MODELING OPTIMIZES A PIEZOELECTRIC ENERGY HARVESTER USED IN CAR TIRES

Siemens is using fluid-structure interaction simulation to ensure the cost effective optimization of a cantilever in a MEMS generator designed to power a tire pressure monitoring system.

By **JENNIFER HAND**

THE DESIRE TO eliminate batteries and power lines is motivating a wide range of research. In the quest for systems that are energy autonomous, the concept of energy harvesting is attracting a great deal of attention. Combine this idea with operation at the micro level, and the "what if" scenarios become even more enticing.

For researchers at Siemens Corporate Technology in Munich, exploring the potential of an energy-harvesting microelectromechanical system (MEMS) generator holds strong appeal. As Ingo Kuehne, a senior engineer explains, "Our mandate is broad. We are looking to develop platform technologies for tomorrow rather than specific products; however, it makes sense to demonstrate the value of our research. Together with our partner Continental AG, we decided to focus on an application with clear commercial potential. Our ultimate goal is to design the MEMS generator to be as small, light, and strong as possible, with enough energy to power a system under a range of conditions." The researchers chose to design a microgenerator for an innovative tire pressure monitoring system (TPMS) driven by motion.

TPMSs are traditionally powered by batteries, they tend to be mounted on the wheel rim. With no reliance on a battery, such a system could be placed inside the tire (see Figure 1) and would be in a position to measure much more than pressure. It could monitor temperature, friction, wear, and torque; assist with optimal tracking and engine control; and convey all this critical infor-

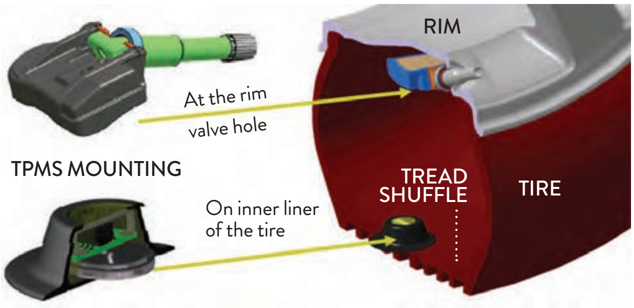

FIGURE 1: Two TPMS mounting options: on the rim or on the inner lining of the tire.

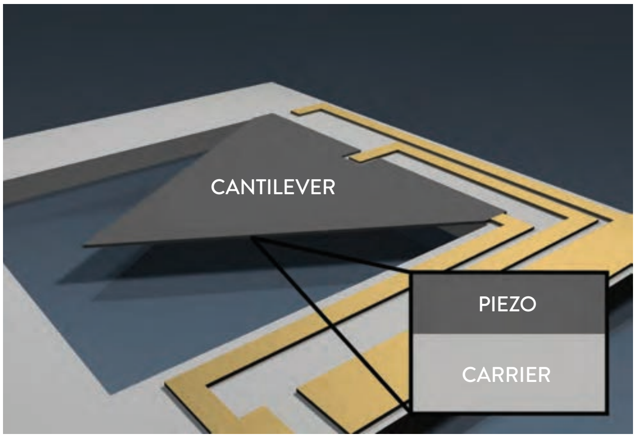

FIGURE 2: Schematic of the piezoelectric MEMS generator energy harvester. The cantilever is made of two materials, and electrical energy is transferred through the circuit from the cantilever.

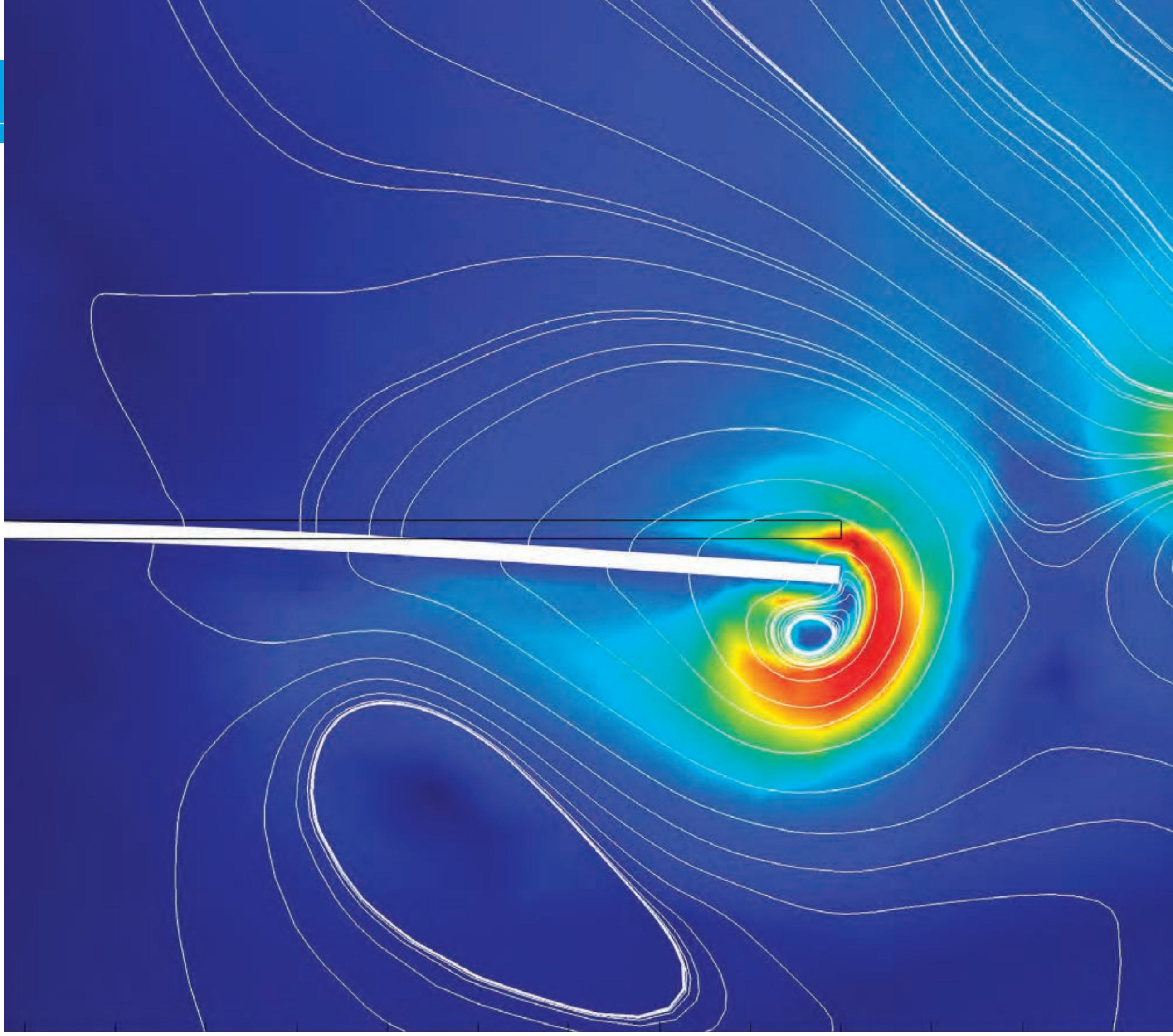

FIGURE 3: A 2-D FSI simulation showing the velocity field caused by feeding mechanical cantilever energy into the disordered kinetic energy of the surrounding gas.

mation wirelessly. It would also be maintenance-free, low in cost, and environmentally friendly.

Yet locating the device within the tire requires that the assembly be extremely robust and able to withstand gravitational accelerations up to 2500 g. Moreover, to avoid tire imbalance it would have to be very light, and in terms of operational life it would need to match that of a tire—a minimum of eight years.

» *FROM MECHANICAL STRESS INTO ELECTRICAL ENERGY*

MOUNTED TO ONE spot on the inside of a tire, a piezoelectric microgenerator would be able to harvest energy from the compression created each time that particular area of the tire touched the ground. The cantilever was designed to incorporate a thin film of self-polarized piezoelectric ceramic material with a silicon carrier layer, which provides mechanical stability and stores harvested mechanical energy (see Figure 2).

The team settled on a triangular design for the spring-loaded piezoelectric cantilever, as such a shape enables a uniform stress distribution in the surface direction. "Typical cantilever designs have substantial mass and are heavy, with a concentrated weight at the tip. This is fine for the conventional method of continuously exciting a cantilever at its natural frequency. However, the high dynamic forces we are dealing with prevent us from using this method of

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>
> **—INGO KUEHNE**

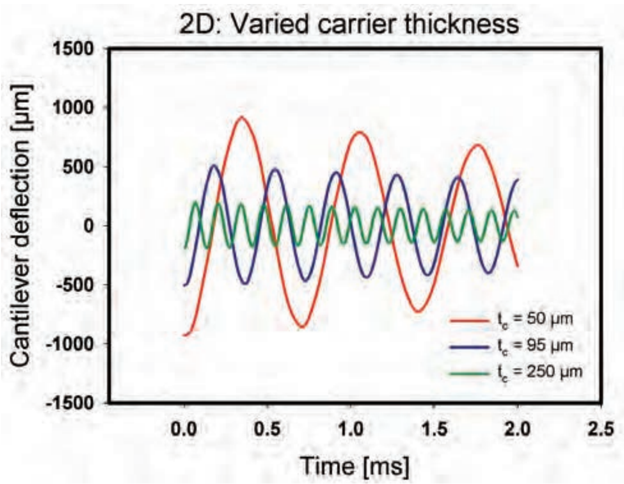


FIGURE 4: 2-D simulations of FSI on a cantilever's deflection at a gas pressure of 1 bar for various carrier thicknesses.

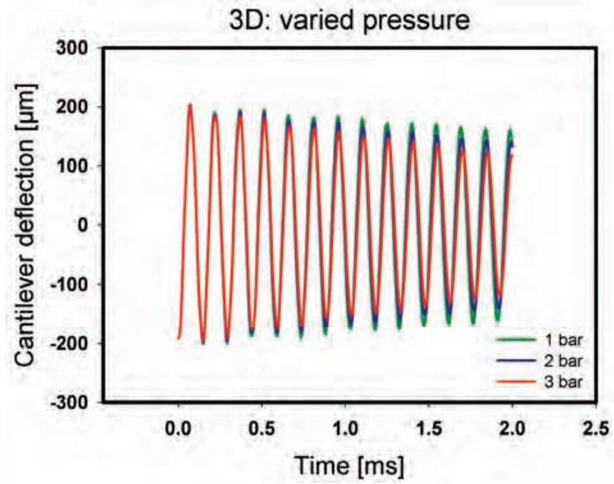


FIGURE 5: 3-D simulations of FSI on a cantilever's deflection as a function of gas pressure, with a carrier thickness of 250 µm.

excitation," says Alexander Frey, a senior engineer. "We had to adopt an unconventional approach and avoid mass and its concentration. This in turn gave us a more serious problem, because damping becomes much more critical."

The big question for the Siemens team was how to optimize the design of the cantilever in order to minimize damping. It appeared that air damping was the dominant effect, and the aerodynamic profile was a critical parameter. Although the cantilever area was limited to 100 square millimeters, the layer thicknesses were design parameters that could be freely changed. "We needed to find suitable values for these parameters so that we could ensure that the mechanical oscillation would continue for

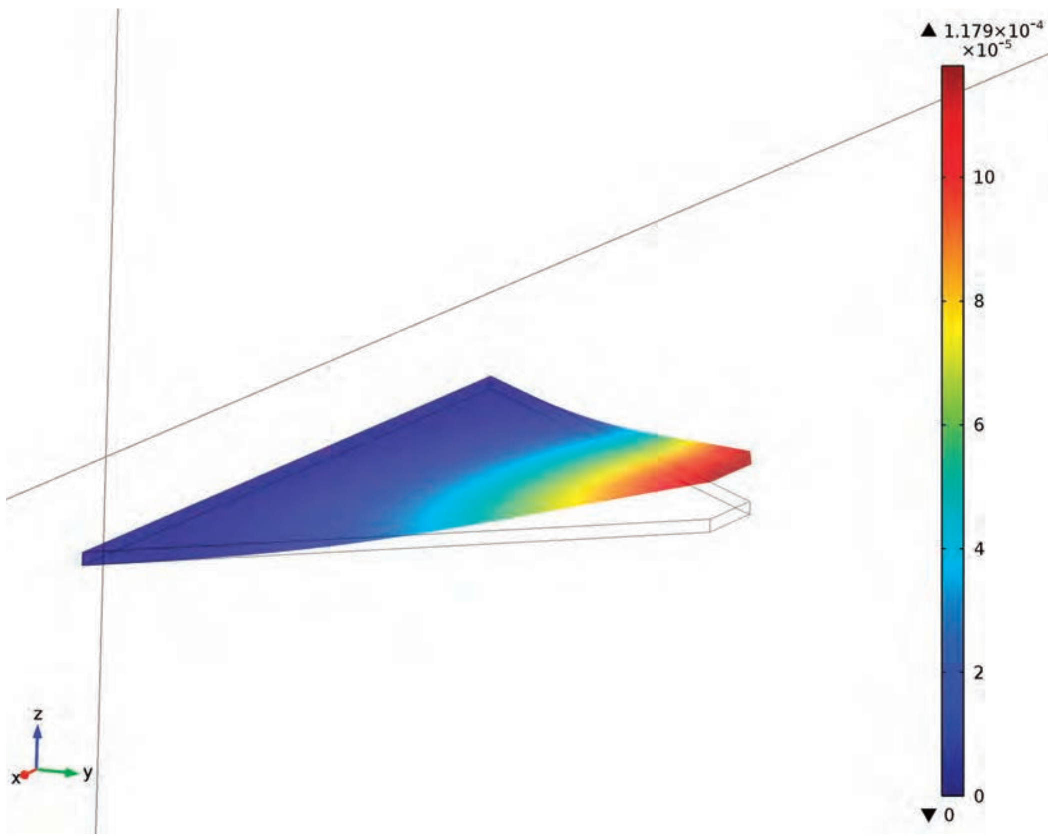


FIGURE 6: A 3-D FSI simulation showing the deflection of the triangular cantilever.

as long as possible and transfer as much of the mechanical energy as possible to the electrical domain," says Frey. "We really needed a numerical tool to determine the optimal structure and ensure that enough energy was being produced."

» FLUID AND STRUCTURE: AN OPEN RELATIONSHIP

HAVING IDENTIFIED THE transfer of mechanical energy to the surrounding air as a critical process, the team first conducted a fluid-structure interaction (FSI) analysis of the cantilever. Kuehne explains: "We started with static simulations, and these gave us some initial values. Then a time-dependent analysis allowed us to see a range of physical effects and understand the impact of the surrounding air on the damping of the cantilever." (See Figures 3 and 4.)

Members of the team went on to conduct a 3-D FSI simulation and to consider the cantilever deflection as a function of external pressure and carrier thickness (see Figures 5 and 6). They examined the maximum stress required for initial deflection at each thickness. With this analysis, Frey says, "we confirmed quantitatively that increasing the thickness of the cantilever led to an improvement in the damping behavior of the MEMS harvester."

» OPTIMIZING THE CANTILEVER'S SIZE AND SHAPE

"**WITH COMSOL** Multiphysics simulation software, we learned how to numerically describe the behavior of our structure, which allowed us to conduct research in the laboratory," says Kuehne. In order to compare the simulated behavior with experiments, the cantilever was periodically excited, and the piezoelectric voltage generated was recorded.

"Comparison of the simulation with physical testing revealed that the overall damping behavior was actually higher," says Kuehne. "The obvious explanation was that we were losing energy because of intrinsic losses in the material. We assumed an accepted value for this internal damping, and after taking these correction factors into account, we arrived at the same results. This reassured us that our simulation process with COMSOL was reliable and that we could continue to investigate the performance of the cantilever using different parameter values." The team was then able to move on to optimizing system components and system integration (see Figure 7).

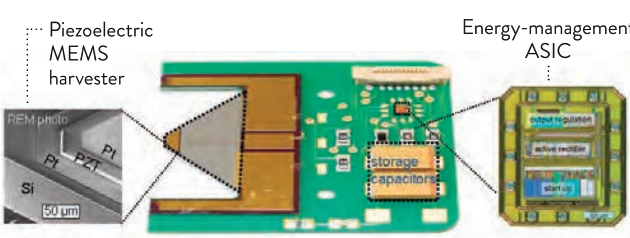
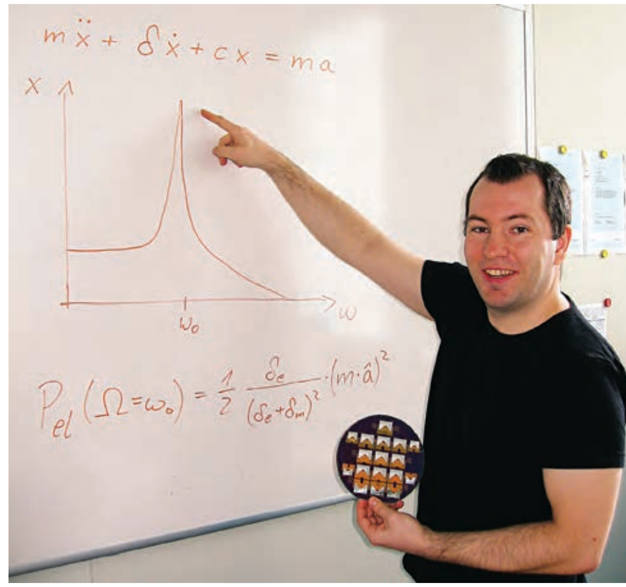


FIGURE 7: Prototype of a piezoelectric MEMS energy-harvesting module and the surrounding system.



Kuehne holding one of the wafers used in the production of the MEMS energy harvester prototypes.

The use of COMSOL was critical to the development of the physical prototypes. According to Kuehne, it takes three people four months to do one technological run, which typically consists of one batch of up to 25 wafers. "One run usually results in a couple of complete prototypes, depending on layout. Testing takes a further two months. In particular, the extra expense of a clean room infrastructure results in development costs of more than €100,000 for a single prototype run over six months. In contrast, you can measure a 2-D simulation in hours and a 3-D simulation in days. In that amount of time it is easy to simulate the performance of up to 2,000 different prototypes within COMSOL Multiphysics."

Frey concludes: "Without COMSOL and the option of numerical modeling, we would have to make numerous physical structures, which would have been time-consuming and expensive. Instead, we were able to get on with the process of optimizing the MEMS design." ◎