Magnetorheological Fluid Engine Mounts: A Review on Structure Design of Semi Active Engine Mounting

M.Z.Sariman, M.Hafiz Harun, A.K.Mat Yamin, F.Ahmad, and M.R Yunos

***Abstract*—** The demand for low cost, quiet operation, and increased operator comfort in automobiles and other applications requires new techniques to be developed for noise and vibration isolation. One approach to reduce noise vibration and harshness (NVH) is to develop a small low cost vibration isolator that can be used to mount components that generate vibration. Passive, semi-active and active control methods as well as different types of smart materials were studied to develop this isolator. Based on this study, the most promising approach seems to be a semi-active magnetorheological isolator. In this paper, an overview of recent advances in semi active engine mounts are presented, in term of working operation of Magnetorheological (MR) Fluid namely flow mode, shear mode, squeeze mode and mix mode. The issues are discussed with regard to the design and performance as vibration isolator device. The finding of this paper proposed the new semi active engine mounts design.

***Keywords*—** Flow mode, Magnetorheolocical Fluid (MR), , squeeze mode, shear mode.

I. Introduction

Magnetorheological (MR) materials are a class of smart materials that are currently used in many applications. Smart materials are the materials with controllable properties that changes by external stimuli such as stress, temperature, pH, moisture, electric or magnetic fields. Magnetorheological material can be a form of fluids, gel or even a solid material such as elastomers. A magnetorheological fluid mainly consists of micron-sized iron particle that is suspended in carrier oil [1]. MR fluid has an ability of changing from free-flowing liquid state into a semi-solid condition with restricted fluid movement in fast response within several milliseconds when exposed to the external magnetic field. The advantages of MR fluids lead to the development of MR based device in a wide range application such as in civil sectors [2],[3], medical sectors and as well as automotive sectors.

There is also another smart material that has the same operating concept as MR fluid which is named electrorheological (ER) fluid. The comparison of the performance of ER fluid and MR fluid had been discussed by many publications [1],[4],[5]. However this paper focused on application the MR fluids for semi active engine mounts because of its ability to stand 50-100 KPa of yield stress and higher density of 0.1 J/cm^3 [6]. Since the ERF and MRF has characteristic to change their properties to from soft to hard and hard to soft therefore it was well-known as the vibration isolator devices [5],[7],[8]. For the automotive sectors, most famous application of MRF on the suspension system was known as MR damper [6],[9]-[13]. Besides that, MR application for rotary damper such as MR brake had been used widely since a long time ago [14]-[18]. There are also others application of MR mount isolator which had been used on DVD or CD player on vehicles that had been discovered by Ahn *et al*. [19].

Mounting systems are one of the most popular MR fluid application devices especially for automotive mounting system. Generally, engine mounting system can be classified into three categories which are passive engine mount system, semi active mount system and active mount system [20]. Passive engine mount system was discovered by Marc Bucuchon [21] earlier, is the common suspension system installed in most vehicles nowadays which typically consists of damper and spring in parallel configuration. Semi active engine mount is similar with the passive system but the stiffness of the component whether spring or/and damper can be controlled to isolate the vibration on the engine. While, active engine mount is a system with involvement of active actuators such as electromagnetic [22], servo-hydraulic [23], hydro [24], pneumatics [25] and piezoelectric [26]. The active actuators function is to provide external force to counter the existing force upon the engine mounting. Thus, active engine mount is the best vibration isolator [27],[28].

The enhancement of engine mount performance is due to the drawback of passive engine mount performance which is unable to isolate at the certain frequency. Therefore, active engine mount and semi active engine mount systems becoming alternatives to replace the conventional system. In this case,

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rubber engine mount is the conventional engine mount that has simple design and less production cost .However the rubber engine mounts work only at certain range of frequencies. Meanwhile, the rotating engine has different Revolution per Minutes (RPM) that also lead to the variable range of frequencies of the vehicle according to speed input from driver. The problem caused by the conventional engine mounts lead to the new findings which are semi-active engine mount and active engine mount as the methods to solve this problem.

Even though the active engine mounts system capable of achieving very good solution in isolating the variable vibration frequency, they has some constrains which are high cost, high energy consumption, complex configuration, instability issues and difficulty during maintenance. Cost and complexity of the active engine mount being the most critical issues as far as automotive industries are concerned. The countermeasure to this problem is to installed semi active engine mounts where it still maintains the simplicity of passive mount and at the same time it can be controlled. Thus, semi active engine mount is said as the mediocre solutions to the vibration isolation problems. The main advantages of these system compared to the active mount system are the semi active mount does not use actuating force resulting in lower power consumption and instability risk. Moreover, semi active mount effectively dissipate vibration energy by controlling the mount's parameter such as damping.

There are many types and classes of semi-active engine mounts that have been developed according to their function and performance. The initial designs of the semi-active engine mounting used the conventional hydraulic design [29] and the difference was the used of MR fluids replacing the hydraulic oil. Besides that, the design of the hydraulic engine mount had been discovered a long previous time by Flower [30]. The electric current flow through the iron core coil will generate magnetic field. Since semi active engine mounts performance depending on the concentration magnetic field region, thus the amount of electric current supply can be controlled. Many publications had discussed the effect of the magnetic field to the performance of engine mounts to isolate the vibration.

The focus of this paper is to provide the study on the current advances in semi active engine mounts, in term of variety innovations of structural and magnetic circuit designs as well as modeling techniques involved in each innovation. The review is started with brief explanations of the operational modes, followed by the classification of semi active mounts. Next, the mathematical equations and different controllers used by the previous researchers were also studied. The proposed new design of semi active engine mounts is discussed in the last section.

II. OPERATIONAL MODES OF MAGNETORHEOLOGICAL FLUID

There are three basic operational modes in any utilization of MR fluid in a device, namely shear mode, flow mode and squeeze mode. However, another working mode was recently been proposed by Goncalves [31], called magnetic gradient pinch mode. Furthermore, MR devices can be operated in a combination of these modes.

Flow mode, also known as the valve mode, occurs when MR fluids is exposed to a magnetic field whilst the fluid flows between two fixed parallel magnetic surfaces. Figure 1(a) illustrates the concept of flow. Similar to shear mode, flow mode has an effective area, which is defined as the area where the flowing MR fluids is exposed to magnetic field. Flow mode is commonly applied in dampers and in other applications in which the devices require a valve to control fluid flow.

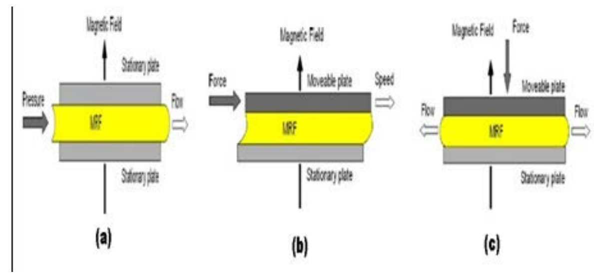


Fig. 1 MR Fluid operation (a) Flow mode, (b) Shear mode, (c) Squeeze mode [32]

Shear modes, also known as the clutch mode, occurs when MR fluid is exposed to the magnetic field between two parallel magnetic surfaces, in which one is moving whilst the other is fixed, as shown in Figure 1(b). The fluid shear area where MR fluid is exposed to magnetic field is called effective area of shear mode.

Squeeze mode occurs when MR fluid is exposed to the magnetic field while at the same time being compressed or decompressed as depicted in Figure 1(c). Squeeze mood is commonly used to isolate small excitation since it involves very small displacement. However, the resistive forces are very high. As the other modes, the magnitude of these resistive forces can be controlled by the magnetic field between the poles. Thus, it has been explored for use in small amplitude vibration and impact damper. Mounting device is one of the applications of squeeze modes operation [33].

The latest working mode is called magnetic gradient pinch mode. The basic idea of this mode is similar to flow mode but with a different design configuration of magnetic circuit. In the magnetic gradient pinch mode, as shown in Figure 2, the magnetic poles are arranged axially along the flow path and separated by a non-magnetic material. This kind of poles arrangement will create elliptical magnetic fibrils, which will block the flow of MR fluid in the valve gap.

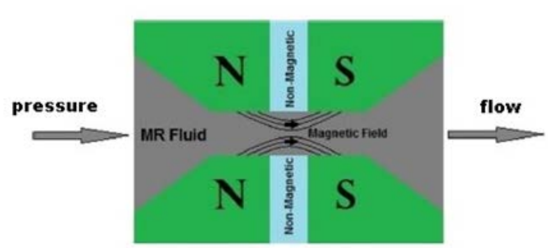


Fig. 2 MR Fluid operation named “gradient pinch mode”[15].

One of the unique characteristics of this mode is the slope between pressure and velocity relationship in magnetic gradient pinch mode will be significantly increased when the magnetic field is increased. This is unique, since in the conventional flow mode the slope tends to remain constant under any magnetic field strength modifications. Another advantage is the possibility to use MR fluid with coarser particles up to 100 µm, since a larger orifice is feasible to be used within the magnetic gradient pinch mode.

III. TYPES OF SEMI-ACTIVE MR MOUNTS

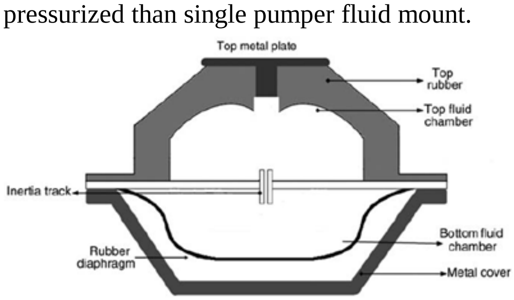
The MR mounts are categorized according to the types of MR operational fluids which are flow mode, shear mode, squeeze mode and gradient pinch mode. However, application of gradient pinch mode as application in mounts device is not common as the other 3 basic modes. The literature review about the application of MR fluid has been discovered in many publications such as Elahinia [34] and Imaduddin [15]

A. Flow mode

Basically, MR mounts is claimed to operate in flow mode also known as valve mode. Most of the designs of ER fluid and MR fluids based are maintaining the principle that conventional passive mounts. The replacement of smart fluids in the mounts enables the stiffness and damping characteristics to be controlled in real time. The MR and ER fluid will flow through the small holes (orifice) or otherwise the fluid flows at special path which called inertia tracks. The diameter size of the holes and the distance of inertia tracks have been discussed by the Barszcz [35].

1) Fluids Engine Mounts

Hydraulic engine mounts also called fluid mounts are elastomeric mounts in which fluid moving in between the top compliant and the bottom compliant rubber chamber. There are 2 types of fluid mounts which are single pumper fluid mounts [36] and double pumper fluid mounts [37]. The illustration of single and double pumper engine mounts is shown in Figure 3. The name of single pumper came because only one of the cavities does pumping while the double pumpers use both cavities. Since the upper and lower of plate are connected, it creates fails-safe condition. In case of one of the rubber fails, the other rubber still can function as they are linked. In addition, the top and bottom rubber section are stiff therefore the double pumper fluid mount are easier to be pressurized than single pumper fluid mount.



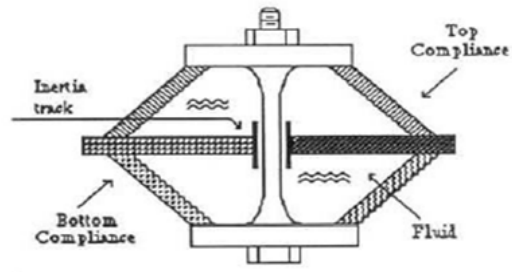


Fig. 3 (a) Typical single pumper hydraulic engine mount [38]. (b) Double pumper hydraulic engine mount [37]

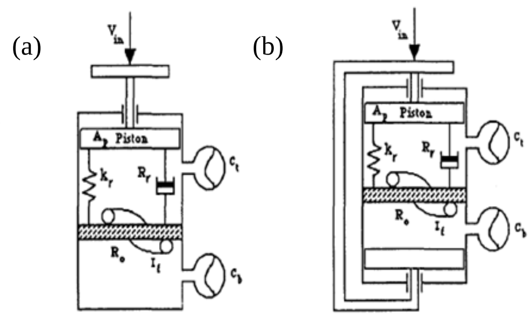
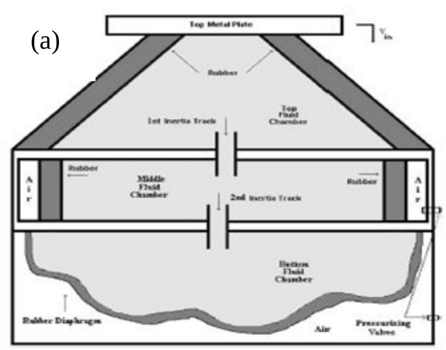


Fig. 4 Simplistic model of a (a) single and (b) double pumper fluid mount [37]

The single pumper fluid mount had discovered in [36],[37] successfully cabin noise and reduction vibration at only one frequency which is at the notch frequency. The notch frequency is produced by the oscillating fluid between the two fluids chambers due to the motion act on the fluid mount [39]. As the technology grows, the design of fluid mount improves in term of application and performance. Thus, new design namely double notch passive fluid mount was discovered to be the same concept design [36],[38] but add one more chamber as illustrate in Figure 6(a). This design able to give vibration and noise isolation at two frequencies compare to the single pumper that only isolate at only one frequency [36].



(b)

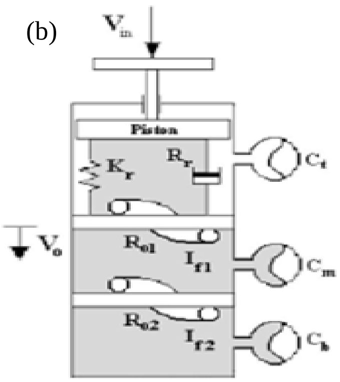
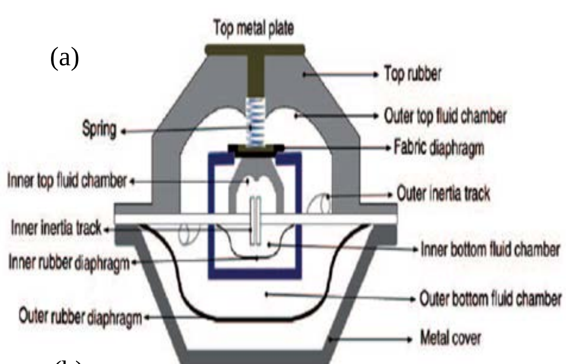


Fig. 5 (a) variable spring rate fluid mount design (b) it simplistic model [36]

The model of double notch fluid mount model is improved by using two different working fluids so that it is able to behave for double notch frequency and also one notch frequency [38]. Besides that, Vahdati [39] had proposed a variable bottom chamber volumetric stiffness fluid mount design as shown in Figure 6 (b). The semi actives type engine mount comes with multi-layer piezoelectric (PZT) beam. This design is able to reduce the notch frequency tuning cycle time, and eliminates fluid mount redesigns and re-manufacturing processes thus it save cost and time relatively. Besides that, due to the dynamic stiffness for a various notch frequency, it suits to a wider range of disturbance frequencies. However, there are some drawbacks had been discussed, PZT multilayer beams can only withstand small dynamic motion and high stress on the three layer PZT beam would cause it breaks or shattered.

(a)



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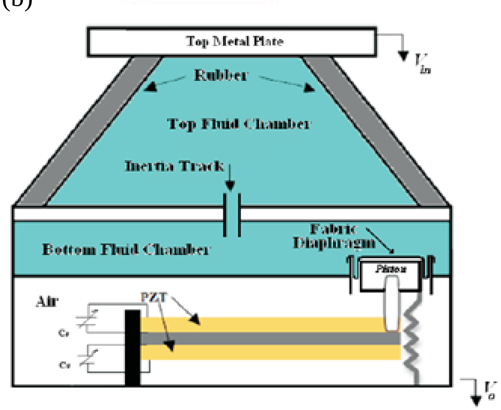

Fig. 6 (a) Double notch passive hydraulic propose by Tikani [38] (b) Variable bottom chamber volumetric stiffness fluid mounts design by Vahdati [39].

2) *Controllable Inertia Track of Hydraulic Mounts*

Changing in the inertia track area affects the dynamic properties of the mount [40]. The controllable inertia track of hydraulic mount design was proposed by Truong [41]. The notch and resonant frequencies of the mount change according to the divergence of the area of the inertia track. However, changing the geometry of the inertia track has a crucial effect on the flow resistance but it was ignored. Besides that, the hydraulic engine mounts' prototype using multiple tracks and orifices had been studied by Barszcz [35]. The prototypes used various design of inertia track and orifice and the number of inertia tracks in a controlled manner as shown in Figure 8.

The effect of diameter sized of the inertia tracks and orifice also had been studied. Also, the performance of the hydraulic prototypes with external capillary tube-type tracks and three internal orifice-type tracks has been discovered. In addition, Zhang [42] has proposed the design of hydraulic engine mounts (HEM) with multiple inertia tracks (MIT). There are 2 types of inertia track were used which has single and double for entrance and exits. However, the significant reduces of transmissibility of the mount require at certain optimal tuning of inertia track area.

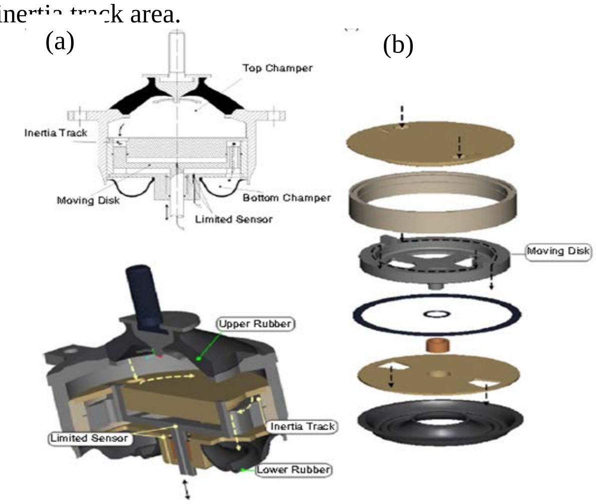

Fig. 7 Hydraulic mount with controllable inertia track: (a) cross section of a hydraulic mount and (b) assembly components [41].

(a)

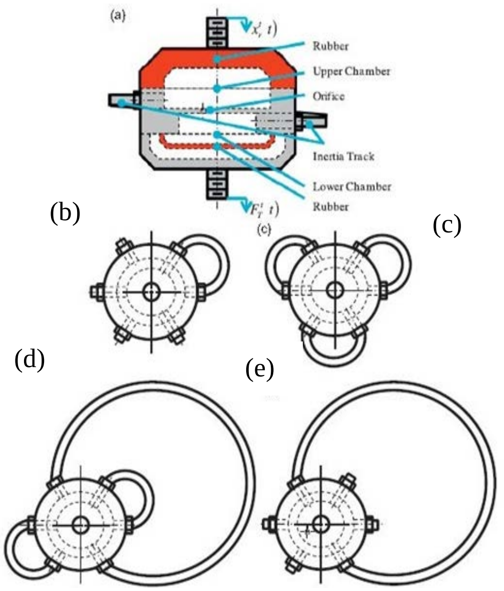

Fig. 8 Configuration of prototype mounts experiment [35]. (a) Schematic diagram with inertia track and orifice. (b, c, d and e) design that use in the experiment (top view).

Many publications have proven the effectiveness of the engine mount with moving plate decoupler, multiple numbers and various distances of inertia tracks. General inertia tracks acts at lower frequencies, while the decoupler is dominant at higher frequency. Thus, proper fine tune controller is needed.

B. Squeeze Mode

For an MR device operating in the squeeze mode, MR fluid is compressed between two end plates that also work as magnetic poles for a magnetic field to pass through as shown Figure 1 (c). As the fluid is compressed, the available volume between these end plates continuously become smaller, requiring a mean for the MR fluids in the gap to escape to avoid hydraulic lock-up. In facts, the MR fluid flow operation has been less applied in automotive industry however it has been discovered very useful to isolate vibration as engine mounting due to the vibration from engine and power trains systems involving small amplitude or displacement [43]. One of the semi active engine mount that had discovered earlier is MR elastomers.

1) MR Elastomers

Gong *et al.* [44] had proposed the good guideline to prepare the new MR elastomer. MR elastomers had shown great potential as a tuneable vibration isolator according to [45] MR fluid Elastomer undergoing an oscillatory input can achieve approximately 75% increase in output force with the addition of a magnetic field. The MR fluid elastomer was used by Wang describe as in Figure 9, where the elastomers act as casing and MR fluid in the centre cavity. The system setup places one magnetic pole directly below the fluid chamber separated by the elastomer, and a magnetic shield above the mount.

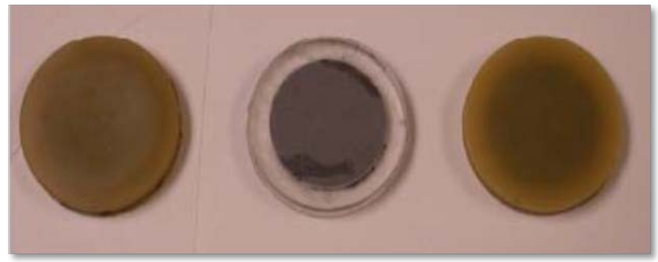

Fig. 9 MR Fluid elastromers [46].

The magnetic circuit, however, has been altered to place the poles of the electromagnet directly above and below the fluid chamber for improved magnetic efficiency. This design uses a large magnetic field generator which may be difficult to package. The magnetic field intensity, however, is able to achieve a sufficient amount of flux density in the fluid. David York et al. [47] had proposed a MR fluid elastomer (MRF-E) mounts developed using RTV615A/B (RTV) silicon and a polybutadiene polyol based polyurethane (poly BD-polyurethane) to be selected as the base elastomer materials for the MRF-E mount. Anna Boczkowska *et al.* [48] proposed urethane magnetorheological elastomers (MREs) which is manufactured using Polyurethane gel. From the compression test conducted under magnetic field, higher compressive strength distinguished. The stiffness of elastomer increases significantly as the number of ferromagnetic particle increases in the material.

S. R. Kumbhar.*et al.* [49] had fabricated four Sylgard's184 MR elastomer (60mm x 20mm) which two of them were prepared by using 20% iron powder with thickness 10 mm and 15 mm and another two of them was using 30% of iron power. A test was conducted to study the fractional change in shear modulus and in resonant frequency versus load (0 N, 2 N, and 4 N). As the results concluded, the fractional change in shear modulus and fractional change in resonant frequency increases by increasing applied magnetic field and also by increasing applied load [49]. The advantage of this MRE is it can operate with and without magnetic field. However, there are some drawbacks within this design including MRE inability to be applied for the high load.

C. Shear Mode

The application of shear mode operation MR fluid in automotive industry had been developed extensively on MR Brake and MR rotary damper. However, there are also mountings that used the principle working fluid but not in single mode operation. The operation of shear mode usually mixed with other modes as explained in mix modes section.

D. Mix mode

The mixed mode consists of flow-squeeze mode, flow-shear mode and shear-squeeze mode. This mode has become main focus in any implement of MR fluid in a device. This is due to the effectiveness of mix modes to give high working performance on the device.

1) Flow-squeeze Mode

The mixed mode MR fluid mount model shown in Figure 10 proposed by Wang [50] has two working modes: flow mode and squeeze mode. They are induced by separate electromagnetic coils so that the effects of each working mode and combined working mode can be investigated. When the MR fluid travel from one chamber to the other through the inertia track, the outer coil is activated and produces the magnetic field and the flow mode is on. The activation of the inner coil can hinder the motion of the rod which makes the squeeze mode. The stiffness and damping are therefore adjusted by the activation of the two working modes.

El Wahed and McEwan [51] proposed a MR fluid cell with mixed squeeze and flow mode MR fluid operation. This paper distinguishes the performance between single modes and mixed mode. The single mode operations tested were squeeze mode and flow mode. The contour line of flux line density and magnetic field distribution for each mode clearly shows using Ansyss software. Experimental assessment was done as to compare the effectiveness of the proposed mixed mode design. The performance of MR fluid under the mixed mode was significant enhanced over those in the squeeze and also flow modes. Although these designs prove the effectiveness of MR fluid in mixed mode MR operation, but the frequency that used is very small, which is 5 Hz. Since the engine vibration may produce larger than the used frequency, thus the capability of the MR fluid cell designed still cannot proved to be work for larger frequency.

2) Flow-shear Mode

Another example of mix mode operation of vibration is as proposed and had been fabricated by Choi *et al* [52] which used flow and shear mode operation. The mounts was successfully fabricated and tested for the purpose to isolate structural vibrations. The design is simple as shows in Figure 11. Furthermore, the mount has compact structure and operates without frictional components. However, there are some drawbacks of this design that can be discussed. Firstly, the natural rubber used has reaction with the MR fluid [53]. After period of time, the rubber will corrode and the elasticity of the rubber will decrease thus affect the stiffness of the rubber to support the object.

3) Shear-squeeze Mode

Even though the flow mode can produce large damping force due to MR effect but performance control can be worse if the excitation magnitude is small. Meanwhile, the squeeze mode is capable to achieve high damping force generated from MR effect. However this mode can work effectively in a very small vibration area only. Lastly, shear mode is capable to avoid solidification state in high field intensity, in contrast to the damping force generated from the MR effect which is relatively small compare the other modes. Thus, due to the drawbacks of single modes MR fluid operation, the mixed modes operation was the main focus as designed in the vibration isolator device. Instead of using flow mode combine with shear mode or squeeze mode, Yazid [54] proposed the squeeze and shear mixed modes via MR damper.

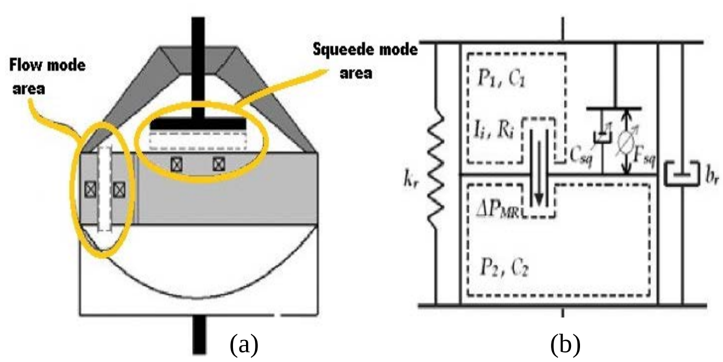

Fig. 10 Mixed mode semi active engine Mound Squeeze and flow mode (A) Schematic diagram (B) Physical Model [50]

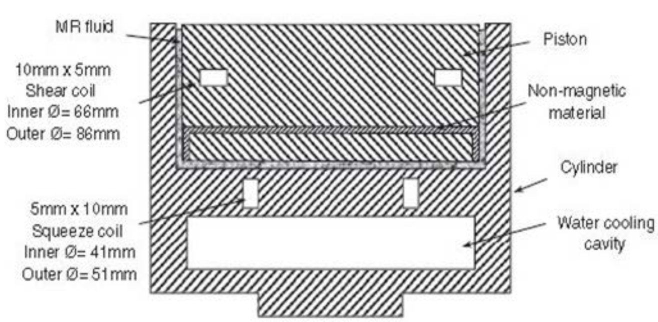

Fig. 11 MR fluid cell [51].

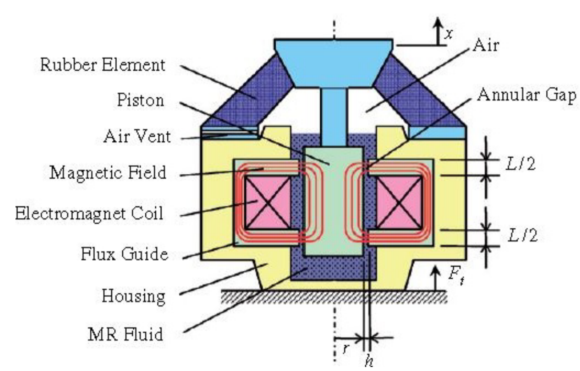

Fig. 12 Mixed mode design proposed by Choi [52].

IV. Modeling the Response of the MR Mounts

The dynamic characteristic models of hydraulic engine mount had been shown in many publications [27], [29], [55]. There are also some publications that used hydraulic mounts model with an addition of smart materials to improve the work performance of semi-active operational which was proposed by Cui [56]. There are also various mathematical model proposed for active engine mounts model for examples, Fakhari [57] was using Langrange’s and Newton-Euler equation to model the engine on the mounts. A Hosseini *et al*. [58] modelled engine mounts with solenoid actuator.

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

Where:

P_1 = pressure in the upper chamber.

P_2 = pressure in lower chamber of the mount.

I_i = fluid inertia.

R_i = fluid drag at zero magnetic field.

Q_i = fluid flow rate through the flow passage.

ΔP_{MR} = pressure drop due to the yield stress of the MR fluid.

The fluid pressure in upper and lower chambers can be calculated from the flow continuity equations:

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

$$\dot{P}_2 = \frac{Q_i}{C_2} \quad (3)$$

Where:

C_1 = compliances of the upper chambers.

C_2 = compliances of the lower chambers.

A_p = piston area of the top rubber part.

$\dot{x}$ = velocity of the top of the mounts.

Assuming that:

$$Q_i = A_i \dot{x}_i \quad (4)$$

Where:

A_i = cross sectional area of the flow passage.

$\dot{x}_i$ = fluid average velocity through the flow passage.

By substituting the integrations of (2) and (3) into (1) yields the following equations of motion for the fluid passing through the flow passage:

$$I_i A_i \ddot{x}_i + R_i A_i \dot{x}_i + A_i \left(\frac{1}{C_1} + \frac{1}{C_2} \right) x_i = \frac{A_p}{C_1} x + \Delta P_{MR} \quad (5)$$

Where:

x = displacement at the mount top.

The pressure difference induced by the MR effect can be expressed as:

$$\Delta P_{MR} = C \frac{L}{h} \tau_y (H) sign(\dot{x}_1) \quad (6)$$

Where:

C = is equal to 2, which corresponds to low-flow condition.

L = length inside the flow channel over which the magnetic field is applied.

h = Distance between the magnetic poles (equal to the gap of the annular duct).

$\tau_Y(H)$ = MR fluid yield stress at which magnetic field (H) is dependent.

The hydraulic-related parameters are defined by Adiguna *et al.* [59]. Since the flow path is straight, the inertia of the fluid inside the flow passage is simplified by:

$$L_i = \rho \, L / A_i \quad (7)$$

Where:

ρ = Density of the MR fluid.

L = Length of the flow passage.

The fluid resistance within the flow passage is approximated based on the orifice geometry which is rectangular,

$$R_i = 128 \eta \, L / \pi D_h^4 \quad (8)$$

Where:

η = MR fluid viscosity, which is shear rate dependent but assumed to be constant for this study.

D_h = Hydraulic diameter for an annular duct $(D_h = D_{outer} - D_{inner} = 2h)$.

The equation of motion pertaining to the squeeze mode is done by Hong *et al*. [7] as shown below:

$$M\ddot{x} + c_e \dot{x} + k_e x + C_{sq} \dot{x} + F_{sq} + A_p P_1 = F_{in} \quad (9)$$

Where:

F_{in} = Excitation force.

c_e = Rubber damping coefficients.

k_e = Rubber stiffness coefficients.

The damping constant associated with the viscous flow is

$$C_{sq} = \frac{3\pi R^3}{2(h_0 + x)^3} \quad (10)$$

The damping force due to the fluid squeeze is

$$F_{sq} = \frac{3\pi R^3}{4(h_0 + x)} \tau(H) sign(\dot{x}) \quad (11)$$

The variables from the previous equations are as follows: h_0 is the gap between the parallel plates at the static deflection and R is the radius of the two plates. After substituting P_1 by (2) into (9), the final equation of motion can be written:

$$M\ddot{x} + c_e \dot{x} + \left(k_e + \frac{A_p^2}{C_1} \right) x + C_{sq} \dot{x} + F_{sq} = \frac{A_i A_p}{C_1} x_i + F_{in} \quad (12)$$

V. CONTROL OF THE MR MOUNTS

Various control algorithms for MR fluid-based devices have been researched and proposed so that these semi-active devices can achieve adequate performance for vibration isolation. The control algorithms studied are described below and include linear quadratic Gaussian (LOG) control, ground hook control, skyhook control, fuzzy logic control, neural networks control, inversion-based control, integrator back stepping-based control, and hierarchical control. These controllers are used in different systems to achieve effective vibration isolation.

A. LOG Control

Hong and Choi [52], [60] designed a linear quadratic Gaussian controller for a mixed mode, flow, and shear, MR fluid-based mount used to isolate the vibration of a structural system. Non-dimensional formulation of the Bingham plastic flow model for the MR fluid was applied in the control strategy. The structural system composes of a vibrating mass, semi-active MR fluid mount, and passive rubber mounts. The MR mount is installed as a semi-active isolator between the vibrating mass and the beam structure which is hold up by two passive rubber mounts. The rubber element on the top of the MR mounts supports the mass on the one side and isolates the vibration transmission at the non-resonant frequency on the other side. The governing equation is presented and rewritten in a state space model. The LOG controller is designed and experimentally verified as shown in

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{13}$$

Where:

$\dot{x}(t)$ = Control state vector

A = The control system matrix,

B = The control input matrix,

$u(t)$ = The control system input,

The performance index chosen to be minimized is shown as follows:

$$J = \int_0^\infty \{x(t)^T Qx(t) + u(t)^T Ru(t)\}dt \tag{14}$$

Where:

Q = state weighting semi positive matrix.

R = input weighting positive matrix.

LQR is obtained as follows:

$$u(t) = -P^{-1}B^T x(t) = -Kx(t) \tag{15}$$

Where:

K = state feedback gain matrix.

P = solution of an algebraic Riccati equation to obtain feedback signals.

Two accelerometers are fixed on the vibrating mass and the flexible beam. The control voltage is calculated by LQG and applied to the MR mount via a digital-to-analog converter and a current generator. The acceleration levels of the structural system are diminished effectively by controlling the damping of the MR mount. The force transmission through the two rubber mounts is also conceals by activating the MR mount. However, the results show that acceleration and force transmission with the LQG control are higher than the one without control at higher frequencies.

B. Skyhook Control

Skyhook control is one of the most popular control methods for the R fluids device. Wang [50], [61] proposed a skyhook control designed for 2 DOF quarter car model using a mixed mode MR fluid mount. The force and displacement transmissibility are controlled to achieve simulation results. The governing equations can be represented as:

$$\begin{cases} \dot{x}(\dot{x}-\dot{z}) > 0 & Field \quad On \\ \dot{x}(\dot{x}-\dot{z}) < 0 & Field \quad Off \end{cases} \tag{16}$$

Where:

$\dot{x}$ = is absolute velocity of engine.

$(\dot{x}-\dot{z})$ = is the relative velocity between the engine and the chassis.

The condition of magnetic turn on is when the absolute velocity of the engine and the relative velocity between the engine and the chassis have the same direction. Meanwhile the off condition occurred when they have the opposite direction. Thus, the skyhook designed was to investigate the effect of skyhook control between flow mode, squeeze mode and combined modes. The skyhook controller has simple design and good to control the transmissibility. However, the displacement and force transmissibility need to be control under different condition.

C. Fuzzy Skyhook/Groundhook Control

Cheng [62] used fuzzy controller to regulate the damping of the MR damper and control the semi- active suspension system of vehicle. Matlab fuzzy logic controller had been used because of it convenient operation, easier and intuitive. As compared to the traditional passive suspension system, the fuzzy control enhances smoothness of the vehicle running with semi-active suspension. Thus, it reduces the body vibration.

Mina M.S. Kaldas [63] proposed adaptive fuzzy logic controller for semi active suspension. The rule base and interface engine are based on Mamdani-Type of fuzzy interface, while the defuzzification process is based on center of area method. The optimization routine was used to minimize the body acceleration and dynamic tire load, but at the same time maintain the suspension working space in the allowable limits.

D. Neural Networks Control

Wang and Liao [64] presented the modeling and control of MR fluid dampers using neural networks. Based on the modified Bouc-Wen constitutive model for MR fluids, the inherent nonlinear behavior of the MR fluid was modeled in feed forward neural networks (FNN) and recurrent neural networks (RNN). The results prove that the direct identification dynamic model using RNN can expect the damping force accurately, and the inverse dynamic mode using RNN can act as a damper controller to provide the command voltage for the MR fluid damper in semi-active mode. The simulation results are impressive and provide a new method for the MR fluid damper controller. However, this controller requires training. The training data needs to cover most situations occurring in practical applications and needs to be simple, in order to speed up the training process. Furthermore, the neural networks control works like a “black box” as the process of generating the outcome is not explicitly stated.

Miao Yu *et al.*[65] proposed a control structure for the purpose to stabilize the passenger vehicle system with magnetorheological (MR) fluid suspensions by using Fuzzy Neural Network (FNN) controller. The general algorithm (GA) and fuzzy associative memory neural network (FAMNN) were adopted in a designed FNN controller in order to improve roll stability. The effectiveness of the proposed controller method was demonstrated and later compared by computer simulation and also road test experiment. The results from both tests were supported and validated by comparing to the conventional sky-hook controller. The significant result shows the effectiveness of FNN controller reduced the vertical acceleration, pitch, and roll angular acceleration in frequency domain compared to the skyhook controller. In other word, the proposed FNN controller via MR suspension can improve both ride comfort and stability of vehicle.

E. Hierarchical Control

R Li et al [66] designed a control system for the squeeze mode MR fluid mount. Based on a model of three degree of freedom MR mount, a hierarchical fuzzy controller has been designed to decrease the vertical vibration force and roll moment transmitted from an engine. Where, a fuzzy controller was designed to isolate the engine vertical vibration on the control level. While, on the coordination level, fuzzy reasoning is adopted to realize a coordination strategy for tuning the damping of each engine mount in order to minimize the transmitted torque. MATLAB simulink software was used for the simulation and the validation of the simulation by using the experimental isolation system which using real engine. Simulation shows significant results between hierarchical fuzzy controller strategy and passive/hydraulic mount. This results was supported from the experimental results confirmed that engine hierarchical fuzzy controller system via MRF mounts performance is greater compared to the passive mounts system. The results of this research provide insight into the development of the control system for other effective isolation devices.

VI. IMPROVEMENT OF THE SEMI ACTIVE ENGINE MOUNTS

From the present and current MR mounts designs there are a few pro and contra that had been discovered. Besides that, the important characters to be had in engine mounts also had been determined. The past researchers mainly focus on the physical design of MR mounts compare to the current researcher that focus on optimization of Magnethorheological fluid characteristic on damper, brake and other automotive application[67]. The factor that affecting the MR fluids which are current supply and magnetic intensity produced can be investigate widely through Finite Element Method Magnetic(FEMM)[68].

Since MR fluid has 4 types of modes, thus MR mounts can be classified into 2 which were single and double modes. Single modes most problems are on the less effective upon the variable frequency disturbance. Squeeze mode is suitable for providing large damping however the working area is small, shear modes performance depending on surface contact area while flow mode has ability to absorb force excitation due to large damping force but to control the small excitation could be worse. The combinations of these modes encounter the drawback from the single modes [51]. However, combinations of these modes require a high current supply to activate the mounts magnetically. Besides that, in term of the performance it shows slightly increment and moreover the complex controller needed to ensure the operation each mode. Therefore, using single mode is more preferred and the drawback could improve by optimization and modification.

Flow modes and squeeze operation is most suitable to be apply in MR mounts however this paper focus on the flow modes operation because the successful application on shock absorber could be imply on the MR mounts. Therefore this paper would proposed the design of MR mounts should consider three parameter which are size of orifice, number of orifice, position of solenoid coil and working tracks area.

VII. NEW DESIGN OF MR MOUNTS

This paper proposed new design of semi-active engine mount using the MR fluid as shown in Figure 13. Generally the concept of this design based on the MR flow mode operation. Since the vibration of engine came from any direction this design assume that there were three motion that act on this design which are pitch, roll and engine vertical acceleration. By assuming these motion acts on the engine mount, the ball joint (1) is used to receive any of those motion excite by the engine. The excitation force act on the ball joint will transfer to the piston rod (4) that connects to the piston (5) sliding upward and downward. In other word, the variable force direction change into single movement by the piston.

The sliding movement of the piston channel by a chamber (9), besides that this chamber is a place where the operation of vibration reduction takes place. There are several parts that involve in the vibration reduction process which are spring (6), bearing seal (7), bearing cover (8), oil seal (10), MR fluid volume (14) and iron coil (12). The function of the spring is to accommodate the load of engine in static position. As the engine excite force to the engine mount, the sliding of piston up and down compress the MR fluid to flow up and down through small holes called orifice. Since the piston is surrounded by the iron core that is used to generate magnetic field in the present on electric current, the viscosity of MR fluid becoming higher. As the result, the force generated from the engine is scaled down before reach the vehicle body. The oil seal is placed in the bearing seal and lock up by the bearing cover. These combinations are to prevent leakage of MR fluid in the system. In addition, the O ring (11) is use at the piston due to the same purpose.

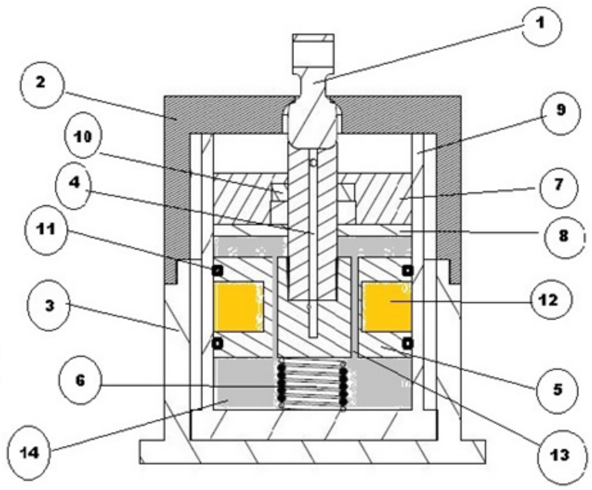

Fig. 13 Proposed a new semi active engine mount design.

VIII. CONCLUSION

An overview of various designs of engine mounts has been presented and categorized based on the MR fluid operational fluids, namely flow modes, shear modes and mix modes. The overview of the flow mode MR mounts was discovered and categorized into two types namely fluid engine mounts also called elastomeric mount and controllable inertia track's mount. Although a lot of MR mount design in flow mode operation had been developed, their potential to generate large damping force however performance could be deteriorated in controlling small excitation magnitude. In contrast, squeeze mode MR mount is also able to produce high damping force but the effective working area is very small. The squeeze mode MR mount can be classified into two types; MR elastromer (MRE) and MR squeeze mount. As compared to shear modes mounts, it produces lower damping force but it can avoid solidification state at high intensity region. The shear mode MR mount was not widely used as single operation in application of MR mounts. It is well known and applied to the rotational MR damper in application of MR brake devices. The mixed modes MR mount can be observed as the superposition of two individual modes. The dynamic stiffness envelope is very large, which can provide desired stiffness at any frequency. Besides that, the ability to set dynamic stiffness for any excitation amplitude optimized the vibration process. This feature also provides the flexibility to design the optimal control design for the mount with the least energy consumption. The future works include designing a suitable control strategy required in order to develop optimal operation of semi active MR mount and the installation of this mounts into a real vehicle body for actual experiment.

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