

MODELING OF AN ELECTROMECHANICAL ENERGY HARVESTING SYSTEM INTEGRATED IN CAR DAMPERS

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ABSTRACT

The complexity of today's vehicles is constantly increasing with new devices enhancing safety or comfort. Unfortunately, these new devices need energy to operate and sometimes their installation and more precisely their wiring is difficult because of moving parts or it complicates maintenance activities. This is the case for the anti-lock braking system (ABS). These systems require energy to power the sensors that allow them to measure the rotating speed of the wheels, but the sensors must be installed on the un-sprung mass side. This article presents an energy recovery system that can be easily integrated in a conventional shock absorber. This work is the result of a collaboration between the company SOBEN and ESTIA Recherche.

INTRODUCTION

Vehicles are a major cause of air pollution by exhaust gases, resulting in emissions to global warming. The enthusiasm of manufacturers and consumers for cleaner and more efficient hybrid and electric vehicles shows the awareness on the need to develop new kind of transportation, considering environmental issues. Renewable energies are a great opportunity to produce cleaner energies; nevertheless, in a world where energy becomes every day more expensive and rare, it becomes necessary to also work on increasing processes and products efficiency.

In this context, even low energy sources are interesting. In the past years, a wide variety of materials, such as piezoelectric materials and dielectric elastomers, and a broad range of mechanisms, such as electromagnetic generators, were developed. These techniques or materials enable to exploit energy sources that are not usually used, then increasing energy efficiency. As far as vehicles are concerned, it is possible to exploit, for example, car dampers repetitive movements. These movements are due to roads irregularities and driving conditions such as acceleration, braking and curves.

In the different car dampers technologies (viscous dampers, friction dampers, viscoelastics dampers, magneto-rheological dampers (MR)...), the conversion of kinetic and vibrational energy into heat can cause undesirable overheating, especially in viscous and MR dampers. Studies on energy dissipation in car dampers have allowed optimizing car dampers functioning. These studies have led to the introduction of controlled, active and semi-active suspensions. These non-conventional dampers automatically adapt their behavior to the road type and driving conditions. These dampers provide comfort and performance using either magneto-rheology [1-8], electro-rheology [9-11] or electro-hydraulic technologies while combining control strategies and optimal design.

As part of the damper design, previous works show the possibility of combining the linear motion of the piston of the damper with devices using electromagnetic induction to produce electricity. These electromagnetic induction dampers (EMI) were the subject of numerous studies over the past ten years, as they can be used in passive, active or semi-active dampers. Thereafter, manufacturers had to redesign conventional dampers in order to include the energy recovery system.

This technology is applied to systems where energy recovery is included in a linear damper [12, 13] or systems using an endless screw [14] to convert linear movement into rotation and then using coils and magnets to produce electricity. In other systems, the energy recovery system is independent of the damper and can be mounted close to it [15]. Other systems are based on the development of a hybrid suspension combining passive dampers simplicity with electromagnetic dampers performances [16], by controlling the damping force between the sprung and un-sprung masses, in order to obtain performances similar to the active damper.

Research works show the interest of such devices [17], by making finite elements studies, prototypes for measurements [18], taking into account the different dimensions of the parts [19] and optimizing the assembly [20]. Benefits of energy recovery by electromagnetic systems are studied and measured [21, 22, 23]. Singla & al. [24] propose to implement an autonomous active damper with a motor-generator. The performances of this system are then compared to active and passive systems at different frequencies.

Other works are dedicated to theoretical calculations to determine the damping force of the shock absorbers according to the characteristics of input parameters such as the excitement produced by the road surface [25]. First, acceleration measurements between the sprung and un-sprung masses of a shock absorber are made in order to determine the transmissibility as function of the damping coefficient, then, in a second step, internal pressure measurements are made while varying the input acceleration and the damper using conditions.

AIM OF THE STUDY

Magneto-rheological (MR) semi-active dampers operation is based on changing damping characteristics by applying a magnetic field whose value is linked to the desired damping factor. Thereafter, MR damper operation requires a sensor which indirectly determines the state of the road and an energy source, to produce the magnetic field and supply the sensor [26]. The integration of an energy recovery system would provide power to the damper, with benefits in terms of reduction of size, weight, cost and maintenance.

The development and integration of an energy recovery system in an MR damper is the objective of the work presented here. This work is carried out within the framework of a collaboration between ESTIA Recherche and SOBEN.

Created in 2005, SOBEN has the know-how and innovative technology that are applied to vehicle dynamics. SOBEN is an expert equipment manufacturer that designs, develops, and manufactures dampers for cars, trucks, motorbikes, and aircrafts. SOBEN focuses on the design, prototyping and production of high performance dampers and landing gear (in small and medium-sized series).

The work presented in this paper was initiated in 2011 in the frame of the European Green-Car Eco-Design project (Interreg SUDOE IVB) which objective is to include the environmental issue in the design stage of the main components of electric vehicles. ESTIA and SOBEN focused more particularly on the harvesting of energy that can be generated by the linear motion inside the vehicles dampers.

The theoretical study concerns a wheel/damper system integrating an energy harvesting system that takes into consideration the variation of road conditions and allows us to quantify the harvested energy. The results of the studies will be compared with measures taken on a quarter car test bench developed by SOBEN. The physical parameters of the test bench (weight, stiffness and damping) have been estimated and serve as input parameters for the mechanical model.

EXPERIMENTAL TEST BENCH

Figure 1 shows the experimental bench on which theoretical studies are based. This bench will be used for the experimental validation of the model. This is a 1/5th scale, quarter car test bench, consisting of a suspended mass representing the weight of the vehicle, a shock absorber linking the sprung mass and the un-sprung mass, which is fixed on the axis of the wheel. The tire bears against a plate actuated by a linear motor reproducing the characteristics of the road.

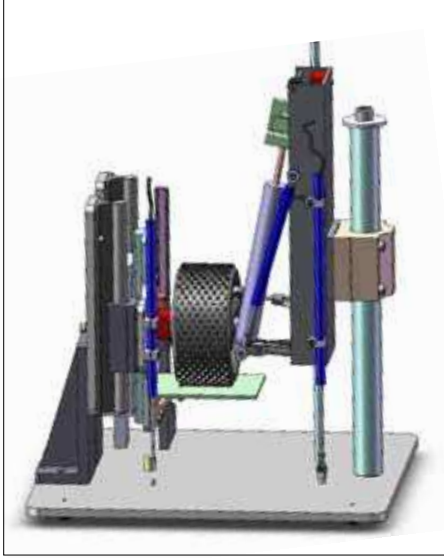


Figure 1: Experimental quarter car test bench

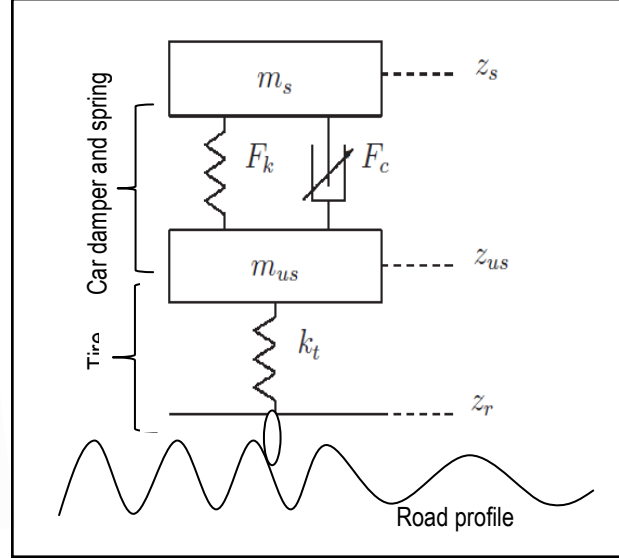


Figure 2: Theoretical model of the quarter car test bench

THEORETICAL MODEL OF THE MECHANICAL SYSTEM

The quarter vehicle test bench can be represented by a system with two degrees of freedom, as shown in Figure 2. The movement equations describing the system are given by (1) and (2). Characteristics of the test bench are given in table 1.

$$m_s * \ddot{z}_s = -F_c * (\dot{z}_s - \dot{z}_u) - F_k * (z_s - z_u) - f \quad (1)$$

$$m_{us} * \ddot{z}_u = F_c * (\dot{z}_s - \dot{z}_u) + F_k * (z_s - z_u) + k_t * (z_r - z_u) + f \quad (2)$$

Name	Value	Description
m_s	3.5 kg	Sprung mass
m_{us}	0.9 kg	Un-sprung mass
k_t	1800 N/m	Tire stiffness
F_k	230 N/m	Suspension stiffness
F_c		Damping factor
F	Negligible	Friction fraction
z_s	0.6 m max	Displacement of the sprung mass
z_{us}	0.3 m max	Displacement of the un-sprung mass
z_r	0.3 m max	Displacement of the tire on the road

Table 2 : Experimental quarter car test bench parameters

This mechanical model was implemented on MATLAB / SIMULINK using the SimScape toolbox (Figure 3). In models of mass (sprung and un-sprung) were taken into account not only the inertia but also the forces of gravity. The damper includes an external spring, then the model used for the simulation takes account of the stiffness of this spring, the damping factor, but also the stiffness of the air. To model the wheel, the block SimScape "Translational Hard Stop" was used because it allows taking into account the stall of the wheel from the plate.

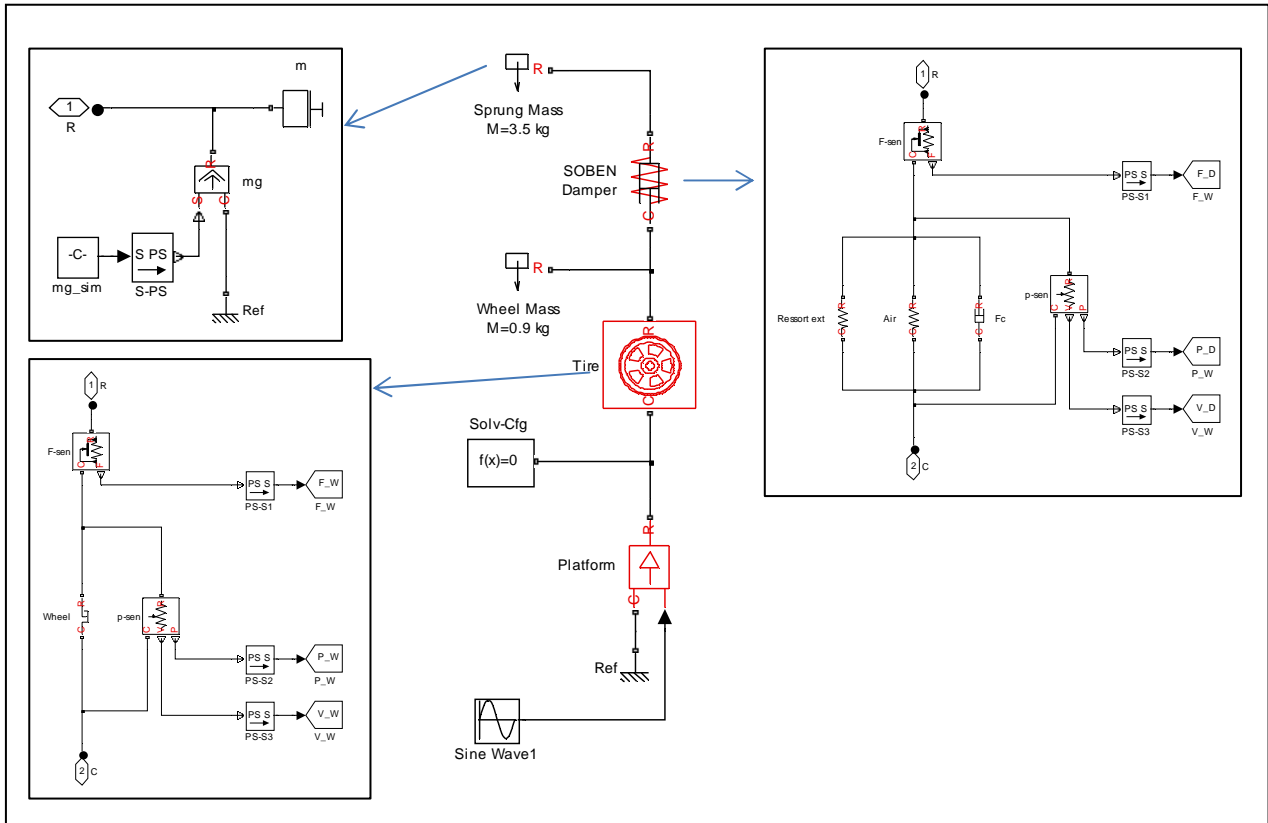
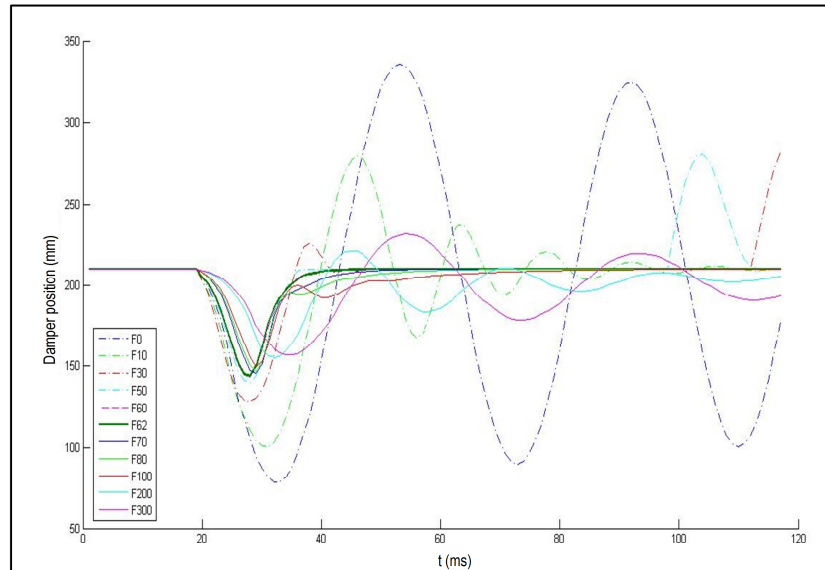


Figure 3: Simulink model of the mechanical system

This model was used to determine the damping characteristics of the system including the shock absorber movement for different damping coefficients and different excitation frequencies. Figure 4 shows an example of the curves obtained for an excitation frequency of 25 Hz. It is this movement which will be exploited by the energy recovery system.



**Figure 4: Damper position vs. Time for different damping coefficients.
Excitation frequency 25 Hz.**

ENERGY HARVESTING SYSTEM

Estimates of the potential energy that could be retrieved on shock absorbers were performed [27] and show interest in developing systems to recover this energy. The author of [27] estimates a potential reduction in CO₂ emissions between 1.4 and 5g/km.

The originality of the designed system is that it is fully integrated into the damper (Figure 5) and does not require vehicle modifications. In the central shaft of the shock absorber are integrated permanent magnets with the magnetic fields in opposition. This arrangement concentrates the magnetic field lines around the coils, placed in the body of the damper. The system was developed and integrated a real shock absorber.

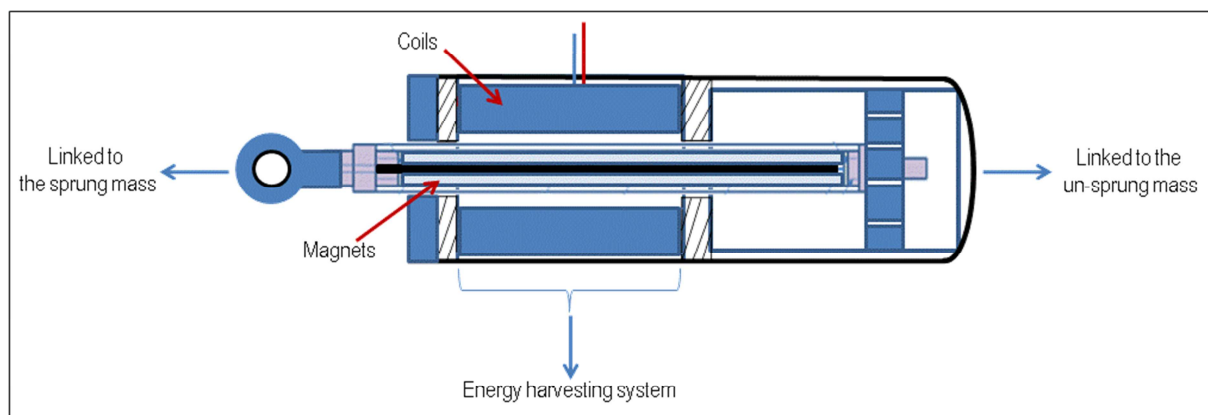


Figure 5: Energy harvesting system integrated in the car damper

Figure 6 shows voltage (blue) and power (green) measured at the output of the energy recovering system, for a linear movement of the shaft of the damper relative to the body having a maximum speed of one meter per second at a variation frequency of 2 Hz. This graph shows that the peak power can reach 25 W. To perform these tests, the coils were connected in parallel and the power was dissipated on a resistive load. In order to optimize the power transfer, the value of the load was chosen to be equal to the overall resistance of the coils.

The connection of the coils in series may also be used to increase the output voltage but the recovered power remains the same.

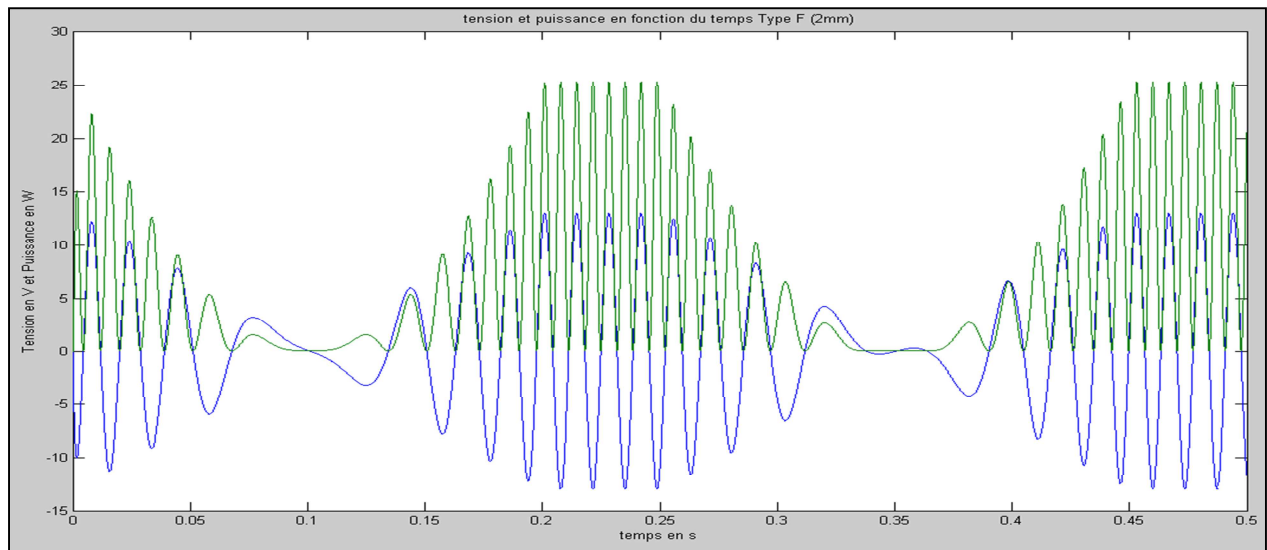


Figure 6: Voltage (blue) and power (green) measured at the output of the energy recovering system (maximum speed 1 m/s, frequency 2 Hz).

CONCLUSION

The first results are encouraging because, although the amount of energy recovered is low, it is sufficient to ensure the autonomy of the damper. This technology can be applied to other types of vehicles such as trucks, trains or bicycles. The current system has been designed with components of standard sizes. The next phase is the optimization of the geometry of the system to match the amount of energy produced with the needs of the damper, taking into account the need for weight reduction and ease of integration into the damper and, more generally, in the vehicle.

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REFERENCES

- [1] G.Z Yao, F.F. Yap, G. Chen, W.H. Li and S. H. Yeo, "MR damper and its application for semi-active control of vehicle suspension system", *Mechatronics*, vol. 12, pp. 963-973, 2002
- [2] R.S Prabakar, C. Sujatha and S. Narayanan, "Optimal semi-active preview control response of a half car vehicle model with magnetorheological damper", *Journal of Sound and vibration*, vol. 326, pp. 400-420, 2009
- [3] Raghavendra D. Naik and Pravin M. Singru, "Establishing the limiting conditions of operation of magneto-rheological fluid dampers in vehicle suspension systems", *Mechanics Research Communications*, vol. 36, pp. 957-962, 2009
- [4] Bartłomiej Dudziak, "Modélisation et analyse de processus de dissipation pendant le fonctionnement d'un amortisseur magnéto-rhéologique", *Thèse de doctorat en Mécanique*, Lille 1, Politechnika Warszawska, 2009

- [5] C. Poussot-Vassal, S.M. Savaresi, C. Spelta, O. Sename and L. Dugard, "A methodology for optimal semi-active suspension systems performance evaluation", 49th IEEE Conference on Decision and Control (CDC 2010), Atlanta, Georgie, United State, 2010
- [6] Pawel Skalski, "Analyse des propriétés viscoplastiques du fluide magnéto-rhéologique dans des conditions de travail d'un amortisseur", Thèse de doctorat en Génie mécanique, Orléans, Politechnika Warszawska, 2011
- [7] Jorge de-J Lozoyas-Santos, Ruben Morales-Menendez, Juan C. Tudon-Martinez, Olivier Sename, Luc Dugard and Ricardo Ramirez-Mendoza, "Control Strategies for an automotive suspension with a MR dumper", 18th IFAC World Congress (IFAC WC 2011), Milan, Italie, 2011
- [8] Jorge de-J Lozoyas-Santos, Ruben Morales-Menendez, Ricardo Ramirez-Mendoza and Juan C. Tudon-Martinez, "Magneto-Rheological Damper – An experimental study", Journal of Intelligent Material Systems and Structures, vol. 23, pp 1213-1232, 2012
- [9] S.R. Hong, S.B. Choi, Y. T. Choi and N. M. Wereley, "A hydro-mechanical model for hysteretic damping force prediction of ER damper: experimental verification", Journal of Sound and Vibration, vol. 285, pp. 1180-1188, 2005
- [10] Wen-Hwar Kuo, Tsong-Neng Wu, Jenhwa Guo, Mao-Hsiung Chiang and Yi-Nan Chen, "Design and performance evaluation of a serial multi-electrode electro rheological damper", Journal of Sound and Vibration, vol. 292, pp. 694-709, 2006
- [11] S.B. Choi, Y.T. Choi, E.G. Chang, S.J. Han and C.S. Kim, "Control characteristics of a continuously variable ER damper", Mechatronics, vol. 8, pp. 143-161, 1998
- [12] John A. Konotchick, "Linear electric generator having an improved magnet and coil structure, and method of manufacture", US Patent Specification US5347186A, San Diego, Californie, 1994
- [13] Ronald B. Goldner, Peter Zeriglan, "Electromagnetic linear generator and shock absorber", US Patent Specification US6952060, Lexington, Arlington, MA, 2005
- [14] Balaram V. Murty, "Electric, variable damping vehicle suspension", US Patent Specification US4815575A, Sterling Heights, Mich, 1989
- [15] Harel Shachar and Eldad Hahmon, "Regenerative shock absorber comprising electromagnetic linear generator or mechanical movement converter", GB Patent Specification GB2465423A, 2011
- [16] R. N. Goldneer, P. Zerigian, and J. R. Hull, "A preliminary study of energy recovery in vehicles by using regenerative magnetic shock absorbers," SAE International Government/Industry Meeting, 2001-01-2071, May 2001
- [17] Isménio Martins, Jorges Esteves, Fernando Pina da Silva and Pedro Verdelho, "Electromagnetic hybrid Active-Passive Vehicle Suspension System", Vehicular Technology Conference, pp 2273-2277, 1999
- [18] Lei Zuo, Brian Scully, Jurgen Shestani and Yu Zhou, "Design and characterization of an electromagnetic energy harvester for vehicle suspensions", Smart Materials and Structures, vol.19, 2010
- [19] Willis O. Agutu, "Characterization of electromagnetic induction damper", Thesis, Faculty of Miami University Oxford, Ohio, 2007
- [20] Badak Ebrahimi, Mir Behrad Khamesee and M Farid Golnaraghi, "Feasibility Study of an electromagnetic Shock Absorber with Position Sensing Capability", Conference of Industrial Electronics, IECON 2008, pp 2988-2991, 2008
- [21] Songye Zhu, Wen-ai Shen and You-lin Xu, "Linear electromagnetic devices for vibration damping and energy harvesting: Modeling and testing", Engineering Structures, vol.34, pp.198-212, 2012
- [22] Reza Sabzehgar and Mehrad Moallem, "A Boost-Type power Converter for Energy-Regenerative Damping", IEEE/ASME Transactions on Mechatronics, Issue 99, pp 1-8, 2012
- [23] R.A. Oprea, M. Mihailescu, A.I. Chirila and I.D. Deaconu, "Design and Efficiency of Linear Electromagnetic shock absorbers", International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), 2012, pp 630-634, 24-26 may 2012

- [24] K.Singal and R. Rajamani, "Simulation Study of Novel Self-Powered Active Suspension System for Automobiles", American Control Conference (ACC) 2011, San Francisco, USA, June 29-July 01, 2011
- [25] P.J.C. Ventura, C.D.H. Ferreira, C. F. C. S. Neves, R. M. P. Morais, A.L.G. Valente and M.J.C.S Reis, "An embedded system to assess the automotive shock absorber condition under vehicle operation", IEEE Sensors Conference, 26-29 Oct. 2008
- [26] Chao Chen and Wei-Hsin Liao, "A self-powered, Self-Sensing Magnetorheological Damper", International Conference on Mechatronics and Automation, Xi'an, Chine ,Août 2010
- [27] Marco Willems, "Estimation of the Recuperation Potential of Shock Absorber Energy", ATZ Worldwide, Issue 09/2012, pages 28-32