz to 67 GHz. This type of antenna is used in their reverberation test systems for 5G measurements; it also helps provide the system with more versatility because it can be used during a measurement without switching the standard test antenna.

The usage of simulation is not limited to antenna designs. To enhance the performance of the reverberation chamber, Bluetest not only investigated the resonance eigenmodes of a customized cavity but also developed circuit-to-waveguide transitions using the RF Module.

“At the beginning stages of building a design, you need simulation, and to confirm your physical device is working properly, you have to do measurements."

— ROBERT REHAMMAR, CHIEF TECHNOLOGY OFFICER AT BLUETEST

» KEEPING UP WITH THE ADVANCEMENT OF TECHNOLOGY

At Bluetest, Rehammar believes that simulation technology and measurement technology complement each other completely. "At the beginning stages of building a design, you need simulation, and to confirm your physical device is working properly, you have to do measurements," said Rehammar. Bluetest's systems are consistently being updated to keep up with the advancement of wireless technology, especially within the mobile phone development industry. "Before 5G, mobile systems operated up to about 2.6 GHz, and now you have 5G systems that can run up to 40 GHz," said Rehammar. To stay on track with this advancing field, Bluetest has been working on supporting as many frequency bands as possible. With the help of simulation, Bluetest can focus on improving their RTS test time and measurement accuracy, while keeping the testing complexity at a high level.

As for the future of wireless technology, Rehammar hopes that Bluetest can play a role in helping provide internet access to parts of the world that are missing it. Says Rehammar: "There are billions of people in the world who still do not have stable internet access, and that is something I really hope we can contribute to change within the next ten years." ◎

Radiotelevisione Italiana (RAI), Italy

PROTOTYPING ANTENNAS FOR MOBILE RECORDING OF TV SPORTS EVENTS WITH SIMULATION

by **DIXITA PATEL**

Researchers at Radiotelevisione Italiana (RAI) are designing and optimizing new circularly polarized antennas to record live sporting events with the help of multiphysics simulation.

Every year in Italy (and its neighboring countries), hundreds of thousands of fans surround one of the most prestigious cycling events, *Giro d'Italia*, or Tour of Italy. This multiple-stage bicycle race is one of the world's three grand cycling tours, the others being the *Tour de France* and the *Vuelta a España*. In addition to the fans at the race, millions of viewers are able to join from home thanks to RAI, Italy's national public broadcasting company.

Recording live sports events on the move has been a traditional activity of RAI for decades. To do so, typically eight motorcycles are equipped with various facilities, including radio cameras, audio radio links for commentators, and geolocalization means (Figure 1). A complex infrastructure, including two recording helicopters and two aircraft relaying the signals to a remote outside broadcast (OB) van, is needed to convey live TV to the broadcasting distribution. In this framework, the Center for Research, Technological Innovation and Experimentation (RAI-CRITS) has been providing technical support in this TV production segment.

FIGURE 1 Motorcycles used for the *Giro d'Italia*, or Tour of Italy, cycling event.

Recently, issues on the commentary radio link from motorcycle to helicopter required a specific investigation. RAI researchers Assunta De Vita, Alessandro Lucco Castello, and Bruno Sacco identified the problem and proposed a solution based on the design of a low-profile, circularly polarized (CP) antenna. The proposed radiating system has been modeled and simulated with the COMSOL Multiphysics® software. The results have been confirmed in the prototypes by means of laboratory measurements and field tests.

» TV SHOOTING OF LIVE SPORTS EVENTS: TRANSITION TO DIGITAL

In recent years, recording live sports events on the move has been progressively digitized. For RAI, when it comes to shooting *Giro d'Italia*, it is important for the commentary to be effectively coordinated throughout the duration of the race. During the live event, motorcycles are equipped with video cameras and audio radio for the commentators that live shoot alongside the racers. Three helicopters and an airplane are employed above the race; two of them for video shooting and the others acting as a "bridge", relaying the signals

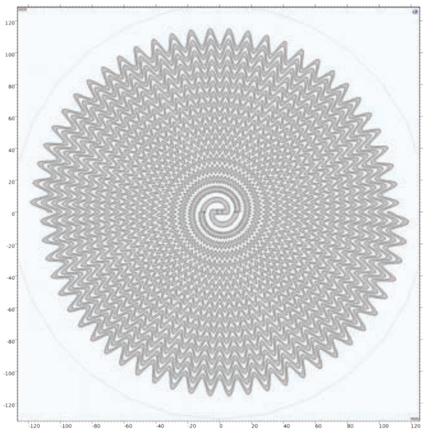


FIGURE 2 Work plane view of the meander spiral UHF CP antenna.

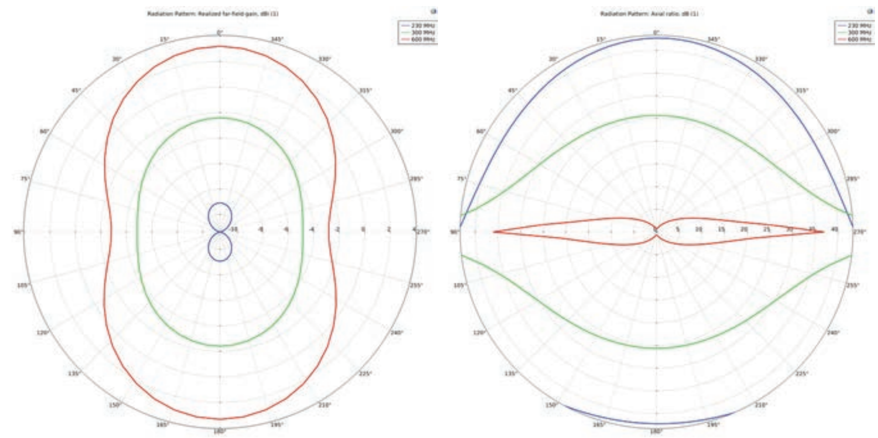


FIGURE 3 Radiation pattern plots showing the antenna gain (left) and axial ratio (right).

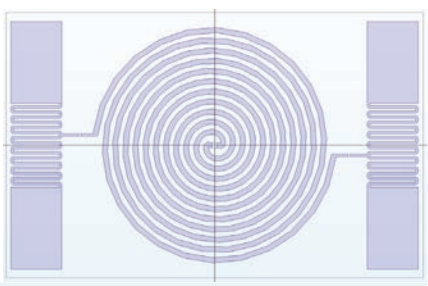


FIGURE 4 The dual-band VHF/UHF CP antenna with a two-arm Archimedean spiral and two inductive-loaded dipoles.

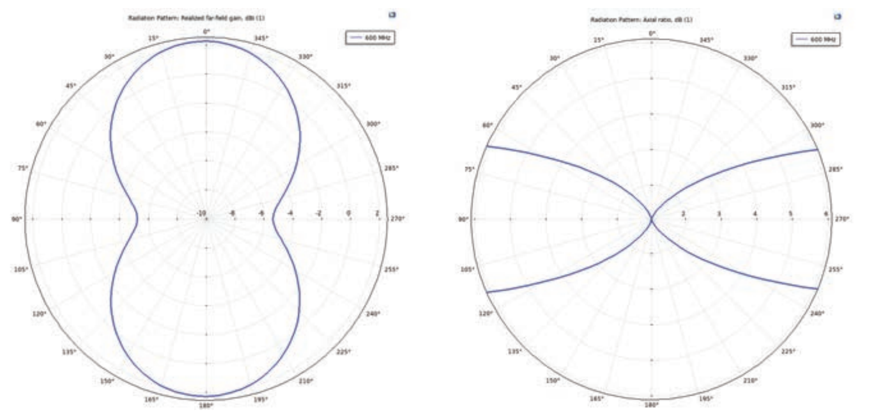


FIGURE 5 Radiation pattern plots showing the antenna gain (left) and axial ratio (right) at 600 MHz.

received from the motorcycles to the OB van at the finish line, where technicians mix the signals from the motorcycles, helicopters, still cameras, mobile interview team cameras, and commentary.

In some cases, the team encounters problems, such as sporadic signal interruptions. "There was an issue when we experienced a break of the radio link between the motorcycles and helicopters. Our investigation identified the problem in the polarization misalignment: a known aspect in airborne radio applications," said Sacco. To improve the communication link, RAI's solution was to design an antenna based on circular polarization (CP) to allow for the correct reception from any reciprocal orientation.

This new antenna design was required to operate in a dual-band, very high frequency/ultrahigh frequency (VHF/UHF), configuration. The antenna also needed to be compact enough to be placed in a motorcycle top case. However, the limited space available in the top case (about 40 cm x 20 cm) is conflicting with the VHF operation that would require somewhat larger dimensions. With these stringent requirements, the researchers modeled and tested many antenna designs in the frequencies' band of interest, in terms of impedance matching, realized gain, and axial ratio.

» PROTOTYPING COMPACT ANTENNA SOLUTIONS WITH NUMERICAL MODELING

To design a compact antenna solution that meets the desired requirements, the researchers implemented various antenna prototypes using COMSOL Multiphysics® along with the RF and Optimization modules. They tested several configurations for the best performance in the frequency range of interest, including an Archimedean spiral CP antenna and a dual-crossed, double-folded dipole (DCDFD) antenna. The gain enhancement and the impact on the bandwidth and polarization purity with the introduction of a reflector was also studied.

The first attempt involved a circularly polarized antenna design based on a conventional two-arm Archimedean spiral structure. After simulating the spiral antenna alone, results showed good CP performance in the UHF band at 500–600 MHz, but not at 230 MHz due to the size limit. "The antenna needed to work simultaneously in both bands. While it worked well for UHF, it definitely suffered for limited size to properly perform in the VHF band," said Sacco. To maximize the RF energy conveyed toward the receiver, the adoption of a conducting plane reflector is often desirable. In order to estimate the influence of the geometrical and electrical parameters on the antenna performance,

FIGURE 6 The deployment into the real system environment, the motorcycle top case.

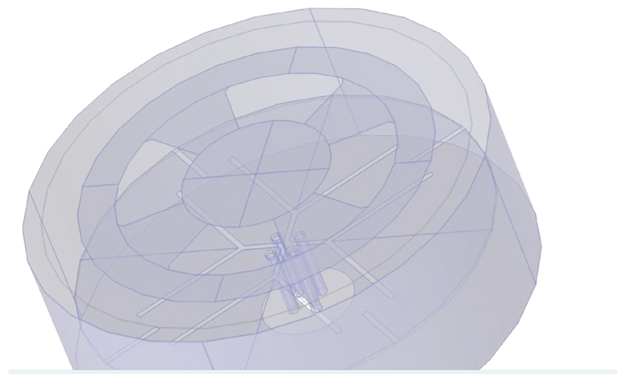


FIGURE 7 Geometry of the DCDFD circularly polarized UHF antenna.

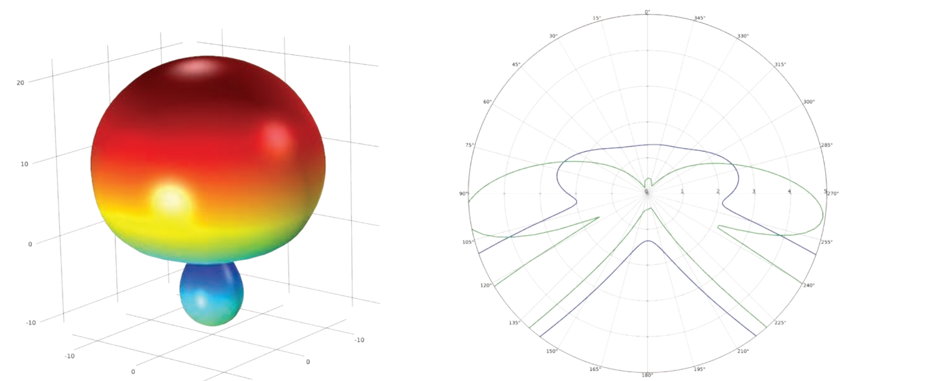


FIGURE 8 3D plot of the realized gain (left), and the axial ratio (right) of the DCDFD CP UHF antenna at 500 and 600 MHz.

the *Parametric Sweep* feature was used. In particular, the influence of the reflector distance on the far-field radiation pattern and axial ratio was investigated. As expected, the reflector improves the antenna gain but worsens the axial ratio (Figure 3), requiring further optimization.

An attempt to extend the operating frequency range downward without increasing the overall size has been done using a meander line in the two-arm Archimedean spiral periphery with a radial perturbation, as shown in Figure 2. To this purpose, the spiral geometry was parameterized within the COMSOL® software. "We adopted the *Parametric Curve* feature because of the geometry complexity," said De Vita. In this case, although simulations showed that the minimum usable frequency was actually extended toward the VHF range, the goal of 230 MHz was not yet fully reached within the available antenna diameter.

The next attempt involved the addition to the flat spiral of two inductive-loaded dipoles (Figure 4) tuned to the desired VHF of 230 MHz. With multiple iterations, the authors optimized the design parameters of this new model in the VHF band for antenna gain and axial ratio (Figure 5) at both 230 MHz and low-UHF bands. "The *Axial Ratio* feature is a nice tool for evaluating the quality for circular polarization," said Sacco.

The prototype antenna has been measured in the laboratory by means of a very near field scanner EMscan RFX2 (Figure 6). The simulated far-field antenna performance has been confirmed by such laboratory measurements, as well as by field tests.

In a second phase, since the operating frequencies have been reassigned and the VHF requirement has been dropped, another design session has been started for the new frequencies (UHF, 500 and 600 MHz). "We continued the analysis of antennas and prototyped another kind that was a bit more complicated because it requires a four-phase feeding network," said Sacco.

The new design was a dual-crossed, double-folded dipole (DCDFD) antenna (Figure 7). This approach would achieve a fair impedance in the presence of the reflecting cavity. Simulation analysis showed good axial ratio, antenna gain, and impedance matching (Figure 8). At present, further tests are ongoing to evaluate the bandwidth performance optimization and the four-phase feeding network design.

» THE FUTURE OF MOBILE TV

In terms of future research, RAI has an ongoing project to study antennas that can receive mobile TV services for smartphones, tablets, and other mobile devices. "We have the possibility to provide TV services to mobile devices, but many problems are to be solved in order to allow for this service," said De Vita. Indeed, the possible integration of antennas in mobile terminals, in the lower part of the UHF band, poses a great challenge for antenna designers, since the limited dimensions of the mobile devices physically set an upper bound to the achievable bandwidth, introducing basic restrictions to the expected performance.

In addition, in the case of a mobile device, the antenna behavior is also influenced when placed in an individual's hand, so this will be an issue to overcome for the researchers at RAI. "This next activity is somewhat complimentary with shooting on the move. Shooting is a professional application, so you have to make sure that the antenna is as good and reliable as possible," said Sacco.

RAI has found that the simulation results appear very promising and will help them continue to make further improvements in their research. ◎

COMSOL, Massachusetts, USA

FULL-WAVE SIMULATION EXTENDS THE RANGE AND DEPTH OF LENS ANALYSIS

by **YOSUKE MIZUYAMA**

Optical lenses are found in your cellphone and laptop and are used to inscribe your devices, food packaging dates, and car door jambs. By using simulation to analyze and optimize optical lenses, designers can reduce the number of prototypes needed and provide valuable insight to conduct better lens experiments.

FIGURE 1 Optical lenses. Image by Bill Ebbesen and licensed under CC BY-SA 3.0, via Wikimedia Commons.

In addition to the optical lenses found in cell phones, laptop computers, and more, we are surrounded by items processed through optical lenses every day. For example, many of the logos and other graphics seen on hardware devices, including cellphones and computers, are inscribed by a laser, or cut out by a high-power laser, in which case a laser beam had passed through many lenses. The same is true for food package date markings, markings on medical devices, and the so-called jamb stickers seen on car doors. As a result, we indirectly benefit to a great extent from computational lens analysis, without even knowing it.

Before such lenses (Figure 1) are used in the real world, a number of computer simulations are typically

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performed. While simulation does not replace testing, it can help reduce the number of prototypes needed and also provide valuable insight to conduct better experiments. For the simulation of lenses, different methods are available, ranging from traditional lens design methods to simulations that solve the full Maxwell's equations. But what might go into the decision to perform a lens simulation using one method over the other?

» DESIGN VERSUS ANALYSIS

For the purpose of this article, lens simulation can be divided into two categories: design and analysis. Design here means optimizing a lens for a particular application, whereas analysis means gaining a deeper understanding of what is going on in the lens system.

For lens design, one tries to find an optimal shape of a lens so that it delivers the beam in a desired way; put another way, to make sure the lens focuses or diverges the beam appropriately. The goal of lens design is usually to minimize the optical aberration. Simulation can be used to achieve an optimal lens design, and this is a standard application of optics simulation. For the purpose of lens design, a simulation is usually carried out by a ray-tracing method for reasons of computational efficiency.

In a ray-tracing simulation, the electromagnetic waves are approximated by rays. The drawback of this approach is that diffraction effects are not included. However, in many cases, understanding the diffraction effects is not critical for the design. When diffraction effects are important, wave-optics methods that solve for the full set of Maxwell's equations without inherent approximations, other than the numerical ones required to fit the simulation in digital form on a computer, are used. When does one use wave optics instead of ray tracing for lens simulations? As it turns out, it is useful for both design and analysis.

In lens design, one of the important characteristics of the lens is the spot size. Ray tracing cannot simulate a focused beam because it is the result of diffraction effects. The detailed simulation of diffraction requires a full-wave optics simulation. To cope with this, ray tracing software often comes with some wave optics simulation tools, such as Fourier transformation and methods based on Huygens theorem and Fresnel diffraction. These three methods are sometimes collectively called physical optics. The formulas used are derived from an approximate theory and typically find a scalar electromagnetic field solution, which is good enough to design the beam size in many cases.

In lens analysis, physical optics may be adequate, but sometimes a more rigorous theory — specifically, Maxwell's equations — are needed to obtain the full vector representation of the electromagnetic fields. This methodology is sometimes called the full-wave method. High-numerical-aperture lenses require a full-wave approach to be accurately analyzed; the physical-optics methods are not applicable for analyzing fast lenses.

When polarization matters or when the material has some anisotropic properties, a full-wave analysis is needed instead of scalar approximations. It is rare that a lens itself has such complicated properties, but it is also rare that the system being analyzed consists of only a single lens; several other optical components are usually involved. If so, it may be best to simulate not only the lens, but also the surrounding optics together with the lens by the full-wave method if possible. Historically, full-wave methods were frequently so computationally demanding that they were impossible to use in practice.

» PHYSICAL OPTICS VERSUS FULL-WAVE OPTICS

There are two underlying differences between physical optics and full-wave simulations.

In the physical optics case, once the field is known in one plane, the method can calculate the field in another plane wherever it is; that is, it does not require the information between the two planes as long as the space between them is uniform. Therefore, it does not need a volumetric mesh in its computational domain.

On the other hand, the full-wave approach needs to solve for Maxwell's equations in the entire domain. A very powerful numerical method for this purpose is the finite element method, in which the domain is meshed; it is subdivided into small elements having a simple shape. The maximum mesh element size is limited to a fraction of the wavelength to satisfy the Nyquist criterion. The shorter the wavelength, the smaller the finite element mesh element size. A smaller element size means a greater number of finite elements are needed and with that comes greater computational resources in terms of computational time and memory.

The physical optics methods typically find an outgoing wave field as a solution neglecting any reflections. This is how the physical optics formulas are derived. Compared to this, the full-wave method finds a solution that automatically includes reflections if there are any. If there are any material interfaces in the simulation model, Maxwell's equations will not give an outgoing wave field only, since it is not the real solution. The real solution is the coherently combined outgoing wave field and the reflections from the material interfaces.

» LENS SIMULATION WITH THE FULL-WAVE METHOD

There are three reasons why lens simulations using the full-wave method are difficult.

Keeping in mind that the full-wave approach requires the mesh and the mesh size needs to resolve the wave, one can immediately understand how difficult it is to simulate a lens with the full-wave method. If the size of the lens and the focal length are of millimeter-scale range, for example, the domain size can be a thousand times the wavelength. Then, the number of mesh elements will be in the billions, so a regular computer cannot handle it.

The refractive index is the second reason. Usually, any optical component has a refractive index higher than one — say, 1.5. Then, the wavelength in the optical component is 1/1.5 times the wavelength, which is shorter than the wavelength in the vacuum. This again increases the number of mesh elements, thereby further increasing the computational demands.

The third reason is interference. Any optical component has material interfaces, where the Fresnel reflection takes place. There is a 4% reflection from a material surface of a refractive index of 1.5 for a beam of normal incidence. This reflection causes an interference with

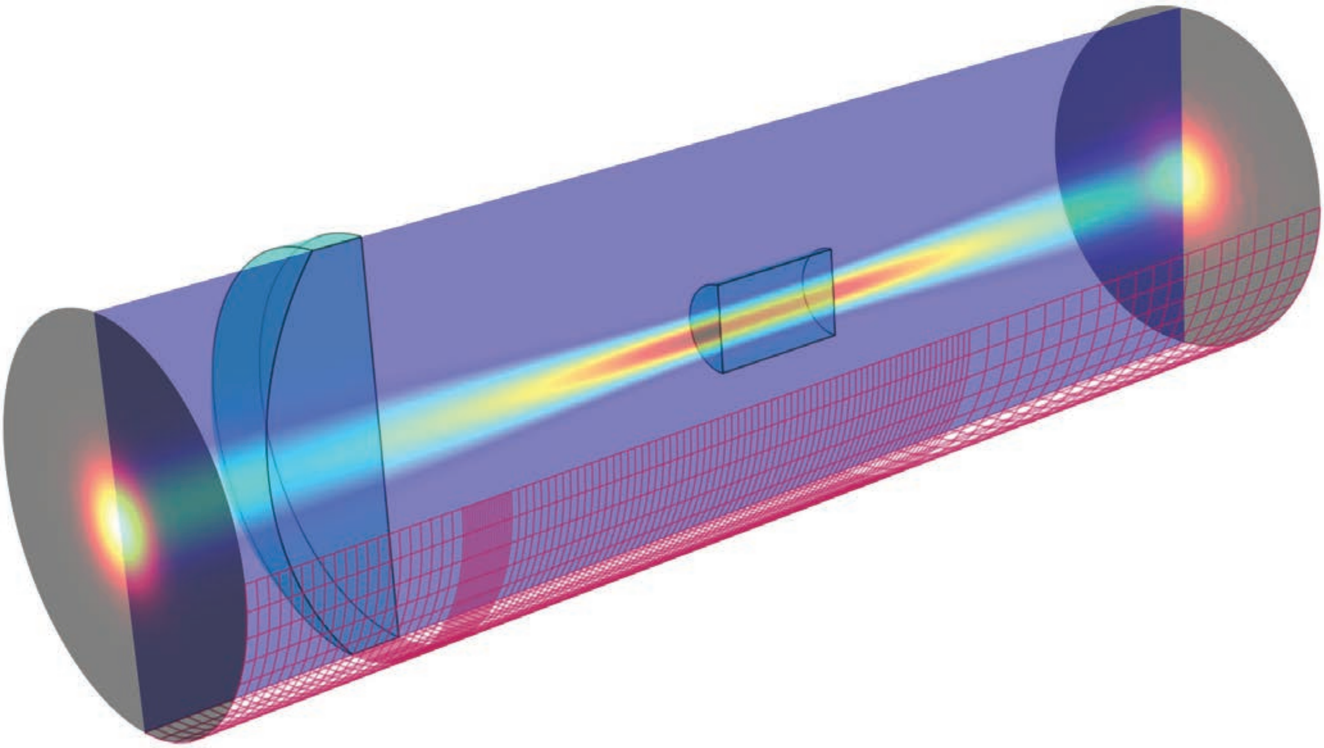

FIGURE 2 Full-wave simulation of a lens system including multiple optical components.

the incident beam, resulting in a fringe with the periodicity of one half of the wavelength. The mesh needs to resolve 1/2 times the wavelength. Combining with the refractive index effect, 1/3 times the wavelength needs to be resolved in the case of an index of 1.5; that is, the situation is three times worse for lens simulations than simulations in the open space, which are already difficult.

» THE BEAM ENVELOPE METHOD AND AR COATINGS

From the above discussions, it sounds like it is almost impossible to simulate lenses. However, using the full-wave method, we have the following two remedies at our disposal: the beam envelope method and antireflective coatings.

Instead of solving for the fast-oscillation electric field, the slowly varying envelope function can be solved for if the wave vector is known. This is called the beam envelope method. In this case, there is no theoretical approximation, but it is equivalent to solving Maxwell's equations. In this formulation, the mesh needs to resolve the envelope function rather than the field itself. The number of mesh elements is greatly reduced if the envelope function is slowly varying, which is the case in practice for many lens simulations.

Even with the beam envelope method, the interference fringes do not give the designer a free pass because the envelope function is no longer slowly varying in the fringes. To remedy this, one can use an AR coating. It is possible to mimic a material interface with an artificial phase jump, which artificially generates a destructive interference with the incident beam and ends up with no fringes. Introducing this artificial AR coating can be motivated, since optical components are AR-coated in almost all practical cases.

The COMSOL Multiphysics® software has these remedies available as built-in functionality. The *Beam Envelopes* interface of the Wave Optics Module is made with the beam envelope formulation and includes the *Transition* boundary condition, which can be used as an AR coating. Full-wave lens simulations (Figure 2) are therefore possible in a straightforward fashion by using a combination of the *Beam Envelopes* interface and the *Transition* boundary condition. It is possible to simulate slow lenses quite easily, whereas the simulation of fast lenses is more computationally demanding due to the fact that a finer mesh is needed. Fast lens simulations are still possible with a powerful-enough computer.

Full-wave simulations for multicomponent optical systems have previously been out of reach. However, using the methods outlined here, an entire optical system, including lenses and other optical components, can be simulated, provided the AR coating approach is applicable. In addition, full-wave simulations make birefringence analyses possible so that it can be used for the simulation of not only lenses, but also liquid crystals or second-harmonic generation (SHG) optics, including the lenses. Full-wave simulations performed in this manner extend the range and depth of lens analysis. ◎

Delft University of Technology, Netherlands

DESIGNING AN ENVIRONMENTALLY FRIENDLY ANODE BAKING PROCESS WITH NUMERICAL MODELING

Researchers at Delft University of Technology in the Netherlands are using multiphysics simulation to design an environmentally friendly anode baking process in collaboration with Aluchemie, an anode production company.

by RACHEL KEATLEY

FIGURE 1 Anode baking furnace at Aluchemie.

Aluminum, the third most abundant element in the Earth's crust, can be found in everything from the foil holding last night's dinner leftovers to the fuselage of a plane traveling across the world. Before aluminum can be used to produce such a variety of items, it has to be smelted and extracted through the Hall–Héroult process. During this process, aluminum is removed from an aluminum-rich rock, bauxite, using green anodes. In order to be effective in the Hall–Héroult process, green anodes need to have a low reactivity and a high strength and conductivity. To obtain these qualities, the anodes need to be baked.

Prajakta Nakate, a PhD student at Delft University of Technology (TU Delft), is part of a research team that is studying the design of the anode baking process. This project is in collaboration with Aluchemie, a carbon anode baking company in the Netherlands. To understand and optimize the anode baking process for increased aluminum production, the team turned to numerical simulation.

» AN ANODE BAKING PROCESS FIT FOR A CHEF

When baking a cake, a variety of ingredients are needed in order to get the right consistency, texture, and flavor. Think of the anode baking process like baking a cake, except the ingredients consist of multiphysics phenomena, such as turbulent flow, combustion processes, conjugate heat transfer, and radiation — and instead of a well-baked pastry, the end product is anodes that can be used in the Hall–Héroult process for aluminum extraction. "I was mainly interested in this project because it is a multiphysics problem," said Nakate. Unlike baking a cake, the anode baking process strives to achieve multiple goals, including uniform heat, reduced energy usage, and decreased soot formation during combustion.

This anode baking process is extremely energy intensive and releases environmentally dangerous emissions, like nitrogen oxides (NOx). This toxic gas is a common air pollutant and can form smog and acid rain. Nakate's research focuses on the reduction of NOx emitted during the anode baking process to limit the negative harmful effects the process has on the environment. "When it comes to environmental studies, chemical processes always get blamed, and that is what motivated me to work on the optimization of the anode baking process and ensure that it has minimal environmental impact," said Nakate.

In order to decrease the formation of NOx during anode baking, it is important to first understand all of the parameters involved in the process. Nakate said, "To understand all these things, you need a more sophisticated approach, and having a mathematical model to understand these parameters is the best choice."

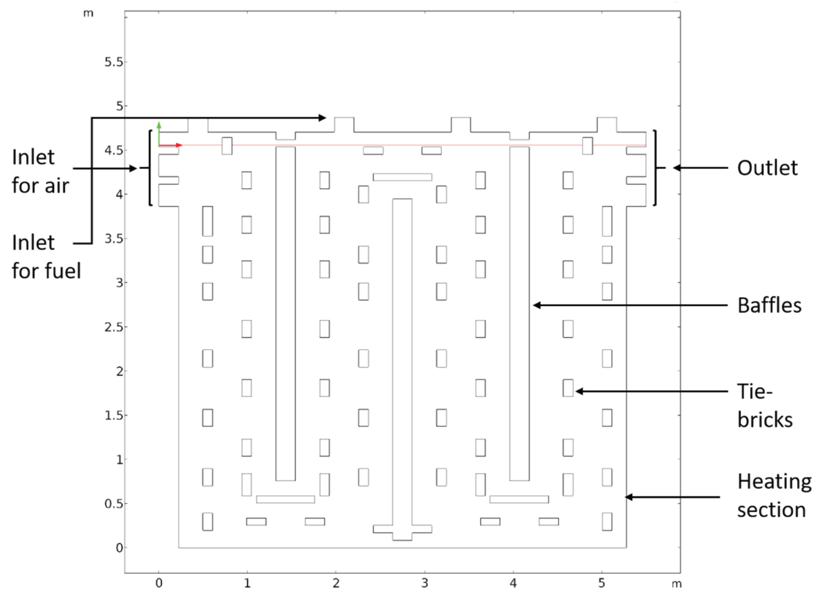

FIGURE 2 Geometry along with the boundaries of the anode baking furnace modeled in COMSOL Multiphysics®. (The most important parts of the furnace are below the horizontal red line.)

» NUMERICAL MODELING: THE SECRET INGREDIENT TO DESIGNING AN IDEAL ANODE BAKING PROCESS

Prior to teaming up with TU Delft, Aluchemie tried to optimize their anode baking furnaces (Figure 1) using trial and error, but this method proved to be time consuming. "The most important part of this project is to identify the anode baking process's problem areas, and I would say that is only possible with simulation," said Nakate. When it came to modeling the anode baking process, the TU Delft research team used the COMSOL Multiphysics® software because it provides a multiphysics environment, which is essential for this particular project.

The researchers studied the anode baking process using two

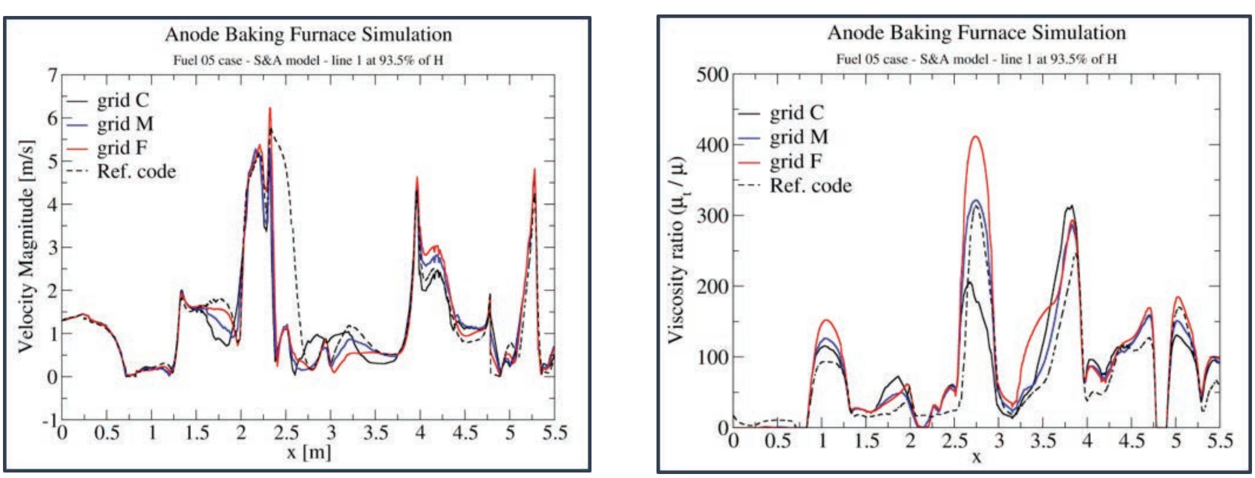

FIGURE 3 Comparison of COMSOL Multiphysics® and IB Raptor code's simulation results for velocity (left) and viscosity ratio (right).

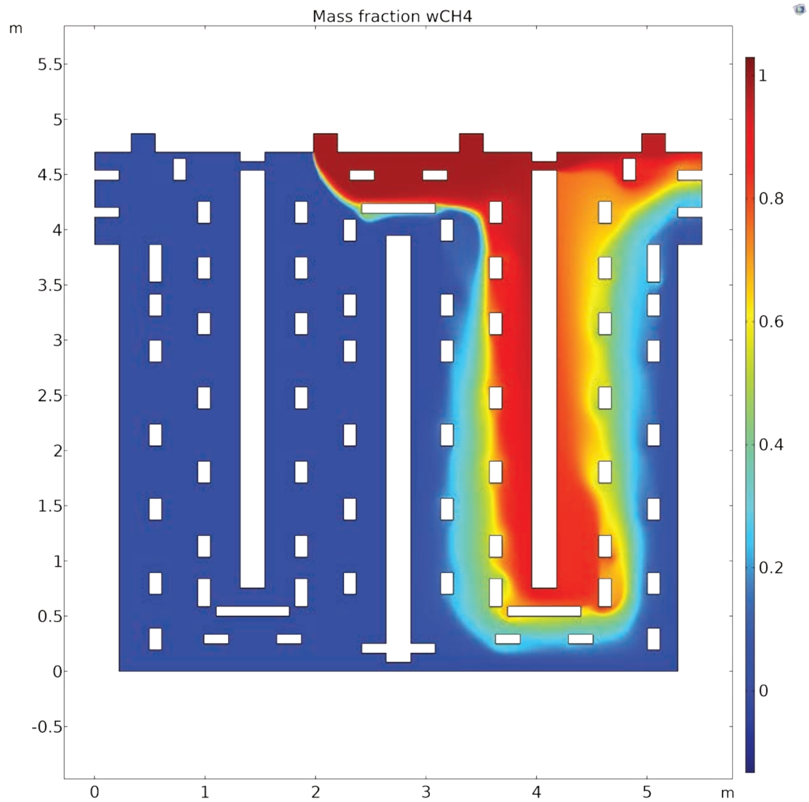

FIGURE 4 Mass fraction of CH_4 in the reactive turbulent flow model.

models. The first model analyzed a nonreactive turbulent flow of air and fuel (methane) in the furnace, while the second model analyzed a reactive flow with radiation in the furnace. The second model was also a continuation of the first model. The multiple physical phenomena involved in the anode baking process were described in a model that translates into a set of mathematical equations, which formed the basis of these numerical models.

Both models included the same geometry: a 2D section from a furnace's heating zone (Figure 2). According to Nakate, working with the complex geometry was one of the most challenging aspects of this project. The geometry of the furnace includes 3 baffles and about 60–70 tie-bricks in each section of the furnace. "If you replace the ties at different positions, they change the flow in the furnace, which affects the anode baking process's chemical species distribution and temperature," said Nakate. The tie-bricks and baffles provide structural strength to the furnace's flue wall from which the furnace's exhaust is released.

» NONREACTIVE AND REACTIVE TURBULENT FLOW MODELS

When working on the nonreactive turbulent flow model, Nakate and the team simulated and compared two turbulent flow models: the Spalart–Allmaras model and the k-ε model. Both of these models have their own advantages, especially in relation to analyzing anode baking.

The team validated the flow field results generated by the Spalart–Allmaras model with the IB Raptor code provided via another simulation environment. "The IB Raptor code is mostly a flow solver; we wanted to validate our results to a software that is dedicated to flow simulations," said Nakate. COMSOL Multiphysics and the IB Raptor code generated similar velocity and viscosity flow results in the furnace (Figure 3).

The research team extended the first model by adding a single step combustion reaction of methane (CH_4) and heat transfer, including radiation in participating media, using the Chemical Reaction Engineering Module and the Heat Transfer Module, add-on products to COMSOL Multiphysics, respectively. The simulation results of the reactive flow model with radiation provided the team with reasonable results (Figure 4). This opens to further improvements of the models for more understanding and optimization of NOx furnaces.

> "The most important part of this project is to identify the anode baking process's problem areas, and I would say that is only possible with simulation."
> — PRAJAKTA NAKATE, TU DELFT

» COOKING UP NEW MODELS FOR ANODE BAKING RESEARCH

Simulation enabled the TU Delft team and Nakate to analyze and identify important regions in the anode baking furnace, which would not have been possible with experimentation alone due to the furnace's large size. "We can only see the furnace from the top by removing the burner and taking photographs with the thermal camera, but viewing the actual temperature or the actual chemical species distribution in the furnace is only possible with simulation," said Nakate.

As for future research, the TU Delft team is currently working on extending their anode baking process's 2D model to a 3D transient model. They also plan to thoroughly investigate combustion in their new model, which will help them learn more about NOx reduction in the anode baking process. Radiation, a primary physical phenomenon in the anode baking process, will also be further analyzed in the extended model.

While discussing her own personal goals, Nakate said: "I wanted to work on a project that had a direct application to industries and a positive environmental impact." Therefore, studying the anode baking process alongside Aluchemie was a perfect combination of her goals. With the knowledge gained, the TU Delft team and Nakate are confident about continuing their research and finding new ways to design an optimized anode baking process with simulation. ◎

Rethinking Medical Device Design in a Post-COVID-19 World

by **DANIEL SMITH**

The introduction of new healthcare technologies has been hampered due to restrictions on trials of medical devices, elective procedures, and access to medical facilities as part of COVID-19 safety protocols. The industry is poised to accelerate the changeover to newer technologies once the dust settles and trials can resume. One example is that device companies are moving toward reversible and irreversible electroporation where an electrical field is applied to increase the permeability of cell membranes in order to surgically target a tumor or improve drug delivery into the cell. This technique can overcome some of the inherent drawbacks in classical RF ablation, but also creates challenges in the power delivery system, since higher intensity, shorter pulses of energy are needed.

Technology development companies, such as Emphysys, are helping to meet this challenge. Our scientists and engineers have expertise in multimodal, high-frequency energy generation and software control systems, along with sophisticated simulation abilities to fully understand the system under design. When combined with numerical simulations, this creates a powerful group able to rapidly prototype any energy-based medical device on a much shorter time scale than traditionally expected.

> **"The window [of operation] provided by the simulations usually means the power supply can meet the needs of the product on the first iteration."**

Our company has roots in power generation for plasma sources, devices typically used in the semiconductor manufacturing industry. As such, we have built RF generators ranging from 10 watts to 100 kilowatts, frequencies from DC all the way up to microwave, and waveforms ranging from single and multifrequency sinusoidal to custom pulsed waveforms running in a closed-loop control system.

All of this institutional knowledge lends itself perfectly to the medical device space, where power requirements are usually less than 100 watts and frequencies are on the order of a few hundred kilohertz. Skilled technology development companies can design custom waveforms in medical devices for electroporation in a way that minimizes unwanted effects, such as neurostimulation and tissue charring. We have developed dedicated physics interfaces within COMSOL Multiphysics® to model the electroporation process, as well as the device itself.

Running electroporation simulations on both a microscopic (of the individual pores) and macroscopic (of the entire handpiece) model allows us to construct a window of operation for the power supply in terms of pulse duration; peak power, current, or voltage; and frequency, in the case that the pulse is an RF signal. This allows us to write a requirement specification for the power supply, which can be constructed in-house by our engineering team. The window provided by the simulations usually means the power supply can meet the needs of the product on the first iteration.

The simulations also allow us to optimize the handpiece, or patient applicator, itself, such that it will work for a wide range of patients' characteristic impedance, since every person is slightly different in terms of weight, muscle density, etc. Once design specifications for the power supply and handpiece are available, the electronics boards; control systems; and software, including the user interface to the device can be constructed and integrated seamlessly into the system. The fact that we can execute all stages of this process in-house is one of the reasons why we have a competitive edge in terms of the time it takes to go from concept to functional prototype.

This array of capabilities is also well suited for project recovery. Once medical device trials get back to normal post-COVID-19, many projects will be significantly behind schedule. Emphysys has the expertise of getting such projects back on track in terms of the system design as well as the project timeline. Moving forward, we expect to see a new generation of medical devices based on electroporation as opposed to traditional thermal ablation. Our company philosophy and diverse employee skill set makes us uniquely qualified to take advantage of this industry trend in the coming years.

ABOUT THE AUTHOR

Daniel Smith, director of modeling and simulation at Emphysys, has 16 years of modeling and simulation experience and worked at COMSOL as the head of development for North America for 12 years, overseeing the development of the MEMS, Plasma, Microfluidics, Particle Tracing, Ray Optics, Semiconductor, and Molecular Flow modules. Previously, he worked at MKS Instruments, where he modeled and optimized various types of fluid calibration and plasma systems. He has a master's degree in both applied mathematics and numerical computing. www.emphysys.com