Temperature Effect Analysis on Magneto-Rheological Damper's Performance

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***Abstract*—Magnetorheological (MR) damper is one of the most advanced applications of semi active damper in controlling vibration. Its use is increasing day by day in the vehicle suspension system due to its continuous controllability in both on and off state. MR damper's damping force can be controlled by changing the viscosity of its internal magnetorheological fluids (MRF). Applying an external magnetic field viscosity of MRF can be controlled. Electromagnet such as solenoid coil is normally used as external magnetic field source. These coils are attached inside the damper's piston head. When the damper operates these coils create heat. That's why the conventional MR dampers normally face wide variations in temperature. This change of temperature results decay in MRF viscosity as well as post-yield damping of the damper. In this paper temperature effect on MR fluids viscosity and on MR dampers performance represented analytically and experimentally. Due to this temperature effect the deviation of MR dampers performance has shown here experimentally. Also a novel technique for solving the problem explained clearly.**

***Index Terms*—magnetorheological damper, semi active suspension, temperature effect, viscosity**

I. Introduction

Suspension system becomes a very famous topic among researchers in recent years. Since there are many opportunities to improve the suspension system and this is directly proportional to ride comfort, researchers are very keen to work on vehicle suspension systems. Suspension system keeps the contact between tires and road surfaces all the time. This specification is important when vehicle is turning, braking or accelerating. To conclude, a vehicle suspension provide passenger comfort and stability of the vehicle. The typical suspension units are paced at the vehicle corners and connected to the vehicle wheels via a link. Spring and damper are the basic elements of each suspension unit which are set parallel. Normally these dampers are passive dampers. Passive dampers design and construction is unchangeable after installation. Due to overcoming these limitations active and semi-active dampers are now being focused. Moreover semi-active dampers performs continuously even in the time of control failure. Magnetorheological (MR) fluid damper is a very good choice as a semi-active device. It has many advantages such as high viscosity control range, comparatively low cost, low power consumption and quick response, small size etc. In these devices magnetorheological fluid is used. After applying a magnetic field the fluid changes its viscosity very quickly. It seems that this liquid becomes semi-solid in few milliseconds, which results an infinitely variable, controllable damper capable of large damping forces. Normally electromagnets such as coils or solenoids are the source of applied magnetic field. Continuous operation this coils produce heat which causes an increase in temperature of the MR fluids as well as dampers body. Viscosity and volume of a fluid is closely related to the temperature, here in case of MR fluids the viscosity decreases due to temperature rise. As the MR dampers damping force is directly related to MR fluids viscosity, so the dampers performance also affected, such as post-yield damping decreases. The gas of the accumulator also heated, which causes extra proliferation of damper's stiffness. Many researches have been conducted in controlling the MR damper. But only limited analytical and experimental studies accomplished on thermal effects on the performance of the MR dampers. In this field, Alonso and Comas [1] projected an analytical method where he shows thermal effects and also fluid compressibility, chamber deformation etc. L. He and G.T. Zheng [2] considered the interaction between viscous heating and also analyzed viscous heating effect in vibration control application both in time and frequency domain. Darrell G. Breese and F. Gordaninejad [3] developed a theoretical model which shows the effect of temperature changes on Magnetorheological Fluid Dampers when experiencing sinusoidal input motion. They also showed for heat generation or dissipation within the damper how the models internal parameters affected. After one year Darrell G. Breese, F. Gordaninejad and Everet O.

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Ericksen [4] developed a theoretical model based on Bingham plastic model for estimating total temperature effect on MR dampers. The governing equation showed MR fluid viscosity as a function of temperature. They also compared the analytical solutions with experimental results and found an excellent agreement. Ismail Sahin, Sevki Cesmeci, Nicholas L. Wilson and Norman M. Wereley [5] tried to illustrate the temperature dependent behavior of an MR damper. They also observed the changed of Bouc-Wen model parameters due to temperature changes within MR damper. However, they concluded that as Bouc-Wen model was not a useful tool to understand the temperature dependency of the damper. Kasemi, B., Muthalif, A. G. a., Rashid, M. M., & Fathima [6] designed a controller for experimentally developed MR damper. In their experiment they also faced deviation in the results due to the heating of the MR damper.

In this study analytical and experimental effects of temperature on MR dampers performance and a new technique for minimizing the effect has been explained. As a solution to the problem recently some researchers has given some solutions. Holger Bose and J. Ehrlich [7] developed magnetorheological Dampers with hybrid magnetic Circuits. He designed three different hybrid magnetic circuits and analyzed new damper's performance. He got better result than the performance of conventional MR damper, the dynamic range of the damper decreased. In this study a new technique has explained. Normally the coil attached in piston head, but here the coil is not attached inside the damper. The MR damper is surrounded by the coil and directly not touched with the dampers body. And its effect on MR dampers performance has shown experimentally.

II. Effect of Temperature on Mr Fluid's Viscosity

Viscosity is one of the most important physical properties of a fluid system. Change in shear rate, temperature, pressure, moisture, or concentration of any fluids may change its viscosity; all these changes can be modeled by equations. The relation between viscosity and temperature can be expressed by Arrhenius equation stated below

$$\upsilon = Ae^{\frac{E_a}{RT}} \tag{1}$$

where dynamic viscosity is denoted by υ ; Pre-exponential factor is denoted by A; exponential constant is denoted by E_a , it is called as activation energy (J/mol); R is gas constant where its unit is (J/mol/K), T is the absolute temperature which is expressed by Kelvin (K). The value of A can be considered as the infinite-temperature viscosity (υ_∞), then equation (1) can be written as follow

$$\upsilon = \upsilon_\infty e^{\frac{E_a}{RT}} \tag{2}$$

Generally the relation between natural logarithmic viscosity and shared value of the temperature is proportional. To make the equation more accurate two constants namely *c* and *d* are presented into the following equation as

$$\ln(\upsilon) + c = \frac{d}{T} \tag{3}$$

From the experimental data if a viscosity VS temperature graph is plotted, it shows that viscosity decreases with increasing temperature and vice versa. So temperature is approximately infinity when $\upsilon \approx \upsilon_{T_\infty}$ and at initial temperature (T_o) $\upsilon \approx \upsilon_{T_0}$, where initial viscosity is comparatively larger. Equation 3 can be rearranged as

$$\upsilon = \upsilon_{T_\infty} (\frac{\upsilon_{T_O}}{\upsilon_{T_\infty}})^{\frac{T_O}{T_\infty}} \tag{4}$$

By comparing equation (2) and (4) E_a can be obtained as follows

$$E_a = T_0 R \ln(\frac{\upsilon_{T_0}}{\upsilon_{T_\infty}}) \tag{5}$$

where R = 8.314 *J/ mol /K*.

Applying natural logarithm on both sides of equation (4) it can be linearized as

$$\ln(\upsilon) = \ln(\upsilon_{T_\infty}) + \frac{T_o}{T} \ln(\frac{\upsilon_{T_\infty}}{\upsilon_{T_0}}) \tag{6}$$

Solution of equation (6) got by plotting the logarithmic value of viscosity and temperature. The value of viscosity for the six temperature points from 323K to 373K at 600 rpm for MR fluid from Lord Corporation MRF-132DG and a prototype MR fluid is plotted. This prototype MR fluid is a combination of Carbonyl Iron power, xanthan gum and silicon oil. These two fluids were fitted with equation (6) where the curves are drawn by Microsoft Excel spread sheet 2010. Viscosity for initial or zero and final i.e. infinite temperature and the R^2 value were also projected. The viscosity was measured by rotational rheometer (MCR300, Physica, Stuttgart, Germany).

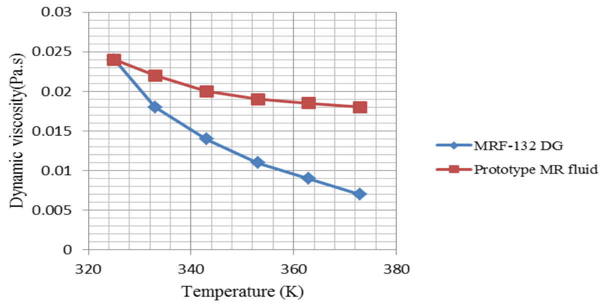


Figure 1. Temperature viscosity relationship comparison of two Magnetorheological Fluids from experimental result.

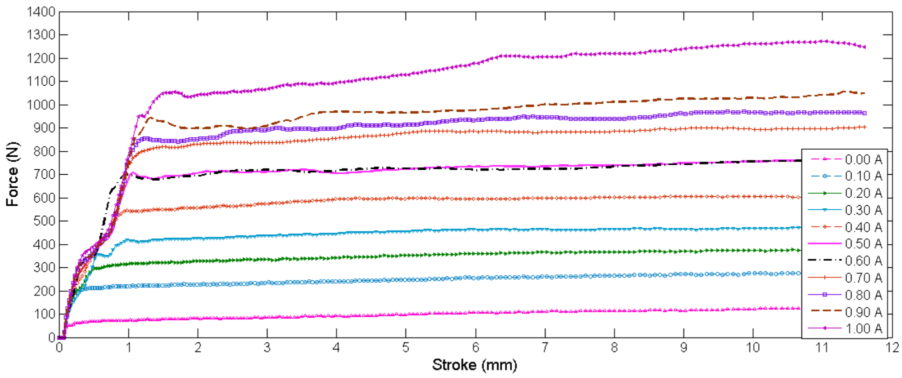
From Fig. 1 it is clear that the change of viscosity for the prototype MR damper is slower than the commercial

MR fluid from Lord Corporation. It's mainly because of sedimentation problem. Sedimentation has a proportional relation with temperature and inversely proportional relation with viscosity. In the MRF-132 sedimentation problem exists whereas in the prototype MR fluids, sedimentation has improved experimentally. So a comparatively rapid change has observed in MRF-132DG.

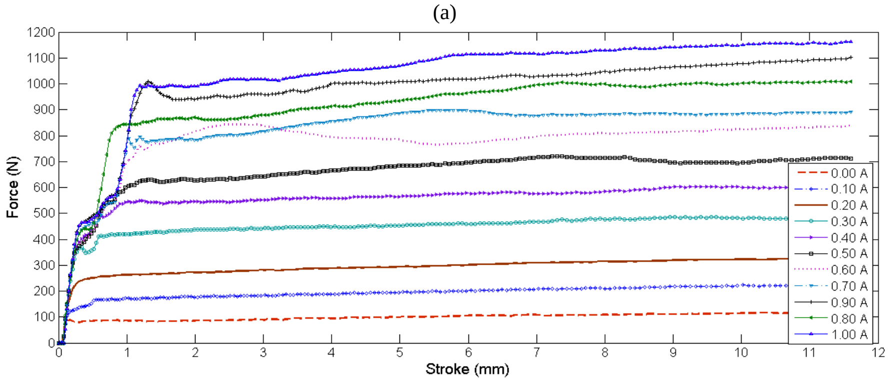
III. Temperature Effect on Mr Dampers Performance and Experimental Results

It is clearly understand that as the viscosity of the MR fluids changes with temperature, so it also affects the dampers performance. In experiment MR damper from Lord Corporation was used. It observed that at the beginning of the day, the data is not the same as that obtained at the end of work due to the temperature effect and also due to the distribution of the iron particles inside the fluid. For this reason, this experiment has been tedious, as most of the time was spent in addressing the temperature changes. When current increases, the outer temperature of the surface of the damper cylinder also increases, which is intuitive, as it requires more energy to break the magnetic flux linkage area between the particles and the coils. When it is more than 1.2 Amperes, and the piston velocity is high, temperature goes high as well. In the manufacturer's manual it is mentioned that 1 Ampere current cannot be supplied, continuously, for more than 30 seconds. This is the reason why the current has been varied from 0 Ampere to 1.0 Ampere for measuring MR dampers performance experimentally.

Fig. 2 shows the force response of the MR damper for both upward and downward modes and for different current, in mid stroke positions, at a fixed piston velocity of 500 mm/minute [8]. From these figures it is clear that the relation between force and field strength is proportional. The force is the smallest when the damper is in off-state (without field). The force in downward motion mode reaches the steady region when the piston stroke is in the 3~5 mm range, while for upward motion mode, the stroke range is 1.5~1.8 mm.



(a)



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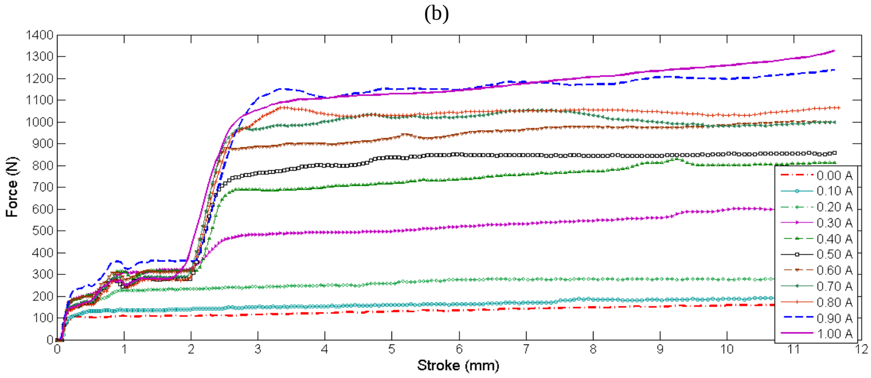
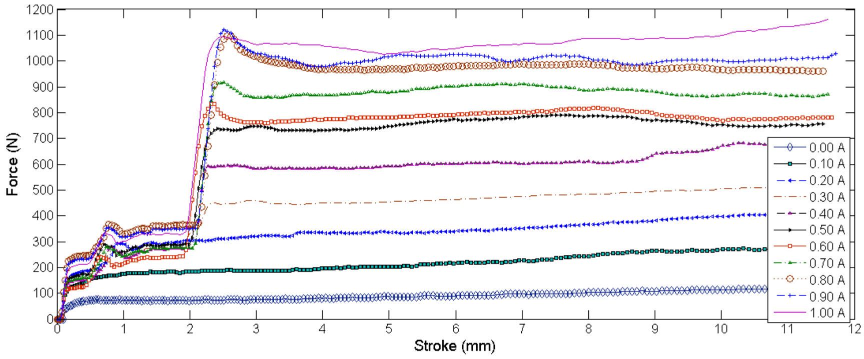


(c)



(d)

Figure 2. Experimental results of variation of force for (a) Upward motion mode at mid stroke position based on initial data (b) Upward motion mode at mid stroke position based on end data (c) Downward motion mode at mid stroke position based on initial data (d) Downward motion mode at mid stroke position based on end data [8].

By observing Fig. 2 it is clear that for the same mode and stroke position the results are different at the starting and end of the experiment. This deviation occurs at both upward and downward mode. After long time operation at the end of the day, force decreased for the same mode and position of the damper. It is due to the heating of the damper.

IV. Design of New Technique for Reducing Heat in MR Damper

For reducing the heat generation and energy consumption in MR dampers many researchers have done many analyses. The concept of Hybrid magnetic circuit is a new one where one of the Hybrid circuit is a combination of Permanent magnet (AlNiCo) and additional coil. In another approach as a permanent combination of hard magnetic NdFeB or SmCo2 and low coercive AlNiCo is used, besides as electromagnet coil or solenoid is used. Hard permanent magnets create a base magnetic field strength in the MR gap of the damper and the corresponding damping force. In case of combination of AlNiCo magnet and coil, magnetization is controlled by the current in those coils; so this base magnetic field strength may be increased or decreased, which depends upon two factors, one is the polarity of the AlNiCo magnetization and another is amount of current passes through the coils. In this kind of design heat generation is little bit reduced, but the dynamic range decrease, which affects the dampers performance. So here a new technique explained here. A coil or solenoid is designed here as electromagnet. Instead of placing it in inside damper's piston head, it is surrounded by dampers body, but there's a gap near 1mm between the damper's outer surface and solenoid. In this there are some big challenges such as optimization of the weight of the solenoid, size of the damper, getting maximum magnetic flux. After trying for several times by trial and error the optimum design is obtained.

The formula for calculating magnetic field (B) inside the solenoid is given by

$$B = \frac{\mu_o NI}{L} \qquad (7)$$

where μ_0 is the permeability in free space has a value equals to $4\pi\ X10^{-7}\ H/m$, N is number of turns, I is the current passes through the coils and L is the total length of the coil. The unit of the induced magnetic field is Tesla (T). From equation (7) it is clear that there's a proportional relation between the magnetic field and the number of turns. So the strength of the magnetic field increases as number of turns increase and vice versa.

Fig. 3 shows how Magnetic field strength changes with numbers of turns of coil in our solenoid design. Here it is clear that it satisfies equation (7). In designing the solenoid, the induced magnetic field strength was tested for different number of turns which is shown in Fig. 3.

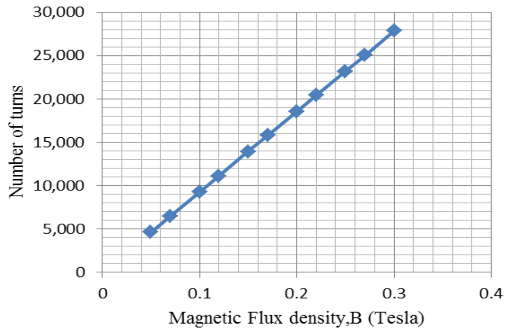


Figure 3. Relation between Total Number of Turns (N) and induced magnetic field strength

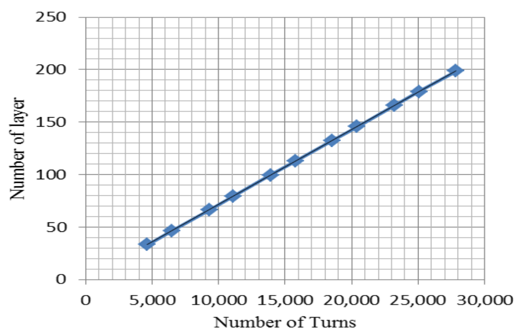


Figure 4. Relation between Total Number of Turns (N) and Number of layers.

The length of the solenoid was fixed in the total design. So relation between numbers of turns and layers is proportional. This relation is shown in Fig. 4. As the length is constant, so thickness is increased with increased number of layers. Fig. 5 showing this relation.

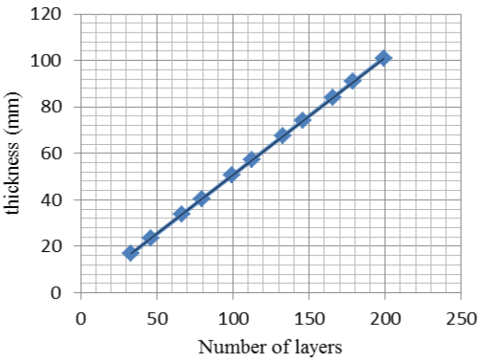


Figure 5. Relation between Number of layers and thickness of the Solenoid

V. CONCLUSION

Magnetorheological dampers face changing of temperature due to generation of heat in coils attached in the piston head. Fluid viscosity has a direct relation with temperature, so the MRF viscosity is affected which is shown both theoretically and experimentally in this paper. As the MR dampers performance is related the MRF viscosity so the dampers performance is also affected. This is the reason for deviation of results for same experiment which is also presented in this paper. For solving the heat production problem a new design technique is introduced. In this technique the position of the electromagnet has changed and for getting the optimum field strength the relation between different design parameters presented here.

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