Optimal Switching Parameter Control of Semi-Active Engine Mount

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Abstract

This paper describes work on isolation of vibration related engine by a hydraulic engine mount with controllable area of inertia track. Automotive engine mounts are required to constrain motion of engine shake resulting from low-frequency road input of shock excitation and also to isolate noise and vibration generated by the engine with unbalanced disturbance at the high frequency range. The property of the mount depends on vibration amplitude and excitation frequency, which means that the excitation amplitude is large in low excitation frequency range and small in high frequency range. In this paper, theoretical works with model of the mount to reduce vibrations related engine were conducted. The volumetric stiffness of the mount is greatly changed according to the switching the area of the inertia track. Therefore, when the area of the inertia track is tuned, the transmissibility of the mount is effectively reduced.

Keywords: Engine mount; Hydraulic mount; Vibration isolation; semi-active vibration control

1. INTRODUCTION

Automotive engine mount are require to constrain motion of engine shake resulting from shock excitation and also to isolate noise and vibration generated by the engine with unbalanced disturbance. Vibration frequency of engine shake is low and vibration amplitude is large, while vibration frequency of unbalanced vibration of engine is high and vibration amplitude is small. High damping and stiffness are needed to reduce the vibration of the engine shake, but low damping and stiffness are required to reduce the noise and unbalanced vibration [1-3].

Damping of a conventional rubber is enough to isolated engine shake. Increasing damping increase noise and vibration in high frequency range. Therefore, hydraulic mounts with inertia track are developed to increase damping in low frequency range and to reduce unbalanced vibration [4-7]. However, the hydraulic mounts have resonance peak created by fluid flow. To reduce the resonance peak, decoupler is inserted in the hydraulic mount.

On the other hand, semi-active and active hydraulic mount have been developed to increase performance of the passive hydraulic mount [9-10]. Since semi-active mounts have more simple structures and lower electric power and lower cost to make the mounts, many researches works on semi-active mounts.

In the paper, a new hydraulic mount with controllable area of the inertia track is proposed. The design parameter of area inertia track in the hydraulic mount is the most sensitivity for performance of the mount. When the area of the inertia track is changed, volumetric stiffness is greatly changed.

The obtained results from numerical simulation show that the transmissibility of the mount is greatly reduced by tuning the area of the inertia track.

2. MATHEMATICAL MODEL OF HYDRAULIC MOUNT WITH CONTROLLABLE AREA OF THE INERTIA TRACK

Physical description of Semi-active hydraulic engine mount is showed as Fig. 1. The mount consists of a rubber structure contain two fluid chambers: upper chamber (main chamber), lower chamber (compression chamber) and controllable area of inertia track which controlled by a servo motor.

Mathematical model of the hydraulic mount is considered such as Fig. 2. The hydraulic and mechanical model can be transferred to mechanical mode shown in Fig. 3. When the area of the inertia track changed, the fluid does not flow in the inertia track. Therefore, the model of the mount is changed from the model of Figs. 3-4. The volumetric damping of chamber is neglected (assumed $B_{vt} = 0$ and $B_{vb} = 0$).

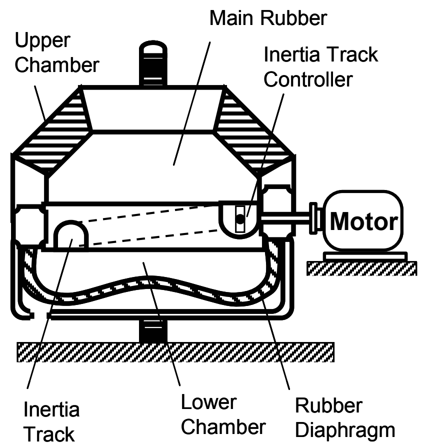

Fig. 1 Schematic diagram of a hydraulic mount with variable inertia track

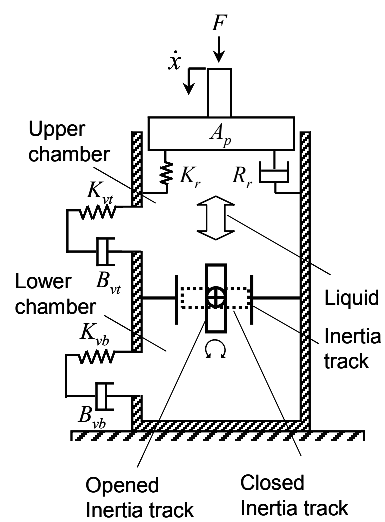

Fig. 2 Hydraulic and mechanical model of the mount with controllable Inertia Track.

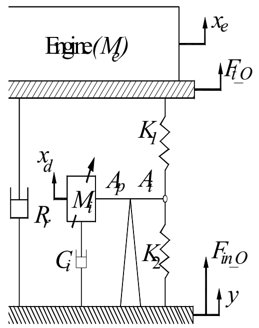

Fig. 3 Mechanical model of the mount with opened inertia track (opened inertia track model).

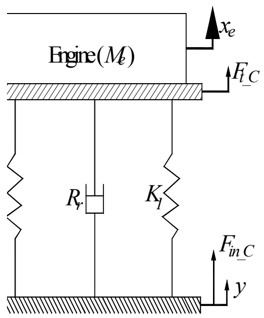

Fig. 4 Mechanical model of the mount with closed inertia track (closed inertia track model).

The equations of motion of the opened and closed inertia track models from Figs. 3-4 are derived by Newton's law and shown as follows,

$$\begin{bmatrix} M_e & 0 \\ 0 & M_i \end{bmatrix}\begin{Bmatrix} \ddot{x} \\ \ddot{x}_i \end{Bmatrix} + \begin{bmatrix} R_r & 0 \\ 0 & C_i \end{bmatrix}\begin{Bmatrix} \dot{x}_e \\ \dot{x}_i \end{Bmatrix} + \begin{bmatrix} (K_r + K_1) & -K_1\dfrac{A_i}{A_p} \\ -K_1\dfrac{A_i}{A_p} & (K_1+K_2)(\dfrac{A_i}{A_p})^2 \end{bmatrix}\begin{Bmatrix} x_e \\ x_i \end{Bmatrix} = \begin{Bmatrix} 0 \\ M_i \end{Bmatrix}\ddot{y} + \begin{Bmatrix} R_r \\ C_i \end{Bmatrix}\dot{y} + \begin{Bmatrix} K_r + K_1(1-\dfrac{A_i}{A_p}) \\ K_2(\dfrac{A_i}{A_p})^2 - K_1\dfrac{A_i}{A_p}(1-\dfrac{A_i}{A_p}) \end{Bmatrix} y \quad (1)$$

$$M_e\ddot{x} + R_r\dot{x}_e + (K_r + K_1)x_e = R_r\dot{y} + (K_r + K_1)y \quad (2)$$

Taking Laplace transform, with zero initial conditions, Eqs. (1)-(2) are collected as

$$\begin{bmatrix} M_e s^2 + R_r s + (K_r + K_1) & -K_1\dfrac{A_i}{A_p} \\ -K_1\dfrac{A_i}{A_p} & M_i s^2 + C_i s + (K_1+K_2)(\dfrac{A_i}{A_p})^2 \end{bmatrix}\begin{Bmatrix} X_e \\ X_i \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \quad (3)$$

$$M_e s^2 + R_r s + (K_r + K_1) = 0 \quad (4)$$

where s is the Laplace operator.

The transmitted forces, F_t of the opened and closed inertia track models can be obtained as shown in Figs. 3-4 and from Eqs. (3) - (4).

$$F_{t\_O} = (K_r + K_1 + R_r s)X - K_1\frac{A_i}{A_p}X_i \quad (5)$$

$$F_{t\_C} = (K_r + K_1 + R_r s)X \quad (6)$$

where

$$X_i = K_1(\frac{A_i}{A_p})\frac{X}{M_i s^2 + C_i s + (K_1 + K_2)(A_i / A_p)^2}$$

From Eqs. (5)-(6), the dynamic stiffness, K_t^* for the opened and closed inertia track models can be obtained as follows,

$$K_{t\_O}^* = K'_{t\_O} + jK''_{t\_O} = \frac{F_{t\_O}}{X} = (K_r + K_1 + R_r s) - \frac{\{K_1(A_i/A_p)\}^2}{M_i s^2 + C_i s + (K_1+K_2)(A_i/A_p)^2} \quad (7)$$

$$K_{t\_C}^* = K'_{t\_C} + jK''_{t\_C} = \frac{F_{t\_C}}{X} = K_r + K_1 + R_r s \quad (8)$$

The real part K' of the dynamic stiffness K^*, which represents the stiffness property of the mount, and imaginary part, K'' which indicates its damping property can be obtained From Eqs. (7) - (8).

$$K'_O = K_r + K_1 - \frac{K_1^2 E(A_i/A_p)^2}{E^2 + (C_i\omega)^2} \quad (9)$$

$$K''_O = R_r\omega + \frac{C_i K_1^2 \omega (A_i/A_p)^2}{E^2 + (C_i\omega)^2} \quad (10)$$

$$K'_C = K_r + K_1 \quad (11)$$

$$K''_C = R_r\omega \quad (12)$$

where

$$E = (K_1 + K_2)(A_i/A_p)^2 - M_i\omega^2$$

Transmissibility T_F for unbalanced vibration the engine and relative transmissibility T_{RD} for engine shake are useful in assessing the isolation effectiveness of the mount and can be obtained from the dynamic stiffness or the real and imaginary parts of the dynamic stiffness.

$$T_{RD} = \frac{X-Y}{Y} = \left|\frac{-Ms^2}{Ms^2 + K^*}\right| = \frac{M\omega^2}{\sqrt{(K' - M\omega^2)^2 + K''^2}} \quad (13)$$

$$T_F = \frac{X}{Y} = \left|\frac{K_O}{Ms^2 + K^*}\right| = \sqrt{\frac{(K'^2 + K''^2)}{(K' - M\omega^2)^2 + K''^2}} \quad (14)$$

3. NUMERICAL SIMULATION RESULTS

The derived equations in the second chapter are used in this simulation with the mount parameter listed in Table 1. Figs. 5-7 obtained from the simulation shows frequency responses of the mount according to the variation of the area of inertia track. In the figures, 100 % means to original area of inertial track of hydraulic mount. When the area increases, the notch and resonant frequency by fluid flow increases as shown in Fig. 5 and resonant peak decreases. When the area is closed and almost closed, resonant frequency is one as shown in Figs 6-7. Furthermore, two resonant frequencies appear according to increasing the area and amplitude of the first resonant peak increases but amplitude of the second resonant peak decreases. When the area is tuned to find optimal area according to the excitation frequency, the transmissibility is greatly reduced as shown in Fig. 8 and the tuned area is shown in Fig. 9. The area is changed from 1-150%.

4. CONTROL SYSTEM

The hydraulic engine mount control system consist a servo motor to adjust area of inertia track, a sensor monitors frequency of engine and send signal to controller, an optimal switching parameter controller receives signal to control servo motor, a PID controller monitors the position of area track.. The Figs. 10-11 show a conceptual diagram of the semi-active engine mount system. The area of inertial track is controlled by servo-motor, at each motor position has resolution 1 percent and control range of 150 percent.

5. CONCLUSION

In this paper, a new hydraulic engine mount with the controllable area of the inertia track is proposed. The motion equation derived from the mechanical model of the mount is used in numerical simulation. The resonant peak, notch and resonant frequencies changed according to the variation of the area of the inertia track. When the area is tuned, the transmissibility of the mount is greatly reduced.

Table 1 Mount parameters used in numerical simulation

Parameters	Original value
A_p	2.5×10^{-3} m^2
A_i	5.72×10^{-5} m^2
I_i	3.81×10^{6} $N\cdot s^2/m^5$
L_i	212×10^{-3} m
ρ	1.028×10^{3} kg/m^3
R_i	1.05×10^{7} $N\cdot s/m^5$
$C_1 = 1/K_{vt}$	3.0×10^{-11} m^5/N
$C_2 = 1/K_{vb}$	2.6×10^{-9} m^5/N
K_r	2.25×10^{5} N/m
R_r	100 N·s/m
M	62 kg

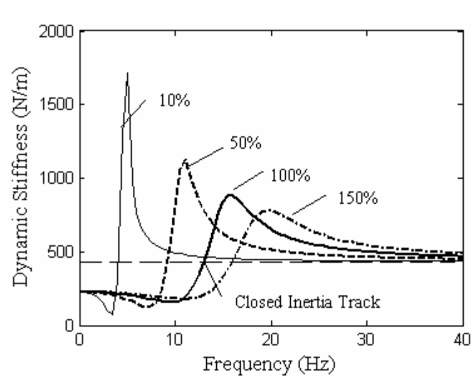

Fig. 5 Dynamic stiffness according to variation of the inertia track area.

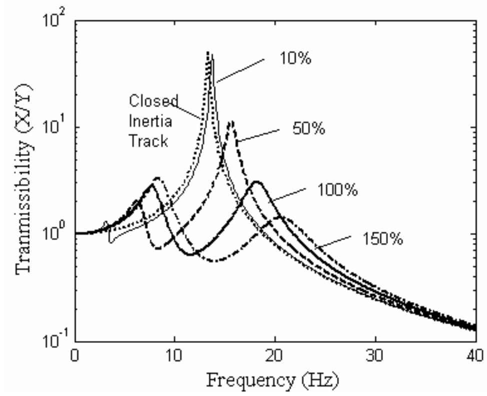

Fig. 6 Transmissibility according to variation of the inertia track area.

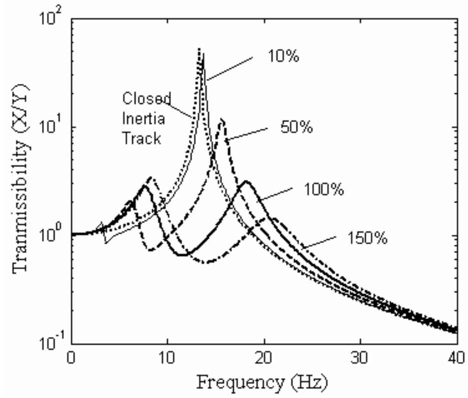

Fig. 7 Relative transmissibility according to variation of the inertia track area.

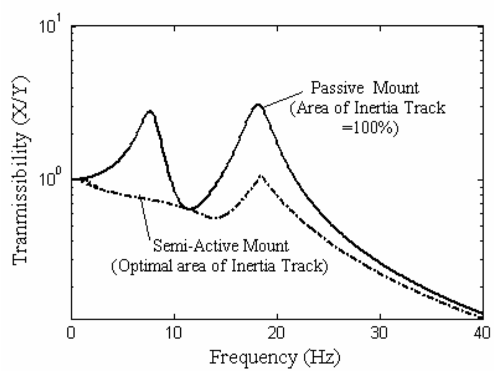

Fig. 8 Transmissibility with optimal Area of inertia track.

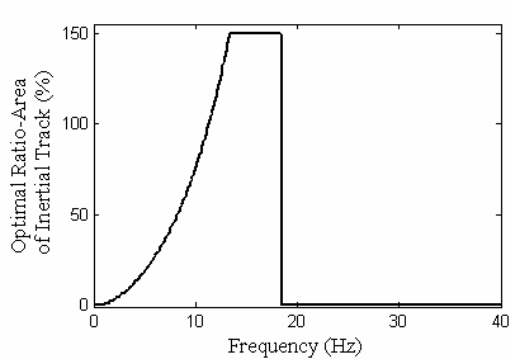

Fig. 9 Optimal Area of inertia track by minimized Transmissibility.

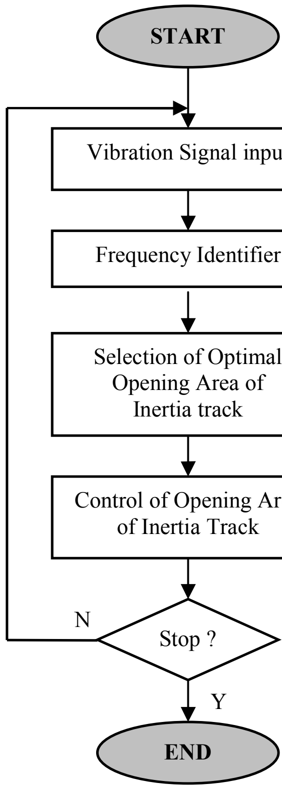

Fig. 10 Flow chart of controller

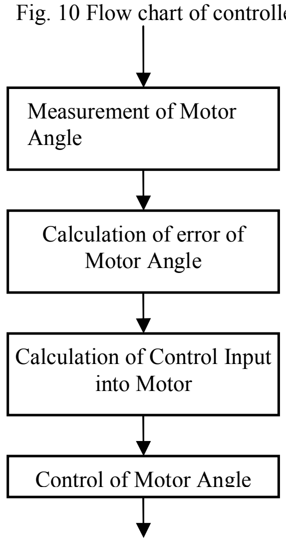

Fig. 10 Block of control opening Area of Inertia Track

NOMENCLATURE

A_p : Effective piston area
A_i : Average cross-sectional area of the inertia track
B_{vt} : Volumetric damping in the top chamber (= 0)
B_{vb} : Volumetric damping in the bottom chamber (= 0)
R_r : Rubber damping coefficient in the top chamber
R_i : Resistance in the inertia track
C_1 : Compliance in the top chamber
C_2 : Compliance in the bottom chamber
C_i : Viscous damping coefficient. in the inertia track ($A_i^2 R_i$)
F_{in_O} : Input force with opened inertia track
F_{t_O} : Transmitted force with opened inertia track
F_{in_C} : Input force with closed inertia track
F_{t_C} : Transmitted force with closed inertia track
Ii : Inertia of the inertia track ($\rho L_i/A_i$)
K_{vt}, K_1 : Volumetric stiffness in the top chamber (Ap^2/C_1)
K_2, K_{bt} : Volumetric stiffness in the bottom chamber(Ap^2/C_2)
K_r : Rubber stiffness coefficients in the top chamber
K^* : Dynamic stiffness
K' : Real part of the dynamic stiffness K^*
K'' : Imaginary part of the dynamic stiffness K^*
L_i : Inertia track length
M_e : Mass of a engine
M_i : Fluid flow mass in the inertia track (= $Ai^2 Ii$)
R_i : Resistance in the inertia track
s : The Laplace operator.
T_F : Transmissibility
T_{RD} : Relative transmissibility
x_e : Displacement of mass of a engine
x_i : Displacement of fluid flow mass in the inertia track
ω : Vibration frequency
ρ : Density of fluid

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