

Thesis Summary

Electromagnetic Shock Absorbers for Vehicle Suspensions

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In recent years, electrification has dominated the development of innovative automotive components. Indeed, this trend aims to increase the overall vehicle efficiency, mitigate its emissions, and enable advanced controls by means of smart components. Alongside the well-known transition towards hybrid and electric powertrains, many "by-wire" actuators are replacing usual passive chassis components, such as the one of the steering and braking systems.

In this context, the suspension system plays a key role, as its behaviour strongly affects not only vehicle comfort and handling, but also energy dissipation and recovery. Active suspensions typically replace the conventional hydraulic damper with a mechatronic device capable of exerting both active and passive forces at any force-velocity operating point within its physical constraints. Particularly, electromagnetic dampers complement this feature with the ability to partially recover vibrational energy from road irregularities by converting it into electrical energy. They consist of a controllable electric machine and a proper transmission stage to the suspension. Both the constant increase of scientific literature and availability of high-segment vehicles equipped with active suspensions demonstrate the strong interest in this field.

However, a clear gap can be pinpointed between the academia and the industry. The former mainly focuses on innovative control strategies and energy harvesting capabilities, often producing just proof of concepts for laboratory activities. The latter instead concentrates on integration feasibility, packaging, and active functionalities, such as roll control during cornering.

The present doctoral dissertation aims to align academic research with industrial development by proposing a holistic design methodology for the design of optimal, vehicle-ready electromagnetic shock absorbers. It follows a V-scheme that starts with the investigation of the technology and packaging studies. Then, the definition of the system requirements and the optimal detailed design of the shock absorbers follow. The demonstrator setup is at the base of the cycle, specifically a D-segment SUV and a naked motorcycle are addressed. From this point, testing, validation, and control tuning finalize the methodology.

The proposed electromagnetic shock absorbers couple a rotary electric machine with either a mechanical or hydraulic transmission. Rotary machines are preferred for their increased torque and power density, while the choice between the two transmissions mainly depends on the packaging constraints. The mechanical transmission under study is a planetary gearbox, chosen for its compactness and high transmission ratio. However, a rotary-to-linear conversion mechanism is required to transform the motor rotary motion into suspension linear motion. This task is performed by a linkage mechanism made of a lever and a push-pull rod. This mechanical layout allows to completely remove the traditional damper and is referred to as RSA. On the contrary, the hydraulic solution requires a hydraulic cylinder for motion linearization; thus, a conventional shock absorber with closed valves can accomplish this task without introducing unwanted damping. The controlled pressure differential is built up by means of a positive displacement pump, i.e., a gerotor pump. For this reason, this kind of damper is also referred to as electro-hydrostatic (EHA).

The proposed design methodology provides tools for a preliminary evaluation of the key dynamic performance of the two electromagnetic shock absorbers and then studying their integration within the target suspension systems. Linear quarter-car simulations are used to derive force-speed requirements for the actuator design: uneven road profiles provide continuous duty requirements, while speed bump simulations define peak duty requirements. Then, an optimization process sizes the electric machine and the gearbox of the RSA, followed by dedicated electromagnetic and mechanical design activities to get a manufacturable device. Due to the more stringent packaging and performance constraints of the EHA, its design focuses on finding the optimal trade-off between space allocation for the electric motor and the hydraulic pump. Ultimately, four fully operational

RSAs are installed on all four corners of a D-segment SUV, while two EHAs are integrated into the front fork of a naked motorcycle.

An extensive experimental campaign is conducted to identify the RSA dynamic response, highlighting concerns related to its inerter-like impedance behaviour and non-linear friction effects. Nevertheless, the tests demonstrate the high bandwidth potential of such actuators. Both technologies were also characterized in terms of efficiency, particularly in the passive operating quadrant associated with energy regeneration. As expected, the RSA achieved higher performance, reaching a 66% regenerative efficiency, while the EHA peaked at 35%. Controlled damping tests were conducted to assess performance under alternating speed inputs, confirming that both technologies provide regenerative damping with nearly linear behaviour. Additionally, the EHA demonstrated the capability to generate active forces. Lastly, noise, vibration, and harshness analysis of the RSA revealed significant vibrational spectra due to gear meshing, resulting in high noise levels at high-speed and high-torque conditions. Those are key considerations in modern electric vehicles.

Finally, vehicle-level performance are investigated. A novel quarter-car model incorporating RSA dynamics is formulated and validated through experimental bump tests on the D-SUV rear corner. Based on this model, an H_∞ controller is designed, simplifying the required feedback to only the directly measured quantities, i.e., the sprung and unsprung mass accelerations and the suspension stroke. Non-linear simulations demonstrate that the controller successfully maintains the sprung mass acceleration below comfort thresholds specified by standards. However, the comfort-oriented tuning decreases road-holding capabilities. Furthermore, the speed bump scenario stands out as a particularly critical challenge for the control strategy. To this end, also a simpler but predictive control strategy is studied. It combines the benefit of the sky-hook control in reducing the peak accelerations on the vehicle body with the capability of the ground-hook control of damping the wheel-hop vibrations on the basis of the bump profile estimation using measurements on the front axle. Simulations demonstrated that the controller successfully reach a trade-off between the comfort and handling performances of the vehicle.

From a mechanical design perspective, fatigue resistance emerges as the main challenge. In particular, the RSA gearbox requires a more robust design, which may necessitate either an increase in size or a relaxation of the reduction ratio requirements. Alternative speed reduction technologies, such as cycloidal drives, could also be considered to address this issue. Regarding the experimental results, the RSA highlights two major criticalities: the inerter effect and noise emissions. To address the inerter effect, given that actuator inertia is linked to the diameter of the motor shaft and gearbox gears, and therefore power and strength requirements, a straightforward solution would be to compensate for actuator dynamics via a feedforward controller, once inertia, stiffness, and friction parameters are identified. On the other hand, noise reduction could benefit from a redesigned casing, tighter gear tolerances, and the implementation of rubber bushings for mounting the RSA to the vehicle chassis. Conversely, the EHA reveals efficiency limitations. Mechanical friction could be partially mitigated by introducing a ball bearing on the outer pump gear, although packaging constraints remain extremely challenging. Despite the adoption of very tight tolerances, hydraulic leakages can not be fully avoided and are also influenced by thermal effects and wear. In this regard, the introduction of a pressure-feedback controller could significantly improve overall force-tracking performance. From the performance standpoint, more advanced control design is required to better balance comfort and road holding objectives. Predictive control strategies represent a promising direction, even including perception systems, enabling adaptive tuning based on anticipated road conditions. Additionally, hardware-in-the-loop testing is a fundamental step before vehicle testing, as simulations alone cannot capture all non-linear phenomena.

Finally, Automotive Safety Integrity Level (ASIL) requirements define the necessary safety standards for automotive components according to ISO 26262. Therefore, both the actuator and its associated power electronics must be designed with these safety requirements in mind. Moreover, ensuring a sufficient level of open-circuit damping in case of electrical failure is crucial. Virtual testing, including driver-in-the-loop simulations, and extensive real-world vehicle testing, are essential to validate these safety aspects. In particular, the more efficient RSA design may require the addition of specific features to ensure safe behaviour in open-circuit failure mode.