Feasibility Study of an Electromagnetic Shock Absorber with Position Sensing Capability

Babak Ebrahimi*1, Mir Behrad Khamesee*2, M. Farid Golnaraghi†3

*Department of Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1

†Mechatronic Systems Engineering, Simon Fraser University, Surrey, British Columbia, Canada V3T 0A3

1bebrahim@uwaterloo.ca
2khamesee@uwaterloo.ca
3mfgolnar@sfu.ca

***Abstract*- This paper presents the feasibility study of an electromagnetic damper, as senor/actuator, for vehicle suspension application. This electromagnetic damper is based on the concept of the tubular, linear, brushless dc motor, and operates in three modes: passive, semi-active, and active. As a self-powered active shock absorber, the proposed damper has the potential to function as a sensor and actuator simultaneously.**

Optimized geometry factors are selected to achieve higher electromagnetic forces and magnetic flux induced in the system, and the maximum achievable damping force is estimated based on analytical models, considering physical restrictions. The estimated damping force seems reasonable for vehicle suspension applications, even in the absence of external power.

I. Introduction

This paper discusses the feasibility of a tubular, slotted linear dc motor as an electromagnetic damper to be used in vehicle suspension systems. Conventional passive springs and shock absorbers, in combination with tires and other suspension geometries, provide several combinations of variables in suspension systems. Unfortunately, choosing these variables is a trade-off between ride comfort and handling. Active suspension in its various forms offers a means to relax those compromises [1]. In active suspension systems, actuators are used to generate the necessary force to suppress the vibrations and they are operated by external power. On the other hand, in semi-active suspension systems the damping characteristics can be controlled externally by supplying a low power signal to the system. Karnopp [2] has shown that for oscillation frequencies, typically expected in road vehicle suspensions, electro-dynamic variable shock absorbers are feasible. Suda *et al.* [3] used a rotating DC motor to convert vibrational energy to electrical energy. They explained some trade offs involved during the design process; for example, they showed that there is a trade off between energy regeneration efficiency and the damping coefficient, which depends on DC machine internal and external resistance. They [4] also used two linear DC motors, one in the primary suspension called “regenerative damper” which regenerates the vibration energy and stores it in the condenser, and the second linear DC motor in the secondary suspension system, which used this energy to attain active control. Suda [5] also proposed another electromagnetic damper using a DC motor, planetary gears, and the ball screw mechanism to convert transverse motion of vibration between car body and wheels into rotating motion of the DC motor. Murty [6] disclosed an electric variable damper for vehicle suspension systems, converting vertical suspension motion into rotary motion via a ball screw mechanism. A rectifier bridge was used to convert the three-phase alternator output to a single DC current. The proposed device dissipated the vibration energy as heat through a variable load resistance and did not recover the energy. Merritt *et al.* [7] proposed a linear electrical generator with a reciprocating armature with rectangular permanent magnets, which were coupled to a source of relative motion. The device does not appear to fully utilize the magnetic field generated by the permanent magnets, since the generator uses only single magnetic pole-coil interaction. Konotchick [8] proposed various designs of linear electric power generators consisting of a cylindrical assembly of rare earth magnets (NdFeB) and coils positioned to move reciprocally relative to each other. The device is most likely designed for relatively large amplitude motions such as wave energy generation. Goldner and Zerigian [9] proposed a new assembly of magnet and coil winding arrays to maximize the radial magnetic flux density in a linear generator acting as a shock absorber. The damper does not appear to be controlled actively, so ride comfort and road handling characteristics suffered.

The present paper utilizes magnetic circuit principles and non-dimensional geometry factors to optimally design an electromagnetic damper for vehicle suspension systems. Physical limits are considered to estimate the highest achievable damping force. The proposed electromagnetic damper operates in three modes: passive, semi-active, and active. It can operate as a generator, converting the vehicle body vibration to useful electrical energy, where the concept of linear motors is used reversely to generate electricity. The damper is also cost-effective, using several permanent magnets in combination with electromagnets as major components, and a straightforward fabrication. Utilizing a linear motor simplifies the mechanical design and eliminates the complex process of linear-to-rotary motion. The Hall effect can be simply used to provide the linear

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position sensing capability, eliminating the need for additional sensors in a vehicle active-control suspension system. The assembly comprises a tubular design as shown in Fig. 1, which has less leakage flux and vastly is better in utilizing the magnetic flux, leading to higher electromotive force (in passive/semi-active mode) and higher thrust force (in active mode). Axially magnetized permanent magnets in the mover cause higher specific force capability rather than radially magnetized ones [10]. The annularly shaped magnets supported by a non-ferromagnetic rod are selected instead of the conventional disk shaped magnets fastened together on a nonmagnetic tube, reducing the effective air-gap. The slotted stator core designs are superior to the slotless designs, in terms of the generated damping force (the former topology provides about 33% more force to volume ratio than that of slotless version [11]). In conclusion, the tubular slotted core with a moving magnet design is chosen, in which the ring-shaped PMs are axially magnetized and fastened together in the mover.

II. Electromagnetic Damper in Passive/Semi-active Modes

In this section, the maximum achievable force is estimated for the passive/semi-active modes. The stator coils are short-circuited in the passive mode, causing a constant damping coefficient. In contrast, the damping coefficient in the semi-active mode can be decreased, relative to the passive mode, increasing the external resistance of the stator coils. According to [12], a damper in a typical vehicle suspension system should produce an RMS force value of 1050 N at the RMS damper velocity of approximately 0.8 m/s, and the maximum damper external diameter and length are 150 and 600 mm, respectively.

Fig. 1 shows the schematic view of the damper configuration. The goal is to design the geometry of the electromagnetic damper topology to improve the damping force according to the volume restriction. Therefore, the design parameters are the dimensions of the magnets and coils. The following equations are used to estimate the overall dimensions of the magnets [13]:

$$\begin{aligned} &\frac{\tau_m}{\tau} = 0.5 \\ &\frac{l_m + s + g}{D + s} = 0.618. \end{aligned} \tag{1}$$

Setting $D = 45$ mm, $g = 0.5$ mm, $s = 5$ mm, and $\tau = 10$ mm, results in $l_m = 25$ mm and $\tau_m = 5$ mm. The

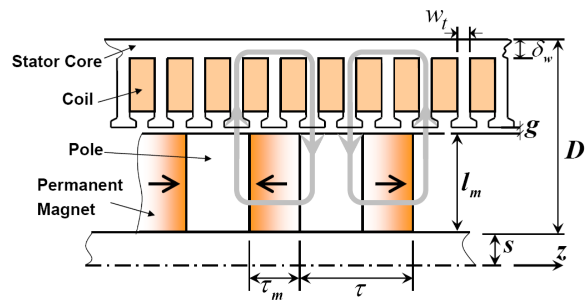

Fig. 1 Sketch of the slotted, tubular, linear, interior PM motor.

voltage induced in each phase depends on the flux linkage in the phase due to the magnets (λ_{PM}) [15], and is

$$E = \frac{d\lambda_{PM}}{dt} = \frac{d\lambda_{PM}}{dz}\frac{dz}{dt}, \tag{2}$$

where

$$\lambda_{PM} = N\phi_g \cos((\pi/\tau)z). \tag{3}$$

N and ϕ_g are the number of turns in the phase, and the air gap magnetic flux, respectively.

The magnetic flux is calculated by using the magnetic circuit principle [14] and represented as

$$\phi_g = \frac{B_{rem}\tau_m\mu_0 H_c A_g}{\left(2B_{rem} \times g + \tau_m\mu_0 H_c \dfrac{A_g}{A_m}\right)}, \tag{4}$$

where the areas of the air-gap and magnet per pole are

$$\begin{aligned} A_g &= 2\pi(s + l_m + g/2)\frac{\tau - \tau_m}{2} \\ A_m &= \pi\left((l_m + s)^2 - s^2\right). \end{aligned} \tag{5}$$

Therefore, for the first phase, (2) is simplified to

$$E = -N\phi_g \frac{\pi}{\tau}\sin\left(\frac{\pi}{\tau}z + \theta\right)\frac{dz}{dt}, \tag{6}$$

where θ is obtained with respect to the current phase shift in different phases. By computing (6), the power loss in damper at 0.7 m/s is calculated as 0.23 kW, and can be used for powering the vehicle accessories. The total opposing force per coil in the generator case is calculated by

$$f = -N\phi_g \frac{\pi}{\tau}\hat{I}\cos\varphi\cos\left(\frac{\pi}{\tau}z + \theta\right), \tag{7}$$

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Table 1 Specification of the proposed electromagnetic damper.

Item /Symbol	Value/Unit
Number of poles p	24 poles
Pole pitch τ	10 (mm)
Magnets' thickness τ_m	5 (mm)
Magnets' outside diameter $2(l_m + s)$	60 (mm)
Rod diameter $2s$	10 (mm)
Rod material	Al Alloy
Mover mass M_m	2.7 (kg)
Magnets' material	Nd-Fe-B, B_y=1.17(T)
Number of slots N_s	3×24 slots
Number of turns per slot N	300-26AWG
Slot pitch τ_s	10/3 (mm)
Slot width $\tau_s - w_t$	2.5 (mm)
Air-gap thickness g	0.5 (mm)
Winding factor λ	0.8
Stator mass M_s	4.4 (kg)
Stator material	Low Carbon Steel, S10C

where $\hat{I}$ and φ are the peak current and phase angle between the voltage and current in the coil, respectively. The electromagnetic damper, as a generator, can act as a semi-active damper by the addition of an external resistance in the system. The electromagnetic damper, as a generator, with the specification given in Table 1 has a maximum damping coefficient equal to 950 kg.s., which is a reasonable damping coefficient for a passive damper for vehicle suspension system in the absence of external power.

III. Electromagnetic Damper in Active Mode

The electromagnetic damper, as a motor, is an active damper. The motor operates through the activation of the stator coils in a proper manner. The peak value of the electric loading K_{sp} (the maximum current density distribution along the motor length) is obtained by

$$K_{sp} = \frac{N_s \lambda N}{p\tau} \hat{I} , \qquad (8)$$

and is restricted by either the magnetic limit or the thermal limit [13]:

• *Magnetic Limit*: The stator winding currents cause a reaction flux density that affects the PMs. The flux density variation in PMs is $\pm\Delta B_m$, and it is calculated by

$$\Delta B_m = \frac{16}{\pi^3} \frac{K_{sp}\tau}{\left((2l_m + 2s)^2 - (2s)^2\right)\left(4R_g + R_m\right)} , \qquad (9)$$

where R_g and R_m are the air-gap and magnet reluctances, respectively. The minimum magnetic flux density in the PM must be higher than a certain amount to avoid an irreversible demagnetization [13]. The electric loading can be calculated due to this magnetic limit.

• *Thermal Limit*: The winding temperature rise should be considered as another limit on the electric loading. This limit is more restrictive than the magnetic limit in most cases [11]. The copper losses (P_{Cu}) are computed by the thermal analysis and given by

$$P_{Cu} = \frac{\pi N_s N^2 (D + l_m + 2s)}{\sigma\lambda S_{cu}} \left[\frac{p\tau K_{sp}}{N_s \lambda N}\right]^2 , \qquad (10)$$

where S_{cu} is the stator coils' cross-section area. The generated heat is transferred through the external surface ($S_e = 2\pi(D+s).p\tau$). The winding temperature rise θ_w is related to P_{Cu} by

$$P_{Cu} = h\theta_w (2\pi(D+s)p\tau) , \qquad (11)$$

where h is the overall heat transfer coefficient. Eq. (11) is rewritten in terms of the thermal resistances between the coil and stator core (R_w), and between the stator core and the external air (R_e) as

$$P_{Cu} = \frac{\theta_w}{R_w + R_e} = \frac{\theta_w}{\frac{\ln[(D+s-\delta_w)/(L_m+s+g)]}{K 2\pi p\tau} + \frac{1}{h_N S_e}} ,(12)$$

where K and h_N are the thermal conductivity of iron and the natural-convection heat transfer coefficient. Two values of the electric loading K_{sp} are calculated from (9) (setting $\Delta B = 0.7\,\mathrm{T}$) and (10) (considering the maximum winding temperature rise $\theta_w = 125^{\circ C}$), and the lowest one is considered. The peak electric loading for the electromagnetic damper with the proposed dimensions is obtained from [11] equal to $K_{sp} = 4.5\times10^4$ A/m, resulting in a peak current of $\hat{I} = 0.6\,\mathrm{A}$ in the stator coils. The maximum force developed by the electromagnetic damper is obtained by computing

$$F = 4p(l_m + s + g)\tau K_{sp} B_g \sin\left(\frac{\pi}{2}\frac{(\tau - \tau m)}{\tau}\right), \qquad (13)$$

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where B_g is the air-gap flux density [13]. The maximum achievable force for the electromagnetic damper in the active-mode $F = 950\,\text{N}$ is obtained from (13), requiring 288 W of electrical power for each electromagnetic damper.

IV. CONCLUSION

The electromagnetic damper concept has been introduced and the research reviewed. Among different potential technologies and topologies, the linear motor approach is chosen. Different possible design approaches are considered and a tubular, interior, slotted permanent magnet motor is selected, seeking higher efficiency. Non-dimensional, geometry design parameters are optimized to obtain the highest damping coefficient. Finally, the maximum achievable force is calculated in different damper operating modes of passive, semi-active, and active, considering the physical restrictions.

Electromagnetic damper developed in this article as a passive damper can be used for energy harvesting purposes. Damping coefficient of the proposed electromagnetic damper could be controlled rapidly and reliably, either by regulating the induced current in the stator coils by adjusting the coils' resistance (semi-active mode), or energizing the stator coils to make an active electromagnetic damper. In the active mode, damping coefficient can be increased or decreased, relative to the passive mode, depending on the voltage applied. The damper acts as a sensor, utilizing the Hall effect position sensing capability, to eliminate the need for additional sensors in a vehicle active-control suspension system. The maximum damping force of 950 N is achievable by the proposed damper specifications, and the peak electrical power equal to 288 W is needed for each suspension unit. This expected power consumption, for a four wheeled vehicle, is one-third of that of a vehicle's air-conditioning system. The novel electromagnetic damper is also applicable in other vibration isolation systems such as precision machinery and structure vibration isolation.

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