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On the Design of Magneto Rheological Recoil Dampers for Fire Out of Battery Control

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ABSTRACT

The application of magneto rheological dampers for controlling recoil dynamics is examined, using a recoil demonstrator that includes a 0.50-caliber gun and a MR damper (referred to as "recoil demonstrator"). Upon providing a brief background on MR dampers and fire out of battery dynamics, we will describe the recoil demonstrator, along with some of the test results from the laboratory and field-testing from the MR damper on the recoil demonstrator. The test results indicate that the MR damper is able to effectively control the recoil dynamics, and provide a different force-stroke curve for different amounts of current supplied to the damper. The current to the damper is used to energize the magneto rheological fluid within the damper and provide different amounts of damping force. Based on the recoil control results achieved by the damper, a technique is suggested for using MR dampers for fire out of battery. The technique, which consists of two stages, is described in detail along with the potential role of MR damper in each stage. Finally, our plans for field-testing the suggested fire out of battery method, using the recoil demonstrator and the MR damper, is briefly discussed.

INTRODUCTION

Conventional recoil mechanisms in larger guns are traditionally comprised of a hydraulic type system. The design of these systems has been used for years in many different ways. For example, the M198 shown in Figure 1 is a 155 mm towed howitzer used in a general support role for the U.S. Marine Corps Air Ground task forces and Army light infantry divisions. The M198 has a conventional split trail carriage and utilizes a hydraulic recoil mechanism [1].

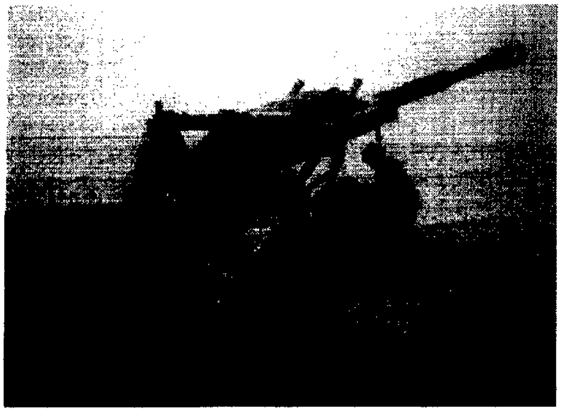

Figure 1. M198 155 mm Towed Howitzer (adapted from [1])

In addition to a towed howitzer configuration, large caliber cannons are also transported by means of a self-propelled vehicle, as in the case of Figure 2, the XM2001 or what it is commonly known as the Crusader Self-Propelled Howitzer (SPH) [1]. The Crusader SPH is a 155 mm fully automatic self-propelled howitzer, which utilizes a hydraulic type recoil system.

Figure 2. XM2001 – 155 mm Crusader Self-Propelled Howitzer (adapted from [1])

As the United States Military defines it direction for the 21st Century, it is asking the defense industry to create lighter and more mobile vehicles, while increasing overall systems effectiveness and firepower. As shown in Figure 3, one of the ways to reduce the total weight is the extensive use of titanium, such as in the 155 mm Ultra-lightweight Field Howitzer (designated the XM777 Lightweight 155 mm Towed Howitzer), making it just over one half of the weight of its predecessor, the M198 [2 – 3].

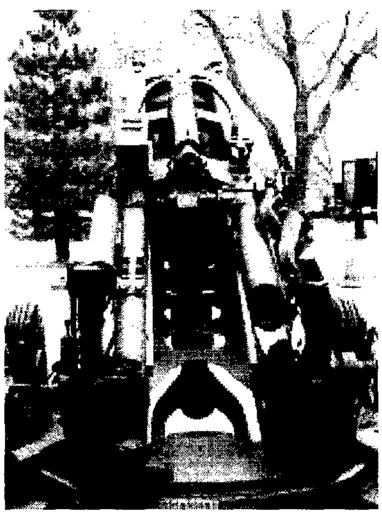

Figure 3. XM777 Lightweight 155 mm Towed Howitzer (adapted from [2])

Based on requests from the US Army, the Crusader Self-Propelled Howitzer has also been trimmed down to a prototype vehicle weight of 40 tons. This lighter platform will allow the Crusader Field Artillery System (the SPH and RSV – Re-supply Vehicle) to be transported aboard the same aircraft (C5 or C17) [4].

The common element among the future weapons—as well as improvement to existing weapons—that are considered by the U.S. Department of Defense are more lethal power and lighter weight. In order to achieve such goals, new recoil technologies must be employed in these weapons to increase their lethal power to weight ratio. This study will discuss one such technology, namely an advanced magneto-rheological damper, that is capable of sensing the recoil force and stroke of the gun and providing the optimal damping force for mitigating the recoil energy, and more importantly react to the fault modes of firing out-of-battery. Specifically, the primary purpose of this study is to highlight the application of a magneto-rheological damper for controlling the recoil dynamics, using a 0.50 caliber gun that is installed in a test apparatus, called here the "recoil demonstrator." Further, this study intends to discuss a control strategy that can be used for accommodating a fire out-of-battery recoil system and deal with the firing faults modes that may occur.

After providing a brief background on MR dampers and fire out-of-battery dynamics, we will describe the test system that was used for this study, along with some of our test results. This is followed by a discussion on fire out-of-battery control, in which we will suggest an approach for controlling MR dampers for assisting FOOB recoil and, more importantly, deal with the firing fault modes.

BACKGROUND ON MR DAMPERS

Magneto-rheological (MR) dampers have been widely studied for vehicle suspension applications, as seen in the studies included in references [5 – 8]. 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 25 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 recoil dynamics that occur upon firing a gun. As described in many past studies—such as [9 – 11]—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 stroke, 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 [12 – 14]. The vast majority of these studies have shown that theoretically it is possible to have a closed-loop recoil control system. This study will extend such results by providing the results of a series of experiments conducted on a gun recoil demonstrator

FIRE OUT-OF-BATTERY DYNAMICS

The circumstances that have led to the necessity for a fire out-of-battery system involves the challenge of designing a large caliber gun recoil system that is able to handle higher impulse munitions while at the same time reducing the recoil force that the vehicle feels through the trunnion pins. The necessity for higher impulse rounds is to have the ability to defeat threats at greater distances. Lower recoil loads through the trunnion pins will allow the vehicle to be lighter which translates into greater mobility, deployabilitly, and range.

The first step to understanding the issues is to look at the governing engineering equations. When applied to gun design, the conservation of momentum law dictates that the momentum that the bullet and propellant receive during the firing of the gun will be equal and opposite to the impulse the recoiling mass must absorb. This recoiling impulse translates to the energy that is absorbed by the gun mount, which ultimately appears as a recoil force on the trunnion pins.

For a typical large gun which has a recoil system, such as shown in the M198, XM777, and the Crusader SPH, a first order approximation of the equations that govern the recoil are:

$$(M_{\text{bullet}} + \tfrac{1}{2} M_{\text{propellant}}) * V_{\text{bullet}} = (M * V)_{\text{recoiling mass}} \qquad (1)$$

Eq. (1) above is used to calculate the recoil mass velocity. With this, the recoiling energy can be calculated and equated to the required recoil force needed over the recoil stroke:

$$\tfrac{1}{2} (M_{\text{recoiling mass}}) * (V_{\text{recoiling mass}})^2 = \text{Recoil Force}_{\text{Constant}} * \text{Distance}_{\text{Acting Force}} \qquad (2)$$

The military has a need to create lighter and more mobile artillery systems, while at the same time developing higher performance level munitions. These more lethal munitions, required to reach targets at much farther distances, demand much higher muzzle velocities, causing greater impulses to be absorbed by the system, and ultimately higher recoil forces seen at the trunnion pins. Various methods have been used and proven to reduce these recoil forces in the past. These include a long recoil stroke design that has the disadvantage of needing a very large swept volume for the recoiling parts. Another approach is the use of a muzzle brake that redirects the exiting propellant gas and thus its momentum as much as possible to the rearward direction of the gun. Muzzle brakes, although widely used, can only redirect the gas impulse and can thus never reduce more than that from the firing loads. Since the largest part of the recoil impulse is due to the bullet impulse, other means must also be used.

A fire out-of-battery (FOOB) mechanism can reduce the firing impulses by imparting a forward momentum (momentum opposite of recoil) of the recoiling parts before ignition. The FOOB mechanism effectively adds another term to Eq. (1):

$$((M_{\text{bullet}} + \tfrac{1}{2} M_{\text{propellant}}) * V_{\text{bullet}}) - ((M_{\text{bullet, propellant, recoiling mass}}) * (V_{\text{forward}})) = (M * V)_{\text{recoiling mass}} \quad (3)$$

In looking at Eq. (3), it becomes obvious that the entire firing impulse can be theoretically cancelled, and thus result in no recoil loads, if the forward velocity of the recoiling mass prior to firing can be high enough. Due to engineering limitations, a 50% reduction in recoil force is currently considered the practical limit. Figure 4 shows the contrasts between a conventional recoil system and a fire out-of-battery recoil system.

Figure 4a shows the three steps involved in a conventional recoil cycle. Step A1 is ignition from the in-battery position, Step A2 is recoil, and Step A3 is counter-recoil. Δx is defined as the maximum allowable recoil distance. Figure 4b shows the four steps involved in a FOOB recoil cycle. Step B1 is the loading position (Battery Position) and is the start of the run-up from the battery position. Step B2 is ignition, Step B3 is recoil, and Step B4 is counter-recoil.

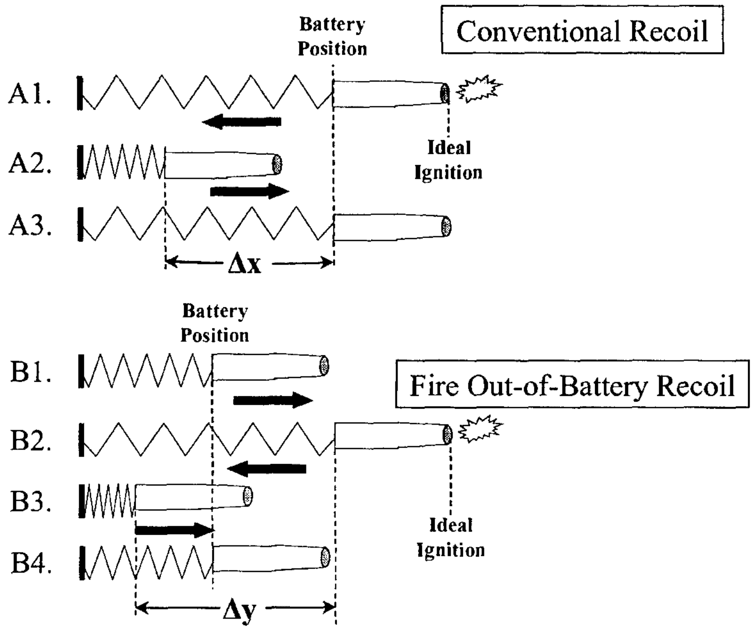

Figure 4. Conventional vs. FOOB Recoil firing sequence;
(a) Conventional firing; (b) FOOB recoil firing

The FOOB recoil system must be designed to handle the highest impulse munitions. The total stroke Δy, forward and rearward of the battery position, will correspond to this impulse level. The US Army and others have successfully tested this fire out-of-battery system in the past, yet there are two major concerns.

First, in order to correctly utilize the advantages of a FOOB recoil system, it is necessary to consistently predict the ignition time. Conventional ignition systems, while sufficient for their use with conventional recoil systems, are not precise enough to gain the desired results from a FOOB system. Research has been completed and successful testing has shown that the use of an Electro-Thermal Chemical (ETC) Ignition system significantly reduces the standard deviation in ignition time over that of conventional ignition. Figure 5 shows a diagram of successful 120 mm ETC Ignition testing completed by the Armament Systems Division, United Defense, L. P, in conjunction with the US Army's Army Research Laboratory.

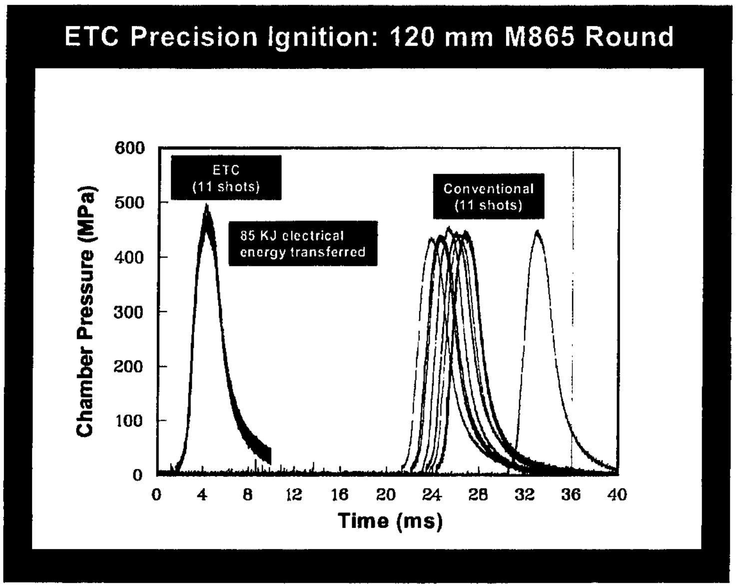

Figure 5. ETC 120 mm Testing

Second, the FOOB recoil mechanism must account for ignition error. The areas of concern are pre-fire (defined in Figure 6a), hang-fire (defined in Figure 6b), and misfire (defined in Figure 6c).

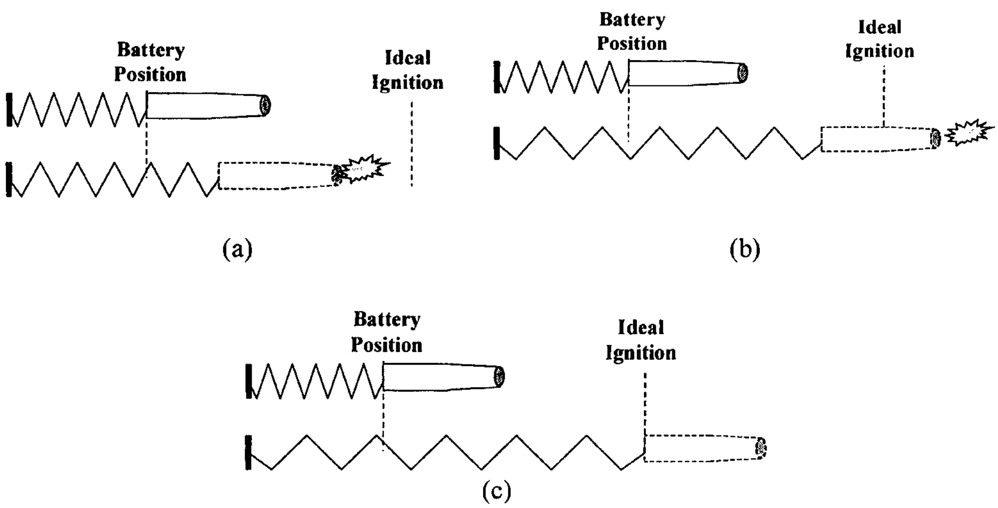

Figure 6. Definition of fault modes associated with Fire Out of Battery:
(a) pre-fire; (b) hang-fire; (c) misfire

In any of these three cases, when generating the momentum required to offset the recoiling impulse, if ignition does not take place at the precise time desired, the recoil system has to be designed to manage this firing impulse and forward momentum. If one of these cases occurs, the system must respond appropriately so that the gun does not damage itself.

The requirements of a Fire Out-of-Battery system are as follows:

1) A recoil system capable of absorbing the impulse from the required munitions
2) A system capable of accelerating the recoiling mass forward (direction opposite of recoil)
3) An ignition system capable of insuring precise and consistent firing times
4) A real time control device able to respond to fault modes associated with FOOB (hang-fire, pre-fire, and misfire)

While the first three requirements have been successfully demonstrated by the Army and ETC Ignition, the last one has yet to have undergone significant full scale testing. With the use of magneto-rheological technology and an active controller, a MR recoil system may be designed to sense normal firing conditions and the fault modes associated with FOOB and respond accordingly to and absorb the required impulse.

TEST SYSTEM

The test system that we designed and built for the purpose of this study is shown in Figure 7. It uses a 0.50 caliber, single-action, Browning Machine Gun (BMG) rifle 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 later, we are able to change the recoil force and displacement, based on the amount of damping force that is generated by the MR damper.

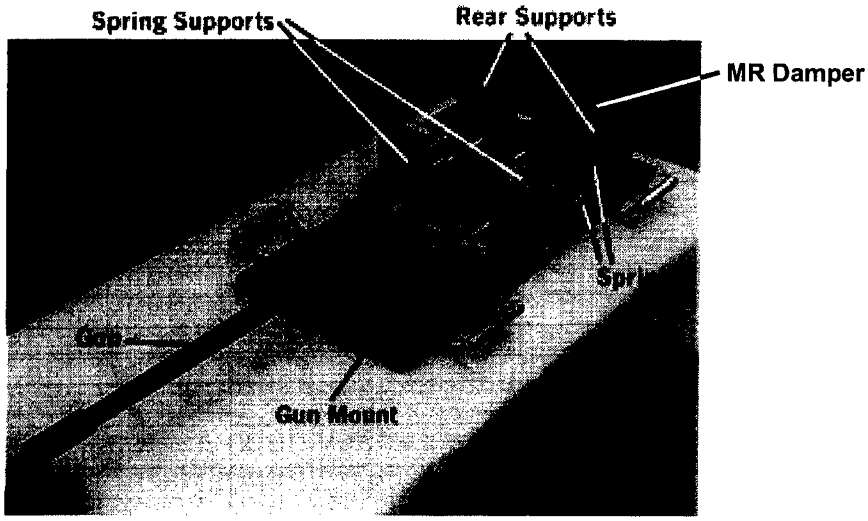

Figure 7. Magneto-Rheological Damper Test Device for Recoil Control

The detail of the MR damper that was designed and fabricated for this study is included in [15]. The damper includes a double-ended piston that can move in the cylinder, guided by two seals that are incorporated into two end caps attached at each end of the piston. In addition to guiding the piston rod, the seals are designed such that they maintain the MR fluid within the piston. A small circumferential clearance (gap) between the piston and the damper body provides the means for energizing the MR fluid, as it passes through the gap due to the movement of the piston 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 a coil designed in the piston.

TEST RESULTS

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 Figure 8, 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 on characterizing the damper at velocities as high as possible with our test machine, and used the results to estimate the damper behavior at the higher recoil velocities. As will be shown later, this approach proved to be reasonably satisfactory.

As shown in Figure 8, 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 dynamic 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.

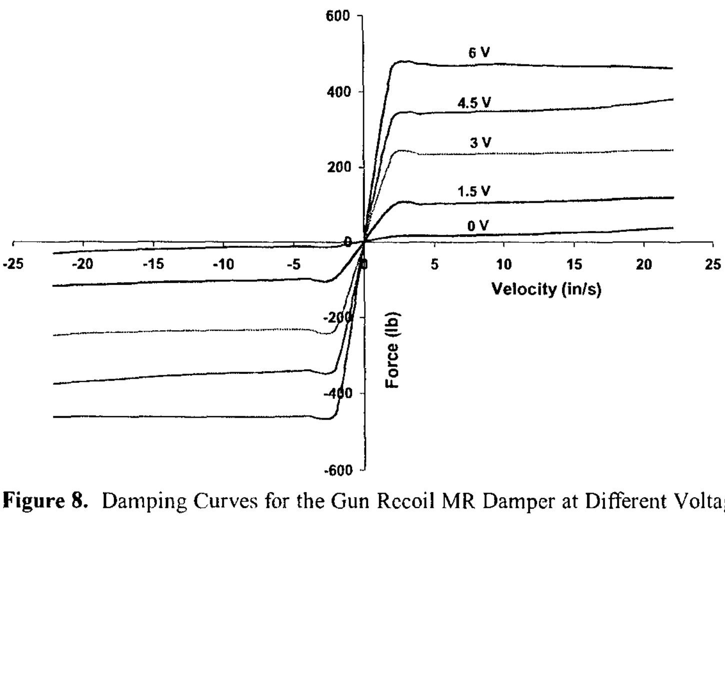

Figure 8. Damping Curves for the Gun Recoil MR Damper at Different Voltages

Although not shown in Figure 8, we tested the damper at voltages much greater than 6V, 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.

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. 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) connected 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.

Figure 9 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 Ohm and 6 Volts corresponds to 2 Ohms. As is expected, Figure 9 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 to the increase in damping force, with larger increases observed at higher voltages to the damper.

The recoil stroke is inversely proportional to the damping force—again exihibiting a nonlinearly dependency to the damping force—as shown in Figures 10. For larger damping forces, the recoil stroke is shortened significantly (less than ½ of the maximum recoil stroke designed into our demonstrator at 6V), 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 indicated in Figure 10.

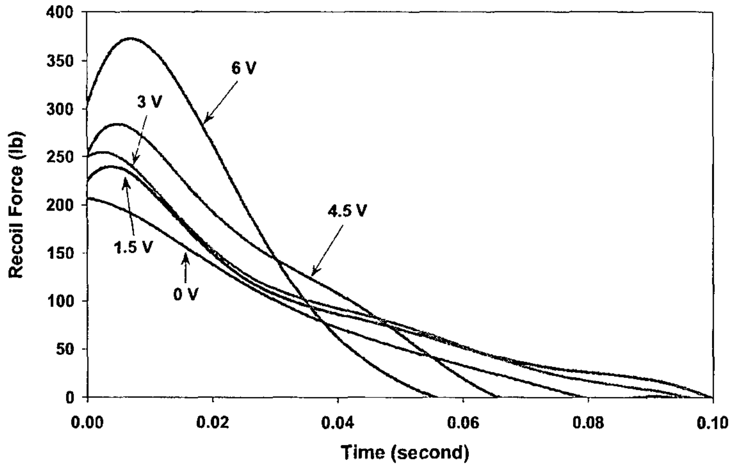

Figure 9. Recoil Force-Recoil Spectrum (Curve-Fitted)

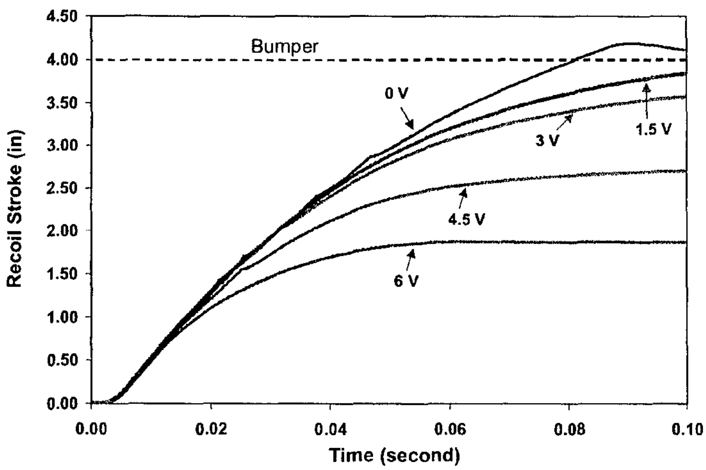

Figure 10. Recoil Force Time Profile

FIRE OUT OF BATTERY CONTROL

Considering the dynamic performance of MR dampers, as stated above, we are considering in our research the fire out of battery control shown in Figure 11. The first stage begins in the maximum displaced position where the gun is latched and loaded. After the round is loaded, the system is unlatched, allowing the gun to propel forward to a predisposed ignition position. The second stage begins with ignition and continues throughout the full recoil stroke (It is important to note that this testing fixture was designed to demonstrate the effectiveness of FOOB, and not designed to re-latch at the Stage 1 initial position as described above. After ignition, the gun recoils rearward until the recoil force is overcome by the spring force, at which point the system changes direction and slams into the front stops).

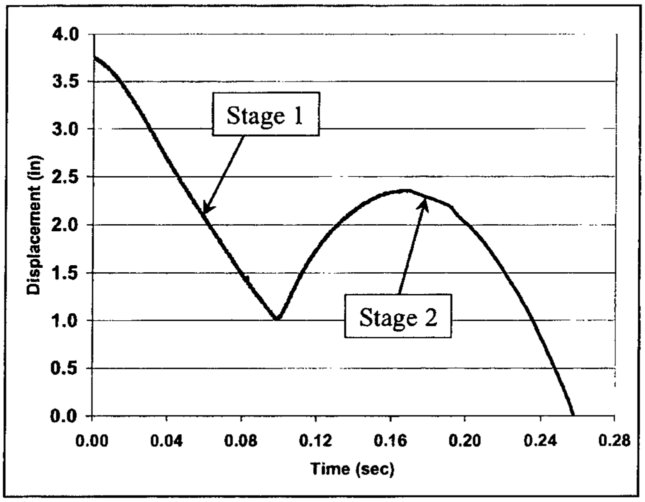

Figure 11. Displacement of the Gun during the Two-Stage FOOB Recoil Process

By sensing the position and velocity of the recoil assembly, we select the most dynamically advantageous position to fire out-of-battery, therefore ensuring lower peak forces, as shown in Figure 12. The recoil stroke and velocity measurements just mentioned above are also used to sense any firing faults, in which case the MR damper is used to react to the dynamics caused by such faults. For instance, incase of a misfire, the

MR damper can be fully energized to counteract the forward momentum of the gun and reduce the impact forces as it returns into the battery position.

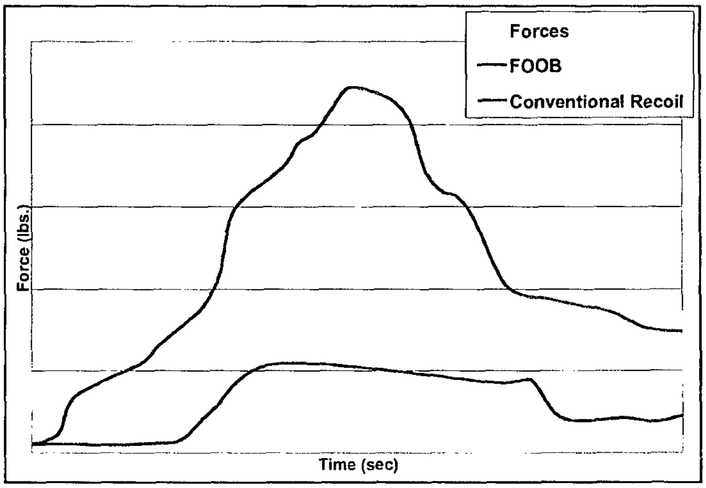

Figure 12. Force Comparison of FOOB and Conventional Recoil

We are currently in the process of implementing the above control technique in our recoil demonstrator. The initial laboratory testing that has been performed on the system indicates promising results. In the near future, we intend to conduct a series of field tests to further evaluate the potential of the MR dampers and the proposed FOOB control technique.

SUMMARY

The application of magneto-rheological dampers for controlling recoil dynamics was examined, using a recoil demonstrator that included a 0.50-caliber gun and a MR damper (referred to as "recoil demonstrator"). Upon providing a brief background on MR dampers and fire out-of-battery dynamics, we described the recoil demonstrator, along with some of the results that have been obtained from testing the MR damper as well as field testing the recoil demonstrator. The test results indicate that the MR damper is able to effectively control the recoil dynamics, and provides a different force-stroke curve for different amounts of current supplied to the damper. The current to the damper is used to energize the magneto rheological fluid within the damper and provide different amounts of damping force. Based on the recoil control results achieved by the damper, a technique was suggested for using MR dampers for fire out of battery. The technique, which consists of two stages, was described in detail along with the potential role of MR damper in each stage. Finally, our plans for field-testing the suggested fire out of battery method, using the recoil demonstrator and the MR damper, was briefly discussed.

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