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An overview of the development of hydraulic mounting systems for internal combustion engines

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ABSTRACT: *Engine mounting system (EMs) is one of the systems that not only reduces noises, but also reduces the whole vehicle vibration at low frequency. The history of the EMs has been formed and developed for nearly 200 years from engine rubber mounting system to semi-active or active control engine mounting systems. In this study, an overview of the development of hydraulic engine mounting systems (HEMs) is analyzed through the research achieved results in recent years. The mathematical models of HEMs are developed from models of rubber engine mounting systems (REMs) using adding hydraulic damping coefficient. Research results have shown that HEMs could reduce vibrations very well compared to REMs at low frequencies which means that the vehicle ride comfort has been significantly improved. In addition, the study results provide researchers with an overview of HEMs in improving vehicle ride comfort at low frequencies.*

KEYWORDS: *Engine, mounting system, REMs, HEMs, ride comfort.*

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I. INTRODUCTION

Various types of internal combustion engine mounting system from rubber to semi-active or active Ems have been developed to improve vehicle noise and ride comfort. Snyman et. al [1] proposed to reduce engine vibration in the mounted 4-cylinder internal combustion engine. A mathematical model and balance mass and lead angle are taken as design variables. The objective function used in their research is the vibratory forces from the engine, transmitted to the engine mounts. The objective function is to be minimized to minimize the vibratory output of the engine, and the Leap frog optimization algorithm is employed to minimize the objective function. Yunhe Yu, et. al [2], made a survey on automotive engine mounts. The survey was based on overview and development of different engine mounts and optimization of the engine mount systems. They made a study about the ideal engine mounting system which would isolate the vibration excitations from the engine and shown the concentration requirement of improvement of frequency and amplitude dependent properties. They explored how the rubber mounts trade-off the static deflection and provides the vibration isolation and what way the hydraulic mounts provide the better performance than the rubber mounts. At the final they reviewed about the different methods of optimization of engine mounting systems and suggested that active mounting systems would be considered for future trend. To study and evaluate the noise and vibration reduction effectiveness of EMs, Karanth, et. Al [3] proposed methods for arranging the position and geometric size of the cushion, respectively, and evaluated the effectiveness of reducing engine noise and vibration at the measured cushion positions. To analyze the influence of engine thermal load on the vibration reduction efficiency of engine cushions, Miroslav Demic et. al [4] studied and showed that engine thermal load has a great influence on the vibration reduction efficiency of engine cushions when the engine temperature is high, and the characteristics of engine cushions are analyzed to affect vibration and noise. Two types of engine cushions are presented rubber and hydraulic mounts. Wang M et al. [5] studied and analyzed the characteristics of semi-active hydraulic mounts, thereby proposing a mathematical model and controller applied to analyze the characteristics of semi-active hydraulic mounts. Thanh Quoc and Kyoung Kwan Ahn [6] developed a theoretical model to isolate the vibrations from engine and to control the area of inertia track under shocks and multi-signal excitation in the passive HEMs. The authors introduced a controllable inertia track and made considerable changes in the dynamic properties with respect to the area of inertia track. They identified that the dynamic properties were varied as the inertia track was changed. The results of the numerical simulations showed that the vibration isolation of the passive engine mount was affected by changing the inertia track area and the optimization, developed based on the frequency band and magnitude, of dynamic properties was made. The authors were also identified that many of the researcher were not considered the displacement of the mount in the reduction of dynamic stiffness to reduce the force transmitted to chassis. Jinfang Hu, et. al [12] proposed an adaptive hydraulic engine mount (AHEM) without external energy device to and analyze its dynamic characteristics at broadband (0–250 Hz). J. Christopherson, et. al [13] proposed a bottomed-up floating decoupler of HEM to analyze its properties. Nader Vahdati et. al [14] proposed a new hydraulic engine mount design was introduced that are amplitude sensitive. The aim of this paper is to analyze an overview of the development of hydraulic engine mounting systems (HEMs) based on the mathematical models of HEMs that developed from models of rubber engine mounting systems (REMs) using adding hydraulic damping coefficient [18].

II. DEVELOPING PHYSICAL AND MATHEMATICAL MODEL OF HEMs

2.1. Development of engine mounting system

Currently, the design of internal combustion engine (ICE) mounting systems constantly evolving from REMs to advanced electromagnetic ICE mounting systems. Diagram of historical development of EMs is shown in Fig.1

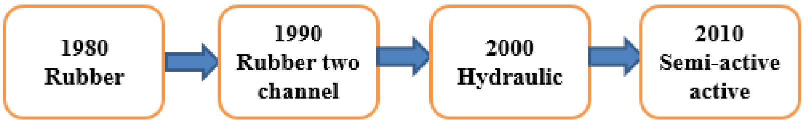

Fig 1. Diagram of historical development of EMs

From diagram of Fig.1, we shown that REMs was born very early, it not only reduces low frequency oscillation, but also reduces high frequency noise. However, it reduces vibrations very poorly at low frequencies due to its small frictional resistance coefficient. Rubber engine mounts is shown in Fig.2.

Fig 2. Rubber engine mounts

In response to the limitations of rubber mounts, hydraulic engine mounting systems were introduced in the early 1990s. These systems, which incorporate hydraulic fluid chambers in conjunction with rubber components, offer enhanced damping characteristics especially effective at low excitation frequencies. HEMs are made of rubber, and they feature a hollow centre filled with hydraulic fluid, usually a glycol/water mixture. As well as supporting the engine, HEMs must absorb two main types of vibration: (i) Low frequency vibration that comes from shock excitation – accelerating or braking hard and driving on rough surfaces for example and (ii) High frequency vibration that comes from unbalanced engine forces, such as from firing pulses or any mass imbalance in the rotating or reciprocal engine parts. To be most effective, a mount must be frequency dependent. This means stiff and highly damped in the low frequency range and the opposite in the high range – soft and light – to prevent the engine from moving due to shock excitation. This is where hydraulic engine mounts come into their own – they can be highly tuned for optimum dampening of vibration, without allowing engine movement. Structure of HEMs is shown Fig.3. From the structure of Fig.3 has shown that HEMs added a linear or nonlinear viscous damping to the system for the whole working range of frequencies and amplitudes. No damping at low amplitude was required, so there was a motivation to design a mechanism that makes the fluid moving only at high amplitude

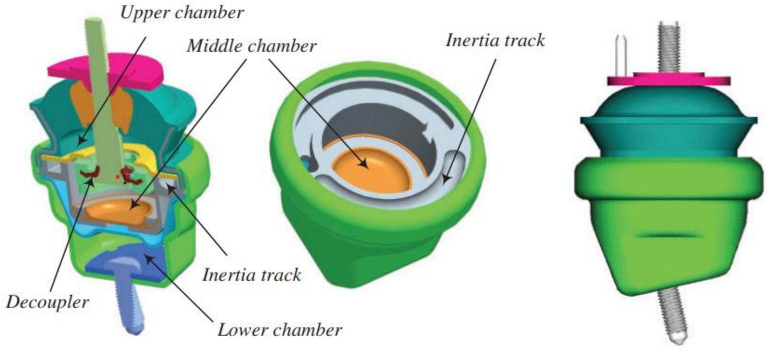

Fig 3. Structure of HEMs [7].

While the combination of hydraulic and rubber vibration isolators has improved ride quality especially under low-frequency excitations thanks to superior damping characteristics, these passive systems fall short in addressing the evolving requirements of modern vehicles. In response to the demand for adaptive and intelligent isolation systems, semi-active vibration isolators have been proposed as a more effective solution, as shown in Fig. 4.

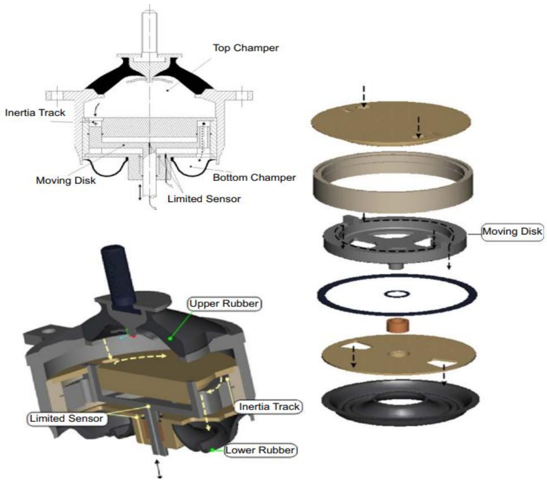

Fig 4. Semi-active HEMs [5]

Currently, in the trend of developing and perfecting the internal combustion engine vibration isolators. Active mounting system is the clearest proof. They are intelligently controlled according to the program both stiffness and drag coefficient parameters, and suitable for all engine operating modes, thereby maximizing effectiveness comfort is shown in Fig.5.

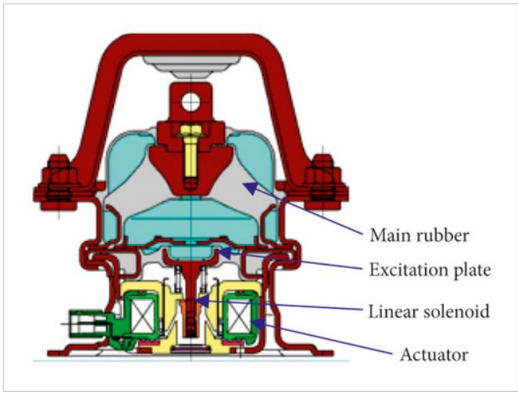

Fig 5. Active electromagnetic engine mounts [8]

2.2. Physical and Mathematical model of HEMs

Structure of HEMs [14] includes a piston, a spring- energized Teflon-coated seal, a Teflon bearing with extremely low surface friction, and a nonlinear spring with low hysteretic damping replace the soft rubber diaphragm. Mathematical model of HEMs established and developed by bond graph model.

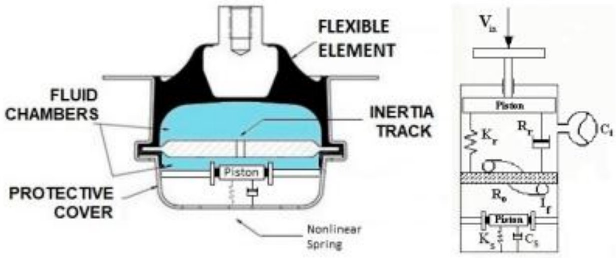

Fig. 6. Physical model of HEMs [14]

Physical model of HEMs [14] is shown in Fig.7, the achieved results has shown that the interior dynamics of HEM was modeled by analyzing the flows Q_d, Q_i and employing the fluid continuity. The moving fluids through decoupler and inertia track was assumed as two moving masses, and a balance of forces provide the equations of motions. The flows passing through the decoupler cage and inertia track are proportional to the flow velocity.

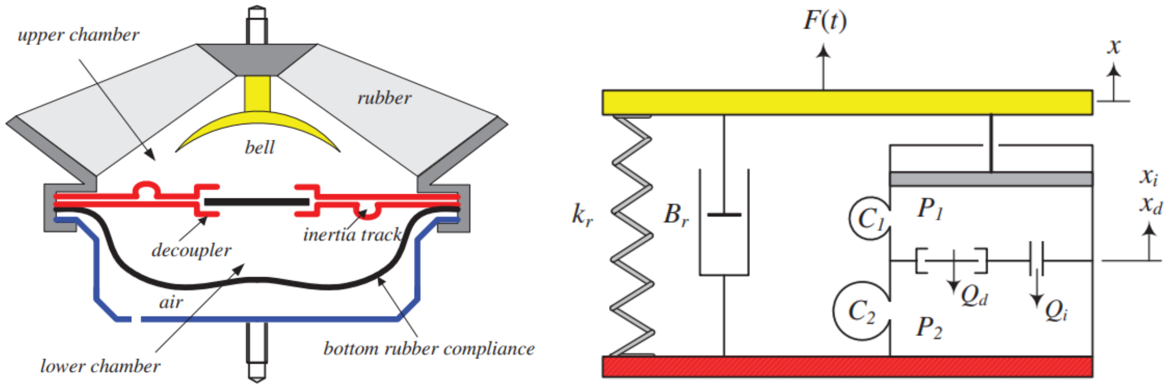

Fig. 7. Physical model of HEMs [14]

Finite element method is used to analyze the characteristics of HEM, the research results suggested a fluid–structure interaction (FSI) finite element analysis (FEA) method and a non-linear FEA technology to determine the system parameters, and a fully coupled FSI model is developed for modelling the static and lower-frequency performance of an HEM. The numerical simulation for an HEM with an inertia track and a free decoupler [15] was suggested based on the FSI model and the LP model along with the estimated system parameters, and again the simulation results are compared with experimental data.

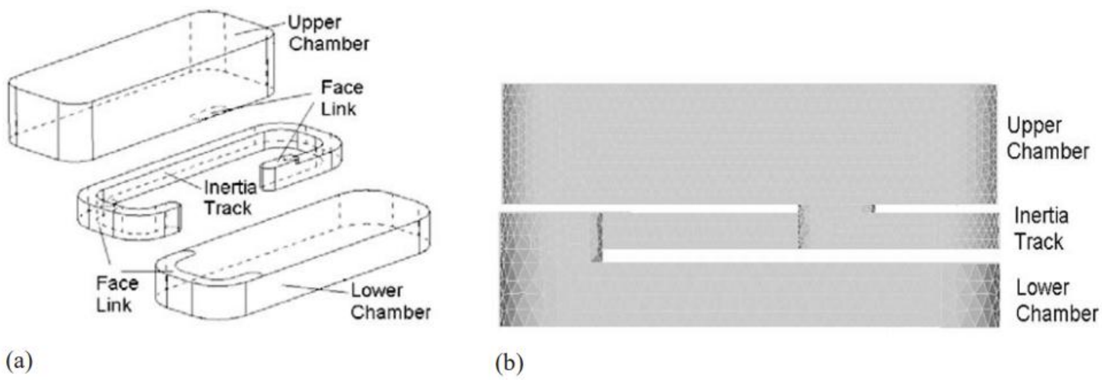

Fig. 8. The fluid model to calculate the inertia and the resistance of fluid in inertia track [15]: (a) Geometry model. (b) FEM model.

The approximate model of HEM with inertia track and decoupler [17] was established, as shown in **Fig. 9**. The model effective values include the inertia track fluid mass $m_i=A_p^2I_i$, the decoupler fluid mass $m_d=A_p^2I_d$, the inertia track damping $c_{hi}= A_p^2R_i$, the decoupler damping $c_{hd}= A_p^2R_d$, the upper chamber fluid stiffness $k_{h1}= A_p^2/C_1$, the lower chamber fluid stiffness $k_{h2}= A_p^2/C_2$, The absolute displacement of the inertia track fluid mass (m_i) z_{hi}, and the the relative displacement between the effective masses (m_i and m_d) z_{hd}.

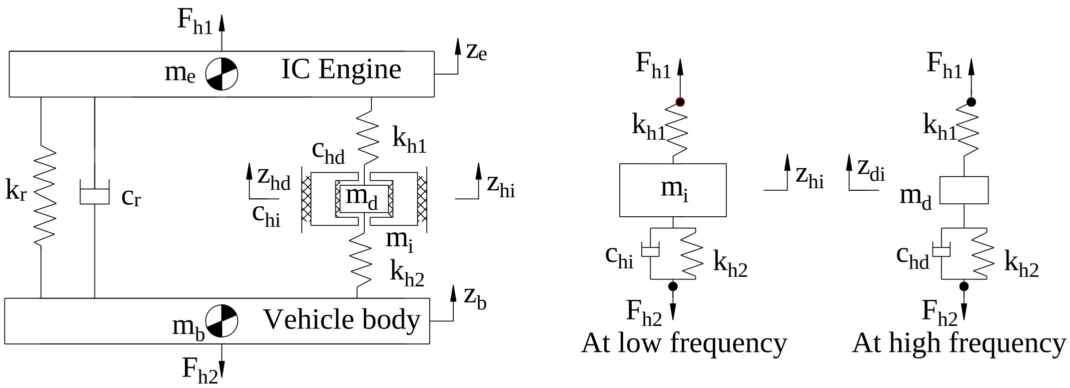

Fig. 9. Approximate model of HEM with inertia track and decoupler.

The vertical forces of HEM with inertia track and decoupler transmitting to the engine and vehicle bodies are considered in two cases below.

Case 1: The decoupler is contacting the cage in which HEM is only considered as an inertia track fluid mass element at low frequencies, $q_d(t)\approx 0$, $R_d\rightarrow\infty$. The vertical forces of HEM transmitting to engine and vehicle bodies are defined as

$$\begin{cases} F_{e1} = F_r + F_{h1} = k_r(z_e - z_b) + c_r(\dot{z}_e - \dot{z}_b) + k_{h1}\left(z_e - z_{hi}\right) \\ F_{e2} = F_r + F_{h2} = k_r(z_e - z_b) + c_r(\dot{z}_e - \dot{z}_b) + k_{h2}\left(z_{hi} - z_b\right) + c_{hi}\left(\dot{z}_{hi} - \dot{z}_b\right) \end{cases} \tag{1}$$

The effective governing equation of the inertia track fluid mass m_i is defined as

$$m_i\ddot{z}_{hi} = k_{h1}\left(z_e - z_{hi}\right) - k_{h2}\left(z_{hi} - z_b\right) - c_{hi}\left(\dot{z}_{hi} - \dot{z}_b\right) \tag{2}$$

Case 2: The decoupler is free and HEM is considered as a decoupler fluid mass element at high frequencies, $q_i(t)\approx 0$, $R_i\rightarrow\infty$. The vertical forces of HEM transmitted to engine and vehicle bodies are defined as

$$\begin{cases} F_{e1} = F_r + F_{h1} = k_r(z_e - z_b) + c_r(\dot{z}_e - \dot{z}_b) + k_{h1}\left(z_e - z_{di}\right) \\ F_{e2} = F_r + F_{h2} = k_r(z_e - z_b) + c_r(\dot{z}_e - \dot{z}_b) + k_{h2}\left(z_{di} - z_b\right) + c_{di}\left(\dot{z}_{hi} - \dot{z}_b\right) \end{cases} \tag{3}$$

The effective governing equation of the decoupler fluid mass m_d is defined as

$$m_d\ddot{z}_{di} = k_{h1}\left(z_e - z_{di}\right) - k_{h2}\left(z_{di} - z_b\right) - c_{di}\left(\dot{z}_{di} - \dot{z}_b\right) \tag{4}$$

III. CONCLUSIONS

In this study: an overview of the development of hydraulic engine mounting systems (HEMs) was analyzed through the research achieved results in recent years. The physical and mathematical models of HEM were developed from models of rubber engine mounting systems (REMs) using adding hydraulic damping coefficient. The overall analysis results showed that HEM not only reduce vibrations at low frequencies but also reduces vibrations at high frequencies under various operating conditions. In addition, the results of model development have shown researchers the direction for developing optimal HEM design.

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