An evaluation of magneto rheological dampers for controlling gun recoil dynamics

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The application of magneto rheological dampers for controlling recoil dynamics is examined, using a recoil demonstrator that includes a single-shot 50 caliber BMG rifle action and a MR damper. The demonstrator is selected such that it can adequately represent the velocities that commonly occur in weapons with a recoil system, and can be used for collecting data for analyzing the effects of MR dampers on recoil dynamics. The MR damper is designed so that it can work effectively at the large velocities commonly occurring in gun recoil, and also be easily adjusted to reasonably optimize the damper performance for the recoil demonstrator. The test results show that it is indeed possible to design and use MR dampers for recoil applications, which subject the damper to relative velocities far larger than the applications that such dampers have commonly been used for (i.e., vehicle applications). Further, the results indicate that the recoil force increases and the recoil stroke decreases nonlinearly with an increase in the damping force. Also of significance is the fact that the adjustability of MR dampers can be used in a closed-loop system such that the large recoil forces that commonly occur upon firing the gun are avoided and, simultaneously, the recoil stroke is reduced. This study points to the need for several areas of research including establishing the performance capabilities for MR dampers for gun recoil applications in an exact manner, and the potential use of such dampers for a fire out of battery recoil system.

1. Introduction

Magneto rheological (MR) dampers have been widely studied for vehicle suspension applications, as seen in the studies included in references [1–4]. Most of these studies consider the application of MR dampers for primary or secondary suspensions of the vehicle, and attempt to take advantage of the properties of MR dampers to more effectively control the dynamics and handling of the vehicle. For most vehicles, it is possible to show that through relatively simple control techniques, one is able to provide a more effective compromise between the ride and handling dynamics of the vehicle. In vehicle applications the relative velocities across the damper, due to the suspension motion, are generally in the range of 0 to 15 inches per second (in/s). The maximum range is commonly experienced during severe dynamics, such as sudden vehicle maneuvers or high-velocity input from the road, such as hitting a pothole.

Other systems that can benefit from the application of MR dampers are those involving shock loading. These are commonly systems that due to a large impact load, experience a sudden shock, such as the dynamics that occur upon firing a gun (commonly known as "gun recoil"). As described in many past studies (such as [5–7]), the dynamic compromise that commonly occurs in shock loading is maintaining the shock forces within the maximum force that the system can sustain, while not exceeding the maximum stroke of the components that absorb the shock (commonly called the "shock absorber" mechanism). For small shock absorber strokes, large forces must be sustained by the system; and conversely for small shock forces, large strokes must be accommodated by the shock absorber mechanism. To provide a more favorable compromise between recoil force and stroke, several studies have examined closed-loop controlled recoil systems [8–10]. The vast majority of these studies, however, have shown that, although theoretically possible, the complications of a closed-loop system outweigh the dynamic benefits.

The primary purpose of this study is to examine the benefits of MR dampers for controlling recoil dynamics, so that the forces resulting from firing the gun can be maintained within the system limits without exceeding the allowable stroke. The system that we will consider for this study includes a gun recoil mechanism for controlling the reaction forces that are caused by firing the gun. When the gun is fired and the projectile starts forward, the propellant gas pressure accelerates

Shock and Vibration 8 (2001) 147–155
ISSN 1070-9622 / $8.00

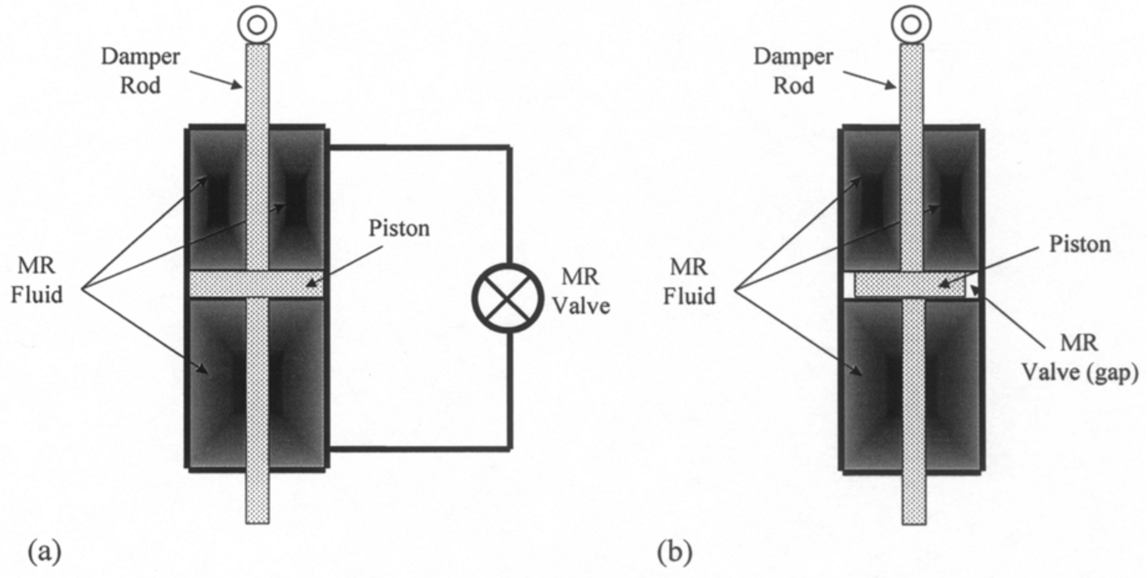

Fig. 1. Functional representation of an MR damper; (a) MR damper with external valve; (b) MR damper with internal valve.

the recoiling parts rearward. The recoil velocity that is created can be extremely large, sometimes more than several feet per second. Although most weapon systems already have a passive recoil mechanism, the desire for building lighter weapons with increased firing power and more mission flexibility have placed new demands on the recoil mechanisms that cannot be met with passive systems. In this study, we will specifically address:

- The effectiveness of MR fluids for controlling gun recoil
- The ability to control the forces transmitted to the gun mount
- The ability to adapt to a variety of energy levels
- The ability to vary the recoil stroke

To achieve the above, we will describe the design and fabrication of a live-fire system, called “MR recoil demonstrator,” for evaluating the performance of MR dampers in different firing conditions. The next sections will describe some of the details of the MR recoil design and fabrication, as well as our test results.

2. Background on magneto rheological fluids

Magneto rheological fluids are materials that exhibit a change in rheological properties (elasticity, plasticity, or viscosity) with the application of a magnetic field. The largest change in rheological properties occurs when the applied magnetic field is normal to the flow of MR fluid. MR fluids are manufactured by suspending ferromagnetic particles in a carrier fluid. The ferromagnetic particles are often carbonyl particles, since they are relatively inexpensive. Other particles, such as iron-cobalt or iron-nickel alloys, have been used to achieve higher yield stresses from the fluid. Fluids containing these alloys are impractical for most applications due to the high cost of the cobalt or nickel alloys. A wide range of carrier fluids such as silicone oil, kerosene, and synthetic oil can be used for MR fluids. The carrier fluid must be chosen carefully to accommodate the high temperatures to which the fluid can be subjected. The carrier fluid must also be compatible with the specific application without suffering irreversible and unwanted property changes. MR fluid commonly contains additives to prevent the coagulation of the ferromagnetic particles, although the particles are generally expected to settle if the fluid remains undisturbed for an extended period of time.

Besides the rheological changes that MR fluids experience while under the influence of a magnetic field, there are often other effects such as thermal, electrical, and acoustic property changes. In the shock and vibration area, however, the MR effect is of most interest since it can be used in a hydraulic damper. MR fluid allows one to control the damping force of a damper by replacing mechanical valves commonly used in adjustable dampers. This offers the potential for a more reliable damper.

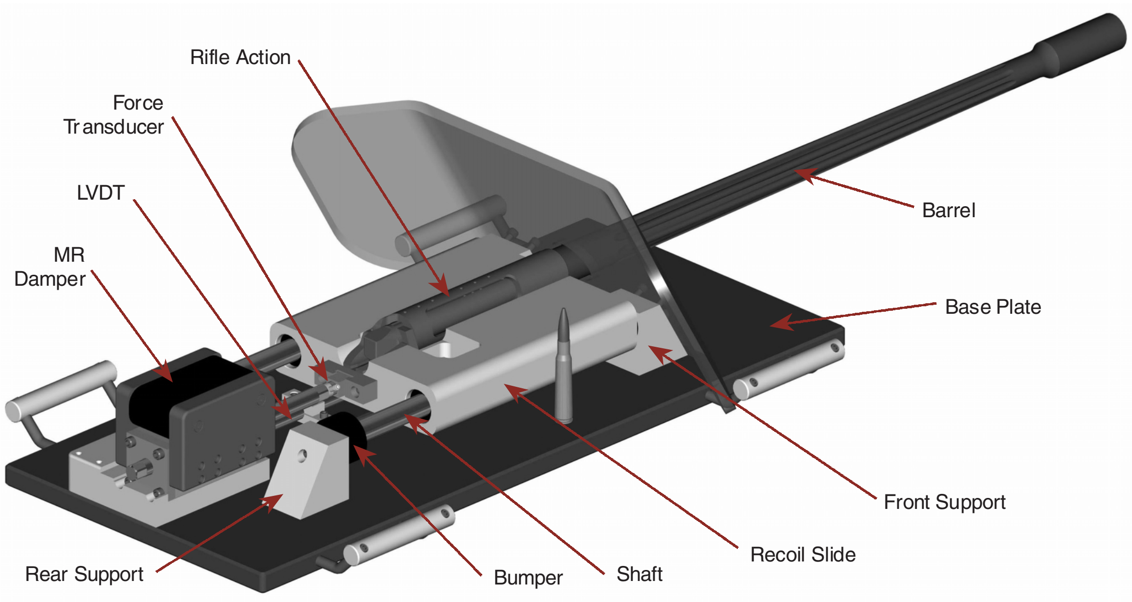

Fig. 2. Gun recoil demonstrator assembly.

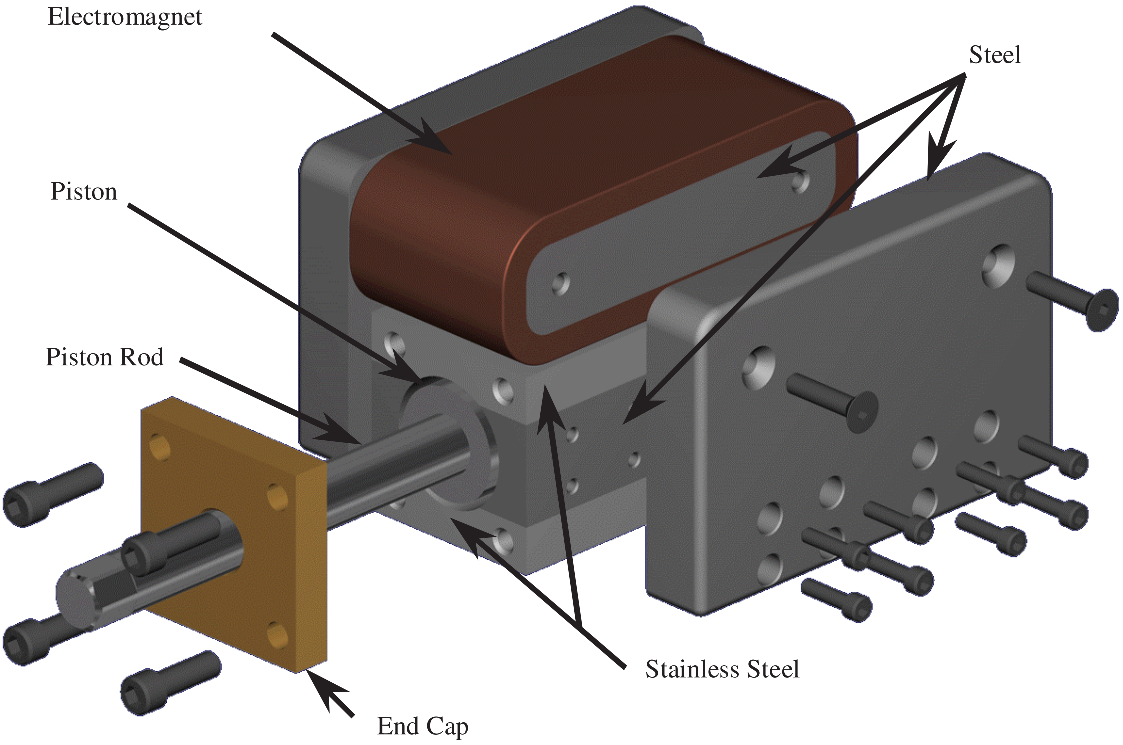

Fig. 3. Magneto rheological (MR) damper design details.

A top-level functional representation of a double-ended MR damper is shown in Fig. 1(a). The term "double-ended" refers to dampers in which the rod is extended through the damper on both ends of the piston, in contrast to single-ended dampers for which the rod exists only from one end of the piston. The fluid

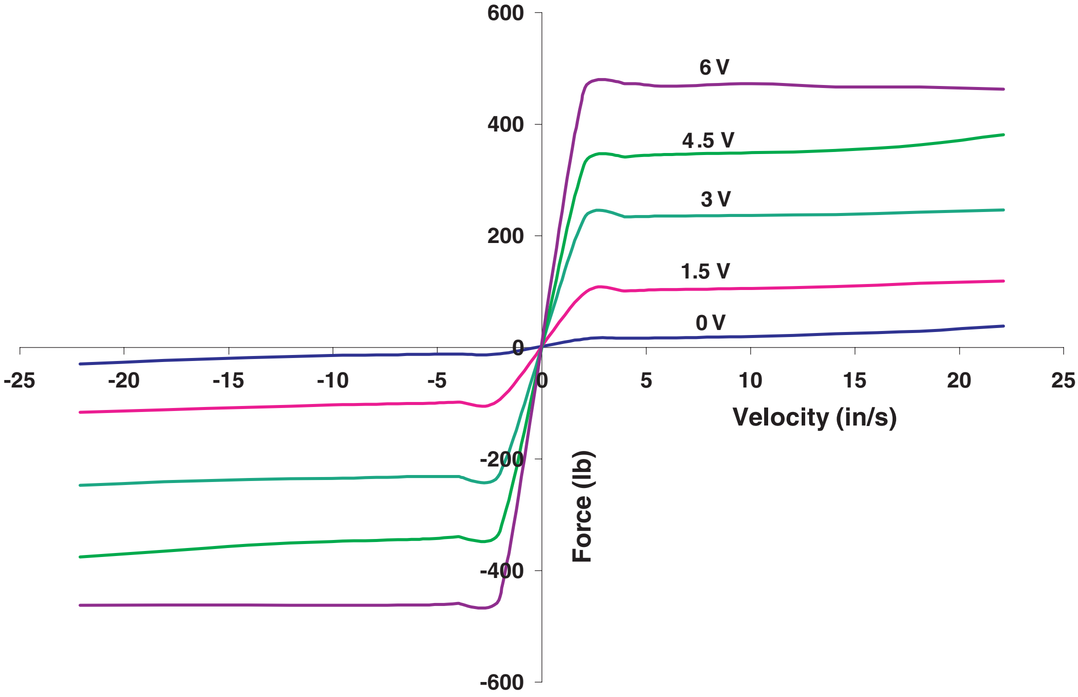

Fig. 4. Damping curves for the gun recoil MR damper at different voltages.

that is transferred from above the piston to below (and vice-versa) must pass through the MR valve. The MR valve is a fixed-size orifice with the ability to apply a magnetic field, using an electromagnet, to the orifice volume. This results in a change in the shear strain rate of the fluid passing through the MR valve, directly proportional to the force required to move the damper rod. The MR valve can be external to the damper as a physical valve for the fluid to pass through, such as shown in Fig. 1(a). Alternatively, as shown in Fig. 1(b), the MR valve can be internal to the damper in the form of a radial clearance (or gap) at the piston, so that the fluid can pass through it as the piston moves within the damper cylinder (body). The latter design is preferred-because it is simpler and can be more easily implemented in an MR damper-and is adopted for our gun recoil demonstrator, which will be described next.

3. MR recoil demonstrator

The demonstrator that we designed and built for the purpose of this study is shown in Fig. 2. It uses a 50 caliber, single-shot, Browning Machine Gun (BMG) rifle action that is mounted to a slider block. The slider block moves back on a pair of linear bearings, as the gun recoils. To the aft of the recoil slider is mounted a MR damper that is used to damp out the recoil dynamics of the gun. As will be described in the next section, we are able to change the recoil force and displacement, based on the amount of damping force that is generated by the MR damper.

The detail of the MR damper that was designed and fabricated for this study is shown in Fig. 3. This damper includes two steel plates that are attached to a cylinder made of steel and stainless steel such that they make contact with the steel portions of the cylinder. The steel plates that are attached to a coil transfer the electromagnetic field to the steel portions of the damper cylinder, which are placed opposite each other. The magnetic circuit is completed from one steel portion of the cylinder to another through the MR fluid, therefore providing the means for activating the fluid.

A double-ended piston can move in the cylinder, guided by two seals that are incorporated into two end caps that are attached at each end of the housing. In addition to guiding the piston rod, the seals are designed such that they maintain the MR fluid within the piston. A small clearance (gap) between the piston and the cylinder inner diameter provides the means for the MR fluid to pass through as the piston moves within the cylinder. As the MR fluid is activated by a different magnetic flux density, it offers a different amount of resistance to the motion of the piston, therefore providing different damping forces. The larger the magnetic flux density is, the higher the fluid resistance to the piston and the larger the damping force. The magnetic flux density is controlled by the amount of electrical current supplied to the coil.

Because the MR damper is expected to work at large velocities that are caused by the recoil dynamics, the gap between the piston and cylinder had to be designed such that it is large enough that it does not unduly stroke the fluid at high velocities, and yet is small enough that sufficient magnetic flux density can be created across it for activating the fluid. After experimenting with different gap sizes, we determined that a radial gap of 2.0 mm (0.080 in) worked the best for our design.

Although we used a variable voltage power supply in the lab for testing the damper, for ease of operation, we opted for a power supply that consisted of 4 AA batteries that were connected in series to provide 6 Volts nominal. This proved to be quite effective and reliable for testing the gun recoil demonstrator in the field.

4. MR damper force characteristics

In order to establish the force-velocity (or damping) characteristics of the MR damper that we had designed for the recoil demonstrator, we conducted a series of tests in a hydraulic material testing machine. In each test, the damper piston was moved at a given sinusoidal velocity relative to the piston and the resistance force due to this motion was recorded. The peak values for the force and velocity, plotted in Fig. 4, provide the curves that characterize the damper. Although we recognize the importance of testing the damper at velocities sufficiently high to characterize recoil velocities, our test machine was not capable of generating such velocities. Additionally, our attempts to create such velocities through a rig with a drop weight proved unreliable. Therefore, we decided to characterize the damper at velocities as high as possible with our test machine and use the results to estimate the damper behavior at higher recoil velocities. As will be shown later, this approach proved to be reasonably accurate.

As shown in Fig. 4, when no current is supplied to the damper, the damping force is relatively minimal (38 lb at 22 in/s). This is a desirable characteristic since the low forces when the damper is not powered provide a larger damping force range, defined as the difference between the damping force at a given velocity for the maximum and zero voltage. The larger the damper force range is, the higher the ability of the damper to affect the dynamics of the system in which it is used. As voltage to the damper is increased, the damping force increases, nearly proportionally. For a supplied voltage of 6 V, the MR damper was able to provide approximately 470 lb of force for velocities larger than 22 in/s. We determined this amount of force to be sufficient for our recoil demonstrator.

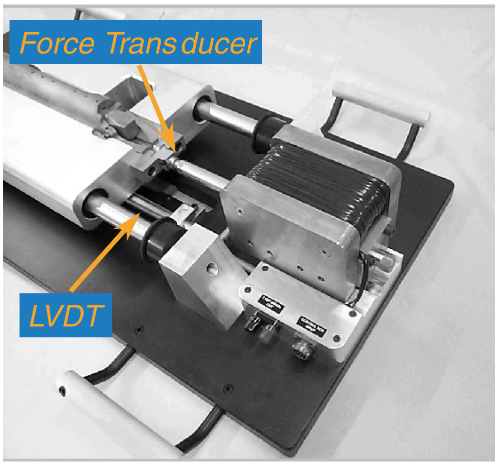

Fig. 5. Transducer placement for MR gun recoil demonstrator.

Although not shown in Fig. 4, we tested the damper at voltages much greater than 6 V, in order to determine how much more force the damper can generate at higher voltages, and also determine the saturation voltage of the damper. The saturation voltage is defined as the voltage at which no significant increase in damping force is observed as the voltage increases. Our test results showed that the MR damper was able to provide nearly a maximum of 700 lb force at 12 V, which proved to be our saturation voltage.

5. Field testing

A series of field tests were conducted to evaluate the effectiveness of the MR damper explained earlier for controlling gun recoil. The data collected in each test included the recoil force and stroke. The recoil force was measured using a force transducer that was installed at the connection of the MR damper to the recoil slider, as shown in Fig. 5. The force transducer is an Integrated Circuit Piezoceramic (ICP) force transducer manufactured by PCB Piezotronics, model number ICP 201B04. It can measure dynamic forces in compression to a maximum of 5000 lb, and has a sensitivity of 5 mV/lb. The recoil stroke was measured by a Linear Variable Differential Transformer (LVDT) con-

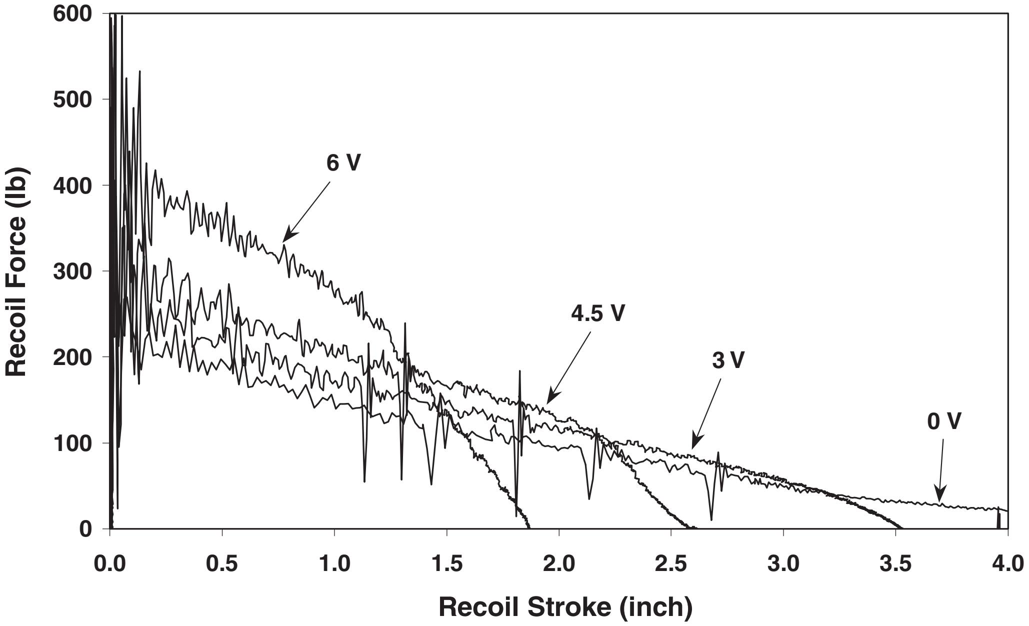

Fig. 6. Recoil force-stroke spectrum (actual).

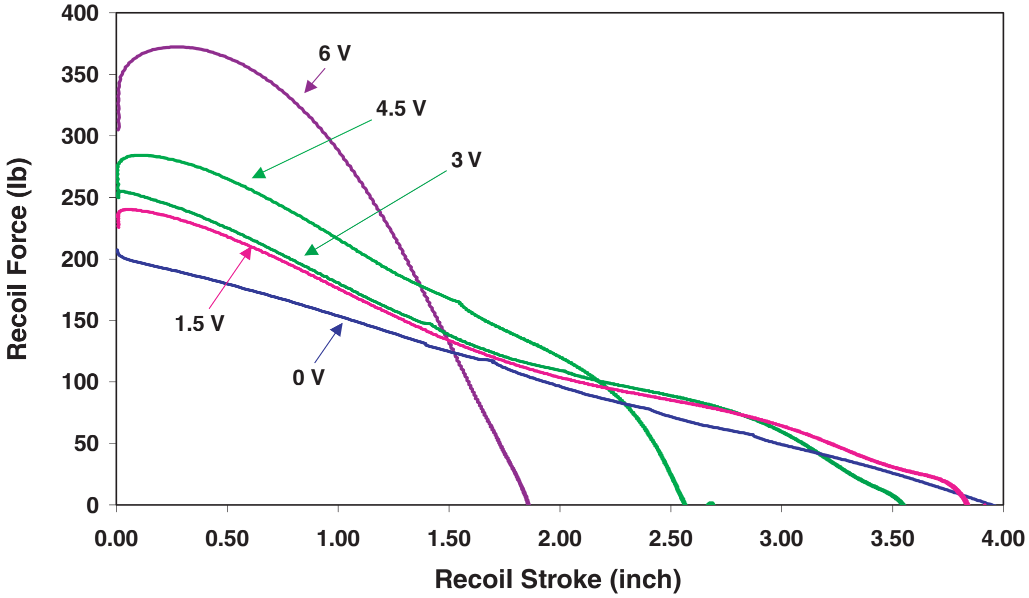

Fig. 7. Recoil force-stroke spectrum (curve-fitted).

nected to the recoil slider. The recoil force and stroke data were recorded, using a 2-channel dynamic signal analyzer, model number HP-35665A, manufactured by Hewlett Packard.

Each test was repeated a minimum of three times to ensure the accuracy of the data, which is represented in Figs 6–10. Figure 6 shows the recoil force vs. recoil stroke for different voltages supplied to the MR damper. As was mentioned earlier, the coil resistance was approximately 3 Ohms; therefore, if desired, the voltages shown in all figures can be converted to current. For instance, 3 Volts corresponds to 1 Amp and 6 Volts corresponds to 2 Amps. In spite of using filters to record the recoil force and stroke data, the plots in

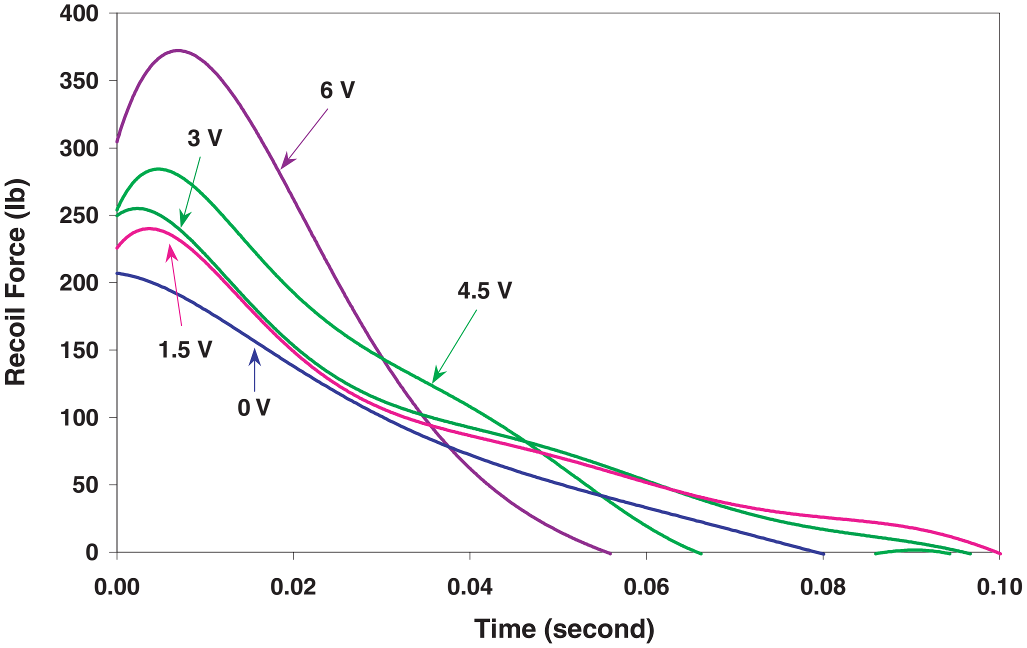

Fig. 8. Recoil force time profile.

Fig. 6 exhibit a significant amount of high frequency behavior which we contributed to the recoil dynamics itself. The plots are particularly difficult to see when the gun is first fired, i.e., at low recoil strokes. In order to better present the trend of the data, it was filtered in a manner that removed the high frequency contents, as is shown in Fig. 7 for recoil force vs. stroke, and in Figs 8–10 for other aspects of the recoil dynamics.

As is expected, Figure 7 shows that the initial peak of the recoil force increases as the damper force increases (through increasing the voltage supplied to the damper). The increase in recoil force appears to be nonlinearly dependent on the increase in damping force, with larger increases observed at higher voltages to the damper, as is shown in Figs 7 and 8. The recoil stroke is inversely proportional to the damping force-again exihibiting a nonlinear dependency on the damping force-as shown in Figs 7 and 9. For larger damping forces, the recoil stroke is shortened significantly (less than 1/2 of the maximum recoil stroke designed into our demonstrator at 6 V), whereas for smaller damping forces the change in recoil stroke appears to be far smaller. When no current was supplied to the damper, the gun recoil exceeded the 4 inch allowable stroke designed into the demonstrator and hit the elastomeric bumpers installed at the end of the travel, as is shown in Fig. 9. The recoil velocity plots, shown in Fig. 10, indicate slightly larger peaks for smaller damping forces, and a faster decrease in the peak velocity due to larger damping forces. Figure 10 further reveals that the recoil velocity peak occurs at different recoil times (and strokes), with larger damping forces having an advancing effect in the occurance of the peak velocity. The effect of this dynamic on gun stability needs to be determined individually in the weapon for which technologies such as the MR dampers are intended.

6. Concluding remarks

The application of magneto rheological dampers for controlling recoil dynamics was examined, using a recoil demonstrator that included a single-shot 50 caliber BMG rifle action and a MR damper. The demonstrator was selected such that it can adequately represent the velocities that commonly occur in weapons with a recoil system, and can be used for collecting data for analyzing the effects of MR dampers on recoil dynamics. The MR damper was designed such that it can work effectively at the large velocities commonly occurring in gun recoil, and also be easily adjusted to reasonably optimize the damper performance for the recoil demonstrator that was used for our study. The results of a series of tests that were conducted with the MR damper reconfirm the expectation that as the recoil damping increases the recoil peak force increases significantly and the recoil stroke decreases by a large amount.

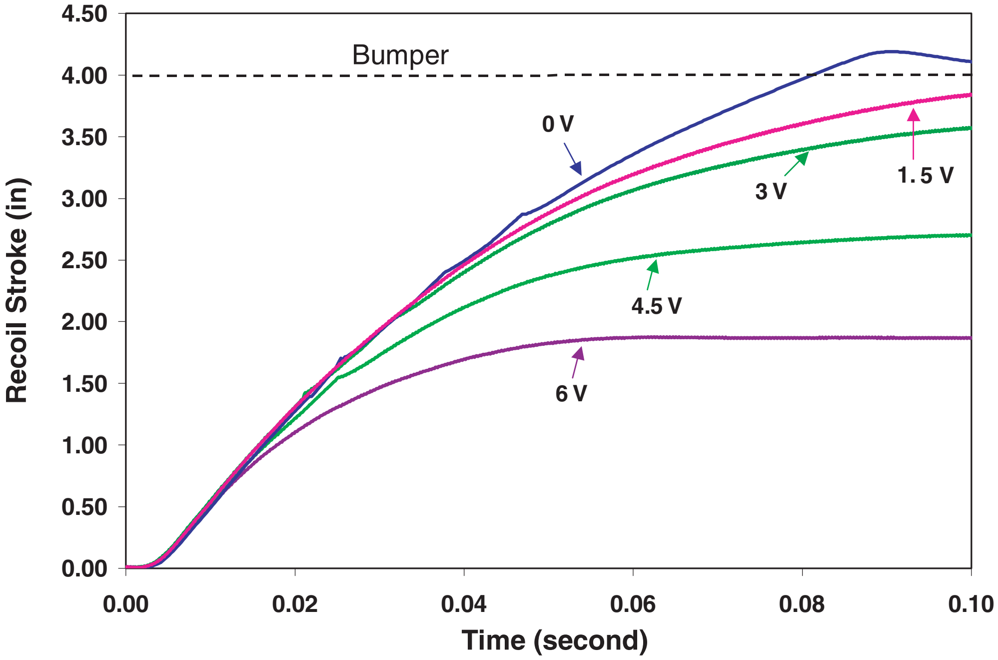

Fig. 9. Recoil stroke time profile.

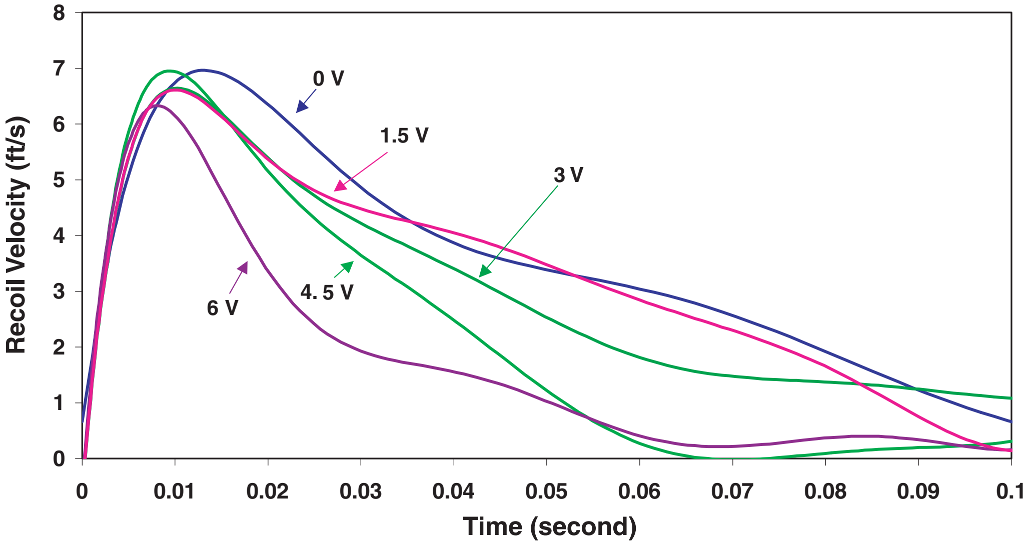

Fig. 10. Recoil velocity time profile.

The results show that the increase in recoil forces and the decrease in the recoil stroke occur in a nonlinear fashion with respect to the increase in damping force. More importantly, the test results show that it is indeed possible to design and use MR dampers for recoil application, which subject the damper to relative velocities far larger than the applications for which such dampers have commonly been used (i.e., vehicle applications).

Also of significance is the fact that the adjustability of MR dampers can be used in a closed-loop system such that the large recoil forces that commonly occur upon firing the gun are avoided and the recoil stroke is reduced, as shown in Fig. 11. Of course, there remain many other issues that are crucial to the successful implementation of MR dampers in a closed-loop recoil control system, including some of the following

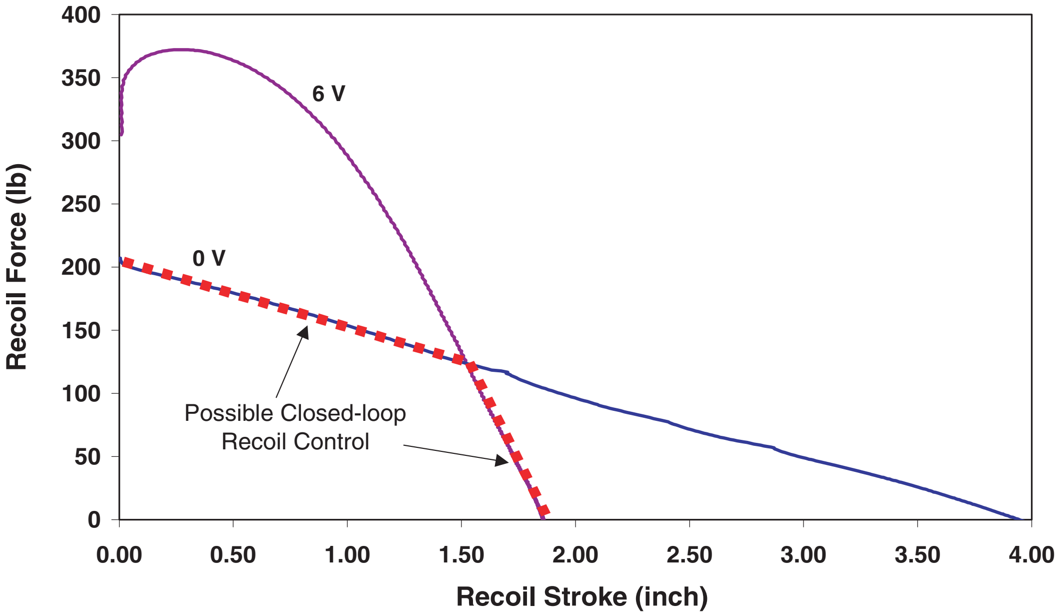

Fig. 11. Possible closed-loop recoil control using MR dampers, to reduce recoil forces while maintaining a short recoil stroke.

questions:

- Can MR dampers be designed to have a dynamic bandwidth that is suitable for impact dynamics occurring in gun recoil? If yes, how? If no, what control policies can be potentially used to make up for any deficiencies of the dampers?
- How can MR damper features be used to extend the capabilities of a recoil system by including fire out of battery capability?
- How can MR dampers be designed and used to sufficiently control such dynamics as misfire, hang-fire, pre-fire that a fire out of battery recoil system is expected to deal with?

These questions, which fell outside the scope of this study, will provide for interesting and challenging research studies in the future.

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