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# Optimized design and characterization of motor-pump unit for energy-regenerative shock absorbers

Renato Galluzzi*, Yijun Xu, Nicola Amati, Andrea Tonoli

*Department of Mechanical and Aerospace Engineering (Mechatronics Laboratory), Politecnico di Torino, Corso Duca degli Abruzzi, 24, Turin, Italy*

## HIGHLIGHTS

- The energy dissipated in automotive suspensions can be recovered.
- The motor-pump unit is a key element for energy regeneration and damping control.
- The proposed design of this unit aims to maximize energy regeneration.
- The construction and testing of a prototype validate the research.

## ARTICLE INFO

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## ABSTRACT

The constant need to reduce emissions in the automotive sector has driven the electrification of powertrain and chassis. To comply with this trend and decrease the bound even further, the present paper proposes the use of hydraulic regenerative shock absorbers for automotive suspension systems. The conversion of linear into angular motion and the suitable control of an integrated electric machine allow to transform part of the vibrational energy into electricity. In these damping devices, the key element is the motor-pump unit that is interfaced onto a conventional hydraulic cylinder architecture. Hence, the proposed research focuses on this component by investigating different design aspects in all the domains of interest. The objective is to optimize the energy conversion efficiency of the unit without affecting its damping control property. To give means of validation, a motor-pump prototype is built and experimentally characterized through a dedicated test rig.

## 1. Introduction

Vehicle suspension systems play a fundamental role in filtering the vibrations induced by the road irregularities onto the automotive chassis. They are designed to meet requirements of road holding, ride comfort and handling performance. Conventional suspension systems basically consist of an elastic member (spring), a damping element (shock absorber) and kinematic linkages. These systems are purely passive: the damping task is achieved by converting the vibrational power into waste heat. Although simple and cost-effective, passive suspensions have a fixed response and cannot adapt to a variety of road unevenness and vehicle dynamic conditions. To address this shortcoming, semi-active and active damping technologies have been developed in the last two decades.

In addition, vehicle $CO_2$ emissions have become a relevant aspect during the past decade: regulations in this matter are more strict mainly due to environmental concerns worldwide. In Europe, for instance, the emission average to be achieved by all registered cars is 130 g/km. By 2020, this value will be reduced to 95 g/km and by 2025, it will be decreased even further (68–78 g/km) [1]. The awareness in $CO_2$ emissions has pushed the electrification of the automobile as a means towards improved energy efficiency.

As demonstrated by Zuo and Zhang [2], the average power dissipated by the suspension is proportional to the tire stiffness, the vehicle speed and the road roughness index defined by ISO [3]. For a typical passenger car that travels at a speed of 32 km/h (the average speed of the New European Driving Cycle), the average dissipation on four corners is 133 W on an ISO C-class road. According to the analysis presented in our previous works [4], the total recovery of the energy in the aforementioned condition would lead to a $CO_2$ emission reduction slightly above 6 g/km for a D-class vehicle.

This background motivates the development of regenerative solutions, i.e. devices able to vary their damping behavior while converting part of the otherwise-dissipated power into electricity. These technologies exploit the intrinsic reversibility of electric machines and a suitable transmission system for their integration into the vehicle.

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* Corresponding author.
*E-mail addresses:* renato.galluzzi@polito.it (R. Galluzzi), yijun.xu@polito.it (Y. Xu), nicola.amati@polito.it (N. Amati), andrea.tonoli@polito.it (A. Tonoli).

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**Nomenclature**

| | |
|---|---|
| $A_p$ | piston cross section |
| $A_s$ | slot cross section |
| $A_w$ | wire cross section |
| $\alpha_{g1}$ | outer gear aspect ratio |
| $\alpha_{g2}$ | inner gear aspect ratio |
| $\alpha_t$ | teeth aspect ratio |
| $\mathscr{A}_z$ | magnetic vector potential *z* component |
| $c_p$ | linear damping coefficient |
| $c_{ref}$ | linear damping reference |
| $c_{sc}$ | maximum rotary damping coefficient |
| $D_p$ | pocket diameter |
| $d_p$ | minimum distance between ports |
| $D_s$ | shaft diameter |
| d | direct axis |
| $\Delta P_g$ | input pressure drop |
| $\delta_g$ | pulsation index |
| $e_g$ | gear eccentricity |
| $\eta_e$ | electrical efficiency |
| $\eta_g$ | pump total efficiency |
| $\eta_{hm}$ | hydro-mechanical efficiency |
| $\eta_t$ | total conversion efficiency |
| $\eta_v$ | volumetric efficiency |
| $f_a$ | axial viscous drag function |
| $F_p$ | piston/damping force |
| $f_v$ | chamber volume function |
| $\mathscr{F}_j$ | emptying rate function of the *j*th chamber |
| $g_a$ | axial clearance |
| $g_i$ | inside diameter clearance |
| $g_o$ | outside diameter clearance |
| $g_t$ | inter-teeth clearance |
| $\gamma_p$ | port opening angle |
| $I_{dc}$ | DC bus current |
| $J_{cyl}$ | cylinder moment of inertia |
| $K_\lambda$ | PM flux per unit length |
| $K_{cp}$ | coil packing factor |
| $K_e$ | back-EMF constant |
| $K_t$ | torque constant |
| $l_{cyl}$ | cylinder length |
| $l_{et}$ | end-turn length |
| $l_g$ | gear axial length |
| $l_m$ | active length |
| $l_p$ | pocket depth |
| $\lambda_p$ | PM flux linkage amplitude |
| | dynamic viscosity |
| $N_c$ | number of coils |
| $N_g$ | number of inner gear teeth |
| $N_t$ | number of turns per coil |
| $\Omega_g$ | angular speed |
| $p$ | number of pole pairs |
| $P_g$ | harvested power |
| $P_{m,avg}$ | average power loss |
| $Q_g$ | input flow rate |
| q | quadrature axis |
| $R$ | phase resistance |
| $R_{1l}$ | outer gear lobe radius |
| $R_{1o}$ | outer gear outside radius |
| $R_{1r}$ | outer gear root radius |
| $R_{2i}$ | inner gear inside radius |
| $R_{2o}$ | inner gear outside radius |
| $R_{cyl,i}$ | cylinder inside radius |
| $R_{cyl,o}$ | cylinder outside radius |
| $R_{ext}$ | external impedance |
| $R_{p,i}$ | port inside radius |
| $R_{p,o}$ | port outside radius |
| $\rho_{Cu}$ | copper resistivity |
| $\rho_{cyl}$ | cylinder mass density |
| $\tau$ | electrohydrostatic transmission ratio |
| $T_a$ | axial viscous drag torque |
| $T_m$ | electromagnetic torque |
| $T_{ro}$ | radial viscous drag torque |
| $\Theta_0$ | initial temperature |
| $\Theta_c$ | winding temperature |
| $\theta_g$ | pump shaft angular position |
| $\Theta_p$ | PM temperature |
| $V_j$ | volume of the *j*th chamber |
| $V_{dc}$ | DC bus voltage |
| $V_g$ | volumetric displacement |
| $v_p$ | piston/damping speed |

Karnopp's research [5] was the first to examine the feasibility of using a permanent-magnet linear motor with variable resistors to substitute the conventional dampers. Gysen et al. [6] developed an active electromagnetic suspension that employs a brushless tubular permanent-magnet actuator to control the roll and pitch of the vehicle. Linear motors seem a straightforward choice for damping in most ground vehicles due to their simple integration into the suspension layout and lack of a transmission system. However, their force density is limited for the task and thus, they work inefficiently and add a substantial heft to the vehicle chassis.

In conventional suspension layouts, rotary electric motors require complex systems to convert the linear motion between the wheel hub and the upper strut mount into an angular displacement. In this regard, the state of the art exploits mainly mechanical or hydraulic working principles.

The rack pinion mechanism can be used for linear-to-rotary conversion. In recent works [7,8], it has been enhanced with clutch systems to allow unidirectional angular motion on an electric machine and improve efficiency. Ball screw transmissions are also common for motion conversion: the literature offers prototypes with rotating screw [9] or rotating nut [10]. Furthermore, unidirectional rotary motion has been also implemented [11,12]. Although promising, electromechanical technologies can be complex and difficult to integrate into the suspension. Moreover, in a high-cycle task like vehicle damping, component wear and fatigue are critical aspects that have not been fully addressed.

Hydraulic shock absorbers with controllable damping and energy harvesting features employ the electrohydrostatic actuation principle. They use a hydraulic actuator directly interfaced to a motor-pump unit by means of a hydrostatic circuit to convert the linear motion of the piston into rotation. The intrinsic lubrication of fluid-based solutions overcomes the main tribology concerns of electromechanical systems. Moreover, since the fluid is used as a means for power transmission, the actuator offers better flexibility for its placement within the suspension.

Many recent works have addressed the design and implementation of hydraulic regenerative shock absorbers. In previous works, it has been studied for lead-lag motion damping in helicopter rotor blades [13]. Fang et al. [14] and Li et al. [15] assessed the damping and regenerative capabilities of prototypes with external hydraulic rectifiers. Zhang et al. [16] exploited the intrinsic fluid rectification of twin-tube shock absorbers to yield and validate a prototype. However, Levant Power Corporation has lead the development in this field with their GenShock solution [17]. From the scientific point of view, they have provided useful guidelines to optimize the hydraulic pump for a regenerative damper [18].

The motor-pump unit is the core element in hydraulic regenerative