Smart Structures and Systems, *Vol. 13, No. 3 (2014) 419-434*
DOI: http://dx.doi.org/10.12989/sss.2014.13.3.419

Investigation of the semi-active electromagnetic damper

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(Received June 19, 2012, Revised April 6, 2013, Accepted May 17, 2013)

Abstract. In this paper, the electromagnetic damper (EMD), which is composed of a permanent-magnet rotary DC motor, a ball screw and a nut, is considered to be analyzed as a semi-active damper. The main objective pursued in the paper is to study the two degrees of freedom (DOF) model of the semi-active electromagnetic suspension system (SAEMSS) performance and energy regeneration controlled by on-off and continuous damping control strategies. The nonlinear equations of the SAEMSS must therefore be extracted. The effects of the EMD characteristics on ride comfort, handling performance and road holding for the passive electromagnetic suspension system (PEMSS) are first analyzed and damping control strategies effects on the SAEMSS performance and energy regeneration are investigated next. The results obtained from the simulation show that the SAEMSS provides better performance and more energy regeneration than the PEMSS. Moreover, the results reveal that the on-off hybrid control strategy leads to better performance in comparison with the continuous skyhook control strategy, however, the energy regeneration of the continuous skyhook control strategy is more than that of the on-off hybrid control strategy (except for on-off skyhook control strategy).

Keywords: semi-active electromagnetic suspension system; electromagnetic damper; ball screw shock absorber; energy regeneration

1. Introduction

During the design of vehicle suspensions, the most important objectives are to minimize the car body acceleration, suspension travel and wheel hop for better ride comfort, handling performance and road holding. Current automobile suspension systems using passive components can only offer a compromise between these conflicting criteria by providing spring and damping coefficients with fixed rates. However, semi-active vibration isolation involves changing the damping coefficient as a function of time. The conventional damper converts vibration energy into heat energy which is finally dissipated to the external environment. Apart from damper configuration, the amount of dissipated energy largely depends on the road roughness and the vehicle velocity. Under normal operating conditions, this energy may be considered insignificant. On the other hand, over rough roads, the energy may be higher and thus has the potential to be used. Therefore, a linear motor/generator may be adapted to replace existing damper in the vehicle suspension system.

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http://www.techno-press.org/?journal=sss&subpage=8 ISSN: 1738-1584 (Print), 1738-1991 (Online)

The device may be alternated between damping and generating device to provide damping as well as extraction of energy. Even the small energy may help in improving the efficiency of vehicle, especially electric and hybrid electric vehicles.

There are several types of energy-regenerative suspension systems already under investigation, such as hydraulic storage suspension (Chen *et al.* 2007), rack and pinion suspension (Chen *et al.* 2006), ball screw suspension (Zhang *et al.* 2008) and linear motion suspension (Wu and Cao 2007). Developments achieved in power electronics, permanent-magnet materials, and microelectronic systems enable the possibility of actual implementation of electromagnetic actuators in order to improve the performance of vehicle suspension systems (Martins *et al.* 2006).

Karnopp (1989) and Ryba (1993) studied the electromagnetic dampers of linear motor and rotary motor, respectively. Gupta *et al.* (2003 and 2006) verified the theoretical researches of Karnopp and Ryba by experiments on a small all-terrain vehicle. Okada *et al.* (1995-1997) proposed an energy-regenerative active suspension system that applied a linear DC electromagnetic motor as an actuator. Suda *et al.* (1998) studied a self-powered active vibration control system. The system utilized two electromagnetic DC linear motors. One motor, called the regenerative damper, was placed in the primary suspension, and the other motor, called the actuator, was located in the secondary suspension. Nakano *et al.* (2003) studied the self-powered active vibration control using a single actuator. The actuator generated power while the speed of the armature is high. The regenerated power would be applied when the speed of the armature is low. Martins *et al.* (2006, 1999) produced the prototype of permanent-magnet linear actuator and investigated the dynamic performances of the actuator in low- and high-frequency excitation. Bose system equips each wheel with its own linear electromagnetic motor (Jones 2005). This system can effectively prevent body roll during turns and keep the car from dipping forward when braking. Suda and Shiba (1996) proposed a regenerative suspension system in which a rotary DC motor was used as an actuator. The rotary motion of DC motor was converted into the linear motion of suspension by the rack and pinion mechanism. Suda *et al.* (2000) produced a prototype of an electromagnetic suspension actuator in which ball screw mechanism was used to convert rotary motion into linear motion. Nakano and Suda (2004) applied this self-powered active vibration control system to the cab suspension of a truck. Kawamoto and Suda (2007) analyzed the frequency characteristics of energy balance of the electromagnetic damper. Experimental verification of energy-regenerative feasibility for an automotive electrical suspension system was carried out by Zhang *et al.* (2007). Zhang *et al.* (2009) investigated the application of the permanent-magnet DC motor actuator in automotive active suspension considering energy regeneration. Mahfoud and Hagopian (2012) investigated the critical speed suppressing by use of the electromagnetic actuators.

Due to the several advantages such as simple structure, high responsiveness, energy saving performance, controllability, etc., electromagnetic damper (EMD) or ball screw shock absorber is the future trend of automotive suspension systems. Despite the studies on the EMD, only a few works have considered the semi-active electromagnetic suspension system (SAEMSS). This paper investigates the feasibility of a semi-active EMD in providing adequate damping for isolation of vibration while generates energy from relative motion between sprung and unsprung masses. That is why the nonlinear equations of the SAEMSS must be developed. This work utilizes a simplified quarter vehicle model with linear spring and the EMD to illustrate its performance. The performances are evaluated in terms of ride index (RI), maximum suspension travel (MST) and maximum tyre deflection (MTD). This paper essentially consists of two parts:

The effects of the EMD characteristics on the passive electromagnetic suspension system (PEMSS) performance are analyzed in part one.

Part two makes use of the on-off and continuous damping control strategies for improving the performance of the EMD. In this part, a simulation study is carried out to show that the SAEMSS has good performance in comparison with the PEMSS while more vibration energy from the road excitation can be regenerated and saved in the capacitor.

2. Passive electromagnetic suspension system

The PEMSS is studied in this section. Fig. 1 shows the assumed model for an electromagnetic suspension system. The EMD consists of the rotary DC motor and the ball screw mechanism as shown in the figure. It converts linear motion of vibration into input torque for DC motor. The EMD applies electromagnetic force as the damping force. In the passive application, the EMD has almost linear damping characteristics.

In Fig. 1, m_s is the sprung mass, m_u is the unsprung mass, k_s is the spring stiffness of the suspension system spring, k_t is the spring stiffness of the tyre, z_s is the body displacement, z_u is the wheel displacement, and z_g is the road excitation.

By applying the Newton's second law, the governing equations may be derived as follows

$$\begin{cases} -k_s z_{su} + f = m_s \ddot{z}_s \\ k_s z_{su} - f - k_t\left(z_u - z_g\right) = m_u \ddot{z}_u \\ z_{su} = z_s - z_u \end{cases} \tag{1}$$

where $\ddot{(\ )} = \mathrm{d}^2(\ )/\mathrm{d}t^2$, $\dot{(\ )} = \mathrm{d}(\ )/\mathrm{d}t$, and t is the time. z_{su} is the suspension travel in Eq. (1).

The modeling of the EMD for automobile suspension was presented by Kawamoto *et al.* (2007) and Zhang *et al.* (2009). The output force of the EMD (f) is in the form

$$f = u - c_e \dot{z}_{su} - I_e \ddot{z}_{su} \tag{2}$$

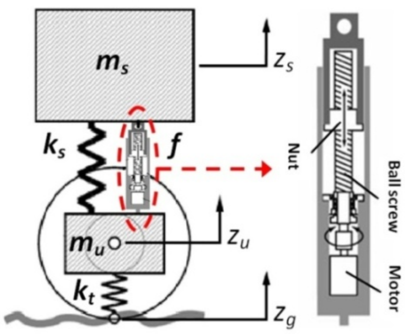


Fig. 1 Electromagnetic suspension system

where

$$\begin{cases} u = -\phi i \\ \phi = \dfrac{2\pi}{L_b} k_m \\ I_e = \left(\dfrac{2\pi}{L_b}\right)^2 \left(J_m + J_b\right) \end{cases} \tag{3}$$

In Eqs. (2) and (3), u is the force, c_e is the equivalent damper coefficient, I_e is the equivalent inertia, Φ is the motor constant, i is the current, L_b is the lead of ball screw, k_m is the torque constant, J_m is the moment of inertia of motor rotor, and J_b is the moment of inertia of ball screw.

As shown in Fig. 2, the motor circuit of EMD is modeled as the equivalent DC motor circuit.

Thus, the circuit equation is written as follow

$$e = \phi \dot{z}_{su} = L_i \dot{i} + Ri \tag{4}$$

where e is the induced voltage, L_i is the inductance, and R includes both the internal resistance of the motor and the additional resistance placed in the circuit.

Using Laplace transform of Eqs. (2)-(4), Eq. (5) is obtained as following

$$F = -\frac{\phi^2 s}{R + L_i s} Z_{su} - c_e s Z_{su} - I_e s^2 Z_{su} \tag{5}$$

where F is Laplace transform of f and Z_{su} is Laplace transform of the suspension travel in Eq. (5).

In this study, the three most important transfer functions used to assess the performance of the electromagnetic suspension system are H_1, H_2, and H_3. H_1 indicates the car body acceleration transfer function, H_2 indicates the suspension travel transfer function, and H_3 indicates the tyre deflection transfer function.

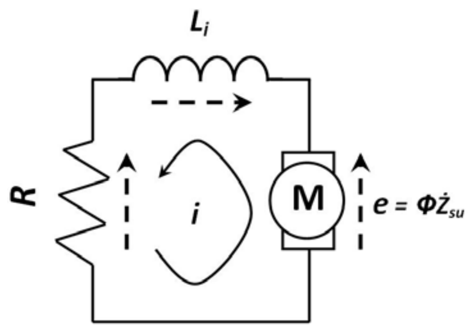


Fig. 2 Circuit diagram of motor

$$H_1(s)=\frac{A_s(s)}{Z_g(s)}=\frac{\left\{\begin{aligned}&\left[k_tI_eL_i^{\,2}\right]s^6+\left[k_t\left(2I_eRL_i+c_eL_i^{\,2}\right)\right]s^5+\left[k_t\left(I_eR^2+2c_eRL_i+L_i\phi^2+k_sL_i^{\,2}\right)\right]s^4+\\&\left[k_t\left(R\phi^2+c_eR^2+2k_sRL_i\right)\right]s^3+\left[k_tk_sR^2\right]s^2\end{aligned}\right\}}{a_0s^6+a_1s^5+a_2s^4+a_3s^3+a_4s^2+a_5s+a_6} \tag{6}$$

$$H_2(s)=\frac{Z_{su}(s)}{Z_g(s)}=\frac{-\left\{\left[k_tm_sL_i^{\,2}\right]s^4+\left[2k_tm_sRL_i\right]s^3+\left[k_tm_sR^2\right]s^2\right\}}{a_0s^6+a_1s^5+a_2s^4+a_3s^3+a_4s^2+a_5s+a_6} \tag{7}$$

$$H_3(s)=\frac{Z_{ug}(s)}{Z_g(s)}=\frac{-\left\{\begin{aligned}&\left[m_s\left(I_eL_i^{\,2}\right)+m_u\left((m_s+I_e)L_i^{\,2}\right)\right]s^6+\left[m_s\left(2I_eRL_i+c_eL_i^{\,2}\right)+m_u\left(2(m_s+I_e)RL_i+c_eL_i^{\,2}\right)\right]s^5+\\&\left[m_s\left(I_eR^2+2c_eRL_i+L_i\phi^2+k_sL_i^{\,2}\right)+m_u\left((m_s+I_e)R^2+2c_eRL_i+L_i\phi^2+k_sL_i^{\,2}\right)\right]s^4+\\&\left[m_s\left(R\phi^2+c_eR^2+2k_sRL_i\right)+m_u\left(R\phi^2+c_eR^2+2k_sRL_i\right)\right]s^3+\left[m_s\left(k_sR^2\right)+m_u\left(k_sR^2\right)\right]s^2\end{aligned}\right\}}{a_0s^6+a_1s^5+a_2s^4+a_3s^3+a_4s^2+a_5s+a_6} \tag{8}$$

where

$$\begin{cases}a_0=m_sm_uL_i^{\,2}+(m_s+m_u)I_eL_i^{\,2}\\a_1=2m_sm_uRL_i+(m_s+m_u)\left(2I_eRL_i+c_eL_i^{\,2}\right)\\a_2=m_sm_uR^2+k_t(m_s+I_e)L_i^{\,2}+(m_s+m_u)\left(I_eR^2+2c_eRL_i+L_i\phi^2+k_sL_i^{\,2}\right)\\a_3=k_t\left(2(m_s+I_e)RL_i+c_eL_i^{\,2}\right)+(m_s+m_u)\left(R\phi^2+c_eR^2+2k_sRL_i\right)\\a_4=(m_s+m_u)k_sR^2+k_t\left((m_s+I_e)R^2+2c_eRL_i+L_i\phi^2+k_sL_i^{\,2}\right)\\a_5=k_t\left(R\phi^2+c_eR^2+2k_sRL_i\right)\\a_6=k_tk_sR^2\end{cases} \tag{9}$$

A_s, in Eq. (6), is Laplace transform of the car body acceleration, Z_{ug} is Laplace transform of the tyre deflection in Eq. (8), and Z_g is Laplace transform of the road excitation.

To insert the effects of road profiles in the analysis, the power spectral density (PSD) relationship between the input and output of the suspension system is utilized.

$$\begin{cases}G_{A_s}(\omega)=\left|H_1(\omega)\right|^2G_{z_g}(\omega)\\G_{Z_{su}}(\omega)=\left|H_2(\omega)\right|^2G_{z_g}(\omega)\\G_{Z_{ug}}(\omega)=\left|H_3(\omega)\right|^2G_{z_g}(\omega)\end{cases} \tag{10}$$

where G_{A_s}, $G_{Z_{su}}$, $G_{Z_{ug}}$, and G_{z_g} are the PSD of car body acceleration, suspension travel, tyre deflection, and road profiles respectively. ω is the frequency in (rad/s). According to ISO 8608 standard (1995), PSD of road profiles is expressed in the form (Wong 2001)

$$G_{z_g}(\omega)=\left(\frac{1}{2\pi v}\right)\times C_{sp}\left(\frac{\omega/2\pi}{v}\right)^{-N} \tag{11}$$

where v is the vehicle speed, C_{sp} and N are constant parameters relevant to the type of road.

In this paper, the ride index is achieved in accordance with ISO 2631-1 standard (1997) for vertical vibration by use of the filter shown in Fig. 3.

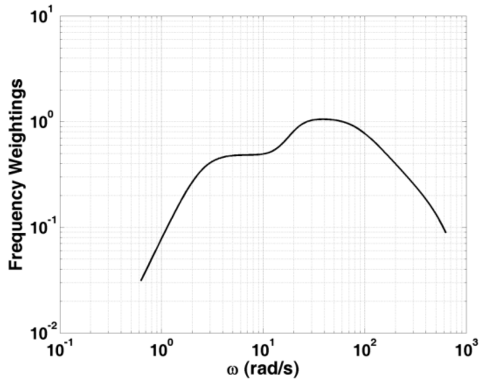


Fig. 3 Frequency weightings for vertical vibration

As seen in the above equations, R is the most effective parameter of the EMD on the performance of the electromagnetic suspension system. Nevertheless, one of the objectives of this part is to investigate the effects of L_i on the performance of the electromagnetic suspension system beside R. The other characteristics of the EMD are considered in accordance with the papers of Hayashi *et al.* (2008) and Zhang *et al.* (2009). The mass of the EMD (m_{EMD}) is assumed to be 10 (kg) added to the unsprung mass. The parameters values of the electromagnetic suspension system are given in Table 1.

Fig. 4 depicts the effect of the resistance (R) on the ride index (RI) in the different speeds of the vehicle for smooth highway (C_{sp} = 4.8×10^{-7} and N = 2.1 in accordance with ISO 8608 standard (1995)) with L_i = 0.002 (H). It indicates that the PEMSS has good performance for R = 5.5 (Ω) in the different speeds of the vehicle in spite of the fact that the RI will increase when the vehicle speed gets larger. Figs. 5 and 6 illustrate the effect of R on the maximum PSD of suspension travel (Max of $G_{Z_{su}}$) and maximum PSD of tyre deflection (Max of $G_{Z_{ug}}$) in the different speeds of the vehicle for smooth highway with L_i = 0.002 (H). It is observed from the figures that when the vehicle speed and R get larger, Max of $G_{Z_{su}}$ and Max of $G_{Z_{ug}}$ will increase which are not desirable.

Table 1 Parameters values of the electromagnetic suspension system

Parameter	value
m_s	344 (kg)
k_s	20053 (N/m)
m_u	40 (kg)
k_t	182087 (N/m)
Φ	66 (N/A)
I_e	18 (kg)
c_e	20 (N s/m)

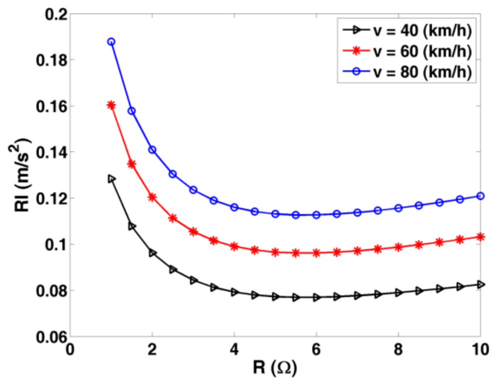


Fig. 4 Effect of the R on the RI for L_i = 0.002 (H) in the different speeds

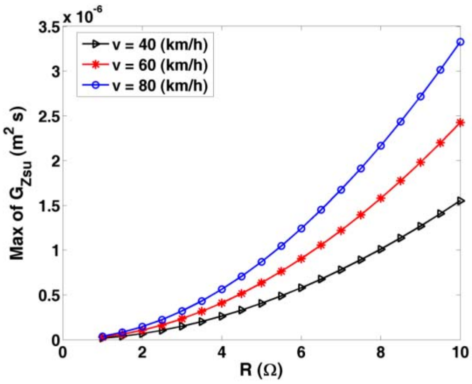


Fig. 5 Effect of the R on the Max of G_{Zsu} for L_i = 0.002 (H) in the different speeds

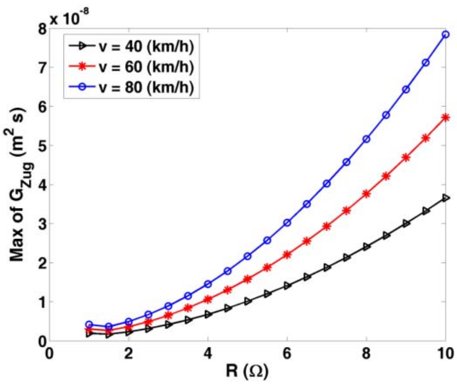


Fig. 6 Effect of the R on the Max of G_{Zug} for L_i = 0.002 (H) in the different speeds

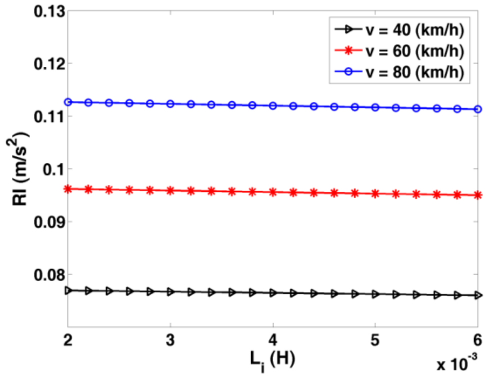


Fig. 7 Effect of the L_i on the RI for R = 5.5 (Ω) in the different speeds

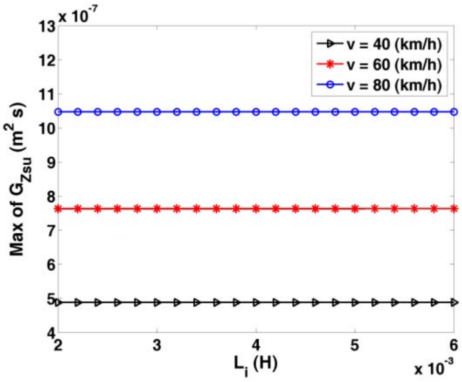


Fig. 8 Effect of the L_i on the Max of G_{Zsu} for R = 5.5 (Ω) in the different speeds

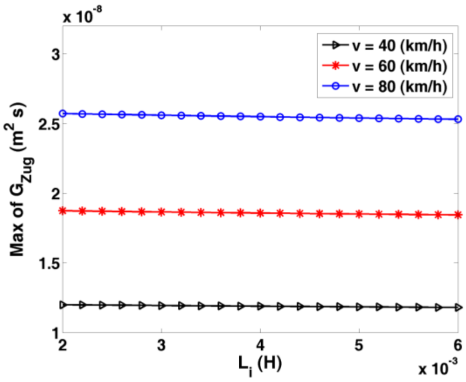


Fig. 9 Effect of the L_i on the Max of G_{Zug} for R = 5.5 (Ω) in the different speeds

Figs. 7-9 show the effect of the inductance (L_i) on the RI, Max of $G_{Z_{su}}$, and Max of $G_{Z_{ug}}$ in the different speeds of the vehicle for smooth highway with R = 5.5 (Ω) respectively. It can be generally inferred that when vehicle speed gets larger, the performance becomes undesirable.

However, the effect of L_i on the RI, Max of $G_{Z_{su}}$, and Max of $G_{Z_{ug}}$ is approximately insignificant.

3. Semi-Active electromagnetic suspension system

High-frequency disturbances cause destructive effects on the performance of the electromagnetic suspension system. It can be shown that relatively high spring stiffness is needed to remove the problem and keep good performance of the electromagnetic suspension system (Graves 2000, Montazeri-Gh and Kavianipour 2012). Therefore, a modified electromagnetic suspension system model is proposed to remove the problem and is shown in Fig. 10.

This model has a spring (k_a) in series with the EMD. The reasoning behind this design stems from the notion that a spring in series with the EMD would isolate the EMD from high-frequency disturbances. In this study, a modified electromagnetic suspension system includes only one added spring under the EMD since the damper would reduce the amplitude of the input disturbance transmitted to the EMD and, consequently, would reduce the regenerative energy efficiency.

The mathematical equations of the modified electromagnetic suspension system are given in Eq. (12).

$$\begin{cases} -k_s\left(z_s - z_u\right) + f = m_s \ddot{z}_s \\ -k_a\left(z_{EMD} - z_u\right) - f = m_{EMD}\ddot{z}_{EMD} \\ k_a\left(z_{EMD} - z_u\right) + k_s\left(z_s - z_u\right) - k_t\left(z_u - z_g\right) = m_u \ddot{z}_u \end{cases} \tag{12}$$

Eqs. (2) and (3) can be used for the modified electromagnetic suspension system. The only difference in this section is related to the parameter of z_{su}. For the modified electromagnetic suspension system, z_{su} (in Eq. (2)) alters to the form of $z_{sE} = z_s - z_{EMD}$.

Due to environmental concerns and fuel price increase, low-emission and fuel-efficient vehicles are of vital importance and are of interest to many researchers in automobile industry. In this direction, electric vehicles and hybrid electric vehicles were introduced as the dominant alternatives for conventional vehicles. The use of electrical components has created new opportunities for vehicle dynamics, safety and performance improvements. Moreover, due to the energy storage systems, these vehicles provide the capability of energy regeneration in the vehicle subsystems.

In this paper, energy regeneration in the modified electromagnetic suspension system shown in Fig. 10 is investigated by numerical evaluation. Since there is a capacitor in the electric circuit of EMD for energy regeneration, the circuit equation should be revised as the following

$$\phi \dot{z}_{sE} = L_i \dot{i} + Ri + E\,\mathrm{sgn}\left(\dot{z}_{sE}\right) \tag{13}$$

where E is the voltage of the capacitor.

It may be shown that the relationship between the variation of the capacitor voltage and the current is expressed in the form

$$\dot{E} = \frac{1}{c_{cap}} i \tag{14}$$

where c_{cap} is the capacity of the capacitor.

The EMD rectifies induced voltage and transfers the energy to the capacitor. The mode in which the EMD regenerates vibration energy is called the regeneration mode (Nakano and Suda 2004). However, when the magnitude of the induced voltage is less than the voltage of the capacitor, the EMD can NOT transfer it to the capacitor. In this mode, the EMD ceases regeneration. This mode is called the dissipation mode (Nakano and Suda 2004). The circumstance of operating the electric circuit of the EMD is illustrated in Fig. 11. To calculate the variation of the capacitor voltage, the nonlinear equations of the EMD electric circuit must be extracted in accordance with Fig. 11.

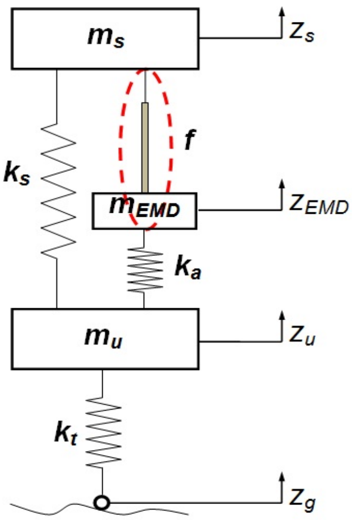
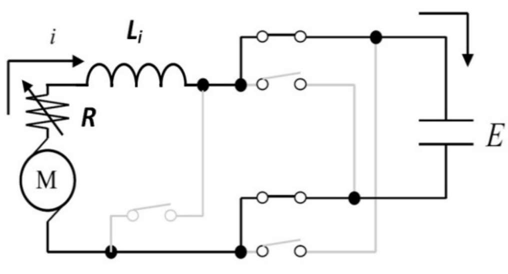
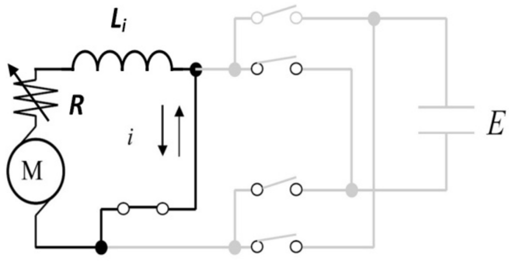


Fig. 10 Modified electromagnetic suspension model



(a) Electric circuit of the EMD in regeneration mode when $\dot{z}_{sE} > 0$



(b) Electric circuit of the EMD in dissipation mode

Fig. 11 Electric circuit of the EMD

Accordingly, the EMD force and the equations of its electric circuit are described as when $\phi|\dot{z}_{sE}| \geq E$ (regeneration mode)

$$\begin{cases} \dot{i} = \dfrac{1}{L_i}\left(\phi\dot{z}_{sE} - Ri - E\,\mathrm{sgn}\left(\dot{z}_{sE}\right)\right) \\ \dot{E} = \dfrac{1}{c_{cap}} i \\ u = -\phi i \end{cases} \tag{15}$$

when $\phi|\dot{z}_{sE}| < E$ (dissipation mode)

$$\begin{cases} \dot{i} = \dfrac{1}{L_i}\left(\phi\dot{z}_{sE} - Ri\right) \\ \dot{E} = 0 \\ u = -\phi i \end{cases} \tag{16}$$

Comparing Eq. (15) with Eq. (16), it can be found that the EMD changes its damping force when it regenerates vibration energy.

Various semi-active control algorithms have been suggested by many researchers. This paper studies the modified SAEMSS performance controlled by on-off and continuous damping control strategies. Adaptive control, fuzzy logic, neural network, H_∞ and sliding mode control are other methods for semi-active suspension system control. Although complicated control strategies may tender some advantages, considerable performance gains can still be realized with more basic control strategies.

3.1 On-Off hybrid control strategy

A control scheme has been developed which utilizes a linear combination of skyhook and groundhook control. With this hybrid control scheme, the suspension can be tuned to respond exactly as it would with skyhook control or groundhook control. In addition, the suspension can be adjusted such that it responds as a combination of the two, with more or less influence given to the skyhook or groundhook component (Ahmadian 1997).

In on-off hybrid control scheme, the damper is controlled by a linear combination of two damping values. Also, the determination of whether the damper is to be adjusted to either its high state or its low state depends on the signs of $\dot{z}_s\dot{z}_{su}$ and $\dot{z}_u\dot{z}_{su}$. The on-off hybrid control strategy for SAEMSS can be designed as

$$R = \alpha R_s + (1-\alpha)R_g \tag{17}$$

where

$$R_s = \begin{cases} R_{\min} & \dot{z}_s \dot{z}_{su} \geq 0 \\ R_{\max} & \dot{z}_s \dot{z}_{su} < 0 \end{cases} \quad , \quad R_g = \begin{cases} R_{\min} & -\dot{z}_u \dot{z}_{su} \geq 0 \\ R_{\max} & -\dot{z}_u \dot{z}_{su} < 0 \end{cases} \tag{18}$$

R_s and R_g are the skyhook and groundhook components of the damping force. The variable α is the relative ratio between the skyhook and groundhook control. When α is 1, the control policy transforms to pure skyhook, whereas when α is 0, the control is purely groundhook.

3.2 Continuous skyhook control strategy

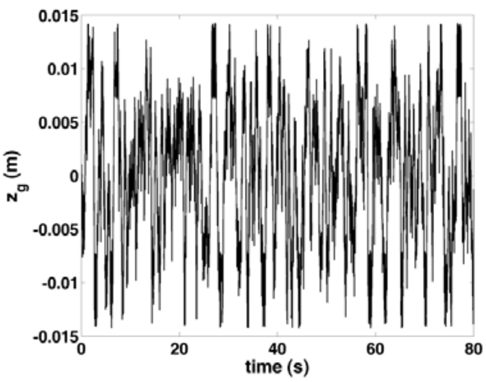
The on-off hybrid system is much simpler than the continuous skyhook system. However, the jerks produced in the on-off model are more than continuous model (Shamsi and Choupani 2008). The continuous skyhook control strategy for SAEMSS can be written as

$$R = \begin{cases} \min\left\{R_{\max}, \max\left\{R_c \dfrac{\dot{z}_s}{\dot{z}_{su}}, R_{\min}\right\}\right\} & \dot{z}_s \dot{z}_{su} \geq 0 \\ R_{\max} & \dot{z}_s \dot{z}_{su} < 0 \end{cases} \tag{19}$$

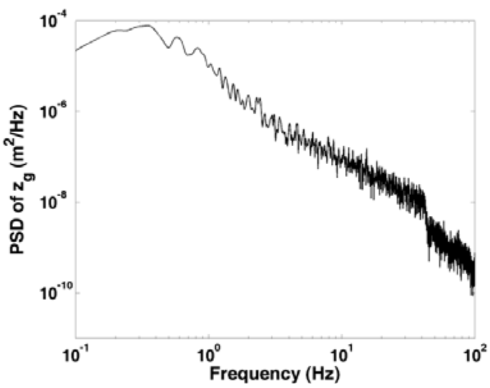
where R_c is the constant value selected by the designer and $R_{min} < R_c < R_{max}$.

The main objective of this part is to compare two basic control strategies in the vibration isolation. The performances of on-off hybrid and continuous skyhook control strategies are investigated and compared with that of a passive EMD.

In this paper, it is assumed that the vehicle is driven on a road with the random irregularities shown in Fig. 12. The time-domain road profile was obtained through the direct measurement of the road irregularities. The measurement was performed in the city of Tehran by the Automotive Industry Research and Innovation Centre of SAIPA Company (Montazeri-Gh and Soleymani 2010). Fig. 12 shows the measured time-domain profile of the mentioned road for one of the vehicle wheels.



(a) Road surface profile measured at 80 (km/h) speed



(b) PSD of road profile

Fig. 12 Road profile

The results of simulation are presented in Figs. 13-18 for the values specified in Table 1, and k_a = 200000 (N/m), L_i = 0.002 (H), c_{cap} = 10 (F), $R_{\min}$ = 1.16 (Ω), $R_{\max}$ = 5.5 (Ω), and R_c = 1.5 (Ω). Also, the value of R is supposed to be 5.5 (Ω) for the PEMSS.

It can be generally deduced from Figs. 13-16 that the SAEMSS has better performance and more energy regeneration than the PEMSS. As seen in these figures, the on-off hybrid control strategy (SAEMSS-A) has better performance in comparison with the continuous skyhook control strategy (SAEMSS-B), however, the energy regeneration of the SAEMSS-B is more than that of the SAEMSS-A (except for α = 1). It can be observed from these figures that the least RI and MTD is related to α = 0.2 while the on-off groundhook control strategy (α = 0) causes the least MST.

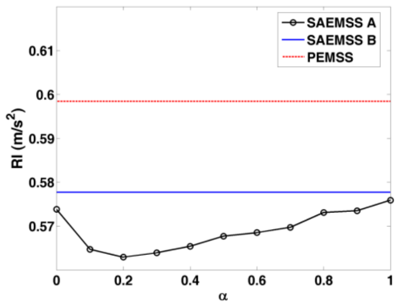


Fig. 13 The comparison of RI between the PEMSS and two types of SAEMSS

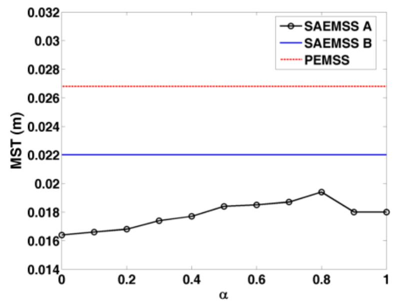


Fig. 14 The comparison of MST between the PEMSS and two types of SAEMSS

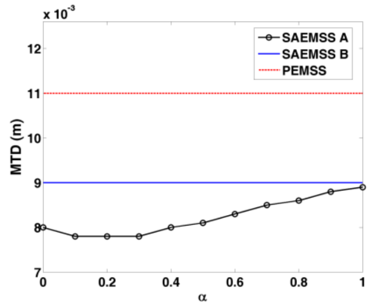


Fig. 15 The comparison of MTD between the PEMSS and two types of SAEMSS

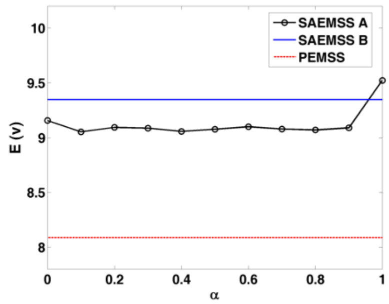


Fig. 16 The comparison of the capacitor voltage between the PEMSS and two types of SAEMSS

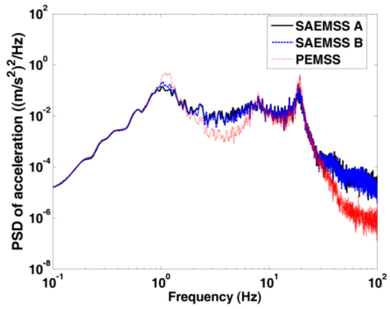


Fig. 17 The comparison of the body acceleration PSD between the PEMSS and two types of SAEMSS considering $\alpha = 1$

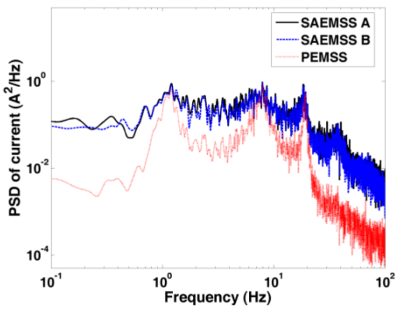


Fig. 18 The comparison of the current PSD between the PEMSS and two types of SAEMSS considering $\alpha = 1$

Fig. 17 reveals that the PSD of the body acceleration of the PEMSS is higher than that of the SAEMSS-B and SAEMSS-A with $\alpha = 1$ (on-off skyhook control strategy) near the first natural frequency of the system caused the RI of the PEMSS becomes more than that of the SAEMSS-B and SAEMSS-A with $\alpha = 1$ (as seen in Fig. 13). It is quite clear from Fig. 18 that the higher PSD of the current results in the less RI. In another word, high current in the motor circuit of EMD leads to the better performance of the suspension system from the RI point of view.

4. Conclusions

In this work, the nonlinear equations of the semi-active electromagnetic suspension system (SAEMSS) were developed and the performance of the SAEMSS and the passive electromagnetic suspension system (PEMSS) were investigated and compared. Furthermore, the effects of the resistance (R) and inductance (L_i) on the performance of the PEMSS in the different speeds of the vehicle (v) were studied. It was distinguished that the maximum PSD of suspension travel (Max of $G_{Z_{su}}$) and the maximum PSD of tyre deflection (Max of $G_{Z_{ug}}$) would increase when R and v got larger. However, the PEMSS had good ride index (RI) for R = 5.5 (Ω) in the different speeds of the vehicle. In spite of this, the RI increased with the increase in v. Moreover, the effect of the L_i on the RI, Max of $G_{Z_{su}}$, and Max of $G_{Z_{ug}}$ was approximately insignificant. In addition, the modified SAEMSS performance controlled by on-off hybrid control strategy (SAEMSS-A) and continuous skyhook control strategy (SAEMSS-B) were investigated. It was revealed that the both type of the SAEMSS have better performance and more energy regeneration than the PEMSS. Likewise, the SAEMSS-A has better performance in comparison with the SAEMSS-B, however, the energy regeneration of the SAEMSS-B is more than that of the SAEMSS-A (except for α = 1). The findings also indicated that the better performance of the electromagnetic suspension system from the RI point of view requires the higher current in the motor circuit of EMD.

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