Chapter 3

Damper Hardware Design/Fabrication and Characterization

The purpose of this chapter is to describe the development of the controllable damper used in this research project. It will introduce the actual hardware along with its fabrication and force velocity characterization.

3.1 Overall Structure of the Designed MR Dampers

The damper used in this project is similar to a conventional twin-tube damper. Conventional twin-tube dampers with similar working dimensions to the controllable MR damper used in this study are readily available. As summarized in Table 3.1, The compressed length of the MR damper is 15.84 inches. When it is extended, it reaches 24.35 inches. The stroke of the damper is 8.50 inches, and the mid-stroke length of the damper is 21.1 inches. The damper is 3.00 inches in diameter. The eyes have inner and outer diameters of 1.00 and 2.38 inches respectively.

Table 3.1. Magnetorheological Damper Working Dimensions

<table>
<thead>
<tr>
<th>Damper Parameter</th>
<th>Dimension (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>total length (extended)</td>
<td>24.35</td>
</tr>
<tr>
<td>total length (compressed)</td>
<td>15.85</td>
</tr>
<tr>
<td>stroke/mid-stroke length</td>
<td>8.50/21.10</td>
</tr>
<tr>
<td>outer shock tube diameter</td>
<td>3</td>
</tr>
<tr>
<td>inner/outer eyelet diameter</td>
<td>1.00/2.38</td>
</tr>
</tbody>
</table>

In terms of internal makeup, the MR damper is similar to a conventional damper. The MR damper used in this study is shown in Figure 3.1 along with a standard heavy truck damper.
Some of the parts that the MR damper have in common with a conventional twin-tube damper are the upper and lower shock eyes, the outer and inner shock tubes, the piston ring and head, the piston rod, and dynamic seals, as defined in the damper schematic shown in Figure 3.2.
3.2 Fluid Paths in MR and Conventional Twin-tube Dampers

The fluid path in the MR damper used in this study is slightly different from a conventional twin-tube damper. As a conventional twin-tube damper compresses, the fluid flows from the inner cylinder, as shown in Figure 3.3, to the outer cylinder through the foot valve. In the outer cylinder there is a free air and fluid interface.

![Figure 3.3. Conventional Twin-Tube Damper Flow Direction](image)

As more of the piston rod enters the volume previously available to the fluid, the air column fills the function of an accumulator by compressing. When the damper is in extension, the flow directions are reversed.

The MR damper is slightly different than the twin-tube damper since the MR piston does not have any valves. Instead of having valving in the piston and base of the damper, the MR damper used has valving at the top and bottom (head and foot) of the damper, as is shown in Figure 3.4.
In compression, the upper check valves open to allow free fluid flow. Compression damping is controlled by the lower foot valves. As the piston rod enters the damper, the accumulator compresses. When the damper is in extension, the lower check valves are open, allowing free flow. Extension damping is controlled by the upper head valves.

3.3 Components of the Designed MR Dampers
This section will detail the various components that are part of the designed MR dampers.

3.3.1 Outer Shock Tube
The outer shock tube has multiple functions, including protection of the damper’s internal parts, housing the fluid, and transferring heat from the damper fluid to the surroundings. These functions are the same in both a conventional and MR dampers. The difference between the shock tube in the MR damper and the shock tube that is used in a conventional damper is that the MR damper shock tube has to allow for the passage of four wires. Of these four wires, one pair goes to each of the two electromagnetic coils (to be discussed later) that allow the damper to be
controllable. As shown in Figure 3.5, in order to allow this wire passage a hole was drilled into
the side of the outer shock tube, and a fitting was brazed onto the hole.

![Figure 3.5. Outer Shock Tube, Wire Passage, Fitting, and Lower End Cap](image)

3.3.2 High Pressure Tubing

High pressure tubing, shown in Figure 3.6, is a component of the MR damper that is not present
in a conventional twin-tube damper.

![Figure 3.6. High Pressure Tubing, Fitting, and Clamps](image)
The length of high pressure tubing used in the MR damper has two functions. These functions include the passage of the internal wiring necessary for controlling the damper, and serving as an accumulator. In a conventional twin-tube damper, there is an air column in direct contact with the fluid. Since MR fluid cannot operate with a free air and fluid interface, it was necessary to add an accumulator to the design. The accumulator has to account not only for the change in volume available to the fluid as more of the piston rod enters the cylinder, but also allow for thermal expansion of the MR fluid. The MR fluid used in this study had a coefficient of thermal expansion of roughly ten percent. The high pressure tubing expands and contracts as needed, and comprises one part of a two part accumulator system. The high pressure tubing is affixed the fitting on the outside of the outer shock tube by hose clamps.

3.3.3 Seal Plug

The seal plug is a piece of tubing approximately one inch long with four wires passing through it, as shown in Figure 3.7.

![Figure 3.7. Seal Plug](image)

The wires are insulated on the ends, and resin coated in the middle. With the wires in place, the tube was filled with epoxy. The seal plug is attached to a threaded insert that is secured into the end of the high pressure tubing with both threads and hose clamps. The seal plug is held in place with a nut and compression fitting and has been shown to be secure.
3.3.4 Inner Shock Tube
The inner shock tube in the MR damper is the same in the as in a conventional twin-tube damper. In both the MR damper and the conventional twin-tube damper the inner shock tube is the tube that guides the piston of the damper. The fluid passage between the inner and outer tubes is slightly different in the MR damper than in a conventional twin-tube design, but the function of the inner shock tube is unchanged. In the MR damper, as the piston rides back and forth, fluid is forced in and out of alternating ends of the inner shock tube. In order for the motion of the fluid to be mechanically useful, the flow has to pass through the damper valving. This requires the inner shock tube to be sealed with both the upper and lower coil assemblies. In the MR damper the inner shock tube has an auxiliary function of having the second part of the accumulator mounted onto its outer surface.

3.3.5 Accumulator
The accumulator has the function of compensating for both changes in the volume of MR fluid due to temperature changes, as well as changes in the volume available to the fluid as the piston rod enters and exits the body of the damper. As previously discussed, a conventional twin-tube damper has a column of air that acts as the accumulator, however this design is not feasible for MR dampers. The length of high pressure tubing previously discussed acts as one part of the two part accumulator system used in the MR damper. The second part of this system is a rectangular piece of closed cell foam that is wrapped around the outside of the inner shock tube, as shown in Figure 3.8. The foam is secured to the inner shock tube with zip ties.

Figure 3.8. Closed Cell Foam Accumulator Used on the Inner Shock Tube
3.3.6 Piston and Piston Rod

The piston and piston rod have almost the same function in the MR and conventional dampers. One difference between the two is that a conventional twin-tube damper incorporates the valving into the piston, whereas the MR damper used includes the valving in the head and foot of the damper. In both MR and conventional dampers, movement of the piston has to force fluid through the damper’s valving. In order for this to happen there must be a seal between the piston and the inner shock tube. In the MR damper a seal was attained by using two o-rings and a teflon band that wrapped around the piston head, as shown in Figure 3.9.

![Figure 3.9. Piston and Piston Rod Shown with O-Rings and Teflon Band](image1.jpg)

3.3.7 Upper Coil Assembly.

The upper coil assembly contains the valving used to control extension damping as well as to provide housing for the upper coil. It consists of three parts, as shown in Figure 3.10.

![Figure 3.10. Upper Coil Assembly](image2.jpg)
The assembly contains two sets of valves through which the MR fluid can pass. One set of the valves are check valves that provide an easy flow path to the fluid while the damper is in compression. These check valves are incorporated in both the upper and lower coil assemblies, avoid pulling on the fluid column and causing cavitation. Once the coil is in place, the channel evident on the top of the assembly was filled in with epoxy.

3.3.8 Upper Coil
The upper coil, which has a resistance of 3.5 Ohms, is housed within the upper coil assembly described in the previous section. When the coil is energized, it creates a magnetic field normal to the fluid flow direction, therefore energizing the fluid. The damping caused by the MR valving is directly proportional to the extent the fluid is energized.

3.3.9 Lower Coil Assembly
The lower coil assembly, shown in Figure 3.11, is similar in function to the upper coil assembly, but is simpler in operation.

![Figure 3.11. Lower Coil Assembly](image)

Instead of a set of check valves allowing easy fluid passage in one direction, the lower coil assembly has a single large check valve. While the damper is in compression, the check valve seats and the flow path is restricted to the active valves.
3.3.10 Lower Coil
The lower coil, shown in Figure 3.12, has a resistance of 1.7 Ohms and sits inside the lower coil assembly.

![Figure 3.12. Lower Coil Detail](image)

The magnetic field applied to the fluid is normal to the direction of fluid flow as the fluid passes through the compression valving. This is the same manner that the upper coil affects damping. The lower coil was found to be extremely prone to breakage at wire interface and was reinforced in our design.

3.3.11 Upper and Lower End Caps
The upper and lower end caps screw onto the upper and lower ends of the outer shock tube. They hold the upper and lower coil assemblies rigidly against the ends of the inner shock tube. The MR damper’s lower shock eye is built into the lower end cap.

3.3.12 Damper Assembly
The MR damper is assembled in stages. The main subassemblies are shown in Figure 3.13.
The first of the main subassemblies, shown in Figure 3.13, includes the piston rod and piston connected together, but without the o-rings and teflon band that wraps around the piston. The second main subassembly consists of the inner shock tube with the accumulator in place, and the upper and lower coil assemblies placed at either end. The third main subassembly comprises the outside of the shock, including the outer shock tube, and the upper and lower end caps.

Once the subassemblies shown in Figure 3.13 are put together, the damper is assembled as shown in Figure 3.14.
After the damper is assembled and both the upper and lower end caps are tightened, the damper is filled by adding MR fluid through the high pressure tubing, as shown in Figure 3.15.

![Figure 3.15. Filling of Magnetorheological the Damper](image)

This completes the assembly of the damper. The fully assembled damper, shown in Figure 3.16, is ready for force-velocity testing.

![Figure 3.16. Fully Assembled Magnetorheological Damper](image)

3.4 Damper Characterization

In order to measure the force-velocity characteristics of the twin-tube MR dampers, a known relative velocity was imposed across the damper, and the damper force was measured. This was
performed for a number of relative velocities. The force-velocity measurements were performed for both the MR dampers and the stock dampers of the Volvo VN truck. In order for the MR dampers to be useful, they must be capable of both higher and lower levels of damping at all relative velocities, as compared to the stock dampers.

3.4.1 General Damper Test Information

Both the MR dampers and the original Volvo VN heavy truck damper were tested using the Material Testing System (MTS) test machine, shown in Figure 3.17.

![Figure 3.17. MTS Test Machine](image)

The MTS test machine has an upper and lower head with grippers that can hold the dampers in place. The lower head is attached to the hydraulic cylinder that can move up and down with velocities in excess of 30 in/sec. The upper head incorporates a load cell allowing the operator to measure the force applied across the damper. Since the original truck dampers were readily available and easily replaced, they were considered expendable. Because of this, it was decided that one should be permanently modified to fit the MTS machine. Since the MR dampers were not easily replaced, fixtures were machined to allow the MR damper to work with the MTS machine, without permanent modification or damage.
3.4.2 Original Damper Modification

The original Volvo VN heavy truck damper had eye type connections on either end. It was designed to be fastened to a vehicle by a bolt and bushings as shown in Figure 3.18.

![Figure 3.18. Original Damper Mounting Configuration](image)

In order to hold the damper in place in the MTS machine, a metal plate was welded to each shock eye as shown in Figure 3.19.

![Figure 3.19. Modified Original Damper Mounting Configuration](image)

3.4.3 MR Damper Test Fixtures

Since the MR dampers were to be placed on the truck after the MTS testing, it was necessary to design fixtures that would allow the dampers to be tested and then removed without any damage. As shown in Figure 3.20, this was accomplished using a fixture similar to the damper brackets on the vehicle.
The bushings used in the MTS machine are made of steel, as opposed to the polyurethane bushings that are used for vehicle installation, to eliminate flexure.

3.4.4 Damper Test Procedure

Once the dampers are mounted in the MTS machine, a pre-defined routine was established to maintain consistency in the testing. Each MR damper was tested at electrical current settings of 0, 1.5 and 3 amps. As shown in Table 3.2, the test started at zero velocity and incrementally ramped up past 30 in/sec.

Table 3.2. Data Sheet for Magnetorheological Damper Testing

<table>
<thead>
<tr>
<th>Velocity (in/sec)</th>
<th>Force in Extension (lbf)</th>
<th>Force in Compression (lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 amps</td>
<td>1.5 amps</td>
</tr>
<tr>
<td>3.1</td>
<td>95</td>
<td>675</td>
</tr>
<tr>
<td>6.3</td>
<td>127</td>
<td>870</td>
</tr>
<tr>
<td>9.4</td>
<td>176</td>
<td>1000</td>
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<td>12.6</td>
<td>230</td>
<td>1135</td>
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<td>15.7</td>
<td>277</td>
<td>1270</td>
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<tr>
<td>18.8</td>
<td>353</td>
<td>1385</td>
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<td>22</td>
<td>446</td>
<td>1500</td>
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<td>25.1</td>
<td>545</td>
<td>1535</td>
</tr>
<tr>
<td>28.3</td>
<td>650</td>
<td>1425</td>
</tr>
<tr>
<td>31.4</td>
<td>745</td>
<td>1535</td>
</tr>
</tbody>
</table>
As the relative velocity across the damper changed from 0 to 31.4 in/sec, the MTS test machine’s load cell was used to acquire force data. As the force data was acquired, it was fed through an elliptic filter with a 15 Hz cutoff, before being displayed. The filter that was used is a Frequency Devices 9002, a low pass elliptic filter, shown in Figure 3.21.

![Elliptic Filter Used in Damper Testing](image)

**Figure 3.21. Elliptic Filter Used in Damper Testing**

Figure 3.22 shows the frequency response of this filter

![Frequency Response of Low Pass Elliptic Filter](image)

**Figure 3.22. Frequency Response of Low Pass Elliptic Filter**

The MTS test machine was programmed to move up and down in a sine wave at 10 Hz. The amplitude of the motion corresponds to the maximum velocity across the damper for each cycle. The resulting force is also sinusoidal, as is shown in Figure 3.23 for an excitation amplitude of .2 inches.
The fact that the maximum force will be due to, and occur at the same time as the maximum velocity was used to match the force and velocity data. For each excitation amplitude, and therefore for each velocity, both the positive and negative force peaks were recorded. This allowed both compression and extension damping to be tested simultaneously.

The MTS test machine’s controller, an MTS 458.20 shown in Figure 3.24, allowed the amplitude of the motion to be adjusted continuously, facilitating the damper tests.

Separate power supplies were used for each of the MR damper’s two coils during the test. The current into each coil was measured continuously during the tests. The power supplies used in the damper testing are shown in Figure 3.25.
The power supply on the top is a Sorenson Nobatron DCR40-10 supply, and the one on the bottom is a Lambda regulated power supply model LA100-03BM. The MR dampers were initially tested without any applied current. Current was then supplied to the coils and the dampers tested again. The current was tested at 0, 1.5, and 3 amps. The data was then converted from voltage to pounds force and plotted versus velocity. Ideally, the resulting plots should be as shown in Figure 3.26.
3.2.5 Damper Test Results

Six MR dampers were fabricated. All six of these dampers were tested at different current levels. The resulting force velocity curves were plotted along with the original Volvo VN heavy truck damper’s force velocity curve. The MR dampers that were fabricated are numbered one to six. Of the six dampers, the four that performed the best were used in the actual vehicle testing. The four best performing MR dampers were damper numbers one, two, four, and five. The force velocity curves for these four dampers are included in Figure 3.27. Note that the velocity across the damper is positive when the damper is in extension.

![Figure 3.27. Experimental Magnetorheological Damper Force Velocity Curves](image-url)
The plots in Figure 3.27 were created using a MATLAB .m file, which is listen in Appendix 1a.

The plots of MR dampers indicate that the high level of damping resulting from an applied current of three amps is greater than that of the original damper. They also show that the low state corresponding to zero applied current is lower than the original damper. In order for the MR dampers to successfully replace the original dampers, it was necessary that the MR damping range extend above and below the original dampers’ force velocity curve, as shown in Figure 3.27.