

Magnetorheological Fluid Technology for Vehicle Applications

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Abstract

In recent years devices and systems using magnetorheological (MR) fluid technology have been commercialized across a wide range of industries, the most prominent and promising being automotive applications. Commercially successful MR fluid systems and devices have been developed for primary suspension in passenger automobiles; driver's seat suspension in off-highway, construction and agricultural equipment; and steer-by-wire operator control in industrial, off-highway and marine vehicles. Today, thousands of vehicles are in operation and more than 100,000 MR dampers, shock absorbers and brakes are in use. For automotive platform applications alone, anticipated annual growth in demand for MR devices is more than 1 million. MR Fluid may be tailored for specific applications, provides high strength and is durable and robust. MR Fluid is highly developed with fundamental material data and device design and models and is backed by extensive experience-based guidelines. This paper summarizes current and developing commercial applications of MR Fluid Technology in automotive and vehicular applications.

Keywords: Magnetorheological, MR fluid, MagneRide, Tactile Feedback Device

1. Introduction

Since the first patent was issued to inventor Jacob Rabinow in the 1940s, magnetorheological (MR) fluids have remained mostly a laboratory curiosity with little practical use. In the late 1980s and 1990s, however, researchers began to get serious about developing the commercial viability of MR fluids, especially when other technologies began to converge that made practical use a real possibility. Microprocessors, sensor technologies and increasing electronic content and processing speeds have created control possibilities that didn't exist in Rabinow's time. Battery technology, fueled by the advance of the burgeoning cell phone industry, as well as new rare earth magnets now provide power in smaller packages than ever possible before.

Lord Corporation, after committing more than a decade of intense R&D, holds the world's most extensive patent portfolio on MR fluid formulations, devices and systems. The company has developed additives, lubricants and suspension aids to keep iron particles in place while preventing them from grinding away at seals, gaskets and metal components. The company also has compiled a body of scientific data through aggressive life cycle testing and installed commercial applications that clearly demonstrate the effectiveness, durability and performance of MR fluids, devices and systems.

2. Description of MR Fluid Technology

Magnetorheological (MR) fluids are materials that respond to a magnetic field with a dramatic change in rheological behavior. These fluids can reversibly change instantaneously from a free-flowing liquid to a semi-solid with controllable yield strength when exposed to a magnetic field. In the absence of an applied field, MR fluids are reasonably well approximated as Newtonian liquids. For most engineering applications a simple Bingham plastic model is effective in describing the essential, field-dependent fluid characteristics.

A typical MR fluid consists of 20–40 percent by volume of relatively pure, 3-10 micron diameter iron particles, suspended in a carrier liquid such as mineral oil, synthetic oil, water or glycol. A variety of proprietary additives, similar to those found in commercial lubricants to discourage gravitational settling and promote particle suspension, are commonly added to Lord's state-of-the-art MR fluids to enhance lubricity, modify viscosity, and inhibit wear.

MR fluids made from iron particles exhibit maximum yield strengths of 50-100 kPa for applied magnetic fields of 150-250 kA/m. MR fluids are not highly sensitive to moisture or other contaminants that might be encountered during manufacture and usage. Further, because the magnetic polarization mechanism is unaffected by temperature, the performance of MR-based devices is relatively insensitive to temperature over a broad

temperature range (including the range for automotive use).

Most devices use MR fluids in a valve mode or direct-shear mode. Examples of valve mode devices include dampers and shock absorbers. Examples of direct-shear mode devices include clutches, brakes, and variable friction dampers.

3. Vehicle System Applications

3.1 Driver seat suspension

MR fluid dampers have been used in commercial seat suspensions for Class 8 trucks since 1997 and have since expanded into a broad range of off-highway, construction and agricultural vehicles. The Motion Master® Ride Management System from Lord is a commercially proven seat suspension technology that has logged billions of road miles.

Unlike standard air suspended seats, which compromise shock and vibration control, the Motion Master system automatically adapts to both the driver's body weight and continually changing levels of shock and vibration, improving operator responsiveness and control while reducing fatigue and risk of injury. Seats equipped with the Motion Master system, enabled by MR technology from Lord Corporation, can reduce vibrations by at least 40 percent compared with most pneumatic seat suspensions.

One of the most current benefits of this system is that it can help equipment manufacturers meet recently enacted guidelines by the European Union's Physical Agents Directive (PAD), which mandate maximum limits on the machine operator's total daily exposure of certain types of vibration. In this context the directives challenge OEM equipment manufacturers to find improved ways to limit the amount of vibration to which operators can be exposed.

Seats equipped with the Motion Master system represent one of the best and most cost-effective technologies available to meet the new standards.

Two components make up the patented Motion Master Ride Management System:

- Controller continuously monitors seat motion and determines optimal damping force, while sensing road conditions and adjusting at a rate of more than 500 times per second.
- Shock Absorber, containing Lord's patented Rheonetic™ magnetic fluid, responds to the controller within milliseconds.

3.2 Automotive primary suspensions

The year 2002 marks the first broad-based automotive application for MR fluid technology. Delphi Automotive Systems, the world's largest automotive industry supplier,

has since developed and commercialized the MagneRide™ shock and strut system for a number of GM model cars and two future European vehicles slated for 2006.

The Delphi monotube design employs an electromagnetic coil wrapped around the passageway between two chambers filled with custom formulated MR fluid from Lord Corporation. When the piston moves within the damper body, MR fluid flows between these two chambers and through the coil. Varying current in the coil controls the magnetic field in the coil, adjusting the yield stress or resistance-to-flow of the fluid, proportionally to the field, up to 1,000 times a second. The design has no electromechanical valves or small moving parts. The iron particles in the MR fluid form a dense network of chains when a magnetic field is applied to them, increasing the damping in the shock. When the magnetic field is removed, particles revert to their free, unchained form, allowing freer movement of the damper and thus lower damping.

All four corners of the vehicle are independently controlled by the MagneRide system with the fluid (and thus damping force) in the four damper/struts changing in response to vehicle speed and sensed road and driving conditions such as pot holes and lateral forces in high-speed turns. The faster response time (under 10 msec) of MR dampers, compared to other semi-active shocks, enables the suspension system to adapt to changing road conditions and dampen sudden impacts when driving over rough terrain.

MagneRide shocks have fewer moving parts than conventional controllable shocks - 60 percent fewer parts than Delphi's conventional semi-active damper system. The MagneRide system also requires very little power. Peak power is 20 watts at each of the system's four dampers. MR dampers are also quieter in operation and simpler to assemble.

The MagneRide system was extensively tested for performance and durability under strenuous environmental conditions prior to launch in 2002 on the Cadillac Seville STS and Chevrolet Corvette. Two areas of performance that have received particular attention were settling stability and durability (wear and seal life) as MR fluids, when first invented, were not stable to long-term settling and could be quite abrasive in use.

The rheological properties of MR fluids depend on the concentration, size, distribution and shape of the iron particles, the carrier oil properties, additional additives, applied field, temperature and other variables. The interdependency of all of these factors is very complex and important to understand in optimizing the performance of these fluids within an MR device and control system for a particular application, as trade-offs must constantly be made in the design process.

After three years in the marketplace and many decades of accelerated testing by Lord and Delphi, the durability and stability of MR fluid and shocks are well proven.

Today, the MagneRide system is additionally in production on the 2004 Cadillac XLR and SRX, the 2005 Cadillac STS, the 2005 Corvette and is to be featured on the 2006 Cadillac DTS. Also, MagneRide will be featured on the 2006 Buick Lucerne, the first non-premium automobile with the groundbreaking active suspension technology and will soon launch on two European vehicles.

3.3 Vehicular steer-by-wire

Automotive design engineers are looking at a host of other potential applications for MR fluid technology, especially in the area of driver feedback, or “feel,” that is often not optimized in electric, by-wire systems.

The trend in vehicle industries toward control-by-wire (steer-by-wire, shift-by-wire, throttle-by-wire, brake-by-wire, etc.) has created a need for highly controllable, rugged, cost-effective devices to provide realistic force-feedback sensations to the operator, whether the manual device is a wheel, a joystick, a pedal, or a lever. Commercialized products for forklift vehicles use the Lord Tactile Feedback Device (TFD) to sense steering wheel position, control over-steer when the vehicle is moving quickly, and simulate the end-stop limit of driving wheel turn.

With MR fluid inside the Lord TFD, the rotor turns freely inside the housing in the absence of a magnetic field. But when the coil is energized, the magnetic field generated causes the iron particles in the MR material to form a chain, creating a resistive torque that is proportional to the current flow in the coil and reacts quickly to changes in the strength of the magnetic field.

The benefits in of MR technology in by-wire applications include:

- Continuously variable, speed-independent torque
- Quick response time (10 milliseconds)
- Smooth, realistic force feedback with high fidelity feel
- Real-time control
- High torque density - 10 times greater than DC motors
- Compact size
- No active forces generated
- Inherent system stability
- Low power consumption (typically 12V, 1 Amp max current)
- Compatible with vehicle electrical systems

United Kingdom-based lift truck manufacturer Linde has taken the technology of programmable feel the furthest in vehicular applications. Linde was the first (in

2000) to incorporate an advanced, fully integrated system developed by Lord, which provides high-fidelity tactile feel in Linde’s all-electric active reach trucks with steer-by-wire control.

Linde incorporated the Lord TFD to improve operator control and safety, because the company realized during development that the vehicle was unsafe to operate without high-quality tactile feedback to the steering wheel. Linde considered using electric motors but rejected the idea due to high cost, size, weight, and energy usage. Linde eventually chose a Lord MR device because it produced a high-fidelity sense of “feel” to the operator with much lower cost, size, weight, and energy usage than electric motors. The Lord TFD is 60 percent smaller than comparable devices and produces the same amount of torque at fraction of the cost and power.

4. MR Status Today

Today, thousands of vehicles are in operation and more than 100,000 MR dampers, shock absorbers and brakes are in use. For automotive platform applications alone, anticipated annual growth in demand for MR devices is more than 1 million.

Production of fluid volume this year (2004) is expected to reach several hundred tons. The cost of MR fluid ranges from about \$600 per liter for small quantities to about \$60 to \$180 per liter for large volume applications.

Lord Corporation’s experience in the development of MR fluids, devices and systems has produced key insights, backed by solid data, into this remarkable technology. Over the past three years, Lord has offered MR Technology Workshops to train others in MR device and system design. Lord offers MR fluid and technology that is:

- Tailored for specific applications
- High strength
- Durable
- Robust
- Highly developed with fundamental material data and device design and models
- Extensive experience-based guidelines