Reduced-Weight Reaction Sphere Makes Way for Extra Satellite Payload

BY LEOPOLDO ROSSINI, EMMANUEL ONILLON, AND OLIVIER CHÉTELAT, CSEM SA, SWITZERLAND, WWW.CSEM.CH

When launching satellites to orbit, every gram of payload is extremely valuable. Depending on the orbit and the launcher, an estimated cost is about 15,000 euros per kilogram. With this in mind, researchers at CSEM, the Swiss Center for Electronics and Microtechnology, are working on ways to minimize the weight of satellite attitude control systems. Here, a single multi-axis reaction sphere is proposed to replace four conventional single-axis reaction wheels. Its geometry and electromagnetic design are quite complex, and only with the help of COMSOL Multiphysics are they able to examine various configurations of magnets to find the one that works best.

Founded in 1984, by grouping three former watch-industry research laboratories, CSEM is today a private applied research and development center specializing in microtechnology, system engineering, microelectronics, and communication technologies. With headquarters in Neuchâtel, it has some 400 employees in Switzerland.

Until Now: Multiple Reaction Wheels

In conventional 3-axis stabilized spacecrafts, three reaction wheels are arranged along the three axes, with a fourth wheel for optimization and redundancy; they are normally employed to implement attitude control systems with the required accuracy and without using fuel to fire jets. This attitude control allows the satellite to be pointed towards an object in the sky, towards a particular location on earth or to stabilize the satellite by compensating for disturbances it might encounter.

The operating principle is relatively simple: an electric motor is attached to a flywheel. If the wheel accelerates, it builds up angular momentum in a certain direction, and the spacecraft rotates in the opposite direction due to the law of conservation of momentum. Note that such a device can only rotate a satellite around its own center of mass and cannot be used to move the spacecraft to a different position.

The researchers at CSEM are operating under the assumption that the work of three reaction wheels can be done with one reaction sphere. That device is an iron ball covered with permanent magnets and held in position with magnetic levitation through magnetic fields generated by a number of electric coils. The sphere, acting as a rotor, is accelerated about any axis of rotation with a 3D motor. An attitude control system based on a reaction sphere would be smaller and lighter than those based on reaction wheels; even with its more complicated control electronics, it is estimated that the device can significantly increase the torque in the same volume. In addition, due to its magnetic bearing, "An attitude control system based on a reaction sphere would be smaller and lighter than those based on reaction wheels"

the reaction sphere is expected to generate less micro vibrations due to the absence of ball bearings and lubricants. Finally, the possibility of using it as a multiple degree-of-freedom active vibration damper to absorb external disturbing forces is another attractive feature.

The concept of spherical actuator is not new and has been known for roughly 30 years. They have been used in robotics for spherical joints such as to mimic the wrist. However, this is believed to be the first application of spherical actuators in satellite technology.

728 Permanent Magnets

A project funded by the European Space Agency was started in 2005 to investigate the viability of a reaction sphere for use in space. CSEM's patented design is based on a 3D permanent magnet motor implemented with a multi-pole rotor and a 20-pole stator (Figs 1 and 2). The rotor, manufactured and tested so far, is measuring roughly 20 cm in diameter, and consists of 728 permanent cylindrical magnets affixed to an iron sphere. To maintain as much symmetry as possible, the number of regularly distributed poles on the rotor follows the distribution of the 8 vertices of a cube. The reaction sphere's rotor can be accelerated about any desired axis and moved in any direction continuously without any disruption using a 20-pole stator that produces an 8-pole rotating field.

The first rotor CSEM developed was not simulated; it was designed just using a pure analytical model of the electromagnetic field. This meant that the size

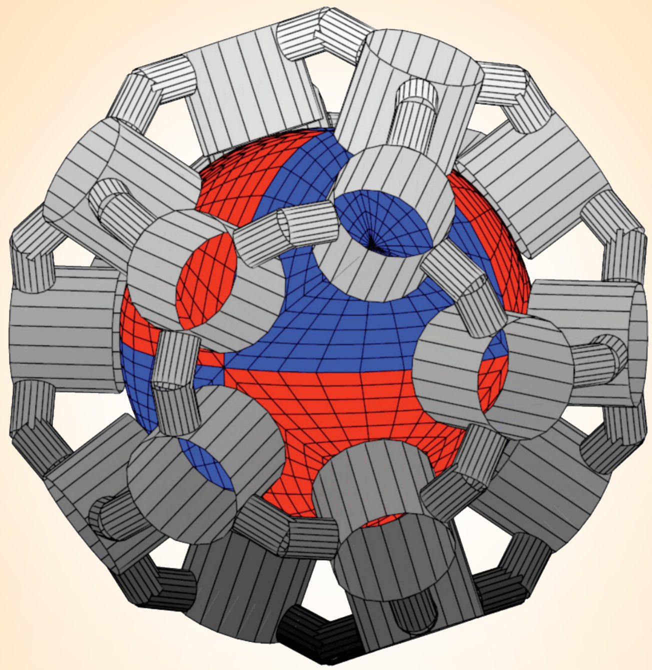

Fig. 1. Geometry of the 3D motor on a magnetic bearing for the reaction sphere; in the ideal case 8 permanent magnets for the rotor (whose fields today we approximate instead using a mosaic of 728 cylindrical magnets) and 20 coils for the stator.

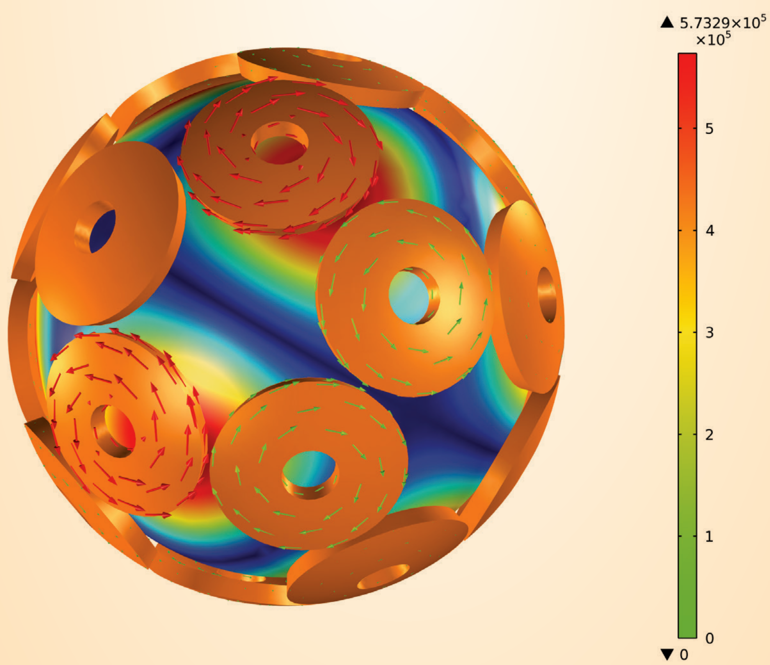

Fig. 2. Model geometry showing the coil distribution around the rotor.

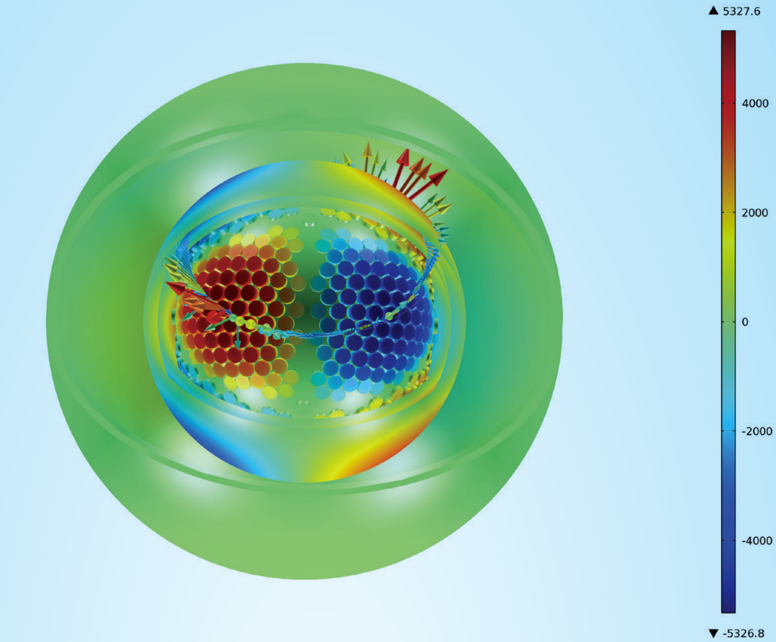

Fig. 3. Radial magnetic flux density at the rotor surface (surface plot) and magnetic flux density (arrow plot).

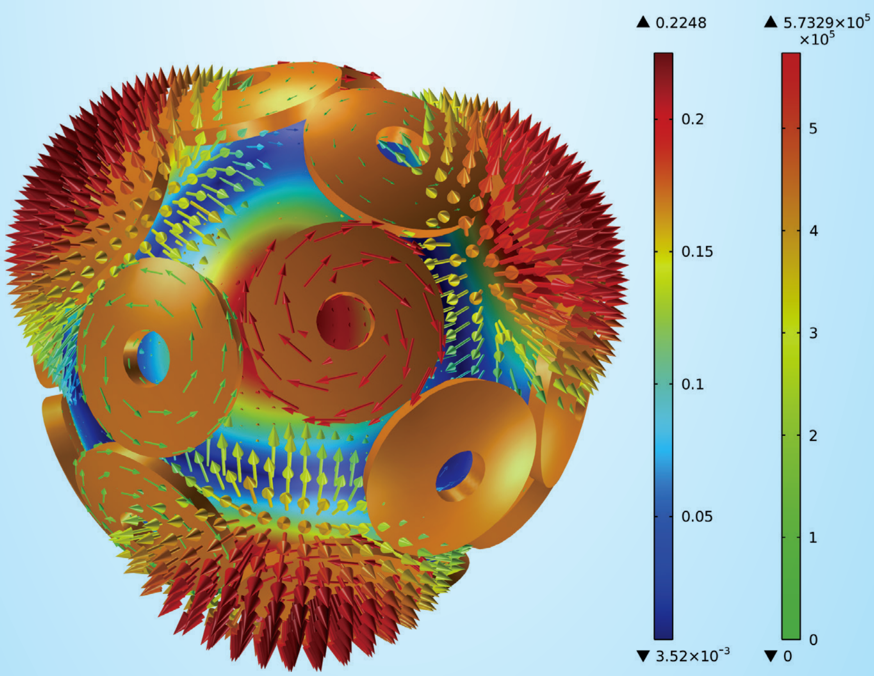

Fig. 4. Taking Fig. 3 and adding the effects of the energized coils adds the current density in the coils (additional arrow plots).

of the magnets had to be adjusted using this analytical model. But in order to synthesize these cylindrical magnets the team had to make several assumptions, which relied on intuition.

Now, with COMSOL, what's powerful is that we take the insight derived from a good initial guess of the analytical model and then run the software to finely tune the design to meet some optimization criteria. We are, however, considering some special designs where the magnets have geometries and very particular magnetization patterns, for which the development of an analytical model would be extremely difficult.

Instead, with software we now can evaluate multiple designs where we vary the reaction sphere's mass, torque and magnetic fields, and we can also investigate unusual geometries for the magnets or create the magnetic field from the coils in different ways. Thanks to COMSOL we can take an intuitive idea, build the geometry, run the simulation and within several hours can evaluate whether a given design should be further investigated. In summary, there are certain designs we are currently evaluating that we would have not been able to test using analytical approaches — but with COMSOL it takes just a few hours.

We conduct our studies in two steps. First we determine if the magnetic field from the permanent magnets on the sphere provide the required flux fields (Fig. 3). In a second step we then simulate the coils being energized and verify the expected forces (Fig. 4) and then compare them to forces seen in a test bench (Fig. 5). The model has proven to be a powerful predictor for the forces because the computed values are in good agreement with the measurements. In a later step we want to add thermal analysis to find out what happens to the stator when the sphere is rotating and also add the LiveLink™ for MATLAB® module so we can design the controller electronics.

Our simulations with current were set up with the rotor orientation matching that on the test bench (Fig. 5). The vertical force is computed by integrating the Lorentz force on each of the twenty coils and summing them to obtain the net force.

Remove the Iron

The ultimate goal is to obtain a specific magnetic flux density within the air gap while minimizing rotor mass and maintaining a level of useful inertia. Using COMSOL, we plan to study a different approach taking advantage of an interesting phenomenon. Like electrical circuits, magnetic circuits must be closed. In our current design, the metal of the rotor holding the magnets serves as the return path, similar to the ground in an electric circuit. However, in what is known as one-sided flux, a special arrangement of magnets can augment the magnetic field on one side while cancelling the field to near zero on the other side.

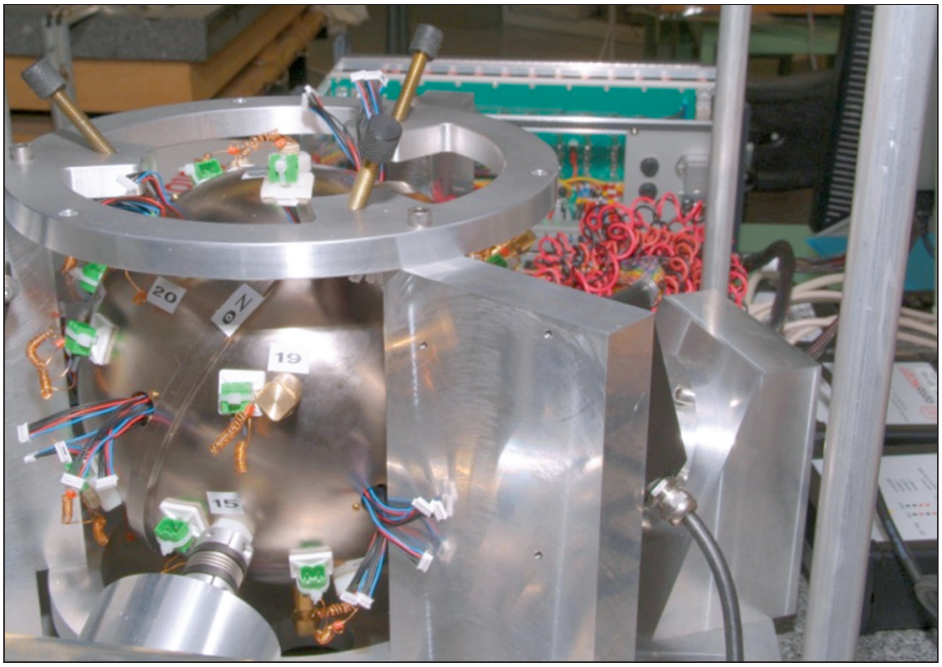

Fig. 5. Test bench for the reaction sphere.

> "The COMSOL model proved to be a powerful predictor for the forces, and this will be an invaluable tool for us as we study further design options."

By taking advantage of this effect, we can possibly replace the rotor's iron core with a lighter weight material. In this new design, there's no need for iron to close the magnetic flux circuit inside the rotor because the flux is directed outwards by the magnetized material. Although the magnets and iron have roughly the same amount of mass, for the same volume/mass, replacing the iron with permanent magnets would increase the magnetic field outside the rotor — and allow us to reduce the current in the coils to operate the motor and thus cut power consumption. Here, again, COMSOL will allow us to immediately predict the performance of a particular design in terms of developed forces/torques and power consumption. ■

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About the Author

Leopoldo Rossini (on the right, sitting next to Senior Project Manager Ivar Kjelberg) received his BSc. degree in Electrical Engineering from the University of Applied Sciences of Southern Switzerland, Manno, Switzerland, and his MSc. in Electrical and Computer Engineering from Purdue University, West Lafayette, IN, United States. Since then, he has been employed in the Systems Division of the Swiss Center for Electronics and Microtechnology (CSEM) in Neuchâtel, Switzerland, and he is also currently a PhD student at EPFL (Lausanne) working on the reaction sphere project.