

Design of an Electromagnetic Regenerative Damper and Energy Harvesting Assessment

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Abstract: - Design of an electromagnetic regenerative shock absorber is proposed in this paper. In order to increase the efficiency of land vehicles the sources of energy losses have to be eliminated, or reduced. For this reason, several systems, recovering kinetic energy and converting it into electrical power, were studied and designed in the last years. This energy, converted into heat in traditional systems, is recovered to increase the autonomy of the vehicle. The proposed device is constituted by a stator part which coils are placed in an innovative disposition. The moving part is constituted by a rod made in stainless steel with alternated permanent magnets and spacers, so that the relative motion generates a great variation of the concatenated magnetic flux on the coils. A damper mathematical model is implemented in order to characterize the device operating. Several finite element analyses, conducted in ANSYS Workbench Magnetostatic, have confirmed the magnetic field and flux values obtained through the theoretical analysis.

Key-Words: - Suspension; Regenerative damper; Energy harvesting; Electromagnetic shock absorber; FE magnetostatic analysis.

1 Introduction

In the last years, automotive research aims to maximize the passengers comfort and the efficiency of all vehicle components. Especially in hybrid vehicles, the energy losses have to be minimized, by recovering more energy as possible from all installed devices. The kinetic energy is commonly dissipated into heat in the case of brakes or suspensions. The amount of recoverable braking energy is much higher than is possible to obtain by a suspensions system. However, there are many studies regarding the possibility of energy harvesting by the vehicles suspensions using electromagnetic dampers which have to be compact and efficient. For this reason, almost all solutions of electromagnetic dampers are based on the use of rare-earth permanent magnets. The electromagnetic dampers are not only used in automotive field, but even in civil structures in order to damp the vibrations and thereby reduce or eliminate the noise. The wind or even the earthquakes, moreover, produce vibrations that must be damped in order to recover the energy. Some authors have proposed different types of electromagnetic dampers. In [1] and [2] these electromagnetic dampers are based on rotary actuators which require a motion converter

involving many complexities. Cassidy et al. [3] studied an electromagnetic device for energy harvesting from civil structures based on the conversion, by means of a ball-screw mechanism, of the linear motion in rotating motion. The same solution is adopted by Amati et al. [4] that use a ball screw mechanism to design an electromagnetic damper for automotive applications. Several Authors have designed and studied this type of solution [5] [6] [7]. Yin et al. [8] compare a damper with ball screw mechanism and a damper constituted by a gearbox and an electric generator. Authors state that a damper constituted by gearbox introduces a significant unsprung mass due to the inertia of the rotating components of the device. Li et al. [9] propose the design, bench experiments and road tests of a retrofit regenerative shock absorber based on a permanent magnetic generator and a rack-pinion mechanism. Results show that variable damping coefficients and the asymmetric feature in jounce and rebound motions are achieved by controlling the electrical load of the shock absorber. Moreover, a peak power of 68 W and average power of 19 W are obtained from a prototype shock absorber when the vehicle is driven at 48 km/h on a fairly smooth campus road. Suda et al. [10] [11]

present a method to solve the problems in active and passive control systems: in passive suspension an energy regenerative damper system which converts vibrations into useful energy is proposed. The hybrid system combines this energy regenerative system and active control in order to achieve good performance of vibration reduction with few energy consumption. Nakano [12] applied the system in a truck cabin suspension. Another important application of regenerative damper is related to renewable energy production. In fact, dampers are used to recovery energy from the sea wave motion [13] [14] [15]. As already mentioned, the use of ball screw mechanism inevitably reduces the device efficiency. Moreover, the rotor inertia of the rotating generator could have side effects on the suspension behavior. For this reason, many studies aim to design linear electromagnetic regenerative shock absorbers. They may have several configurations, though is strictly necessary the use of rare-earth permanent magnets that produce a strong magnetic field. On the other hand, the configuration of the stator coils can be varied in order to investigate the better solution in terms of damping coefficient, stability and efficiency. More frequently studied configurations have the coils arranged with their axis aligned with the magnets axis and with the damper axis [16] [17] [18] [19]. Oprea et al. [16] analyzed an electromagnetic damper optimizing the device configuration by means of finite element analysis. They correctly affirm that the rod supporting the magnets and spacers should be highly reluctant but they do not specify the used material. Moreover, they used the optimal size of magnets and spacers [20] and, finally, Authors carry out a thermal analysis. Nagode et al. [17] study two types of electromagnetic dampers for railroad applications and implement a prototype. Zuo et al. [18] design and carry out analysis on a retrofit regenerative shock absorber. The wave form of the regenerated currents is much irregular and for this reason [18] the Authors study a circuit in order to correct the power output. Tang et al. [19] design and optimize a tubular linear electromagnetic damper consisting of an aluminum rod with axial magnets and spacers. They optimized the thickness of magnet and spacer to obtain the maximum power density. Moreover, they analyzed a new configuration of magnets and coils and compared the results. In the paper [21] two configurations of regenerative electromagnetic shock absorbers are developed: a linear device and a rotary device. Performance of these shocks in a laboratory test stand and in a small all-terrain vehicle is described. The paper [22] shows that the magnetic damper

system using a phase lead controller is excellent in reducing the vibration of a one degree of freedom suspension system.

In this work, Authors study an innovative electromagnetic damper consisting of a stainless steel rod having a great reluctance and a greater mechanical strength than the aluminum alloy rod used in [16]. The main difference consists in a new disposition of the coils with respect to other literature studies; in fact, the axis of each coil is perpendicular to the damper axis. The magnets are stacked with reverse magnetization axis [23] [24], in order to direct the magnetic flux toward the spacers (which have great magnetic permeability) and, finally, toward the coils. The mathematical model of the damper is defined considering the variable inductance of the coils with the movement of the stem. In fact the magnetic circuit reluctance is variable because the thickness of the air gap varies during the stem displacement. The mathematical model is implemented in Matlab Simulink environment in order to characterize the device operating. The magnetic flux density, previously analytically calculated, is verified by means of FE analysis using Ansys Workbench Magnetostatic. Finally, the damping coefficient and the energy harvesting potential are evaluated considering that the connection to a harvesting system produces substantial variations in the suspension behavior.

2 Geometry and magnetic flux determination

The studied device is constituted by a sliding and a ferromagnetic cylindrical part setting up the stator; some slots are realized in order to place the electromagnetic coils. The stroke of the damper is equal to 207 mm, the stator outer diameter is equal to 66 mm and 100 mm in the section where the coils are placed (Fig.1). The slots allow placing 20 coils, positioned in order to synchronize their effect, in terms of force on the stem. Fig 1(a) shows the longitudinal section of the stator and the layout of the coils (schematically shown). In particular the coils axes are disposed perpendicularly to the translation axis of the stem. The tubular part, where the coils are not present, acts as a rail for the stem in order to support possible bending actions. Rings of rare-earth permanent magnets are placed in the rod constituting the sliding part (Fig. 1b). The magnets are stacked with alternated magnetization direction and they are separated by means of ferromagnetic spacers. This configuration, in accordance with [19], allows maximizing the magnetic flux connected

with the coils. The diameter of the spacers is slightly lower than the inner diameter of the stator, in order to leave an air gap as small as possible between the stator and translating parts, since these parts are constantly in relative motion during the operation. The movement of the stem produces a magnetic flux variation through the coils. The magnetic circuit of the device changes cyclically: in particular, when the spacer is set in correspondence of the coils core (minimum air gap $\tau=0.5\text{mm}$), the reluctance of the circuit assumes the minimum value and the flux lines are optimally directed.

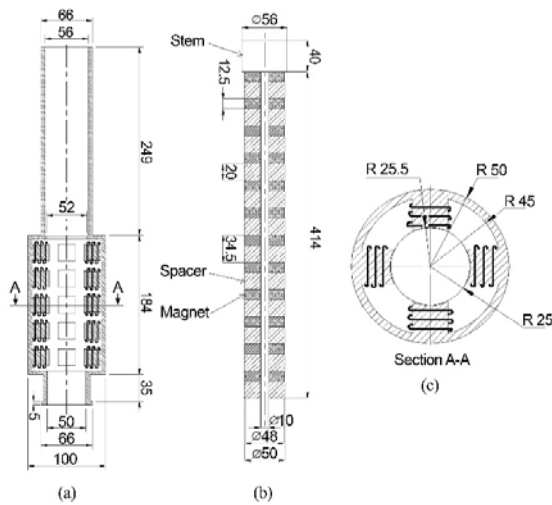


Fig.1: (a) longitudinal section of the stator part and (b) sliding part; (c) transversal section of the stator.

When the stem is shifted of an amount equal to half of the spacers pitch (fig. 3), the opposite situation is established and the magnetic circuit reluctance increases due to the assumed geometric configuration and to the increment of the air gap. Assuming that the ferromagnetic material reluctance is negligible, the only reluctance of the circuit is due to the two air gaps. The operating curve of the magnets can be evaluated by relationship (1):

$$\phi_m = -\frac{A_m}{2R_t} \quad (1)$$

After the operating point determination, the flux generated by a magnet, passing through the magnetic circuit, is equal to $\phi_m = 2.48 \cdot 10^{-3} \text{Wb}$. In particular Fig.1(c) shows that the total magnetic flux is generated by two consecutive magnets and it involves four coils for each considered section. Finally, the flux that passes through each coil is obtained by relationship (2):

$$\phi_c = \frac{2 \cdot \phi_m}{4} = 1.24 \cdot 10^{-3} \text{Wb} \quad (2)$$

This is the maximum flux value, generated when the stem is positioned with the spacers aligned with the coils cores. The mean electromagnetic induction in each coil core is calculated by means of relationship (3):

$$B_m = \frac{\phi_c}{\Sigma} = 2.43 \text{T} \quad (3)$$

The mean induction and the concatenated flux are compared with the results obtained by means of finite element analysis performed in Ansys Workbench Magnetostatic environment. Fig. 2 shows the directional magnetic flux density (value of mean induction calculated along the perpendicular direction to the surface of the coils cores) that allows the flux calculation and the induced electromotive force.

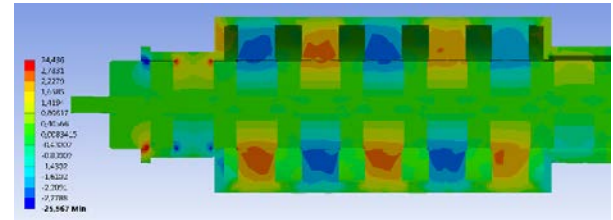


Fig. 2: Directional magnetic flux density (maximum concatenated flux position).

The numerical simulation provides a mean induction value on the coils cores, equal to: $B_c^* = 2.3 \text{T}$. This value is slightly lower than that obtained by the analytical study, because the ferromagnetic material reluctance is omitted. For each coil, the concatenated flux is equal to: $\phi_c^* = B_c^* \cdot \Sigma = 1.1475 \cdot 10^{-3} \text{Wb}$.

The stem displacement (with an amount equal to the magnets pitch) provides a concatenated flux variation through coils. Since the magnetization directions are opposite, flux passes from a maximum positive value $(\phi_c^*)_{\max} = 1.1475 \cdot 10^{-3} \text{Wb}$ to the maximum negative value $(\phi_c^*)_{\min} = -1.1475 \cdot 10^{-3} \text{Wb}$. Consequently the magnetic flux must assume zero value for an intermediate position of the stem.

The magnetic flux distribution density provides values near to zero in the direction orthogonal to the surface of the coils (fig. 3).

The mean induction value in the direction of the coils axes is equal to $B_c^* = 0.03 \text{T}$. The mean flux is equal to $\phi_c^* = B_c^* \cdot \Sigma = 2.55 \cdot 10^{-5} \text{Wb}$.

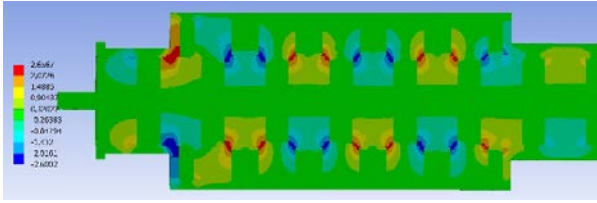
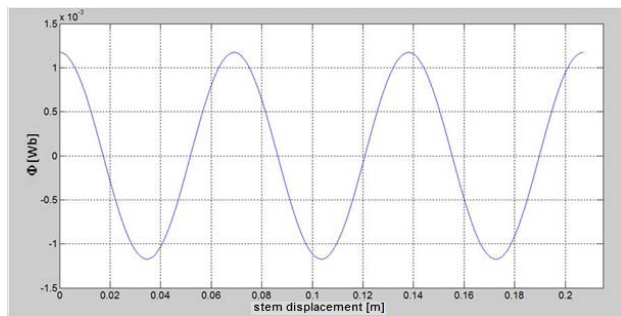


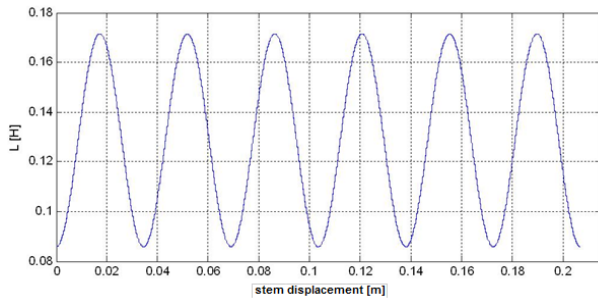
Fig. 3: Directional magnetic flux density (minimum concatenated flux position).

3 Mathematical model and operating analysis

Relative motion between sliding part and the stator generates a magnetic flux variation through coils.



(a)



(b)

Fig. 4: flux (a) and the inductance (b) variation of each coil versus the stem displacement.

Several analyses, conducted varying the relative position between the parts mentioned above, show that the variation is well approximated by a sinusoidal law. In particular, fig. 4(a) e 4(b) show, respectively, the flux and the inductance variation of each coil versus the stem displacement. The inductance, in fact, is related to the stem movement that yields the reluctance variation. The electromotive force expression in each coil can be analytically determined by means of relationship (4).

$$\varepsilon_i(x) = -N \frac{d\Phi(x)}{dx} V_s = -N \left[-\phi(x)_{\max} \frac{\pi}{p} \sin\left(\frac{\pi}{p} x\right) \right] \omega \frac{C}{2} \sin(\omega t) \quad (4)$$

Considering the equivalent circuit of each coil, the relationship (5) describes the physical operating principle.

$$\varepsilon_i(t) = (R_{int} + R_{ext}) \cdot i(t) + L(t) \frac{di}{dt} \quad (5)$$

where R_{int} is the resistance of the coil itself, R_{ext} is the external resistance (load connected to the damper) and $L(t)$ is the inductance. By multiplying the terms of the relationship (5) by the current $i(t)$, the electric power provided to the coils is obtained. The force applied to the stem and the damping coefficient of the device can be determined by means of relationship (6), considering the energetic balance.

$$C_d(t) = \frac{n \varepsilon_i(t) i(t)}{V_s^2(t)} \quad (6)$$

The mathematical model, implemented in Matlab-Simulink environment, allows analyzing the damper operation by varying the input data. The first analysis is carried out disregarding any external resistance, so that the coils are short-circuited. In this case one can demonstrate that, for fixed geometric dimension of the coils, the value of the damping coefficient does not depend on the turns number of the coils. In particular fig. 5 shows the value of the damping coefficient, imposing a sinusoidal translation of the stem.

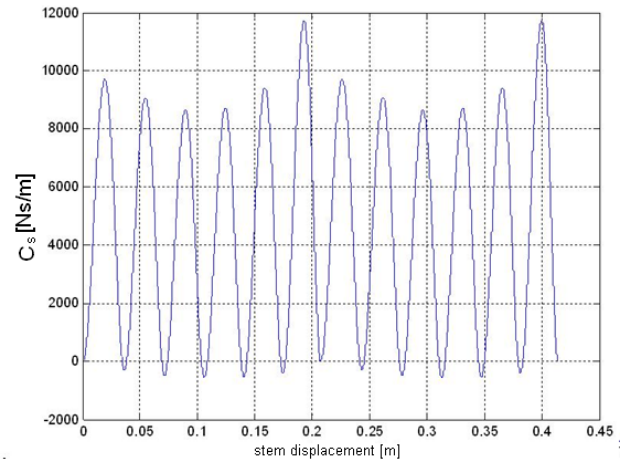


Fig. 5: Damping coefficient versus the stem displacement (short-circuited coils).

In the examined case, the damping coefficient strongly depends on the stem position; in particular the trend of two successive strokes of the stem is reported (outward stroke and return stroke). By observing fig. 5, one can note that the studied device has to be modified because the damping coefficient of an automotive suspension system has to be as much as possible constant varying the stem position. The stator geometry is then modified in order to optimize the operating device, so that the effect of

the coils in terms of force on the stem is out of phase. A block of coils (constituted by 10 coils) is shifted by an amount equal to the half-pitch of the magnets, in order to implement the phase-shift. In this way, the concatenated magnetic flux is phase-shifted by 90 degrees and the damping coefficient assumes a more stable trend around its mean value, as fig. 6 shows.

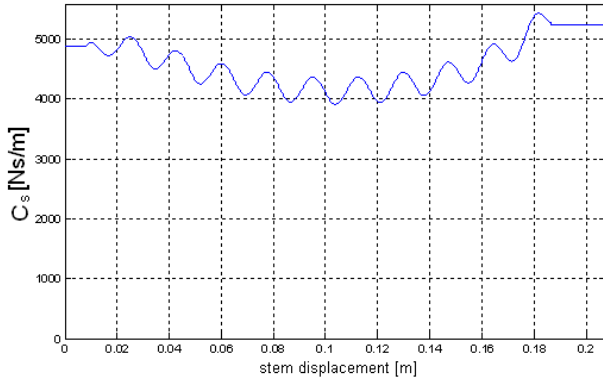


Fig. 6: Damping coefficient versus the stem displacement (optimized solution with short-circuited coils).

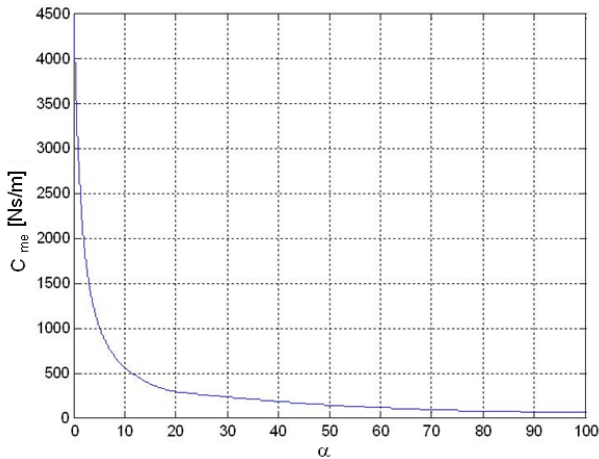


Fig. 7: Mean damping coefficient versus $\alpha = \frac{R_{ext}}{R_{int}}$.

Coils have to be connected to an electric storage system, in order to harvesting the energy produced by the damper. The harvested power is equal to $P_{acc}(t) = R_{ext} \cdot i(t)^2$. The introduction of an external load causes electric current decrease and reduction of the forces applied to the stem, because the interaction between magnetic field and electric current affects the loads value. The mean damping coefficient appears strongly dependent on the resistance ratio $\alpha = \frac{R_{ext}}{R_{int}}$. In fact, increasing the value

of the external resistance, the mean damping coefficient decreases as fig. 7 shows.

The damper/generator efficiency is given by relationship (7).

$$\eta = \frac{P_{acc}}{P_{gen}} = \frac{P_{acc}}{P_{diss} + P_{acc}} = \frac{R_{ext} i^2}{R_{int} i^2 + R_{ext} i^2} = \frac{R_{ext}}{R_{int} + R_{ext}} = \frac{\alpha}{1 + \alpha} \quad (7)$$

A high damping coefficient needs a low value of external resistance and then a low value of accumulation power.

In this work the hypothesis is done that the damper is installed on an electric car with mass $m_{tot}=800\text{kg}$. Considering a uniformly load distribution (the mass on each wheel is equal to $m=200\text{kg}$ about) and assuming a simplified model of the suspension with one degree of freedom, the optimal damping coefficient can be obtained by relationship (8):

$$C_{opt} = \sqrt{\frac{k \cdot m}{2}} = 1566 \text{ Ns/m} \quad (8)$$

where the spring constant is obtained imposing that the spring is compressed of an amount of $\Delta x=80\text{mm}$ [25] under static load. The resistance ratio α can be calculated in correspondence of the optimal damping coefficient (8). Fig. 6 shows that the damping coefficient is not perfectly constant with the stem position, but presents some fluctuation around the mean value. In order to take into account this aspect and to avoid that the minimum value of the damping coefficient assumes lower value than the optimal, the optimal damping coefficient C_{opt} is increased of about 12%, so that the value of $C_{opt}=1750 \text{ Ns/m}$ ($\alpha = 2.35$) is assumed.

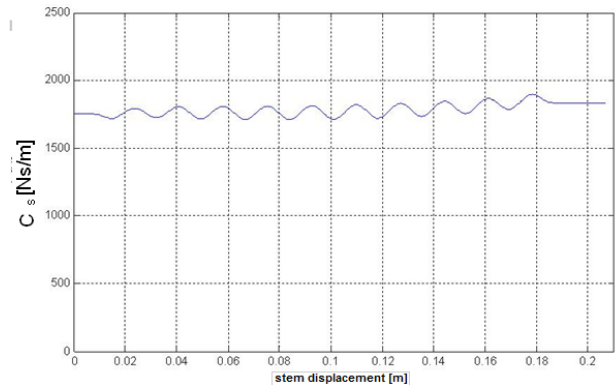


Fig. 8: Damping coefficient versus the stem position (optimized solution with coils connected to an electric storage system).

The trend of the damping coefficient versus the stem position is reported in fig. 8.

4 Conclusions

In this paper, an electromagnetic regenerative damper for automotive applications is studied. Today the use of electromechanical devices is necessary in vehicle construction to increase not

only the driving comfort, but also safety and performances. The main purpose of vehicles manufacturers is the optimization of each component, aiming at the reductions of fuel consumption and pollutant and at the increment of the efficiency. The innovative suspension system, constituted by an electromagnetic damping system, allows harvesting energy, dissipated in the traditional shock absorbers. The use of rare-earth permanent magnets allows designing electric machines with high values of power that were not possible to reach until short time ago. A shock absorber, constituted by a permanent magnet linear generator, is designed and optimized. The mathematical model is implemented in Matlab-Simulink environment, obtaining the main operating parameters. Moreover, the magnetic field and flux values, analytically calculated, are verified by FE analysis. One can observe that the damping curve is strongly dependent on the external load resistance value. The regulation of the suspension damping behavior can be obtained by the modulation of the harvesting system. The electromagnetic damper is, therefore, semi-active.

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