Smart Fluids Move into the Marketplace

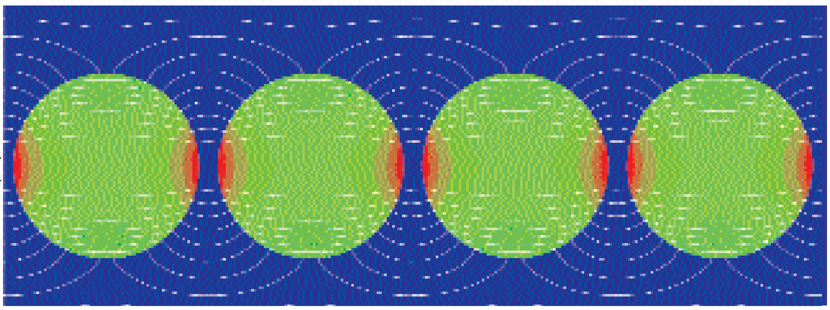
FEATURE

by Jennifer Ouellette

Magneto- and electro-rheological fluids find new uses

Once viewed primarily as novelty materials, smart fluids have attracted a resurgence of interest with the emergence of improved chemistries and a budding commercial demand for their unique properties. They are finding use as dampers for vehicle vibration control, rotary brakes for aerobic exercise equipment, special-purpose devices for medical rehabilitation, and erasable Braille displays for the blind, as well as for seismic damping and virtual surgery.

Smart fluids, shape memory alloys, and piezoelectrics fall under the rubric of smart materials. There are two primary classes of smart fluids: magneto-rheological fluids (MRFs) and electro-rheological fluids (ERFs). J. David Carlson, who heads the materials division at Lord Corp. (Cary, NC), the leading supplier of MRF materials, defines MRFs as dense suspensions of micrometer-sized particles in liquids that solidify into a pasty consistency in the presence of a magnetic field, and re-liquefy when that force is removed (Figure 1). Adding iron filings to corn oil produces a primitive MRF. Industrial-grade MRFs are essentially the same mix, but producers use a specially designed hydrocarbon as the oil and smaller particles. ERFs are nearly identical to MRFs, except they stiffen when an electrical field is applied. Both fluids can replace some intricate moving parts, making smart fluids attractive to manufacturers in search of innovative cost-cutting measures.



John Ginder and Craig Davis, Ford Motor Company

Figure 1. The field-dependent strength of a magneto-rheological fluid and its variation with material properties may be predicted by modeling the magnetic field (white lines) and nonlinear magnetization (color contours) of a horizontal chain of particles in the direction of the applied field.

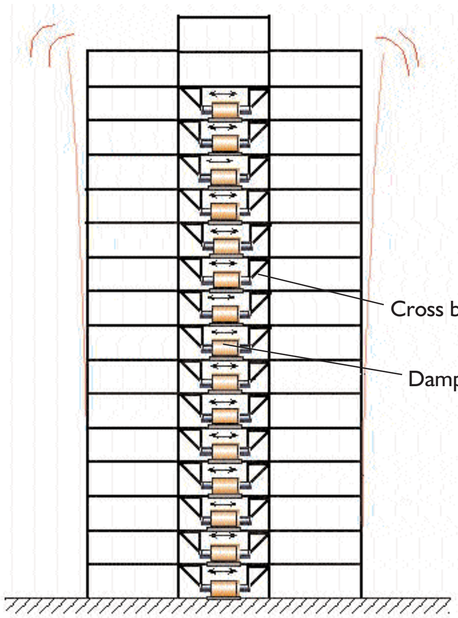
Like many scientific advances, ERFs were discovered by accident. Researchers using marble and oil to construct a high-voltage switch in the 1940s noticed that as the switch operated, the marble eroded into a dust in the oil, which turned from a liquid to a paste in the presence of a high voltage, recounts Henri Gavin, assistant professor of civil and environmental engineering at Duke University. Jacob Rabinow, then with the National Bureau of Standards, independently invented MRFs in 1947, but their instability—the suspended particles eventually settled and clumped—and the lack of a market hindered their development. Nonetheless, MRFs proved useful in magnetic-power clutches in automotive transmissions in the 1950s and in the Apollo service modules in the 1960s.

After the initial novelty wore off, interest in smart fluids languished through the 1970s and 1980s. But in the 1990s, interest exploded as stable MRFs became commercially available, as did advanced computer algorithms, faster control circuits, and improved sensor technology. A major breakthrough in ERFs occurred in the late 1980s, when Frank Filisco of the University of Michigan invented so-called dry ERFs. Unlike other ERF materials, they did not require water as part of their fluid for the electro-rheological effect to occur, thus lowering the currents needed to activate the material. "That really invigorated the field, because now these materials could be practically applied," says Gavin. "The power supply could be driven by a simple car battery."

Ultimately, the primary driver for the current explosion of MRF and ERF R&D is the emergence of commercial applications, which began in 1997 when MRFs entered the market as resistance brakes in exercise equipment, such as step machines and exercise bicycles.

Generally speaking, MRFs and ERFs are complementary rather than competitive, with each offering specific advantages or disadvantages that make them suitable for different applications. "The major advantage of MRFs is the large forces they can resist. The major advantage of ERFs is the small size of the actuating elements we can develop," says Constantinos Mavroidis, associate professor of mechanical and aerospace engineering at Rutgers, the State University of New Jersey, in Piscataway. For instance, vehicle-suspension systems and structural seismic-vibration damping require substantial forces, such as those supplied by MRFs. However, newer applications, such as haptic interfaces and biomedical instrumentation, require smaller forces and have size constraints. Because MRFs need bulky magnets, while ERFs require only two electrodes connected by wires to activate the fluid, designers find ERFs more attractive for those uses.

Currently, the most lucrative application for MRFs is in automotive-suspension technology. Using materials supplied by Lord Corp., Delphi Corp. (Troy, MI) now supplies its MagneRide systems to manufacturers such as General Motors. The technology debuted in the 2002 Cadillac



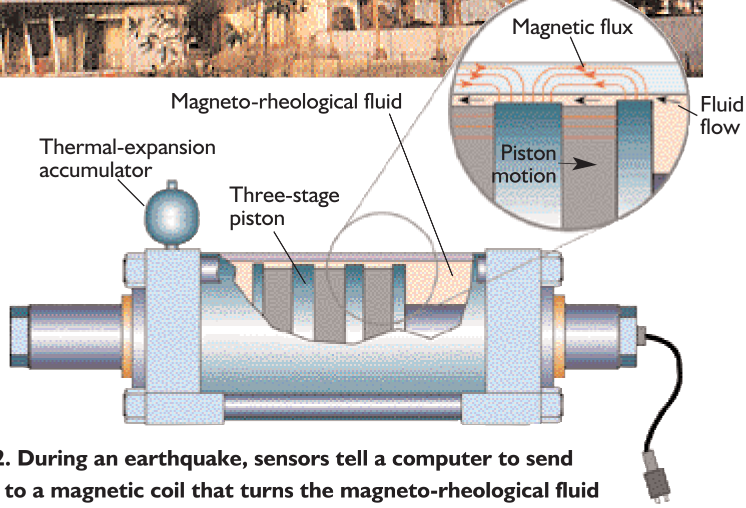


Figure 2. During an earthquake, sensors tell a computer to send current to a magnetic coil that turns the magneto-rheological fluid in the dampers into a solid thousands of times a second, supplying major resistance to the displacing forces in buildings such as Japan's Museum of Emerging Science and Engineering, Tokyo.

Seville STS and 2003 Chevrolet Corvette, and it will appear in two 2004 Cadillac models: the SRX sport utility and XLR roadster. Benefits include a 40% reduction in mechanical parts, mostly valves; elimination of the traditional shock-absorber fluid; and the capability of adapting to changing levels of shock and motion 500 times/s.

Ford has yet to incorporate MRF systems as shock absorbers. "The cost-to-benefit ratios just are not there yet," says John Ginder, a scientist at the Ford Research Laboratory (Dearborn, MI). Currently, Ford focuses its smart-fluids R&D toward clutches that use MRFs to better control torque transfer and MRF dampers mounted in steering columns and seatbelts to dissipate more energy in front- or rear-end collisions.

Several applications are emerging for MRFs—beginning with industrial forklifts—in the area of steer-by-wire, in which no mechanical connection exists between the steering wheel and the drive wheels. Carlson envisions ultimately extending the technology to brake-by-wire, clutch-by-wire, and shift-by-wire. Replacing mechanical and hydraulic components with simple wire connections enables manufacturers to reduce vehicle weight. Active MRF engine mounts may further reduce vibration and quiet noise before it enters a vehicle.

Although MRFs have gained a footing in automotive applications, some potential for ERFs still exists in the sector. Mavroidis and Yoseph Bar-Cohen, a senior scientist at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, have explored the development of ERF-based haptic elements to remotely operate various robotic devices. And Smart Technology Ltd. (Birmingham, England) is going head-to-head with MRFs by developing ERF-based suspension damping systems, with plans to initially target European car manufacturers. Alex Smith, the company's technical director, says that because MRFs are ferromagnetic, residual particle interactions can occur that result in tiny oscillations, which slip past MRF shock-absorption systems because they are below the forces necessary to activate the material's damping effect. ERFs do not exhibit the same residual yield stress as MRFs.

Engineers in Japan were the first to install MRF damping technology to help stabilize buildings against earthquakes (Figure 2), and the diagonal cables of China's Dong Ting Lake bridge are kept steady in high winds by the technology. According to Gavin, using MRF materials in seismic-isolation systems can reduce the displacement of structures during near-field earthquakes. These events exhibit much larger pulsed ground tremors than average earthquakes, particularly close to the epicenter—movements so large that non-MRF isolation systems may not accommodate them. Although MRF damping systems are costly to implement, Gavin believes the investment would prove worthwhile for critical structures such as hospitals and major data centers.

Other applications include using MRFs for magneto-rheological optical finishing. QED Technologies a

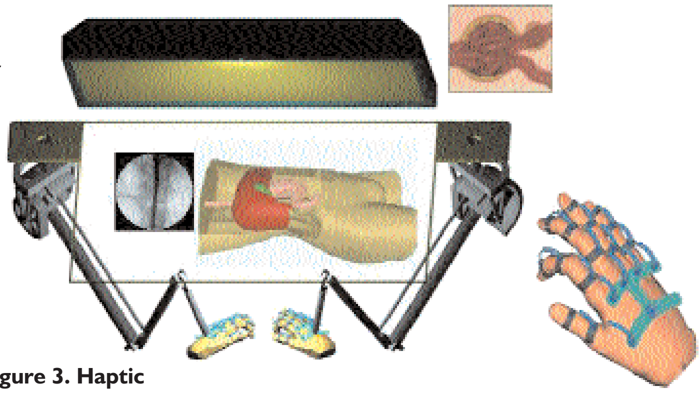


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Figure 3. Haptic interfacing can be achieved by a process called mechanical mirroring using controlled stiffness and actuators. A potential application is virtual endovascular telesurgery, shown from the front (a) and side (b).

Yoseph Bar-Cohen, NASA/JPL/Caltech, Pasadena, California; Dinos Mavroidis, Rutgers University, New Jersey; Rodney White, Harbor-UCLA Medical Center, Los Angeles, California

(Rochester, NY) markets machines with real-time control of the polishing rate that use a polishing material based on MRFs. The more magnetic field applied, the faster the rate of material removal. “It is a great concept, because it takes advantage of the tunability of these fluids,” says Ginder. Systems Planning and Analysis, Inc. (Greenbelt, MD), is developing MRFs for damping gun-barrel recoil, and researchers at the University of Maryland want to develop MRFs as dampers in helicopter blades. Lord Corp. is exploring washing machines equipped with MRF dampers, which would operate with little vibration and almost no noise.

Haptic devices

Smart fluids are proving especially useful as actuators in haptic devices, which seek to impart a sense of tactile pressure, if not the actual sensation of touch (Figure 3). For example, Smart Technology is developing an ERF-based Braille display tablet for the visually impaired. Current devices on the market allow users to either read or write. Smart Technology plans to create an integrated ERF input–output interface that enables users to do both.

Smith compares the concept to the braking system in a car, which has a master cylinder and numerous slave cylinders, all controlled by a computer. Rows of plastic pins are activated by an underlying ERF valve, which stiffens with the application of an electric field and enables researchers to control the fluid flow. Negative pressure erases the display, much like a high-tech Etch A Sketch. The company has already developed a small prototype device with three rows and three columns of plastic pins activated by underlying ERF valves. A single-line Braille display of about 40 characters is currently being tested by user groups. The full-size graphical array will feature 128 × 64 individual actuators that display either Braille characters or simple tactile graphics.

For Carlson, an exciting new application for MRFs is as real-time controlled dampers in advanced prosthetic devices. In 2000, Biedermann Motech GmbH (Schwenningen, Germany) introduced its Smart Magnetix prosthetic knee, developed in collaboration with Lord Corp. More than a dozen are in use today. The artificial joint is a mechanical assembly that includes a hydraulic piston–cylinder damping element with an electromagnet to activate the MRF when needed. Sensors determine the state of the knee and feed signals to a microprocessor-based controller that determines how much electrical current to apply to the MRF. Once calibrated to an individual, the system automatically adapts in real time to that person’s walking speed and to stairs, slope of terrain, and changes in temperature without the user needing to consciously control the prosthetic.

Mavroidis and Bar-Cohen are developing prosthetic devices for rehabilitation using ERFs, such as knee braces that resist the motion of the knee for better rehabilitative training. Because a computer controls the amount of force, a doctor can tailor the training program to specific patients and monitor each person’s progress. Their focus now is on moving the prototype devices into the marketplace.

Another Bar-Cohen–Mavroidis project is the On-Demand Operational Exoskeleton (ODOE), a type of virtual-reality suit for astronauts to provide them the resistance needed to combat muscle atrophy in zero gravity. The ODOE can be adjusted to provide the resistance an astronaut needs to generate for any given function. The concept envisions mounting a robot on a robotic arm in space that performs external vehicle activities while the operator, seated inside wearing the ODOE, controls the robot’s movements. Bar-Cohen and Mavroidis have already demonstrated proof of concept by building a large piston with slots on the side that serve as valves. Pushing on the piston causes the ERF to travel from one side to another along those channels, and applying an electric field within that zone causes the fluid to become viscous. The result is a valve that could be incorporated as part of a glove, for example.

Because ERFs mimic the rheology of biological tissues, Bar-Cohen also envisions one day training surgeons by having them operate on virtual patients, using smart fluids to simulate the resistance of human flesh. For his part, Mavroidis is now trying to develop hybrid actuators. “Both ERFs and MRFs are semiactive, in the sense that one can only resist forces, not generate them, but the latter is highly desirable for haptic applications,” he says. Hybrid actuators would have one component with ERFs to resist external forces, and electromagnetic actuators to generate new forces if needed.

Fluids for the future

Further afield, scientists envision injecting biocompatible MRFs directly into the bloodstream, where they could control the flow of blood to cancerous tumors—the current research focus of Jing-Liu Helmersson, professor of physics and astronomy at California State University, Long Beach. Indeed, MRFs might someday flow in the veins of robots to animate hands and limbs as naturally as those of humans, or provide active hand grips that conform to the shape of each individual hand or fingers. Other future applications include creating magneto-liquid-mirror telescopes that bend and deform to cancel out the twinkling of starlight, enabling astronomers to make better observations, and shock absorbers for payloads in spacecraft.

In the meantime, researchers have many technical and engineering challenges to overcome, particularly issues of control. Currently, MRF clumping and settling problems are addressed with additives that keep particles suspended. But learning more about the fundamental principles behind the clumping phenomenon could lead to better solutions, and the best place to study the problems is in space, where gravity does not distort the clumping pattern. NASA’s InSPACE experiment, headed by Alice Gast, vice president for research and associate provost at the Massachusetts Institute of Technology, is now orbiting Earth onboard the International Space Station. The experiment exposes weightless MRFs to magnetic pulses and records what happens to gain insight into their basic physics.

For Lord Corp.’s Carlson, the challenge is scaling up the MRF manufacturing process. “There is a big difference between making this stuff 1 liter at a time in the laboratory, and making it in 55-gallon drums for the automotive industry,” he says, pointing out that a barrel of MRF typically weighs a little more than half a ton. “Logistically speaking, it’s a challenge of mixing and handling the material on a large scale.”

ERFs have their own challenges, one of which is temperature dependence. It would also be desirable to extend the lifetime of the materials; currently, the unique properties of ERFs last only a few months in heavy-duty applications. Bar-Cohen sees two other challenges: generating higher resistance levels and, as with MRFs, addressing the problem of settling. ERFs also absorb humidity from the environment, which degrades performance. “These problems are not showstoppers, but you have to take them into account,” Bar-Cohen says. And building up a market for the materials certainly remains a challenge. “There is no huge commercial demand right now for ERFs,” Smith admits. “We are setting out to develop it.”