DESIGN AND OPTIMIZATION OF INNOVATIVE MAGNETORHEOLOGICAL DAMPER WITH LOW TEMPERATURE

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I dedicate this thesis to my lovely family, who offered me unconditional love and support throughout the course of this thesis.

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ABSTRACT

Magnetorheological (MR) damper is a controllable shock absorber that can be applied in semi-active suspension systems. Recently, many researchers have utilized this appliance in vast applications. However, there are only a few published works on analysis and performance enhancement of the MR fluids and dampers in terms of controlling their temperature. In this research, a novel MR damper with low temperature property was proposed in which a new wiring arrangement is utilized for the electromagnetic coil in order to achieve higher performance in comparison to conventional MR dampers. A finite element method was used to demonstrate the performance enhancement of the new MR damper using Ansoft Maxwell software. A dynamic test was carried out to realize the dynamic characteristics of the new MR damper and its temperature was experimentally obtained by using thermal camera FLIR i7. The experimental result showed that the amount of input current can be raised up to 9A. Furthermore, the MR damper can withstand high input current for a long time by using the cooling system. Another experimental study was performed to compare the thermal properties of the new and conventional MR dampers and numerically characterised the dynamic behaviour of the conventional MR damper by using adaptive network-based fuzzy inference system (ANFIS). The experimental result showed that after an hour, the new MR damper had a stable temperature of 35.3ºC while the conventional MR dampers reached more than 63ºC. ANFIS modelling result illustrated the distinct influence of input current, piston displacement and velocity on the damping force. A fuzzy-PID controller was applied in a quarter-car suspension system by using the constructed ANFIS model. The simulation result demonstrated the capability of fuzzy-PID controller in improving the performance of PID controller by 69.6%. An accurate model of the MR damper can enhance the performance of the control strategy.

ABSTRAK

Peredam magnet-reologi (MR) ialah penyerap hentakan terkawal yang boleh digunakan dalam sistem suspensi semi-aktif. Kebelakangan ini, ramai penyelidik telah menggunakan aplikasi ini dalam pelbagai bidang. Namun, kertas kerja penyelidikan sangat terhad berkaitan analisis dan peningkatan prestasi cecair dan peredam MR dari segi kawalan suhu. Dalam kajian ini, peredam MR bersuhu rendah telah dicadangkan dengan susunan pendawaian baru untuk gegelung elektromagnet bagi mencapai prestasi yang lebih baik berbanding peredam MR konvensional. Kaedah elemen terhad digunakan bagi menggambarkan peningkatan prestasi peredam MR yang baru dengan menggunakan perisian simulasi Ansoft Maxwell. Ujian dinamik dijalankan untuk mendapatkan ciri-ciri dinamik peredam MR yang dicadangkan dan suhu yang terhasil diperolehi dengan menggunakan kamera haba FLIR i7. Hasil eksperimen menunjukkan bahawa jumlah arus masukan boleh dinaikkan sehingga 9A. Sebagai tambahan, peredam MR boleh bertahan dengan arus masukan yang tinggi untuk jangka masa yang panjang dengan menggunakan sistem penyejukan ini. Satu lagi kajian dilakukan untuk membandingkan sifat haba bagi peredam MR yang baru dengan peredam konvensional dan secara numerik telah mencirikan tingkah laku dinamik bagi peredam MR konvensional dengan menggunakan model *Adaptive Network-based Fuzzy Inferences System* (ANFIS). Hasil eksperimen menunjukkan bahawa selepas satu jam, MR peredam baru mempunyai suhu yang stabil pada 35.3ºC manakala peredam MR konvensional mencapai suhu melebihi 63ºC. Hasil pemodelan ANFIS menggambarkan pengaruh yang berbeza bagi setiap arus masukan, anjakan omboh dan halaju pada daya redaman. Pengawal fuzzy-PID diaplikasikan dalam sistem suspensi kereta seperempat dengan menggunakan model ANFIS yang dibina. Hasil simulasi menunjukkan keupayaan pengawal fuzzy-PID dalam meningkatkan prestasi PID kawalan kepada 69.6%. Model yang tepat bagi peredam MR boleh meningkatkan prestasi strategi kawalan.

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α	-	Winding coil aspect ratio
B	-	Magnetic flux density
β	-	L_1/L_{c1}
χ	-	L_2/L_{c1}
δ	-	L_3/L_{c2}
$\dot{\gamma}$	-	Shear rates
F_η	-	Passive (off-state) damping force
F_τ	-	Active (on-state) damping force
h	-	Mixed-mode gap thickness
L_1	-	Upper piston boundary length
L_2	-	Lower piston boundary length
L_3	-	Radial piston boundary thickness
L_{c1}	-	Coil length
L_{c2}	-	Coil width
L_a	-	Effect length of mixed-mode gap area
R	-	Inner piston radius
R_p	-	Piston radius
τ_0 / τ_y	-	Yield Stress
τ	-	Shear stress
μ_{po}	-	Post-yield viscosity
μ_{pr}	-	Pre-yield viscosity
W	-	Width of mixed-mode gap area

CHAPTER 1

INTRODUCTION

1.1 Background

Magnetorheological (MR) damper is a kind of controllable shock absorbers whose characteristics can be changed by altering the amount of exerted input current. The capability of a MR damper as a semi-active system to produce high force capacity and wide dynamic range attracted researchers to focus more on MR dampers. Some comprehensive reviews have considered a wide variety of studies involving MR dampers: design and modelling for a rotary MR damper (Imaduddin et al., 2013a), structure design and analysis (Zhu et al., 2012), state of the art of structural control (Spencer & Nagarajaiah 2003) and parametric modelling (Wang and Liao, 2011). Fig. 1.1 shows a schematic of an MR damper and its components.

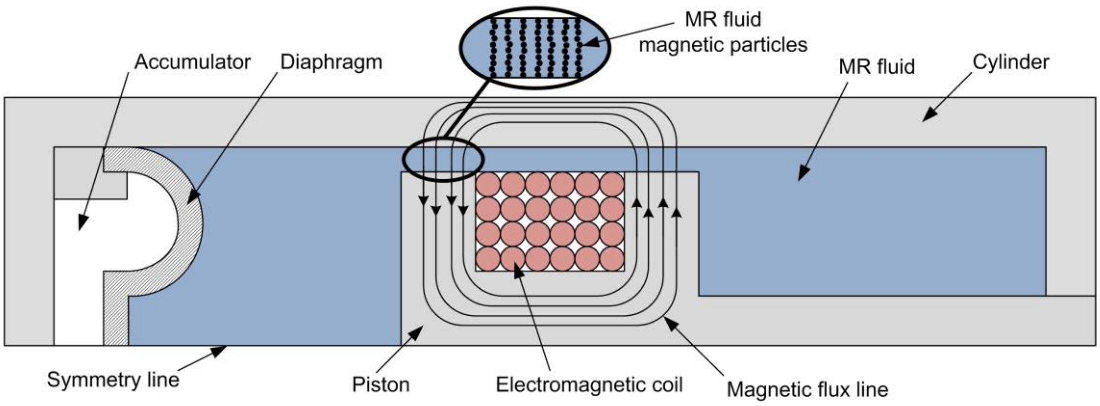

Figure 1.1 Schematic of an MR damper with an accumulator

The MR fluid provided in MR damper has micron size magnetic particles. These magnetic particles are capable to change the characteristics of MR fluid when the magnetic field is applied to the fluid. The applied input current produces a magnetic flux in which the flux lines are perpendicular to the MR fluid flow. The produced magnetic field influences MR fluid magnetic particles arrangement to increase the MR fluid viscosity in terms of magnetic flux density (the magnified ellipse in fig. 1.1). This phenomenon generates a complex relation between the effective input parameters such as piston displacement, which represents the behaviour of the accumulator as a spring, velocity, which corresponds to the damping behaviour of the MR damper, and input current.

1.2 Motivation of Study

According to Chae et al. (2013) and Ding et al. (2013), undesired movement or disturbance is a major portion of researches which needs to be eliminated from the system. Suspension system is a device to reduce or eliminate the effect of disturbances on specified target. Controllability of the suspension system is a key parameter in enhancing the performance of the system. Thus, an appropriate controllable shock absorber needs to be utilized in the suspension system. An MR damper is a promising appliance for semi-active suspension systems, due to its capability of damping undesired movement using an adequate control strategy.

In the MR fluids, numerous internal and external forces are affecting on magnetic particles; Van Der Waals (Ebner et al., 2000), repulsive (Melle et al., 2002), Brownian (Kim, 2004), viscous, magnetic (Liu et al., 2012), gravitational and buoyant forces. The effect of these forces on magnetic particles is studied in particle dynamics criteria (Han et al., 2010; Liu et al., 2012; Ly et al., 1999). The presence of the magnetic particle among carrier fluid causes to increase the amount of friction and consequently increase the temperature of MR fluid. Therefore, the main sources of heat generation in MR fluid are amongst the particle-particle and particle-fluid interactions.

The temperature analysis of the conventional MR fluid illustrates that the increase of temperature causes to reduce the viscosity of the MR fluid and its performance as well (Dogruoz et al., 2003; Gordaninejad and Breese, 1999; Susan-Resiga, 2009). There are few studies related to heat transfer and the effects of temperature changes in MR damper behaviour and performance (Breese and Gordaninejad, 1999; Dogruoz et al., 2003; Gordaninejad and Breese, 1999). Breese & Gordaninejad (1999) conducted a theoretical study on heating of MR fluid damper and proposed a theoretical model to estimate the temperature rise of the MR damper during a sinusoidal piston movement. In another study, they performed an experimentally study and investigated the effects of temperature increase on damping force capacity in different input currents and sinusoidal movement frequencies (Gordaninejad and Breese, 1999). The results showed that the force, or peak force, is related to the temperature of the MR damper. Time is another considerable parameter that affects the MR damper's performance. In continuous duty, the temperature is increased until achieving a saturating temperature. Higher input current, which produces higher magnetic field and consequently damping force, causes the temperature rise of MR damper. Kordonsky et al. (1993) experimentally investigated the magnetic field influence on the thermal developments in MR suspensions. Zheng et al. (2014) showed that the majority of the temperature rise is caused by the friction inside the MR damper rather than the electromagnetic coil (wires). In another study, Wilson et al. (2013) obtained the temperature of the MR fluid with respect to time for a continuous duty of 15min. As seen in fig. 1.2, they showed that the linear MR damper temperature is raised up to 100ºC in few minutes (around 16min for 0A and around 3min for 2.5A).

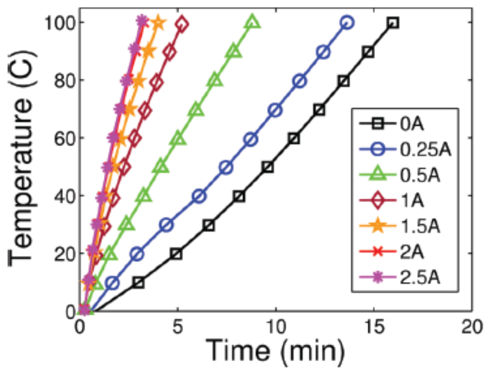

Figure 1.2 Temperature vs. time in continuous duty (Wilson et al., 2013)

Dogruoz et al. (2003) utilized fins in order to enhance heat transfer of fail-safe MR damper. The results, experimental and theoretical, showed that the use of fins has successfully enhanced the heat transfer of MR damper. In addition, they proposed a theoretical model to describe the relationship between temperature and the characteristics of MR damper and its wiring system. The proposed relationship has governed from energy equation which is as,

$$\dot{Q} - \dot{W} = \frac{dU}{dt} \tag{1.1}$$

where $\dot{Q}$, $\dot{W}$, and $\frac{dU}{dt}$ are the rates of heat transfer, work and internal energy change of the MR damper, as a closed system with consistent boundaries, respectively. Hence, the relationship can be defined as (Dogruoz et al., 2003),

$$\left[F\dot{x}(t)\operatorname{sgn}(\dot{x}(t)) + I^2R\right] - hA_s\left(T(t) - T_{amb}\right) = \sum_n mc_p \frac{dT}{dt} \tag{1.2}$$

where $\dot{x}(t)$ is piston velocity, I and R are exerted input current and resistance of winding coil, h and A_s are heat transfer coefficient and surface area of MR damper and $T(t)$ and T_{amb} are the damper transient temperature and ambient temperature, respectively. $\sum_n mc_p$ is the accumulated heat capacity of the MR damper elements consisting piston, cylinder, MR fluid, etc. A numerical method, e.g. Runge-Kutta, needs to be utilized to solve the above equation.

All presented studies focused on describing the behaviour of MR fluid with respect to temperature changes (Breese and Gordaninejad, 1999; Dogruoz et al., 2003; Gordaninejad and Breese, 1999; Susan-Resiga, 2009). Among all researches, Dogruoz et al. (2003) endeavoured to reduce the temperature of MR fluid by using fins. They successfully reduced the temperature of the system by using the fans around the cylinder (see fig. 1.3). Thus, the heat generated by MR fluid is emitted to the air. However, the main issue is that the winding coil which is bounded by the MR fluid has a heat concentration. This heat generates from both wire resistance and MR fluid. Therefore, this research has motivated a new design of MR damper in which a cooling system is utilized to create a new heat transfer method in order to control the temperature of both MR fluid and winding coil. In the proposed method, an air circuit is utilized to transfer the heat from winding wire and MR fluid to the cooling system. The MR damper is expected to outperform the conventional MR dampers in terms of damping force capacity and durability.

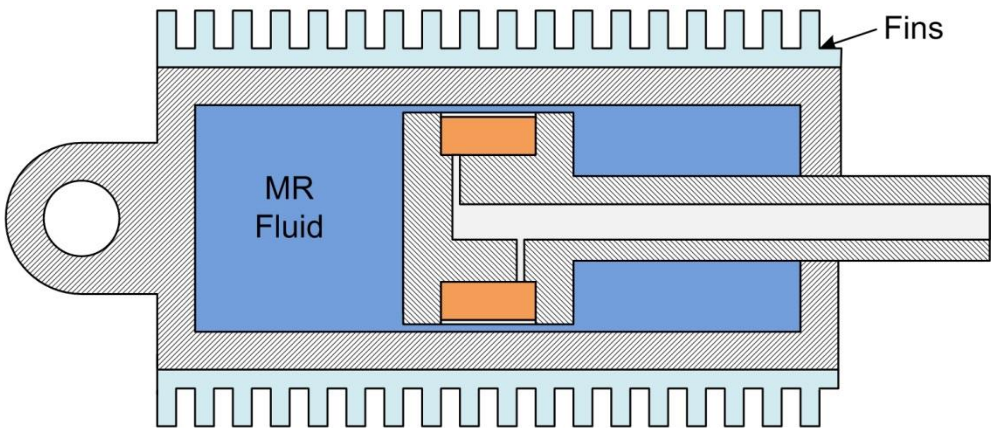

Figure 1.3 The heat transfer mechanisms proposed by Dogruoz et al. (2003)

1.3 Objectives

The objectives of the current research are as follows:

- To develop a new concept of high current MR damper with low temperature property.
- To characterise the new MR damper by utilizing a finite element method and experimentally evaluate its performance.
- To experimentally compare the thermal properties of new and conventional MR dampers and numerically characterise the dynamic behaviour of the conventional MR dampers.

1.4 Scope

An investigation of a novel concept of MR damper with low temperature property is carried out. The research focused on the introduction of a new wiring arrangement and cooling system in MR damper in order to control the temperature of carrier fluid and wiring system. MR fluid MRF-132DG is used as the carrier fluid. The performance of the new MR damper is numerically and experimentally analysed. A 2D simulation study is carried out to investigate the performance of the MR damper in terms of magnetic flux density. The effects of piston radius, coil dimension and coil boundary lengths on MR damper performance is numerically investigated.

Another aspect of the study is to compare the thermal properties of the new MR damper to the conventional one. The temperature of both MR dampers is experimentally obtained for a continuous duty of an hour. The dynamic behaviour of the conventional MR dampers is characterised by using an intelligent approach. This model is validated by experimental results. The proposed model is a combination of artificial neural network and fuzzy logic approaches and able to accurately predict the phenomenon in specific inputs interval. The inverse model of the MR damper is constructed on the basis of experimental result. The aim of constructing inverse model is to produce an appropriate input of the MR damper model with respect to the controller decision. An intelligent controller is utilized to evaluate the influence of the MR damper model on the MR damper's performance. The controller is employed on a quarter-car suspension system.

1.5 Thesis Outline

The thesis consists of five chapters which are introduction, literature review, methodology, results and discussions, and conclusions. In the first chapter, an introduction of the study is presented and the objectives and scope of the research are proposed. Second chapter deals with the literature of the MR damper structure design, modelling, control, and applications in numerous criteria. The methodology of this work is presented in chapter three. The results of the research are provided in fourth chapter. Last chapter has summarized the conclusions of this research.

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