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A comparison of the performance of hydraulic engine mounting system with rubber engine mounting system via vehicle ride comfort

Doan Thanh Binh, Vi Thi Phuong Thao[2], Hoang Thi Them[3], Nguyen Thi Kim Thoa[4]

[1, 4]*Faculty of Automotive and Power Machinery Engineering, Thai Nguyen University of Technology, Thai Nguyen, Vietnam*

[2 ,3]*Faculty of International Training, Thai Nguyen University of Technology, Thai Nguyen, Vietnam*

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ABSTRACT: The engine mounts affect largely the noise, vibration, and harshness comfort of vehicle. This studypresents a comparison of the performance of hydraulic engine mounting system (HEMs) with rubber engine mounting system (REMs) via vehicle ride comfort. A full-vehicle dynamic modelis established under the combination of two excitation sources such as internal combustion engine and road surface excitations.The time domain and power spectral density (PSD) acceleration responses of the vertical motion, pitch and roll angles of vehicle body are chosen as objective functions to compare the vehicle ride comfort performance of the HEMs and REMs. The obtained results indicate that the peak amplitude values of the time domain and PSD acceleration responses with HEMs respectively reduce in comparison with REMs under the different operating conditions. The study results propose a theoretical basis for the optimal design of the internal combustionengine mount systems for vehicles.

KEYWORDS: Internal combustion engine (ICE), Hydraulic engine mount (HEM), Rubber engine mount (REM), Full-vehicle Dynamic model, Ride comfort.

I. INTRODUCTION

Engine vibration not only has an important effect on the vehicle noise, but also has an important effect on vehicle ride comfort. So, vehicle engine mount has an important role in reducing the sources of engine vibrations transmitting to the vehicle body and vehicle body vibrations transmitting to the engine which uses to improve vehicle ride comfort and reduce vehicle noise. The effect of the adding damping coefficient values into the rubber mounting system on vehicle ride comfort was analyzed and evaluated unsing a full-vehicle vibration model with 10 degrees of freedom is established under the combination of road surface roughness and ICE excitations [1]. The hydraulic engine mounts (HEMs) were proposed and analysed its effects on on the engine shake performance by comparing the results obtained from the known 13 DOF model [2].The vehicle ride comfort performance between the hydraulic engine mount system (HEMs) and rubber engine mount system (REMs) were proposed and analysed using a full-vehicle dynamic model under the combination of two excitation sources such as internal combustion engine and road surface excitations [3]. In orderto improve vehicle comfort, designers and manufacturers are constantly improving the technology of the engine mounting system. A hierarchical fuzzy control (HFC) system for a magnetorheological fluids (MRF) mount was proposed to decrease the vertical vibration force and roll moment transmitted from an engine to a foundation [4]. A study presented the modelling, simulation and design of a semi-active engine mount that is designed specifically to address the complicated vibration pattern of variable displacement engines (VDE). The ideal isolation for VDE was required the stiffness to be switchable upon cylinder activation/deactivation operating modes [5].The vibration control of a passenger vehicle using an electronically controllable electro-rheological (ER) engine mount wasproposed and analyzedthrough a hardware-in-the-loop simulation (HILS), and control responses [6].

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The main purpose of this study is to propose a comparison of the performance of hydraulic engine mounting system (HEMs) with rubber engine mounting system (REMs) via vehicle ride comfort. A full-vehicle dynamic modelis established on the basis of the results of the reference under the combination of two excitation sources such as internal combustion engine and road surface excitations [3].The time domain and power spectral density (PSD) acceleration responses of the vertical motion, pitch and roll angles of vehicle body are chosen as objective functions to compare the vehicle ride comfort performance of the HEMs and REMs.

II. FULL-VEHICLE DYNAMIC MODEL

In order to evaluate the vehicle ride comfort performance of the hydraulic engine mount system (HEMs) compared with rubber engine mounting system (REMs), a full-vehicle dynamic model is established on the basis of the results of the reference [3] under the combination of two excitation sources such as the internal combustion engine and road surface excitations, as shown in Fig.1.

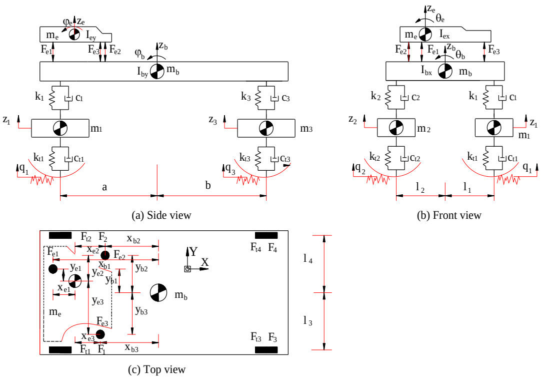

Figure 1. Full-vehicle dynamic model [3]

Explanation of the symbols for Fig. 1, the vertical displacements of engine body, vehicle body, and axles are m_e, m_b, and m_s, the angular and vertical displacements are z_e, z_b, and z_s, the angular displacements of engine and vehicle bodies are φ_e, θ_e and φ_b, θ_b, the inertia moments of engine and vehicle masses are I_{ex}, I_{ey} and I_{bx}, I_{by}, the stiffness and damping coefficients of vehicle suspension systems, engine mounting systems and tires are k_{en}, and c_{en}, k_s and c_s and k_{ts} and c_{ts}, the distances are a, b and l_s, X and Y-position of engine mount No.1, No.2 and No.3 with respect to the center of gravity of the vehicle body are x_{bn} and y_{bn}; X and Y-position of engine mount No.1, No.2 and No.3 with respect to the center of gravity of the engine body are x_{en} and y_{en} and the road surface excitations are denoted by q_n (s=1÷4, n=1÷3).

The equations of motion of the bodies in Fig.1could be written by using a combined method of the multi-body system theory and D'Alembert's principle as follows.For example, the equations of motion for the vertical, pitch and roll motions of engine body are written by Eq.(1). Where, F_{en} are the vertical forces of engine mount system, F_{ez}, M_{ex} and M_{ey} is the vertical force and momentsof the internal combustion engine excitations.

$$\begin{cases} m_e\ddot{z}_e = F_{ez} - \sum_{n=1}^{n=3} F_{en} \\ I_{ey}\ddot{\varphi}_e = M_{ey} + F_{e1}x_{e1} - F_{e2}x_{e2} - F_{e3}x_{e3} \\ I_{ex}\ddot{\theta}_e = M_{ex} + F_{e1}y_{e1} + F_{e2}y_{e2} - F_{e3}y_{e3} \end{cases} \quad (1)$$

To determine the vertical forces of rubber engine mount (REM), the linear dynamics model of REM is shown in Figure 2.

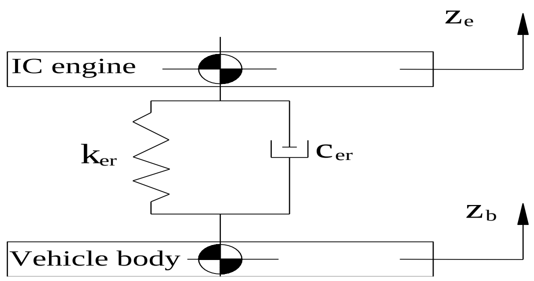

Figure 2. The linear dynamics model of rubber engine mount (REM)

From Figure 2, the vertical forces of REM transmitting to engine and vehicle bodies[3] are defined as

$$F_{en} = k_{ern}\left(z_{en} - z_{bn}\right) + c_{ern}\left(\dot{z}_{en} - \dot{z}_{bn}\right) \quad (2)$$

where, k_{ern} and c_{ern} are the stiffness and damping coefficients of REM.

To determine the vertical forces ofthe hydraulic engine mount (HEM), the linear dynamics model of HEM is shown in Figure 3.

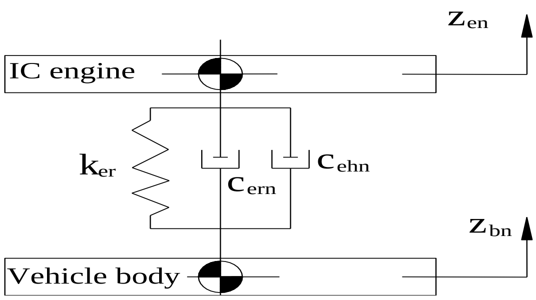

Figure 3. The linear dynamics model of rubber engine mounting system (REMs)

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From Figure 3, the vertical forces of HEM transmitting to engine and vehicle bodies[3] are defined as

$$F_{en} = k_{ehn}\left(z_{en} - z_{bn}\right) + c_{ern}\left(\dot{z}_{en} - \dot{z}_{bn}\right) + c_{ehn}\left(\dot{z}_{en} - \dot{z}_{bn}\right) \quad (3)$$

where, k_{ehn} and c_{ern} are the stiffness and damping coefficientsof HEM, c_{ehn} are the hydraulic damping coefficients of HEM.

Road surface excitation[3]:In this study, the filtering white noise method is used to describe the time domain excitation of the road surface based on reference [3] and time domain representation of the road surface can be given

$$\dot{q}(t) + 2\pi f_0 q(t) = 2\pi n_0 \sqrt{G_q(n_0) v} w(t) \quad (4)$$

where, $G_q(n_0)$ is the road roughness coefficient which is defined for typical road classes from A (very good) to H (very poor) according to ISO 8068(1995) [7], v=f/n is the speed of vehicle from 10 m/s to 30 m/s, n is the road space frequency from 0.013 m^{-1} to 3.33 m^{-1}, and it can guarantee the temporal frequency of road surface *f* ranges from 0.33 Hz to 28.3 Hz which is the low excitation frequencies of road surfacetransmitted to vehicle body; f_0 is a minimal boundary frequency with a value of 0.0628 Hz;n_0 isareference spatial frequency which is equal to 0.1 m; w(t) is a whitenoise signal.

Internal combustion engine excitations [3,8]: In this study, the vertical inertia excitation force due to the reciprocating mass of engine, the roll and pitch excitation moments of engine with a 4-stroke in-line engine are defined as

$$F_{ez} = 4m_p r\lambda\omega^2 \cos(2\omega t) = 4m_p r\lambda\omega^2 \cos(2\pi ft) \quad (5)$$

$$M_{ex} = M_e\left[1 + 1.3\sin(2\omega t)\right] = M_e\left[1 + 1.3\sin(2\pi ft)\right] \quad (6)$$

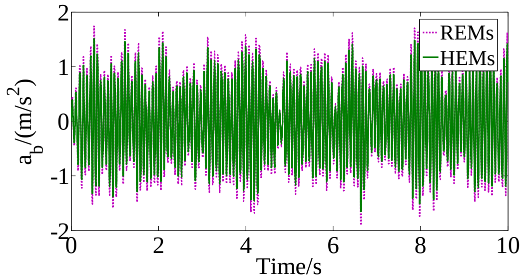
$$M_{ey} = 4m_p r\lambda\omega^2 l_r \cos(2\omega t) = 4m_p r\lambda\omega^2 l_r \cos(2\pi f t \quad (7)$$

where, ω=2πf is the angular velocity of crank shaft, f= n_e/60 is the excitation engine frequency, n_e is the engine speed, m_p is the pistonmass, M_e is mean value of ICE torque M_e= -6.810$^{-6}n_e^2$ + 0.059n_e + 112.5 N.m, r is the rotational radius of crank arm, λ is the ratio of r to the length of the shaft, l_r isthe distance between the CG and the centre-line of the second and third cylinders.

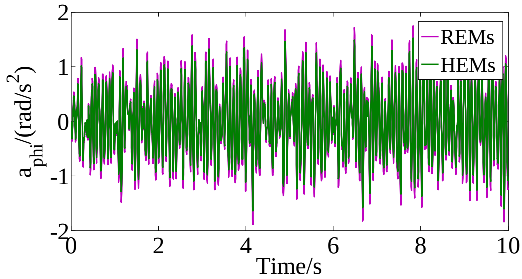
III. RESULTS AND ANALYSIS

In order to compare the ride comfort performance of the hydraulic engine mounting system (HEMs) with that of rubber engine mounting system (REMs), Matlab/simulink software is used to solve the equations of motion in the above section with vehicle and engine parameters in references [3]when the vehicle and engine operate under different road conditions. The simulation results of the time domain acceleration responses of the vertical motion (a_b), pitch and roll angles (a_{phi} and a_{teta}) of vehicle body are shown in Figure.4when the vehicle moves on ISO class B surfaces road condition and ICE engine operates at the speed of 1680prm (vehicle speed of 72 km/h).

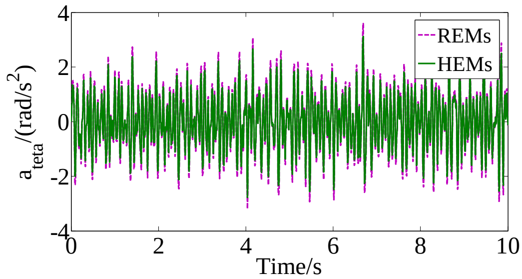
From the results of Figure 4, the peak amplitude values of the time domain acceleration responses of the vertical motion (a_b), pitch and roll angles (a_{phi} and a_{teta}) of vehicle body with HEMsare respectively reduce in comparison with REMs. The hydraulic damping coefficient plays an important role in reducing body vibrations. It proves thatthe vehicle ride comfort performance of HEMs is significantly improved in comparison with REMs.Other operating conditions will be further considered below.



(a) Vertical motion of vehicle body



(b) Pitch angle of vehicle body

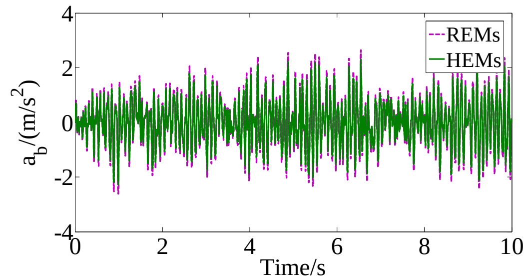


(c) Roll angle of vehicle body

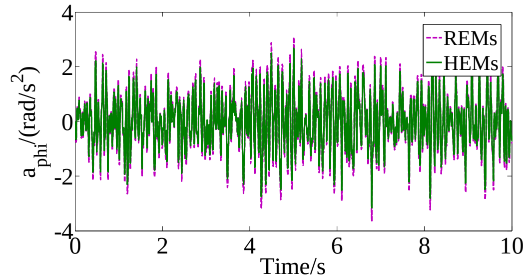
Figure 4. The simulation results of the time domain acceleration responses of the vertical motion (a_b), pitch and roll angles (a_{phi} and a_{teta}) of vehicle bodywhen the vehicle moves on ISO class B

surfaces road condition and ICE engine operates at the speed of 1680prm (vehicle speed of 72 km/h).

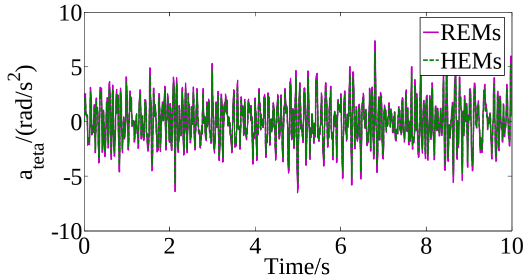
The simulation results of the time domain acceleration responses of the vertical motion (a_b), pitch and roll angles (a_{phi} and a_{teta}) of vehicle body are shown in Figure 5when the vehicle moves on ISO class D surfaces road condition and ICE engine operates at the speed of 1400prm (vehicle speed of 48 km/h). Similarly,the obtained results of Figure 5 show that the peak amplitude values of the time domain acceleration responses of the vertical motion (a_b), pitch and roll angles (a_{phi} and a_{teta}) of vehicle body with HEMsare respectively reduce in comparison with HEMs.However, the peak amplitude values of the time domain acceleration responses of the vertical motion (a_b), pitch and roll angles (a_{phi} and a_{teta}) of vehicle bodyincrease rapidly when vehicle moves on bad road surface.



(a) Vertical motion of vehicle body



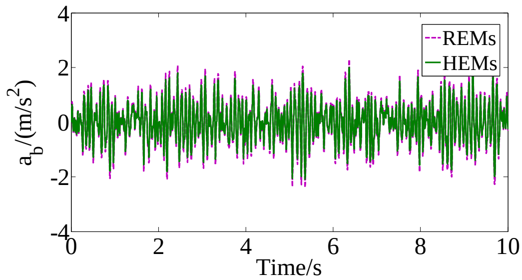
(b) Pitch angle of vehicle body



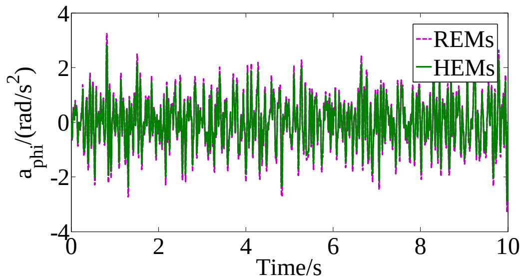
(c) Roll angle of vehicle body

Figure 5. The simulation results of the time domain acceleration responses of the vertical motion (a_b), pitch and roll angles (a_{phi} and a_{teta}) of vehicle bodywhen the vehicle moves on ISO class D surfaces road condition and ICE engine operates at the speed of 1400prm (vehicle speed of 48 km/h).

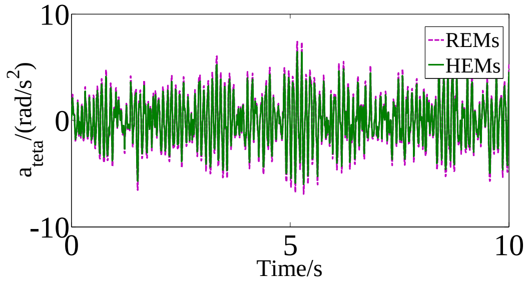
The simulation results of the time domain acceleration responses of the vertical motion (a_b), pitch and roll angles (a_{phi} and a_{teta}) of vehicle body are shown in Figure 6when the vehicle moves on ISO class D surfaces road condition and ICE engine operates at the speed of 1400prm (vehicle speed of 36 km/h). From the results of Figure 6, we show that the peak amplitude values of the peak amplitude values of the time domain acceleration responses of the vertical motion (a_b), pitch and roll angles (a_{phi} and a_{teta}) of vehicle body with HEMsare respectively reduce in comparison with HEMs. The peak amplitude values of a_b, a_{phi} and $a_{teta}$are respectively reduce when the moving speed of the vehicle decreases. Therefore, the performance of reducing the vibration of the hydraulic damping coefficient is better than that of the internal friction coefficient of rubberat the low frequency excitations.



(a) Vertical motion of vehicle body



(b) Pitch angle of vehicle body



(c) Roll angle of vehicle body

Figure 6. The simulation results of the time domain acceleration responses of the vertical motion (a_b), pitch and roll angles (a_{phi} and a_{teta}) of vehicle

bodywhen the vehicle moves on ISO class D surfaces road condition and ICE engine operates at the speed of 1400prm (vehicle speed of 36 km/h).

IV.CONCLUSION

In this study, a full-vehicle dynamic modelunder the combination of two excitation sources such as the internal combustion engine and road surface excitationsproposed to analyzethe ride comfort performance of HEMscompared with that of REMsunder the different operating conditions. The major conclusions drawn from the analysis can be summarizedas follows:(1)The peak amplitude values of a_b, a_{phi} and $a_{teta}$with HEMs are respectively reducein comparison with REMs under survey conditions; (2)The peak amplitude values of a_b, a_{phi} and a_{teta}increase rapidly when vehicle moves on bad road surface; (3)The peak amplitude values of a_b, a_{phi} and $a_{teta}$are respectively reduce when the moving speed of the vehicle decreases.The development directions, the author's team will focus on controlling the hydraulic damping coefficients of semi-active mounting system for the internal combustion engines.

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