

Design and characterization for regenerative shock absorbers

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Outlines

- Motivation and State of the Art
- Suspension assessment
- Design method for motor-pump unit
- Prototype assembly and efficiency assessment
- Experimental tests and results
- Conclusion and work in progress



Motivation and State of the art

Conventional suspensions

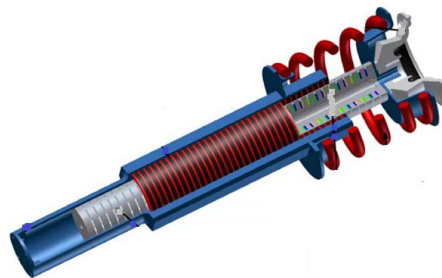
Conventional suspensions dissipate the kinetic energy as heat waste, regenerative shock absorbers can convert the kinetic energy into electrical energy.



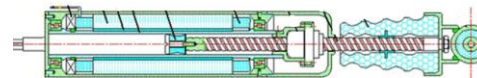
Regenerative shock absorbers



Electro-hydrostatic (EHA)



Linear



Ball screw



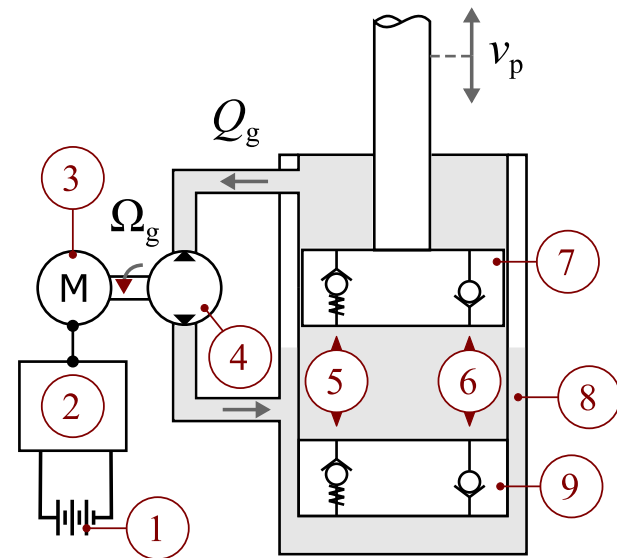
Rack and pinion

Why EHA dampers?

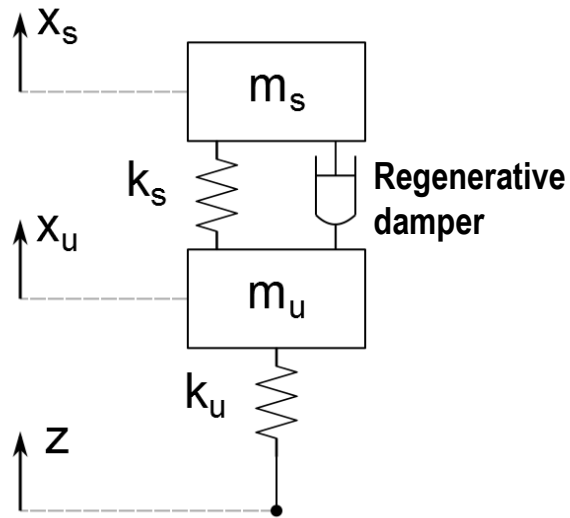
Advantages comparison with other solutions

- *Linear motors* force density is limited, work inefficiently, additional heft to the vehicle
- Electromechanical technologies (*Ball screw, rack and pinion...*) are complex and difficult to integrate into the suspension also with wear and fatigue issues
- Fluid-based *EHA* solution overcomes the main tribology of electromechanical systems, the fluid is used as power transmission, the actuator offers better flexibility for its placement within suspension

No.	Component
1	Battery
2	Power stage
3	Electric motor
4	Hydraulic pump
5	Pressure-relief valves
6	Check valves
7	Piston
8	Gas accumulator
9	Base

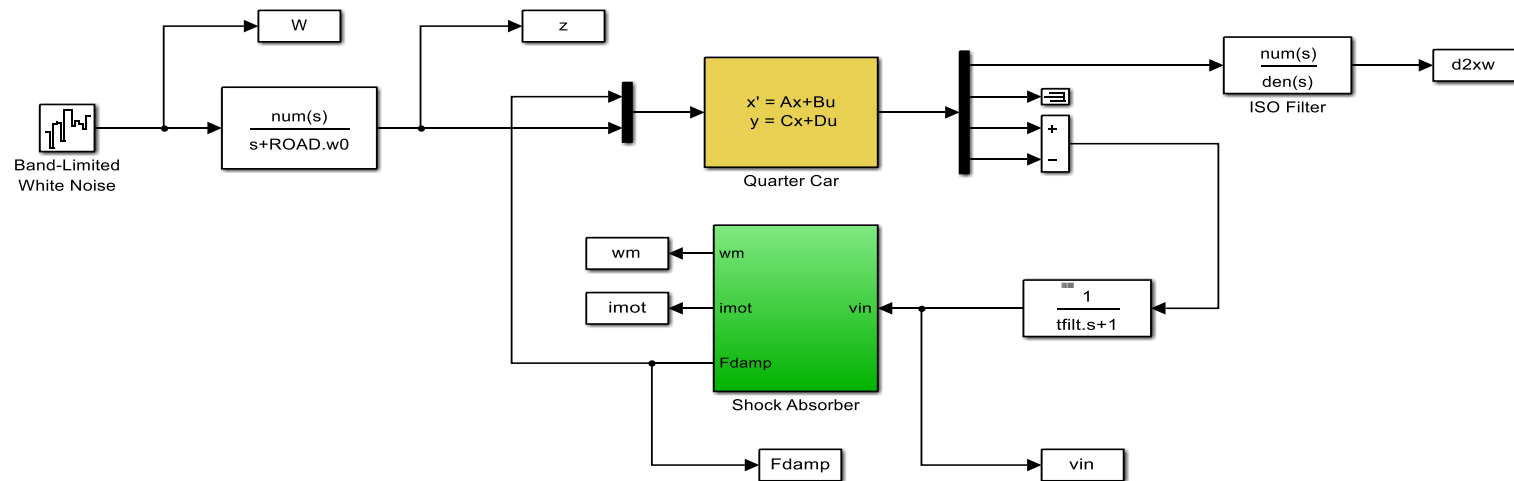


Quarter car model

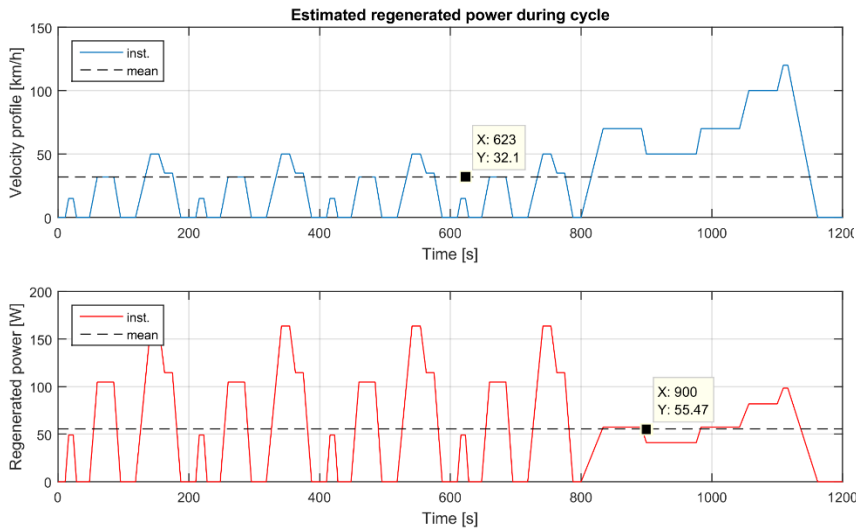


Parameter	Symbol	Front	Rear
Sprung mass	m_s	416.5 kg	256 kg
Unsprung mass	m_u	40 kg	30 kg
Suspension stiffness	k_s	23256 N/m	21739 N/m
Tire stiffness	k_u	226 kN/m	206 kN/m

Reference vehicle:
Jeep Renegade



Suspension assessment

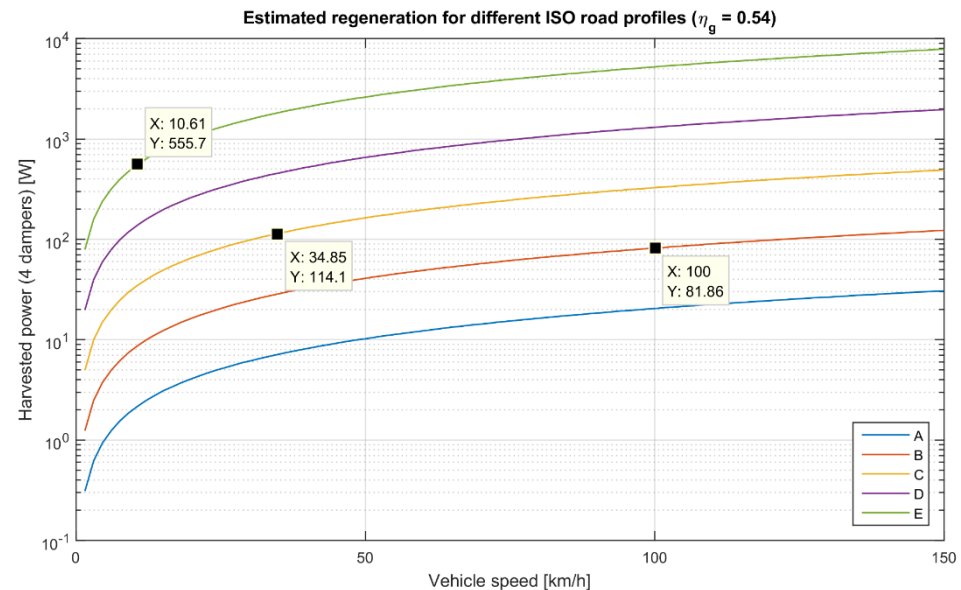


Road class	Description	Gr [m cycle]	S _{CO2} [gCO2/km]
A	Very good	1.60E-07	1.6E-01
B	Good	6.40E-07	6.4E-01
C	Average	2.56E-06	2.6E+00
D	Poor	1.02E-05	1.0E+01
E	Very poor	4.10E-05	4.1E+01

The emission reduction can be calculated by using the following expression :

$$S_{CO_2} = \frac{\eta_{conv} \eta_g}{\eta_{alt}} \pi^2 G_r \cdot \sum_{i=1}^4 k_{u,i} \cdot V_{PE,D} C F_D$$

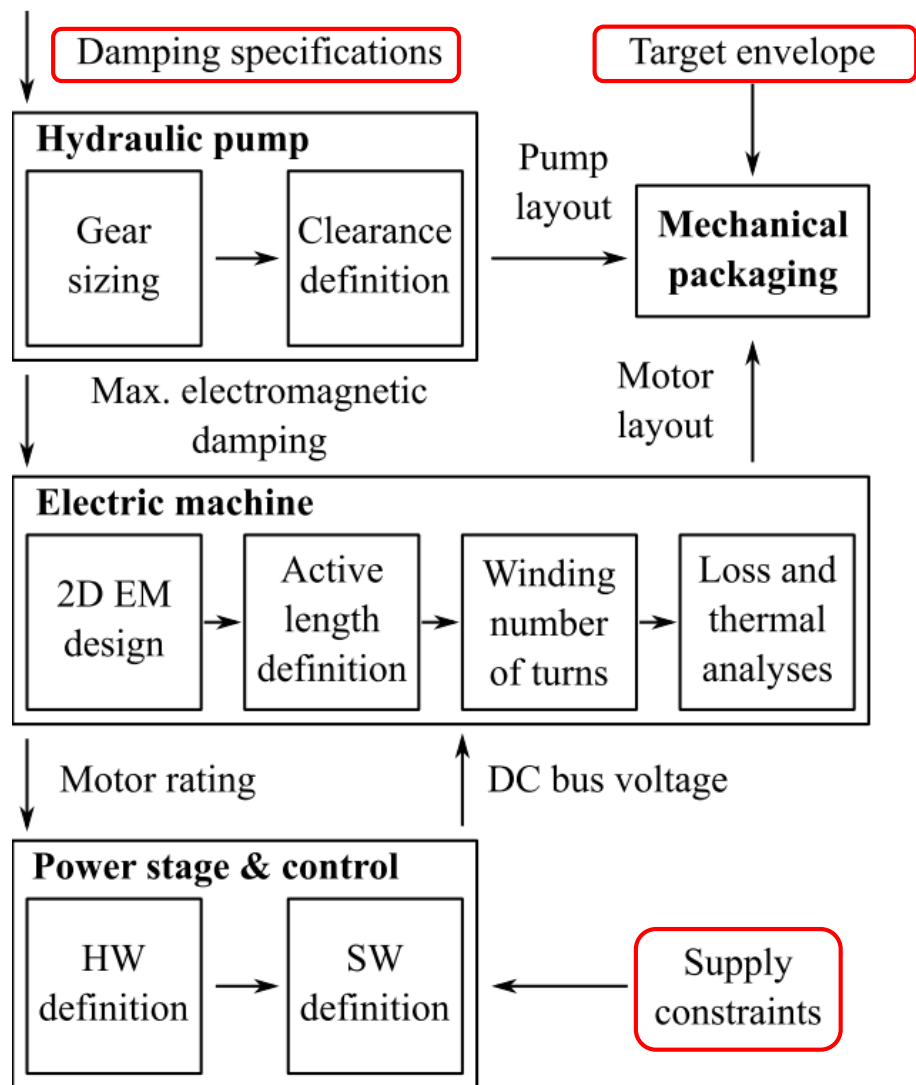
Power converter (0.9) → η_{conv}
 Mechanical (0.54) → η_g
 Car alternator (0.67) → η_{alt}
 Global efficiency term (0.73) → $\frac{\eta_{conv} \eta_g}{\eta_{alt}}$
 Tire stiffness sum (860 kN/m) → $\sum_{i=1}^4 k_{u,i}$
 Diesel consumption of effective power (0.22 l/kWh) → $V_{PE,D}$
 Diesel conversion factor (2640 gCO₂/l) → $C F_D$



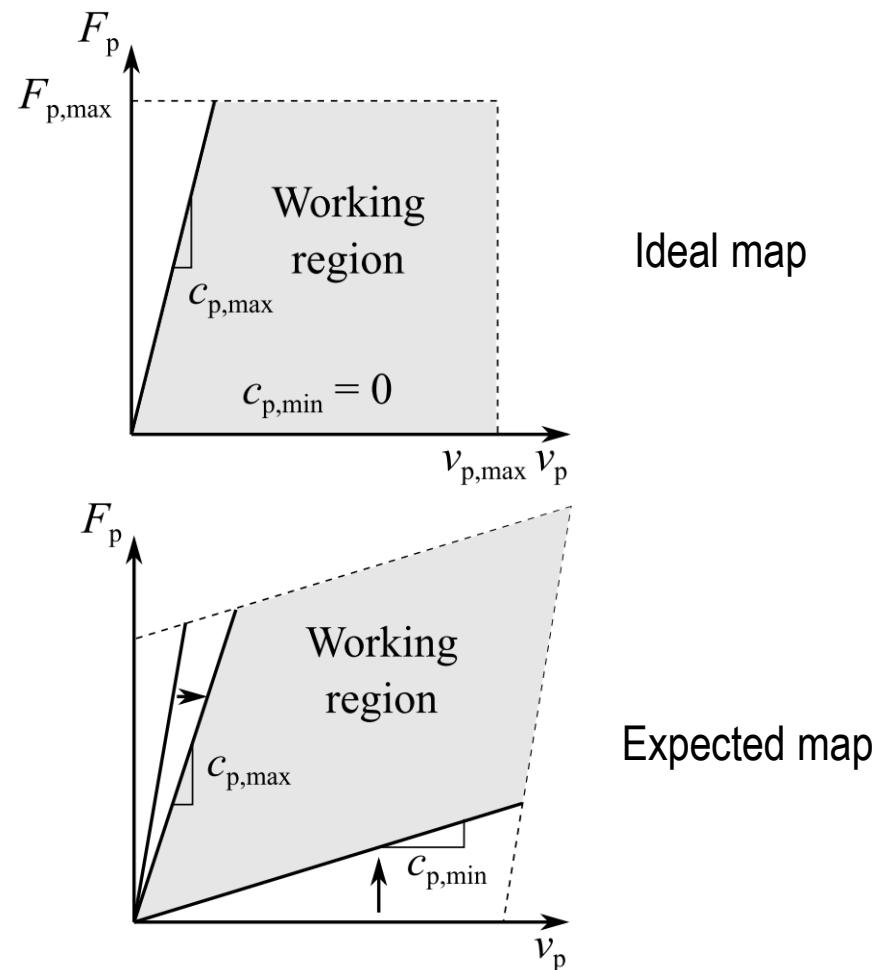
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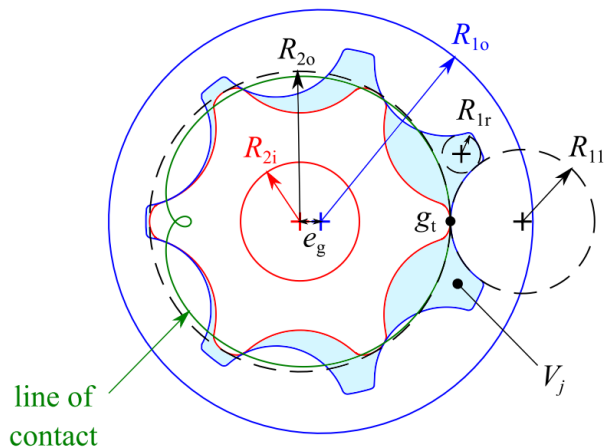
Design method for the motor-pump unit



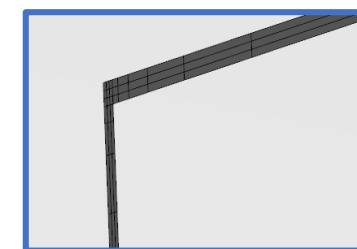
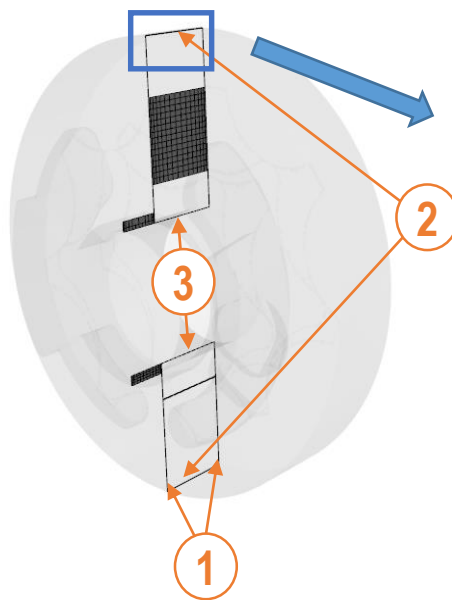
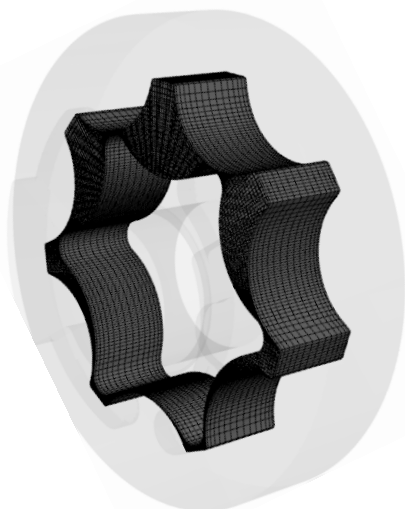
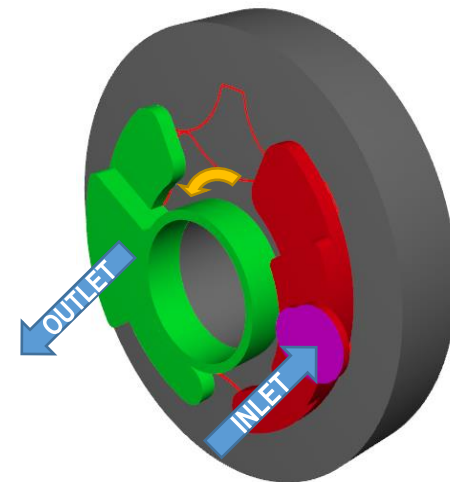
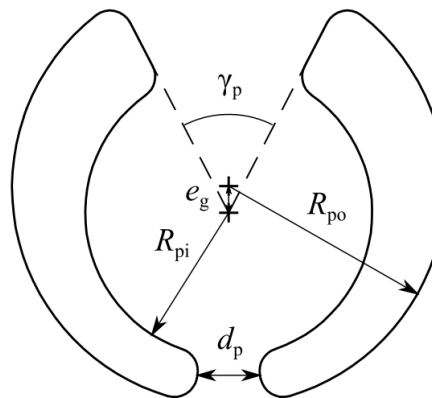
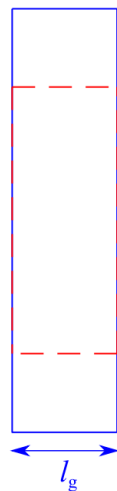
Force-speed maps of the regenerative shock absorber limited by damping, force and speed values



Hydraulic pump design



Displacement: $3.572 \text{ cm}^3/\text{rev.}$

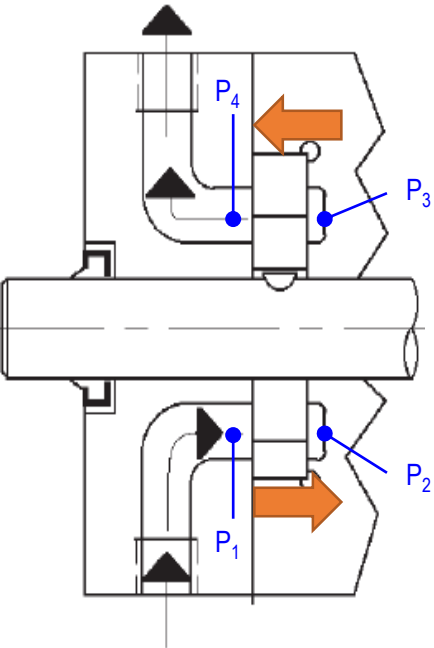


3-node mesh refinement

- 1: Axial clearance
- 2: Radial clearance between inner gear and shaft
- 3: Radial clearance between outer gear and pocket

Pressure balance inside the case

Discharge



Forces due to pressure unbalance

Inlet

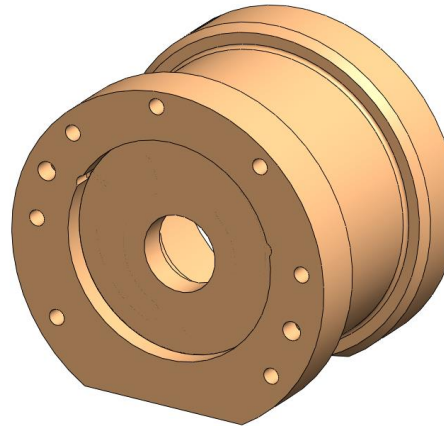
Pressure balance

Unbalanced condition

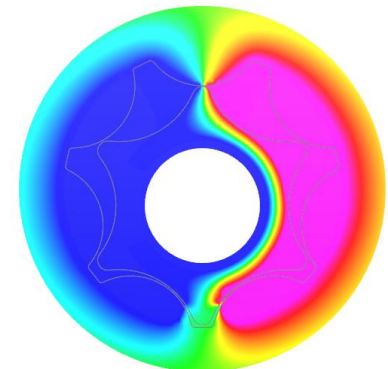
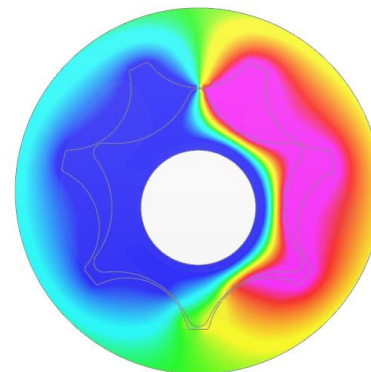
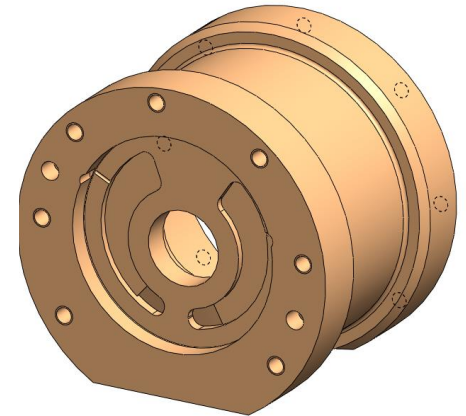
$$P_1 > P_2 > P_3 > P_4$$

$$\begin{aligned} P_1 &= P_2 \\ P_3 &= P_4 \\ P_2 &> P_3 \end{aligned}$$

Case without grooves



Case with grooves



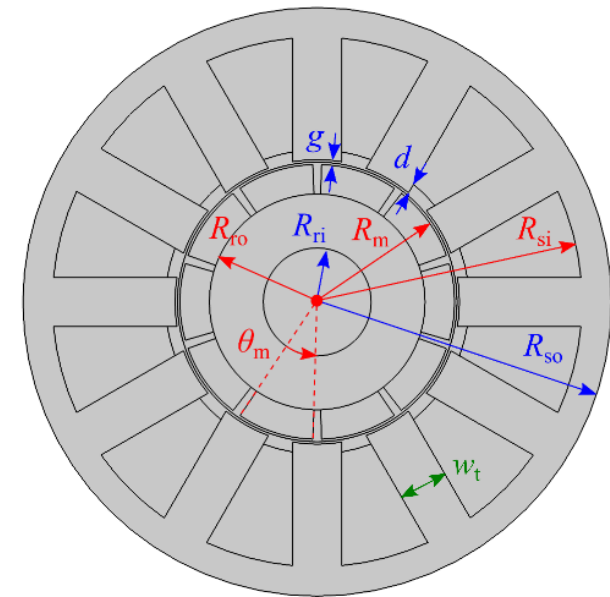
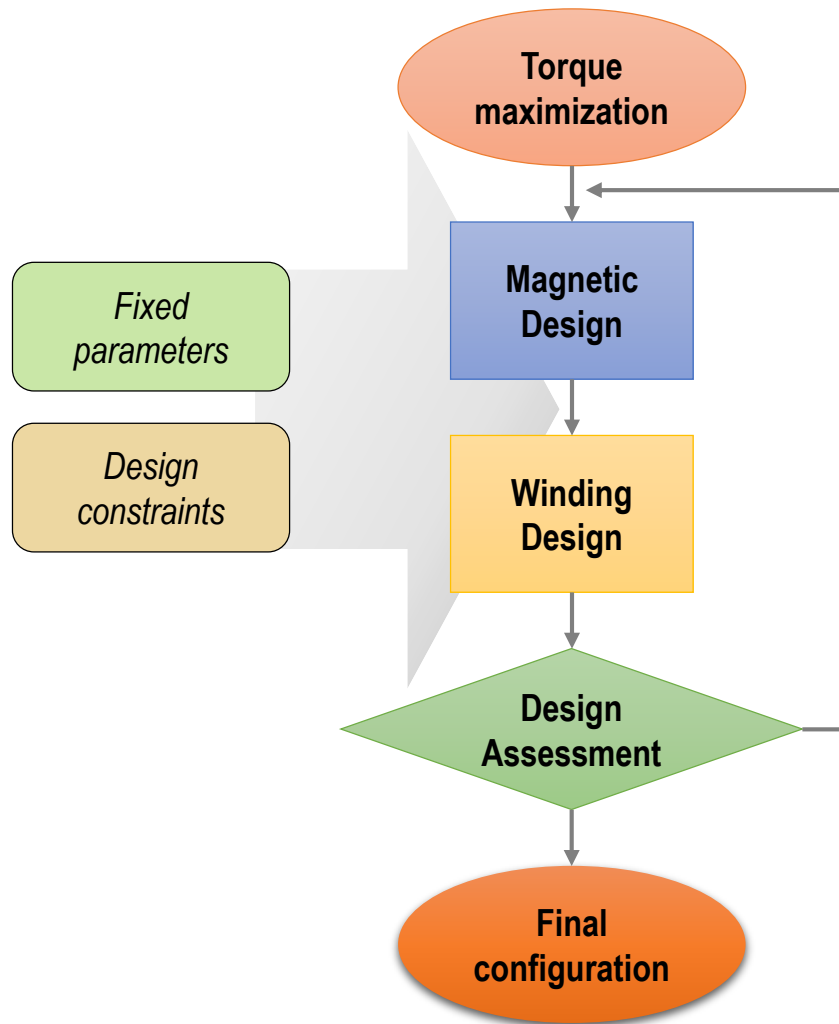
Flow: Pressure [Pa]

2.2e+06



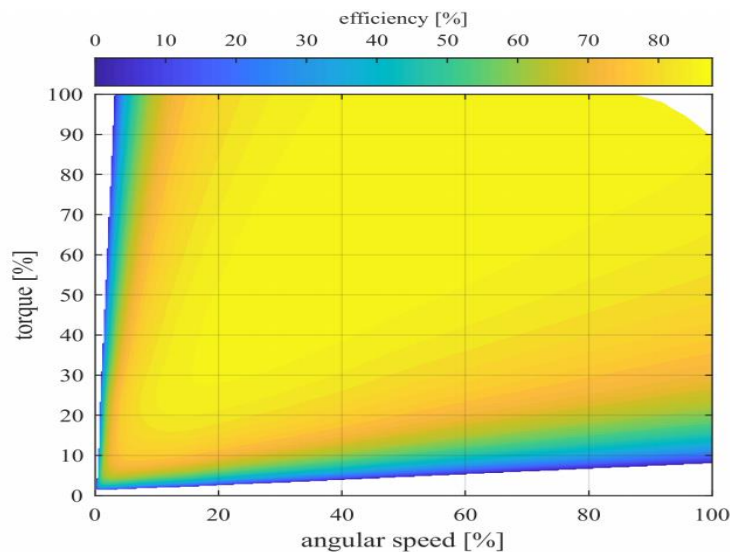
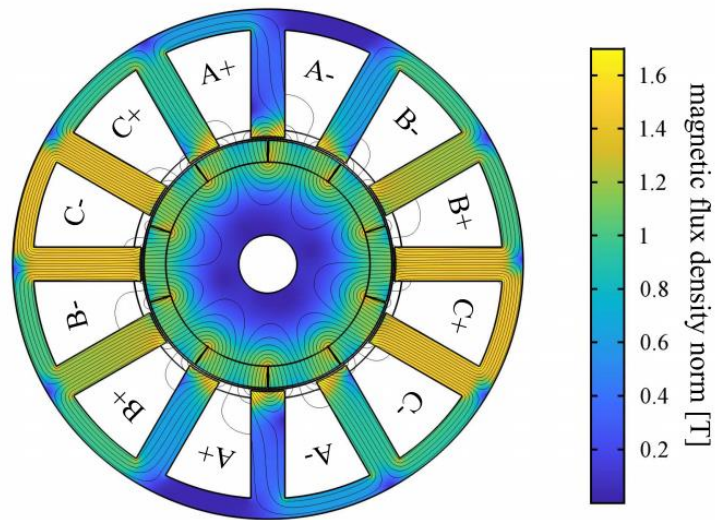
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Electric machine design

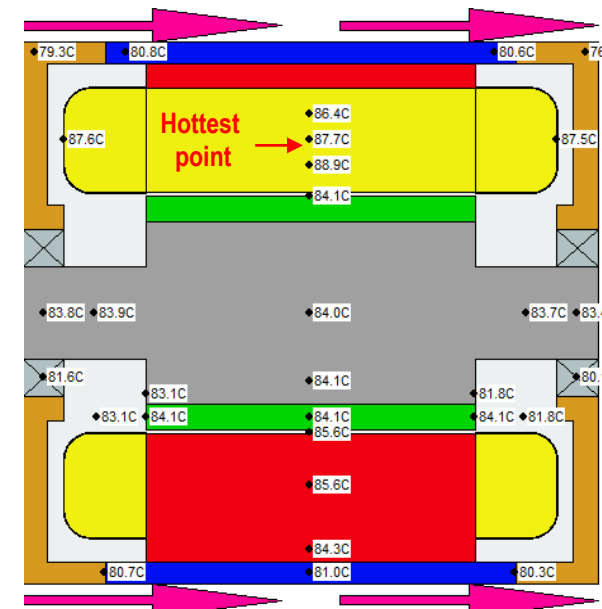


Parameter	Value	Description
R_{ro}	10 mm	Rotor outside diameter
R_m	15 mm	Magnet diameter
R_{si}	29.5 mm	Stator inside diameter
R_{so}	32 mm	Stator outside diameter
d	1 mm	Tooth-winding gap
g	0.5 mm	Air gap
L	30 mm	Active length
N_m	10	Number of magnets
N_s	12	Number of slots

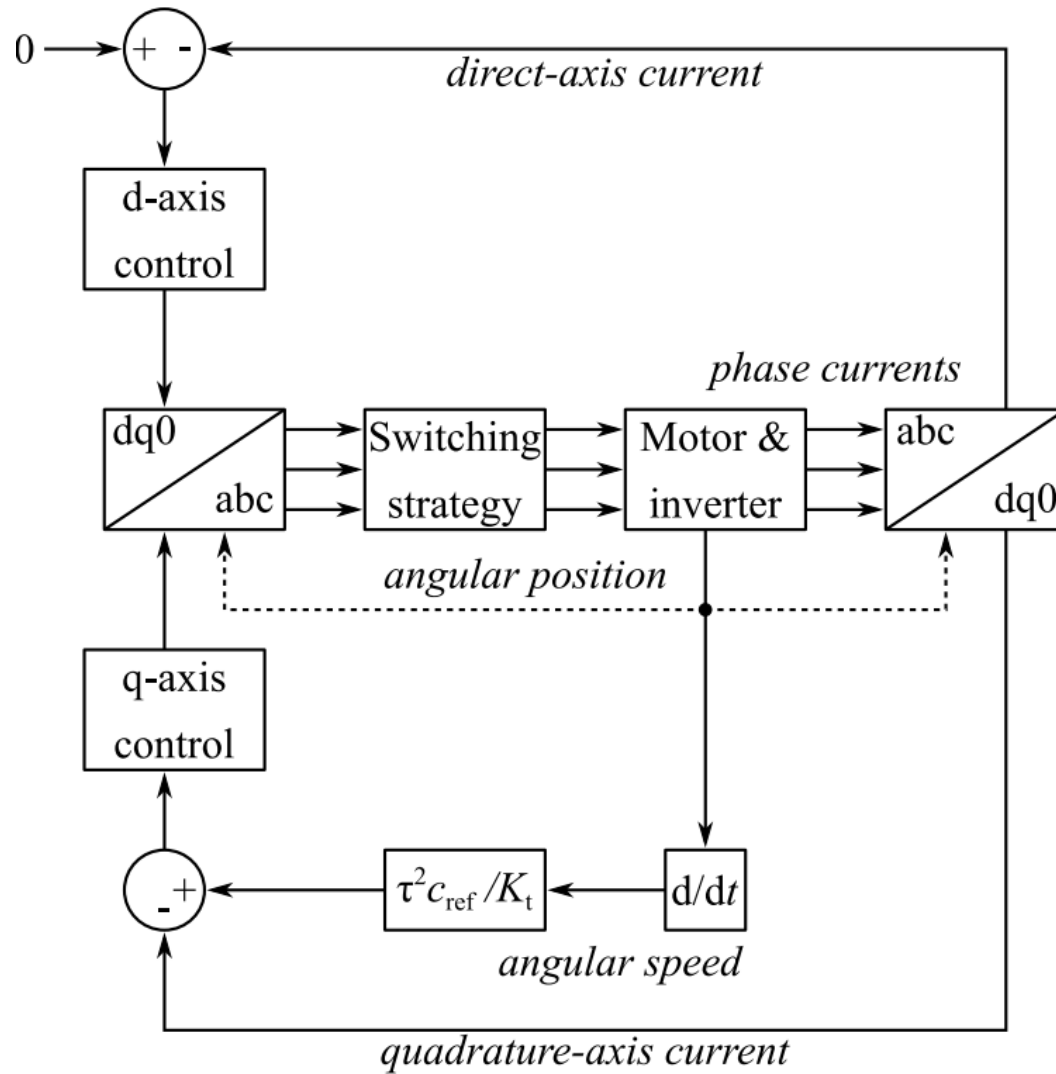
Electric Machine assessment



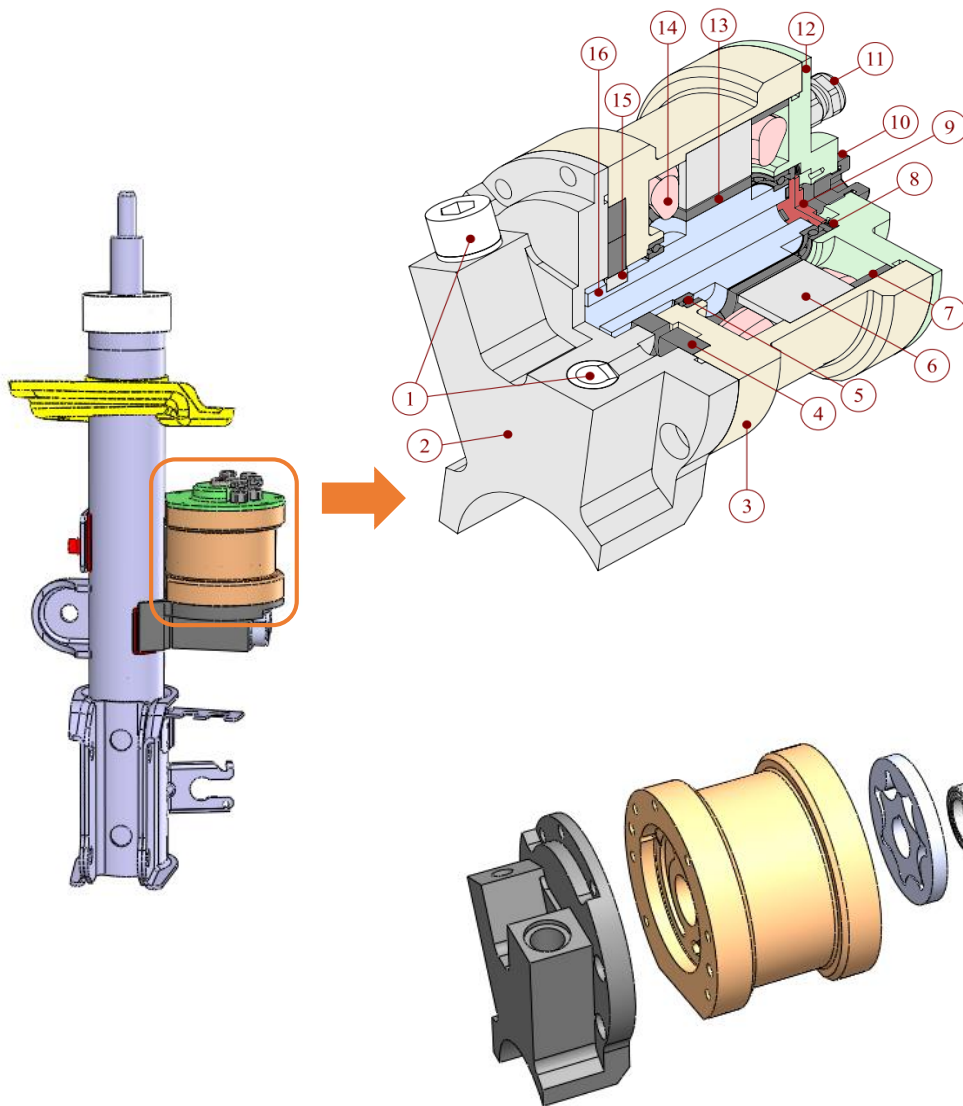
Symbol	Value	Description
N_{tc}	14	Number of turns per coil
K_e	21.4 mVs/rad	Back EMF constant
R	20 mΩ	Phase resistance
S_w	2.19 mm ²	Wire cross section
λ_p	4.22 Wb	Permanent magnet flux linkage
p	5	Number of pole pairs
k_{cp}	0.3	Coil packing factor
B_r	1.3 T	Magnet remanent flux density
B_{sat}	1.2-1.8 T	Iron saturation flux density



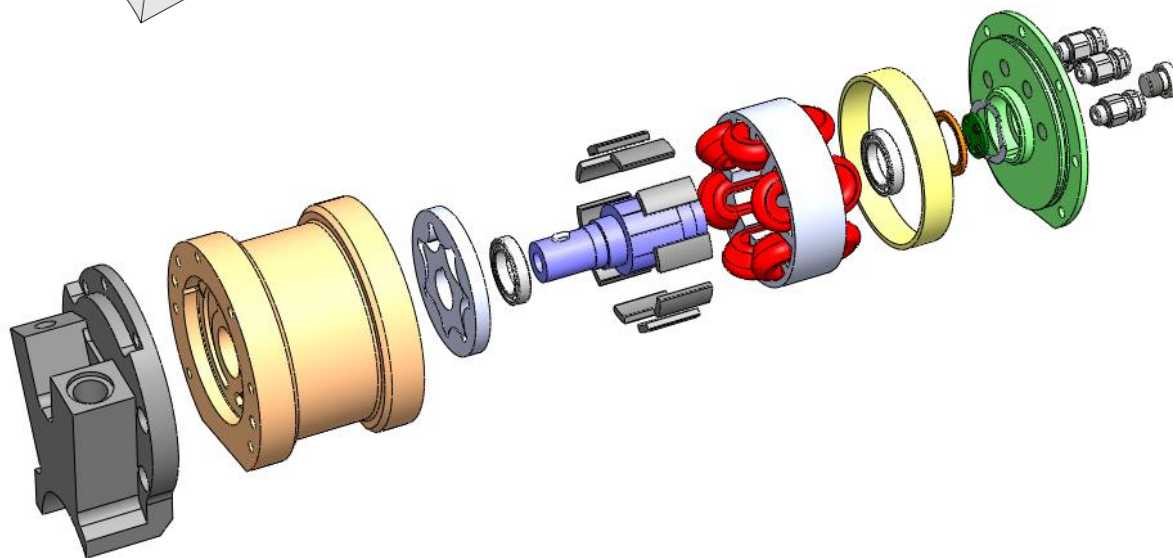
Control strategy



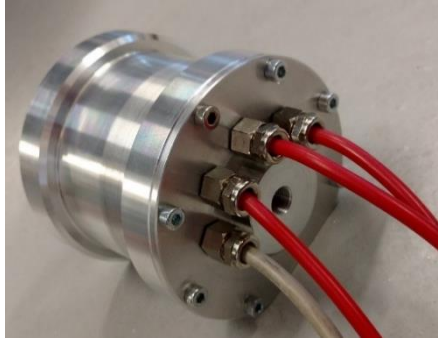
Prototype layout



No.	Component	No.	Component
1	Pump port plugs	9	Position sensor
2	Pump cover manifold	10	Drain cap
3	Casing	11	Cable gland x 4
4	Gerotor gear	12	Motor cover
5	Ball bearing x 2	13	Permanent magnets x 10
6	Stator	14	Winding coil x 6
7	Motor spacer	15	Key
8	Wave spring	16	Rotor shaft



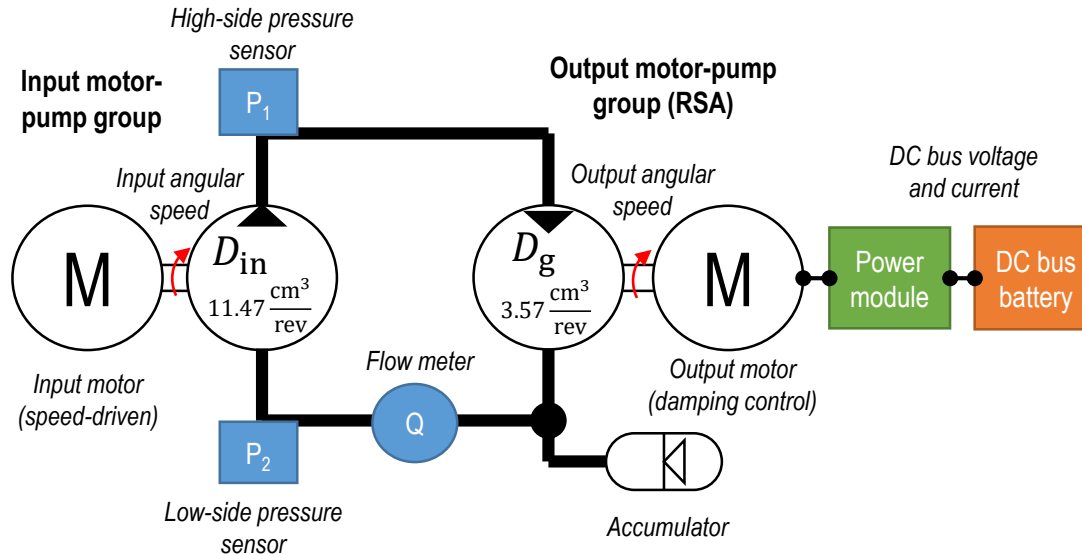
Prototype layout



Main data	Unit	Value
Added mass per corner	kg	2.1
Max diameter	mm	88
Max axial size	mm	84
Pump displacement	cc/rev	3.57
Max e-motor torque	Nm	0.67



Efficiency assessment in static test rig



Hydraulic efficiency

$$\eta_h = \frac{D_g \Omega_g}{Q}$$

Mechanical efficiency

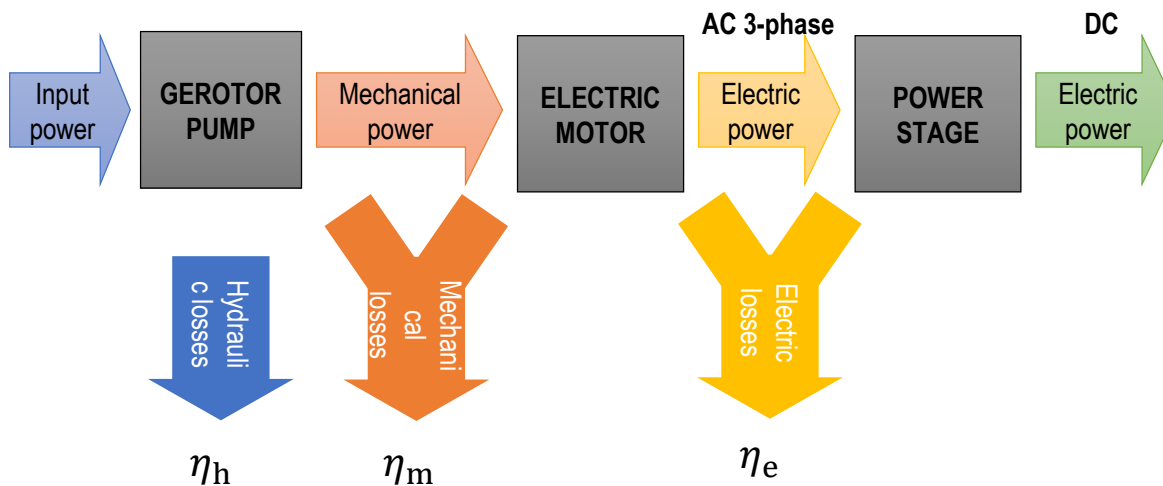
$$\eta_m = 1 - \frac{c_m \Omega_g}{D_g \Delta P}$$

Electric efficiency (motor and power stage)

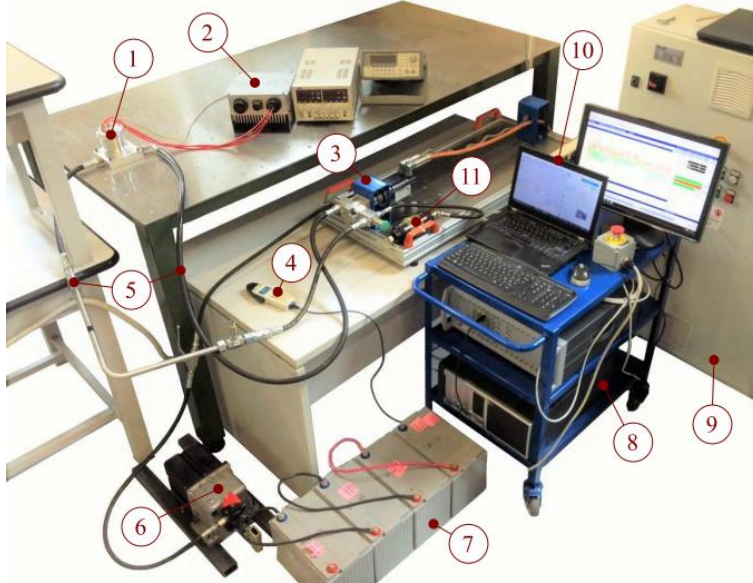
$$\eta_e = 1 - \frac{2(R + R_{on})T_{em}}{3K_e^2 \Omega_g}$$

Total efficiency

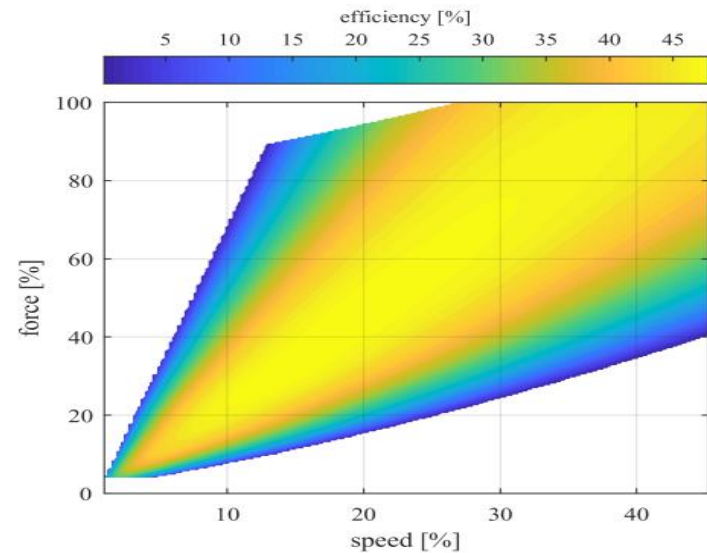
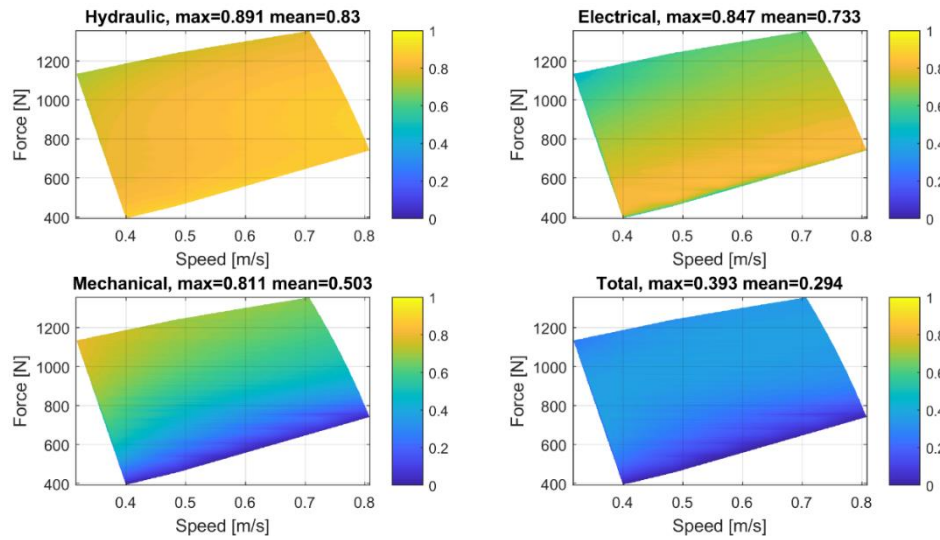
$$\eta_{tot} = \eta_e \eta_m \eta_h = \frac{V_{dc} i_{dc}}{\Delta P Q}$$



Static test results

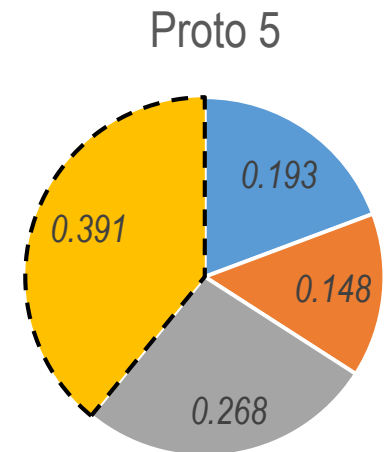
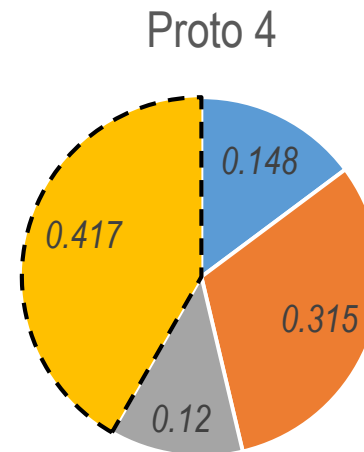
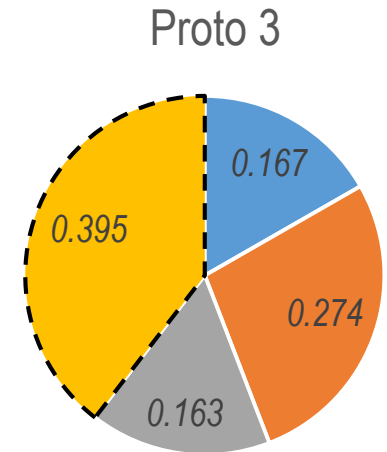
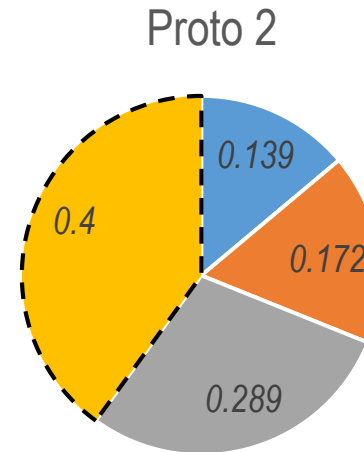
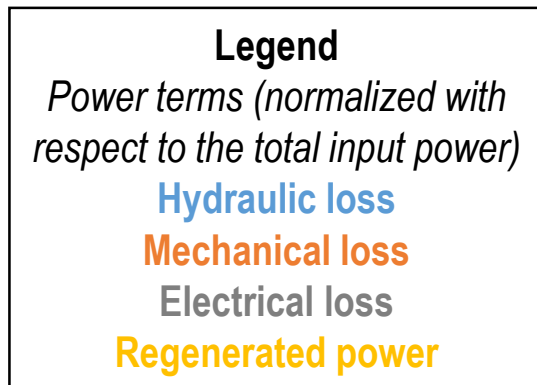
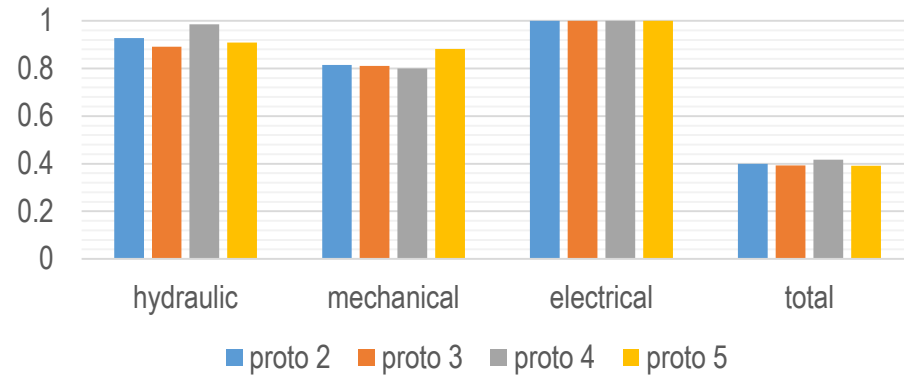


No.	Description	No.	Description
1	Motor-pump prototype	7	Battery array
2	Power stage	8	Data logging PC
3	Driving motor-pump unit	9	Driving motor switchboard
4	Current probe	10	Control PC
5	Hydraulic lines	11	Gas-loaded accumulator
6	Hand pump to fill the circuit		

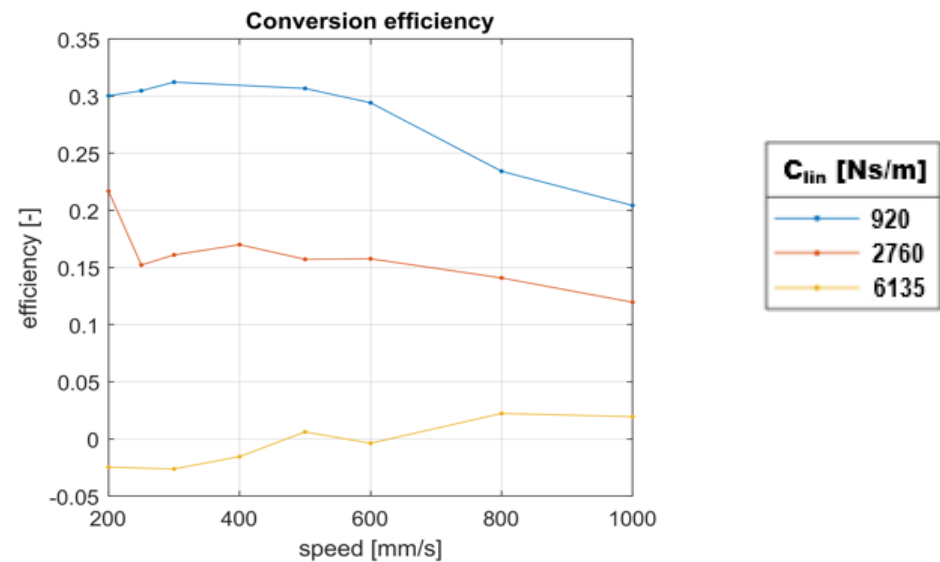
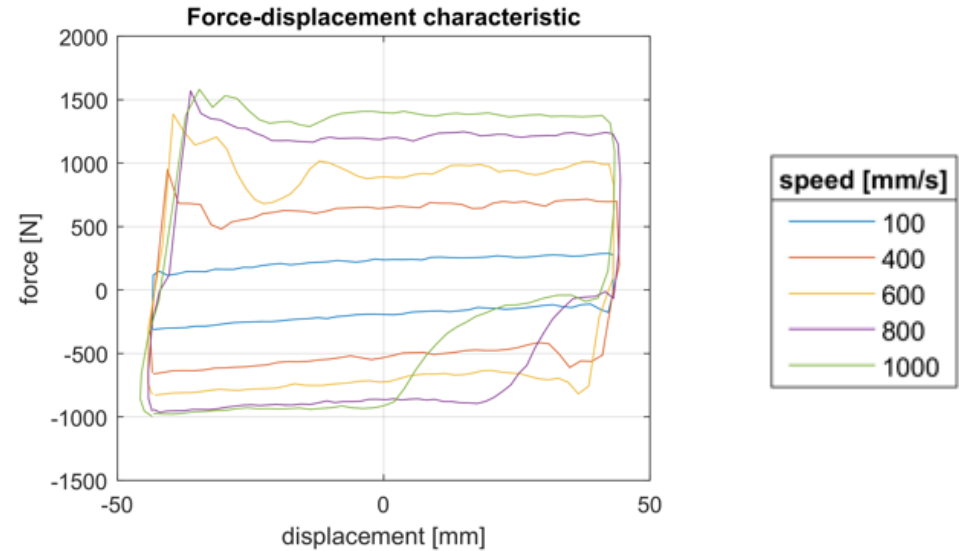
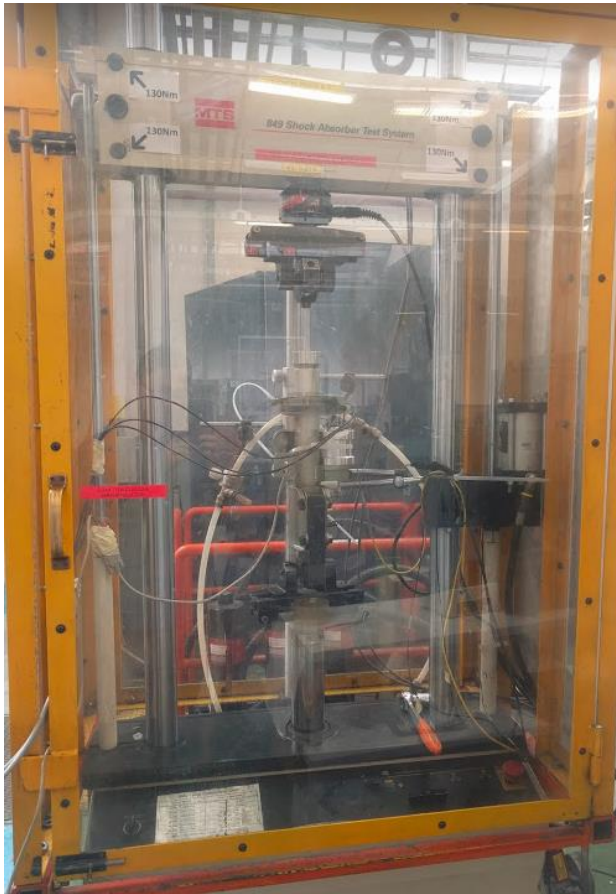


Static test results

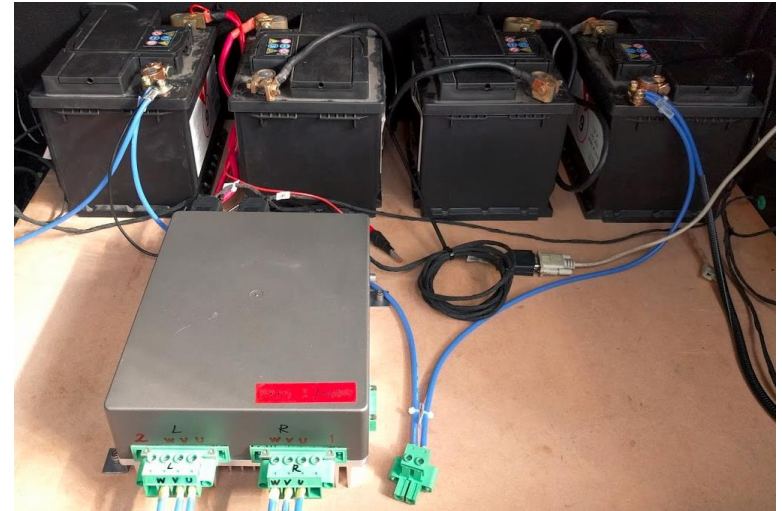
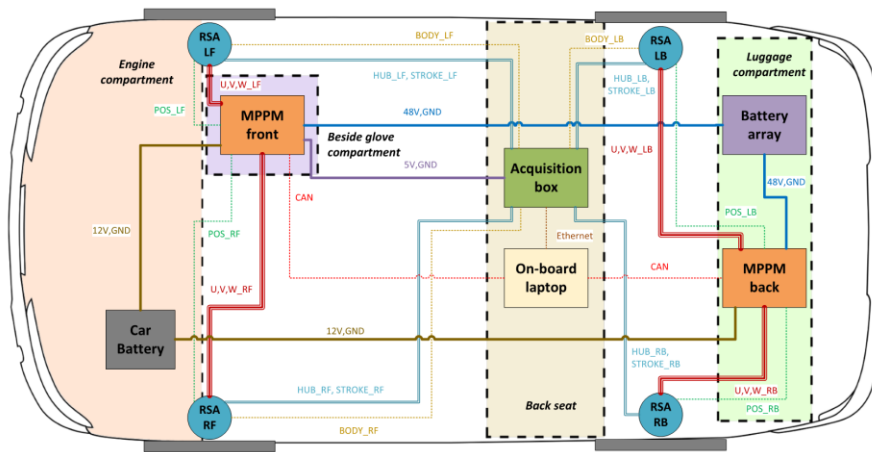
Peak efficiency in the characterized area



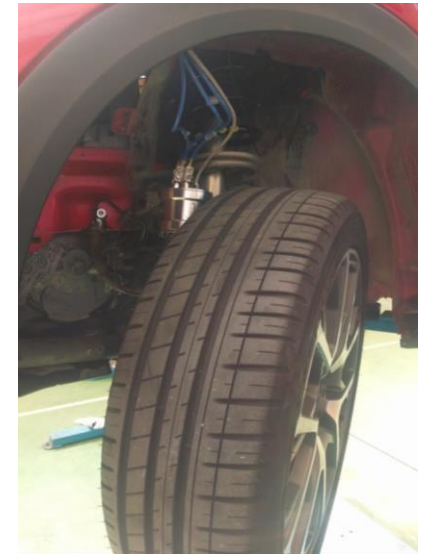
Damper characterization on the test bench in Marelli



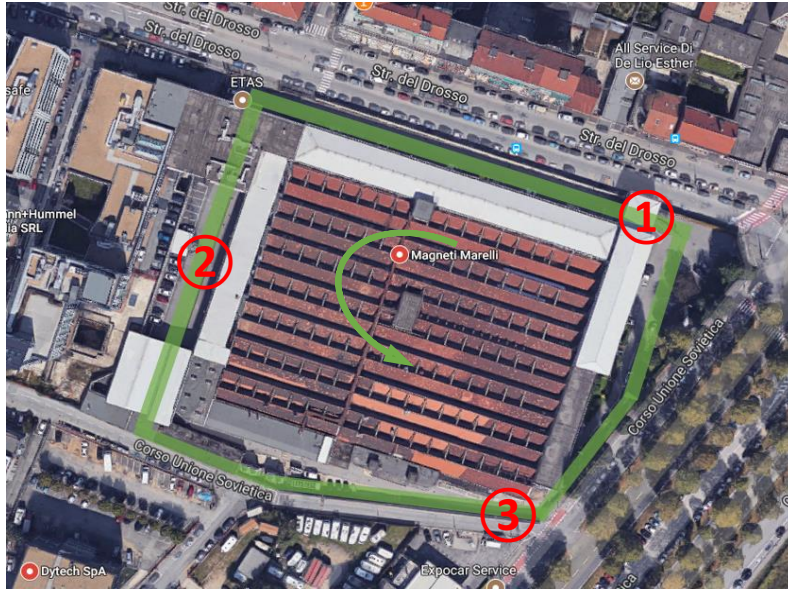
Final prototype assembly on the vehicle



MPPM Front axle									
FRONT_Vdc	none	Read Only							
FRONT_Isc	none	Read Only							
FRONT_RegPower	none	Read Only							
FL_Ctrl	none								
FL_OFF	none								
FL_Fault	none	Read Only							
FL_FaultReset	none								
FL_State	none	Read Only							
FL_Ngrots	none								
FL_EnableDamping	none								
FL_Speed	none	Read Only							
FL_IqRef	none								
FL_Cref	none								
FR_Ctrl	none								
FR_OFF	none								
FR_Fault	none	Read Only							
FR_FaultReset	none								
FR_State	none	Read Only							
FR_Ngrots	none								
FR_EnableDamping	none								
FR_Speed	none	Read Only							
FR_IqRef	none								
FR_Cref	none								
MPPM Rear axle									
REAR_Vdc	none	Read Only							
REAR_Isc	none	Read Only							
REAR_RegPower	none	Read Only							
RL_Ctrl	none								
RL_OFF	none								
RL_Fault	none	Read Only							
RL_FaultReset	none								
RL_State	none	Read Only							
RL_Ngrots	none								
RL_EnableDamping	none								
RL_Speed	none	Read Only							
RL_IqRef	none								
RL_Cref	none								
RR_Ctrl	none								
RR_OFF	none								
RR_Fault	none	Read Only							
RR_FaultReset	none								
RR_State	none	Read Only							
RR_Ngrots	none								
RR_EnableDamping	none								
RR_Speed	none	Read Only							
RR_IqRef	none								
RR_Cref	none								



Testing track and setup



The testing was carried out inside Magneti Marelli (shown in green)

The Fiat 500X is equipped with 4 regenerative shock absorbers which are controlled by 2 ECUs (Front and Rear)

The tests are performed under 3 different conditions with damping values of 920, 2760 and 6135 [Ns/m]

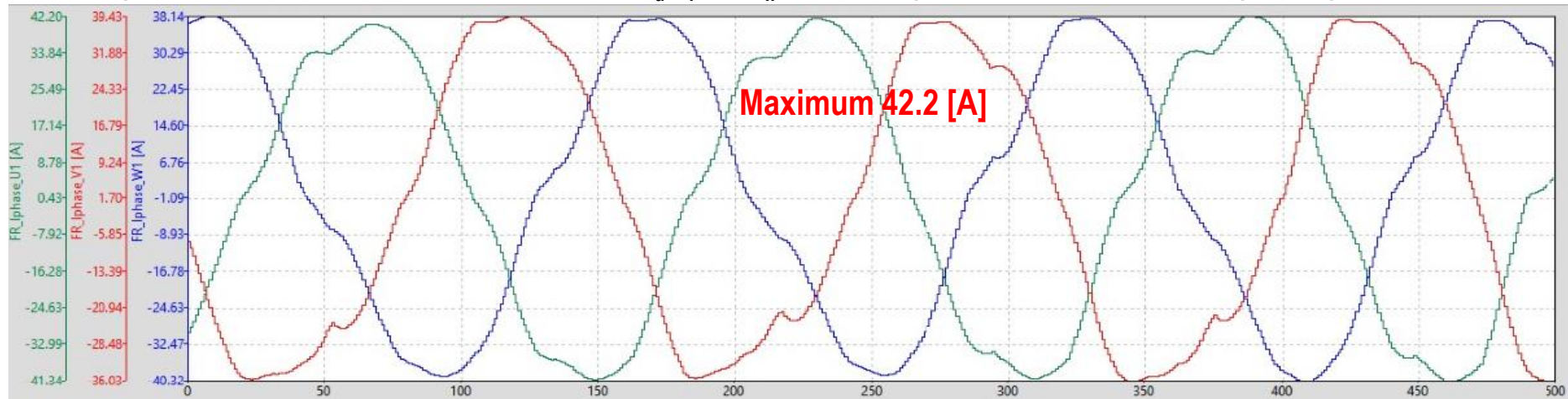
- Position 1 : road with rush downhill
- Position 2 : where perform “S” maneuver
- Position 3 : road with step
compression forces exerted
to the right wheels of the car

Testing result – phase current and power regenerated

Damping value: 6135 [Ns/m]

Phase current I_u , I_v and I_w for front right corner

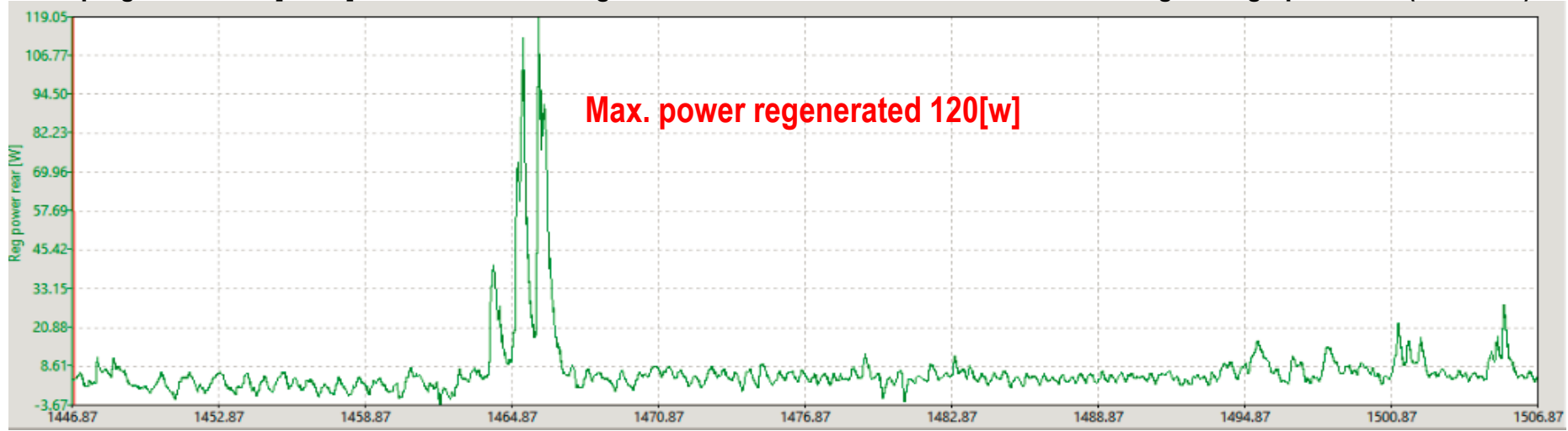
Passing through position3 (Step)



Damping value: 920 [Ns/m]

Power regenerated for the rear axle

Passing through position1 (Downhill)



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Conclusions and work in progress

- The method adopted for designing the motor-pump unit for hydraulic shock absorbers guarantees the damping functionality and maximize the energy regeneration capability of the system.
- The results shows the role of different components on the total conversion efficiency and it turns out that the hydro-mechanical losses were identified as the most critical aspect of the design.
- Next step is to evaluate comfort ,handling and regeneration on a test track with different road profiles.



The End

Thank You for Your Attention

