Reducing Noise and Vibration of Hydraulic Hybrid And Plug-In Hybrid Electric Vehicles

Phase III Final Report

By

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Abstract

The University of Toledo University Transportation Center (UT-UTC) has identified hybrid vehicles as one of the three areas of the research. The activities proposed in this research proposal are directed towards the noise, vibration, and harshness (NVH) solutions for hybrid vehicles. The soaring fuel prices require imperious steps in developing alternate propulsion technologies. The design and development of hybrid vehicles is a critical issue for an economy dependent on an efficient, fast, and secure transportation system. To date, better fuel economy has been mainly achieved by combining two propulsion sources (hybridization) and/or by developing better managing algorithms for the internal combustion engines. Examples for the hybridization are the plug-in hybrid electric and the hydraulic-hybrid vehicles. An example of managing internal combustion engines is the cylinder on demand as a solution that Honda has recently introduced. One common problem with these solutions is excessive noise and vibration that is caused by switching between the propulsion sources and propulsion modes. To mitigate this problem there is a need to develop vibration isolation devices that can provide isolation over a wide range of frequencies. This proposal seeks to study the NVH problem of the hybrid vehicles and to introduce isolation mounts to overcome these issues.

Hydraulic and elastomeric mounts are generally used to dynamically isolate engines and power trains from the chassis, while statically holding these elements together. Hydraulic mounts overcome some of the drawbacks of the elastomeric mounts. The stiffness and damping of the hydraulic mounts varies with frequency and amplitude of vibration. It is possible to design a hydraulic mount that has a significantly larger static stiffness, compared to an elastomeric mount, and has a much smaller dynamic stiffness at a specific frequency. To achieve low vibration transmissibility, the mount can be tuned to the primary frequency of the vibration source. On the other hand, to isolate the high frequency vibration of the engine, the mount should have low stiffness and low damping, which is not possible to achieve.

This project proposes to develop a semi-active mount, which will be realized by improving the existing hydraulic mounts through adding a magnetorheological (MR) fluid element. In response to magnetic fields, MR fluids change their viscosity, which can be harnessed in a variable stiffness and damping mount. The resulting mount will provide shock and vibration isolation over a wide range of frequencies. This extended isolation frequency range will be achieved through the variable dynamic stiffness of the MR portion of the mount. This solution will make it possible to improve the noise and vibration characteristic of hybrid vehicles with alternative propulsion systems. The focus of phase 3 of the project is to design a control system for the mount and to evaluate this control system in a simulation environment. This objective is realized as summarized in this final report.

Technical Approach or Methodology

It is proposed to develop an MR fluid based semi-active mount by modifying the existing hydraulic mounts. In this design, the existing mount will be modified to adapt the MR fluid technology in the hydraulic part of the mount. Specifically, the hydraulic fluid will be substituted with MR fluid and a coil will be added to provide the magnetic field required to excite the fluid. The research activities for the first three phases of the grant are the following.

Stage 1:

Perform sensitivity analysis Design the mount based on sensitivity analysis
Developing a mathematical model for the MR mount

Stage 2:

Implementing the MR fluid behavior model
Simulate the semi-active mount
Correlating with hydraulic mount data

Stage 3:

Design a control algorithm based on the mathematical model and simulation results

Publications

The following is the list of publications, which resulted by the end of the last three phases of the project:

Journal papers:

1. Nguyen, T. M. and Elahinia, M. H., "Vibration Isolation for Hydraulic Hybrid Vehicles," Journal of Shock and Vibration, February 2008, 15(2):193-204.
2. Nguyen, T. M., Ciocanel, C., and Elahinia, M. H., "A squeeze-flow mode magnetorheological mount: design, modeling, and experimental evaluation," Journal of Vibration & Acoustics – Transactions of the ASME, accepted for publication.
3. Wang, S., Elahinia, M., and Nguyen, T., " Displacement and Force Control with a Mixed Mode MR Mount", Journal of Shock and Vibration, in review.

Conference papers:

1. Nguyen, T. M. and Elahinia, M. H., "A Magnetorheological Vibration Isolator for Hydraulic Hybrid Vehicles," ASME International Mechanical Engineering Congress, November 5-11, 2005, Orlando, Florida.
2. Nguyen, T. M. Elahinia, M. H. and Olson, W., "6-DOF Magnetorheological Vibration Isolation System for Hydraulic Hybrid Vehicles," 9th International Conference on Mechatronics Technology, December 5-8, 2005 Kuala Lumpur, Malaysia.
3. Nguyen, T. M. and Elahinia, M. "A 6-DOF vibration isolation system for Hydraulic Hybrid Vehicles," 2006 SPIE Smart Structures and Materials, March, 6-10, 2006, San Diego, California.

4. Elahinia, M. H. Olson, W. Nguyen, T. M. and Fontaine, P. "Chassis Vibration Control for Hydraulic Hybrid Vehicles," SAE 2006 Automotive Dynamics Stability and Controls Conference and Exhibition, February 14-16, 2006, Novi, Michigan.
5. Ciocanel, C., Nguyen, T. Elahinia, M. and Naganathan, N., "Squeeze Flow Mode Magnetorheological Fluid Damper - Design and Control," The 10th International Conference on Electrorheological (ER) Fluids and Magnetorheological (MR) Suspensions, June 18-22, 2006, Lake Tahoe, USA.
6. Nguyen, T., and Elahinia, M., "Nonlinear Control of a Magnetorheological (MR) Mount for Hydraulic Hybrid Vehicles," Eleventh Conference on Nonlinear Vibrations, Stability, and Dynamics of Structures, August, 13-17, 2006, Blacksburg, Virginia.
7. Nguyen, T., and Elahinia, M., "Vibration Isolation Control for Hydraulic Hybrid Vehicles," ASME International Mechanical Engineering Congress, November 5-10, 2006, Chicago, Illinois.
8. Ciocanel, C., Nguyen, T., Elahinia, M. and Naganathan, N. G., "On the Design of a Combined Squeeze-Flow Mode Magnetorheological Fluid Mount," SPIE Smart Structures and Materials, March 14-22, 2007, San Diego, California.
9. Mohaghegh Motlagh, A., Elahinia, M. H., Abuhaiba, M., and Olson, W., "Application of Smart Materials for Noise and Vibration of Hydraulic Systems," ASME DETC/CIE, September 4-7, 2007, Las Vegas, Nevada.
10. Nguyen, T., Ciocanel, C. Schroeder, C. and Elahinia M., "On the Design and Control of a Squeeze-Flow Mode Magnetorheological Fluid Mount," ASME DETC/CIE, September 4-7, 2007, Las Vegas, Nevada.
11. Nguyen, T., Ciocanel, C., and Elahinia M., "Performance of an Adaptive Magnetorheological Fluid Mount," ASME International Mechanical Engineering Congress, November 11-15, 2007, Seattle, Washington.
12. Nguyen, T. M., Ciocanel, C., Schroeder, C., and Elahinia, M. H., "Performance of a Mixed Mode MR Mount," 10th Cansmart Meeting International Workshop on Smart Materials and Structures, October 10-11, 2007, Montreal, Quebec, Canada.
13. Ciocanel, C., Nguyen, T., and Elahinia, M., "Design and modeling of a mixed mode magnetorheological (MR) fluid mount," SPIE Smart Structures and Materials, March 9-13, 2008, San Diego, California.
14. Ciocanel, C., Nguyen, T., M., Schroeder, C., and Elahinia, M. H., "Performance evaluation of a semi-active magnetorheological mount," SAE 2008 World Congress, April 14-17, 2008, Detroit, Michigan
15. Ciocanel, C., Nguyen, T., M., and Elahinia, M. H., "An Adaptive Magneto-hydraulic Vibration Isolator," 3rd International Conference, Advanced Concepts in Mechanical Engineering, Iaşi, Romania, 5 - 6 June 2008.
16. Nguyen, T., Ciocanel, C. and Elahinia M., "Parameter optimization in designing an MR mount," 15th International Congress on Sound and Vibration, 6-10 July 2008, Daejeon, Korea
17. Nguyen, T., Ciocanel, C. and Elahinia, M. H., "Theoretical and experimental development of a semi-active mount," ASME International Mechanical Engineering Congress, October 31 - November 6, 2008, Boston, Massachusetts.

18. Mohaghegh Motlagh, A., and Elahinia, M. H., “Research Simulation of a Series Hydraulic Hybrid Vehicle to Study Noise and Vibration,” ASME International Mechanical Engineering Congress, October 31 - November 6, 2008, Boston, Massachusetts.
19. Nguyen, T. M., Ciocanel, C. and Elahinia, M., “Analytical modeling and experimental validation of a magnetorheological mount” Proceedings of SPIE Smart Structures and Materials, March 8-12, 2009, San Diego, California.
20. Anderson, W., Elahinia, M., and Nguyen, T., “Vibration Mitigation with a Multi-axial Magnetorheological Mount,” SMASIS09 ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems September 20 - September 24, 2009, Oxnard, California.
21. Nguyen, T., Ciocanel, C. and Elahinia, M. H., A Magnetorheological Mount for Hydraulic Hybrid Vehicles,” SMASIS09 ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems September 20 - September 24, 2009, Oxnard, California.
22. Anderson, W. and Elahinia M., “Multidirectional vibration isolation through the use of magnetorheological fluid technology,” Proceedings of the 15th Asia Pacific Automotive Engineering Conference, October 25-29, 2009, Hanoi, Vietnam.
23. Nguyen, T. Ciocanel, C. and Elahinia M., “Structural considerations in designing magnetorheological fluid mounts,” Proceedings SPIE Active and Passive Smart Structures and Integrated Systems, 7 - 11 March 2010, San Diego, CA.
24. Anderson, W. Ciocanel, C. and Elahinia, M. “A Geometric Parametric Analysis of a Magnetorheological Engine Mount,” ASME International Design Engineering Technical Conferences (IDETC), August 15-18 2010, Montreal.
25. Wang, S. The, N. Anderson, W. Ciocanel, C. and Elahinia, M., “Skyhook Control of a Mixed Mode Magnetorheological Fluid Mount,” ASME International Design Engineering Technical Conferences (IDETC), August 15-18 2010, Montreal.
26. Anderson, W. Wang S. Nguyen, T. Ciocanel, C. Elahinia, M. “Comparison of a hydraulic engine mount to a magnetorheological engine mount,” SAE Commercial Vehicle Engineering Congress, October 5-8, 2010, Rosemont, Illinois.
27. Wang, S. Elahinia, M. The, N. Anderson, W. and Ciocanel, C., “Analysis and Control of Displacement Transmissibility and Force Transmissibility for a Two DOF Model Based on Quarter Car Concept using a Mixed Mode Magnetorheological Fluid Mount,” SAE Commercial Vehicle Engineering Congress, October 5-8, 2010, Rosemont, Illinois.

Detailed Technical Report

This section of the report includes the details of the technical achievements of the research in phase III. Magnetorheological (MR) mounts have been developed to replace hydraulic mounts because the MR effect makes the mount controllable and more adaptive. A MR mount was developed and its performance was experimentally investigated. Control systems were designed and evaluated in simulation.

Introduction

The novel design of the MR mount is expected to be functional in a wide range of frequencies. More specifically, a fluid mount with a higher number of inertia tracks has a higher notch frequency (lowest dynamic stiffness point). Utilizing this fact, a wide-bandwidth MR mount is designed as illustrated in Figure 1.

The existing mount designs often have a fixed number of inertia tracks, either single or multiple. On the other hand, in the configuration illustrated in Figure 1, each flow channel is powered by an electro-magnetic coil. With the design shown in Figure 1 and the coil arrangement in Figure 2, it is possible to control the flow through the specific channels. A higher magnetic field allows a smaller flow rate, and the flow is stopped when the field reaches a certain level. The squeeze mode configuration remains the same as in the mixed mode MR mount.

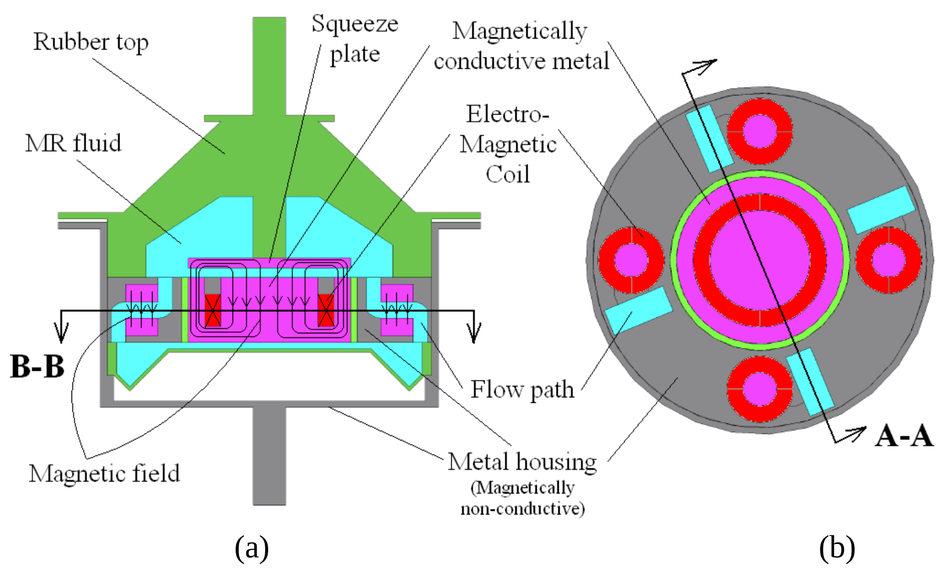

Figure 1 - Schematic of the wide-bandwidth MR fluid mount: (a) Sideview B-B, (b) Topview A-A.

The wide-bandwidth MR mount can be presented as multiple MR flow passages as shown in Figure 3. Four flow paths shown in Figure 3 are selected arbitrarily for exhibition and can be changed for each application.

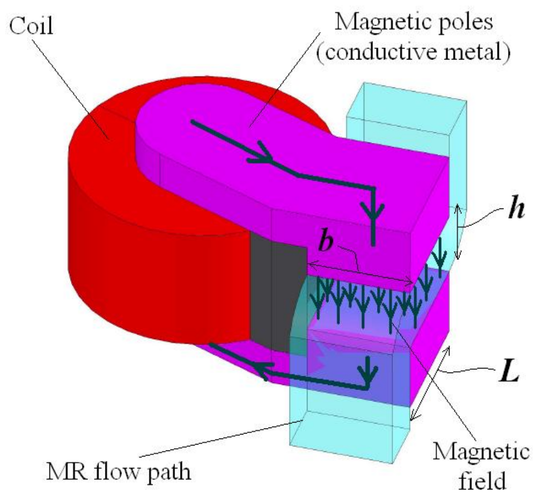

Figure 2 - Coil arrangement to individually control the flow paths.

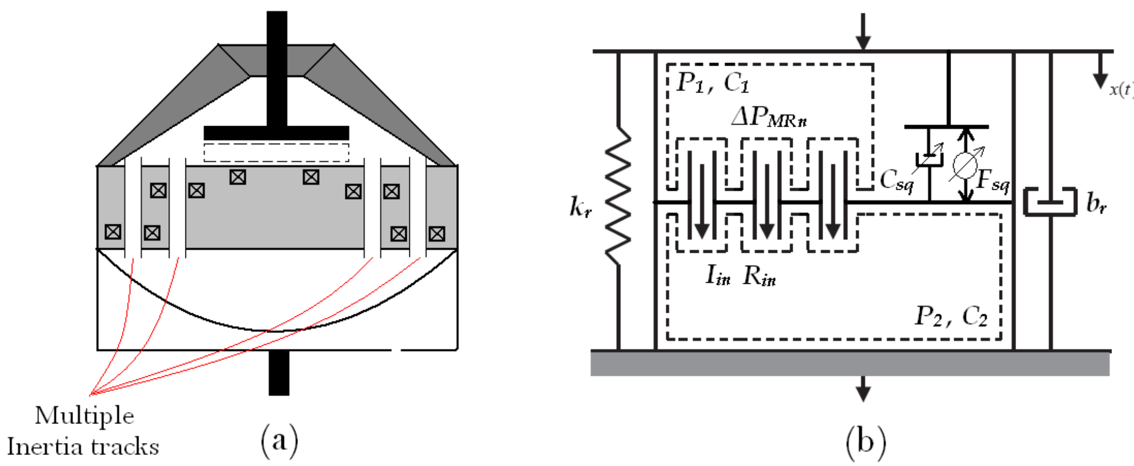

Figure 3- Simple representation of the wide-bandwidth MR mount: (a) physical model, (b) schematic.

Based on the physical model, the mathematical equations for the wide-bandwidth MR mount can be started with:

$$P_1 - P_2 = I_{in}\dot{Q}_{in} + R_{in}Q_{in} + \Delta P_{MRn}$$

$$\dot{P}_1 = \frac{A_p}{C_1}\dot{x} - \frac{\sum Q_{in}}{C_1}$$

$$\dot{P}_2 = \frac{\sum Q_{in}}{C_2}$$

$$M\ddot{x} + b_r\dot{x} + k_r x + C_{sq}\dot{x} + F_{sq} = A_p P_1$$

where n = 1, 2, 3 …

The final system consists of $n+1$ equations in which the first n equations describe the behavior of the fluid inside n flow passages and the last equation is the overall motion of the mount.

Parameter identification

The mathematical models are constructed based on the physics of the mount. However, in order for the models to predict accurately the behavior of the mount, the numerical value of the physical parameters of the mount should be identified. In this mixed mode MR mount, the needed parameters are the equivalent piston area A_p, the top chamber compliance C_1, the bottom chamber compliance C_2, the fluid inertia I_i, the flow resistance R_i, the top rubber stiffness k_r and damping b_r. In this section the experimental procedure for identifying a parameter is explained.

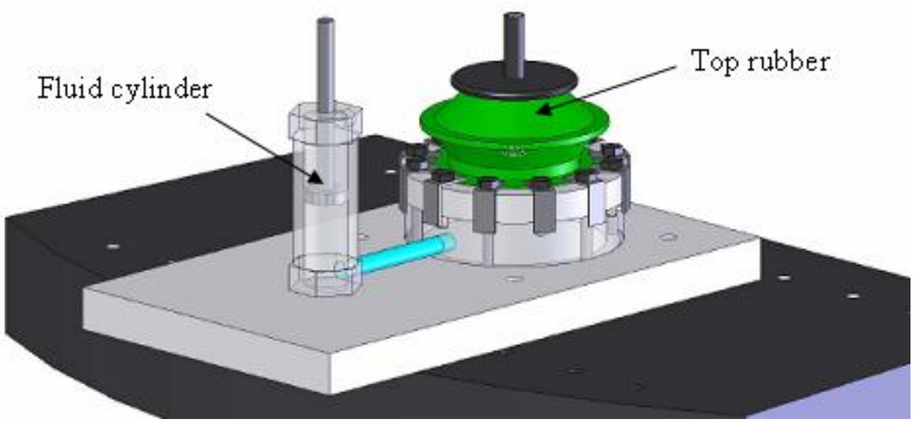

Figure 4 - Setup to identify the equivalent piston area of the top rubber.

Top rubber parameters – The top rubber was separated from the mount to be tested alone for the stiffness, damping and equivalent piston area. Quasi-static tests were run at 0.01Hz to measure the rubber stiffness. Harmonic tests were run to characterize the damping. A special setup was constructed for the equivalent piston area measurement. The setup, exhibited in Figure 4, allows the top rubber to pump the fluid from a master chamber into a cylinder. As the top rubber is excited with a known displacement, a certain volume of the fluid is pumped into the cylinder. This volume of fluid is calculated by measuring the displacement of the piston in the cylinder. Using the relationship $A_p X_r = A_{cylinder} X_{piston}$ with known X_r (excitation amplitude), $A_{cylinder}$ and X_{piston} (measurable), A_p can definitely be computed.

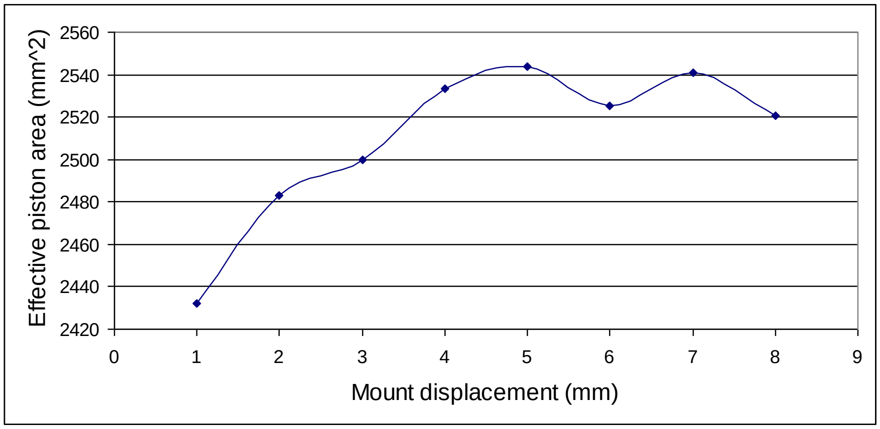

Figure 5 - Effective piston area as function of displacement amplitude.

It can be seen from Figure 5 that the equivalent piston area varies as a function of the excitation displacement. The area stabilizes when the excitation exceeds 4mm. Since the fluctuation at this stable range is not significant, the piston area is assumed to be 2530 mm^2. This value is then used in analytical model.

Hydraulic related parameters – These values can be identified using the Parameter Identification Toolbox in MATLAB/Simulink®. Since equations of motion are nonlinear, the module for estimating the nonlinear grey-box models was used. The term "grey-box models" expresses the ability to represent the physics of a system by mathematical ODEs explicitly. Grey-box modeling can be used when the relationships between variables, constraints, parameters or explicit equations representing system dynamics are known. In the mixed mode MR mount case, equations of motion represent the physics of the mount.

Table 1 - Identified values of the hydraulic parameters.

	0.2mm	**0.4mm**	**0.6mm**	**0.8mm**	**1.0mm**
Rubber stiffness K_r	2.28E+04	2.26E+04	2.20E+04	2.15E+04	2.15E+04
Rubber damping B_r	100	75	60	100	80
Top compliance C_1	3.2E-11	3.38E-11	3.75E-11	4.45E-11	5.13E-11
Bottom compliance C_2	1.20E-10	1.20E-10	1.20E-10	1.20E-10	1.20E-10

The function *idnlgrey* is used to define the physics of the systems, i.e. the ODEs. Consequently, the function *pem* is used to estimate the parameters. It is noticed from using the Parameter Identification Toolbox that there are key features determining the convergence of the programs. Higher number of parameters needed to be estimated will exponentially increase the number of computational iterations. Large error between the initial condition and the real value also causes the program a long time to converge. Sometimes, if the initial error is too large, the program is not converging at all.

After the identification process was done with the experimental data, the identified values for the mount's parameters are displayed in Table 1. It is remarked that the rubber stiffness and the top chamber compliance are affected the most by the displacement amplitude. The rubber damping and the bottom chamber compliance do not change significantly.

Experimental Results

The mixed mode MR mount prototype was manufactured and tested to obtain the experimental results. The experiments were conducted in such a procedure that harmonic excitations with known displacement amplitudes were imposed on the top of the mount while the transmitted force was measured by the load cell at the bottom of the mount. The test setup is shown in Figure 6.

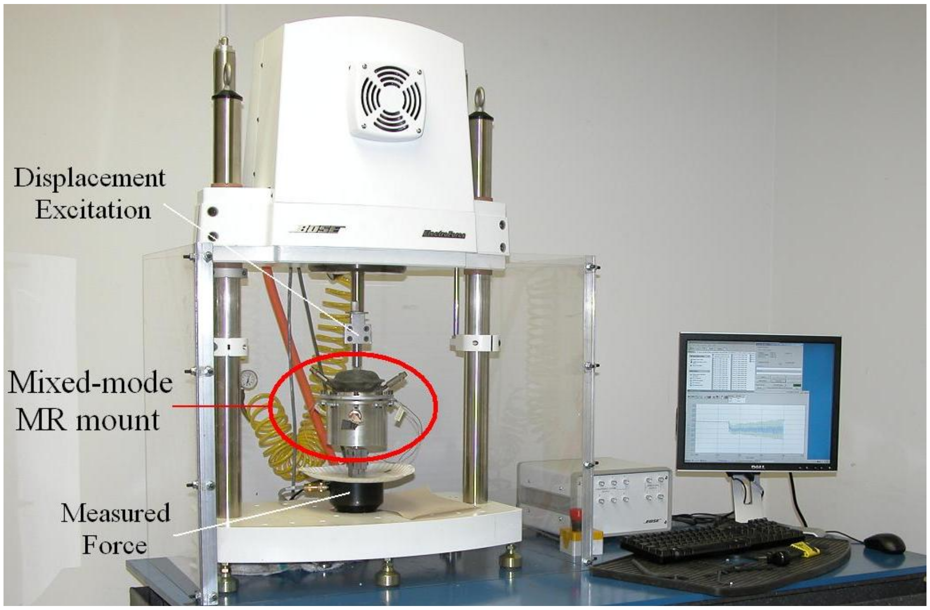

Figure 6 - Experimental setup for the mixed mode MR mount.

With the known displacement and the measured transmitted force, the dynamic stiffness and phase of the mount were calculated. The dynamic stiffness is used for evaluation of the mount as vibration isolator since the stiffness is directly related to the amount of transmitted force.

Magnetic Field/Force Investigation

Since it was not possible to measure the magnetic field strength in the MR fluid when the mount was operating, the field investigation in air was conducted. Figure 7 shows the results from the magnetic field measurement at the flow (3mm) and squeeze gap (3mm) at a range of applied current. It can be seen that the field is almost linearly increasing with the current. The squeeze mode curve has steeper slope and higher magnetic field values due to a good concentration provided by the inner coil circuit. However, even measured in air, both of the modes provide acceptable ranges of field for the selected MR fluid .

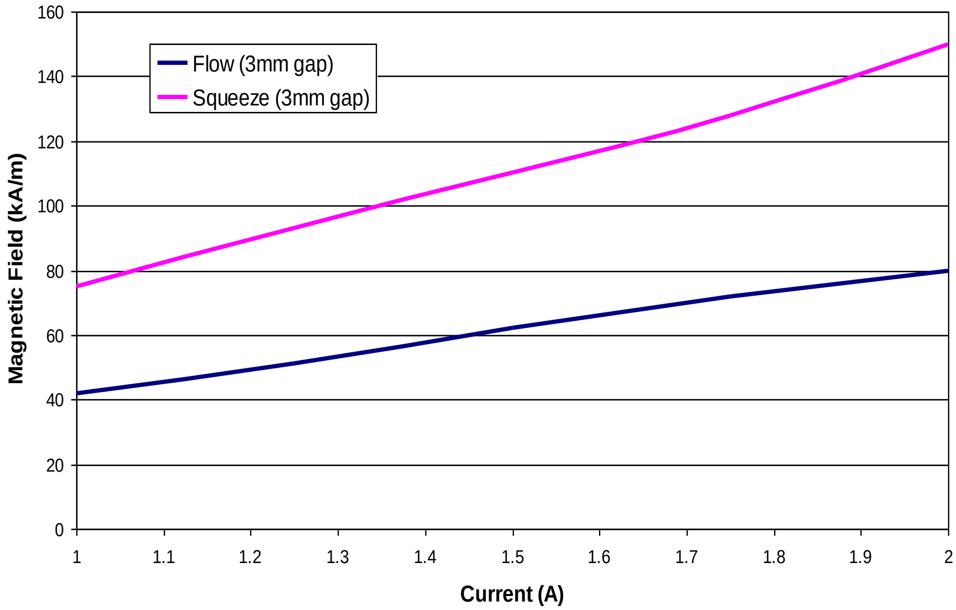

Figure 7 - Magnetic field strength in the flow and squeeze gap measured in air.

Another set of tests were conducted to examine the amplitude of the magnetic force and field when a current is applied to the squeeze mode electromagnet. These measurements are important because below a certain squeeze gap the plates may be attracted to each other inducing an unexpected force in the system. Also, a lack of understanding of this force and its dependence on the squeeze gap may lead to an undesired lock-up state (due to the magnetic attraction) during mount operation. To perform the measurements, the squeeze plate was set parallel to the upper surface of the middle assembly. Then, the gap between the two surfaces was varied and the magnetic force and field were measured for several values of the applied electric current.

Table 2- Magnetic force (in Newtons) induced by the electromagnet in squeeze mode at different gaps and values of the applied electric current.

Gap	Off	0.5A	1.0A	1.5A	2.0A	2.5A	3.0A
2.0mm	15	15.5	17	20	24	29	35
2.5mm	18	18.7	19.8	22	24.5	27.6	31.1
3.0mm	19	19.6	20.3	21.6	23.3	25.5	28
3.5mm	19.5	20	20.4	21.5	22.8	24.4	26.1
4.0mm	20	20.1	20.6	21.3	22.2	23.5	25.1

Table 3 - Magnetic field (in kA/m) measured between the squeeze plates at different gaps and values of the applied electric current.

Gap	Off	0.5A	1.0A	1.5A	2.0A	2.5A	3.0A
2.0mm	3	30	58	86	114	143	170
2.5mm	2	25	48	72	96	119	143
3.0mm	2	21	41	61	81	101	119
3.5mm	1	19	35	53	71	89	105
4.0mm	1	16	31	46	62	78	94

Table 2 shows the force measured with a load cell, while Table 3 displays the magnetic field measured with a Hall probe. All the measurements were made in air. Analysis of the results listed in Table 2 indicates that the magnetic force developed between the plates is just a fraction of the force applied to the mount during actual testing (i.e. 1000 N in average). Therefore, neglecting this force in the mathematical model should not alter the predicted response of the mount when the squeeze mode is considered. The measurements reported in Table 3 indicate that the magnetic field (measured in air) at an applied current of about 1.0A and above is sufficient to activate the MR fluid.

Model Validation

Figures 8-10 illustrate the ability of the mathematical model in predicting the response of the mount in flow mode only, squeeze mode only and combination of both modes. From Figure 8, it can be seen that the theoretical model can predict precisely the behavior of the mount working only in flow mode when the applied current is small. At a higher applied current, i.e. higher magnetic field, the prediction is good within the middle range of frequency.

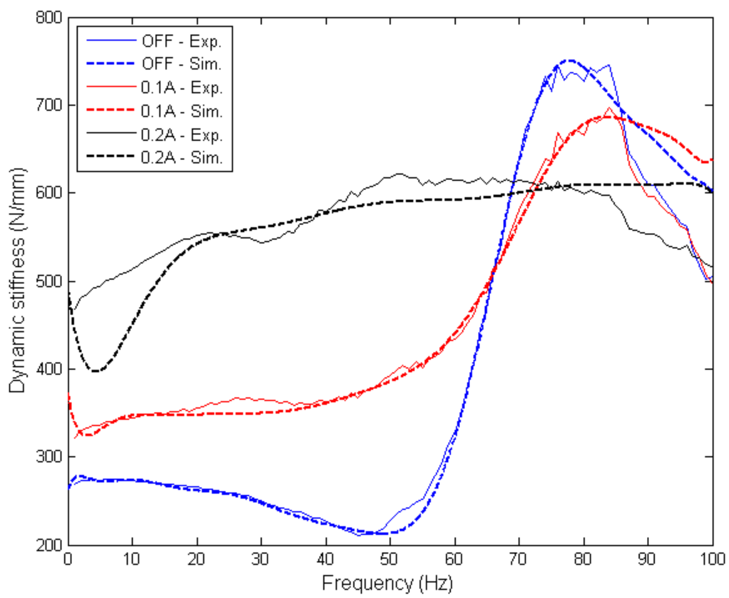

Figure 8 Theoretical prediction vs. Experimental result for flow mode only.

A small discrepancy happens at the very low frequency range in Figure 8. This inaccuracy does not happen to the squeeze mode as shown in Figure 9. The analytical simulated results approximate closely the experimental ones. These results are also close when both modes are activated, as displayed in Figure 10. The error between the simulated curve and the experimental curve is minimally small in the whole range of frequency.

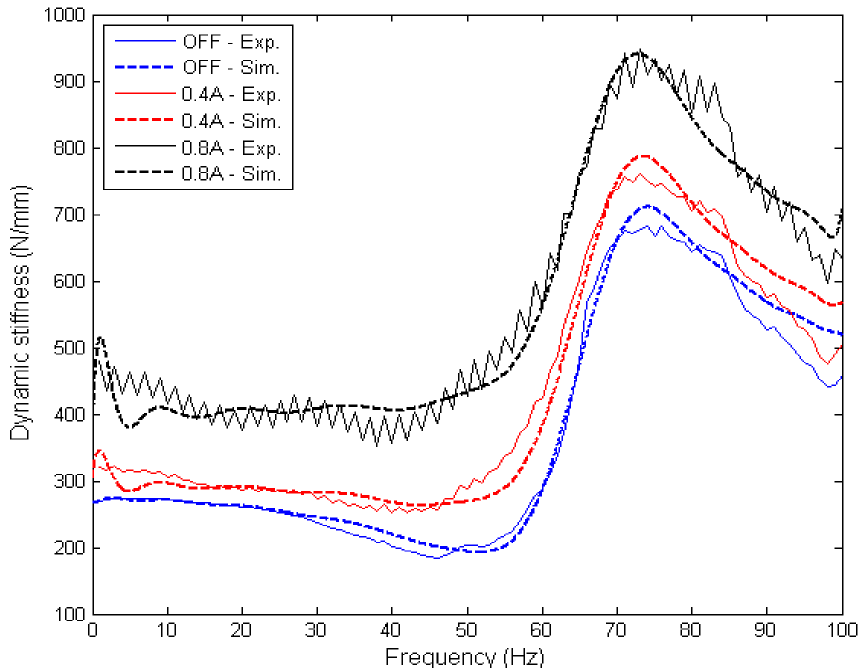

Figure 9 Theoretical prediction vs. Experimental result for squeeze mode only.

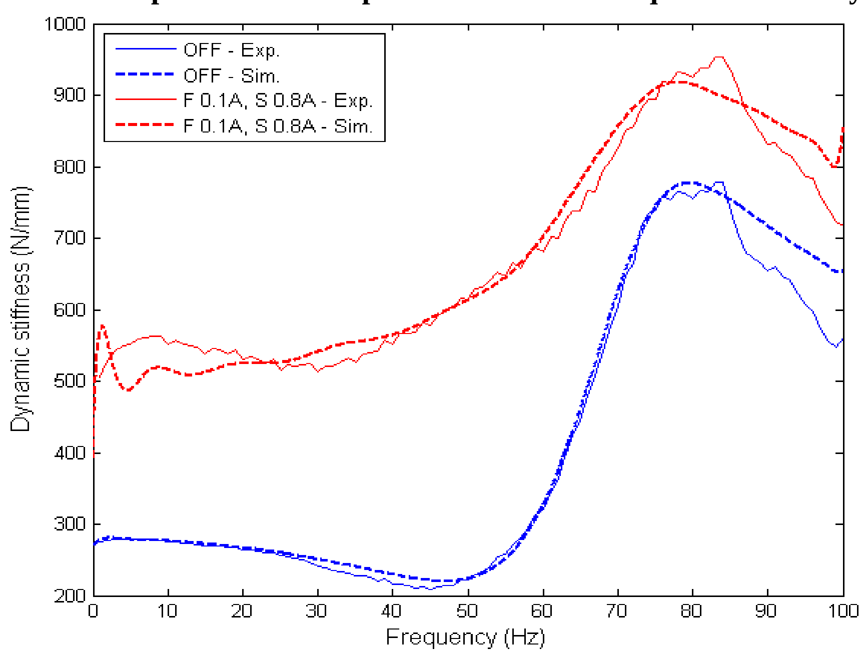

Figure 10 Theoretical prediction vs. Experimental result for combined mode.

It should be noticed that the predicted results only approximate the experimental ones from zero until about 85Hz. This phenomenon can be seen in all figures. This error is due to the fact that the mount is not absolutely degassed. When little amount of air is trapped in the mount and mixed with fluid, the stiffness of the mount at high frequency range, e.g. after the peak, declines sharply. This study has not been able to explain the mount response due to the trapped air. Therefore, the mathematical model can only predict the behavior of the mount until 85Hz. Despite the error at the higher frequency range, the analytical model is capable of forecasting the response of the mount within the most important range of operating frequency. The model is therefore utilized for the control of the mount.

Controller Design and Evaluation

Without a controller, the MR mount developed in the research, works only as effective as a passive isolation. The control system is designed to adjust the behavior of the system in order to function effectively in various working conditions. In other words the control logic adjusts damping and stiffness of the system so that the system can minimize the noise and vibration transmissibility.

A simple Skyhook controller has only one reference value. That design can cause the non-smooth transition between states of the MR damper. Alternatively, a modified Skyhook controller, which utilizes multiple reference values, was designed. In ON states, the damping force amplitude depends on the magnitude of the reference values. The bigger the reference value, the greater damping force is applied. With these multiple ON states, the difference between damping forces is smaller, so the transition is smoother.

The following equations show structures of simple Skyhook and modified Skyhook algorithm:

Simple Skyhook:

$$\zeta_{MR} = \begin{cases} 0 & \text{If} \quad |\dot{x}_P| < \dot{x}_{ref} \\ \zeta_0 = .02 & \text{If} \quad |\dot{x}_P| \geq \dot{x}_{ref} \end{cases}$$

Modified Skyhook:

$$\zeta_{MR} = \begin{cases} 0 & \text{If} \quad |\dot{x}_P| < \dot{x}_{ref1} \\ \zeta_1 & \text{If} \quad \dot{x}_{ref1} \leq |\dot{x}_P| < \dot{x}_{ref2} \\ \zeta_2 & \text{If} \quad \dot{x}_{ref2} \leq |\dot{x}_P| < \dot{x}_{ref3} \\ \ldots\ldots & \ldots\ldots \\ \zeta_{\mathbf{n}} & \text{If} \quad |\dot{x}_P| \geq \dot{x}_{ref\mathbf{n}} \end{cases}$$

ζ is the damping ratio of the mount. The damping ratio is increasing $(0 < \varsigma_1 < \varsigma_2 < ... < \varsigma_{\mathbf{n}})$ when reference value of velocity is increasing $(0 < \dot{x}_{ref1} < \dot{x}_{ref2} < ... < \dot{x}_{ref\mathbf{n}})$.

These skyhook control methods are effective because they can deliver variable damping effects to the mounting system. The mount can have high damping within low frequency range with the MR element is ON, and low damping within high frequency range with MR element is OFF. The skyhook algorithm simultaneously achieves the simplicity and effectiveness.

The three figures 11-13 illustrate the comparison of those methods. These figures show the advantages that the modified skyhook controller has over the simple one. Firstly, the damping force provided from the MR element using modified skyhook algorithm is always less than the one using simple skyhook algorithm. Thus, that modification helps to save the energy. Secondly, the damping force provided by ON states of the MR component is proportional to the velocity reference value in modified skyhook structure, i.e. the bigger velocity of the hybrid vehicle results in the larger damping force provided from the MR element. Figures 11 to 13 show the difference in smoothness of the curves indicating the smoother damping effects to the system when using modified skyhook controller.

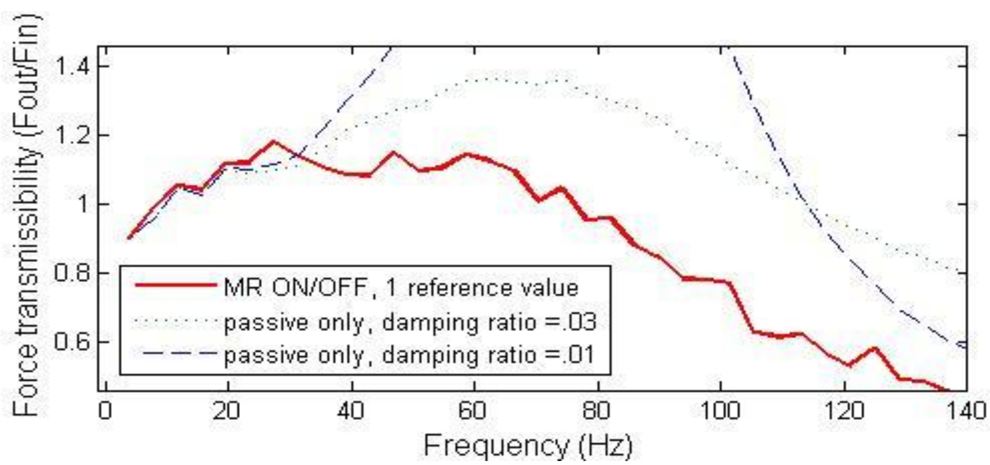

Figure 11- Force transmissibility curve of MR controlled ON/OFF with only one velocity reference value is oscillatory.

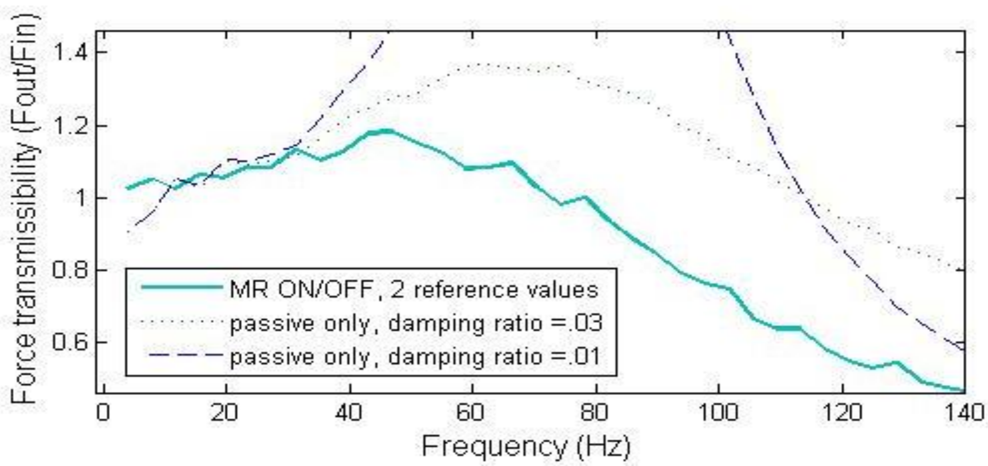

Figure 12- Force transmissibility curve of MR controlled ON/OFF with two velocity reference values shows smoother trace.

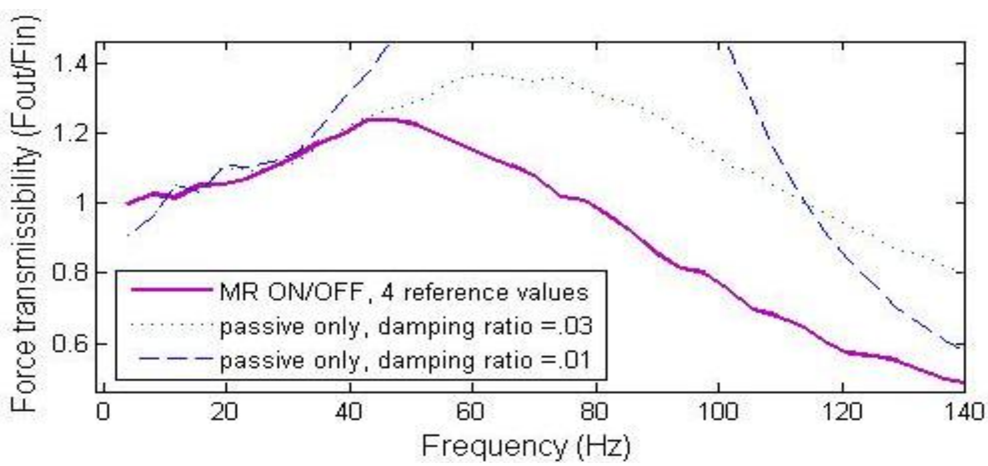

Figure 13- Force transmissibility curve of MR controlled ON/OFF with four velocity reference values has smooth path.

In summary in phase III of the project a controller was designed and numerically evaluated for the MR mount. This stage provides the foundation for experimental evaluation of the MR mount in closed-loop mode. To this end, the controller designed in this work will be implemented in a micro-controller and applied to the MR mount that was previously fabricated and evaluated.

Acknowledgment

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