Innovative Designs for Magneto-Rheological Dampers

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Abstract

Magnetorheological dampers, or as they are more commonly called, MR dampers, are being developed for a wide variety of applications where controllable damping is desired. These applications include dampers for automobiles, heavy trucks, bicycles, prosthetic limbs, gun recoil systems, and possibly others.

This thesis first introduces MR technology through a discussion of MR fluid and then by giving a broad overview of MR devices that are being developed. After giving the reader an understanding of MR technology and devices, MR damper basics are presented. This section includes a discussion of MR damper types, mathematical fundamentals, and an approach to magnetic circuit design.

With the necessary background information covered, MR dampers for automotive use are then discussed. Specifically, designs for MR dampers that were built for a Mercedes ML-430 and for a Ford Expedition are presented along with their respective test results. These test results are presented and compared with the original equipment hydraulic dampers.

After discussing automotive MR dampers, designs for gun recoil applications are presented. Specifically, two different MR damper designs are discussed along with live-fire test results for the first damper.

Finally, two hybrid dampers that were based on a modified adjustable hydraulic damper are presented. These hybrid dampers, if pursued further, may develop into controllable replacements for large hydraulic dampers such as those installed on large vehicles and field Howitzers. In conclusion, recommendations are made for materials as well as for seal selection and other design aspects.

Acknowledgements

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Chapter 1

Introduction

The purpose of this chapter is to orient the reader with the topic of magnetorheological fluid technology. From this point forward, magnetorheological fluid will be referred to simply as MR fluid. MR fluid belongs to a class of materials that are known as "smart materials". The physical attributes of smart materials can be altered through the application of an electrical, magnetic, or thermal stimulus. Some smart materials, known as Piezoceramics, exhibit a change in physical size when an electric current is passed through them. Other materials, known as Shape Memory Alloys, can be deformed and then returned to their original dimensions through the application of heat. Still other materials, known as ER (electrorheological) fluids and MR fluids, exhibit a change in apparent viscosity when activated. ER fluids are activated by exposure to an electric charge and MR fluids are activated by exposure to a magnetic field.

1.1 A Broad Overview of MR Fluid and MR Devices

Although MR fluids have existed for more than 50 years, there has been relatively little interest in the technology until recently. During the late 1940's and early 1950's, there was a flurry of interest in MR devices [1]. This interest, however, soon died out, probably due to limitations in sealing technology and difficulties in preventing caking and particle sedimentation within the fluid.

MR fluid consists of a liquid carrier, ferrous particles on the order of a few microns in diameter, and surfactant additives that are used to discourage particle settling. Three different carrier fluids are currently used, namely hydrocarbon-based oil, silicon oil, and water [1]. When exposed to a magnetic field, the ferrous particles within the fluid line up in columnar structures along lines of magnetic flux. These columnar structures cause a distinct change in the apparent viscosity of the MR fluid. The reason why the phrase "apparent viscosity" is used instead of "viscosity" is that the carrier fluid exhibits no change in viscosity, but the MR fluid mixture thickens—even becoming a solid—when it is exposed to a magnetic field. The magnetic field changes the shear strain rate of the

MR fluid, in the same sense that the fluid becomes more sensitive to shearing with an increasing magnetic field.

In recent years, there has been a renewed interest in MR fluid devices. For instance, Lord Corporation has been developing MR fluids and devices since the early 1990's. In the mid 1990's, Lord Corporation began manufacturing an MR damper line called "Motion Master". These dampers have found their way into truck seat suspensions and prosthetic legs. The Motion Master damper is arguably the first commercially successful MR device made. In addition to their line of MR dampers, Lord Corporation also produces a rotary MR brake that has been considered for exercise machines [2]. Another example of the renewed interest in MR technology is General Motor's announcement that an MR damper suspension system will be available on certain 2003 Cadillac models [3].

MR dampers are not, however, restricted to vehicle applications. Recently, the military has shown interest in using MR dampers to control gun recoil on Naval gun turrets and on field artillery. Another area of study that has incorporated MR dampers is the stabilization of buildings during earthquakes. For this application, Lord Corporation has developed a special MR fluid that will never settle out [4]. This increase in commercial interest is largely due to the success of research projects and through the efforts of Lord Corporation, which is a leader in the field of MR fluids and devices.

There are still other ways that MR fluids are being used that differ greatly from damper and brake applications. Two unusual applications immediately come to mind. The first is an optical polishing machine that uses a slurry-like mixture of MR fluid and abrasive particles. This slurry-like mixture of MR fluid and abrasives is ideal since it will conform to the surface of the lens being polished and its stiffness can be controlled through the use of a magnetic field. This MR polishing machine is being built by QED Technologies of Rochester, New York [5]. The other unusual application for MR fluids involves its use for fixturing fragile components such as turbine blades so that they can be machined without damage. Parts such as turbine blades are difficult to fixture because of their complex shape. Often parts such as these are damaged when they are held in a fixture of conventional design (using clamps of one type or another). To eliminate this fixturing problem, Dr. Kevin Rong and Dr. Rongjia Tao are working on a flexible fixturing process that involves the use of MR fluid that is activated by a water-cooled electromagnet. The part to be machined is held, partially submerged, by activated MR fluid that has been compressed slightly to increase its yield strength.

We expect that the unique rheological and physical properties of MR fluids make them suitable for many other future applications, beyond what has been envisioned thus far. For the purpose of this document, however, we will focus our attention on the application of MR fluids for dampers or shock absorbers.

1.2 Research Objectives

The primary objectives of this research are to

1. study different designs that are commonly used for MR dampers.
2. explore design alternatives to existing MR damper designs, and
3. provide recommendations for the effective design and fabrication of MR dampers.

1.3 Approach

During the course of this research, several different MR damper prototype designs were designed, built, and dynamically evaluated. Specifically, six different dampers were built. Of these six, four were for automotive applications, and two were for gun recoil applications. Of the dampers that were built for the automotive application, two were of the mono tube MR design and two were of the hybrid design. For the gun recoil application, two different double-ended MR dampers were built along with a “gun recoil demonstrator” that was used for damper evaluation.

1.4 Outline

Chapter 2 discusses background information about MR fluids and MR devices, the theory behind MR fluid, and several different devices that use MR technology. Chapter 3 discusses MR damper basics, which includes types of MR dampers, mathematical fundamentals of MR fluid, and magnetic circuit design. Chapter 4 gives a detailed discussion of MR dampers that were designed and built for a 1999 Mercedes ML-430 sport/utility vehicle and for a 2000 Ford Expedition sport/utility vehicle. Chapter 5 discusses two different MR dampers that were built for controlling gun recoil dynamics of a gun. Chapter 6 discusses two designs for hybrid dampers that were built and tested. Finally, Chapter 7 gives a summary of work that was completed as well as recommendations for future MR damper designs.

Chapter 2

Background

This chapter will provide an overview of MR fluids, MR dampers, and some of the other MR devices that have been commercialized or proposed for commercial applications. It further provides a summary of some of the past studies that have been conducted on MR dampers.

2.1 MR Fluid

MR fluids are non-colloidal suspensions of magnetizable particles that are on the order of tens of microns (20-50 microns) in diameter. The fluid was developed by Jacob Rabinow at the US National Bureau of Standards in the late 1940's [1]. Although similar in operation to electro-rheological (ER) fluids and ferrofluids, MR devices are capable of much higher yield strengths when activated. The main difference between ferrofluids and MR fluids is the size of the polarizable particles. In ferrofluids, these particles are an order of magnitude smaller than MR fluids, i.e. they are 1 – 2 microns, in contrast to 20 – 50 microns for MR fluids. For the first few years, there was a flurry of interest in MR fluids but this interest quickly waned. In the early 1990's there was resurgence in MR fluid research that was primarily due to Lord Corporation's research and development.

MR fluid is composed of oil, usually mineral or silicone based, and varying percentages of ferrous particles that have been coated with an anti-coagulant material. When unactivated, MR fluid displays Newtonian-like behavior [6]. When exposed to a magnetic field, the ferrous particles that are dispersed throughout the fluid form magnetic dipoles. These magnetic dipoles align themselves along lines of magnetic flux, as shown in Figure 2.1.

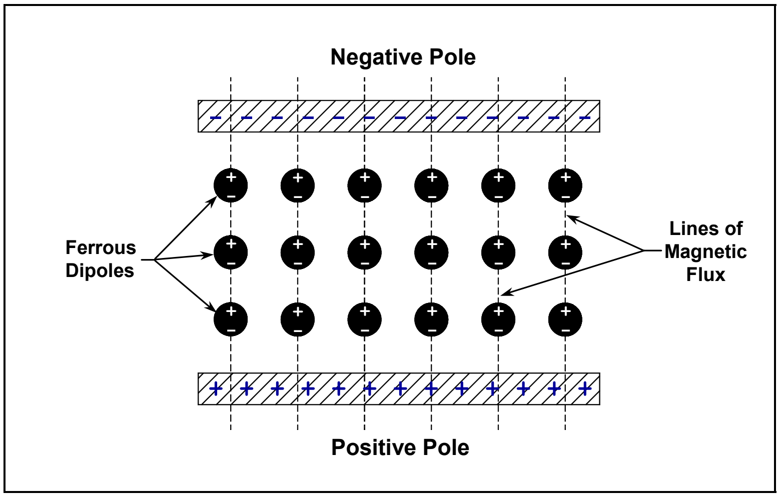


Figure 2.1 Dipole alignment of ferrous particles

On a larger scale, this reordering of ferrous dipole particles can be visualized as a very large number of microscopic beads that are threaded onto a very thin string as is shown in Figure 2.2. One can picture this thin string stretching from one magnetic pole to the other and perpendicular to each paramagnetic pole surface.

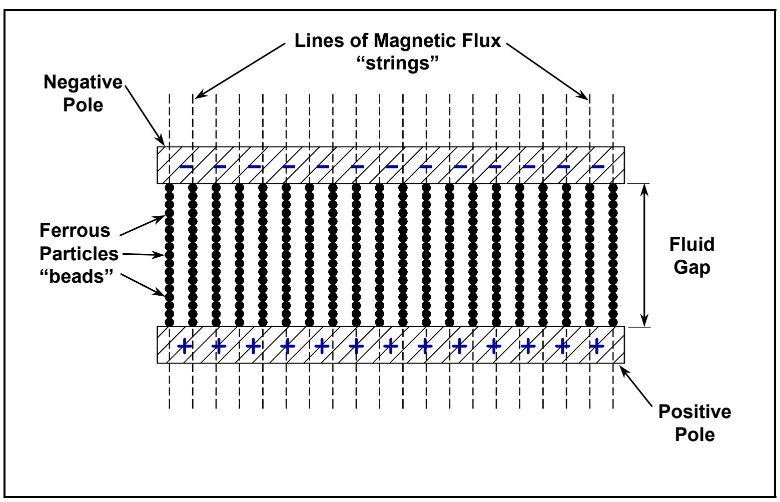


Figure 2.2 String and beads analogy of activated MR fluid

In this analogy, the spherical beads represent iron particles and each string represents a single flux line. One can picture many of these strings of beads placed closely together much like the bristles of a toothbrush. Once aligned in this fashion, the ferrous particles resist being moved out of their respective flux lines and act as a barrier to fluid flow.

Typically, MR fluid can be used in three different ways, all of which can be applied to MR damper design depending on the damper's intended use. These modes of operation are referred to as squeeze mode, valve mode, and shear mode. A device that uses squeeze mode has a thin film (on the order of 0.020 inch) of MR fluid that is sandwiched between paramagnetic pole surfaces as shown in Figure 2.3.

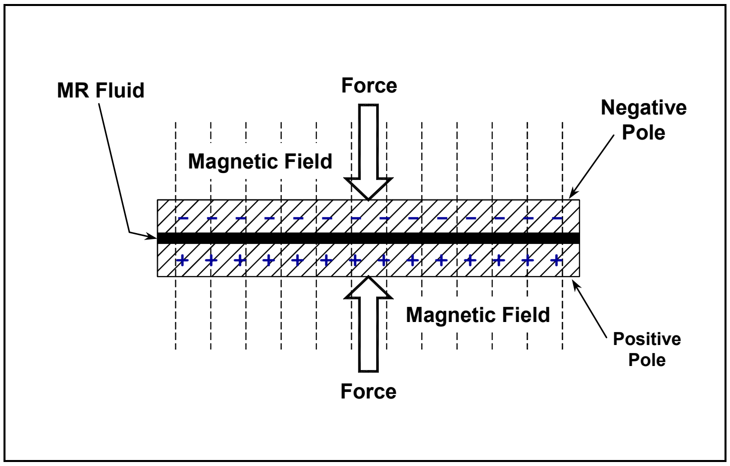


Figure 2.3 MR fluid used in squeeze mode

As depicted in Figure 2.4, MR fluid device is said to operate in shear mode when a thin layer (≈ 0.005 to 0.015 inch) of MR fluid is sandwiched between two paramagnetic moving surfaces. The shear mode is useful primarily for dampers that are not required to produce large forces or for compact clutches and brakes.

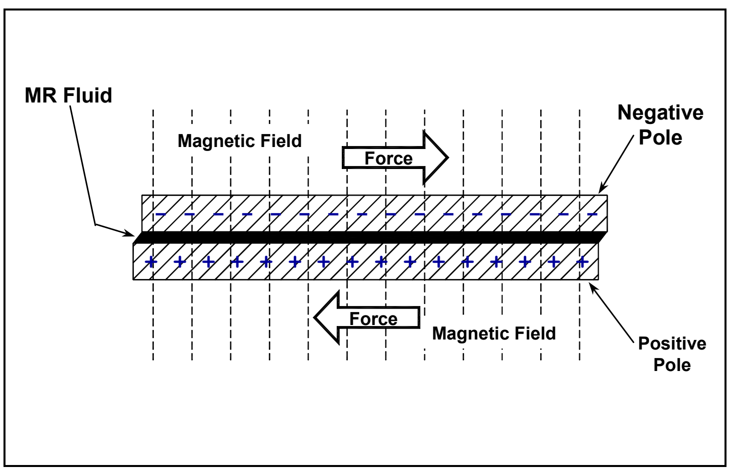


Figure 2.4 MR fluid used in shear mode

The last mode of MR damper operation, valve mode, is the most widely used of the three modes. An MR device is said to operate in valve mode when the MR fluid is used to impede the flow of MR fluid from one reservoir to another, as is shown in Figure 2.5. With the exception of a single hybrid MR damper design, all of the dampers used in this project operate in the valve mode.

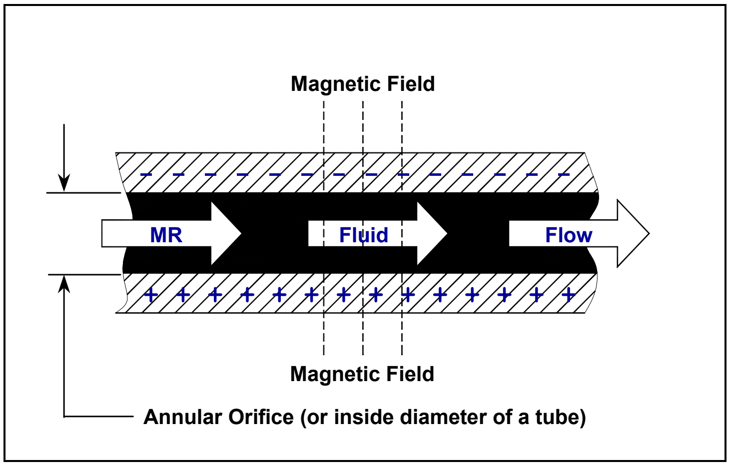


Figure 2.5 MR fluid used in valve mode

When MR fluid is used in the valve mode, the areas where MR fluid is exposed to magnetic flux lines are referred to as "activation regions" for the purpose of this study. In the case of the damper depicted in Figure 2.6, there exist two activation regions, which resist the flow of fluid from one side of the piston to the other when a magnetic field is present.

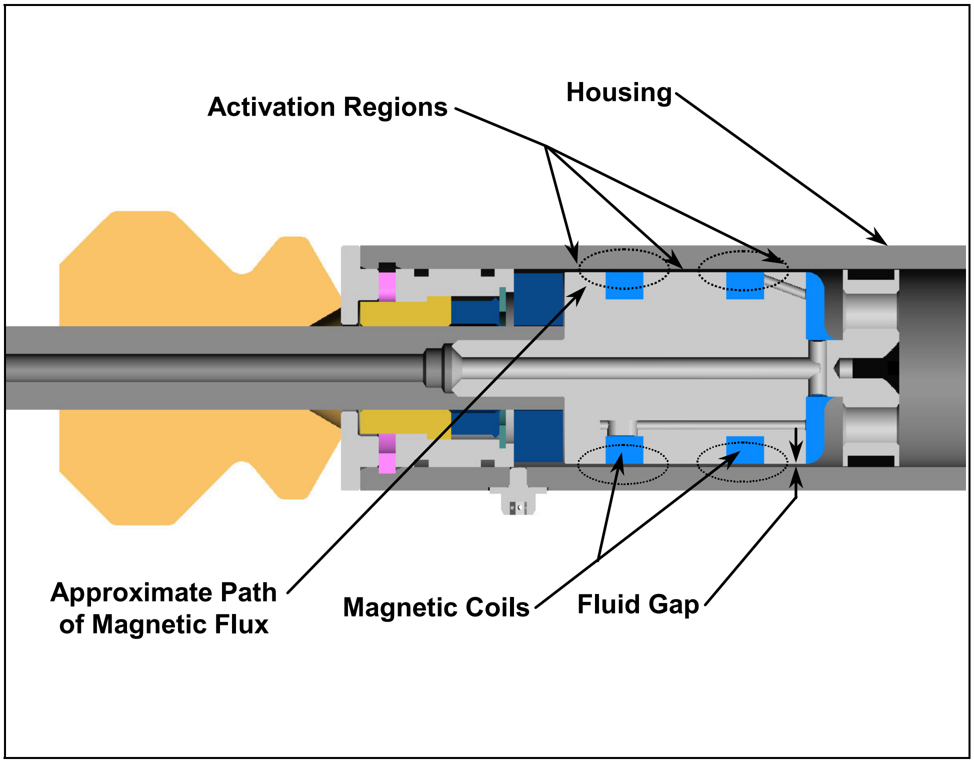


Figure 2.6 Typical MR damper

Varying the magnetic field strength has the effect of changing the apparent viscosity of the MR fluid. The reason why the phrase "apparent viscosity" is used instead of "viscosity" is that the carrier fluid exhibits no change in viscosity, but the MR fluid mixture thickens—even becoming a solid—when it is exposed to a magnetic field. The magnetic field changes the shear strain rate of the MR fluid, in the same sense that the fluid becomes more sensitive to shearing with an increasing magnetic field. As the magnetic field strength increases, the resistance to fluid flow at the activation regions increases until the saturation current has been reached. The saturation current occurs when increasing the electric current fails to yield an increase in damping force for a given velocity. The resistance to fluid flow in the activation regions is what causes the force that MR dampers can produce. This mechanism is similar to that of hydraulic dampers, where the force offered by hydraulic dampers is caused by fluid passage through an orifice. Variable resistance to fluid flow allows us to use MR fluid in electrically controlled viscous dampers and other devices.

2.2 MR Devices

In addition to dampers or shock absorbers, MR fluid can be used in a variety of other devices, including rotary brakes, clutches, prosthetic devices, and even for uses such as polishing and grinding.

One of the most innovative commercial applications for MR fluids is in the polishing of optical lenses. QED Technologies is currently producing a multiple axis CNC polishing machine that uses a slurry made of MR fluid and an abrasive. According to a QED publication cited in reference [5]: *"Unlike conventional rigid lap polishing, the MR fluid acts as a compliant polishing lap, whose shape and stiffness can be magnetically manipulated and controlled in real time. The optic's final surface form and finishing results are precisely predicted through the use of computer algorithms that map and control material removal across the workpiece."* Figures 2.7 and 2.8 show the QED Technologies' Q22 magnetorheological finishing machine and the process by which it works.

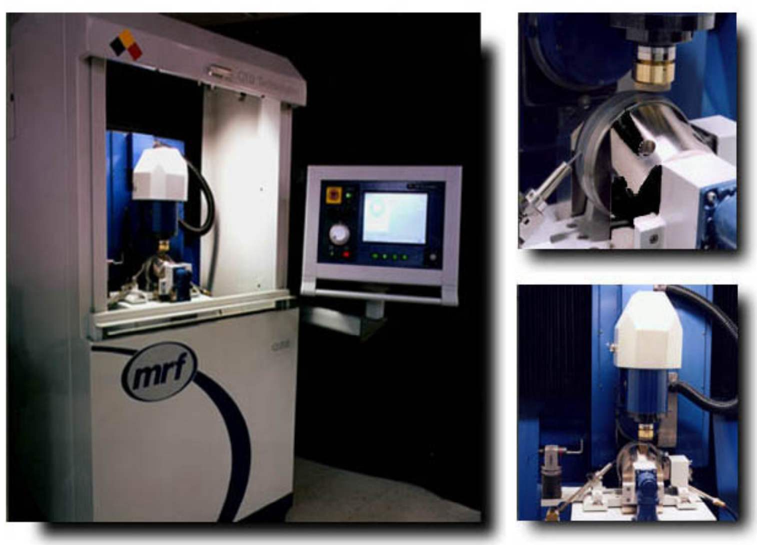


Figure 2.7 QED Technologies' Q22 magnetorheological finishing machine [5]

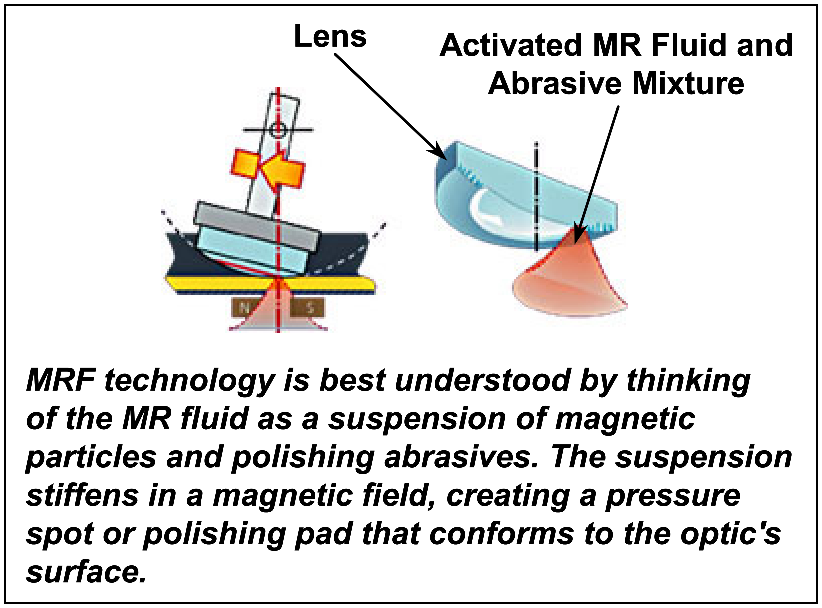


Figure 2.8 Description of polishing process [5]

Another commercial use for MR fluids is rotary brakes. Lord Corporation currently manufactures a MR rotary brake, shown in Figure 2.9, which can be used for exercise equipment, pneumatic actuators, steer-by-wire systems, and other similar applications; according to their sales brochure [2]. This device offers high controllability, fast response time (10 to 30 milliseconds), high torque at low speed, and requires very low power. Other benefits of this device include ease of integration, programmable functionality, rugged construction, and long service life. Functionally, this rotary brake consists of a steel disk that rotates in a bath of MR fluid. The MR fluid is used in shear mode and is activated by an electromagnetic coil that surrounds the periphery of the device.

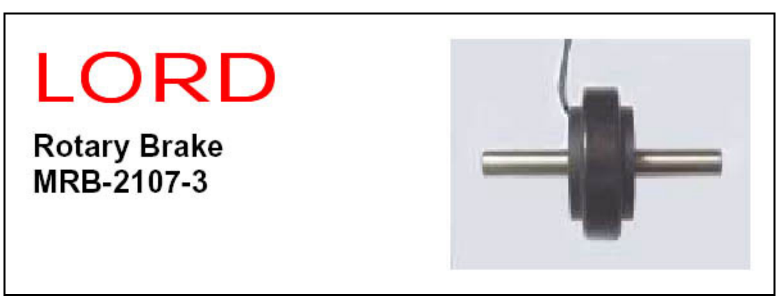


Figure 2.9 Lord Corporation's rotary MR brake [2]

Probably the most commercially successful MR device to date is the Rheonetic RD-1005-3 MR damper that is manufactured by Lord Corporation [7]. The damper has a mono tube construction and an extended and compressed length of 8.2 and 6.1 inches, respectively, measured from eye to eye. When compressed, the damper is 6.1 inches long also measured from eye to eye. The RD-1005-3 MR damper is capable of having more than 500 lbs of damping force at velocities of larger than 2 in/sec with 1 Amp of current. When no current is supplied to the damper (i.e. the off-state), the damper has a force of less than 150 lbs at 8 in/sec.

The Rheonetic RD-1005-3 MR damper is used in a seat suspension system called "Motion Master", which consists of the elements shown in Figure 2.10. This system, which is intended as a retrofit to existing hydraulic truck seat dampers, as well as for use by the original equipment manufacturer, has been very well received by the industry. In fact, in an effort to reduce worker compensation claims, West Virginia school transportation officials are considering a proposal to specify that Motion Master Ride Management Systems be used for all new bus purchases later this year [11].

Figure 2.10 Motion Master MR damper

Variations of this damper are being used for the Lord Motion Master™ truck seat damper [8] as well as for a prosthetic leg that is being developed by Biedermann Motech GmbH [9]. For the seat damper application, these small mono tube MR dampers are used in conjunction with a control unit and an accelerometer to minimize driver fatigue in large trucks. As can be seen in Figure 2.12, the prosthetic leg mentioned earlier uses a damper that is very similar to the one that is shown in Figure 2.10.

Figure 2.11 Biedermann Motech prosthetic leg

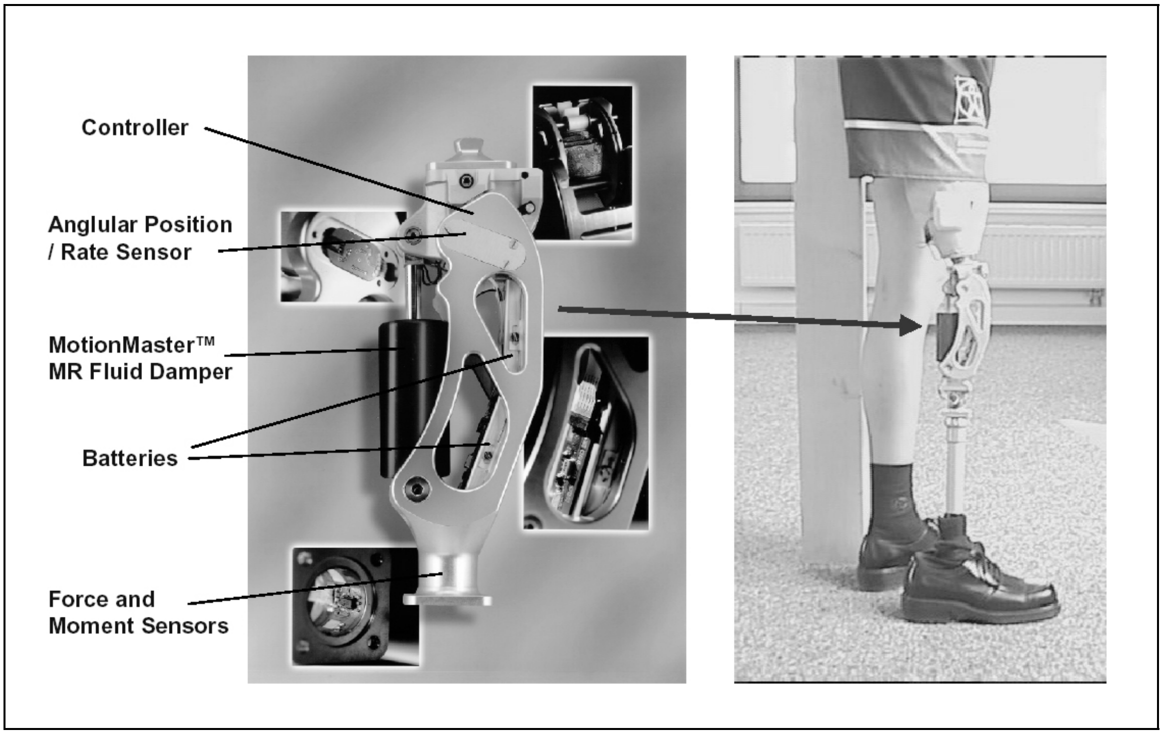


Figure 2.12 Diagram and picture of prosthetic leg

Another application of MR fluid that has recently been investigated is a fixturing device for holding turbine engine blades while they are being machined. This research is being carried out by Kevin Rong and Rongjia Tao at Worcester Polytechnic Institute [10]. According to Rong and Tao, the part to be held is partially submersed in MR fluid that is contained in a water-cooled electromagnet surrounded housing. Once the fluid is activated, the sides of the housing are moved inward slightly, therefore compressing the activated MR fluid around the work piece. When compressed, activated MR fluid can be up to 10 times stronger than uncompressed activated MR fluid [10]. Figure 2.13 shows a part being held in an experimental flexible MR fluid fixture. If successful, this fixturing technique could make many difficult to hold parts easier to machine and could also reduce damage that can be caused by conventional clamp type fixturing.

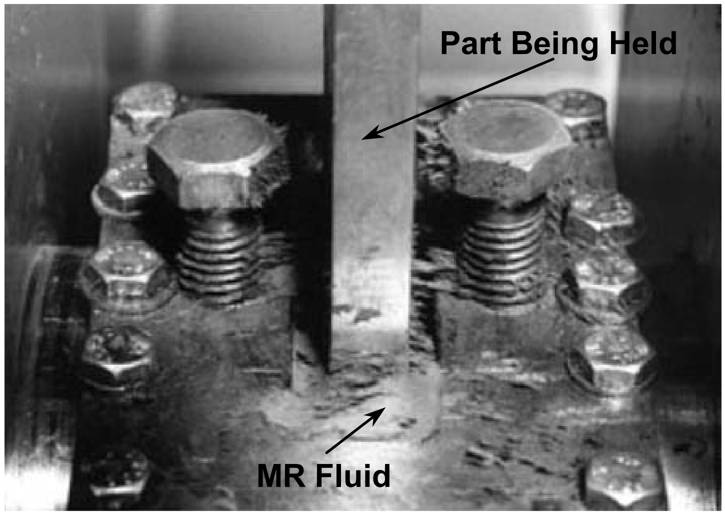


Figure 2.13 Flexible MR fluid fixture in use [adapted from 10]

In the next section, we will provide a summary of an extensive literature search that we conducted during this study.

2.3 Literature Search

A literature search was completed using two different Engineering databases. The two databases that were used were the Compendex*Plus database, which is a primary Engineering database and the Applied Science & Technology Abstracts database, which is a secondary Engineering database. The search was carried out using several different word combinations. These word combinations, as shown in Figure 2.14, were as follows: "magnetorheological damper", "magneto-rheological damper", "magneto rheological damper", "mr damper", "magnetorheological shock absorber", "magneto-rheological shock absorber", "magneto rheological shock absorber", "mr shock absorber". These versions of the term "magnetorheological" constitute all known variations that we are aware of.

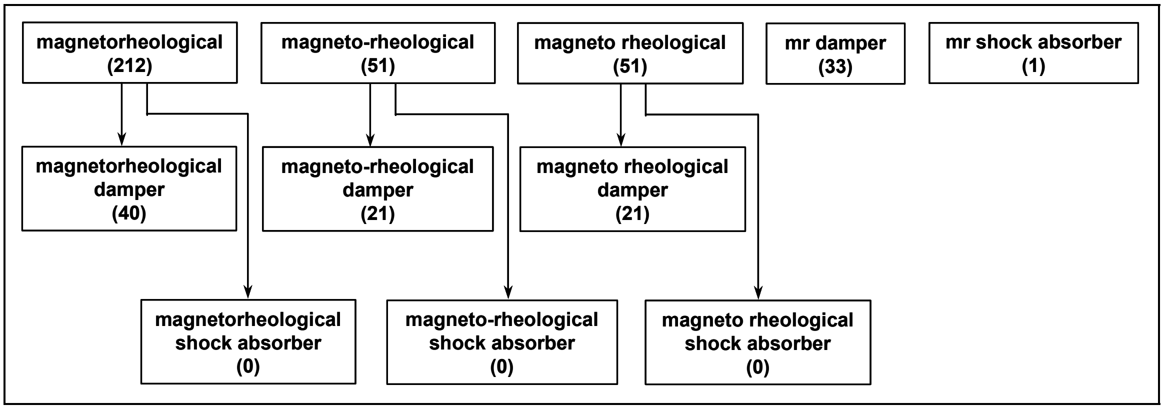


Figure 2.14 Keyword search diagram

2.3.1 Keywords: magnetorheological damper

The results of this search yielded 40 hits. Of these 40, the vast majority of the papers were either about mathematical modeling or control schemes and only 3 papers were written about MR damper design. A brief description of these papers will now be given.

Linder, et al. [16], discusses a double-adjustable MR damper for automotive use. By "double-adjustable", the author implies that the damper is individually adjustable for both jounce and rebound. Background information on double-adjustable shock absorbers is provided, the equations of Newtonian fluid theory are discussed, the Bingham Plastic model of MR fluid is presented, the MR damper that was built is discussed, and a discussion of concentric and non-concentric annular orifices is provided.

Gordaninejad, et al. [17], present the development and evaluation of an MR shock absorber that is intended for a High Mobility Multi-Purpose Wheeled Vehicle (HMMWV). The MR damper emulates the OEM shock absorber while operated in the passive mode and allows for a wide range of damping force when used in a non-passive mode. The shock absorber is studied theoretically and a electromagnetic finite element analysis model is developed. The damper performance that is predicted theoretically is compared with experimental test results.

Peel, et al. [18], discuss optimizing the design of an MR damper for controlling lateral vibrations in a modern rail vehicle. The authors show how, using generalized test data, the applied magnetic field can be related to the damping characteristics of the MR damper. Theoretically, it is shown how an MR damper can outperform a conventional lateral railcar damper. In addition, the expected power consumption of such a damper is discussed.

2.3.2 Keywords: magneto-rheological damper

This search yielded 21 hits. Like the previous search, these were mostly concerned with either MR damper control or with mathematical modeling. Out of the 21 hits, only 2 papers discussed MR damper design. A brief description of these two papers follows.

Ahmadian [13] discusses the design and fabrication of two MR dampers for use in a bicycle suspension. The two dampers represent different approaches of converting a stock 1998 Judy bicycle damper to an MR damper. The first approach involved reusing as many original parts as possible when converting the damper to an MR configuration. The second approach allowed more flexibility in retrofitting the damper to the MR configuration. The study shows that MR dampers offer considerable improvements in performance over conventional passive bicycle dampers.

Ahmadian and others [12], discuss the design and implementation of an MR damper for controlling gun recoil dynamics. The paper proves that MR dampers are compatible with shock loading applications. This paper is a direct result of the research presented in this thesis.

2.3.3 Keywords: magneto rheological damper

The results of this search were identical to the previously search using "magneto-rheological damper". Since no new hits were found, nothing is listed in this section.

2.3.4 Keywords: mr damper

This search yielded 33 hits, none of which were new.

2.3.5 Keywords: mr shock absorber

This search yielded 1 hit, which was not new.

Chapter 3
MR Damper Basics

Among MR devices, MR dampers have been most widely studied and developed for commercial applications, as was stated earlier. The commercialized success of MR dampers reaches beyond the Motion Master System by Lord Corporation, described earlier. It also includes automotive applications such as the recent announcement by Delphi Corporation to manufacture MR dampers for certain 2003 Cadillac models [3]. Other proposed applications for MR dampers include building control systems, for earthquake mitigation, and gun recoil dampers, for managing the impact dynamics of the gun. Therefore, for the remainder of this document, we will focus our discussions on MR dampers only. The remainder of this chapter is dedicated to describing the common types of MR dampers, the mathematical fundamentals of MR dampers, and magnetic circuit design.

3.1 Types of MR Dampers

There are three main types of MR dampers. These are the mono tube, the twin tube, and the double-ended MR damper. Of the three types, the mono tube is the most common since it can be installed in any orientation and is compact in size. A mono tube MR damper, shown in Figure 3.1, has only one reservoir for the MR fluid and an accumulator mechanism to accommodate the change in volume that results from piston rod movement. The accumulator piston provides a barrier between the MR fluid and a compressed gas (usually nitrogen) that is used to accommodate the volume changes that occur when the piston rod enters the housing.

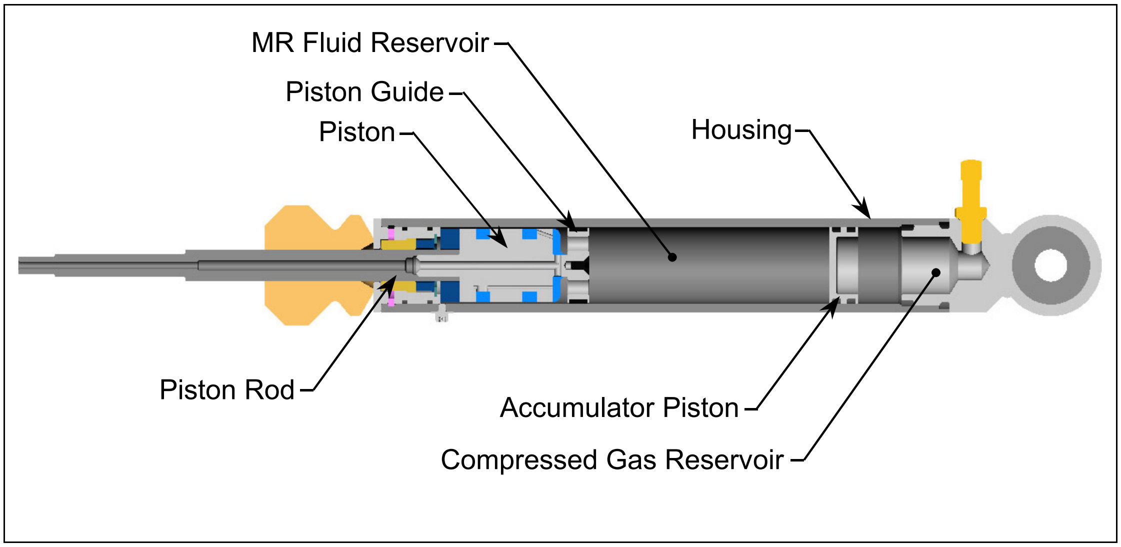


Figure 3.1 Mono tube MR damper section view

The twin tube MR damper is one that has two fluid reservoirs, one inside of the other, as shown in Figure 3.2. In this configuration, the damper has an inner and outer housing. The inner housing guides the piston rod assembly, in exactly the same manner as in a mono tube damper. The volume enclosed by the inner housing is referred to as the inner reservoir. Likewise, the volume that is defined by the space between the inner housing and the outer housing is referred to as the outer reservoir. The inner reservoir is filled with MR fluid so that no air pockets exist.

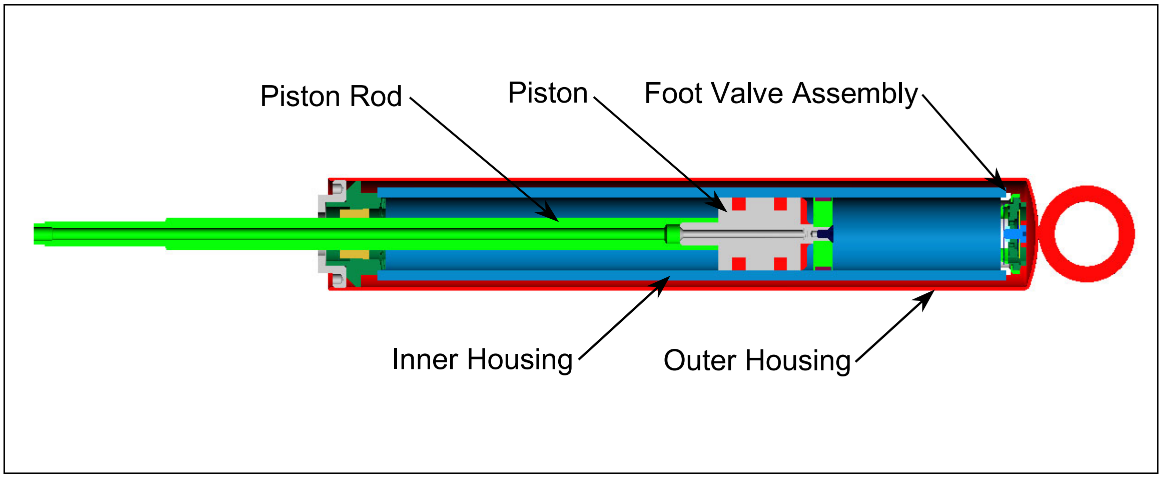


Figure 3.2 Twin tube MR damper

To accommodate changes in volume due to piston rod movement, an outer reservoir that is partially filled with MR fluid is used. Therefore, the outer tube in a twin tube damper serves the same purpose as the pneumatic accumulator mechanism in mono tube dampers. In practice, a valve assembly called a “foot valve” is attached to the bottom of the inner housing to regulate the flow of fluid between the two reservoirs. As the piston rod enters the damper, MR fluid flows from the inner reservoir into the outer reservoir through the compression valve, which is part of the foot valve assembly. The amount of fluid that flows from the inner reservoir into the outer reservoir is equal to the volume displaced by the piston rod as it enters the inner housing. As the piston rod is withdrawn from the damper, MR fluid flows from the outer reservoir into the inner reservoir through the return valve, which is also part of the foot valve assembly.

The final type of MR damper is called a double-ended damper since a piston rod of equal diameter protrudes from both ends of the damper housing. Figure 3.3 shows a section view of a typical double-ended MR damper. Since there is no change in volume as the piston rod moves relative to the damper body, the double-ended damper does not require an accumulator mechanism. Double-ended MR dampers have been used for bicycle applications [13], gun recoil applications [12], and for controlling building sway motion caused by wind gusts and earthquakes [4].

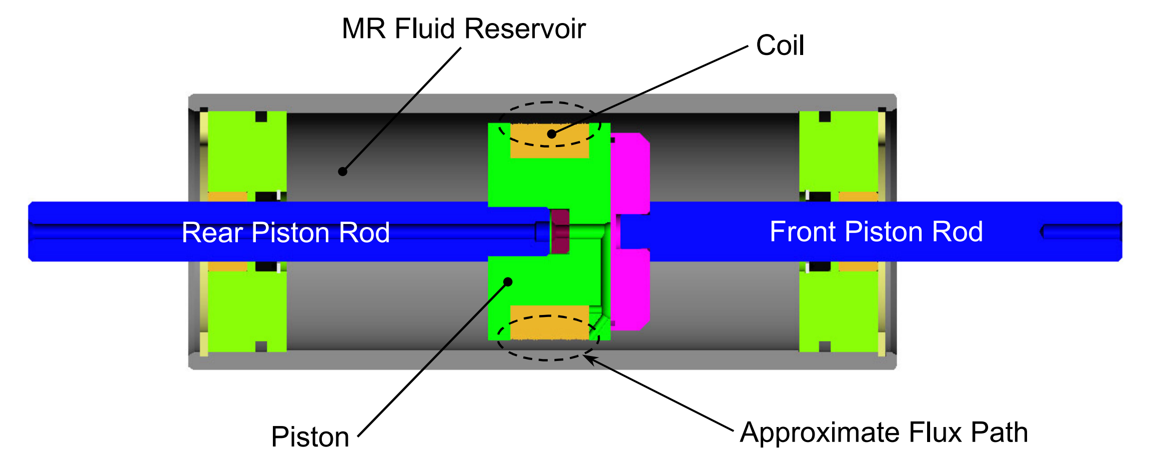


Figure 3.3 Double-ended MR damper

3.2 Mathematical Fundamentals of MR Dampers

To assist the reader in understanding the following mathematical discussion, Table 3.1, which lists all nomenclature that is used, has been included.

Table 3.1 Mathematical Nomenclature

Symbol	Meaning
τ	Fluid stress
τ_y	Field dependent yield stress: Found in MR fluid spec sheets
H	Magnetic field
η	Plastic viscosity (H=0): Found in MR fluid spec sheets
$\dot{\gamma}$	Fluid shear rate
γ	Fluid shear
G	Complex material modulus
ΔP	Pressure drop
ΔP_η	Viscous component of pressure drop
ΔP_τ	Field dependent induced yield stress component of pressure drop
Q	Pressure driven fluid flow
L	Length of fluid flow orifice
g	Fluid gap
w	Width of fluid flow orifice
c	Constant *
F	Force that is developed between pole plates in shear mode
F_η	Viscous shear force
F_τ	Magnetic dependent shear force
S	Relative velocity between pole plates used in shear mode
A	Pole area
V	Activated fluid volume
k	Constant
λ	Control ratio
W_m	Required controllable mechanical power level

* $c = 2$ (for $\Delta P_\tau / \Delta P_\eta$ less than ~ 1); $c = 3$ (for $\Delta P_\tau / \Delta P_\eta$ greater than ~ 100)

MR fluid is often modeled as a Bingham solid that has variable yield strength [6]. For this model, fluid flow is governed by Bingham's equations, which are displayed below as Equations (3.1a) and (3.1b).

$$\tau = \tau_y(H) + \eta\dot{\gamma} \tag{3.1a}$$

$$\tau < \tau_y \tag{3.1b}$$

In Equations (3.1a) and (3.1b), τ represents the fluid stress, τ_y represents the field dependent yield stress, H represents the magnetic field, $\dot{\gamma}$ represents the fluid shear rate, and η represents the plastic viscosity; in other words, the viscosity when H=0. Below the fluid's yield stress (pre-yield state), the fluid displays viscoelastic behavior. This viscoelastic behavior can be represented by Equation (3.2), where G represents the complex material modulus.

$$\tau = G\gamma, \quad \tau < \tau_{\mathrm{y}} \tag{3.2}$$

The pressure drop in an MR fluid device that is used in the flow mode can be represented by Equation (3.3), where the pressure drop (ΔP) is assumed to be the sum of a viscous component (ΔP_η) and a field dependent induced yield stress component (ΔP_τ).

$$\Delta P = \Delta P_\eta + \Delta P_\tau = \frac{12\eta QL}{g^3 w} + \frac{c\tau_y L}{g} \tag{3.3}$$

In Equation (3.3), Q represents the pressure driven MR fluid flow, and L, g, and w represent the length, fluid gap, and the width of the flow orifice that exists between the fixed magnetic poles as can be seen in Figure 3.4.

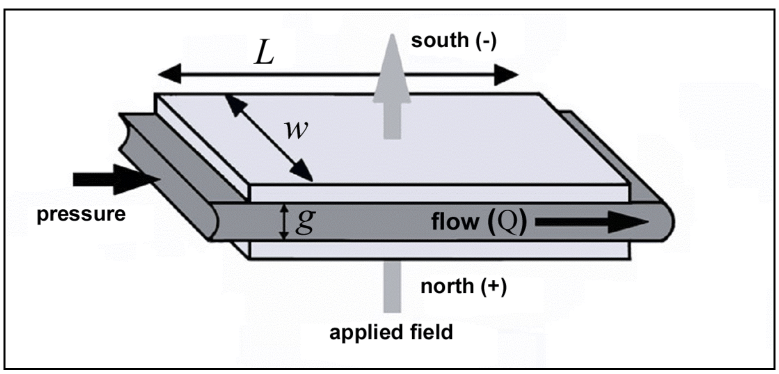


Figure 3.4 MR fluid in valve mode [adapted from 1]

The constant c, varies from 2 to 3 depending on what $\Delta \mathrm{P}_\tau / \Delta \mathrm{P}_\eta$ ratio is present in the device being considered. For $\Delta \mathrm{P}_\tau / \Delta \mathrm{P}_\eta$ ratios of approximately 1 or smaller, the value for c is chosen to be 2. For $\Delta \mathrm{P}_\tau / \Delta \mathrm{P}_\eta$ ratios of approximately 100 or larger, the value for c is chosen to be 3.

For a direct shear mode MR device, shown in Figure 3.5, we can use

$$F = F_\eta + F_\tau = \frac{\eta S A}{g} + \tau_y A \tag{3.4}$$

to calculate the force that is developed between the two pole plates when one pole plate is moved relative to the other and parallel to the fluid gap. This equation assumes that the total force developed is the sum of a viscous shear force component and magnetic field dependent shear force component. In Equation (3.4), F represents the force that is developed between the pole plates, F_η is the viscous shear force, F_τ is the magnetic dependent shear force, and A is the pole plate area, which is defined by $A{=}Lw$.

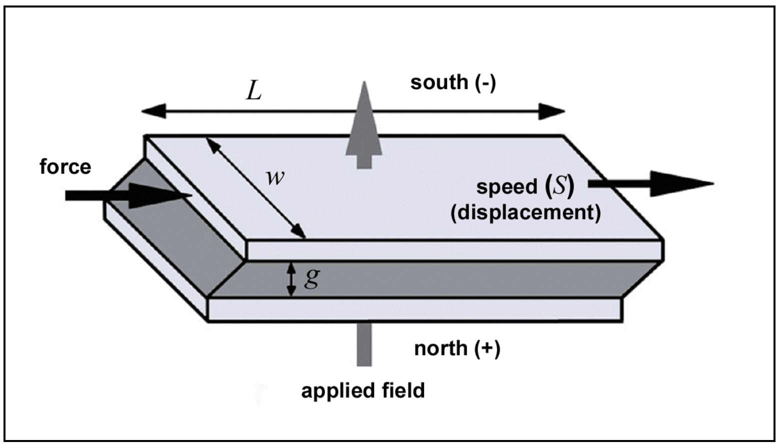


Figure 3.5 MR fluid in direct shear mode [adapted from 6]

Equations (3.3) and (3.4) can be algebraically manipulated to yield the volume of MR fluid that is being activated, which can be represented by

$$V = k\left(\frac{\eta}{\tau_y^2}\right)\lambda W_m \,. \tag{3.5}$$

In Equation (3.5), V can be regarded as the minimum active fluid volume that is needed to achieve a desired control ratio λ at a required controllable level of mechanical power dissipation W_m [6]. This volume represents the amount of MR fluid that is exposed to the magnetic field. The parameters in Equation (3.5) can be calculated as

$$k = \frac{12}{c^2} \tag{3.6a}$$

$$\lambda = \frac{\Delta P_\tau}{\Delta P_\eta} \tag{3.6b}$$

$$W_m = Q\Delta P_\tau \tag{3.6c}$$

for valve mode operation. Further, for shear mode operation, they can be calculated as

$$k = 1 \tag{3.7a}$$

$$\lambda = \frac{F_\tau}{F_\eta} \tag{3.7b}$$

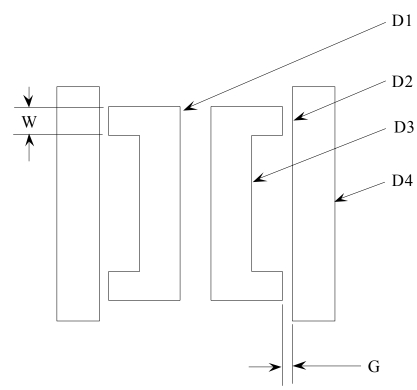
$$W_m = F_\tau S \tag{3.7c}$$

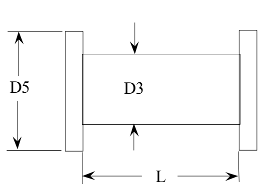
3.3 Magnetic Circuit Design

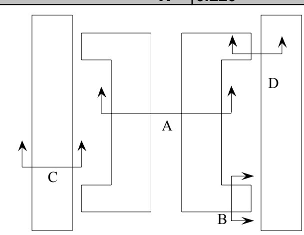
Another important aspect of MR damper design is the magnetic circuit. In order to assist in designing pistons for MR dampers, an Excel spreadsheet, such as the one shown in Figure 3.6, can be used to output the parameters for the electromagnetic circuit. Throughout the following discussion, the variable names are referenced as depicted in Figure 3.6.

Wire Gauge	Decimal Diameter (in)	Number of Turns Possible	Length of Wire (ft)	Resistance of Cu Wire (ohm)	Current Possible (A)
14	0.0641	8	3	0.01	1756.77
15	0.0571	9	4	0.01	1097.88
16	0.0508	15	4	0.02	683.19
17	0.0453	17	6	0.03	429.48
18	0.0403	25	7	0.04	267.60
19	0.0359	28	9	0.07	167.74
20	0.0320	40	11	0.11	105.46
21	0.0285	45	15	0.18	66.11
22	0.0253	60	18	0.29	40.92
23	0.0226	79	23	0.46	25.98
24	0.0201	101	29	0.74	16.21
25	0.0179	128	37	1.18	10.18
26	0.0159	160	47	1.90	6.32
27	0.0142	197	59	2.99	4.01
28	0.0126	263	75	4.83	2.48
29	0.0113	315	94	7.48	1.61
30	0.0100	407	120	12.21	0.98

Input Parameters		Output Data	
D1 =	0.156	Area A (in^2) =	0.624
D2 =	1.313	Area B (in^2) =	0.624
D3 =	0.905	Area C (in^2) =	0.624
G =	0.020	Area D (in^2) =	0.081
L =	0.28	D4 =	1.587
Supply Voltage =	12	D5 =	1.273
		W =	0.220







NOTE: The decimal wire diameter divided by 10 has been added to wire diameters in the "*Number of Turns Possible*" and "*Length of Wire*" equations where appropriate to compensate for insulation thickness.

Figure 3.6 Excel spread sheet developed to assist in MR damper design

The most important aspect of magnetic circuit design is that the region of highest reluctance is the region where the MR fluid will be activated. When a new damper is to be designed, several dimensions are usually known or can be determined from experience. These dimensions are the hole diameter through which the wiring must pass to supply the electromagnetic coil (D1), the bore diameter of the housing (D2), the desired fluid gap (G), and the coil recess length (L). The piston core minor diameter (D3) must be selected iteratively until the desired result is obtained, therefore posing a challenge in that the designer must have a feel for what the coil parameters must be for a given design situation. A good design will provide a reasonable number of turns in the coil with as heavy a gauge wire as possible, given the geometric dimensions of the piston.

The remaining dimensions, which are the outside diameter of the housing (D4), the major piston diameter (D5), and the piston flange width (W) are given as functions of the input parameters. To have an efficient magnetic circuit, it is advantageous to have the following areas match: the piston cross-sectional area (A), the housing cross-sectional area (C), and the piston radial root area (B). The reason for matching these areas is to avoid a "bottleneck" in the magnetic circuit. Also, for the most efficient magnetic circuit, the fluid gap (G) should be minimized since MR fluid presents the greatest reluctance in the circuit. Excessively small fluid gaps, however, can throttle the fluid and increase the damping at higher relative velocities across the damper.

One of the lessons learned empirically during this research was that having a large number of turns in an electromagnet does not necessarily guarantee a powerful magnetic circuit (high flux density). The designer must attempt to achieve a "healthy" compromise between the number of turns and the amount of current that can be achieved by a power source. Reducing the wire diameter (increasing the gauge) will result in a larger number of turns, but at the expense of much higher electrical resistance and much lower currents through the coil. This can severely limit the electromagnetic flux density. Conversely, a larger diameter wire will reduce the number of turns, but increase the current throughput. Our experience showed that this provided more favorable results (i.e. higher magnetic flux density) than the former option. In practice, the wire gauge should be selected such that it can accommodate a minimum of 4-6 Amperes of electrical current and yet provide a reasonably large number of coil turns.

Chapter 4

Automotive MR Dampers

Dampers for automotive use, or as they are more commonly known, shock absorbers, fall into two categories, mono tube and twin tube. Although at AVDL we have worked on both mono tube and twin tube MR dampers, the vast majority of our designs have been mono tube dampers. Therefore, this chapter will mainly focus on our development of mono tube MR dampers. Our work with twin tube MR dampers is continuing and will be reported in a separate publication.

4.1 Mono tube MR Dampers

Mono tube MR dampers are by far the most common types of MR dampers for automotive applications. The popularity of mono tube dampers (not only MR types) is due mainly to their compact size, reliability, and their ability to function properly in any installed orientation.

A mono tube damper is defined as a damper that has a single fluid reservoir and a piston rod that extends through only one end of the damper housing. An accumulator is used to accommodate changes in reservoir volume that occur when the piston rod moves into or out of the damper housing. If no accumulator section is provided, the piston rod will not be able to enter the housing since a "fluid lock" condition will exist. The accumulator is filled with a non-oxidizing gas such as nitrogen and is usually inflated to between 150 and 350 psi. The accumulator is pressurized to reduce the chance of MR fluid cavitation, which is a condition that occurs when the pressure of a fluid decreases to the point where the fluid begins to boil. When a fluid boils bubbles are formed, which cause a decrease in damper force since the bubbles are compressible.

4.2 Mercedes ML-430 MR Dampers

In the fall of 1999, a company that will remain confidential approached the Advanced Vehicle Dynamics Laboratory (AVDL) with the desire to develop a set of MR dampers. These MR dampers were intended to replace the original equipment dampers on a 1999 Mercedes ML-430 sport/utility vehicle. Because of AVDL's experience with MR dampers, we were selected to carry out this research. The proposed dampers were to replace the original equipment Mercedes dampers without any modifications to the vehicle. AVDL's role was to design, build, and test the MR dampers and then turn them over to the sponsoring company. To establish the damper's force-velocity characteristics, testing was to be carried out with a Material Testing Systems (MTS) machine.

The design that was chosen for the ML-430 dampers is shown in Figure 4.1. The housing is made of 1018 steel and the accumulator is bounded by an aluminum piston with o-ring seals.

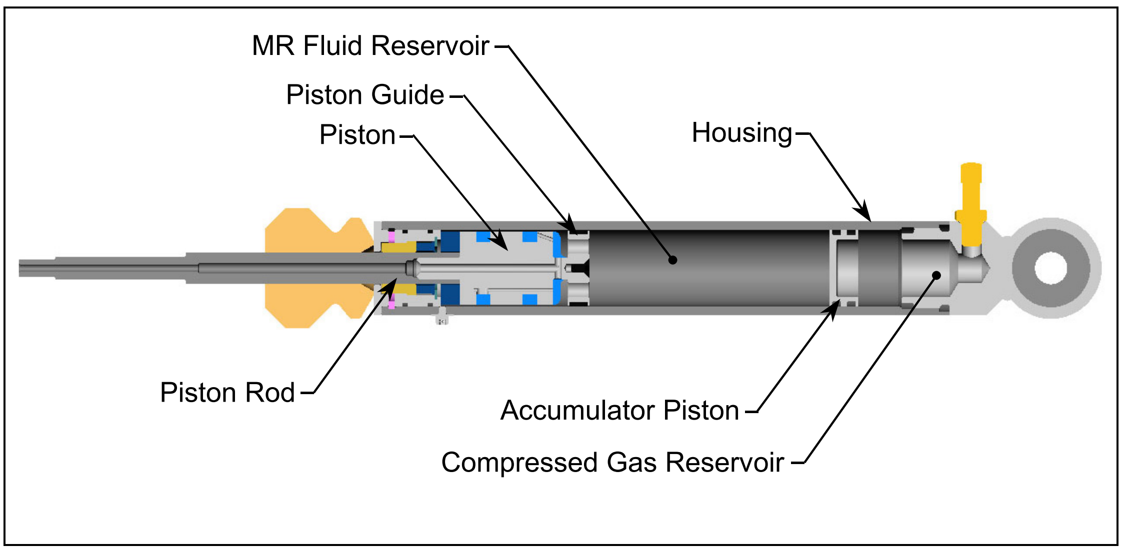


Figure 4.1 Mono tube MR damper section view (front damper shown)

Nitrogen gas, pressurized to 200 psi, was used in the accumulator. To lubricate the accumulator seals and to aid in preventing a nitrogen leak, a small amount of SAE 30 motor oil was placed within the accumulator during assembly. MR dampers are very sensitive to the gap that exists between the piston and the housing (this gap, hereafter, will be referred to as the fluid gap). Due to this sensitivity, the fluid gap needs to be made as small as possible without causing excessive off state damping which is important for ride comfort. Piston length also affects the off state damping force but it does not contribute as much as the fluid gap. This relationship can be seen by examining [14]

$$P = \frac{3\pi D^3 \ell \left(1 + \frac{2d}{D}\right)}{4d^3} \mu v_o \tag{4.1}$$

where P represents the damping force, D represents the piston diameter, d represents the fluid gap, ℓ represents the piston length, μ represents the viscosity of the fluid, and v_o represents the piston velocity. All viscous dampers that the author has been exposed to had fluid gaps that were much less than one inch, usually on the order of 0.015 inch. Since the fluid gap is cubed and is in the denominator, the fluid gap has a large impact on the off state damping. The piston diameter is usually greater than 1.0 inch and since it is cubed and located in the numerator, the piston diameter also has a significant effect on off-state damping. Therefore, the fluid gap and the piston diameter are the two most important geometric dimensions for the off state damping of an MR damper.

A two-stage piston design was chosen for this project since MR dampers with two-stage pistons are less sensitive to the fluid gap than MR dampers with single stage pistons. This reduced sensitivity is due to an increase in the number of activation regions that the additional coil produces. The more activation regions that exist, the larger the damper force can be with the same cross sectional geometry. Activation regions, in this case, refer to the band shaped volumes of MR fluid that are activated by a magnetic field. Figure 4.2 shows the approximate magnetic flux path and the activation regions that occur in an MR damper of this design. Although it is not explicitly clear in Figure 4.2, the magnetic flux paths are toroidal in shape. For this reason, the section view represents the toroidal flux path as two dashed ellipses.

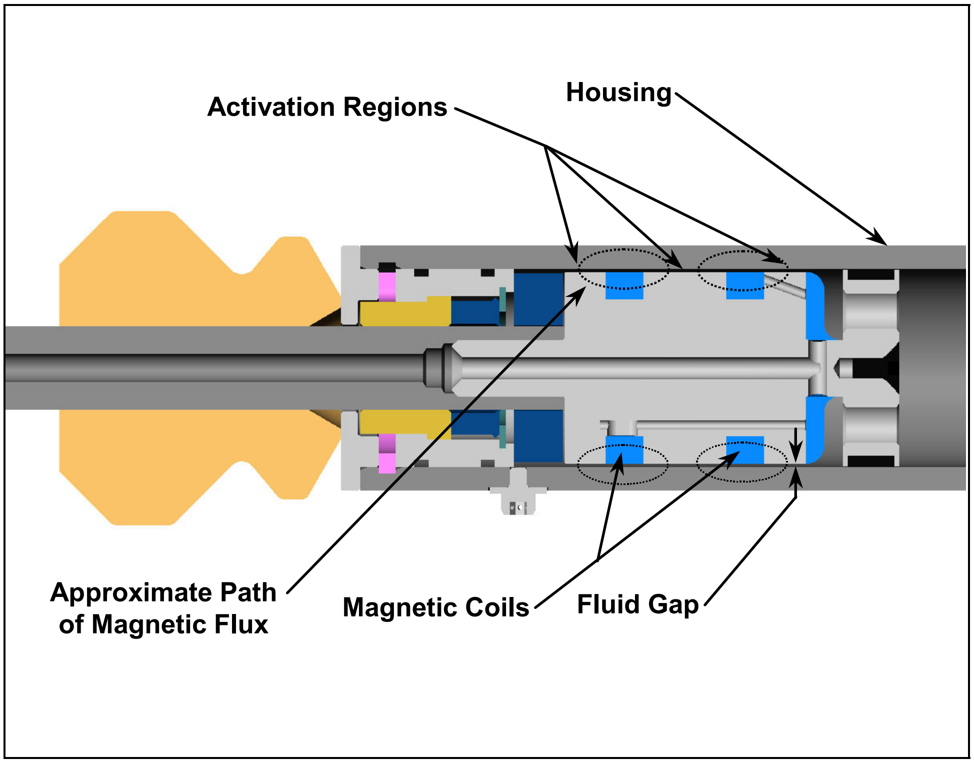


Figure 4.2 Cross-sectional view of an MR damper equipped with a two-stage piston

As depicted in Figure 4.2, the piston and piston rod are mutually concentric and in turn, are concentric with the damper housing. Electromagnetic coils are built into the piston to provide the flux field that is needed for MR fluid activation. A piston guide with holes that permit fluid flow together with a nylon wear band is used to keep the piston concentric with the damper housing. On the other end of the piston, an end cap and bushing maintain concentricity between the piston rod and the damper housing. A set of o-rings and a polyurethane dynamic seal (Hercules Hydraulics part number MUUL-14X24X8) are incorporated into the end cap assembly so that the MR fluid can be sealed within the damper.

The electromagnetic circuit of this damper consists of a 12L14 steel piston that has two integral magnetic coils. These coils were wound into two machined grooves that are located on the periphery of the piston as is shown in Figure 4.2. The coils were wrapped with 24 gauge magnet wire, each having 48 turns, and wound in opposite directions. The coils were wound in opposite directions so that the magnetic fields produced between the coils would not cancel each other out. To simplify construction, the coils were wired in series. This configuration produced a piston with two 48-turn electromagnetic coils that were wired in series for a total resistance of 0.67Ω.

Once the coils were wound, the piston was coated with epoxy. There are a couple of reasons for the epoxy's use. The first reason was to "pot" the coils so that they would not break or short out during use. The second reason was to provide a smooth, uninterrupted transition from one side of the coils to the other. After the epoxy cured, the piston was machined to its final diameter. Machining the piston to its final diameter after applying the epoxy ensured that discontinuities between the steel portions of the piston surface and the epoxy regions would not be present. Making the piston with a smooth, constant diameter reduced the chance of causing turbulent fluid flow at high velocities.

A unique aspect of these dampers is that the housing is used as part of the magnetic circuit. Usually, an outer pole ring is used for the electromagnetic circuit such as the one used in the Lord "Motion Master" MR damper depicted in Figure 4.3. The outer pole ring serves three purposes, the first of which is to hold the nylon wear band. The nylon wear band maintains concentricity between the piston and the damper housing and also reduces friction. The second purpose of the outer pole ring is to form an annular fluid gap or orifice with the piston. The third reason is to provide a return path for the magnetic flux that is produced by the coil.

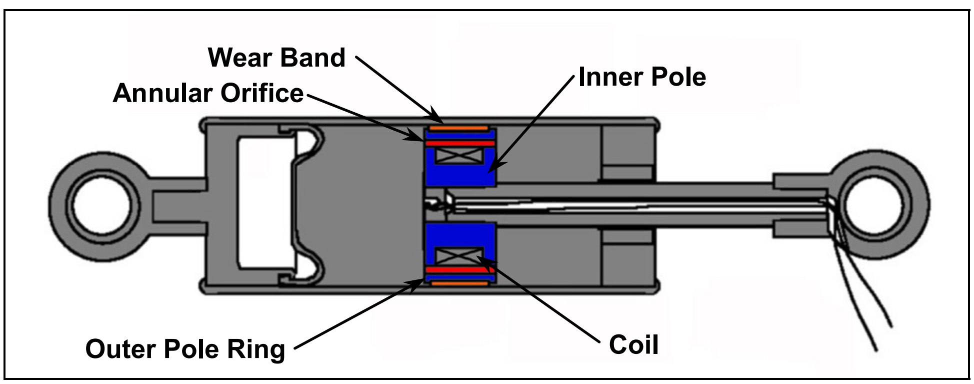


Figure 4.3 Lord Motion Master damper section view [adapted from 1]

As mentioned earlier, the magnetic circuit of the dampers depicted in Figure 4.1 and Figure 4.2 utilize the housing as a magnetic pole. This magnetic pole is located on the other side of the fluid gap where it serves as a flux return path.

4.2.1 ML-430 MR Damper Testing

In order to determine the amount of damping force that was needed for the ML-430 MR dampers, the vehicle's original equipment dampers were tested in a Material Testing System (MTS) load frame, shown in Figure 4.4.

Figure 4.4 MTS machine used for testing dampers

The tests were conducted by collecting the peak force and velocities due to a sinusoidal input for the data points shown in Table 4.1.

Table 4.1 Data points for testing ML-430 dampers

f (Hz)	Displacement (in)	Velocity (in/sec)
0.0	0.00	0.0
2.0	0.05	0.6
2.0	0.10	1.3
2.0	0.15	1.9
2.0	0.20	2.5
2.0	0.30	3.8
2.0	0.40	5.0
2.0	0.50	6.3
2.0	0.60	7.5
2.0	0.70	8.8
2.0	0.80	10.1
2.0	0.90	11.3
2.0	1.00	12.6

As shown in this table, the input displacement was varied, while the frequency was maintained at 2 Hz.

It is important to mention that the damper test results presented in this thesis have been “zeroed”, in the sense that the force-velocity curves have been adjusted so that each respective curve passes through the point (0,0) (The only exception being the gun recoil damper data discussed and presented in Chapter 5). This means that we have zero damping force at zero velocity for each curve, as is expected. The zeroing process involved two steps, the first of which was to calculate the location of the midpoint (in the force direction) between the first pair of force-velocity data points in jounce and rebound relative to the zero force axis. Once this distance was known, each curve was shifted upwards by half of this amount. This process results in pairs of initial data points for each damping curve that are symmetric with respect to the zero force axis. Figure 4.5 shows this “zeroing” procedure graphically.

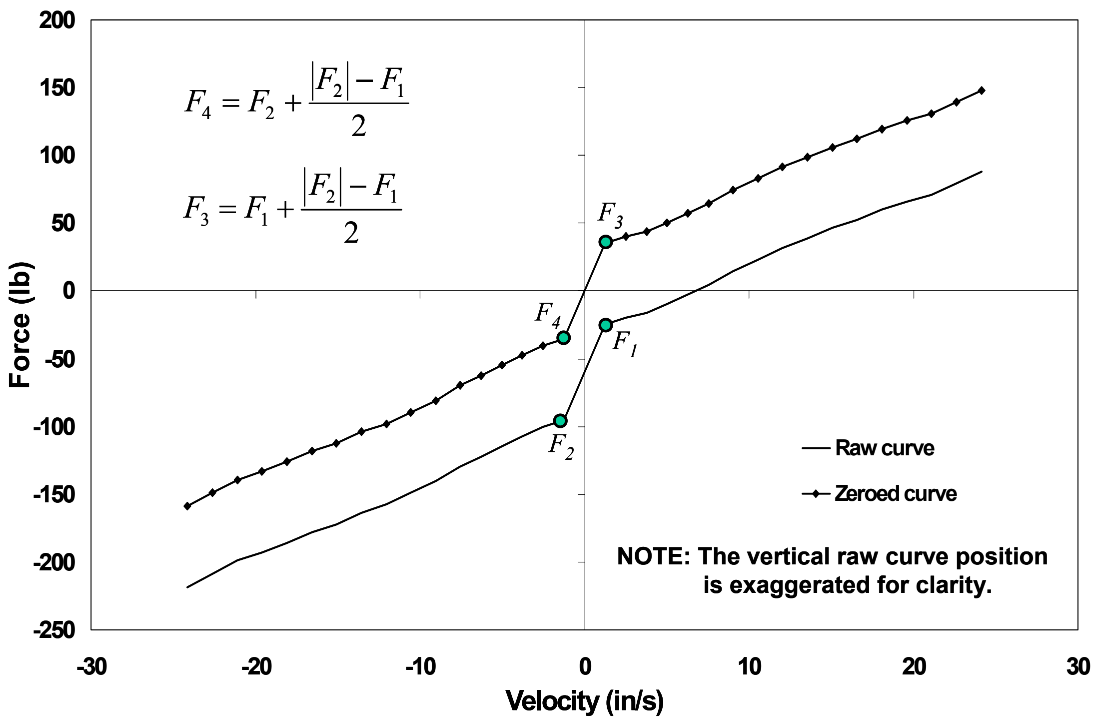


Figure 4.5 Process of zeroing damping curves

The test results for the ML-430 stock dampers are shown in Figure 4.6. It is worth noting that although it is desirable to record the forces at higher velocities, our testing of the stock dampers was limited to 12.6 in/s due to the testing procedure that was in place at the time of these initial tests. These procedures, however, were modified to allow testing at much higher velocities than 12.6 in/s, as will be discussed later.

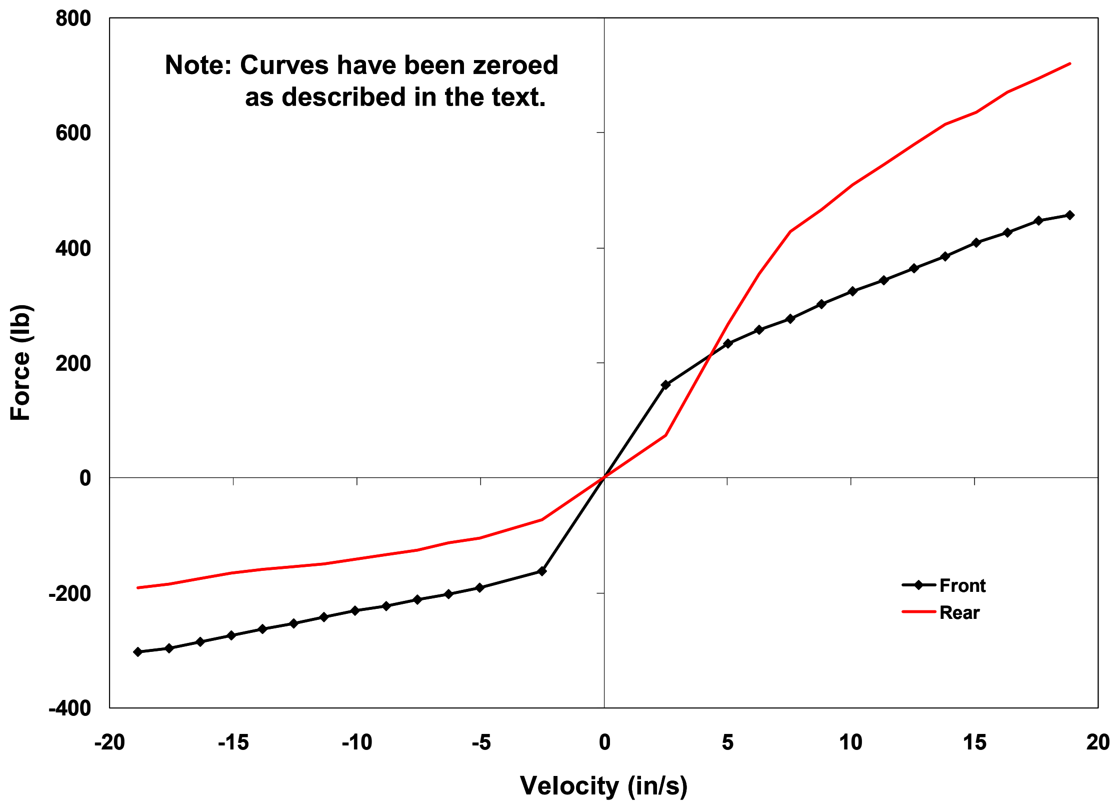


Figure 4.6 Original equipment Mercedes ML-430 damper force-velocity relationships

The test results in Figure 4.6 show a maximum of approximately 700lb for rear dampers in rebound. The front dampers provide considerably more damping in jounce (approximately 150 lbs at the highest velocity tested), when compared to the rear dampers. The data shows a front rebound-to-jounce ratio of 2.5:1 and a rear rebound-to-jounce ratio of 3.5:1.

The ML-430 MR dampers were designed with the force characteristics shown in Figure 4.6 in mind. As is shown in the test results in Figure 4.7, we ensured that the maximum achievable force with the ML-430 dampers was higher than the stock dampers and that the minimum damping forces (i.e., when no current is supplied to the damper) remained considerably smaller than the original passive dampers. A general rule of thumb for designing MR dampers for vehicle applications is to maintain the no-current (off-state) damping at less than 50% of the stock dampers and also keep the maximum current damping to more than 150% of the stock dampers.

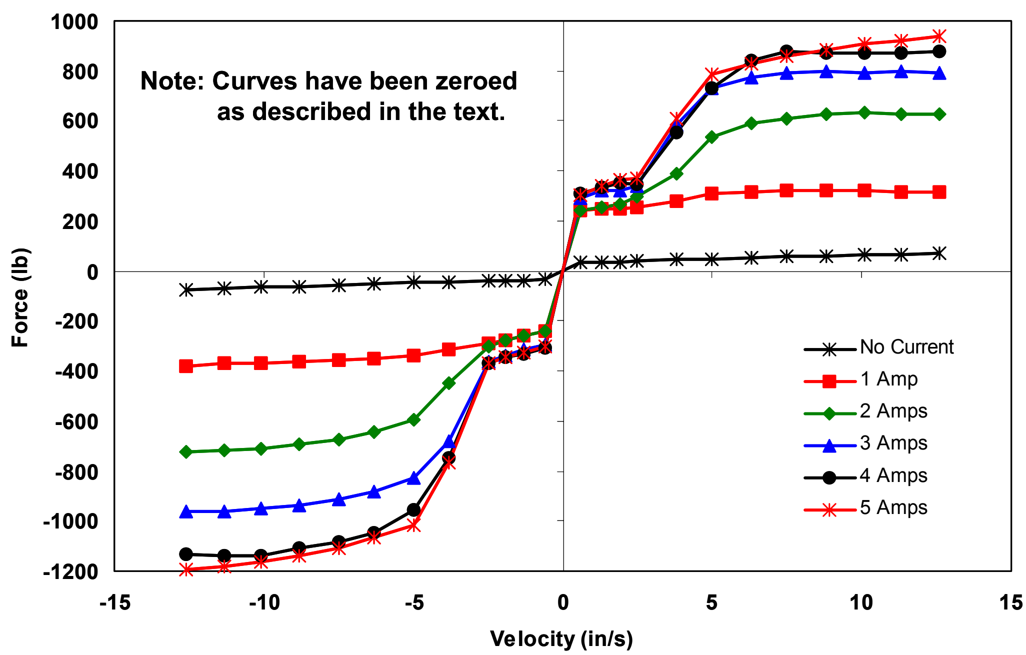


Figure 4.7 Experimental damping characteristics for ML-430 MR damper

A couple of interesting aspects of the results in Figure 4.7 that are worth mentioning. These are the saturation current and the flat region ("step") that is present at the low velocities. The saturation current can be identified by observing that there is very little change in damping force between a power supply setting of 4 Amps and a power supply setting of 5 Amps. For this reason, power supply settings in excess of 4 Amps will not yield additional damper force with this particular geometry and electromagnetic circuit design. The other interesting aspect of the data is the step that exists at low velocities when the displacement amplitude across the damper is small. We believe that this is caused by the dynamic interaction between the MR piston and the accumulator piston at higher supply currents. This phenomenon can best be described by using Figures 4.8 and 4.9.

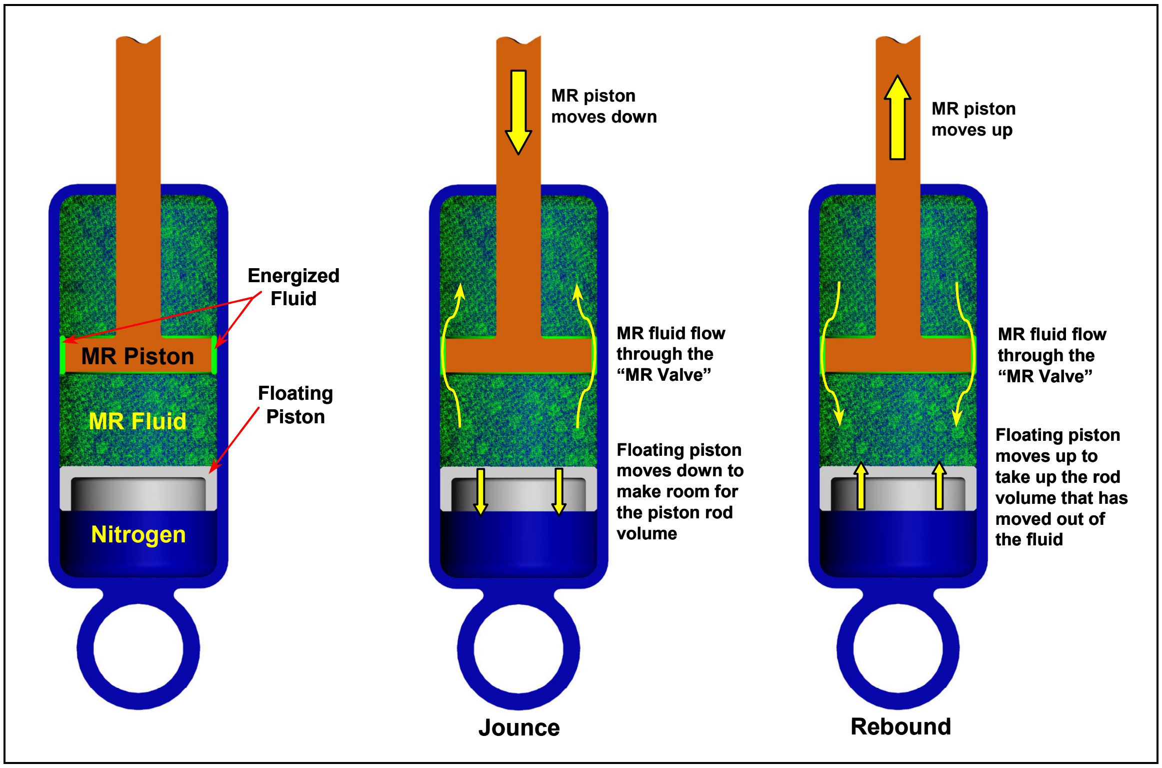


Figure 4.8 MR damper functioning properly

Figure 4.8 shows a mono tube MR damper functioning properly. As expected in this configuration, as the piston moves up and down the MR fluid flows through the MR valve and the accumulator piston moves to accommodate the damper rod volume as it enters and leaves the fluid chamber. In this case, the fluid chamber is filled with MR fluid and no vacuum is created.

In contrast, Figure 4.9 shows a mono tube MR damper when it is not functioning properly. In this configuration, the high currents supplied to the damper has energized the fluid to the point that it acts like a seal between the two fluid chambers that are divided by the MR piston; therefore not allowing any passage of fluid from one chamber to the other as the piston moves up and down.

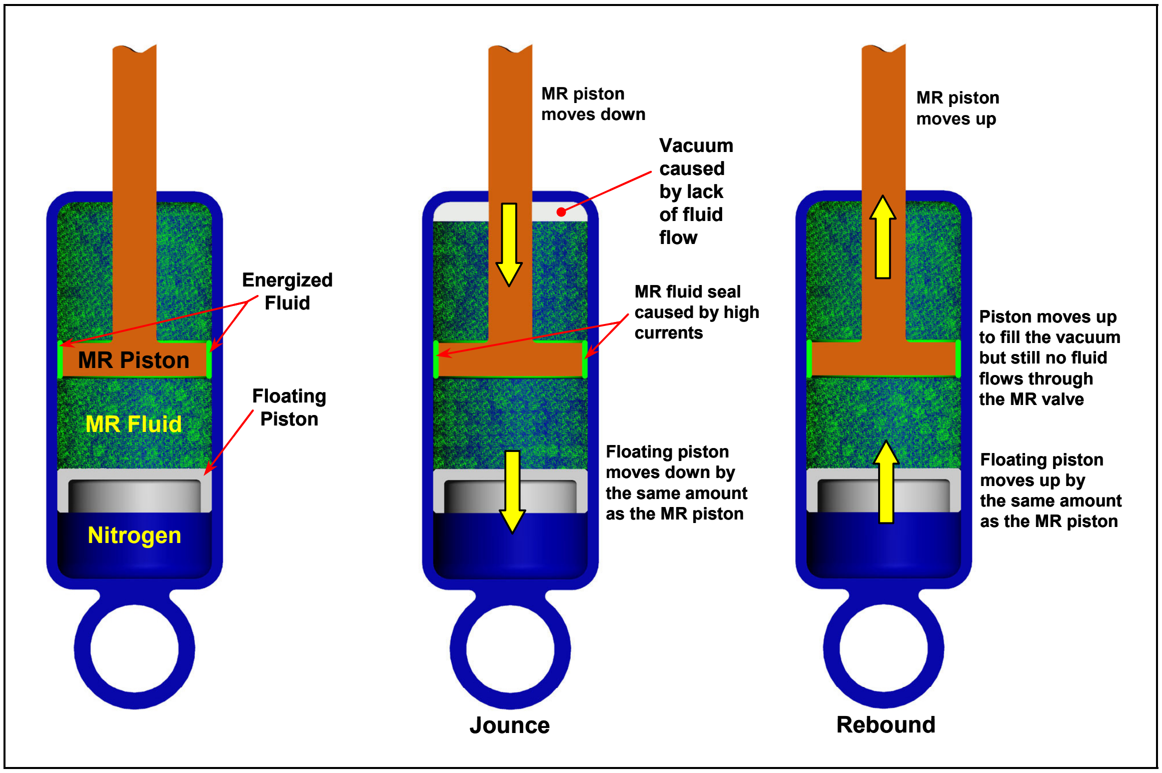


Figure 4.9 MR damper cavitation due to lack of fluid transfer at high currents

The fluid in the lower chamber pushes against the accumulator piston and moves it down by the same amount as the MR piston. The increased pressure caused by the movement of the floating piston downward is not sufficient to yield the fluid plug created at the MR valve. Therefore, the piston and the fluid plug slide down against the damper body with the MR fluid acting like a dynamic seal, not allowing any fluid to pass through the MR valve. This situation causes a vacuum to occur in the upper fluid chamber that cavitates the fluid and significantly reduces damping forces.

In rebound, the exact opposite happens. The piston and the MR plug slide against the damper body to fill the vacuum in the upper chamber. As this happens, the accumulator piston moves up to maintain the pressure balance between the air chamber and the lower fluid chamber. Therefore, increasing the current supplied to the damper may not increase the damping force at low amplitude displacements unless the forces caused by the accumulator are sufficiently large to overcome the MR seal that is caused by high electrical currents. Increasing the accumulator force, however, may necessitate pressures that are beyond the safe limits of mono tube dampers in most applications. Additionally, the higher pressure will result in substantially larger forces in jounce at all currents, which can be undesirable for most applications.

It is worth noting that much of the dynamic that is highlighted in Figure 4.7, which is described above, is caused by the periodic (sinusoidal) nature of our testing input. For most real-world applications, such a phenomenon may not occur so prevalently, or at least not be observed so easily. Nevertheless, these dynamics do exist and MR damper designer needs to be aware of it.

Realizing the shortcomings in our test procedure for accurately capturing the damping characteristics of our MR dampers, we revised the testing points to what is shown in Table 4.2.

Table 4.2 New data points for testing MR dampers

f (Hz)	Displacement (in)	Velocity (in/sec)
0.0	**0.0**	0.00
1.0	**0.2**	1.26
1.0	**0.4**	2.51
1.0	**0.6**	3.77
1.0	**0.8**	5.03
1.0	**1.0**	6.28
1.0	**1.2**	7.54
1.2	1.2	9.05
1.4	1.2	10.56
1.6	1.2	12.06
1.8	1.2	13.60
2.0	1.2	15.10
2.2	1.2	16.60
2.4	1.2	18.10
2.6	1.2	19.60
2.8	1.2	21.10
3.0	1.2	22.60
3.2	1.2	24.10

**Bold entries indicate the variable that is varied for each data point, from the previous data point*

The major difference between our new testing procedure (Table 4.2) and the original testing procedure (Table 4.1) is that the low-velocity data is collected at lower frequencies and higher amplitudes. We first maintained the test frequency at 1.0 Hz and increased the amplitude until the damper maximum stroke was nearly reached. Beyond this point, the amplitude was kept fixed and the input frequency was increased, as is shown in Table 4.2. Another improvement is that the dampers were tested up to 24.1 in/s, in contrast to 12.6 in/s in the original test procedure.

The test results shown in Figure 4.10 indicate that the new testing procedure provides a much more accurate representation of the MR dampers' force-velocity characteristics. The plots clearly exhibit the pre- and post-yield behavior of the MR dampers, as is expected and commonly documented.

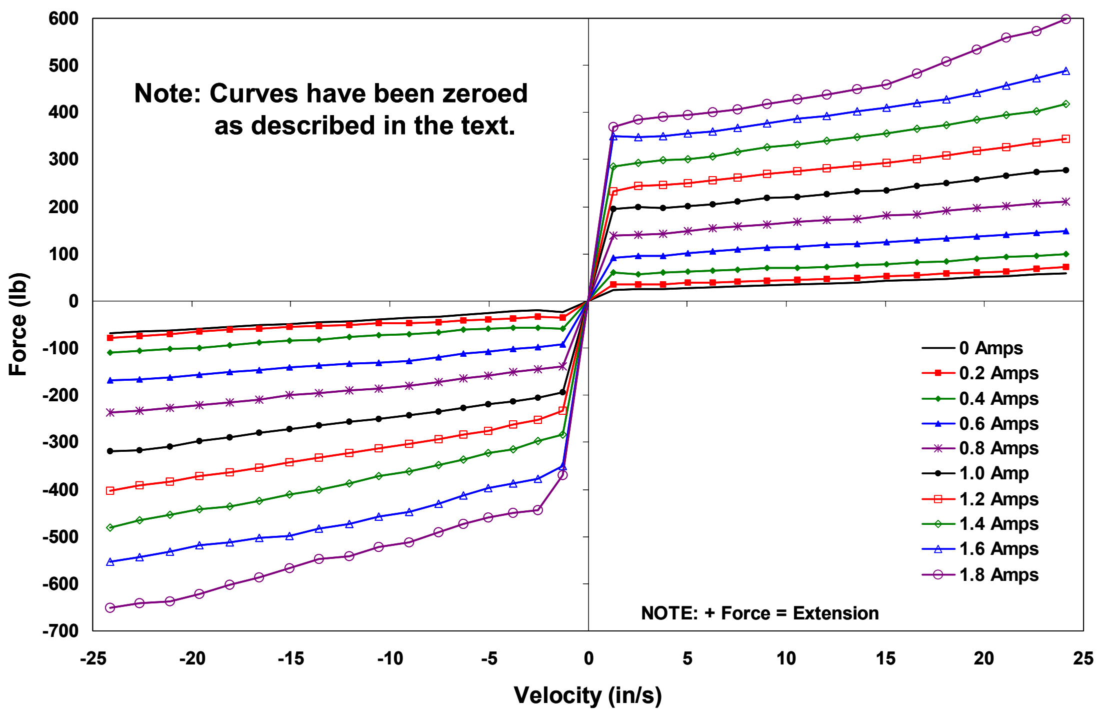


Figure 4.10 Experimental damping characteristics for ML-430 MR damper

The result in Figure 4.10 shows a pre-yield behavior that is dominated by the current that is supplied to the damper. The higher the supply current, the higher the yield force and therefore, the damping force achieved. With increasing velocity, the force increases in a nearly linear fashion.

Of course, this relationship only exists prior to reaching the saturation current of the damper, as was explained earlier. Beyond the yield point, the damper behavior is nearly independent of the current supplied to the damper, as judged by the nearly similar slopes that result for different currents.

4.2.2 ML-430 MR Damper Hardware

Figure 4.11 shows the principal components of a front ML-430 MR damper next to a completed front damper assembly. The piston rod assemblies and the accumulator pistons are identical in the front and rear dampers. Only the housings and the bottom end caps differ. Figure 4.12 shows a partially assembled rear damper.

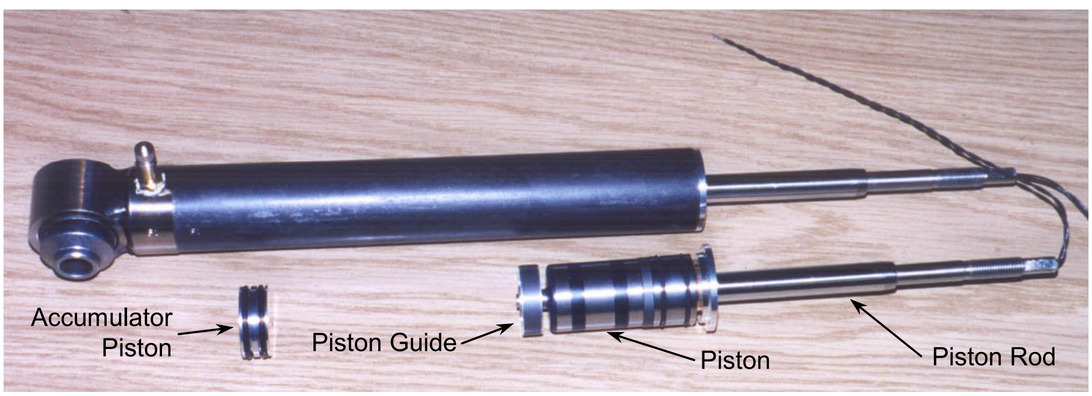


Figure 4.11 ML-430 front MR damper

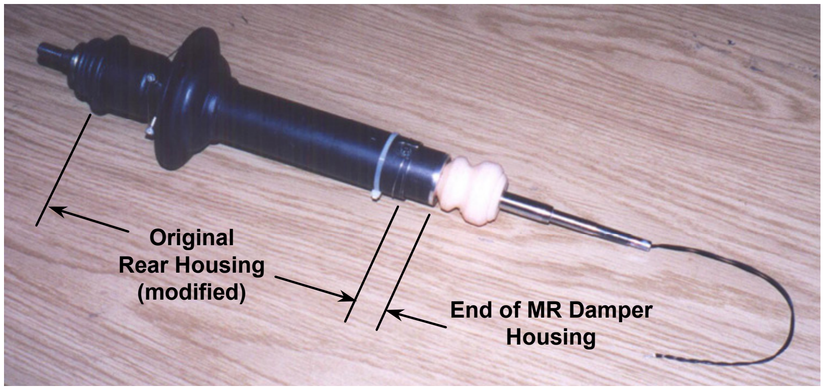


Figure 4.12 Partially assembled ML-430 rear MR damper

As can be seen in Figure 4.12, the rear MR dampers were slid into cut down original equipment housings and then doweled in place. These dowels can be seen in the fully assembled rear damper as shown in Figure 4.13. The dowels were of the pullout variety so that they could be removed with a slide hammer in the event that disassembly became necessary. The dowels were held in place with an interference fit with both the original housing and with the lower damper end cap. As a safety precaution, safety wire was used to keep the dowels in place in the event that the interference fits failed during extreme use. To keep the safety wire in place it was threaded through drilled head cap screws that were screwed into the threaded ends of the pullout dowel pins.

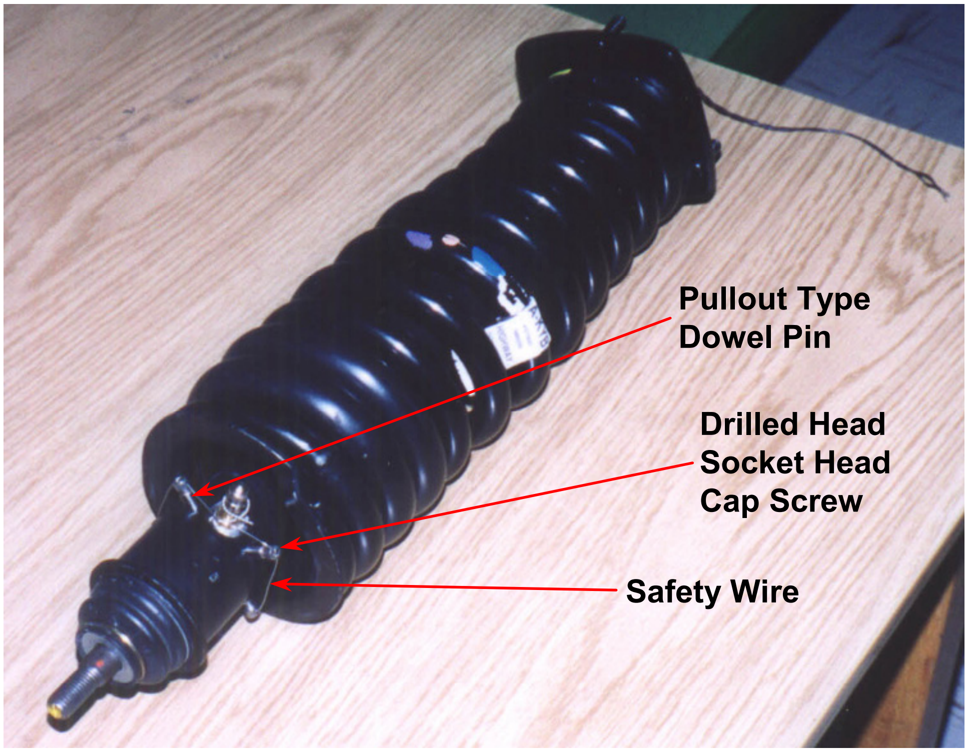


Figure 4.13 Fully assembled ML-430 rear damper

4.3 Ford Expedition MR Dampers

This section includes the work that was conducted for designing and building a set of prototype MR dampers for a 2000 Ford Expedition. These dampers were designed for a vehicle safety study at AVDL. The design and manufacturing implementation of these dampers was different in several respects from the ML-430 dampers discussed earlier.

The first step in the design process involved characterizing the stock dampers by using the MTS machine. As shown in Figure 4.14, the front and rear dampers had nearly identical damping characteristics, with the rear dampers only slightly more damped in extension.

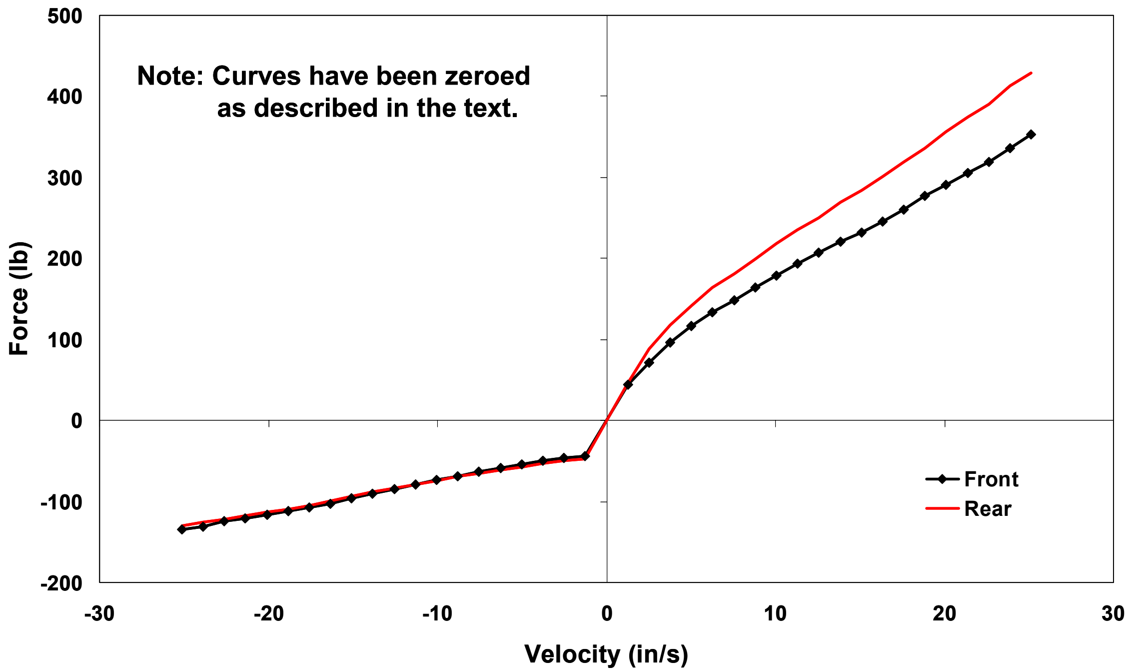


Figure 4.14 Damping characteristics of original equipment Ford dampers

Both dampers had the same damping force characteristics in compression. The rebound-to-jounce ratio for the dampers was about 2:1, which is on the low end of what is typically used for vehicle dampers. Commonly, a larger rebound-to-jounce ratio (sometimes as high as 5:1) is designed into vehicle dampers to provide the ability for more aggressive maneuvering and yet keep the ride comfort nearly unaffected. For the Expedition, however, the rebound-to-jounce ratio was kept smaller, possibly because the high center of gravity of this vehicle would limit its ability for aggressive maneuvering. In other words, a larger ratio may not result in any maneuvering benefits, and would most likely cause a harsher ride.

With the damping characteristics of the original dampers known, the next step was to begin designing the replacement MR dampers. Since the MR dampers had to be direct replacements, careful sketches were made of the original dampers along with all of the critical dimensions such as the overall extended lengths, the overall compressed lengths, and the dimensions of the mounting geometries. Figure 4.15 shows a picture of an original front damper and Figure 4.16 shows a picture an original rear damper.

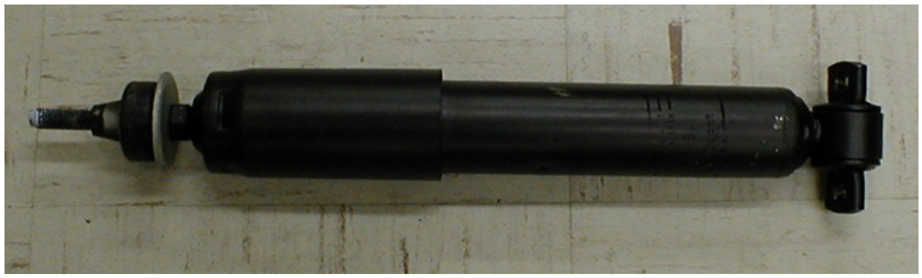


Figure 4.15 Original Ford front damper

Figure 4.16 Original Ford rear damper

With all necessary information about the original dampers known, a new set of dampers were designed, similar to those designed for the Mercedes ML-430. To enhance the ease of manufacturing, we designed the new dampers so that they could be built in a modular manner. Figure 4.17 shows a cross sectional view of this new design.

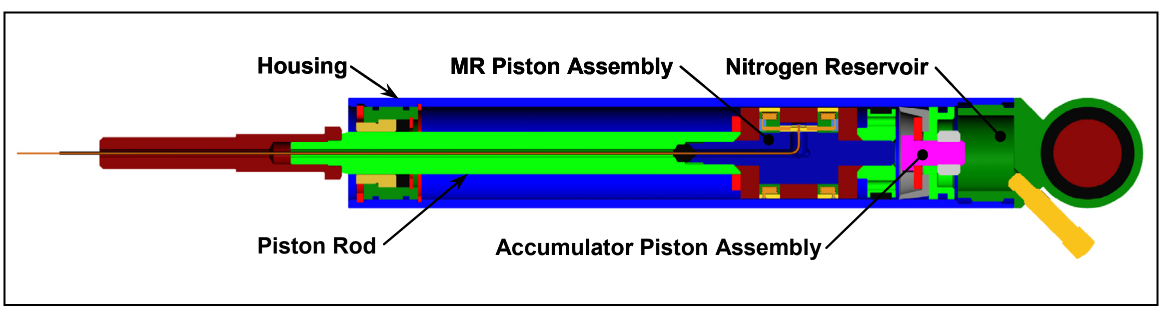


Figure 4.17 Expedition MR damper section view (front damper shown)

As shown in Figure 4.17 and detailed in Figure 4.18, the new design includes a two-stage piston that is similar to the earlier design but is assembled from modular components. This modular design has removable coils that allow for the use of any even number of piston stages desired as long as there is enough room in the piston core for lead wires. Only the number of middle stages and the piston core length needs to be changed with the addition of new stages. Multiple stage pistons with odd numbers of coils can also be made but they require two different coils, some wound in one direction and the others wound in the opposite direction. This change in winding direction is needed to avoid canceling the magnetic field that exists between some of the stages in an odd numbered multi-stage piston. For the Expedition dampers, a two-stage design was adopted based on the available room within the dampers and the amount of damping force required.

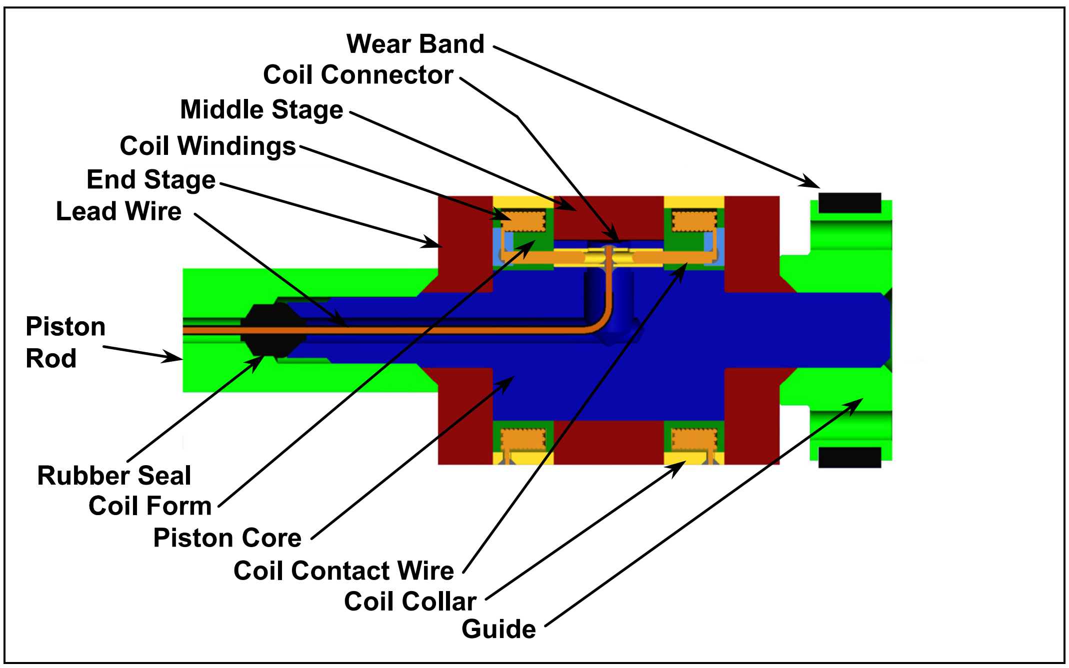


Figure 4.18 Section view of modular piston

In the new modular piston assembly, the two coils are not integral as they were in the ML-430 MR dampers. These coils are separate assemblies that in this case are installed in pairs. The coils are made of 24-gauge magnet wire that is wound around a paper based phenolic (Garolite grade XX) coil form. There are 48 turns in each coil and the resistance per coil is 0.36Ω. Since the coils are wired in parallel, this configuration gives a total resistance of 0.18Ω per piston assembly. As stated earlier, any number of these coil pairs can be installed as long as the piston core is long enough to accommodate them and enough middle stages are provided. Unlike the pistons that were used for the ML-430 dampers, these can be disassembled and reassembled. The assembly process consists of the following steps:

1) Installing the lead wire (which is pre-soldered to the connector)
2) Sliding the middle stage collar over the piston core
3) Sliding each coil over the piston core so that they but up against the middle stage
4) Sliding the end stages onto both ends of the piston core
5) Screwing the guide and the piston rod onto the piston core

A removable grade of thread locking compound is used to seal the threads as well as to prevent the piston assemblies from unscrewing during operation.

The electrical circuit of this damper differs from many others in that the piston rod itself was used as part of the circuit to simplify coil construction. If the piston rod was not used as part of the electrical circuit, the coil connector would have to provide two electrical connections per coil which would have been much more difficult to implement. In operation, the electrical current flows from the supply wire to the coil connector where it splits and flows to each coil. Once the electric current reaches each coil, it flows through the coil windings until it reaches the solder joint at the coil collar. After the current reaches the coil collar, it flows into the piston end stages and then to the piston rod. For this reason, a reliable electrical connection to the piston rod must be provided.

An electrical connection could also be made at the damper housing but this type of connection might be unreliable since it would rely on a good electrical connection between moving parts that were not designed with this in mind. For this reason, any electrical connection that is not directly attached to the piston rod should be avoided (with the present design). Operationally, this damper is identical to the ones presented in section 4.2 and therefore do not require additional explanation.

4.3.1 Ford Expedition MR Damper Testing

As mentioned and described in detail earlier, the damper test results that are presented have been zeroed so that each damping curve passes through the point (0,0). Only the gun recoil damper test results, displayed and discussed in chapter 5, are an exception.

The test results for this new damper were very good with the exception of being a little bit high in off state jounce when compared to the original equipment Ford dampers. Figure 4.19 shows one of these dampers installed in the MTS machine for testing. In this figure, the mid section of the damper is covered with a cooling jacket that was developed for regulating the operating temperature of the dampers. Keeping the dampers as close to the same operating temperature as possible is necessary for obtaining the most accurate test results.

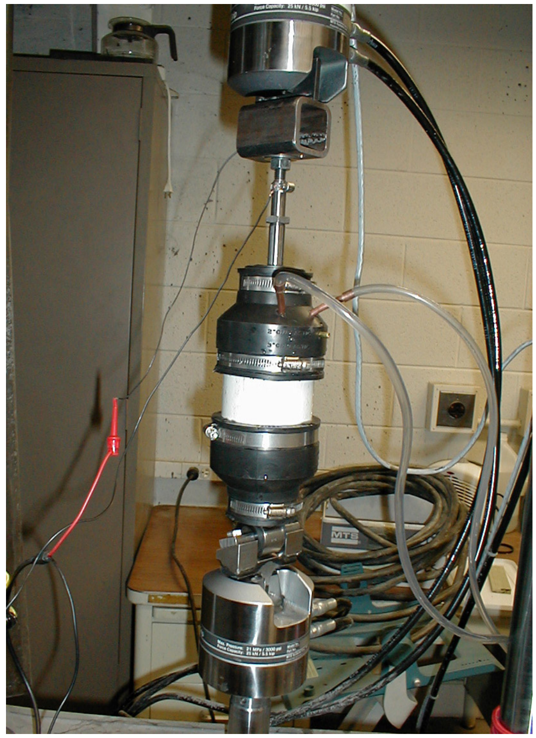


Figure 4.19 Ford Expedition MR damper in the MTS machine (cooling jacket installed)

The cooling jacket that can be seen in Figure 4.19 is made of a section of 3 inch PVC pipe, two rubber pipe reducers, a few pieces of rubber hose (used to adapt the inner diameter of the reducers to the damper housings), four pipe clamps, some ¼ inch copper tubing, some ¼ inch plastic tubing, and an adapter for attaching a garden type hose to the copper tubing. When in use, the jacket is filled with water and a slow but steady stream of cold water is passed through the copper tubing that then exits through a length of plastic tubing into a drain. Figure 4.20 shows an interior view of the cooling jacket when partially disassembled.

Figure 4.20 Interior view of cooling jacket

The damper force-velocity characteristics were established using the data points listed in Table 4.2. The test results, shown in Figure 4.21 indicate that the damper is able to generate a considerable amount of force in a symmetric manner for rebound and jounce.

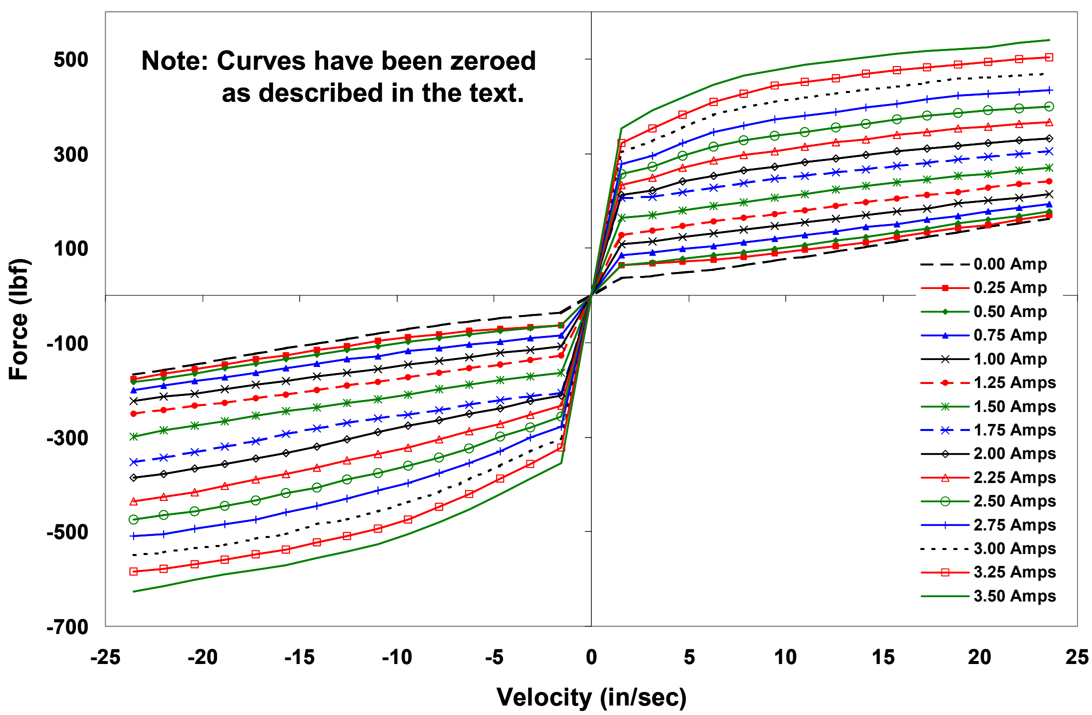


Figure 4.21 Force-velocity plot for Ford Expedition MR damper

These test results quite clearly match the characteristics that are expected from MR dampers when they are properly designed and function correctly. Furthermore, the damping force due to the MR dampers emulates the forces of the stock dampers, as shown in Figure 4.14.

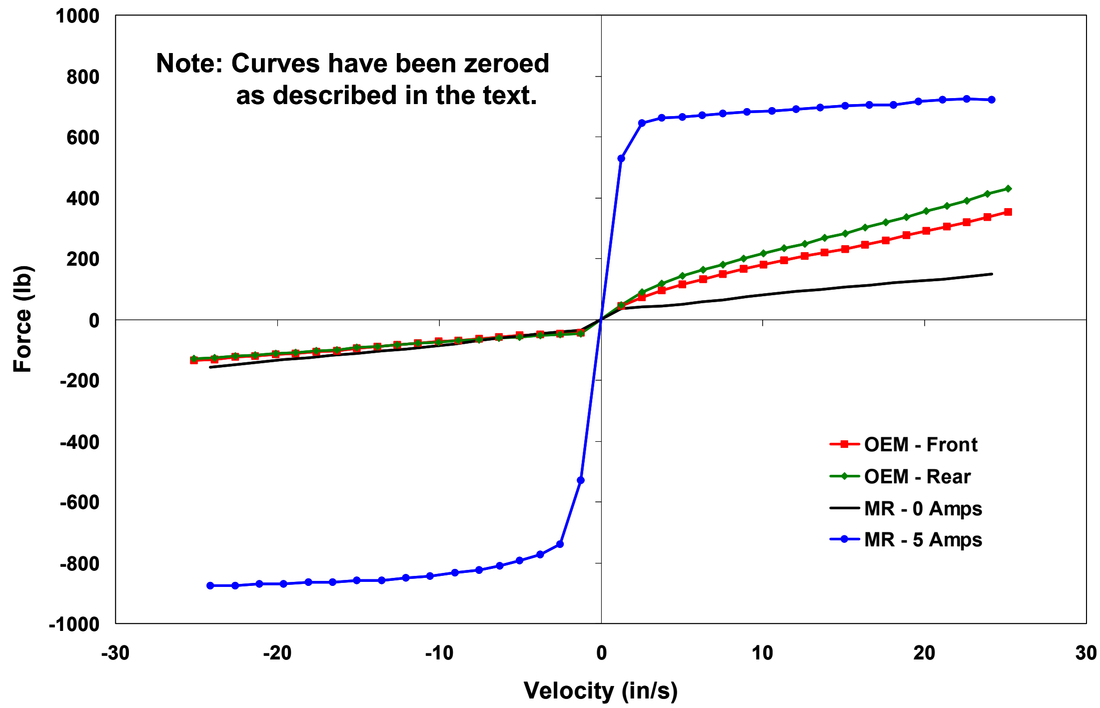


Figure 4.22 Comparison between OEM and MR Ford Excursion dampers

It is worth noting that at higher currents, we would have experienced the same peculiar effects that we observed for the ML-430 dampers, if we had tested the dampers at higher frequencies and lower amplitudes. Testing the dampers at the data points shown in Table 4.3 resulted in the force-velocity characteristics shown in Figure 4.23 for electrical currents between 4.5 and 5.0 Amps.

Table 4.3 High frequency testing points for Expedition MR damper

f (Hz)	Displacement (in)	Velocity (in/sec)
2.5	0.1	1.57
2.5	0.2	3.14
2.5	0.3	4.71
2.5	0.4	6.28
2.5	0.5	7.85
2.5	0.6	9.42
2.5	0.7	11.00
2.5	0.8	12.57
2.5	0.9	14.14
2.5	1.0	15.71
2.5	1.1	17.28
2.5	1.2	18.85
2.5	1.3	20.42
2.5	1.4	21.99
2.5	1.5	23.56

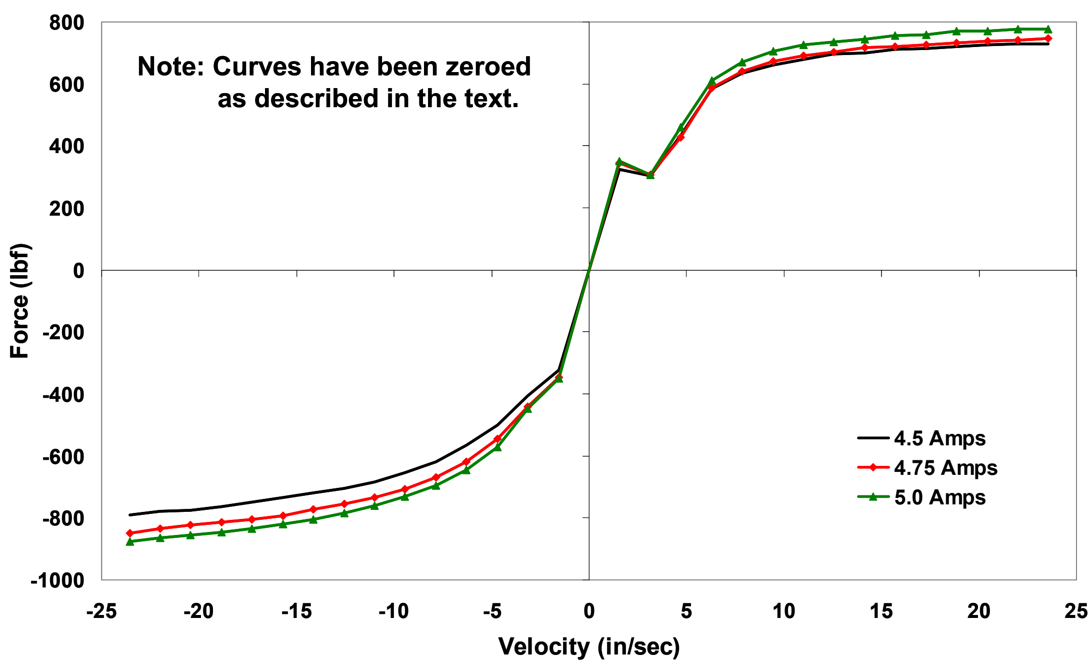


Figure 4.23 Ford Expedition MR damper operated at high currents

This current range was highest that these dampers were designed to handle. Again, the peculiar effect that is evident in Figure 4.23 is caused by the dynamic interaction between the MR piston and the accumulator piston, as was described in detail earlier.

Damper evaluation was carried out by cycling the damper in the MTS machine at a fixed frequency of 2.5 Hz and with a stroke of up to ± 1.5 inches in 0.1 inch steps. This testing procedure is outlined in Table 4.3. Current was supplied to the damper in 0.25 Amp increments from 0 to 5 Amps.

Figure 4.24 shows a plot of the force-velocity data that was captured for one of these dampers using the data points that were outlined in Table 4.2.

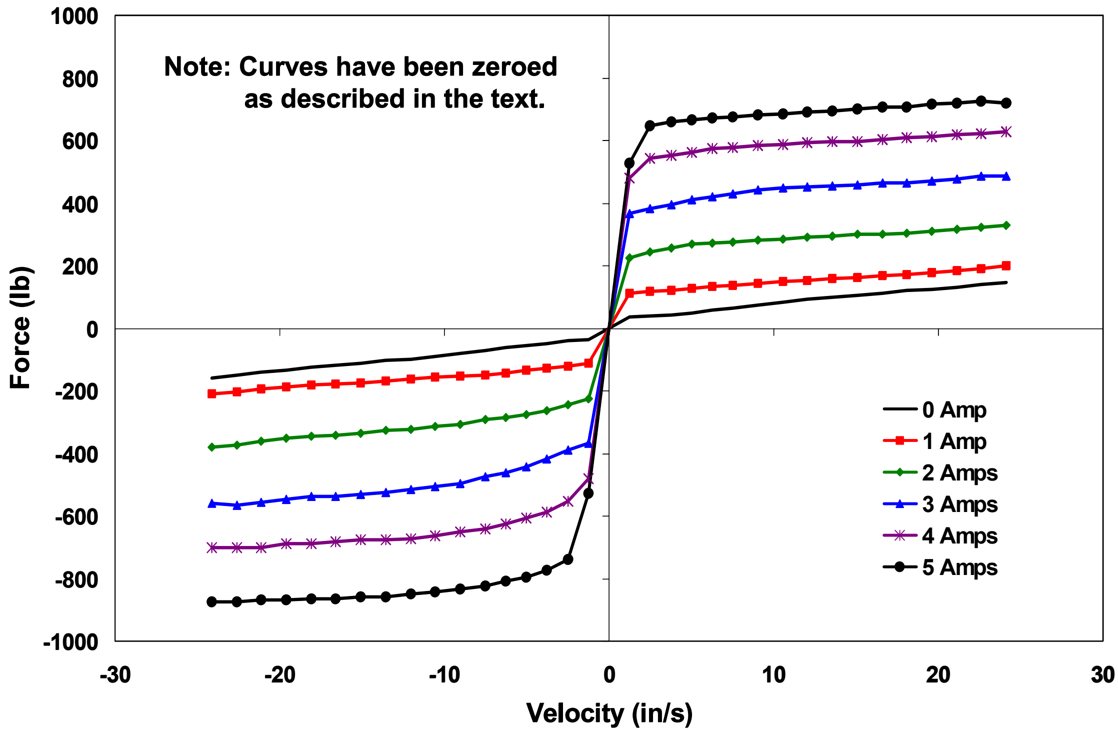


Figure 4.24 Ford Expedition MR damper test data

4.3.2 Semi-Active Control of an ML-430 MR Damper

The development and implementation of control policies was not part of this research. This topic, however, was considered in another research study at AVDL [15]. Some of the results of that study are included here for the sake of completeness.

Figure 4.25 shows the quarter car test rig that was used to obtain the semi-active test results that will be presented.

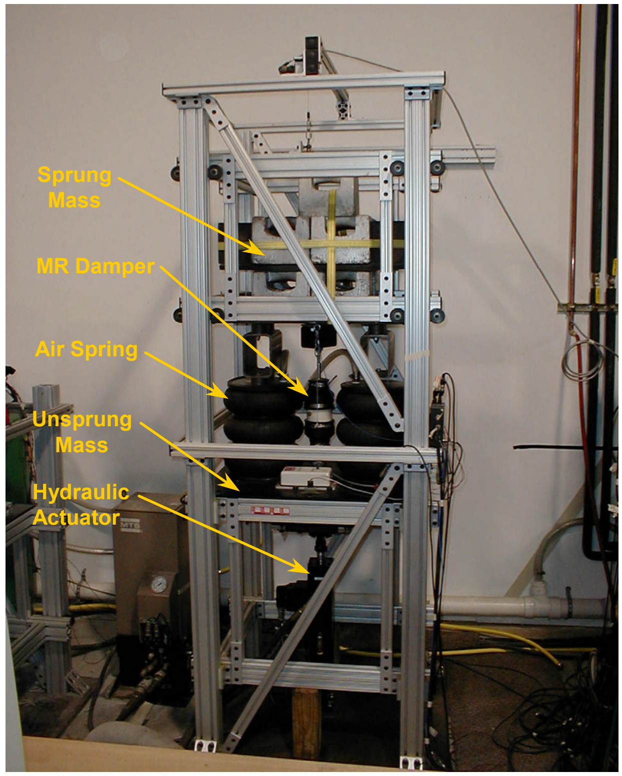


Figure 4.25 Quarter car test rig

The quarter car test rig is a piece of equipment that is used to simulate ¼ of a car suspension. In Figure 4.25, the unsprung mass is excited by a hydraulic actuator to simulate road input. This unsprung mass represents ¼ of the unsprung weight of the car to be represented. The sprung mass, which is supported on air springs, carries an adjustable mass that represents ¼ of the sprung weight of the car. To capture data, the hydraulic actuator is used to excite the unsprung mass that in turn excites the sprung mass. A linear variable differential transformer (LVDT) is provided to obtain displacement data for the unsprung mass and likewise, another is used to obtain displacement data for the sprung mass.

Figure 4.26 shows a representative test result of an ML-430 MR damper that is used in the passive mode of operation (no control algorithm). Figure 4.27 shows a representative test result of an ML-430 MR damper that is used with a skyhook control policy.

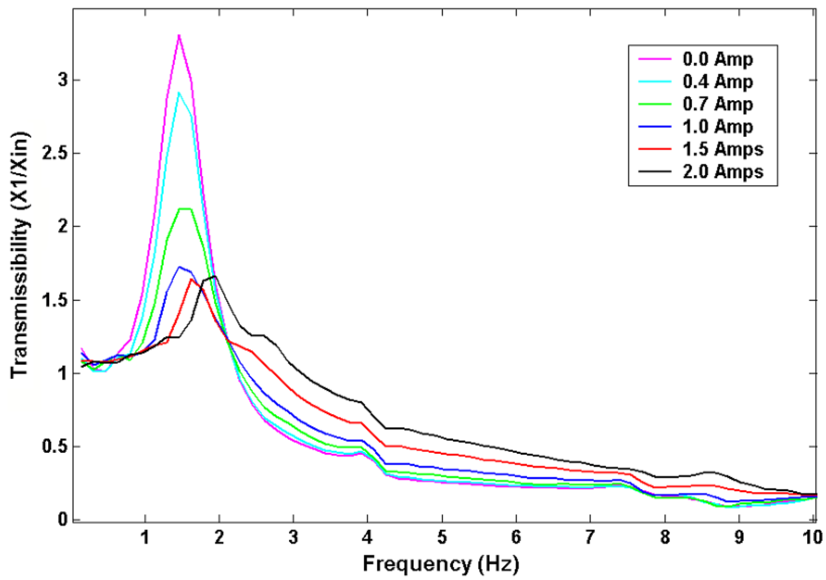


Figure 4.26 Passive transmissibility for ML-430 MR damper [15]

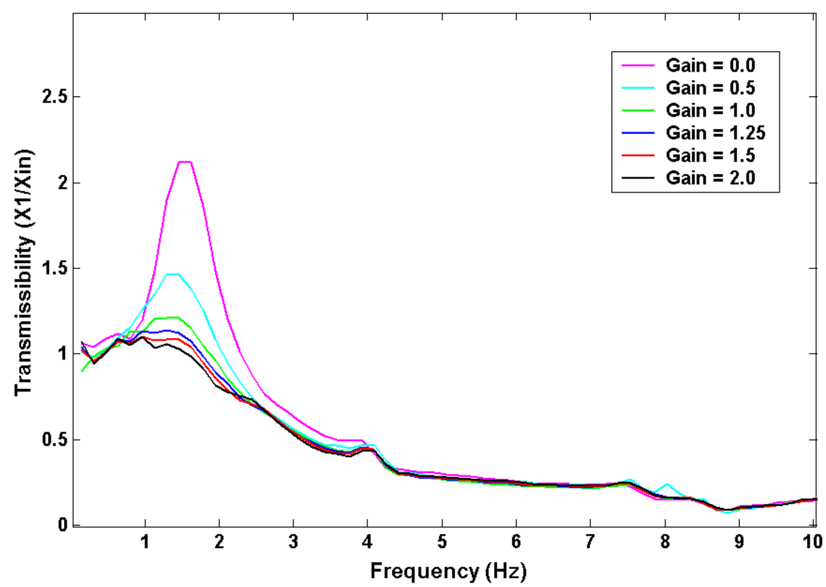


Figure 4.27 Skyhook control transmissibility for ML-430 MR damper [15]

Chapter 5
MR Damper Design for Gun Recoil Control

During the course of this work, two different MR damper designs for the gun recoil application were designed and built. Of these two designs, the first was a significant departure from conventional MR damper design and the second was of a more conventional design. The following two sections will discuss these designs in detail.

5.1 First Generation Gun Recoil Damper

The first generation gun recoil MR damper was, according to the Naval Surface Warfare Center, the first MR damper specifically built and tested for the gun recoil application. Since operational velocities were expected to be on the order of 10 ft/sec, an unconventional approach for this design was taken. This unconventional approach led to a damper in which the entire fluid reservoir was activated by a magnetic field. A damper of this type was thought to be more capable of handling high velocities than typical MR dampers since it was assumed that the piston to cylinder wall gap could be made larger with this type of damper than is typically done. This larger piston to cylinder wall gap, which was initially 0.040 inch, would minimize throttling effects at high velocities (off state damping). Later, this assumption was proven false since a damper of conventional design with a piston to cylinder wall gap of 0.115 inch and a larger bore proved to be just as effective and more efficient.

5.1.1 Damper Construction

The component of this damper that differs most from conventional MR damper design is the bi-metal housing. As can be seen in Figure 5.1, this housing is composed of two different types of steel: austenitic stainless steel and carbon steel. Austenitic stainless steel was used for the upper and lower parts of the housing because it is non-magnetic and would not influence the magnetic flux lines that pass through the carbon steel center sections.

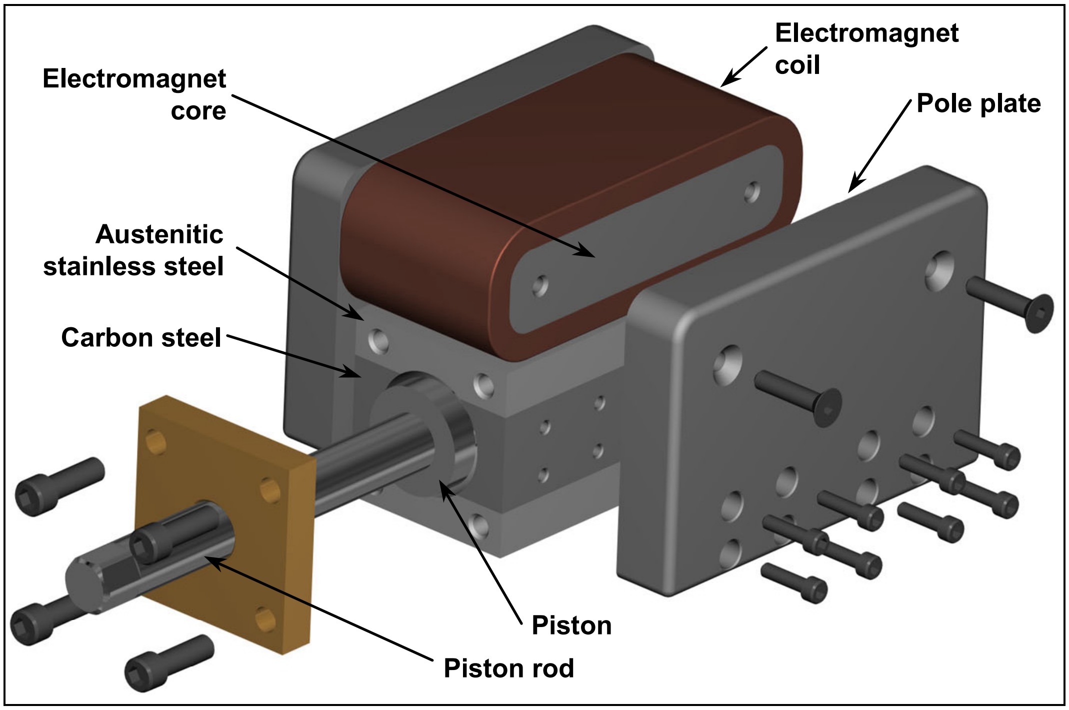


Figure 5.1 First generation gun recoil damper

Ideally, the bore in this type of damper should be square so that the perpendicular distance from one carbon steel housing component to the other is always constant. This ideal design would result in flux lines that evenly cover the entire volume of MR fluid since the flux lines would be of equal length and remain perpendicular to both carbon steel housing components at all times. A square bore, however, would require the use of a square piston that would need to be keyed in some way to prevent rotation about its longitudinal axis. Any rotation about the piston's longitudinal axis would cause a non-constant piston to housing-wall gap, which would cause erratic damping characteristics. For this reason, a round housing bore with a round piston was chosen.

The bore size that was chosen was 1.625 inches and it was decided that the damper should have a 4 inch stroke. The housing components were TIG welded together and then finish machined in order to create a one-piece housing. Carbon steel (1018 alloy) was chosen for the piston since it would minimize the distance that the magnetic flux would have to jump across. If the piston were made of a non-magnetic material, the magnetic flux lines would have to jump all the way to the piston rod in order to encounter a paramagnetic material. The pole plates were made of 1018 steel and were sized so that the cross-sectional area that the magnetic flux would "see" remained constant throughout its path. The electromagnet core piece was also made of carbon steel and sized to match cross-sectional areas of the other carbon steel components in the magnetic circuit.

To complete the electromagnet, the core was wound with 18-gauge magnet wire and then wrapped first with friction tape and then with electrical tape. The two types of electrical tape protected the windings from damage and also prevented the magnet wire from unraveling. As many turns of magnet wire as would fit were wrapped around the electromagnet core to ensure that the resulting electromagnet would be as powerful as possible given the already established dimensions.

The power supply for this first damper was 8 AA Nickel Cadmium batteries that were wired in series to yield a supply voltage of 12 volts. In order to vary the amount of current supplied to the damper, a rheostat was employed. The number of turns of magnet wire that were wound around the rectangular magnet core is unknown but is estimated to be approximately 300 turns. Figure 5.2 shows the control box that was used to house the batteries for the power supply along with other batteries that were used to power an LVDT.

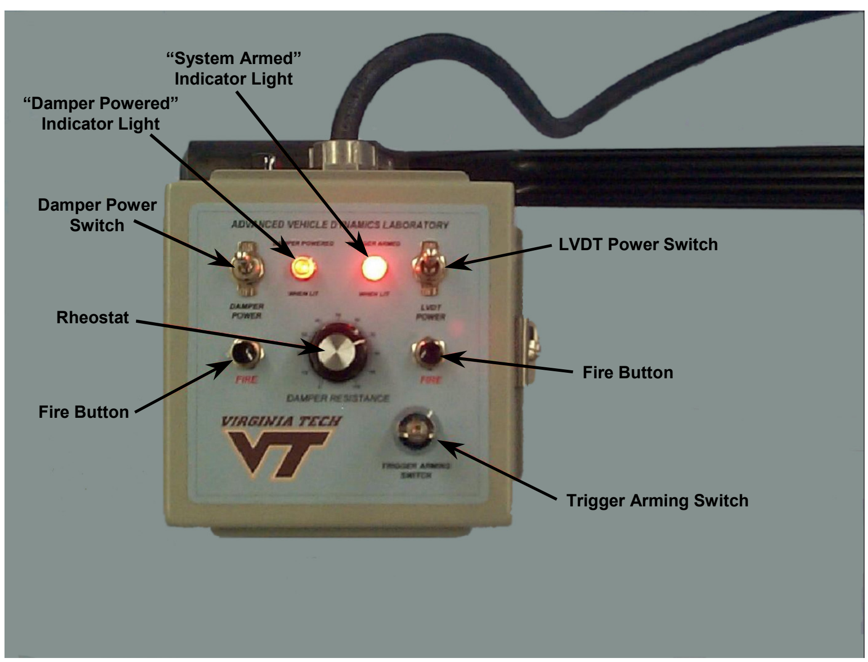


Figure 5.2 Control Box

5.1.2 Test Apparatus

To properly evaluate this MR damper, a gun recoil demonstrator was built. The gun recoil demonstrator incorporates a single-shot, bolt-action McMillan Bros. barreled rifle action that is mounted on a ball bearing recoil slide. The caliber that we chose for this test apparatus was the 50-caliber Browning machine gun (50BMG) cartridge. This cartridge was chosen because of its high recoil energy, and its availability. As can be seen in Figure 5.3, the MR damper was placed aft of the recoil slide with a PCB Piezotronics model number ICP 201B04 force transducer mounted between the recoil slide and the front piston rod of the MR damper. This force transducer has a sensitivity of 5 mV/lb and a maximum load capacity of 5000 lb.

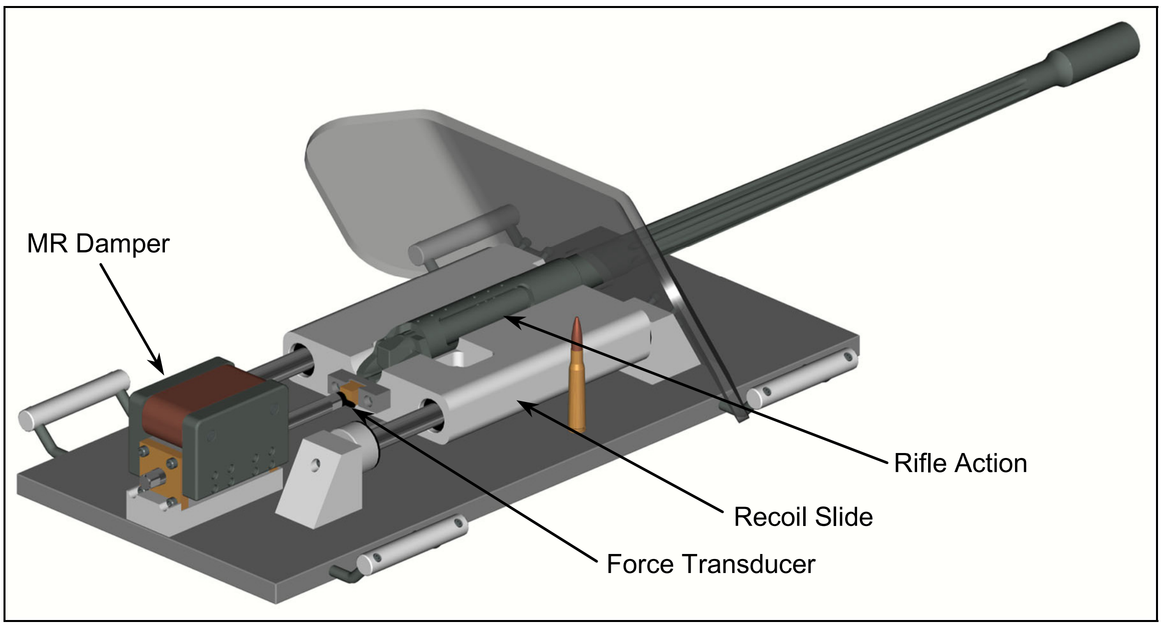


Figure 5.3 Gun recoil demonstrator

In order to measure displacement and velocity, the LVDT was mounted below the recoil slide. The LVDT used was a Macro Sensors model DC-750-2000-0314 linear LVDT. The LVDT's housing was attached to the recoil demonstrator base with two clamps and the inner rod was attached to the recoil slide with a steel block. Figure 5.4 shows an overhead view of the gun recoil demonstrator and the location of the LVDT and the force transducer. Figure 5.5 shows the gun recoil demonstrator set up at the firing range during testing.

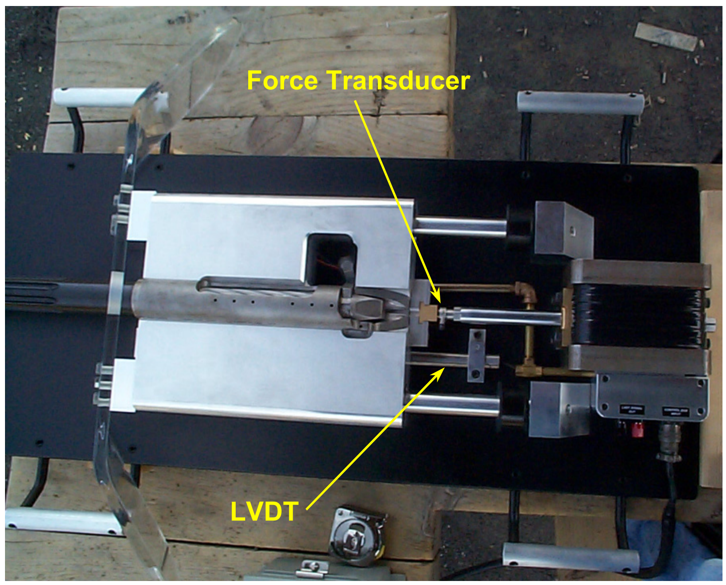


Figure 5.4 Overhead view of gun recoil demonstrator

Figure 5.5 Gun recoil demonstrator at firing range

5.1.3 Damper Evaluation and Performance

The damper was evaluated by firing the recoil demonstrator and recording force, displacement, and time data. All data was captured with a 2-channel Hewlett-Packard model HP-35665A dynamic signal analyzer which is shown in Figure 5.6. Figure 5.7 shows the gun recoil demonstrator set up at the firing range and ready for data acquisition. Figure 5.8 shows the raw force-displacement data as captured using the HP dynamic signal analyzer.

Figure 5.6 Hewlett Packard dynamic signal analyzer used for data acquisition

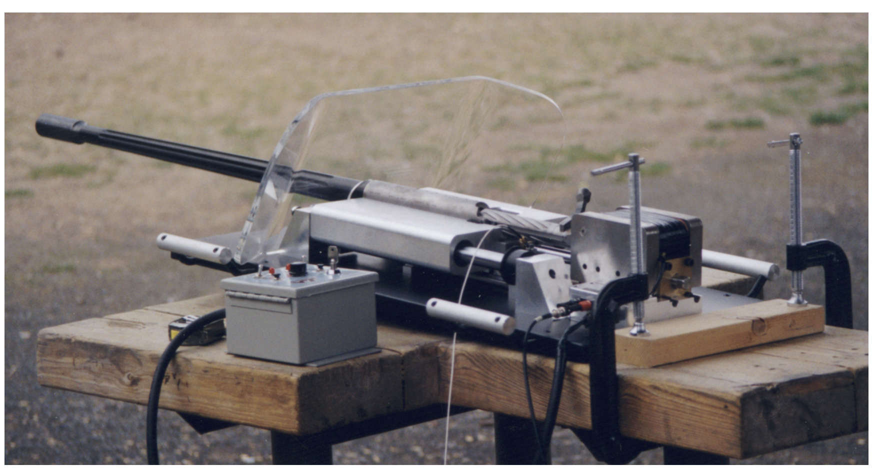


Figure 5.7 Gun recoil demonstrator set up for data acquisition

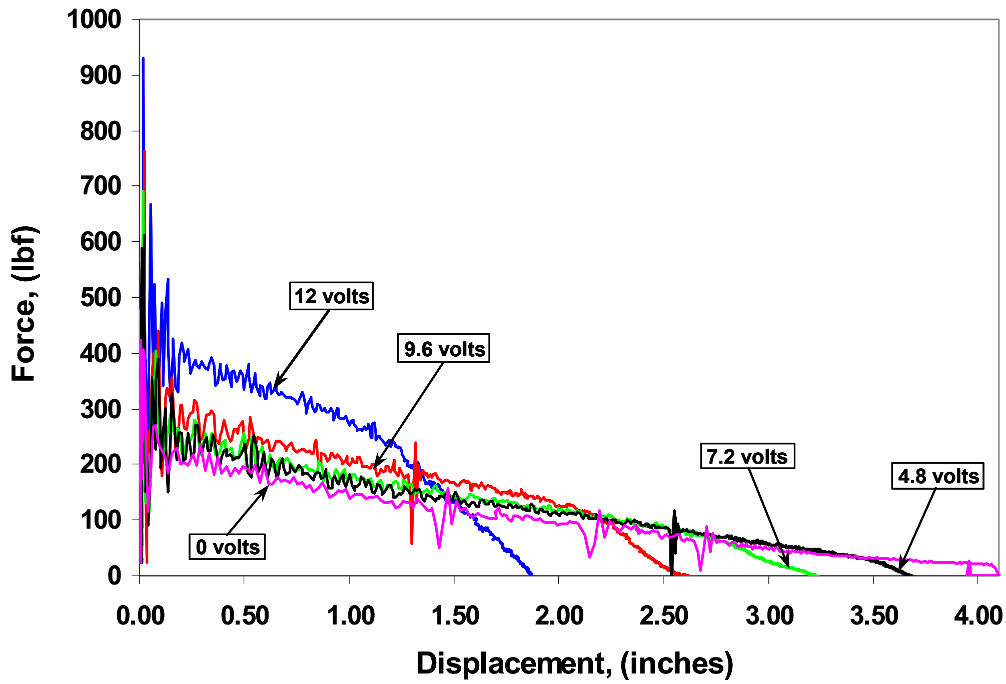


Figure 5.8 Raw MR damper force-displacement data

Through a process of removing "flyers" and implementing a least-square curve fit, the data shown in Figure 5.8 was transformed into what is shown in Figure 5.9. The important thing about Figure 5.8 and Figure 5.9 is that both figures prove that an MR damper can be used to vary the recoil stroke of a weapon, and therefore, the amount of force that the gun mount is subjected to. As mentioned earlier, the power supply used to operate the damper consisted of 8 AA NiCd batteries that were connected in series. To vary the voltage, and therefore the current supplied to the damper, a rheostat was used as part of the power supply circuit.

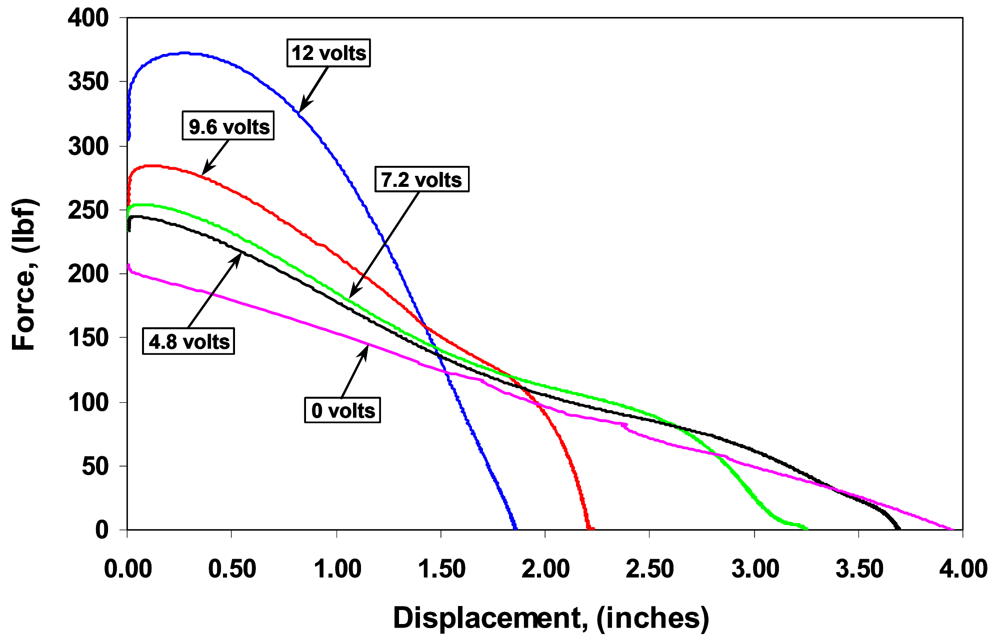


Figure 5.9 Curve fitted MR damper force-displacement data

Figure 5.10 shows the electrical schematic for the control box that was used to power the MR damper, energize the firing solenoid, and power the LVDT.

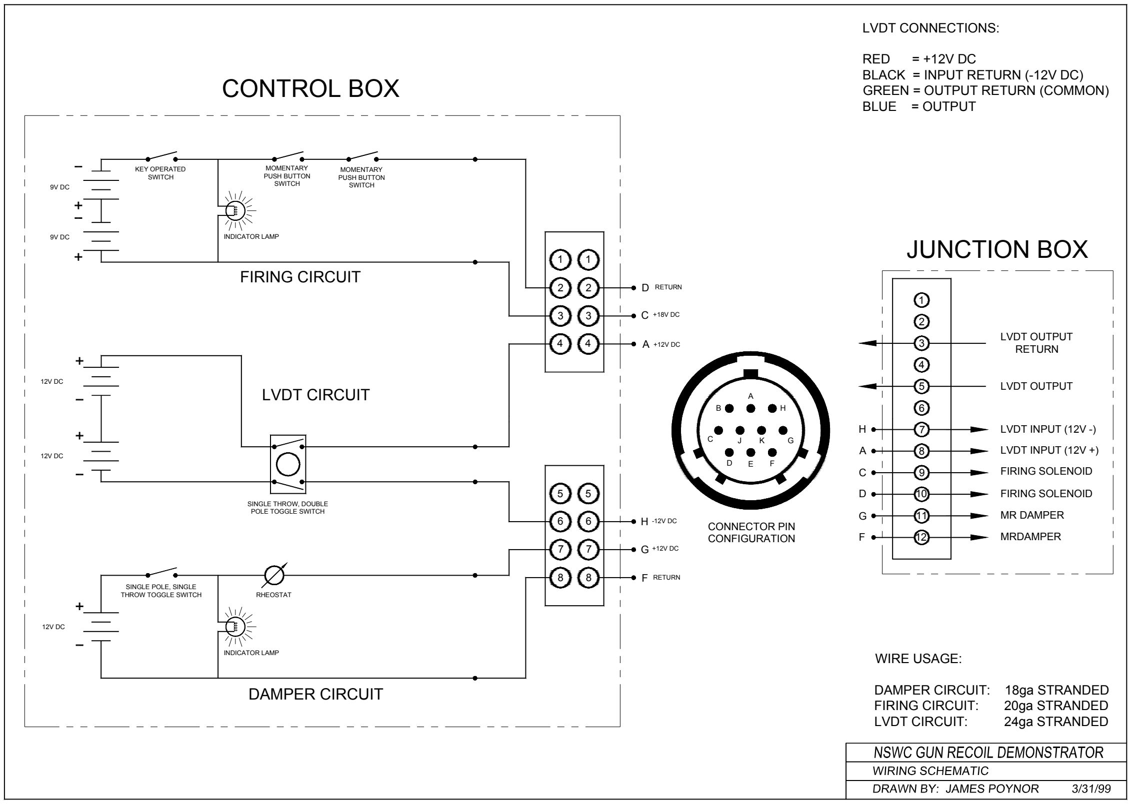


Figure 5.10 Wiring schematic of gun recoil demonstrator control box

One can observe by studying Figure 5.8 and Figure 5.9 that an increase in supply voltage, and therefore current, to the MR damper produces a corresponding increase in damper force and a reduction in damper travel (recoil stroke). This increase in damper force is brought about by an increase in magnetic flux strength that keeps the MR particles more rigidly aligned against fluid flow as the magnetic flux density increases.

Although only the passive case was explored in this research, one can readily see the benefit of applying a control policy to the MR damper. The dashed red line in Figure 5.11 represents one possible force-displacement profile that could be approximated with a closed-loop control policy. A profile of this type will yield the lowest peak force in the shortest recoil distance, which is always the main goal in an anti-recoil system.

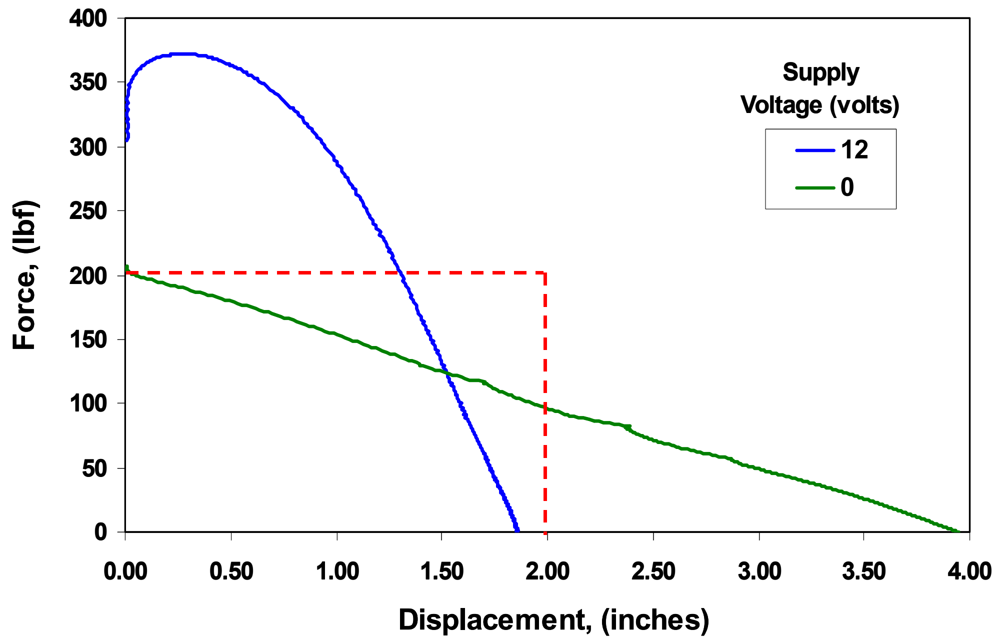


Figure 5.11 Ideal force-displacement profile

5.2 Second Generation Gun Recoil Damper

Once the first gun recoil MR damper was proven effective, we decided to build one with a more conventional design to see how well it would perform. To satisfy this goal, an MR damper of the double-ended variety was built.

5.2.1 Damper construction

This damper is a typical double-ended MR damper. The housing is made from a solid bar of 1018 steel and has an internal bore size of 3 inches and a wall thickness of 0.25 inch. The piston rods are both 0.750 inches in diameter and the end caps are held in place with internal lock rings at either end. The gap that exists between the piston and the housing bore is 0.115 inch and the magnetic coil is wound with 20 gauge magnet wire. Approximately 230 turns of magnet wire are wound around the piston to form the electromagnetic coil. A cross-sectional view of the damper is shown in Figure 5.12.

Figure 5.13 shows the damper just after being built and Figure 5.14 shows this damper installed on the gun recoil demonstrator.

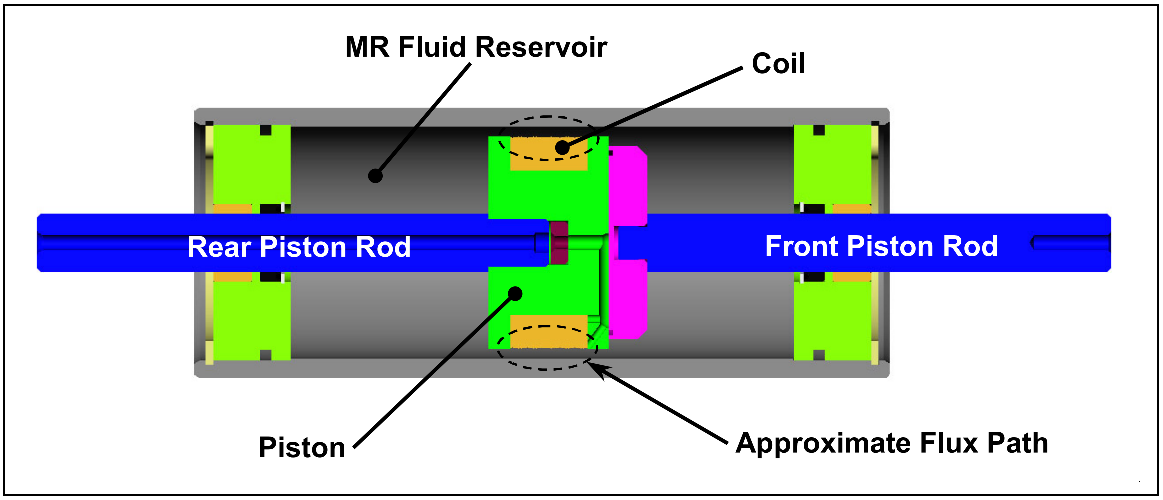


Figure 5.12 Second generation gun recoil MR damper

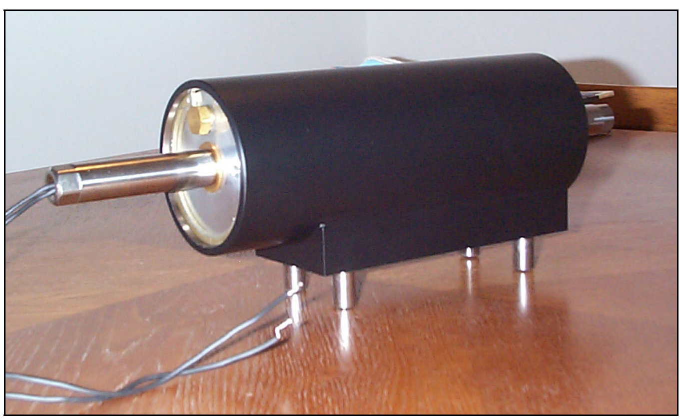


Figure 5.13 Second generation gun recoil MR damper

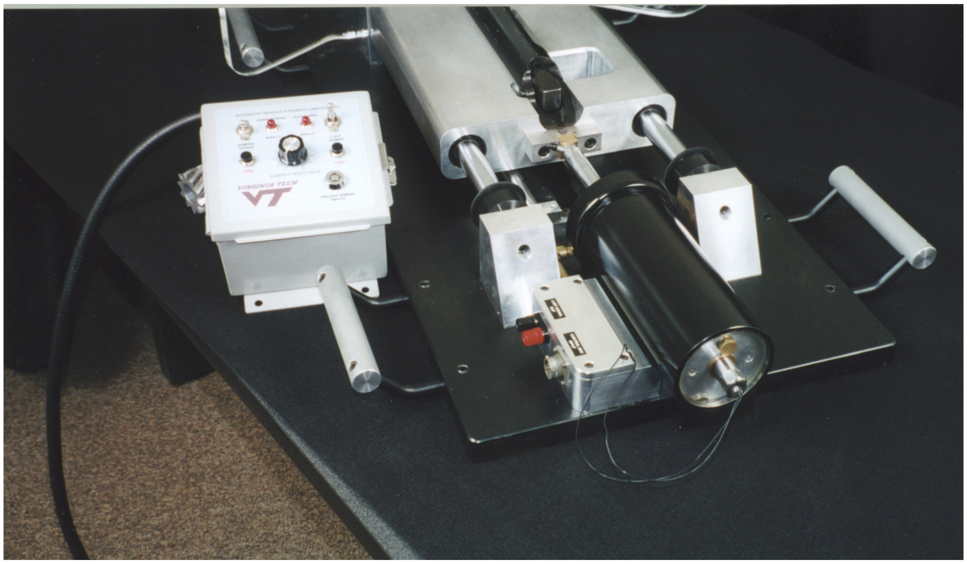


Figure 5.14 Second generation MR damper installed on gun recoil demonstrator

5.2.2 Damper operation

As can be seen in Figure 5.12, the MR fluid must flow around the piston from one end of the damper to the other as the piston rod is moved. As the electromagnetic coil (that is part of the piston) is energized, the MR fluid that is in the path of the magnetic flux is activated. This activated MR fluid then restricts the flow of MR fluid from one side of the piston to the other. This restriction in the flow of MR fluid produces an increase in damper force that is proportional to the voltage, and therefore current, that is supplied to the damper.

5.2.3 Test Apparatus

The test apparatus used for this damper was the same as that used for the first generation gun recoil damper with the exception that an MTS machine was used for an additional battery of tests. Unfortunately, data that could be compared with the earlier gun recoil damper design was not taken since this damper was not evaluated in the passive mode of operation.

By the time this damper was ready for use, a group of students was using it to explore the feasibility of semi-active control and a mode of operation that is known as "fire-out-of-battery". Fire-out-of-battery is a mode of operation where the gun is fired and then held back at its most rearward recoil position. When the weapon is to be fired again, the recoil slide is released and the rifle is fired at some point just before the recoil slide reaches its battery, or forward most position. The advantage of a fire-out-of-battery mode of operation is that the inertia produced by the forward acceleration of the recoil slide partially counteracts the recoil force that results from firing. Figure 5.15 shows the second-generation damper installed on the gun recoil demonstrator.

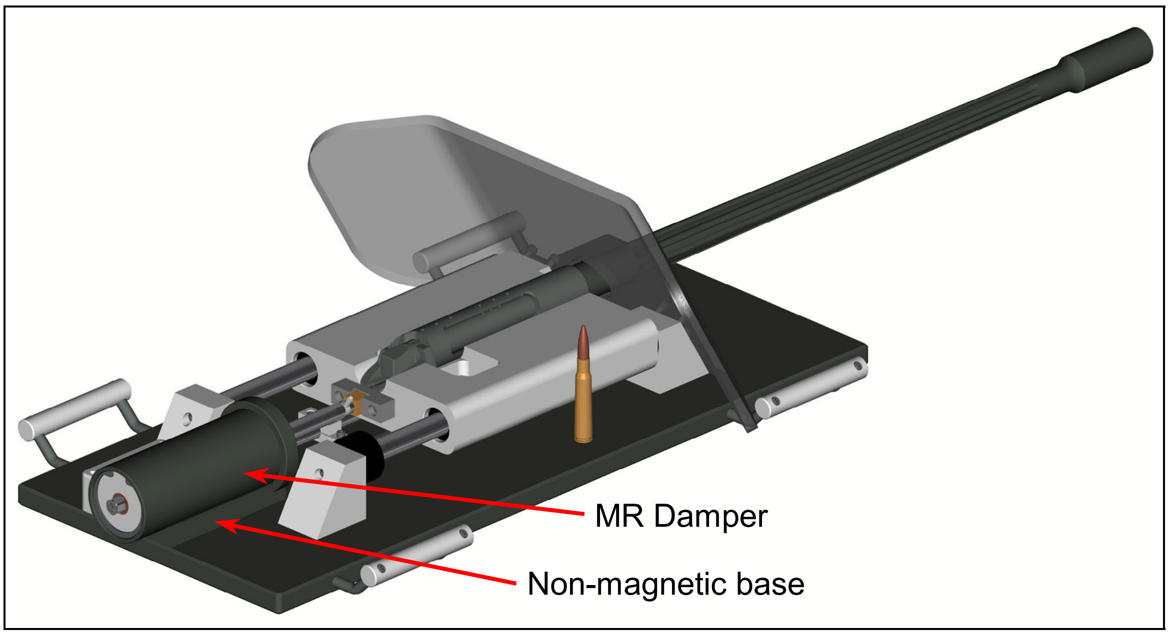


Figure 5.15 Second generation gun recoil damper installed on gun recoil demonstrator

Note that a non-magnetic base is used to mount the MR damper to the gun recoil demonstrator's base plate. This non-magnetic base is used so that the MR fluid will be activated as uniformly as possible within the activation region.

Since this damper was going to be used with a semi-active control policy, it was decided that the damping characteristics of this damper should be determined by testing it in the MTS machine. A fixture was built to facilitate mounting the damper in the MTS machine and the damper was tested at velocities of up to 22 inches per second. Figure 5.16 shows the results of this test.

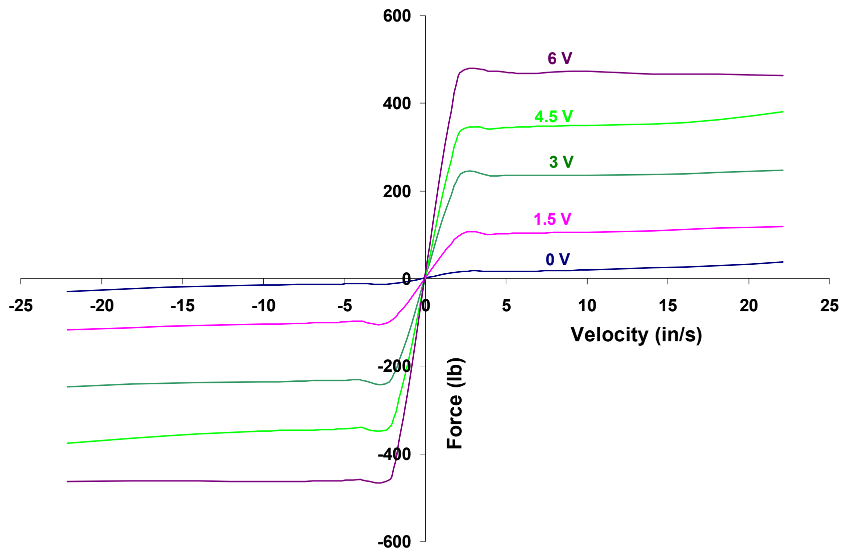


Figure 5.16 Damping characteristics of second-generation gun recoil damper

The primary advantages of this damper is its efficiency and its simple design. Where the original gun recoil MR damper required (8) AA NiCd batteries for operation, this damper only requires (2) AA NiCd batteries. Since this damper does not require a bi-metal housing, it is more economical than the first generation damper design.

5.3 Remarks

During the course of this research project, a live fire gun recoil demonstrator that incorporates an MR damper was built for the first time (to the best of our knowledge) and tested in the passive mode of operation. The suitability of MR dampers for controlling gun recoil/impact dynamics was proven. The following list of objectives, as specified by the Naval Surface Warfare Center (NSWC), was successfully proven with this gun recoil demonstrator:

1. The effectiveness of MR fluids for controlling gun recoil
2. The ability to control the forces transmitted to the gun mount
3. The ability to adapt to a variety of energy levels
4. The ability to vary the recoil stroke

Chapter 6

Hybrid MR Dampers

The term "hybrid MR damper refers to a type of damper that has both an MR section and a hydraulic section. The dampers that were built to test this concept can be described as MR-piloted hydraulic dampers. This name comes from the fact that a small MR device is used to control a valve that in turn controls the hydraulic section of the damper. The primary advantages of this type of damper are reduced cost and reduced weight. These large dampers are used in used in the anti-recoil systems of field Howitzers such as the M1985 Howitzer shown in Figure 6.1 and on stationary gun turrets such as the Mk45 5 inch gun turret depicted in Figure 6.2. In addition to excessive cost, the weight of a large MR fluid filled damper, such as the one described, may be prohibitively heavy for a Howitzer that must be airlifted to the deployment site.

Figure 6.1 U.S. M1985 field Howitzer

Figure 6.2 U.S. Mk45 5-inch Naval gun turret

6.1 First Hybrid Damper Design

The goal of this first hybrid damper was to match the damping characteristics of an adjustable Koni "Special D" model 88 1417 hydraulic damper. Both hybrid dampers that were built at AVDL were made from modified versions of this damper. Figure 6.3 shows the force-velocity characteristics of the stock Koni damper for both extremes of the manual adjustment range. From this data, it was determined that a maximum on-state extension force of 1000 lbf at 26 in/sec was to be the goal for this hybrid damper. In addition, the damper should have an off-state extension damping force of no more than 600 lbf at 26 in/sec.

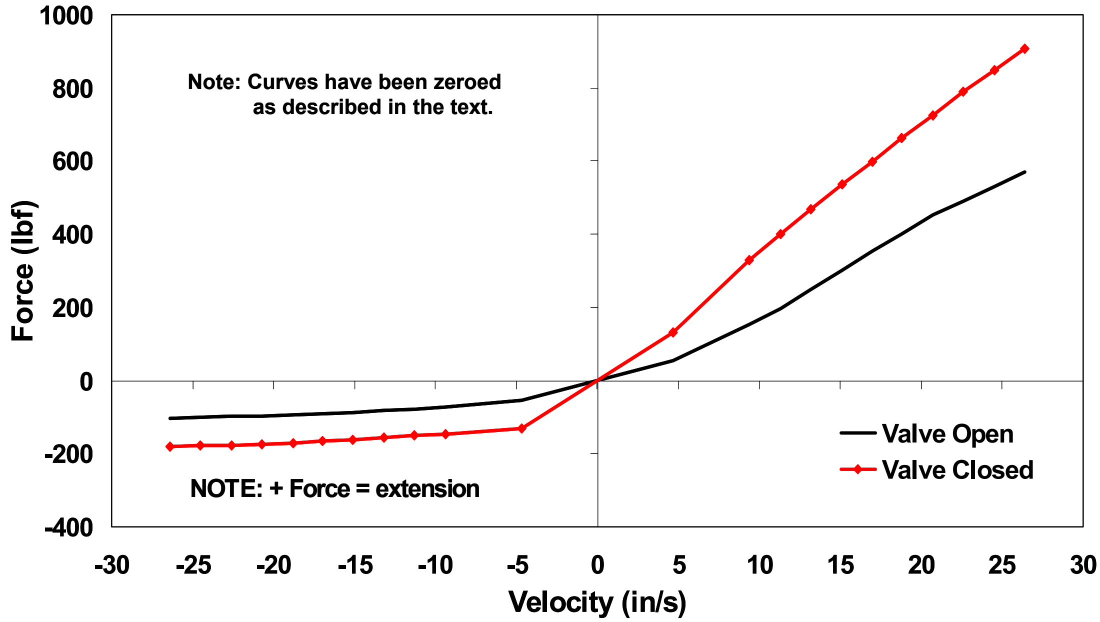


Figure 6.3 Damping profile for Koni Special D model no. 88 1417 adjustable damper

With the damping goals set, the first damper was built using the design depicted in Figure 6.4. As can be seen in Figure 6.4, a miniature MR damper is used to control the hydraulic extension valve. Since controlling the compression stroke was not a goal, the original compression valving was retained.

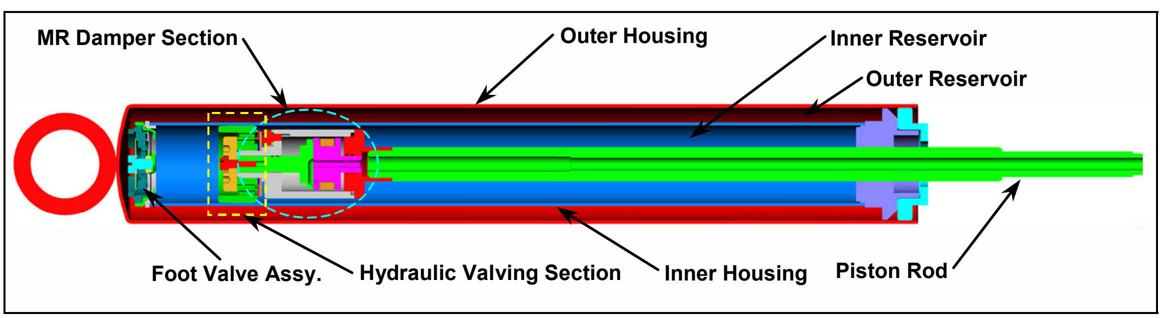


Figure 6.4 Hybrid damper section view, first design

The MR Section's housing is constructed of 17-4 PH stainless steel and the MR Piston is constructed of 1018 steel, both of which are paramagnetic. The Front MR Piston Rod is made of bronze and the MR Section End Cap is made of 304 stainless steel, both of which are non-paramagnetic. The bore size of the hydraulic section is 1.417

inches and the stroke is 9 inches. The bore size of the MR section is 1.00 inch, the fluid gap is 0.025 inch, and the stroke is the distance that the extension valve opens during operation. As can be seen in Figure 6.5, a coil spring that is located within the MR Section is used to keep the hydraulic extension valve in the closed position. This coil spring is the original spring that was used to preload the extension valve in the Koni damper. The electromagnetic coil in the MR damper section is wound with 250 turns of 30-gauge magnet wire and has a resistance of 5.6 Ω.

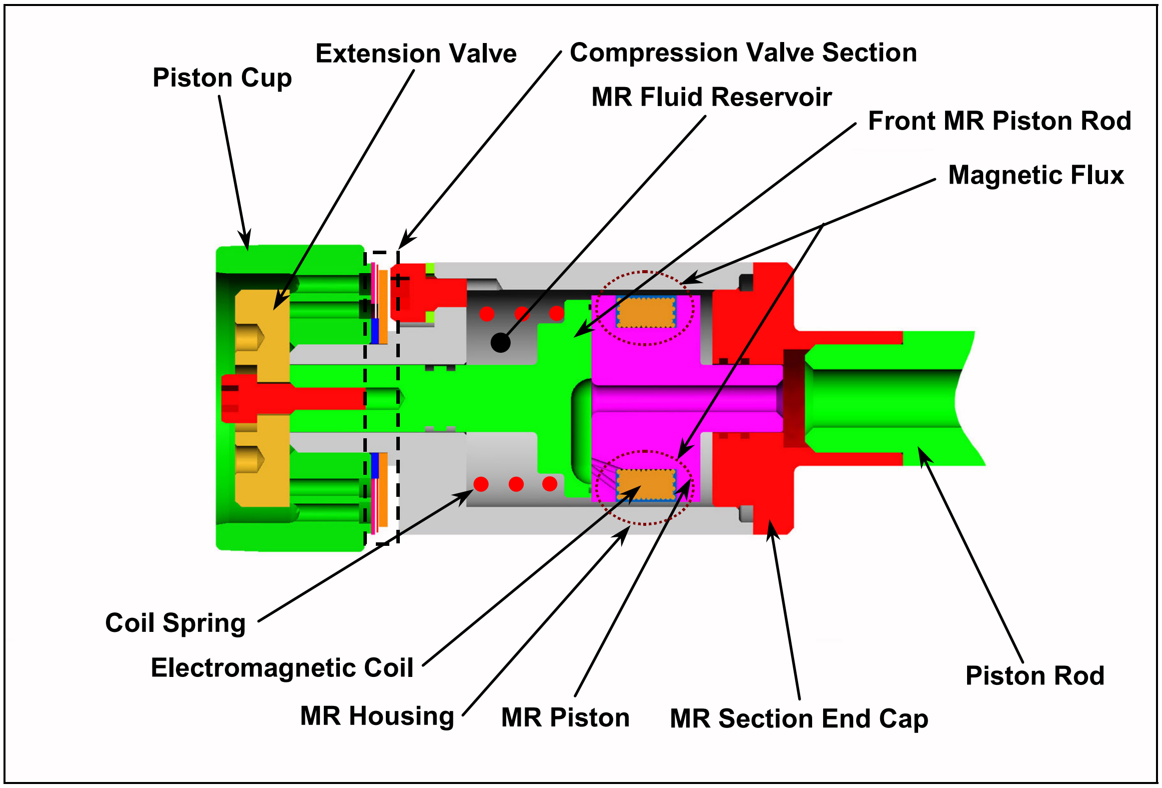


Figure 6.5 Detail view of first hybrid damper piston assembly

In theory, the MR damper section should resist the opening of the extension valve with a force that is proportional to the amount of current that is passing through the electromagnetic coil. This will work reasonably well as long as, at high currents, the power is turned off at the end of each stroke so that the extension valve can reset. For the damper to operate successfully, the voltage (or current) being supplied to the MR section would have to be controlled by a source that has piston rod velocity feedback. Otherwise, this damper will only work in applications where the velocity of the piston rod is either increasing throughout the entire extension stroke or remains the same throughout the entire extension stroke once attaining a certain velocity.

At the time of construction, only a passive evaluation of this damper was possible. In the future, however, other interested parties could use a semi-active, closed loop control policy to properly evaluate this design. Figure 6.6 shows the experimental test results for this damper operated passively.

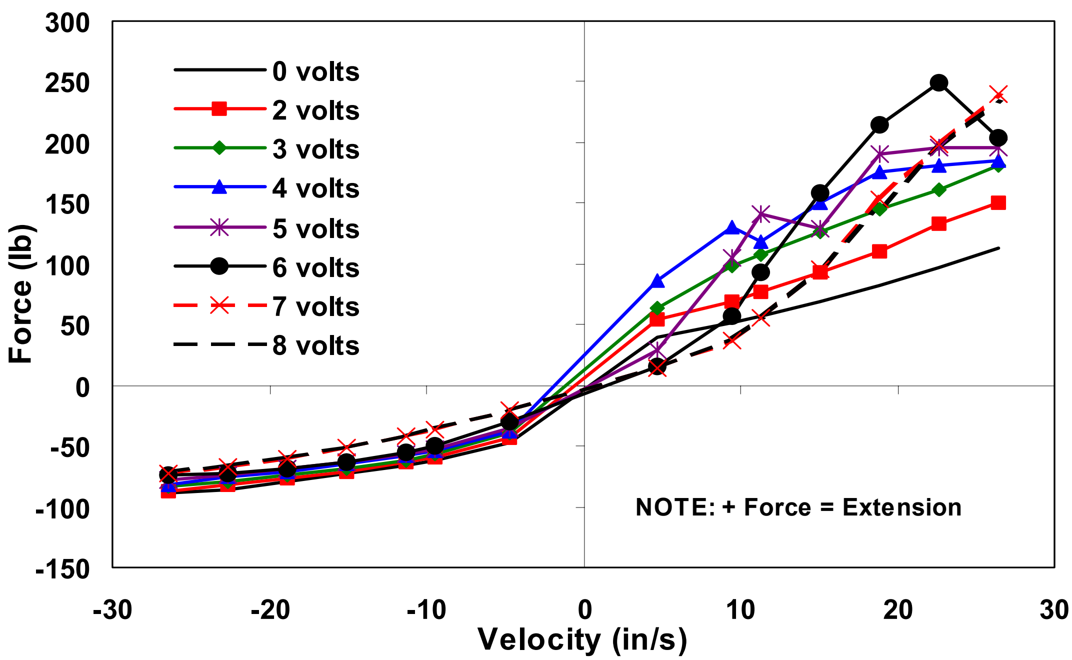


Figure 6.6 First design hybrid damper passive test data

These test results are disappointing because the extension damping force became erratic at supply voltages in excess of 3 volts. A note must also be made concerning the coil spring that is shown in Figure 6.5. Originally, the intention was to use the original Koni extension valve spring to preload the new extension valve but doing so made filling the MR section nearly impossible. This difficulty in filling the MR section was due to the extension spring partially obscuring the hole that the MR fluid was to be injected through. To alleviate this problem, a smaller diameter spring was installed in the MR section to preload the extension valve. This spring was not as strong as the original and therefore caused a reduction in extensive damper force. This was not much of a problem since our main interest was in the range of extension force variation that the MR controlled extension valve could provide. With further effort, the baseline damping force could be remedied by increasing the spring preload on the MR piston and/or by reducing the fluid gap in the MR section. These modifications were never tried since the construction of a hybrid damper that was thought to be more promising was already in progress.

6.2 Second Hybrid Damper Design

A second approach to the hybrid damper concept was attempted since it was determined that an MR section that operates in "squeeze mode" would be better for this application (short stroke, high force). The main shortcoming of the first design was that the MR section did not behave as a variable rate spring (this would be the ideal behavior). An MR device that is used in squeeze mode should more closely approximate a variable rate spring than the previous design for the small displacements that are required. It was estimated that the maximum extension valve travel, and therefore the greatest MR piston travel would be no more than approximately 0.020 inch. The performance goals for this damper were identical to those of the first hybrid design. Figure 6.7 shows a section view of the second hybrid damper.

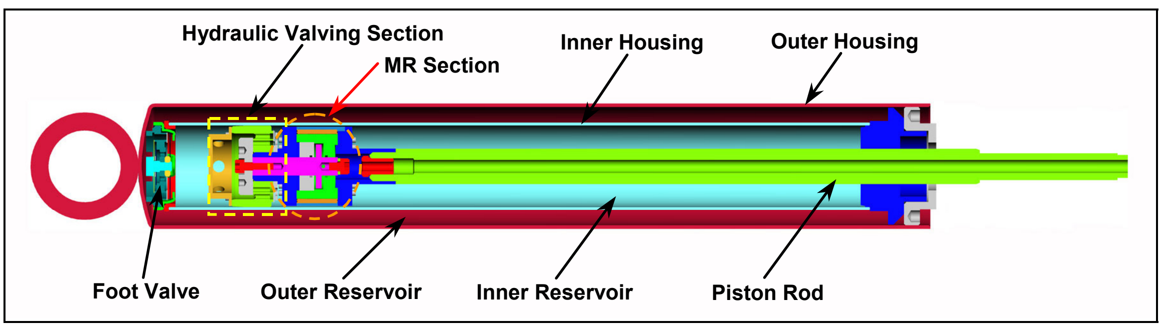


Figure 6.7 Section view of second hybrid damper

The construction of the second hybrid damper differs considerably from that of the first. Like the previous design, the piston assembly is made up of an MR section and a hydraulic section. The MR section only affects the extension stroke and the hydraulic valving section affects only the compression stroke. As can be seen in Figure 6.8, the MR piston rod is attached directly to the extension valve and a coil spring preloads this valve in the closed position. It is worthwhile to note that the extension valve preload spring is the original equipment spring from the original Koni damper.

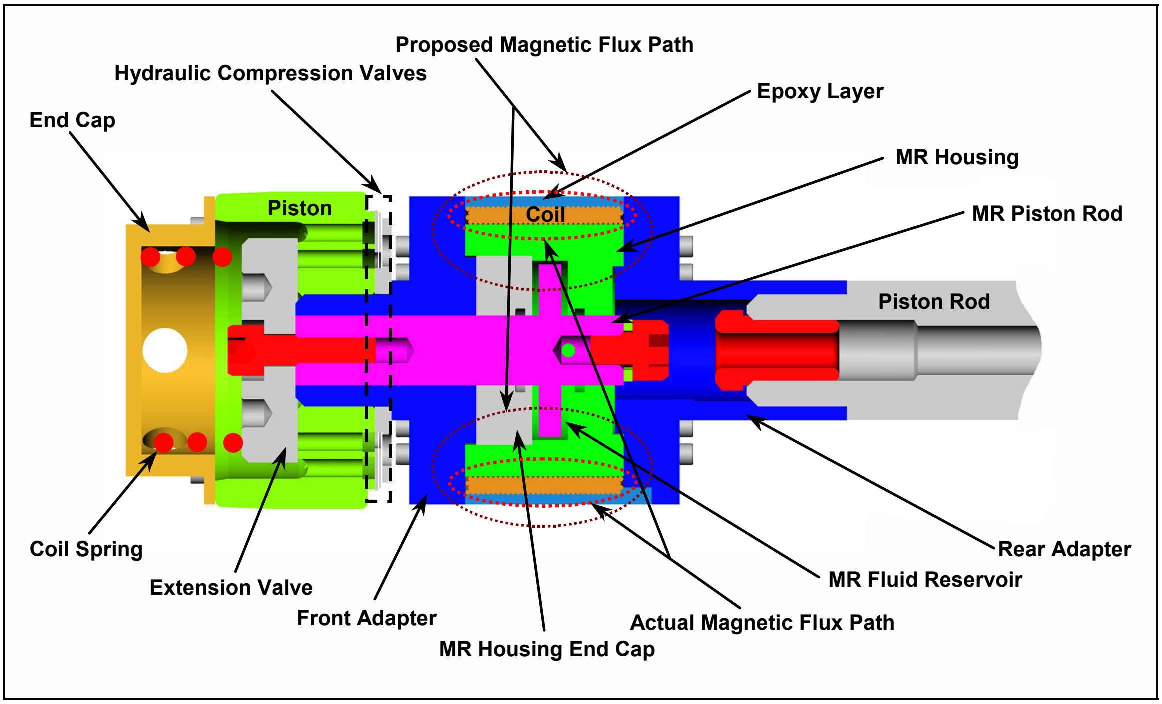


Figure 6.8 Detail of second hybrid piston assembly

In order to activate the MR fluid, an electromagnetic coil is wound around the MR housing. This electromagnetic coil produces a magnetic field whose flux path is approximated in Figure 6.8. To enhance activation of the MR fluid, the MR piston as well as the MR housing and MR core plug are made of 12L14 steel. Making the MR piston out of a paramagnetic material shortens the distance that is required for the magnetic flux to bridge the poles. The front and rear adapters are both made of 300 series stainless steel so that they will not affect the path that the magnetic flux takes. Since the compression valving is the same as in the original damper, as shown in Figure 6.3, the damping profile in compression should be virtually identical to the original.

During the extension stroke, hydraulic fluid must flow through the extension valve in order for the piston rod to move. This hydraulic fluid flow exerts pressure on the face of the extension valve that in turn pulls on the MR piston rod. The action of pulling the MR piston rod begins the process of buckling the microscopic columns of MR fluid particles that are formed by the application magnetic flux. The denser the magnetic flux, the more resistant to moving the MR piston (and therefore the extension valve) will be. By adjusting the amount of current that is supplied to the MR section, the damping rate in extension can be adjusted. To shift the MR controllable damping envelope, one needs only to adjust the amount of spring preload on the extension valve.

In theory, this design seemed like a good one. However, a serious design flaw became evident after the piston rod assembly was tested outside of the damper. With the coil wound and the MR section filled with fluid, the coil leads were connected to a current controlled power supply and the extension valve was moved by hand to check for resistance. No resistance to movement was detected with power supply currents of up to 5.0 Amps.

The reason for the MR fluid not being activated was that the magnetic flux is taking a different path than was anticipated. Since MR fluid is usually the material with the most reluctance in the magnetic circuit of an MR device [1], the magnetic flux will take another path if possible. The design flaw of this device is that the magnetic flux could take a path that crossed directly underneath the inside of the coil as shown in Figure 6.8. In every other MR damper built during the course of this research, the magnetic flux had no other choice but to jump across the MR fluid, therefore activating the fluid.

Looking back, it is difficult to understand how this result was not predicted given this design. The only way that this design could work is if the magnetic flux is of sufficient density as to cause the magnetic flux to take a path through the MR fluid. This level of flux density would probably require an electromagnetic coil that would be too large to fit in the designated space. In conclusion, the lesson to be learned is that the magnetic flux in an MR device must not be allowed to take any path that does not pass directly through the MR fluid.

6.3 Remarks

Although mostly unsuccessful, the research presented on the subject of hybrid dampers is a good start. More research into these types of dampers, particularly the squeeze mode variety, should be carried out along with the development of control policies that would be beneficial to this class of dampers. The combined benefits of reduced weight and cost for large controllable dampers make this endeavor worthwhile.

Chapter 7
Concluding Remarks

During the course of the research presented, several types of MR dampers were designed and evaluated through building and testing prototypes. An MTS dynamic material testing machine was used to acquire the force-velocity characteristics for most of the prototype dampers.

7.1 Summary

The following section provides a brief summary of the research that was completed. The successes, as well as failures, of each project are briefly discussed below.

The first research project involved building and testing a set of MR dampers to replace the original equipment shock absorbers on a 1999 Mercedes ML-430 sport/utility vehicle. A somewhat unusual design approach was taken for the magnetic circuit. The unusual thing about this design is that the damper housing is used for the magnetic flux return. During testing, these dampers performed well and did so without being overly complex.

The second research project was to design and build a set of MR dampers to replace the original equipment shock absorbers on a 2000 Ford Expedition. Due to the author's dissatisfaction with the commercial suitability and reliability of the ML-430 MR dampers, a new design was developed (patent applied for). This new design is built on a modular concept that allows for the easy assembly of multiple stage pistons. Both reliability and manufacturability are greatly enhanced over previous designs.

The third research project involved building and testing two MR dampers for the gun recoil application. Using the first generation gun recoil damper along with the gun recoil demonstrator, we were able to prove that MR dampers can be used successfully to:

1. Prove the effectiveness of MR fluids for controlling gun recoil
2. Control forces that are transmitted to the gun mount
3. Adapt to a variety of energy levels
4. Vary the recoil stroke

To improve upon the original gun recoil MR damper, a second generation MR damper was built. This second design is simpler to build and uses considerably less voltage than the first generation gun recoil MR damper (2 AA batteries vs. 8 AA batteries).

The fourth research project was to design and build and test a hybrid MR damper. Two different hybrid MR dampers were designed and built to explore possibilities in this area. The first design worked but fell short of our expectations. The second design failed to work at all but was probably the most promising of the two. If more time was available, and an appropriate semi-active control policy implemented, the author is confident that a device of this type could be built and operated successfully.

Although not originally planned, the need for a new testing routine became evident. To improve the test results when evaluating mono tube MR dampers, a new testing routine was developed. This new testing routine uses both variable displacement as well as variable excitation frequency to overcome the difficulties that are common when determining force-velocity characteristics of mono tube MR dampers. Test results for the original as well as the new testing routine are presented using the same MR damper, as documented in section 4.3.

In conclusion, this research was successful overall. There were a few setbacks since some designs did not work as planned but nevertheless, some important developments have come out of this research. The capability to control gun recoil with MR dampers was proven for the first time and an improved MR piston design that is worthy of a patent was developed and tested. It is the author's hope that in the future, others will be able to use this work and carry it further.

7.2 Recommendations

The following recommendations can be made after completing this research. The recommendations are grouped according to topic.

7.2.1 Seals for MR Damper Applications

If possible, the use of o-ring seals for dynamic sealing applications should be avoided. When o-rings are used with MR fluids in a dynamic application, they can cause aggravated wear because of the wedge shaped space that is formed between the surface to be sealed and the surface of the seal itself. The reason why this wedge shaped space aggravates wear is that MR particles get trapped between the seal and the sealing surface. Once under the seal, these MR particles are forced against the surface that is in contact with the o-ring. For this reason, accelerated wear is likely when using o-rings for seals in dynamic, MR fluid, applications. When used for static seals, o-rings work very well as long as the parts are machined to the proper tolerances that are recommended by the seal manufacturer.

The best type of seal for dynamic seal applications is a scraper type seal. For both gun recoil dampers, seals of this type manufactured by Parker were used for the piston rod seals (Parker 426312500750-250B). For all subsequent designs, Hercules Hydraulics seals of this type were used where possible for the piston rod seals (Hercules MUUL-14X24X8 or Hercules U12-0.62-SQB). The reason for the change in seal manufacturers was because Hercules Hydraulics offered a wider range of metric and English sizes. The only dampers for which this type of seal could not be used were the two hybrid dampers. O-rings had to be used as dynamic seals in the hybrid designs because of the small MR piston rod diameters that were used. For the accumulator pistons in the ML-430 MR dampers, o-ring seals were used since a better substitute could not be found. For the accumulator pistons in the Ford Expedition MR dampers, a combination of an o-ring seal and a "U" cup seal were used (Hercules 9137-062F). The "U" cup type piston seal was used since it has a scraper type of edge that is better for use with MR fluids.

For sealing reservoir bleed screws, sealing washers purchased from McMaster-Carr were used (McMaster-Carr 93783A007). These washers work well when used in conjunction with ordinary socked head cap screws.

7.2.2 Bearing Materials

Two different bearing materials were used in the construction of these MR dampers. One material that was used is SAE 841 bronze. This bronze alloy is sintered, oil impregnated, and works well for piston rod bushings since it is self-lubricating and wears well. The only caution that the author can think of related to SAE 841 bronze is that it should never be used for a sealing surface. This is because of this alloy's porous nature.

The other bearing material that was used is MDS filled nylon. This material is good for use in wear bands since it is durable and the particles that are in MR fluid can imbed themselves its surface. No long term testing has been carried out but it is hoped that having the MR particles imbedded in the nylon will cause less wear to the damper bore than if a harder material were used.

7.2.3 Materials for Use in Magnetic Circuits

From an overall point of view, the best material for use in the magnetic circuit is 12L14 steel. This steel is easily machined to close tolerances and it yields a very good surface finish without extensive polishing. Other suitable steels are those with carbon contents less than 1018 steel. These steels are good magnetically but suffer in machinability since they leave torn, rough surfaces when cut that required extensive polishing or grinding.

7.2.4 Magnetic Coils

The author has found through experience that magnet wire should never be wound directly into a machined groove on a piston. Instead, additional insulation of one type or another should separate the magnet wire from contact with the walls of the machined groove. Even though the grooves that were machined into the periphery of the ML-430 dampers piston had a carefully prepared surface finish, the coils would short out unpredictably. This happened despite the use of potting epoxy and extra plastic insulation wherever the wire had to make a sharp bend. It is assumed that the shorts occurred after the magnet wire's insulation rubbed through in areas where the magnet wire contacted the piston groove. This location for shorting is assumed since at all other places, the magnet wire was thickly insulated.

Any sufficiently strong non-conducting material can be used for insulation but there are some particularly good choices for some situations. For coil forms such as the ones used in the Ford Expedition MR dampers, a paper-based phenolic material (Garolite grade XX) is very good. This material is easy to machine, dimensionally stable, and inexpensive. For areas where the magnet wire must make sharp turns, a small piece of insulation that has been stripped from a piece of solid core wire can be used effectively. For other areas where a coil form or a piece of wire insulation cannot be used, electrical tape or several layers of paper can be used with good results. Another method that would work well for pistons is to fill the coil grooves with epoxy and then machine smaller size grooves once the epoxy has cured.

As for the coils themselves, the author has found that it is important to match the coil to the power supply that is available. In particular, coils with approximately 50 turns that are wound with 24-gauge magnet wire work very well when used with low voltage power supplies (1 to 12 volts). For applications where high voltage power supplies are used, 30-gauge magnet wire and coils with approximately 200 should work well. The key is to make sure that the coil can draw sufficient current from the power supply so that the highest flux density possible can be produced given whatever coil size limitations exist.

7.2.5 Piston Rod Materials

For piston rods, we have found Thomson linear shafting material to be best. This material is available case hardened and hard chrome plated. The case hardening ensures that the piston rod will wear well and the hard chrome protects the piston rod from corrosion as well as wear (the chrome is harder than the case hardened steel). The only drawback to this material is its machinability. The case hardening depth tends to be quite deep, on the order of 0.080 inch for a 0.500 inch diameter shaft. For this reason, the designer must be sure that all internal threads in the piston rod are of a diameter that is less that the diameter of the unhardened steel core. Simple turning operations on the outside diameter of the shaft present little trouble as long as the lathe being used is rigid and carbide tooling is used. In particular, Kennametal KC730 grade, positive rake carbide inserts have worked very well.

7.2.6 Housing Materials

Several different materials have been used for MR damper housings during the course of this research. Of the materials that have been used, the best has been a steel drawn over mandrel (DOM) tubing material that has a honed inside diameter. This material is made for the hydraulic cylinder industry and is available from Scot Industries. Several grades of steel are available with a range of bore finishes and tolerances. A surface finish of at least 16 or better should be used in applications where the cylinder bore will be in contact with a seal. Since 12L14 is not available in tube form, we used 1020 DOM steel, which is readily available and works very well.

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Vita

James C. Poynor was born on October 22, 1967 in Baltimore, Maryland. At an early age, he developed a keen interest in how things worked. This interest was encouraged by growing up on a farm where his father had a woodshop and a number of tractors and vehicles that needed to be worked on from time to time. After completing High school in Columbus, New Jersey; he went on to pursue an Associates degree in Applied Science with a major in Gunsmithing at Trinidad State Junior College in Trinidad, Colorado.

After completing the Associates degree, James went on to complete an 8000-hour apprenticeship in Moldmaking/Precision Machining. After becoming certified as a Precision Machinist, both Federally and with the state of New Jersey, he decided to build on his previous experiences and earn a degree in Mechanical Engineering. At first, he attended Burlington County Community College in Pemberton, New Jersey. After attending Burlington County College for several years, James transferred to Virginia Tech where he earned a Bachelor of Science degree in Mechanical Engineering.

After completing a Bachelor of Science degree, James went on to pursue a Masters of Science degree in Mechanical Engineering, also at Virginia Tech. In the near future, he will begin working at the Naval Surface Warfare Center in Dahlgren, Virginia where he hopes to continue participating in his favorite hobbies, which include: antique automobiles, learning about history through collecting and researching medieval documents, and metalworking.