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ANALYSIS OF AN ELECTROMAGNETIC SUSPENSION SYSTEM FOR GROUND VEHICLES

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ABSTRACT

This paper introduces a novel passive suspension system for ground vehicles. The system is based on a flexible Electromagnetic Shock Absorber (EMSA). After designing and providing a model, the results of the test model are compared with behavior of tubular linear induction motor, which is connected to DC supply. Therefore, its dynamic equations in arbitrary reference frame are obtained, and are added to a quarter car equations. The results of simulation of the new system moving along randomly profile road show reduction of the body acceleration hence increase passenger comfort when the field voltage of the EMSA increases. Its performances are compared with a same passive suspension system. By using position and speed sensors on the vehicle body and suitable electronic circuit this system may be improved and near to semi-active suspension system.

KEY WORDS:

Electromagnetic Shock Absorber (EMSA), Tubular Linear Induction Motor (TLIM) and Suspension System

1. INTRODUCTION

The suspension industry is always looking for improvements in comfort, security and performance. All vehicles have a suspension system: it is the essential interface between the vehicle and its environment. Vibration isolating systems in vehicles normally use elastic elements (spring) and dissipative elements (dampers). Today the classic passive suspension is not the best way to satisfy these constraints (comfort, security…). The passive suspension system is the simplest that we can imagine. It strikes a compromise between a high level of ride comfort and a reasonable ability to follow the main features of the road, thus ensuring safety. Over the last few years, various active and semi-active strategies have been proposed to improve performance and remove the restrictions of passive suspensions. The first controlled suspension to appear was the active suspension system, which requires a power source to generate suspension forces according to some prescribed criterion. With such a strategy, ride comfort and road-holding ability can be enhanced simultaneously. However, such a system suffers from high cost, complexity and a considerable external power requirement. As a result, another strategy has appeared, which uses basically dissipative elements for which the force can be actively modulated: semi-active suspension. In this system, the power required to perform the modulation is insignificant in comparison with the power needed for a fully active suspension. However, the performance of a semi-active suspension is not exactly the same as that of an active suspension [1,2,3,4].

In some designs the spring rate can also be modulated. In many situations the performance of a semi-active suspension in terms of suppression of vertical vibrations can approach that attainable for fully active devices. There are limitations, however, for low frequency inputs as well as in breaking, acceleration, and cornering maneuvers [5,6,7].

Nowadays, in some studies, a novel semi-active damper, which is composed of a cylinder, injected with Magnetic Rheological Fluid (M.R.F) is proposed. The M.R.F has the very interesting property that the viscosity is changed by a magnetic filed. However, the damping coefficient of this system is absolutely positive even if the control signals for changing the viscosity fail [8].

In this paper a novel passive suspension system is introduced. The system is based on a flexible Electromagnetic Shock Absorber (EMSA) [9,10]. Secondly we present simulation of a quarter car model that is moved along randomly profiled road.

2. ELECTROMAGNETIC DAMPER

In active and semi-active suspension systems, controlled force generators are needed. In this study, force generators of the type "zero signal - zero force" are considered because of the absence of high - frequency transmission problems often encountered with hydraulic servo-cylinders (the "harshness" mentioned in various studies). This choice leads to electric motors or to frictional electromagnetic elements [11]. Such force generators can be thought of as linear motors acting directly on the driver cabin or the sprung mass of a car. Nowadays, suitable linear motors are available and can be designed for this purpose. One type of linear motor has been suggested in [12]. This paper introduces a flexible Electromagnetic Shock Absorber (EMSA). After designing and providing a model, the results of the test model are compared with behavior of Tubular Linear Induction Motor (TLIM), which is connected to DC supply. This system is low cost and controllable.

The scheme of an EMSA is given in Fig. 1. The primary winding is supplied with DC voltage by electronic circuit or car's battery. Radial magnetic field exists in air-gap between primary and secondary. When the primary moves into the secondary, a circulating current is produced in the copper rings. Consequently, damping force is produced in direction opposite that of primary movement [13]. Therefore, increasing primary current increases the damping force. The Electromagnetic damper is constructed and tested by the computer shock absorber test Unit, and its experiment results are shown in Fig. 2.

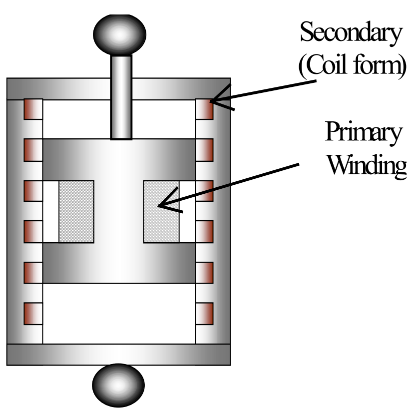

Fig. 1 Schematic of New Electromagnetic Damper

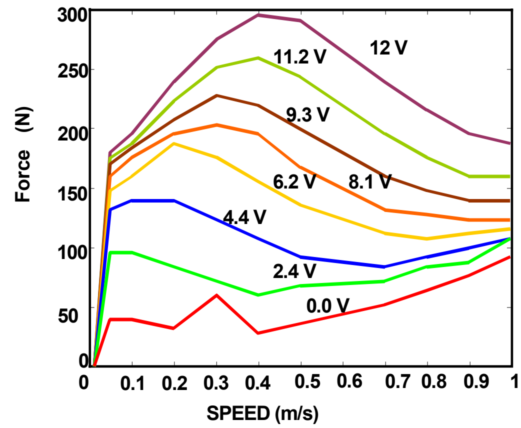

Fig. 2 Test Results of Electromagnetic Damper

3. DYNAMIC BEHAVIOR OF EMSA

Tubular Linear Induction Motor (TLIM) can ideally be realized by unrolling a rotational induction motor and by winding the obtained flat single-side linear induction motor off around an axis parallel to the direction of motion. These kinds of motors are suitable for applications where short linear motion is required [14,15].

Electromagnetic damper is similar to tubular linear induction motor, but this system has only a winding on the primary (stator), which is connected to dc supply, and the secondary (rotor) is around the primary as in Fig. 1. In other words, the primary is moving into the secondary. Furthermore, an effective form of tubular linear induction motor braking is to disconnect the motor from the ac system and inject current from a dc source, the magnetic filed is now stationary, so the slip is directly proportional to the velocity. [14,16]. Consequently, dynamic behavior of electromagnetic damper is similar to tubular linear induction motor braking. Finally, we can use dynamic equations of TLIM and simulate a quarter car model with electromagnetic shock absorber as shown in Fig. 5. If the dc source is disconnected, we will have a normally passive suspension system $(u = 0)$, and if the primary current / field current is controlled by driver or an electronic circuit, we will have a novel passive suspension system with flexibility not equal to zero $(u \neq 0)$.

3.1 Voltage Equations

The winding arrangement for a 2-pole, single-phase tubular linear induction motor is shown in Fig. 3. The primary (stator) winding is identical, sinusoidally distributed windings, with N_S equivalent turns and resistance r_S. For the purpose at hand, the secondary (rotor) winding will also be considered as two identical sinusoidally distributed windings, displaced $\tau / 2$ (τ is pole pitch), with N_r =1 equivalent turns and resistance r_r. The positive direction of the magnetic axis of each winding is shown in Fig. 3. The voltage equations in machine variables my be expressed as:

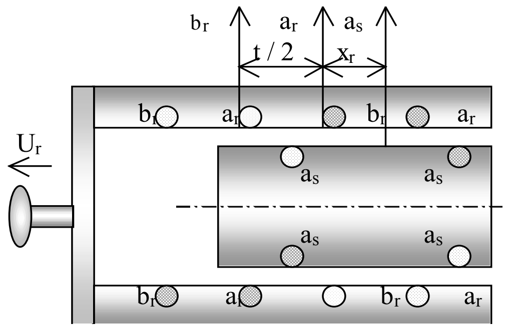

Fig. 3 Two-pole, single-phase Tubular Linear induction machine

$$V_{as} = r_s . i_{as} + p\lambda_{as}$$
$$V_{abr} = r_r . i_{abr} + p\lambda_{abr} \qquad (1)$$

where

$$(f_{abr})^T = \left[f_{ar} \; f_{br} \right] \qquad (2)$$

$\mathbf{r}_r$ is a diagonal matrix. For magnetically linear system, the flux linkages may be expressed as:

$$\begin{bmatrix} \lambda_{as} \\ \lambda_{abr} \end{bmatrix} = \begin{bmatrix} L_s & L_{sr} \\ (L_{sr})^T & L_r \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{abr} \end{bmatrix} \qquad (3)$$

The winding inductances are :

$$L_s = L_{ls} + L_{ms}$$
$$L_r = \begin{bmatrix} L_{lr} + L_{mr} & 0 \\ 0 & L_{lr} + L_{mr} \end{bmatrix} \qquad (4)$$
$$L_{sr} = \begin{bmatrix} \hat{L}_{sr} \cos(\beta x_r) & -\hat{L}_{sr} \sin(\beta x_r) \end{bmatrix}$$

In the equation (4), L_{ls} and L_{ms} are the leakage and magnetizing inductances of the primary winding respectively; L_{lr} and L_{mr} are for secondary windings. The inductance $\hat{L}_{sr}$ is the amplitude of the mutual inductances between primary and secondary windings. $\beta = \pi / \tau$.

This TLIM is not equipped with coil-wound secondary (rotor) windings; instead, the current flows in copper or aluminum rings, which are uniformly distributed and embedded in a ferromagnetic material. It may at first appear that the mutual inductance between a uniformly distributed secondary winding and a sinusoidally distributed primary winding would not be of the form given by (4). However, in most cases a uniformly distributed winding is described by its fundamental sinusoidal component and is represented by an equivalent 2-phase winding. Generally, this representation consists of one equivalent winding per phase [17].

When expressing the voltage equations in machine variable form it is convenient to refer all secondary variables to the primary winding by appropriate turns ratios.

$$i'_{abr} = (\frac{N_r}{N_s}) i_{abr}, V'_{abr} = (\frac{N_s}{N_r}) V_{abr}, \lambda'_{abr} = (\frac{N_s}{N_r}) \lambda_{abr} \qquad (5)$$

The magnetizing and mutual inductances are associated with the same magnetic flux path; therefore L_{ms}, L_{mr} and L_{sr} are related. In particular

$$L'_{sr} = (\frac{N_s}{N_r}).L_{sr} = L_{ms}\left[\cos(\beta x_r) \quad -\sin(\beta x_r)\right]$$
$$L_{ms} = (\frac{N_s}{N_r})^2 . L_{mr} \qquad (6)$$

3.2 Equations of Transformation For Secondary Circuit

In [17] the concept of the arbitrary reference frame was introduced and applied to stationary circuits. However, in the analysis of tubular linear induction machines it is also desirable to transform the variables associated with the symmetrical secondary windings to the arbitrary reference frame. A change of variables, which formulates a transformation of 2-phase variables of the secondary circuits to the arbitrary reference frame is

$$f'_{qdr} = K_r . f'_{abr} \qquad (7)$$

where

$$(f'_{abr})^T = \left[f'_{ar} \; f'_{br} \right]$$
$$(f'_{qdr})^T = \left[f'_{qr} \; f'_{qr} \right] \qquad (8)$$

$$K_r = \begin{bmatrix} Cos\ \gamma & Sin\ \gamma \\ Sin\ \gamma & -Cos\ \gamma \end{bmatrix} \qquad (9)$$

$$\gamma = \beta(x - x_r) \qquad (10)$$

x, x_r are the linear displacement of arbitrary reference frame and secondary windings, respectively. And the angular displacements $\theta_r = \beta x_r , \theta = \beta x$ are defined as:

$$\theta_r = \beta x_r = \int_0^t \beta U_r(\xi)\,d\xi + \beta x_r(0)$$
$$\theta = \beta x = \int_0^t \beta U(\xi)\,d\xi + \beta x(0) \qquad (11)$$

where ξ is a dummy variable of integration and U, U_r are the linear velocity of arbitrary reference frame and secondary windings, correspondingly. The angular velocities are $\omega_r = \beta x_r, \omega = \beta x$. Although this change of variables needs no physical interpretation, it is convenient to visualize these transformation equations as trigonometric relationships between vector quantities as shown in Fig. 4.

3.3 Voltage Equations in Arbitrary Reference-Frame Variables

Using the information in [17] and in the previous section we derive the form of the voltage equations in the arbitrary reference frame without any further analysis. In particular

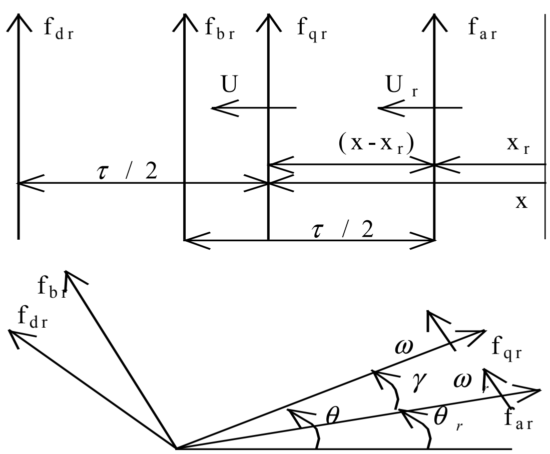

Fig. 4 Transformation for moving circuits portrayed trigonometric relationships

$$V_{qs} = r_s i_{qs} + p\lambda_{qs}$$
$$V'_{qdr} = r'_r . i'_{qdr} + \beta(U - U_r).\lambda'_{dqr} + p\lambda'_{qdr} \qquad (12)$$
$$(\lambda'_{dqr})^T = \begin{bmatrix} \lambda'_{dr} & -\lambda'_{qr} \end{bmatrix}$$

The set of equations is complete once the expressions for the flux linkage are determined. Substituting the equations of transformation into the flux linkage equations expressed in *ab* variables (3) yields the flux linkage equations for a magnetically linear system

$$\begin{bmatrix} \lambda_{qs} \\ \lambda'_{qdr} \end{bmatrix} = \begin{bmatrix} L_s & L'_{sr}(K_r)^{-1} \\ K_r (L'_{sr})^T & K_r L'_r (K_r)^{-1} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i'_{qdr} \end{bmatrix} \qquad (13)$$

Where L_s is defined by (4), L'_{sr} by (6) and if $M = L_{ms}$, It can be shown that

$$K_r L'_r K_r^{-1} = \begin{bmatrix} L'_{lr} + M & 0 \\ 0 & L'_{lr} + M \end{bmatrix} \qquad (14)$$

if $U = 0$ (the stationary reference frame), It can be shown that

$$L'_{sr} K_r^{-1} = (K_r (L'_{sr})^T)^T = \begin{bmatrix} M & 0 \end{bmatrix} \qquad (15)$$

The voltage equations are often written in expanded form. From (12)

$$V_{qs} = r_s i_{qs} + p\lambda_{qs}$$
$$V'_{qr} = r'_r . i'_{qr} + \beta(-U_r).\lambda'_{dr} + p\lambda'_{qr} \qquad (16)$$
$$V'_{dr} = r'_r . i'_{dr} - \beta(-U_r).\lambda'_{qr} + p\lambda'_{dr}$$

Substituting (14) and (15) into (13) yields the expressions for the flux linkages. In expanded form

$$\lambda_{qs} = L_{ls} i_{qs} + M(i_{qs} + i'_{qr})$$
$$\lambda'_{qr} = L_{ls} i'_{qr} + M(i_{qs} + i'_{qr}) \qquad (17)$$
$$\lambda'_{dr} = L_{ls} i'_{dr} + M(i_{ds} + i'_{dr})$$

Substituting (17) into (16) yields the single-phase tubular linear induction motor equations. They are

$$\begin{bmatrix} v_{qs} \\ v'_{qr} \\ v'_{dr} \end{bmatrix} = \begin{bmatrix} r_s + L_s p & L_{ms} p & 0 \\ L_{ms} p & r'_r + L'_r p & -\beta . U_r . L'_r \\ \beta . U_r . L_{ms} & \beta . U_r . L'_r & r'_r + L'_r p \end{bmatrix} \begin{bmatrix} i_{qs} \\ i'_{qr} \\ i'_{dr} \end{bmatrix} \qquad (18)$$

3.4 Electromagnetic Force Equation

The energy stored in the coupling field may be written as:

$$W_f = \frac{1}{2} L_{ms} i_{as}^2 + i_{as} L'_{sr} i'_{abr} + \frac{1}{2} (i'_{abr})^T . (L'_r - L'_{lr} . I) i'_{abr} \qquad (19)$$

where I is the identity matrix. Since the machine is assumed to be magnetically linear the field energy W_f is equal to the co-energy W_c, the electromagnetic force of a P-pole machine may be evaluated from

$$F_e(i_j, x_r) = \left(\frac{p}{2}\right) \frac{\partial W_c(i_j, x_r)}{\partial x_r} \qquad (20)$$

where F_e is the electromagnetic force positive for motor action (force output) and x_r actual displacement of the secondary. Since L_S and L'_r are not function of x_r , substituting W_f from (19) onto (20) yields the electromagnetic force in Newton (N)

$$F_e = (\frac{p}{2}).i_{as}.\frac{\partial}{\partial x_r}[L'_{sr}].i'_{abr} \tag{21}$$

The force and secondary velocity are related by

$$F_e = M_r(\frac{p}{2})\frac{dU_r}{dt} + F_L \tag{22}$$

where M_r is the mass of the secondary (kg) and in some cases the connected load. The expression for the electromagnetic force in terms of arbitrary reference frame variables may be obtained by substituting the equation of transformation into (22). Thus

$$F_e = (\frac{p}{2}).i_{as}.\frac{\partial}{\partial x_r}[L'_{sr}](K_r)^{-1}.i'_{abr} \tag{23}$$

This expression yields the force expressed in terms of currents as

$$F_e = (\frac{p}{2}).L_{ms}.\beta.i_{qs}.i'_{dr} \tag{24}$$

where F_e is positive for motor action.

4. THE VIHICLE SUSPENSION SYSTEM

4.1 Road Excitations

The vehicle excitation is assumed by the car's forward speed along a road having an irregular profile. Some classic studies on road profile have shown that surface irregularities may be considered as a Gaussian random process with zero mean and with a single-side power spectral density given by S_f [18].

The mathematical description is given by

$$\dot{z}(t) = A_2(t)z(t) + B_2(t)w(t)$$

in which (E[w(t)] = 0) and $E[w(t)^T w(\tau)] = W\delta(t-\tau)$ where E[.] is a mathematical expectation, δ is Dirac's delta function and w is white noise [19].

4.2 Suspension System Model

A quarter car as shown in Fig. 5 is the simplest model that can simulate the ride quality, suspension travel and tire deflection. An actuator (Electromagnetic Shock Absorber) is added in parallel with the passive spring and damping elements. The differential equations describing the vehicle dynamics are given below

$$\begin{aligned} &M_s\ddot{Z}_s + C_s(\dot{Z}_s - \dot{Z}_u) + K_s(Z_s - Z_u) = F_e \\ &M_u\ddot{Z}_u - C_s(\dot{Z}_s - \dot{Z}_u) + C_u(\dot{Z}_u - \dot{Z}_r) - K_s(Z_s - Z_u) + K_t(Z_u - Z_r) = -F_e \end{aligned} \tag{25}$$

The resulting state-space equation of suspension motion can be formulated in the state-space form of Equation (26), in which state vector x is given by:

$$\begin{aligned} &x = \begin{bmatrix} Z_s & \dot{Z}_s & Z_u & \dot{Z}_u \end{bmatrix}^T \\ &\dot{x}(t) = A(t).x(t) + B(t).u(t) + D(t).Z_r(t) \end{aligned} \tag{26}$$

Where x is the space vector of our car model, A is an $n \times n$ matrix, B an $n \times r$ matrix, and D an $n \times p$ matrix. Control force $u = f_e$ can be determined by dynamic equation of electromagnetic damper (24). Since the tire damping is usually very small, most studies have neglected its effect ($C_u = 0$) [20].

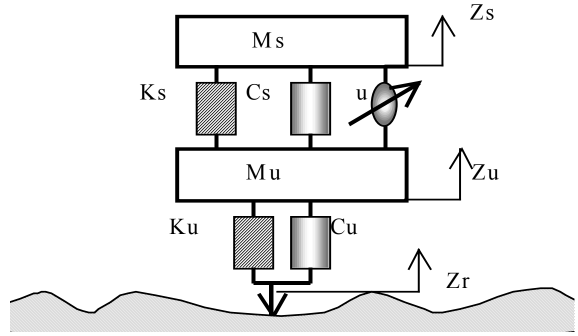

Fig. 5 a quarter car model

5. RESULTS AND ANALYSIS

In the numerical calculation the following numerical values for a quarter car model are used: M_s =250 kg (body), *M_u =100 kg* (un-spring mass), *k_s = 25000 N/m, k_u = 250000 N/m, C_s = 500 Ns/m* and *C_u=0*. Numerical values for an EMSA are *$P = 2$, τ = 0.05 rad / m, R_s = 7.25 Ω , L_s = 2.74 H, R'_r = 50.074 Ω , L'r = 2.64 H, L_{ms} = 2.64 H, M_r = 1.0 kg, N_s = 1120, N_r = 1 turn.*

A sample function of the irregular profile of the road is simulated and shown in Fig. 6-1. The spectrum power density gives the excitation:

$$S_z = \frac{S_w}{\omega^4 + 2\omega_d^2(2\xi_d^2 - 1)\omega^2 + \omega_d^2} \tag{27}$$

$\omega_d = 10.96$ rad/s, $\xi_d = 6.4$ and its associated equation (25), where

$$B_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, A_2 = \begin{bmatrix} 0 & 1 \\ -\omega_d^2 & -2\xi_d\omega_d \end{bmatrix} \tag{28}$$

Using the results from the previous section, we compute the behavior of our car model. In figures 6-2 till 6-4, we can see the body travel (Z_s), velocity (Z'_s) and acceleration (Z''_s).

We have drawn these curves so that the performance of different types of suspension can be compared. Because they are similar, we use terms of "*passenger comfort*" and "*vehicle body acceleration*" interchangeably. To show the improvement that new passive suspension can offer, we observe the acceleration of the body. From Equation (24), we can determine the various behaviors with increasing primary current (i_{qs}) in EMSA. The vehicle body acceleration decreases when the primary current / voltage (V_f) in EMSA varies between *2-11.5 V* hence improved comfort. But higher values of V_f give worse body acceleration isolation.

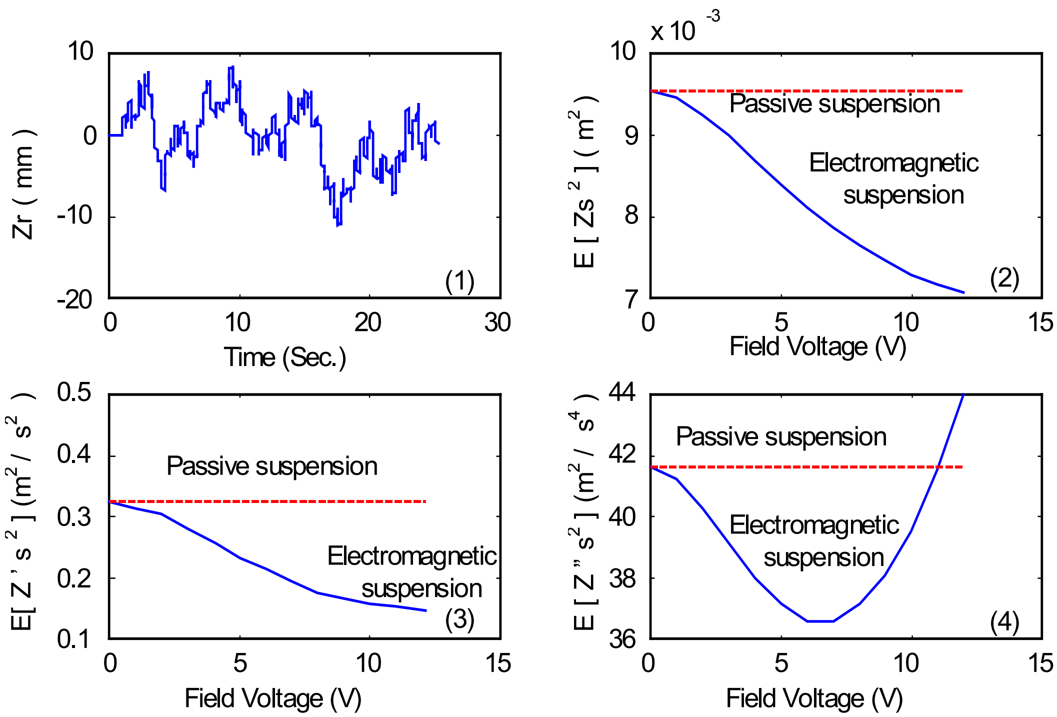

Figure 6 Influence of the primary voltage (vf) on system performances
(1) Road displacement (2) r.m.s body travel (Zs)
(3) r.m.s body velocity (Z's) (4) r.m.s body acceleration (Z"s)

We simulated this system for different velocities of vehicle (or different irregular profile of the road) and obtained the various domains for primary voltage V_f. In practical applications, the driver can determine the amount of damping by volume that is on car's dashboard according to Fig. 7. Putting position and speed sensors on the car's body and applying a suitable electronic circuit may improve this system.

Figure 8-1 shows the rms distance of car's body and unsprung mass. The rms variable of tire form is shown in figure 8-2. In Fig. 8-3 is shown the primary current of EMSA, when voltage is *12 V* and the irregular profile of the road is according to Fig. 6-1. Finally, the current induced in the secondary winding referred to primary winding is shown Fig. 8-4.

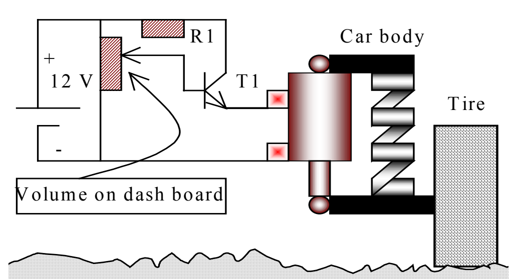

Figure 7. The circuit of regulating of damper coefficient

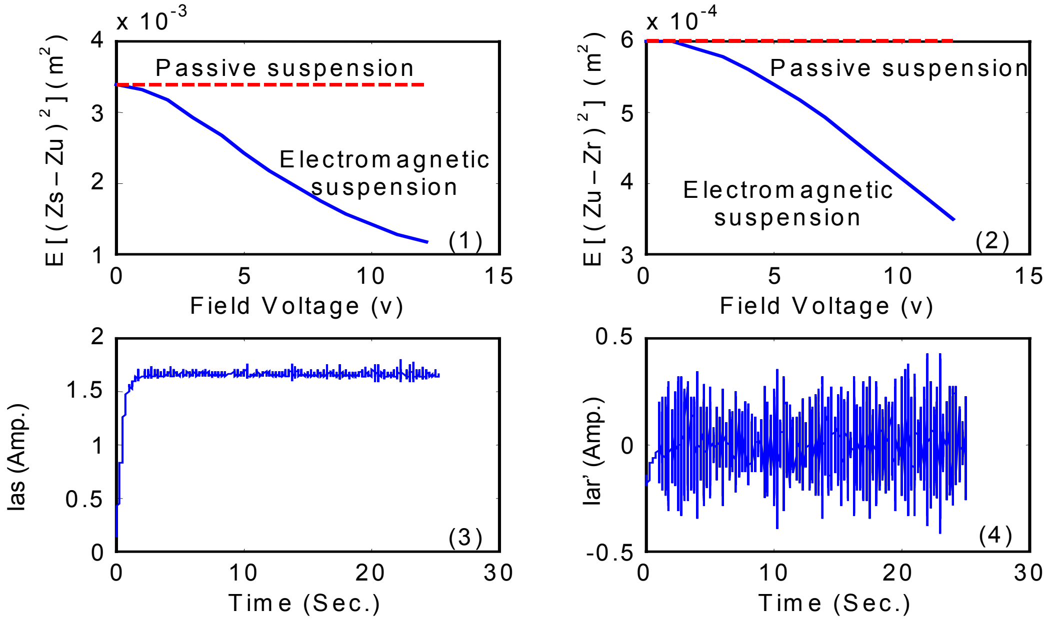

Figure 8. Influence of the primary voltage (vf) on system performances
(1) The rms distance of car's body and unsprung mass
(2) The rms variable of tire (3) the primary current at the voltage vf =12 V
(4) The current induced in the secondary winding referred to primary winding at vf = 12 V

6. CONCLUSION

This paper deals with a new passive suspension for vehicles that is composed of an EMSA. Such a system can adjust the damping coefficient by varying field current / voltage that is controlled by driver or an electronic circuit. The new electromagnetic shock absorber is paralleled with passive suspension system. If the control signals or power supply fail, the passive suspension will work normally. Electromagnetic damper is similar to TLIM but this system has only a winding on the primary that is connected to dc supply. It will have dynamic behavior very close of TLIM that is connected to dc supply.

Therefore, we can use dynamic equations of TLIM and simulate a quarter car model moving along randomly profiled road with electromagnetic shock absorber. Usually, the body acceleration decreases as field voltage (V_f) in EMSA increases, so that passenger comfort is improved. In practical applications, the driver, will regulate the amount of damping by varying the volume on dashboard. By using position and speed sensors on the vehicle body and suitable electronic circuit this system may be improved.

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