Presentation for the admission to the 3rd year of the PhD programme

Doctoral Program in Mechanical Engineering

XXXIV cycle

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Profile

PhD student:
Salvatore Circosta

Fellowship:
Government funding

Supervisor:
Prof. Nicola Amati

Main PhD topic

Regenerative shock absorber for automotive and motorcycle application

Partnership with

MAGNETI MARELLI

VRM MARZOCCHI

Side PhD projects

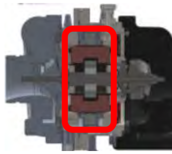
- Analysis and development of a wave-energy harvesting system.

eni — WAVE FOR ENERGY

HYPERLOOP TRANSPORTATION TECHNOLOGIES

- Study and stabilization of electrodynamic levitation system for next-generation transportation system.

- Development and experimentation of a hysteresis electric machine prototype for an electrified turbo-compound system.



- Design and implementation of brake and steering actuation systems for a driverless Formula Student electric vehicle.

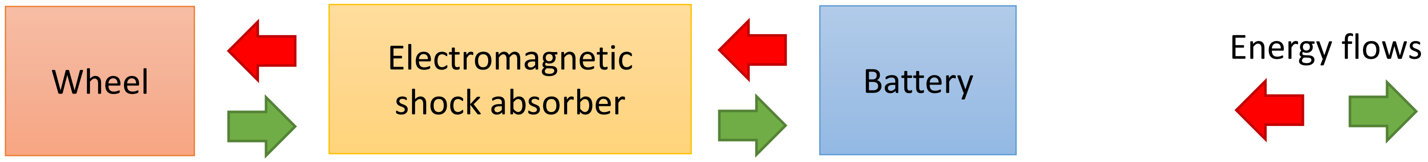
Electromagnetic shock absorber

What is it?

It is a device mounted in the suspension that provides damping through a suitably controlled electric machine (EM). Some solutions implement a conversion stage between the EM and the wheel.

How does it work?

It works in active mode when the suspension must be actuated, in regenerative mode when the device works as a damper. The latter allows to harvest the energy coming from road unevenness.



Which are its advantages?

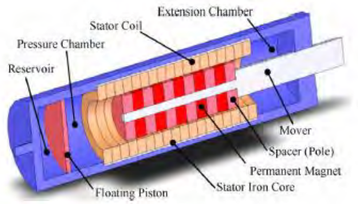
Energy harvesting → Lower vehicle emission
Variable damping → Handling improvement
Suspension actuation → Better comfort

Electromagnetic shock absorber

State of the art

Linear solution

Linear permanent-magnet electric machines feature low power density. Hence, large amount of permanent magnets is required thus increasing cost and mass.

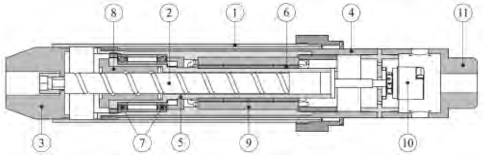


Rotary solutions

Rotating electric machines feature high power density, but a <u>conversion stage</u> is needed to convert the wheel linear motion into rotation of the electric machine.

Ball screw stage

Large mass and rotating equivalent inertia noise are the main drawbacks. In the figure, a prototype developed at Laboratorio Interdipartimentale di Meccatronica (LIM), Politecnico di Torino.



Rack-pinion stage

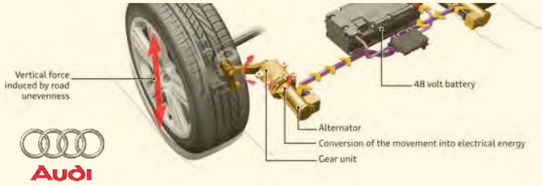
Mechanical robustness and noise are the main drawbacks. Prototypes were developed by university-based research activities.

Electrohydrostatic stage

It is a non oil-free solution. A prototype was developed at LIM and tested on a Fiat 500 X. Industrial solution is provided by Clear Motion.

Linkage and Gearbox stages

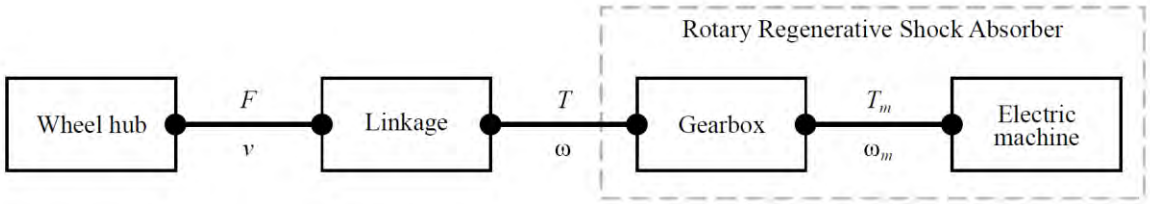
Noise is the main drawback. Industrial solution was proposed by Audi AG in 2016 (eROT), with declared harvestable powers ranging from 100 W to 150 W.



Research work

Proposed layout

Rotary electric machine with linkage and gearbox stage



Timeline

Design methodology | **Prototyping** | **Experimental setup** | **Numerical modeling** | **Experimental test**

Ongoing activity

Design methodology

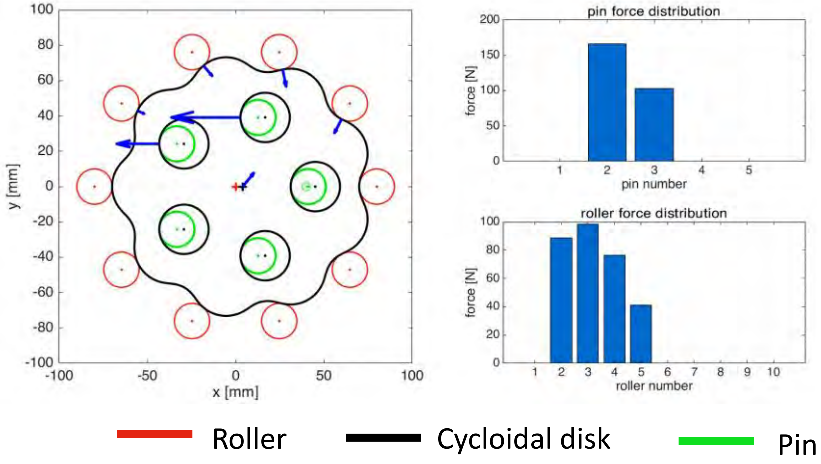
Requirements definition	⇒	Damping specification Road profile Envelope constraints
Electric machine design	⇒	Cross-section Active length Overall transmission ratio
Linkage definition	⇒	Linkage transmission ratio
Gearbox design	⇒	Gearbox layout Gear geometry

Gearbox design

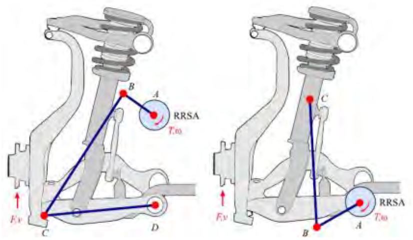
Planetary gearbox and cycloidal drive are investigated.

- Gear sizing of the planetary gearbox is carried out through KISSsoft software.
- Cycloidal drive geometric and equilibrium relationships are developed. A multi-objective optimization process is defined to design the cycloid cross section.

Cycloidal drive model



Linkage definition

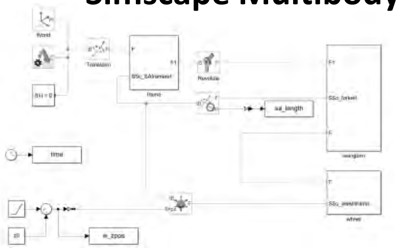


- Diverse solutions are investigated.

CAD model

⇨

Simscape Multibody



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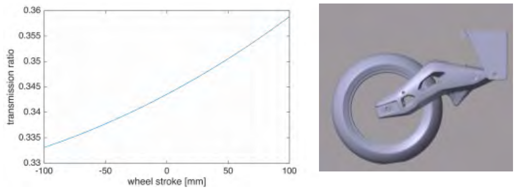
Suspension behavior

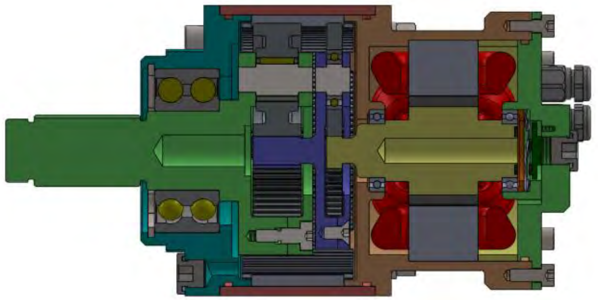


- Suspension kinematics and linkage performance are addressed through a Simscape Multibody procedure.

Prototyping

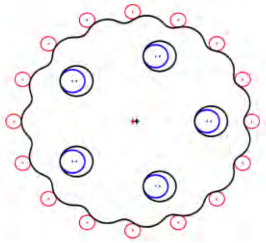
RRSA prototype was designed for automotive application (class-B SUV):

- Two-stage planetary gearbox with PM electric machine.
- Full integration between electric machine and gearbox.
- Splined-shaft to interface with the linkage.



Cycloidal drive was designed. Functional prototype was built in rapid prototyping and tested.

1. MATLAB



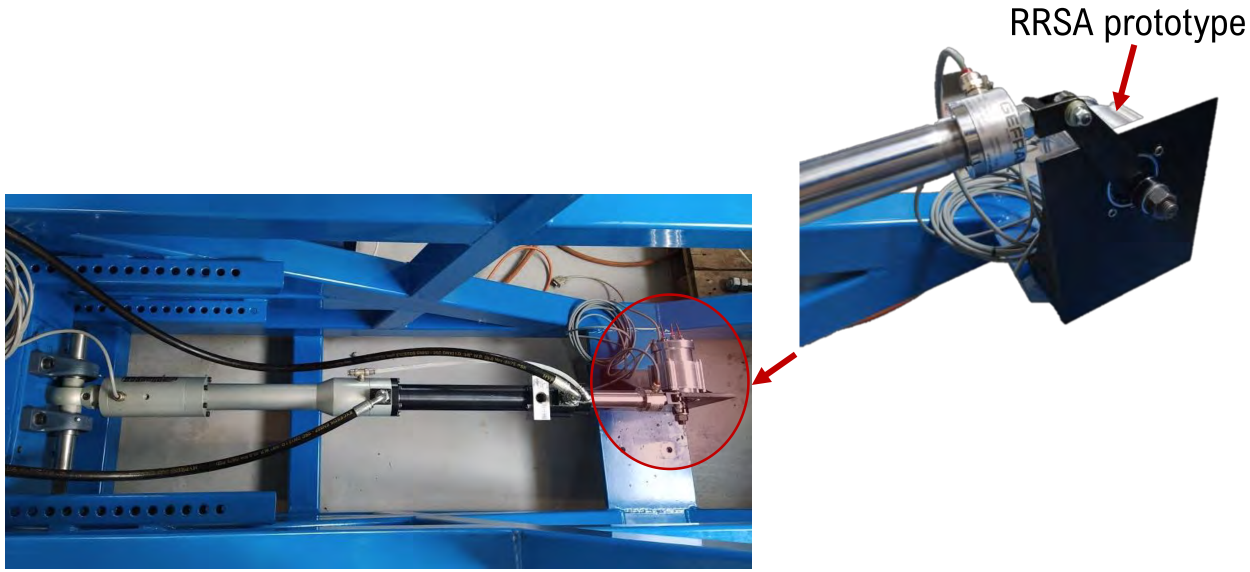
2. CAD

3. Prototype

Experimental setup

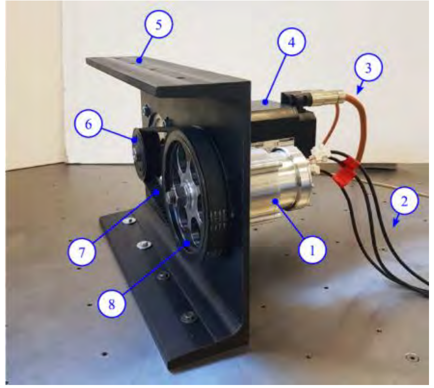
Hydraulic test bench

- The prototype is actuated through a hydraulic actuator driven by a motor-pump unit.
- Alternate and complex profiles can be given as input.
- The bench is designed for HIL implementation.
- dSpace is used for acquisition and control purposes.



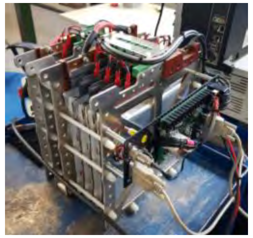
Belt-driven test bench

- The prototype is interfaced with the load motor through a pulley-belt system.
- Constant speed profiles can be given as input.
- The bench is designed for running-in and static characterization.



RRSA electric machine can be interfaced to:

- A diode-bridge rectifier with a variable shunt resistance to synthetize diverse damping conditions.
- A controlled power module with a 48V battery pack to recovery energy or operate in active mode.

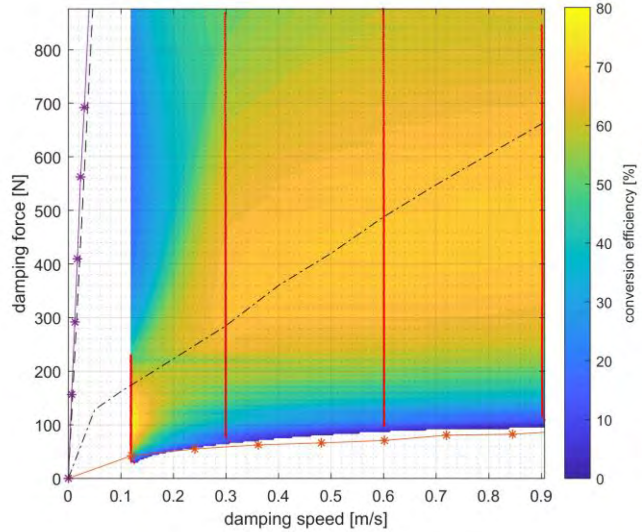


Power module ⇄ RRSA ⇄ Bench actuator

Experimental results

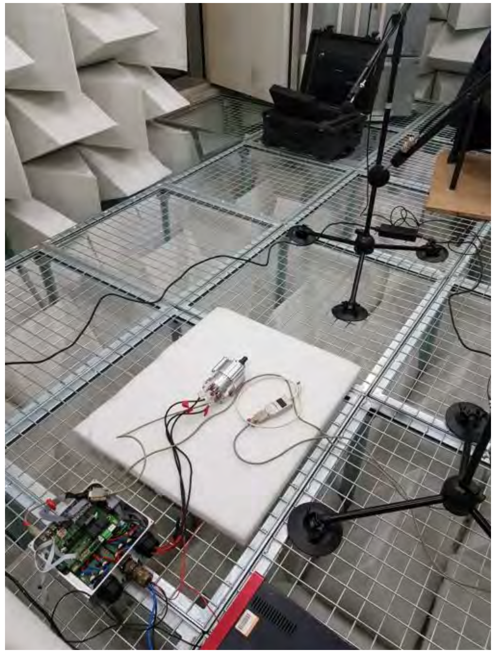
Static efficiency characterization

- The belt-driven test bench is used.
- A controlled power module in used to recovery the energy coming from the load motor.
- Maximum conversion efficiency spot at 82% is found.
- The efficiency is dominated by the electric machine.



Acoustic assessment

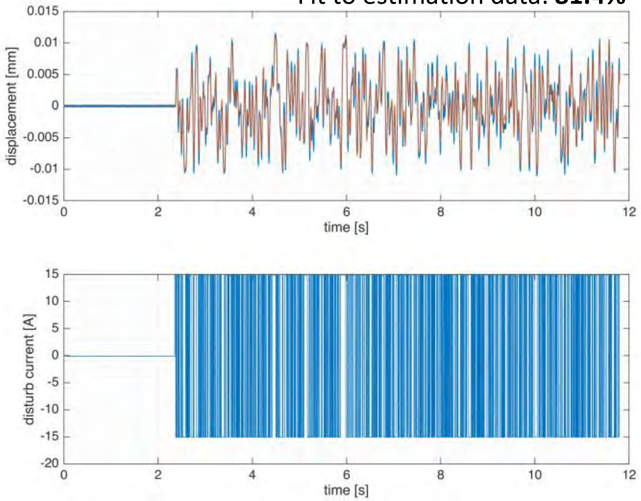
- The actuator was placed inside an anechoic chamber and driven in active mode.
- The device was driven in active mode.
- In the worst case, the noise level is lower than **50 dBA**.



Hydraulic bench model tuning

- The hydraulic bench linear model was built in the state-space.
- The bench was disturbed through a current input and piston displacement was measured.
- Experimental data were used for grey box identification process.
- The tuned model is used for tuning the hydraulic actuator controller.

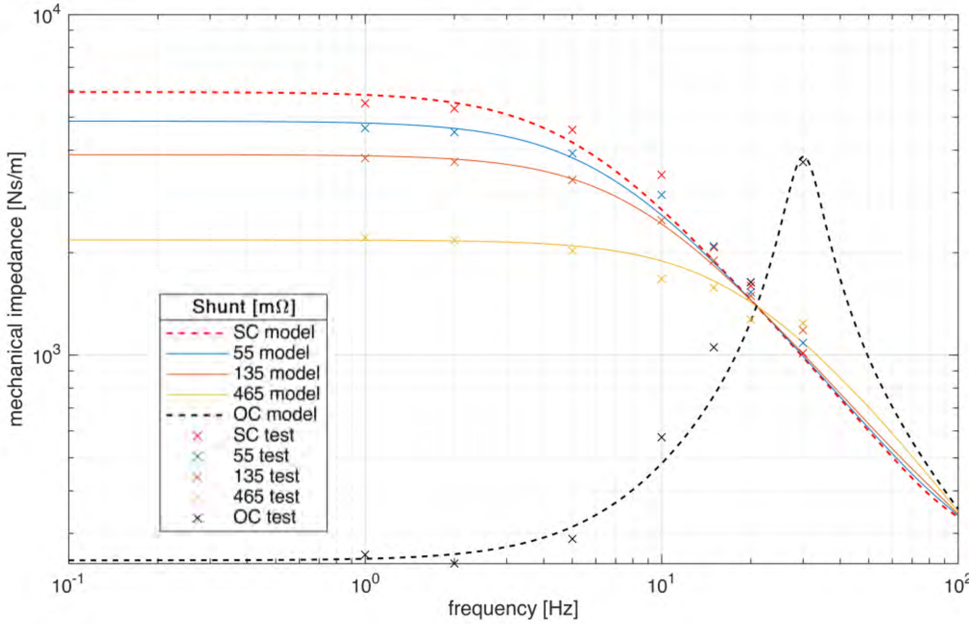
Fit to estimation data: **81.4%**



Experimental results

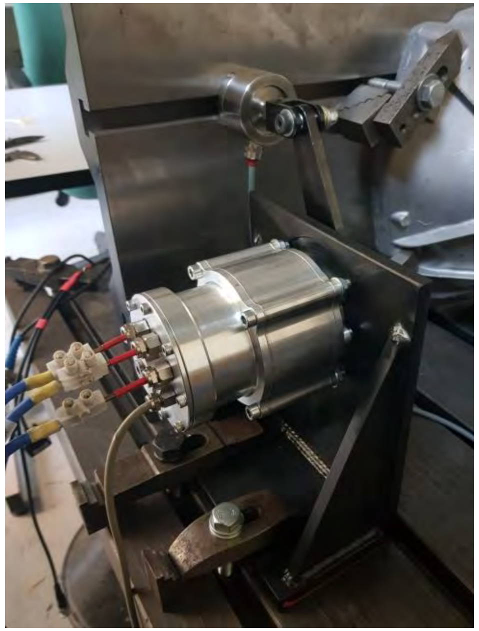
Mechanical impedance FRF

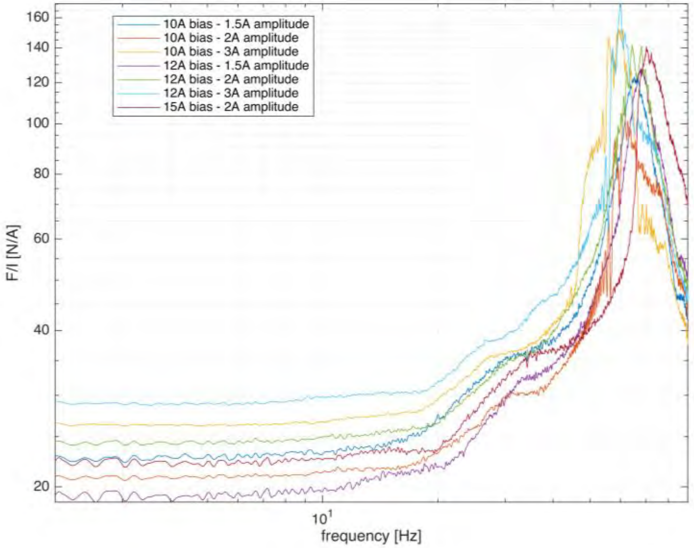
- Sinusoidal displacement profiles imposed through the hydraulic test bench.
- The RRSA is connected to the diode-bridge rectifier to test diverse shunt resistances.
- Experimental data are used to tune the RRSA lumped parameter model.



Active mode FRF

- The RRSA shaft is jointed to the seismic mass through a load cell.
- RRSA electric machine is driven through sinusoidal current profiles.
- The FRF in active mode is extracted.





Next steps

- **Hardware in the loop**
  - Implement the HIL strategy on the hydraulic test bench to simulate the RRSA on-vehicle operation.

- **Develop RRSA control strategies to improve vehicle handling and comfort.**

- **According to partner time-scheduling, implement the prototype on the reference vehicle.**

Publications

Circosta, S., Bonfitto, A., Lusty, C., Keogh, P., Amati, N. and Tonoli, A., 2018, December. *Analysis of a Shaftless Semi-Hard Magnetic Material Flywheel on Radial Hysteresis Self-Bearing Drives.* Actuators (Vol. 7, No. 4, p. 87). MDPI.

Circosta, S., Galluzzi, R., Bonfitto, A., Castellanos, L., Amati, N. and Tonoli, A., 2018, December. Modeling and Validation of the Radial Force Capability of Bearingless Hysteresis Drives. Actuators (Vol. 7, No. 4, p. 69). MDPI.

Circosta, S., Galluzzi, R., Amati, N., Bonfitto, A., Molina, L.M.C. and Tonoli, A., 2019, May. *Improved 1-D Model for Semi-Hard Magnetic Material-Based Electromagnets.* 2019 IEEE International Electric Machines & Drives Conference (IEMDC) (pp. 870-874). IEEE.

Galluzzi, R., **Circosta, S.**, Amati, N., Tonoli, A., Bonfitto, A., Lembke, T. A., and Kertész, M., 2020. *A Multi-domain Approach to the Stabilization of Electrodynamic Levitation Systems.* ASME. J. Vib. Acoust. December 2020; 142(6): 061004.

Galluzzi, R., **Circosta, S.**, Amati, N. and Tonoli, A., 2020. *Rotary regenerative shock absorbers for automotive applications.* Elsevier. Mechatronics. **(Under review)**

Circosta, S., Galluzzi, R., Tonoli, Amati, N., A., Bonfitto, A., Lembke, T. A., and Kertész, M., 2020. *Passive Multi-Degree-of-Freedom Stabilization of Ultra-High-Speed Maglev Vehicle.* ASME. J. Vib. Acoust. **(Under review)**

Thank You!

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