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IMPACT PERFORMANCE OF MAGNETORHEOLOGICAL FLUIDS

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ABSTRACT

As part of an emerging effort in what is now termed the area of mechamatronics [1], an effort was begun to assess the suitability of MR (magnetorheological) material based devices for impact energy management applications. A fundamental property of MR materials is that their yield stress alters almost instantaneously (and proportionally) to changes in the strength of an applied magnetic field. Based on this property, MR based devices, if found suitable, would be desirable for impact energy management applications because of attendant response tailorability. However, it was identified that prior to adopting MR based devices for impact energy management applications several key issues needed to be addressed. The present study focused on one of the most significant of these, the verification of the tunability of the response of such devices at stroking velocities representative of vehicular crashes. Impact tests using a free-flight drop tower facility were conducted on an MR based energy absorber (shock absorber) for a range of impact velocities and magnetic field strengths. Results demonstrated that over the range of impact velocities tested – 1.0 to 10 m/s – the stroking force/energy absorption exhibited by the device remained dependent on and thus could be modified by changes in the strength of the applied magnetic field.

Keywords: MR fluids, impact energy management

INTRODUCTION

For over 15 years there have been activities at GMR&D directed at developing innovative approaches for providing enhanced vehicle performance and functionality beyond that which is possible with traditional fixed-response materials and fixed geometry structures that historically have dominated the vehicle industry. Traditionally, most of the approaches that were developed fell into the category of what has been termed mechatronics, essentially electronically controlled mechanical systems. Focusing on just automatic crash safety devices, essential elements of such systems are sensors, controllers, and mechanical devices whose mechanical elements such as orifices can be adjusted to provide differing responses based on sensor input as processed by control logic. However, our interest has expanded to include magnetorheological fluids. These were recognized as having the potential, though unproved, of dramatically enhancing the performance of crash safety devices by allowing the responses of devices based on them to be automatically tailored for the specific crash scenario – crash severity and occupant anthropometry. The addition of an active material as a potential enabler for a tunable response mechanical device controlled by electronics placed this study into what we have chosen to term the field of Mechamatronics (Mecha – mechanical, ma – materials – tronics – electronics) [1]. Documented in the present paper is one of our mechamatronics studies this being an assessment of the suitability of MR (magnetorheological) fluids for crash safety applications. It is to be noted that impact studies of MR fluid response have been conducted by other researchers including Ahmadian [2] and Wereley [3]. However in the majority of these studies the regime of flow was at significantly lower strain rates than of interest here.

The critical property of MR fluids of interest here is that their yield stress can be changed rapidly, within a few milliseconds, and in proportion to the strength of an applied magnetic field. As illustrated in Fig. 1, MR fluids change from a free-flowing, linear, viscous liquid to a semi-solid (a Bingham plastic in which Shear stress = yield stress + viscosity x shear rate) with field dependent yield strength (but field independent viscosity) when exposed to a magnetic field. When the field is removed, the behavior of the MR fluid reverts to that of a Newtonian liquid. The basis for this change is illustrated in Fig. 2. A typical MR fluid consists of anywhere between 20 to 40 percent by volume of magnetically soft iron particles, typically from 3 to 5 microns in size, with chemically anchored surfactants, that are suspended in a carrier liquid such as mineral oil or even water with numerous additives, which among other benefits help prevent settling. Application of a magnetic field reorients the particles from a random dispersion into nominally parallel chains of particles aligned with the field flux lines. It is the resistance of these “chains” of particles to shear that produces the field strength proportional yield stress of the MR material. Other important properties are that the MR effect is temperature independent up to ~220^{o}C and that the viscosity of MRF is less temperature-sensitive than single-phase fluids of similar viscosity.

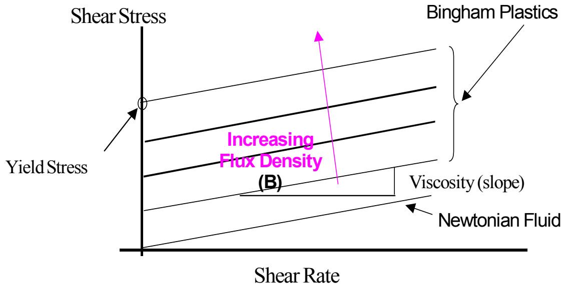

Fig. 1. Field Dependent Shear Stress of a Typical MR Fluid

MR fluids made from iron particles typically exhibit maximum yield strengths of 30–90 kPa for applied magnetic fields of 150–250 kA/m (1 Oe . 80 A/m). It is the verification and quantification of the shear force levels over the relevant shearing/flow velocity rates and applied field strengths that constitute the scope of the study reported here.

TEST PROGRAM

Experimental Setup/Test Procedure

The MR fluid damper used in this study is the larger of the two shown in Fig. 3. This is a mixed mode – shear plus flow – MR device built and studied at GM R&D in the early 1990’s as part of a vehicle shock program. A cross section of the shock appears in Fig. 4. The MR fluid is shown in light tan, the windings in the head of the piston in violet. The MR fluid that was used was synthesized at GM R&D with 20% volume fraction of carbonyl iron particles. Particle size does have an effect on the yield stress of the MR fluid and hence on the actuator forces. In general a bimodal distribution of particle sizes was found to provide higher yield stress than an all large size particle distribution and such was used in the MR device tested here.

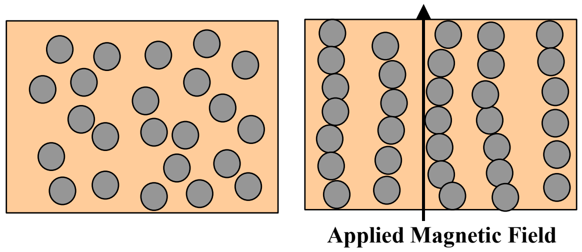

Fig. 2 Alignment of Iron Particles in Response to Applied Magnetic Field

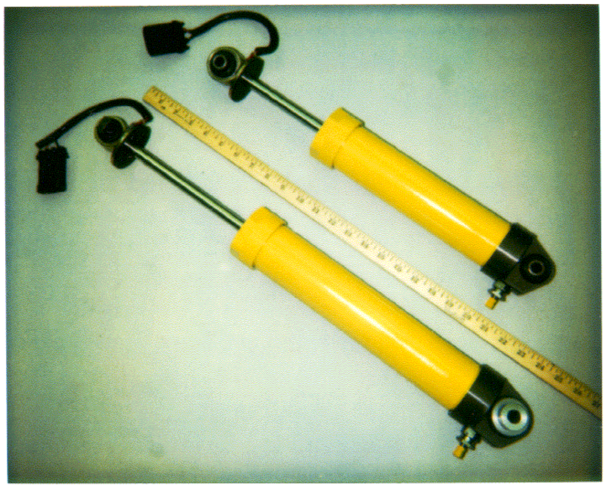

Fig. 3 GM R&D MR Fluid Dampers

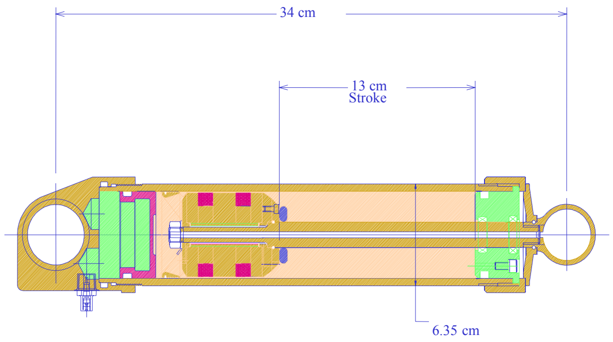

Fig. 4 Cross Section of MR Fluid Mixed Mode Damper

Dimensions and specifications of the MR fluid damper appear in Table 1.

Table 1. MR Fluid Damper Specifications

Parameter	Value
MR Valve Gap	1.0 mm
Tube O.D.	63.5 mm
Stroke Length	243 mm
Max. Coil Current	20 Amps
Field Strength	289 kA/m
Max. Power	60 watts

Test Procedure

Dynamic axial impact tests were conducted using the two drop tower facilities located at the GM R&D Center. The high mass facility, which has an unballasted drop mass of 140.2 kg, is shown in Fig. 5. The low mass facility has an unballasted drop mass of 45.8 kg.

Fig. 5 High Mass Drop Tower Facility

The standard procedure for conducting the dynamic axial impact tests was as follows. The MR fluid damper was attached firmly to the top surface of the mounting plate and aligned with its central axis perpendicular to the ground plane (Fig. 6). A 60x60x50 mm block of aluminum honeycomb of nominal crush strength of 1725 kPa was attached using double sided tape to a small flat plate that had been mounted to the upper end of the damper rod. This honeycomb cube served to eliminate the ringing in the load cells due to metal to metal impact which would have otherwise occurred and also helped to diminish the inertial spike associated with the impact upon/acceleration of the piston/piston rod. Note that the magnitude of this inertial spike is dependent on the impact velocity and not on the strength of the applied magnetic field. (In tests such as those reported in [2] in which precautions were not taken to avoid direct metal to metal contact and thus reduce the magnitude of the initial inertial spike, this spike can be dominant. This fact may have contributed to the finding in [2] that the strength of the applied field had no effect on the shear strength of the MR fluid.) The large blocks of aluminum honeycomb positioned to the side of the test device as seen in Fig. 6 were used to arrest the drop platform after approximately 10 cm of stroke in those cases in which the drop energy exceeded the energy absorbing capability of the damper. Instrumentation included an accelerometer mounted to the drop platform, four load cells positioned beneath the mounting plate and an LVDT (Fig. 6) mounted to the MR fluid damper that provided the amount of stroke as a function of time.

Fig. 6 MR Fluid Damper Mounted for Impact Testing

To conduct a test, the damper rod was fully extended, the drop tower raised to the drop height corresponding to a pre-selected impact velocity, a pre-selected amount of current applied to the MR fluid damper, and the drop platform released to fall freely under the action of gravity until striking the MR damper test assembly. Note that in the intended vehicle applications, sensor input will be used to ensure that current will be on as required. Usually the response time limitation of an MR device arises out of the eddy currents in the magnetic circuit and it is possible to design an MR device to minimize these effects and achieve fast enough response time (of the order of 1ms to 5ms) to provide the desired damping force. Data from each of four load cells plus the LVDT and accelerometer were recorded.

The sampling interval was 50 µs. A high speed digital video record was made of each impact test and Fig. 7 contains time spaced frames taken from the video of a representative MR damper impact test conducted on the low mass drop tower. More complete descriptions of the theory behind and the practical aspects of impact testing using a free-flight drop tower facility are given in [4] and [5] respectively.

Table 2. Test Conditions		
Drop Height (cm)	Impact Velocity (m/s)	Applied Current (amps)
5.1	1	0, 5, 10, 15, 20
20.4	2	0, 5, 10, 15, 20
81.5	4	0, 10, 20
183.5	6	0, 10, 20
326.2	8	0, 10, 20
509.7	10	0, 10, 20

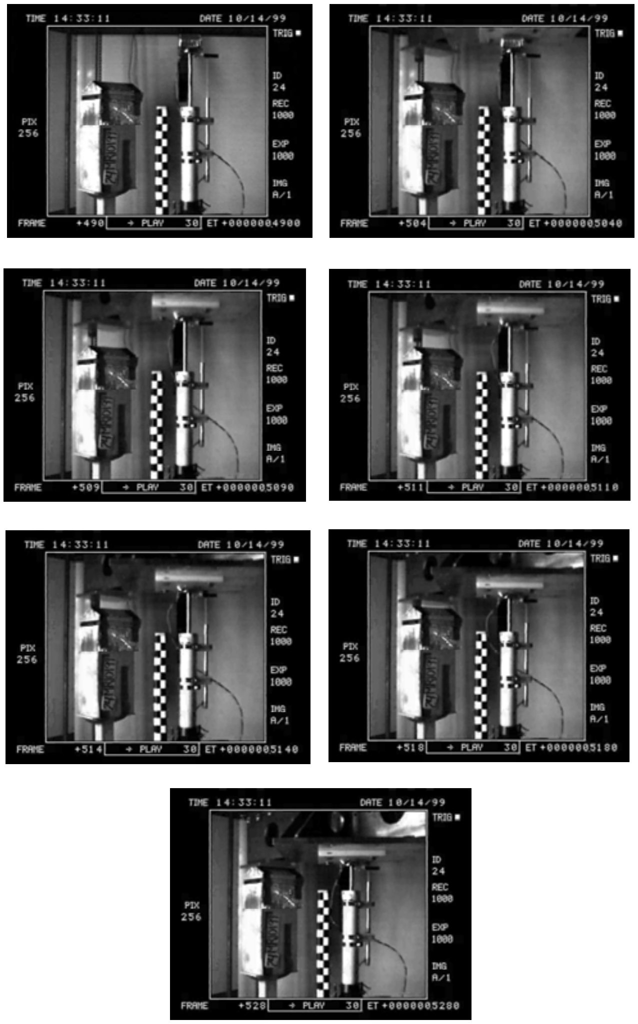

Fig. 7 High Speed Video Frames from MR Shock Impact Test

STUDY FINDINGS

Test Conditions

Test conditions for the dynamic axial impact tests are listed in Table 2. The tests at 1, 2, and 4 m/s were conducted using the high mass drop tower. To avoid potential bottoming out of the MR fluid damper due to excess impact energy, the tests at 6, 8, and 10 m/s were conducted using the low mass drop tower.

Test Results

Table 3 displays the measured peak values of stroking force for each of the combinations of impact velocity and applied current that were considered in this study. Peak stroking force is seen to increase with both increasing current level and with increasing impact velocity. The increase with increasing velocity (Fig. 8) is attributed to the viscosity related component of shear stress and the increase with increasing applied current (Fig. 9) is attributed to the increase in the yield stress portion of the shear stress. Note that over the range of impact velocities that were considered, the change in peak force associated with a 20 amp increase in the applied current remained approximately constant. The percentage change achievable in the peak stroking force achievable through changes in the strength of the applied field, i.e. the ability to dramatically tune the level of this force, thus diminished with increasing impact velocity.

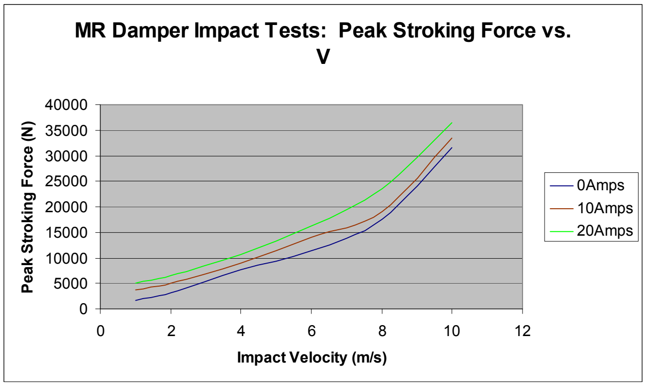

Fig. 8 Peak Stroking Force vs. Impact Velocity

Table 3. Peak Stroking Force (N)

V (m/s)	Amps				
	0	5	10	15	20
1	1700	2400	3800	4400	5000
2	3200	3900	5000	6000	6600
4	7600		9000		10600
6	11400		14000		16300
8	17500		19000		23500
10	31500		33500		36500

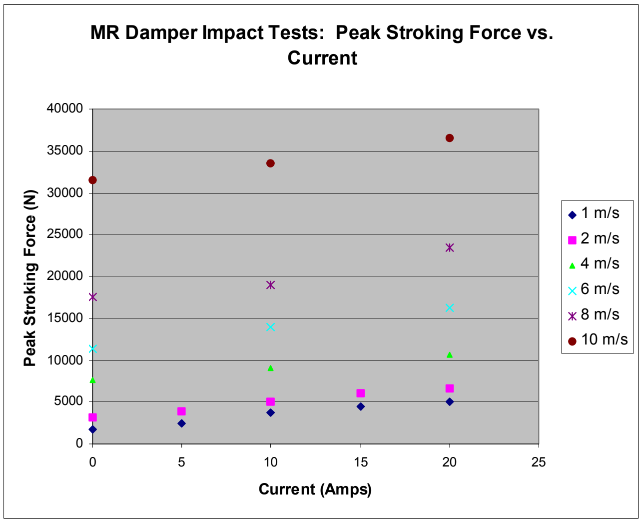

Fig. 9 Peak Stroking Force vs. Applied Current

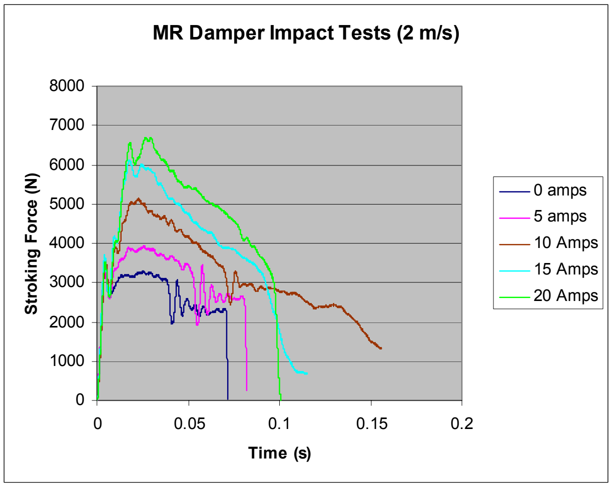

Fig. 10 Stroking Force vs. Time for Impact Tests at 2 m/s

Traces of stroking force as a function of time for five levels of applied current for impact tests at 2 m/s are plotted in Fig. 10. These traces illustrate the fully tunable nature (by changing the strength of the applied field) of not only the peak stroking force but also the energy dissipated by the MR damper at this velocity. Two additional features of these traces merit further discussion. The small common magnitude initial spike seen in each of the five traces is the reduced initial inertial spike associated in this case with the impact of the drop platform against the block of aluminum honeycomb. The effectively common negative slope of the five traces over the majority of the event is attributed to the decrease in viscosity related component of shear stress (the component attributable to the carrier component of the MR fluid) with decreasing stroking velocity.

CONCLUSIONS

This study was successful in verifying experimentally the robustness, over a significant range of stroking velocities, of the tunable nature of the stroking force of an MRF (magnetorheological fluid) device of the type in which the MR fluid is subjected to combined shear and flow. Specifically, results demonstrated that over the range of impact velocities tested – 1.0 to 10 m/s – the stroking force/energy absorption exhibited by the device remained dependent on and thus could be modified by changes in the strength of the applied magnetic field. This demonstration that the response of such a device remains tunable under impact loading over this range of speed was one of many critical issues that need to be addressed before such devices can be considered for use as automotive crash energy absorbers and occupant and pedestrian protection devices.

ACKNOWLEDGEMENTS

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