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

Phase I Final Report

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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 varys 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.

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 year of the grant are the following.

Stage 1:

1-1) Implement the amplitude and frequency dependent elastomer model for the mount housing.
1-2) Correlate to experimental data.

Stage 2:

2-1) Implement the MR fluid behavior model.
2-2) Correlate with hydraulic mount data.

Stage 3:

3-1) Design the mount based on sensitivity analysis.
3-2) Simulate the semi-active mount.
3-3) Design the control algorithm.

Publications

The following is the list of publications which resulted from phase 1 of the project:

1. Nguyen, T. M. and Elahinia, M. H., "Vibration Isolation for Hydraulic Hybrid Vehicles," Journal of Sock and Vibration, February 2008, 15(2):193-204.
2. Nguyen, T. M., Ciocanel, C., and Elahinia, M. H., "Design and Modeling of a Mixed Mode Magnetorheological Fluid Mount," Journal of Vibration and Control, in review.
3. Nguyen, T., Ciocanel, C. Schroeder, C. and Elahinia M. H., "On the Design and Control of a Squeeze-Flow Mode Magnetorheological Fluid Mount," DETC/CIE, September 4-7, 2007, Las Vegas, Nevada.
4. Nguyen, T., Ciocanel, C., and Elahinia M. H., "Performance of an Adaptive Magnetorheological Fluid Mount," ASME International Mechanical Engineering Congress, November 11-15, 2007, Seattle, Washington.
5. 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.
6. 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

Detailed Technical Report

This section of the report includes the details of the technical achievements of the research in phase I. Magnetorheological (MR) mounts have been developed to replace hydraulic mounts because the MR effect makes the mount controllable and more adaptive. An MR mount, except for the added damping due to the magnetic field, operates similarly with a hydraulic mount. Therefore, the geometrical structure affects significantly the mount behavior. In this study, different geometries for the flow paths (inertia tracks) of an MR mount designed to operate in flow mode are considered and their effect on the mount behavior is simulated. The effects of the different geometries considered are quantified through changes in displacement transmissibility of the mount over a 0 to 70 Hz frequency range. The results of this analysis provide useful insights about model parameter values. These insights are determinants for the successful design of a flow mode MR mount.

Introduction

In the automotive industry, the engine/powertrain mounts are important since they reduce the vibration transmitted from the engine to the vehicle cabin. Hydraulic mounts have been developed and proven to be more effective then elastomeric mounts in both amplitude and frequency ranges. However, a hydraulic mount is yet a passive element that is efficient only within a limited range of operation. Emerging automotive technologies, i.e., electric hybrid, hydraulic hybrid and variable cylinder management, require adaptive mounts to effectively mitigate random or periodic vibrations induced by either the road profile or engine firing. Adaptive mounts can be active or semiactive. Active mounts have been developed and implemented only in luxurious classes of vehicles due to their high cost. Semiactive mounts are more common as their design is not very complex and thus the cost is lower. However, semiactive mounts are not capable of providing a force input like the active ones do. Semiactive mounts can only alter their response during operation, i.e., damping and stiffness (to some extent). Currently, semiactive mounts rely on changes in geometry of the flow paths or on changes in properties of the working fluid. As changes in geometry of the flow paths in real time require rather complex actuation mechanisms to be incorporated in the mount, it is more desirable to be able to change the mount response through changes in the working fluid characteristics. Consequently, semiactive fluid mounts have been proposed to use electrorheological (ER) or magnetorheological (MR) fluids as the working fluid. The benefit is that ER/MR fluids can change their rheology upon the application of an electric/magnetic field. Even though these fluids (ER & MR) are similar in operation, it has been proven that MR fluids develop higher yield stress for the same amount of energy consumed, therefore being more suitable for applications where high levels of energy dissipation are required.

ER/MR fluids can operate in one or a combination of the following three modes: flow (or valve) mode, shear mode and squeeze mode. The most popular type is the flow mode since it is somewhat simpler to design devices making use of the fluid working in that mode. The flow mode happens when the fluid flows between two fixed parallel boundaries that are perpendicular to the direction of the applied field [1].

Hong, *et al.* [2] introduced an ER mount capable to support a static load of 70 kg, with the fluid working in flow mode. Stelzer, *et al.* [3] proposed a compact MR isolator to mount the air conditioning compressor in a vehicle based on the flow mode. Choi, et al. [4] presented a mixed-mode MR engine mount that has the MR fluid operate in flow and shear modes simultaneously. The existing literature exhibits several ER/MR mount designs along with their response to various levels of excitation. However, the effects of hydraulic behavior of the ER/MR fluid flow on the mount characteristics have not been investigated in depth.

In this study, the design of a flow mode based MR mount is presented. Several orifice geometries are considered and the effects of these geometries on the fluid flow are formulated mathematically. The simulation results indicate how the flow path design affects the response of the MR mount. It is noticed that a suitable controller is important to a semiactive magnetorheological mount. However, this study only focuses on the behavior of the MR mount based on the structural design and constant levels of the magnetic field. This research can serve as a basis to design effective control schemes which are not included in this document.

Modeling

Figure 1 shows the side view and top view of the studied MR mount design. Similar to a hydraulic mount, the MR mount is comprised of a rubber element at the top that supports the static load, two hollow chambers connected through flow paths called inertia tracks, and a thin rubber membrane at the bottom that is used to contain the fluid inside the mount. In addition, unlike a hydraulic mount, the MR mount has an embedded coil (electromagnet) that is used to generate the magnetic field required to change the MR fluid flow characteristics.

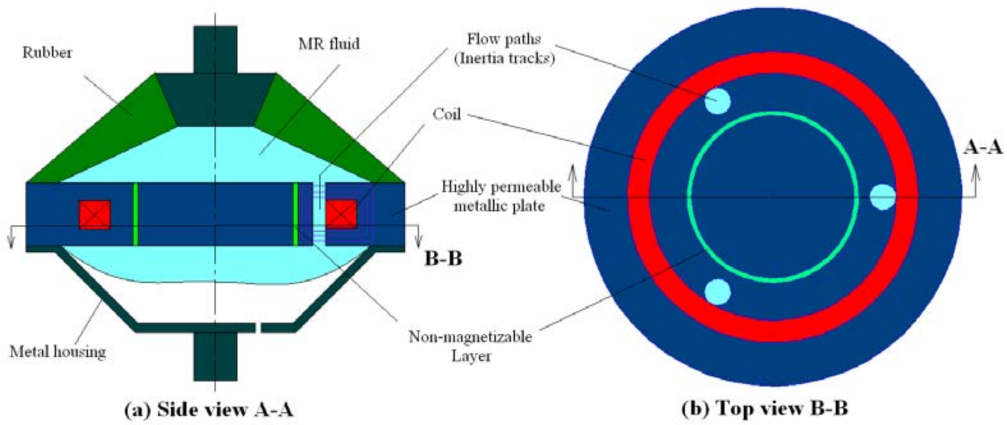

Figure 1: Schematic of the MR mount (a) Side view, (b) Top view.

The mathematical model was developed as illustrated in the paragraphs below. Itis worth noting that the pressure drop due to hydraulic loss is usually considered when dealing with a hydraulic system. On the other hand, a calculation was conducted to conclude that the loss-induced pressure drop is insignificant compared to the viscosity and MR induce effects.

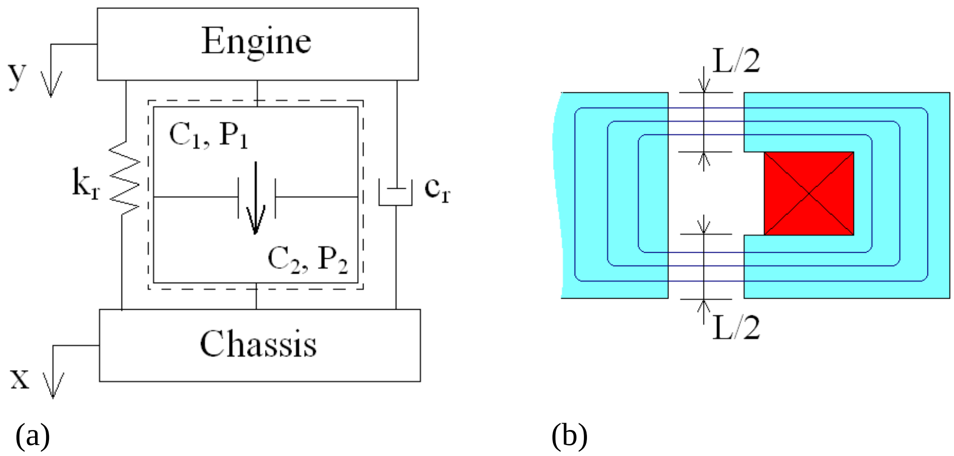

Figure 2: (a) Physical model of the mount; (b) Effective length of the inertia track.

The physical model of the mount, as seen in Figure 2 (a), is used to derive the governing equations for the MR fluid mount. The pressure drop due to the flow of the MR fluid through the inertia track of the mount is evaluated from the linear momentum equation as:

$$P_1 - P_2 = I_i \dot{Q}_i + R_i Q_i + \Delta P_{MR} \tag{1}$$

where P_1 is the pressure in the upper chamber, P_2 is the pressure in lower chamber of the mount, I_i is the fluid inertia, R_i is the fluid drag at zero magnetic field, Q_i is the fluid flow rate through the inertia track, and ΔP_{MR} is the pressure drop due to the yield stress of the MR fluid.

In addition, applying the generalized flow continuity equations to the system (Woods and Lawrence [5]) yields:

$$\dot{P}_1 = \frac{A_p}{C_1}(\dot{x} - \dot{y}) - \frac{Q_i}{C_1} \tag{2}$$

$$\dot{P}_2 = \frac{Q_i}{C_2} \tag{3}$$

where C_1 and C_2 are the compliances of the top and bottom chamber, respectively, A_p is the piston area of the upper rubber part, $\dot{x}$ is the velocity of the supported mass, and $\dot{y}$ is the velocity of the bottom of the mount.

Assuming $Q_i = A_i \dot{x}_i$, where A_i is the cross sectional area of the inertia track and $\dot{x}_i$ is the fluid velocity through the inertia track, using equations (2) and (3) to plug into equation (1) gives

$$I_i A_i \ddot{x}_i + R_i A_i \dot{x}_i + A_i\left(\frac{1}{C_1} + \frac{1}{C_2}\right)x_i = \frac{A_P}{C_1}(x - y) + \Delta P_{MR} \tag{4}$$

According to Srinivasan, *et al.* [6], the pressure difference induced by the MR effect can be expressed as

$$\Delta P_{MR} = C\frac{L}{h}\tau_y(H)sign(\dot{x}_i) \tag{5}$$

where C is a constant in the range of 2 to 3 depending on the steady-state flow conditions. In this research, it is assumed that C is equal to 2, which corresponds to low-flow conditions.. The other parameters appearing in equation (5) are: L - the length inside the inertia track where the magnetic field is effective, as illustrated in Figure 2 (b), h - the distance between the magnetic poles, which is equal to the height of the inertia track channel, b - the width of the channel, $\tau_y(H)$ – the MR fluid yield stress that is magnetic field (H) dependent. In the case of a circular orifice, h is assumed to be equal to the diameter of the circle.

From the work of Adiguna, *et al.* [7], the hydraulic related parameters are defined. Since the flow path is straight, the inertance of the fluid inside the inertia track is $I_i = \rho L / A_i$ where ρ is the density of the MR fluid. The fluid resistance within the inertia track is approximated based on the orifice geometry. If the orifice is circular, $R_i = \frac{128\eta L}{\pi d_i^4}$ where d_i is the diameter of the orifice, η is the MR fluid viscosity which is shear rate dependent but assumed to be constant in this study. If the orifice is rectangular, $R_i = \frac{12\eta L}{bh^3}$. The cross-sectional geometries considered in this study for the orifice and their orientations with respect to the direction of the field are shown in Figure 3. In the work of Ciocanel, *et al.* [8], the magnetic field cannot be uniformly distributed over the cross section. However, in this research, the magnetic field is assumed to have identical magnitude everywhere within the cross section.

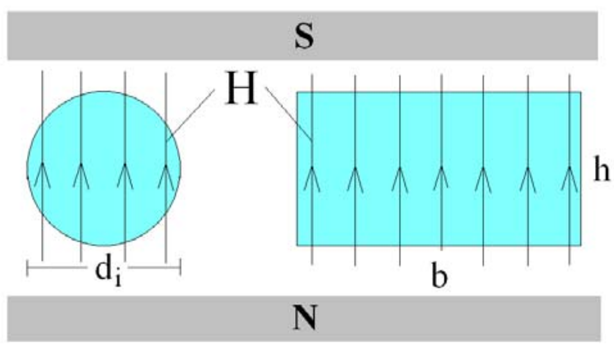

Figure 3: Geometry of the orifice in relation with the magnetic field direction.

The equation of motion of the entire mount can be expressed as

$$M\ddot{x} + c_r(\dot{x} - \dot{y}) + \left(k_r + \frac{A_p^2}{C_1}\right)(x - y) = \frac{A_i A_p}{C_1} x_i \qquad (6)$$

where c_r and k_r are the damping and stiffness of the upper rubber part, respectively.

The governing system of equations of the mount is obtained from combining equation (4) and (6) as

$$\begin{cases} \ddot{x}_i = \dfrac{1}{I_i A_i}\left\{ -R_i A_i \dot{x}_i - A_i\left(\dfrac{1}{C_1} + \dfrac{1}{C_2}\right)x_i + \dfrac{A_P}{C_1}(x - y) + 2\dfrac{L}{h}\tau_y(H)\,sign(\dot{x}_i) \right\} \\ \ddot{x} = \dfrac{1}{M}\left\{ -c_r(\dot{x} - \dot{y}) - \left(k_r + \dfrac{A_p^2}{C_1}\right)(x - y) + \dfrac{A_i A_p}{C_1} x_i \right\} \end{cases} \qquad (7)$$

The system of equations (7) is constructed in MATLAB/Simulink® to obtain numerically the response of the MR mount. The numerical model is capable of generating the results in both time and frequency domains.

MRF 132AD is the working fluid in this application. Using curve fitting, the fluid yield stress dependence on the magnetic field was determined from data provided by Lord Corporation (see Figure 4). To determine the best fit equation, the curve shown in Figure 4 was extrapolated to origin and then a best fit equation was determined. The curve fit equation listed in the plot was derived under the assumption that at zero field the yield stress is zero. Regarding the viscosity of the MR fluid, even though it is believed to be dependent on both shear rate and magnetic field, these dependencies were not considered in this approach.

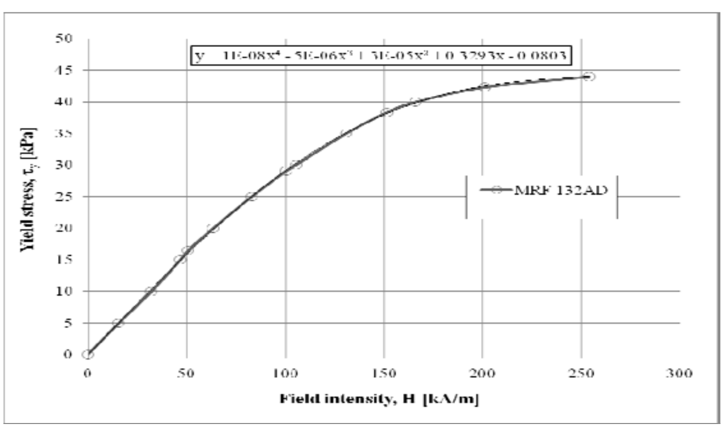

Figure 4: Yield stress as a function of magnetic field intensity for MRF-132AD.

Simulation results

Simulations have been performed to estimate the effect of geometry changes on the MR mount characteristics. The focus was on the following parameters: the effective length of the inertia tracks, *L*, the width, *b*, and height, *h*, (for rectangular) or the diameter, *d*, (for circular) of the orifice, and the number of the orifices, *N*. The comparison is carried between two geometries under the condition that the cross sectional area and the length are equal for both shapes.

It is important to reiterate that the MR mount is designed upon the principles of a hydraulic mount. Therefore, as the field is off, the MR mount behavior is affected solely by the hydraulic parameters including the inertia track length. As illustrated in the modeling section, the mount was modeled as a 2DOF system. One DOF is represented by the rubber and the loading mass while the other DOF is represented by the fluid mass flowing through the inertia track. Consequently, the simulation of the displacement transmissibility exhibits two peaks at two natural frequencies of the system as shown in Figure 5. The lower frequency peak indicates the contribution from the rubber element and the mass, while the higher frequency peak illustrates the contribution from the fluid mass flowing through the inertia track.

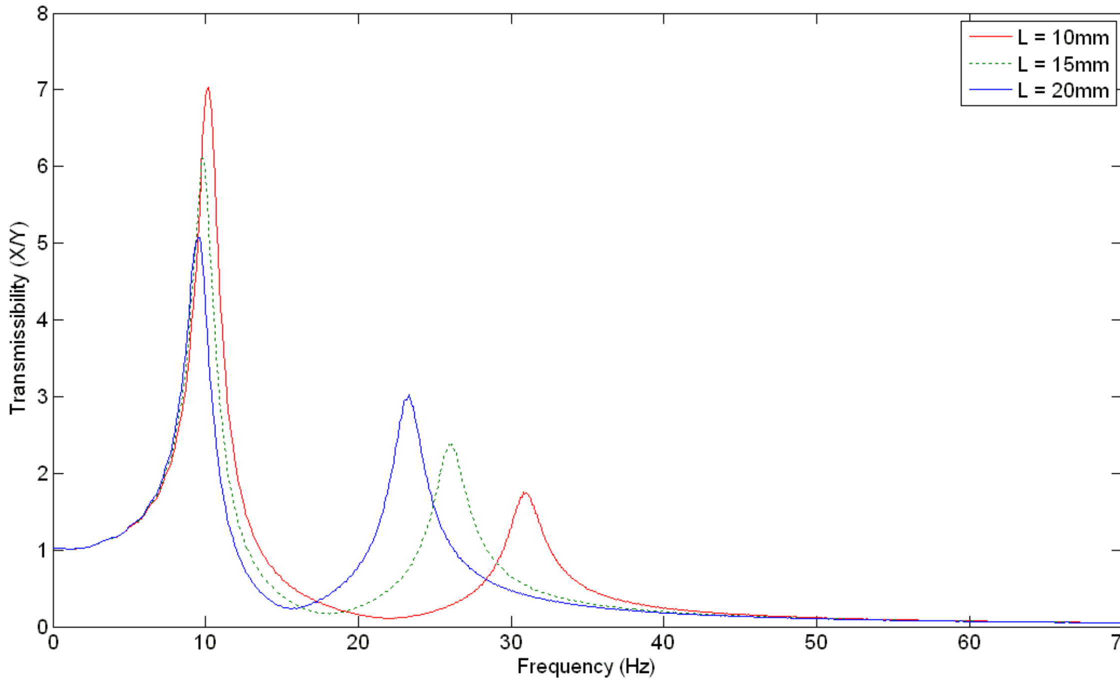

Figure 5: Displacement transmissibility of the mount with the field off when the length of the inertia track changes.

Figure 5 indicates that the longer the inertia track, the closer the peak frequencies and amplitudes get to each other and the narrower the operating frequency range for the mount becomes. It can be seen that as the track gets shorter, the transmissibility curves exhibit deeper valleys (the lowest amplitude region between the two peaks) that indicates good isolation for the low frequency range. On the other hand, if the forcing frequency is high, for instance higher than 30 in this case, a long inertia track is preferred.

Another important parameter to the characteristics of the mount is the number of orifices which determines the overall cross-sectional area of the inertia tracks. Figure 6 shows that the change in the number of inertia tracks mostly affects the second natural frequency in both location and amplitude. Adding more flow paths widens the low transmissibility region in between the peaks. This phenomenon is desirable when one wants to isolate the low frequency vibration source. High frequency isolation, on the other hand, requires fewer orifices. Capability of controlling the number of the flow paths makes the mount actively effective in a wider frequency range. This capability can be facilitated by wiring the coil such that the magnetic field is controlled to have an effect on each inertia track individually. In this condition, one can open any orifice by keeping the field off or block it turning the field relatively high. In order for this characteristic to be efficiently utilized in vibration isolation, an adaptive controller is required. However, the controller design is not included in the scope of this phase of the project.

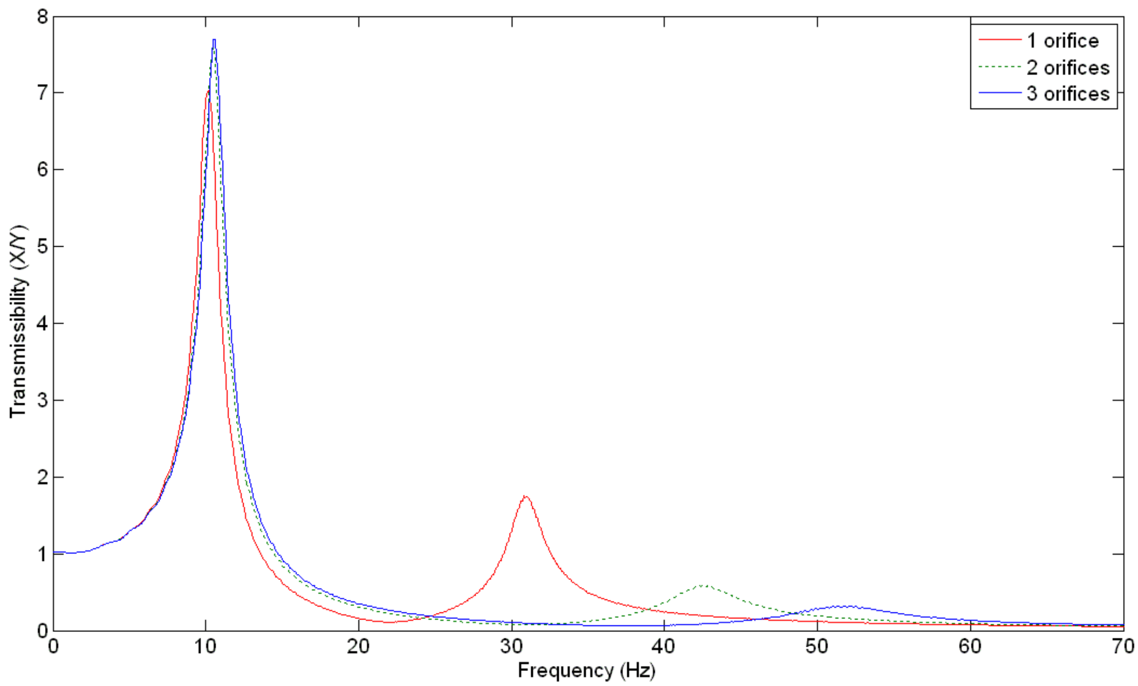

Figure 6: Displacement transmissibility of the mount with the field off when the number of the inertia tracks change.

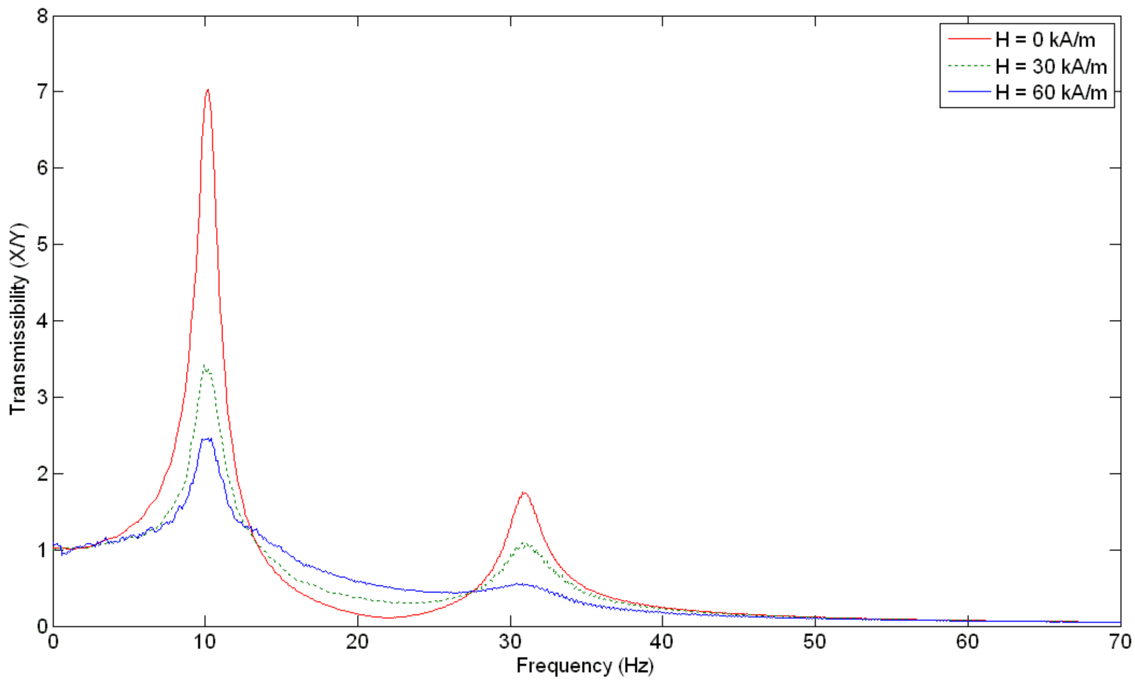

Figure 7: Displacement transmissibility of the mount with varying field.

Figure 5 and 6 have shown the behavior of the mount when the field is zero. However, the proposed mount is expected to operate with the magnetic field on. Therefore, in the following paragraphs the effect of the field on the transmissibility will be discussed.

Figure 7 displays how the magnetic field affects the response of the MR mount. The field strength applied is moderate so that the valve effect (the orifice is totally blocked) does not occur. It is observed that increasing the magnetic field creates a similar effect as increasing damping in the system. The magnetic field helps in bringing down the peak amplitude, but causes the valley amplitude to increase. This indicates that in order to always achieve the lowest transmitted displacement, the field should be on within the resonant regions and should be off in the valley region. The geometrical shape of the orifices is an important design aspect since the shape determines the resistance on the flow in both field on and field off conditions.

Figure 8 compares the effect of a square orifice to a circular orifice. Their areas are equal. It is realized that at zero field, the circular orifice induces lower transmissibility in both resonant peaks. However, when the field is turned on, the lower transmissibility caused by the circular orifice only happens at the second resonance. This phenomenon is expected since the second resonance is contributed from the motion of the fluid passing through the inertia track, and the magnetic field directly affects this flow. To obtain this result and the following ones, the magnetic field strength is kept in a low range, i.e., 0 – 60kA/m. The reason for this selection is to minimize the coil weight added to the mount. The geometrical dimensions, through this study, can be determined to work with this range of magnetic field.

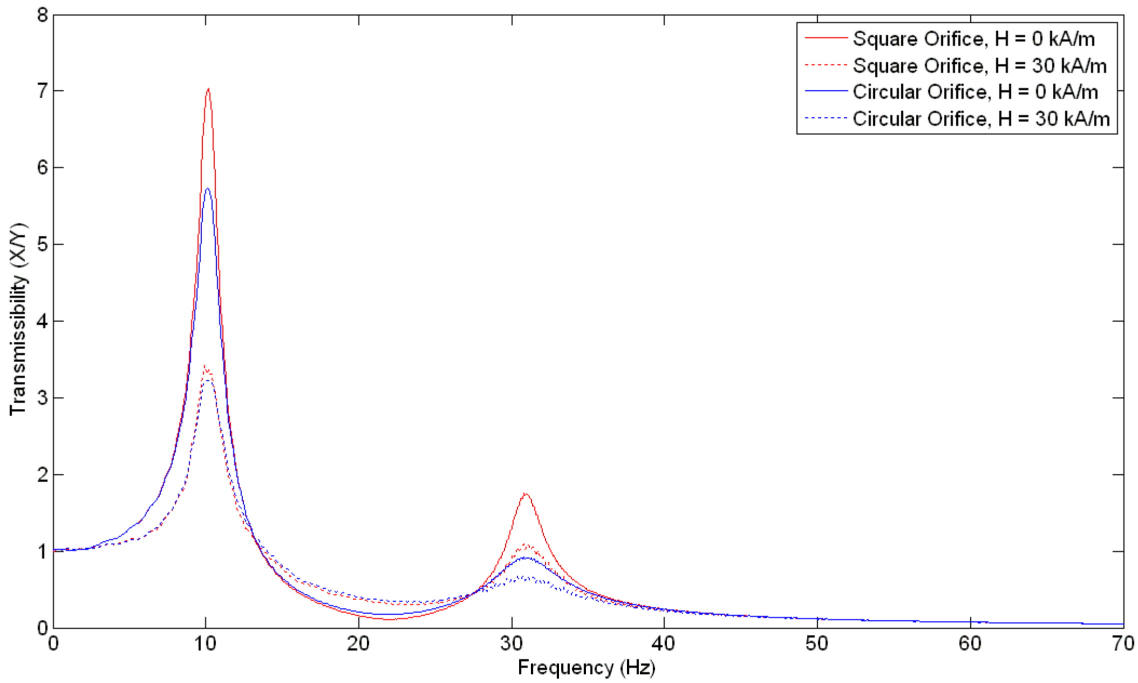

Figure 8: Comparison of square and circular orifices with equal cross-sectional area.

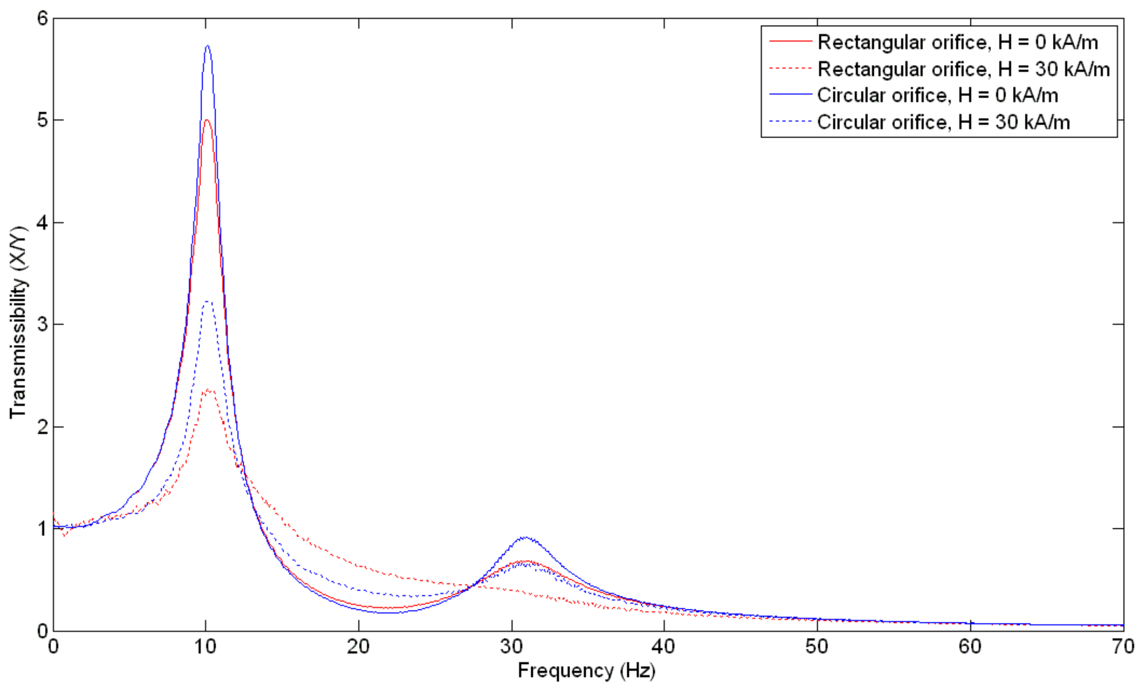

Figure 9: Comparison of rectangular and circular orifice with equal cross-sectional area.

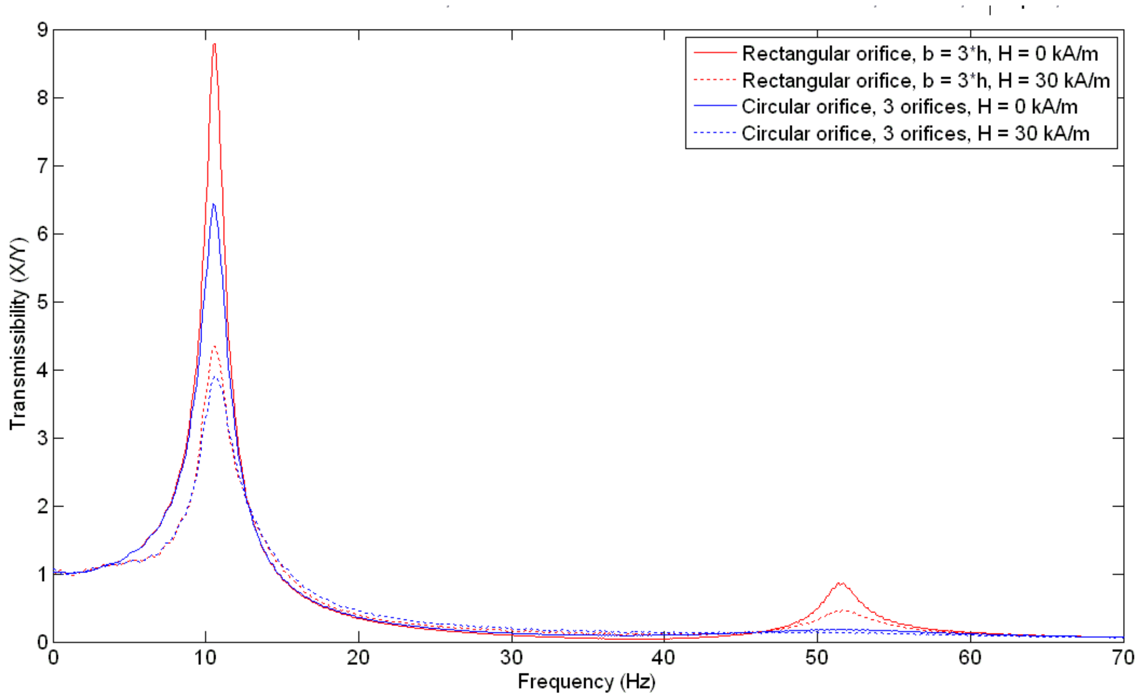

Figure 10: Comparison of a rectangular orifice with width = 3 x height and 3 circular orifices, the overall areas are equal.

The effect of a rectangular orifice on transmissibility is compared in Figure 9 to that of a circular orifice. The cross sectional areas and the lengths of the two orifices are kept equal. It is seen that the rectangular orifice mount gives lower transmissibility at the resonant regions both with and without field. When the field is OFF, the transmissibility induced by either rectangular or circular orifice is relatively close. The main reason for this behavior is the slender shape of the rectangle. With this geometry, the viscosity-induced resistance is higher at zero field. When the field is ON, the particle chains in the rectangular orifice are shorter and more uniform. Therefore, the damping force provided by the rectangular orifice is higher. On the other hand, the high damping from the rectangular orifice when the field is ON makes the transmissibility higher in the region between the peaks which is not desirable. Again, an appropriate control scheme can turn the field OFF within the valley region to obtain a low transmitted displacement.

As shown in Figure 9, the rectangular orifice is more effective than the circular one. Figure 10 shows the difference in performance of the two configurations. The first one is a rectangular orifice, which has the width equal to three times the height. The second one is a combination of three identical circular orifices. The overall area of the three circular inertia tracks is equal to that of the rectangular one. In this comparison, circular tracks outperform the rectangular counterpart especially at the zero field. However, when the field is turned on to the level shown in Figure 10, the transmissibility by the circular orifice mount is minimally lower than that by the rectangular one. It indicates that the rectangular shape is more effective for the MR mount since the percentage of transmissibility reduction induced by the rectangular orifice mount is higher than its circular counterpart.

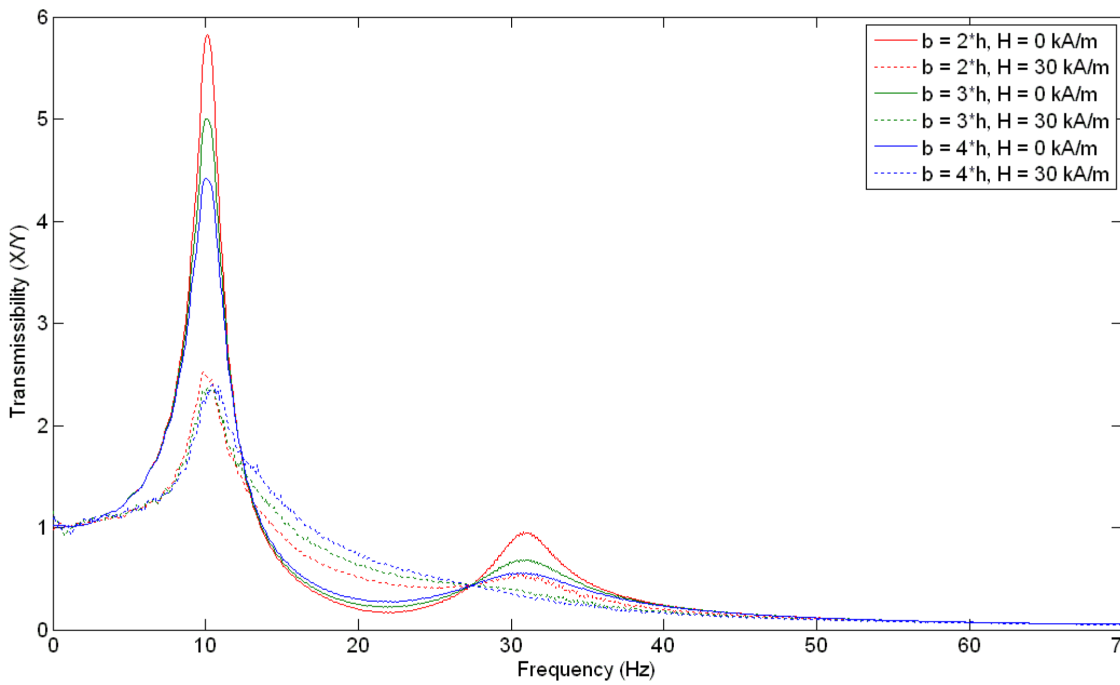

Figure 11: Comparison of rectangular orifices with different ratio between the width and the height, the overall areas are equal.

Previous results have shown that rectangular shape is the most effective for the MR mount. A further analysis was done to examine how the ratio between the width and the height affects the performance of the mount. The ratio was changed while the cross-sectional area was kept constant. At zero field, the mount with a higher ratio has higher damping, i.e., lower peak amplitudes at resonances and higher amplitude in the valley region. Conversely, at the field on condition, the mount with a higher ratio provides the least reduction percentage in the resonant regions and causes the highest transmissibility amplitude in the region between the peaks. Within the three ratio values shown in Figure 11, when the width is equal to three times the height, expressed by the green curves, the mount performance can be optimized. In the first resonant region, i.e.. from 0 to 12 Hz, the field can be on to make the green curve the lowest one. In the valley region, i.e., from 12 to 27 Hz, the field can be off to make the green curve the second lowest, above the red one. Finally, in the second resonant region, the field can be turned on again to achieve the second lowest amplitude, slightly above the blue curve.

Conclusion

In this project, the mathematical model for a semiactive MR fluid based mount was derived. The resulting system of equations of motion was constructed in MATLAB/Simulink® to simulate the behavior of the mount. The simulation results were used to assess the contribution of the geometry of the inertia tracks on the characteristics of the mount. The mount was aimed to have small coil, i.e., minimal added weight, so the magnetic field strength used was in a relatively low range. Adaptive controllers, not included in this work, can potentially improve the performance of the mount and therefore can be considered for future works.

The results indicated that the length of the inertia tracks and number of inertia tracks define the frequencies of the resonant peaks. Therefore, these parameters should be carefully selected on an individual basis depending on the application intended for the designed mount. The number of active tracks can be controlled by suitable wiring configurations of the coils.

Several shapes of the orifice were considered for an effectiveness analysis. The circular orifice was compared to the rectangular one. It was concluded that the rectangular orifice is the most efficient for the MR mount. It not only provides high damping to the mount when the field is off, but it is also highly effective when the field is on. In a rectangular orifice, the ratio between the width and the height of the cross section significantly affects the response of the mount, especially when the field is applied. It is noticed that a rectangular orifice is more efficient than multiple circular ones provided that the total overall area is identical.

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