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Experimental and analytical study of secondary path variations in active engine mounts

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ABSTRACT

Active engine mounts (AEMs) provide an effective solution to further improve the acoustic and vibrational comfort of passenger cars. Typically, adaptive feedforward control algorithms, e.g., the filtered-x-least-mean-squares (FxLMS) algorithm, are applied to cancel disturbing engine vibrations. These algorithms require an accurate estimate of the AEM active dynamic characteristics, also known as the secondary path, in order to guarantee control performance and stability. This paper focuses on the experimental and theoretical study of secondary path variations in AEMs. The impact of three major influences, namely nonlinearity, change of preload and component temperature, on the AEM active dynamic characteristics is experimentally analyzed. The obtained test results are theoretically investigated with a linear AEM model which incorporates an appropriate description for elastomeric components. A special experimental set-up extends the model validation of the active dynamic characteristics to higher frequencies up to 400 Hz. The theoretical and experimental results show that significant secondary path variations are merely observed in the frequency range of the AEM actuator's resonance frequency. These variations mainly result from the change of the component temperature. As the stability of the algorithm is primarily affected by the actuator's resonance frequency, the findings of this paper facilitate the design of AEMs with simpler adaptive feedforward algorithms. From a practical point of view it may further be concluded that algorithmic countermeasures against instability are only necessary in the frequency range of the AEM actuator's resonance frequency.

1. Introduction

Due to the higher demand for fuel economy and legal restrictions to reduce emissions, an increased use of modern engine-concepts, e.g., cylinder-on-demand (COD), downsizing, turbochargers, can be observed in today's vehicles. However, in combination with lightweight car bodies, it becomes an increasingly challenging task to satisfy the noise, vibration and harshness (NVH)

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Nomenclature

A_A	decoupler area (m^2)
A_B	equivalent bulking area (m^2)
A_K	cross-sectional area of fluid channel (m^2)
A_S	secondary path amplitude (dimensionless)
A_T	equivalent piston area of main rubber spring (m^2)
B	magnetic field strength (T)
c_1, c_2	stiffness coefficients of elastomer model (N/m)
c_A	actuator stiffness (N/m)
$c_{B,\text{dyn}}$, $C_{B,\text{dyn}}(s)$	dynamic stiffness of main rubber bulking properties (N/m)
$c_{B,1}$, $c_{B,2}$	main rubber spring bulge stiffness 1 and 2 (N/m)
$c_{T,\text{dyn}}$, $C_{T,\text{dyn}}(s)$	dynamic stiffness of main rubber spring (N/m)
$c_{T,1}$, $c_{T,2}$	main rubber spring stiffness 1 and 2 (N/m)
$C_{A,\text{dyn}}(s)$	actuator transfer function (N/m)
$C_{K,\text{dyn}}(s)$	fluid channel transfer function (N/m)
d_1, d_2	stiffness coefficients of elastomer model (N s/m)
d_A	actuator damping (N s/m)
$d_{B,1}$, $d_{B,2}$	main rubber spring bulge damping 1 and 2 (N s/m)
d_K	damping coefficient induced by loss of fluid flow along inertia track (N s/m)
$d_{K,\text{quad}}$	quadratic damping coefficient induced by loss of fluid flow along inertia track (N s^2/m^2)
$d_{T,1}$, $d_{T,2}$	main rubber spring damping 1 and 2 (N s/m)
$d(n)$	chassis vibration (dimensionless)
$e(n)$	error signal (dimensionless)
$f_1(t)$, $F_1(s)$, $f_2(t)$, $F_2(s)$	internal forces of elastomer model (N)
$f_A(t), F_A(s)$	actuator force (N)
$f_x(t), F_x(s)$	transmitted force to the engine (N)
$f_y(t), F_y(s)$	transmitted force to the chassis (N)
$i(t)$	current (A)
j	complex unit $\mathrm{j}=\sqrt{-1}$
k_M	voice coil constant (kg m/A s^2)
l	coil length (m)
l_K	length of fluid channel (m)
L	moving coil inductance (H)
m_A	actuator mass (kg)
m_K	fluid mass of inertia track (kg)
n	sample number (dimensionless)
$p(n)$	impulse response of $P(z)$ (dimensionless)
$p_i(t)$	pressure inside upper fluid chamber (N/m^2)
$P(z)$	primary path (dimensionless)
$P_{xx}(s)$	passive dynamic AEM characteristics $F_x(s)/X_T(s)$ (N/m)
$P_{yx}(s)$	passive dynamic AEM characteristics $F_y(s)/X_T(s)$ (N/m)
r	engine order (dimensionless)
R	moving coil resistance (Ω)
s	Laplace variable (dimensionless)
$s(n)$	impulse response of $S(z)$ (dimensionless)
$\hat{s}(n)$	impulse response of $\hat{S}(z)$ (dimensionless)
$s_{p,1}$, $s_{p,2}$, $s_{p,3}$	poles of $P_{xx}(s), P_{yx}(s), S_x(s), S_y(s)$ (dimensionless)
$s_{yx,1}$, $s_{yx,2}$, $s_{x,1}$, $s_{y,1}$	zeros of $P_{xx}(s), P_{yx}(s), S_x(s), S_y(s)$ (dimensionless)
$S(z)$	secondary path (dimensionless)
$S_x(s)$	active dynamic AEM characteristics $F_x(s)/U(s)$ (N/V)
$S_y(s)$	active dynamic AEM characteristics $F_y(s)/U(s)$ (N/V)
$\hat{S}(z)$	secondary path estimate (dimensionless)
t	continuous time (s)
T	sample time (s)
$u(n)$	control output of adaptive filter (dimensionless)
$u'(n)$	control output of adaptive filter filtered by secondary path dynamics (dimensionless)
$U(t), U(s)$	voltage (V)
U_{ind}, U_R, U_L	induced, resistance, inductance voltage (V)
$v(n)$	engine vibration (dimensionless)
$w(n)$	complex filter weight (dimensionless)
$x_A(t), X_A(s)$	displacement of actuator mass (m)
$x(t), X(s)$	displacement of elastomer model at engine side (m)
$x_B(t), X_B(s)$	displacement of upper fluid chamber bulking area (m)
$x_K(t), X_K(s)$	displacement of fluid in inertia track (m)
$x_T(t), X_T(s)$	displacement of AEM at engine side (m)
$x(n)$	complex reference signal (dimensionless)
$x'(n)$	complex reference signal filtered by secondary path estimate (dimensionless)
$y(t), Y(s)$	displacement of AEM at chassis side (m)
z	variable of z transform
$z(t), Z(s)$	internal displacement of elastomer model (m)
φ_S	secondary path phase angle (deg)
$\kappa_{B,\text{dyn}}$	volumetric compliance of upper fluid chamber (m^5/N)
μ	adaptation step-size
ρ_f	Fluid density (kg/m^3)
ω	engine speed (rad/s)
AEM	active engine mount
COD	cylinder on demand
FIR	finite impulse response
FxLMS	filtered-x least mean squares
HEM	hydraulic engine mount
LMS	least mean squares
NVH	noise, vibration and harshness
SISO	single input single output

demands of the customer. While passive engine mounts reach their technical limits in solving this task, active engine mounts (AEMs) provide an effective contribution to further improve the acoustic and vibrational comfort of passenger cars.

Several concepts for AEMs have been proposed in the past [1–13]. They have all in common that a conventional passive hydraulic engine mount (HEM) is extended by an actuator, e.g., of electromagnetic or piezoelectric type, to generate active