DIGEP
Department of Management and Production Engineering

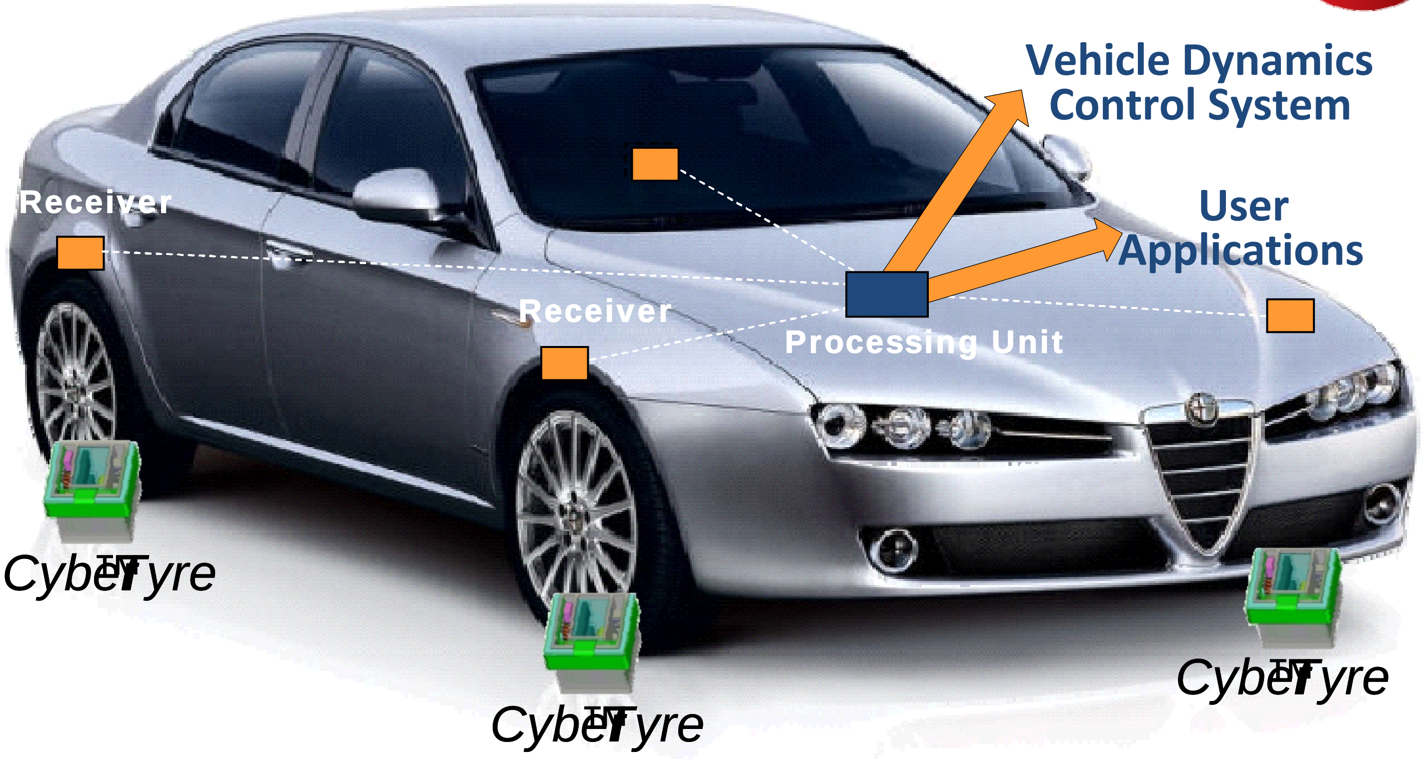
POLITECNICO DI TORINO

Magneto-mechanical Energy Harvester for wireless sensors in Tyre, Shoes and other components

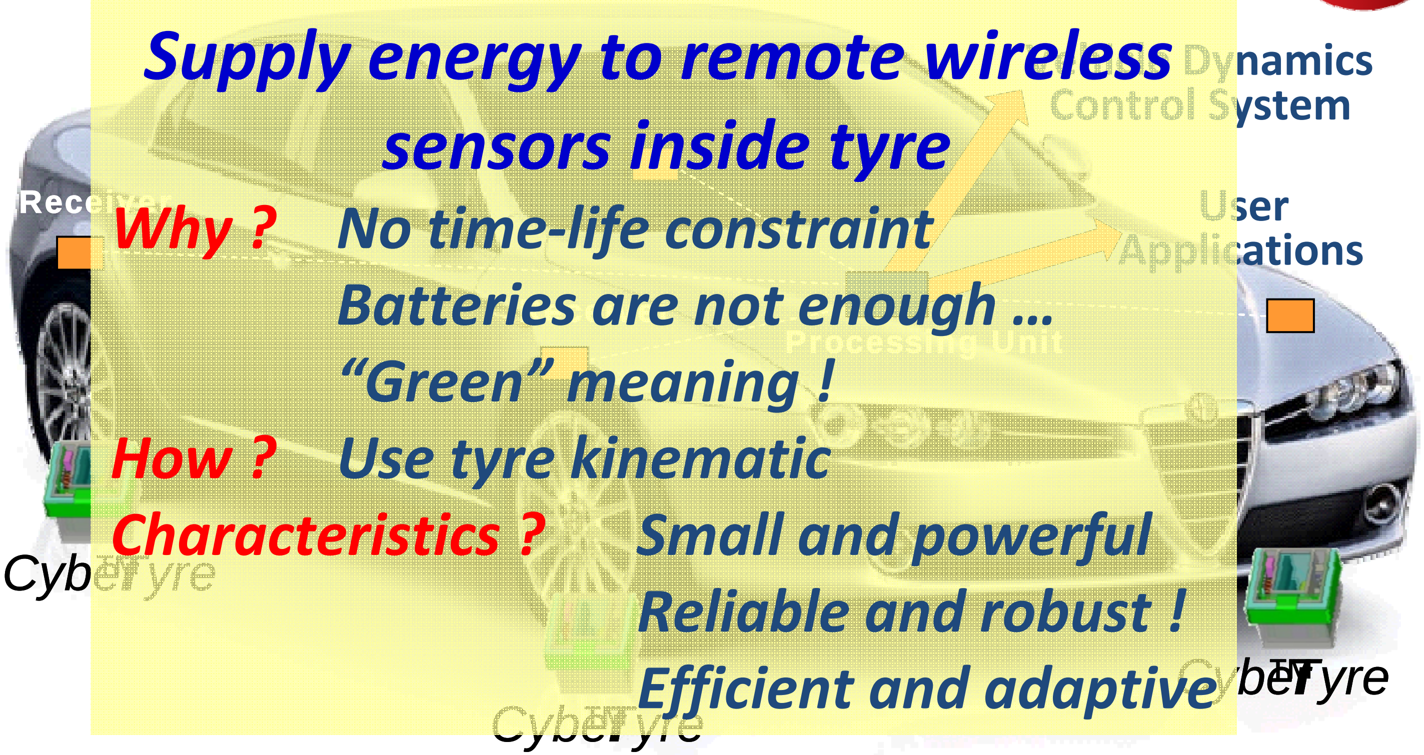
Elvio Bonisoli

Aim: ***supply energy to remote wireless sensors inside tyre, shoes or other items***

- *Presentation of the Cyber Tyre project*
- *Requirements, source characteristics and boundary constraints*
- *Description of the harvesting device dynamics*
- *Optimization aspects*
- *Performance index and comparison*
- *Other applications: shoes and mouse devices*
- *Conclusions*



Tyre like a sensor !



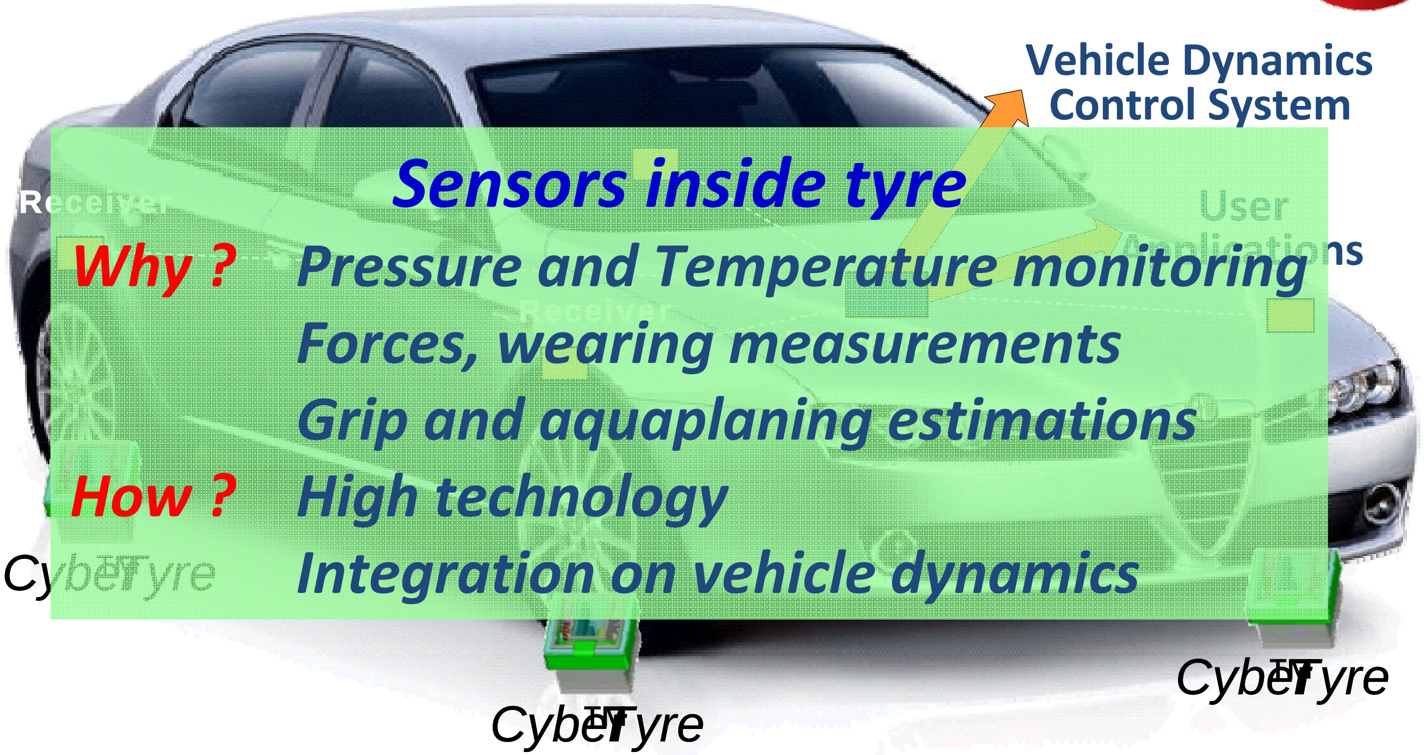
Supply energy to remote wireless sensors inside tyre

Why ? *No time-life constraint*
Batteries are not enough …
"Green" meaning !

How ? *Use tyre kinematic*

Characteristics ? *Small and powerful*
Reliable and robust !
Efficient and adaptive

Tyre like a sensor !



Sensors inside tyre

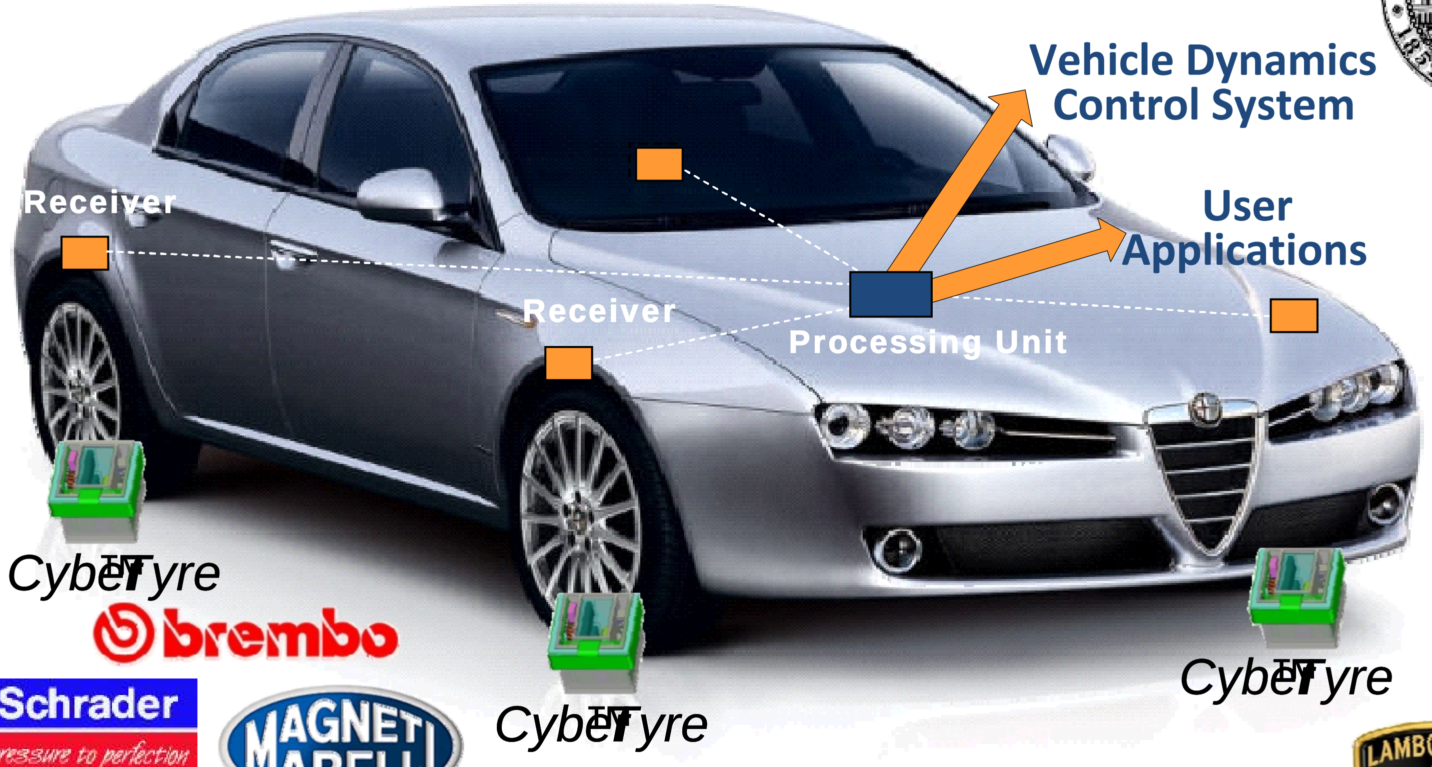
Why ? *Pressure and Temperature monitoring*
Forces, wearing measurements
Grip and aquaplaning estimations

How ? *High technology*
Integration on vehicle dynamics

Tyre like a sensor !

Pirelli Tyre Project

University

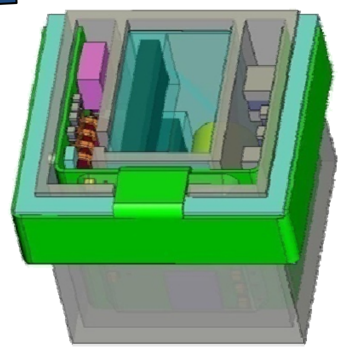


Car maker

Industrial partners

Cyber Tyre:

- ***Temperature, pressure and grip evaluation on each tyre***
- ***Integrated vehicle dynamic control (ABS, ESC, …)***



Inside each node

- ***Sensors (temperature, pressure, 3-axial accelerometer)***
- ***Electronic circuits***
- ***UWB Antenna + PAN on vehicle***
- ***Energy Harvester (mechanical-electro-magnetic)***
- ***Harvester Interface (active control)***

Energy Harvester history

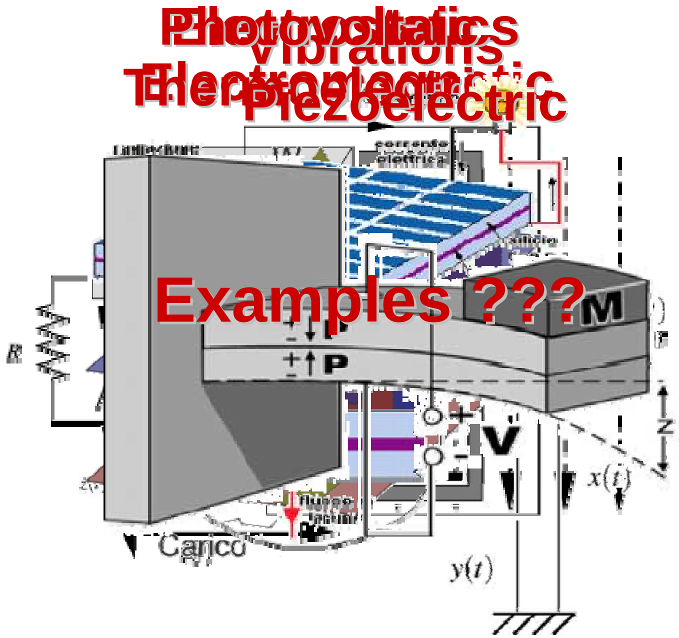
- Very long historical connection to the water wheel, windmills and waste heat

- Ironically, before batteries (Volta, 1799) and the dynamo (Faraday, 1831), energy scavenging or energy harvesting was the only way to get any useful power !

- Today, great interest in the community for powering ubiquitously deployed sensor networks and mobile electronics

- All depends on the application (source characteristics, power density requirements, …) – No one-size-fits-all !

- Mean power and power density, obtained through scavengers, are usually small (μW, mW, W)
- Source of power, excitation characteristics and harvesting technologies
- Energy scavenging principles:
  - **Radio waves**
  - **Vibrations**
  - **Electromagnetic**
  - **Electrostatics**
  - **Piezoelectric**
  - **Thermoelectric**
  - **Photovoltaic**
  - **Biological**



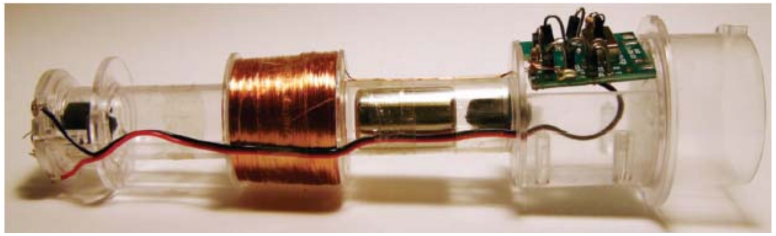
Some examples …

Solar panels

IEEE

PZT generators in shoes

Mechanical watches



Shake-driven flashlight

Piezoelectric pavement

Electrostatic generator in shoes

Power density

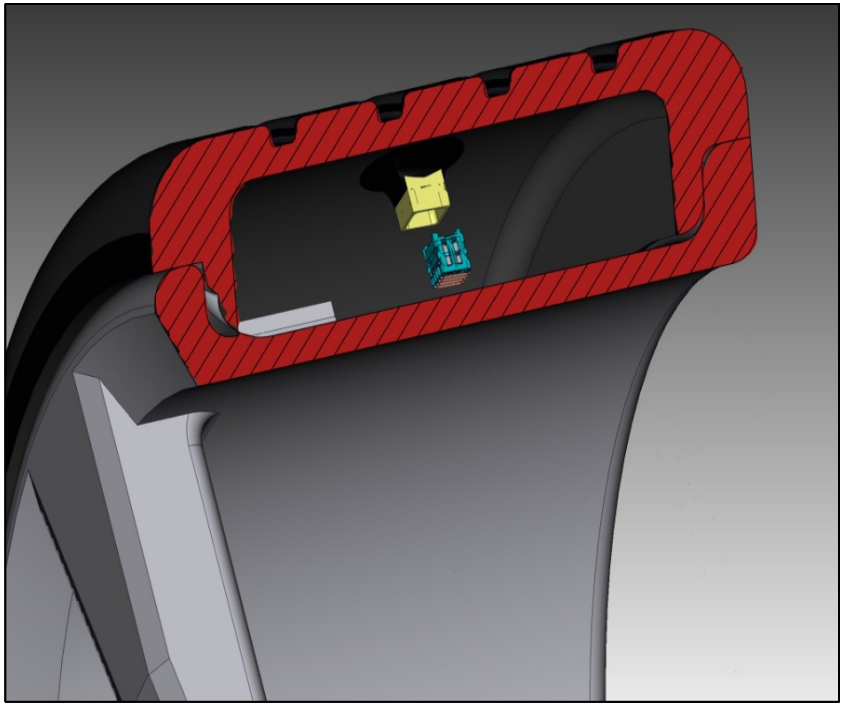
Environmental Energy Source	Transduction Principle	Power Density*	Volume/Area to get 1mW
solar energy	photovoltaic cells /	15 W/cm^2 (directly enl.) 150 mW/cm^2 (cloudy day)	0.06 W/cm^2
			W/cm^2
electromagneti	coupling	scavenging	//
thermal gradients	seebeck effect	15 mW/cm^2 @ 10 K	66.6 mW/cm^2
mechanical vibrations	electromagnetic	10 mW/cm^3	100 mW/cm^3
	electrostatic	50 mW/cm^2	20 mW/cm^2
	piezoelectric	250 mW/cm^3	4 mW/cm^3
pressure gradients	electrostatic	1 mW/cm^2	1000 mW/cm^2

depend heavily on the ambient excitation and harvesting technologies

* *"A study of low level vibrations as a power source for wireless sensor node" S. Roundy, P. Wright, J. Rabaey, Computer communications, Elsevier 2002 (Berkeley)*

Characteristics and operational requirements:

- *Small dimensions: about 10x10x10 mm*
- *High power density*
- *Wake-up velocity 20-30 km/h*
- *Velocity range up to 300 km/h*
- *Voltage > 1.3 V*
- *Lowest mean power 2.5 mW*



Nonlinear electro-magnetic device (resonant and adaptive)

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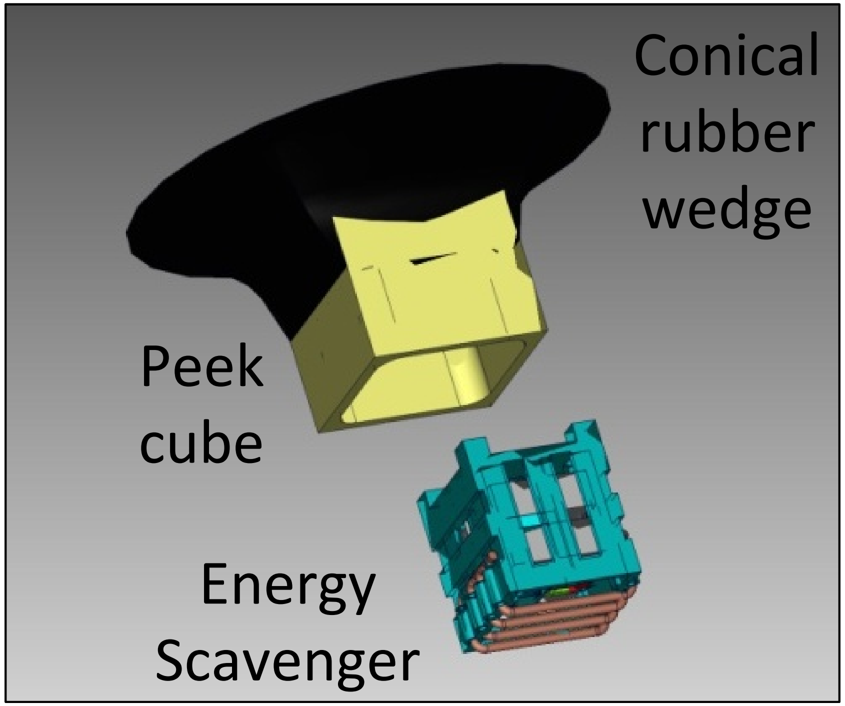
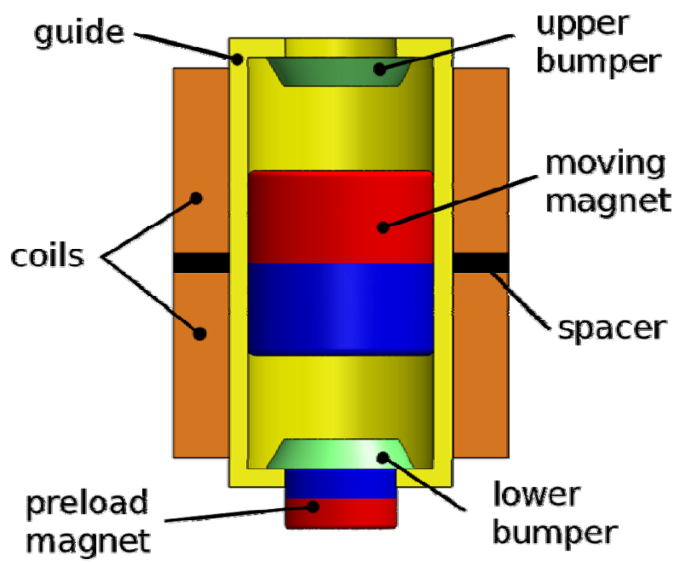
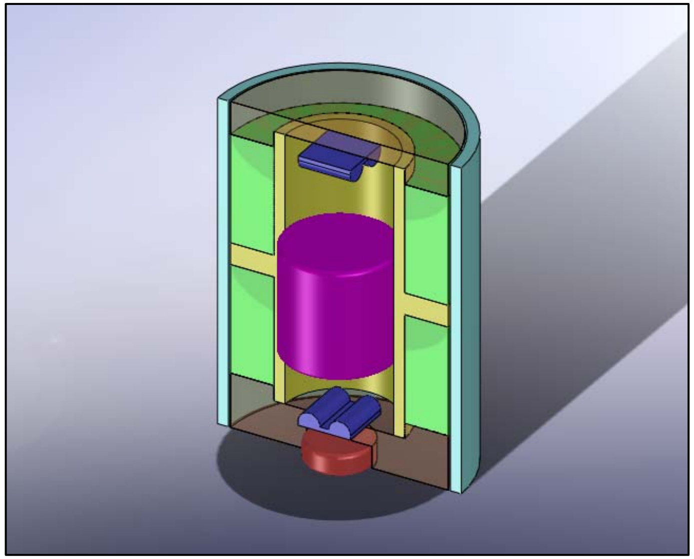
Nonlinear electro-magnetic device (resonant and adaptive)



How it works:

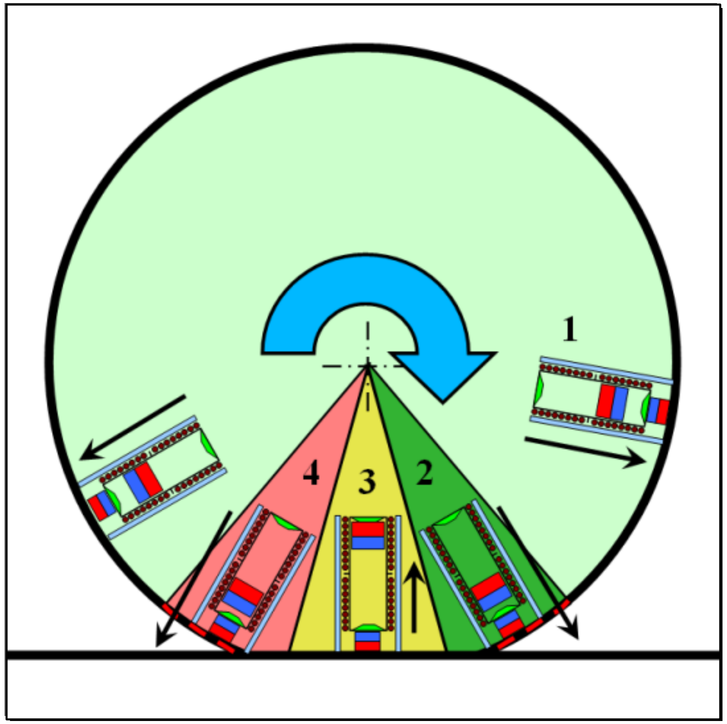
- A floating magnet slides into the guide
- Around the guide are wound two coils
- Preload obtained through magnets
- Use of rare-earth permanent magnets (high power density)
- Electric-magnetic coupling with imposed dynamic

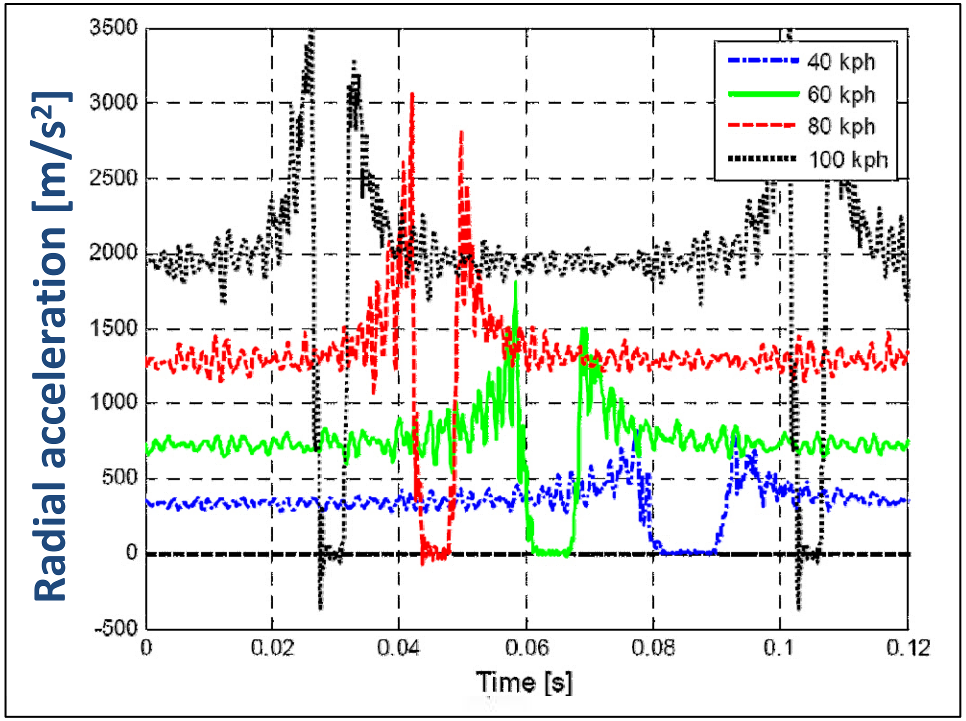




Source characteristics:

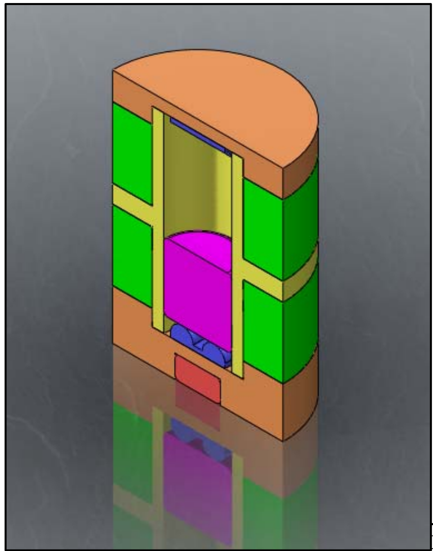
- Variations in the radial acceleration impose dynamic to a floating permanent magnet
- One-wheel-turn gives one pulse of energy



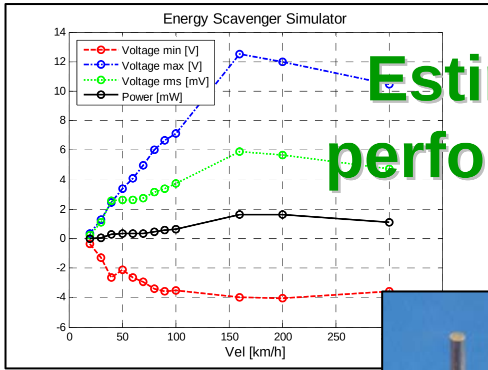


Simulated performance

Geometrical parameters



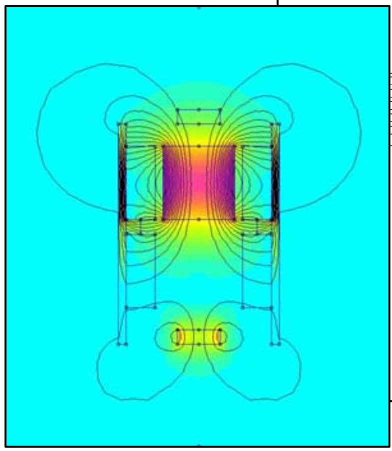
CAD

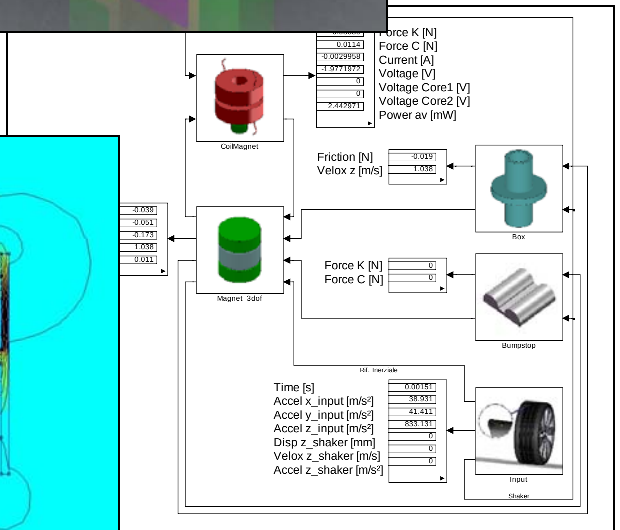


Estimated performance

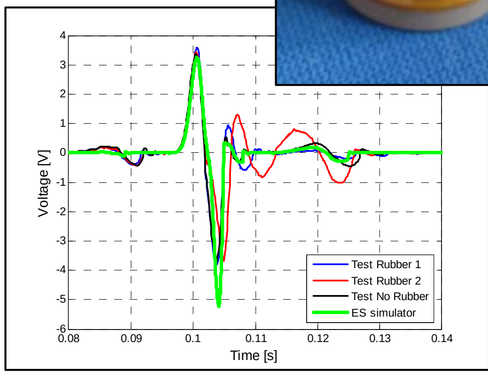
Prototype and tests

FEM



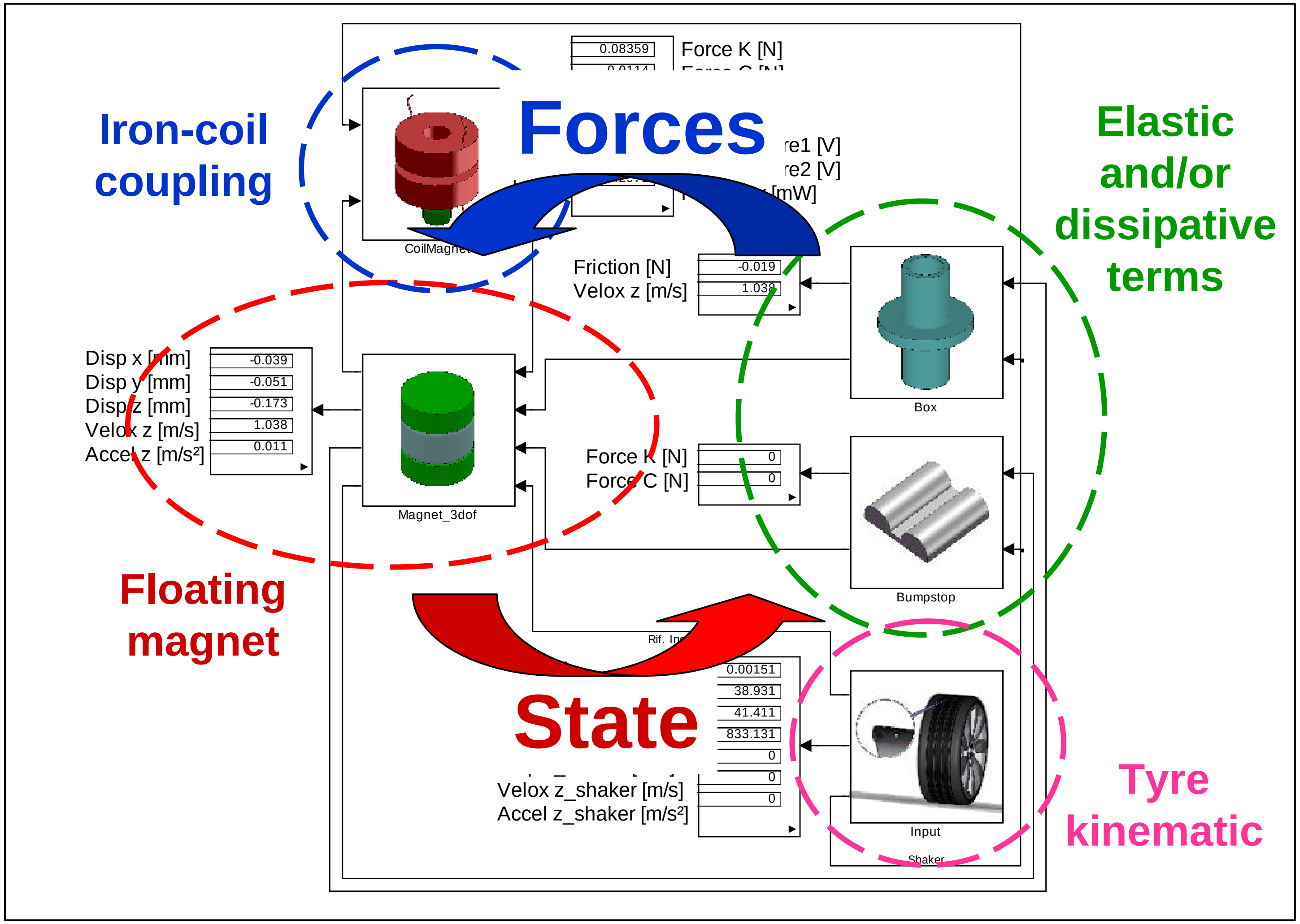


SIM

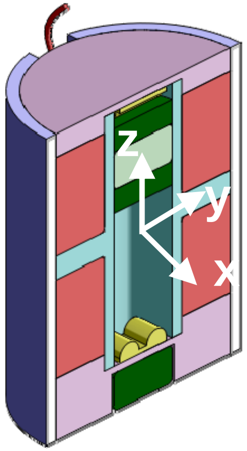


Comparison

Simulated performance



Modelling aspects



- Dynamic equilibrium of the floating magnet:

$$m\,\ddot{x} = F_x^C$$
$$m\,\ddot{y} = F_y^C$$
$$m\,\ddot{z} = F_z^C + F^{fric} + F^{bump} + F^{air} + F^{em}$$

- from Pirelli exp.

$$F_x^C = -m\,g\,\tilde{\ddot{x}}$$
$$F_y^C = -m\,g\,\tilde{\ddot{y}}$$
$$F_z^C = -m\,g\,\tilde{\ddot{z}}$$

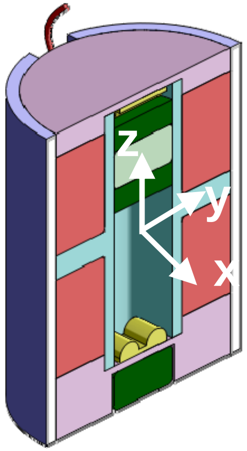
- Rubbery bumpers

$$\begin{aligned} F^{bump} &= -k\,(z - z_{\lim}) - c\,\dot{z} && \text{if } z > +z_{\lim} \vee F^{bump} < 0 \\ &= 0 && \text{if } -z_{\lim} \le z \le +z_{\lim} \\ &= -k\,(z + z_{\lim}) - c\,\dot{z} && \text{if } z < -z_{\lim} \vee F^{bump} > 0 \end{aligned}$$

- Adhesion and friction

$$\begin{aligned} F^{fric} &= -f(\dot{z})\,\mathrm{sign}(\dot{z}) && \text{if } x = \pm x_{\lim}\ ,\ y = \pm y_{\lim} \\ &= 0 && \text{if } -x_{\lim} < x < +x_{\lim} \vee -y_{\lim} < y < +y_{\lim} \end{aligned}$$

Modelling aspects

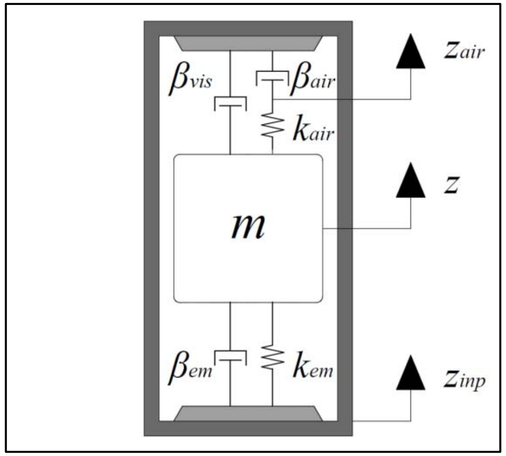


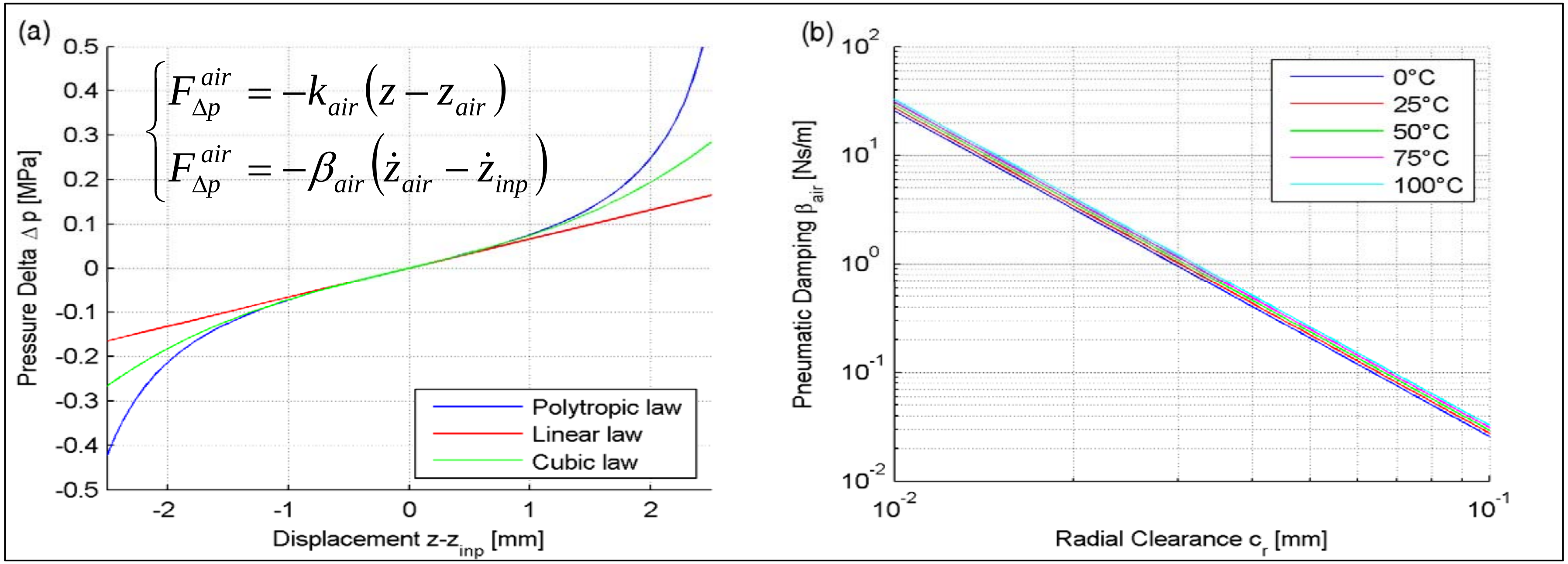
- **Pneumatic effects**

$$F^{air} = F^{air}_{\Delta p} + F^{air}_{vis}$$

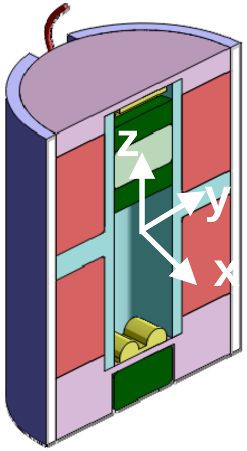
$$F^{air}_{\Delta p} = \frac{\pi d^2}{4}\left(p_2 - p_1\right)$$

$$F^{air}_{vis} = -\beta_{vis}\left(\dot{z} - \dot{z}_{inp}\right) = -\frac{\pi \mu d h}{c_r}\left(\dot{z} - \dot{z}_{inp}\right)$$





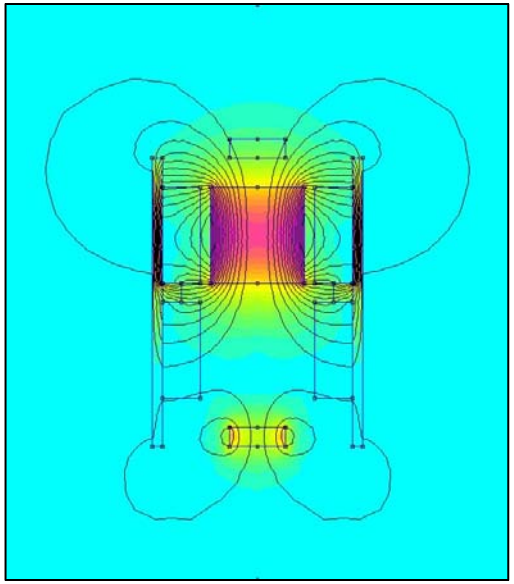
Modelling aspects



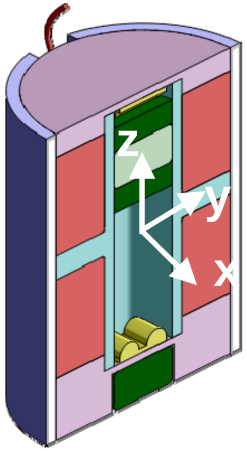
- Dynamic equilibrium of the floating magnet:

$$m\,\ddot{x} = F_{c,x}$$
$$m\,\ddot{y} = F_{c,y}$$
$$m\,\ddot{z} = F_{c,z} + F_{em} + F_{fric} + F_{bump}$$

- Electro-magnetic coupling from FEM



$$F_{em} = F_{em,k} + F_{em,c}$$
$$F_{em,k} = F_{em,k}(z)$$
$$F_{em,c} = e\,\frac{i}{\dot{z}} = -N\,\frac{d\phi}{dt}\,\frac{i}{\dot{z}} = -N\,\frac{d\phi}{dz}\,i$$
$$L\frac{di}{dt} + (R+R_l)\,i + \frac{1}{C_l}\int_0^t i\,d\tau = e$$



- Dynamic equilibrium of the floating magnet:

$$m\,\ddot{x} = F_{c,x}$$

$$m\,\ddot{y} =$$

$$m\,\ddot{z} =$$

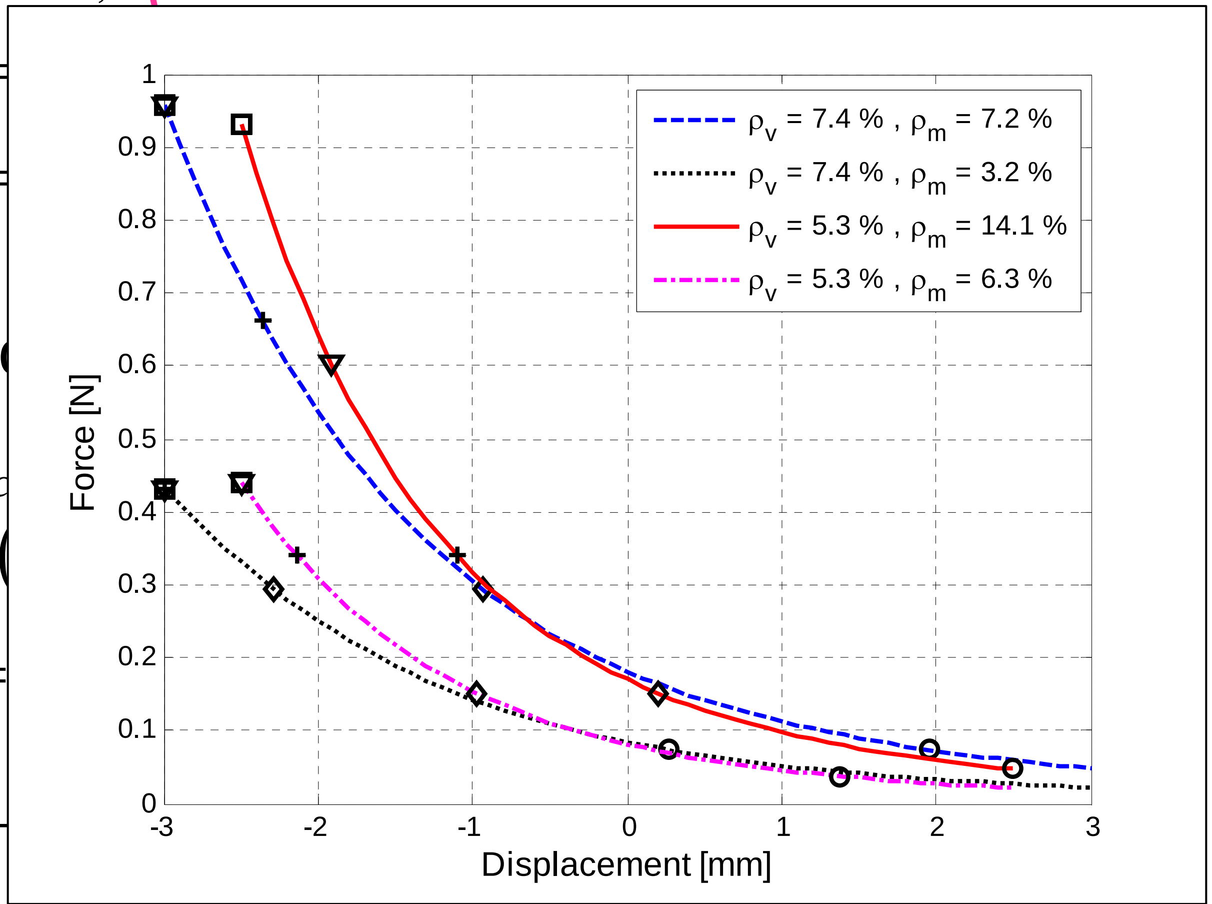
- Electro-magnetic

$$F_{em} = F_{em,k} + F_{em,c}$$

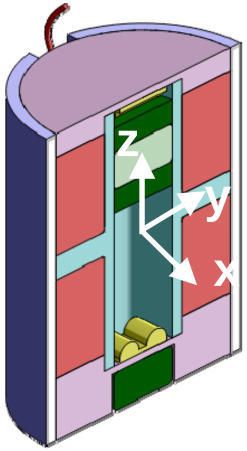
$$F_{em,k} = F_{em,k}\Big($$

$$F_{em,c} = e\,\frac{i}{\dot{z}} =$$

$$L\frac{di}{dt} + \left(R + R_l\right) i +$$



Modelling aspects



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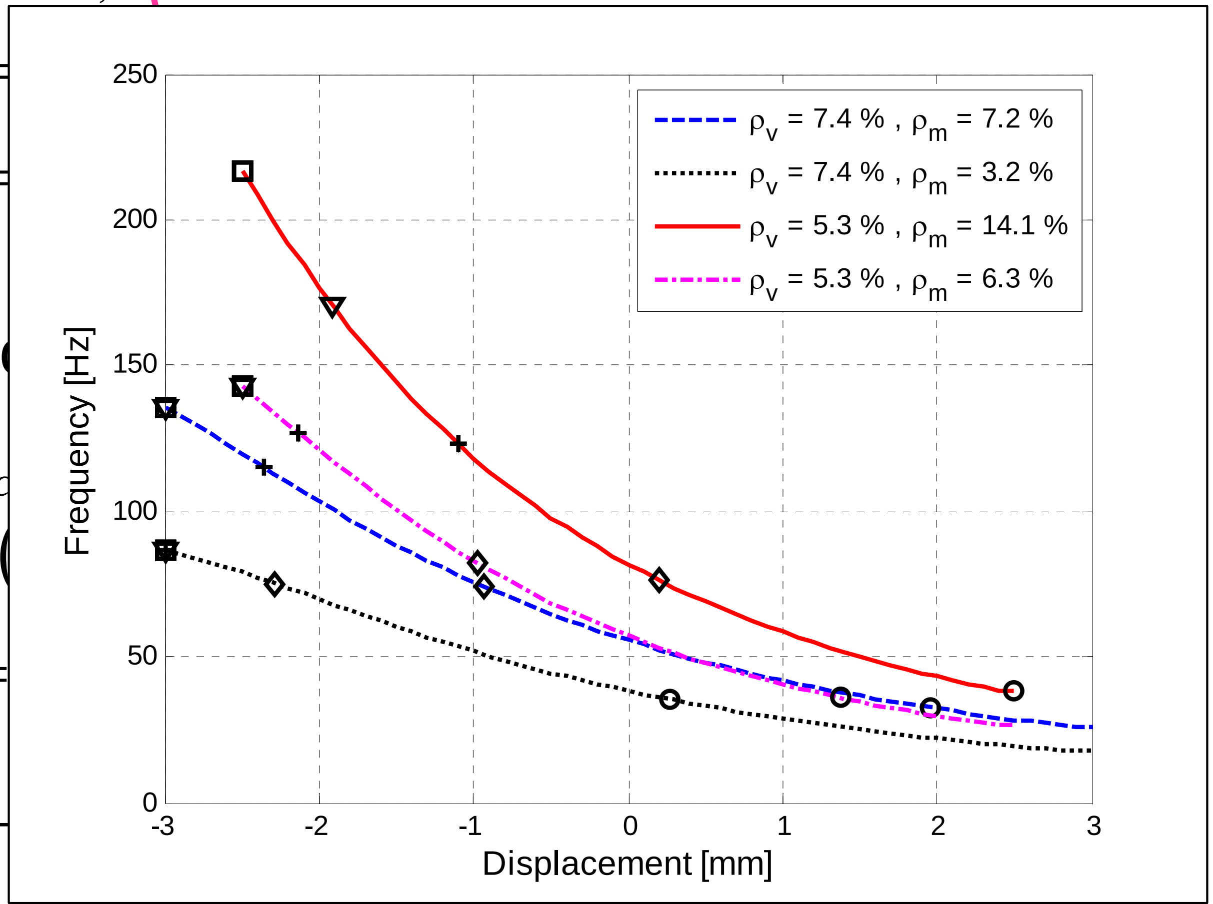


- Electro-magnetic

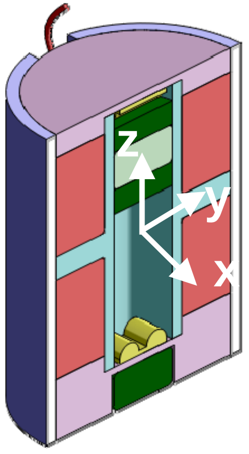
$$F_{em} = F_{em,k} + F_{em,c}$$

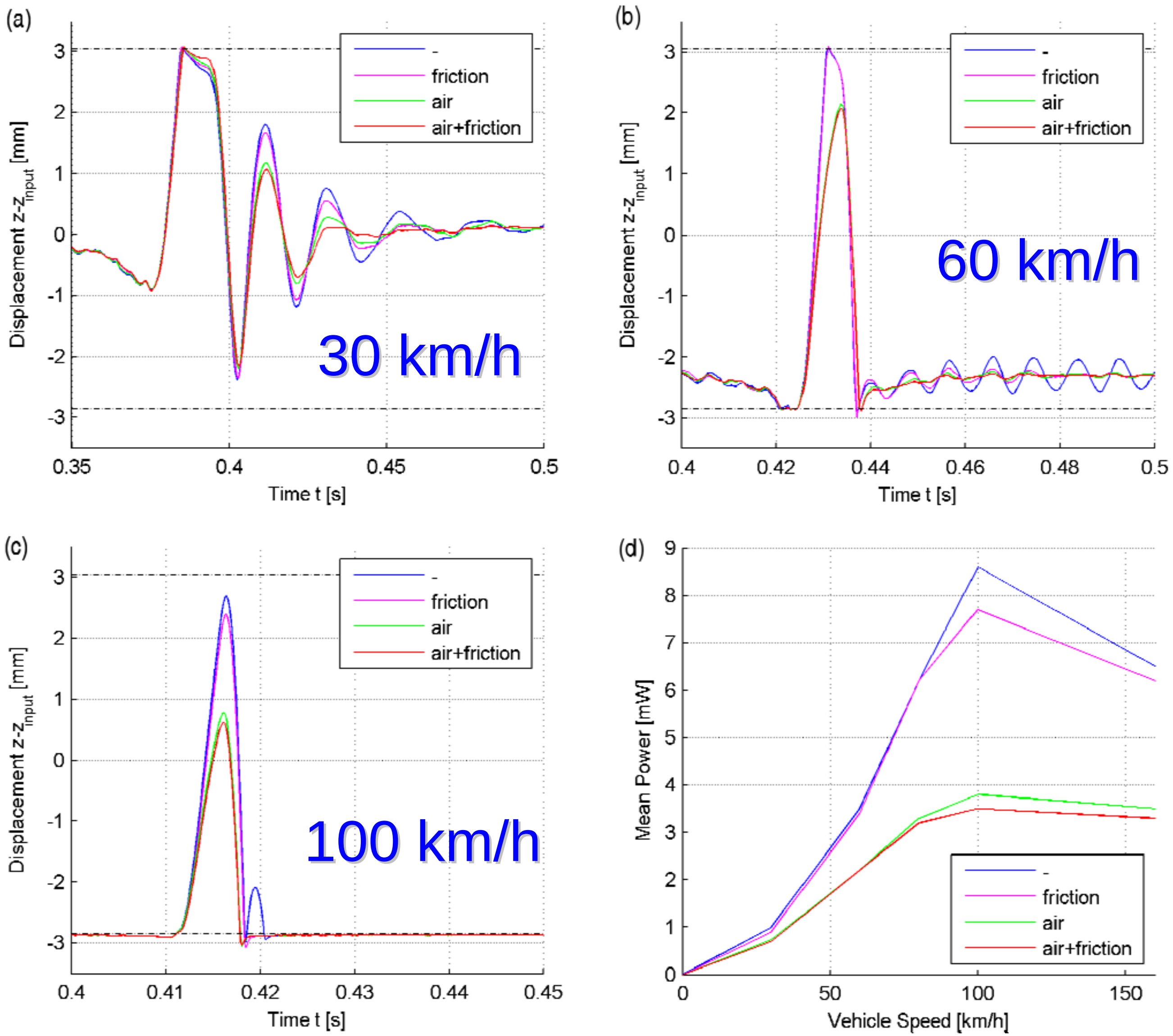
$$F_{em,k} = F_{em,k}\big($$

$$F_{em,c} = e\,\frac{i}{\dot{z}} =$$

$$L\frac{di}{dt} + \left(R + R_l\right) i +$$

Comparison of dynamics

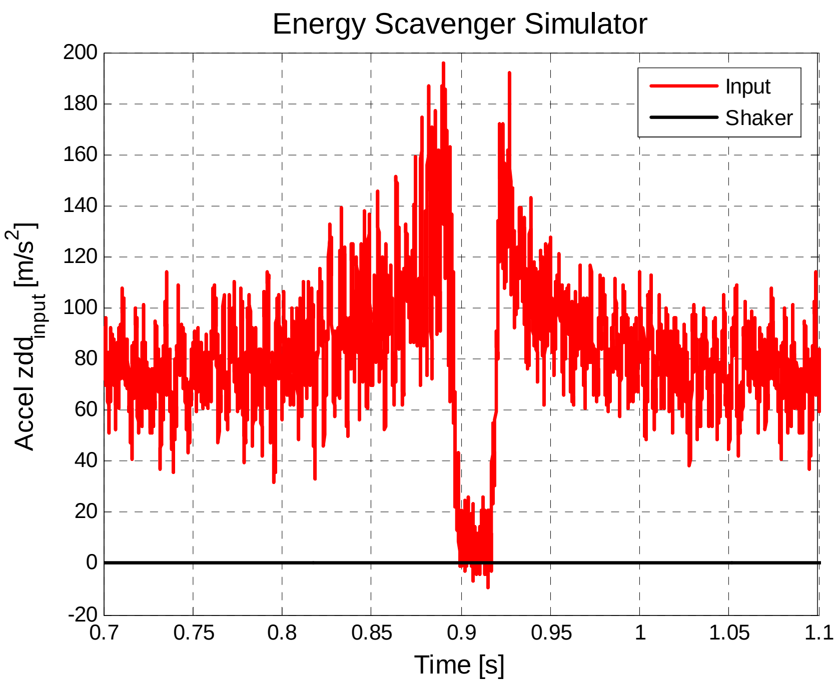


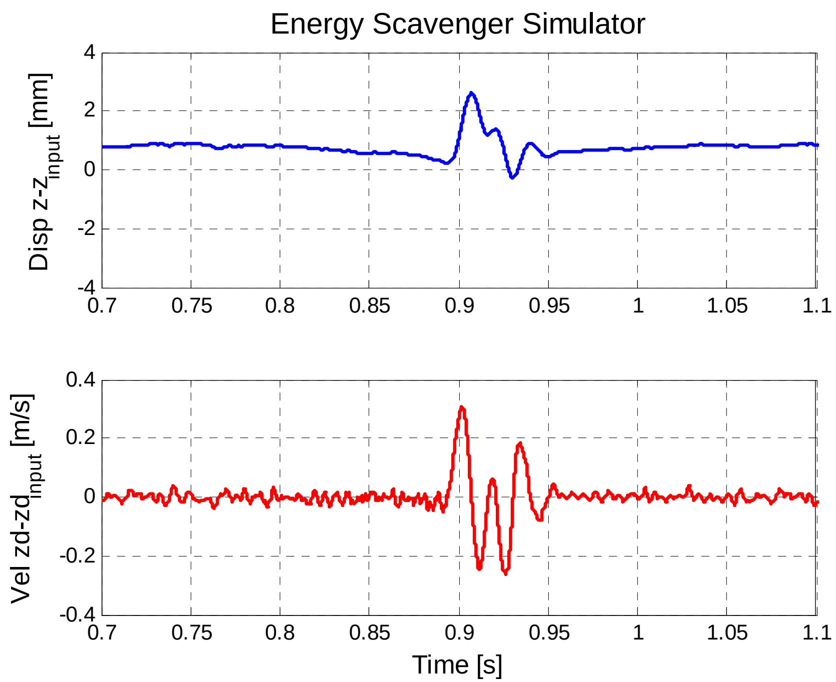


Simulated performance

Velocity of 20 km/h → not working …

- ***Magneto-elastic preload confines magnet displacement to no dynamic***
- ***Electric-magnetic coupling is close to be null***

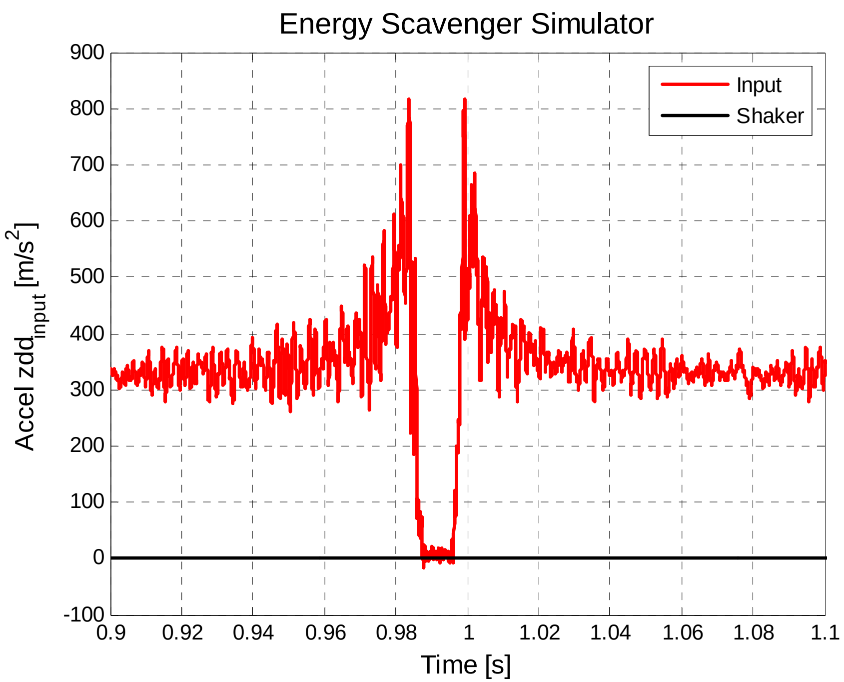


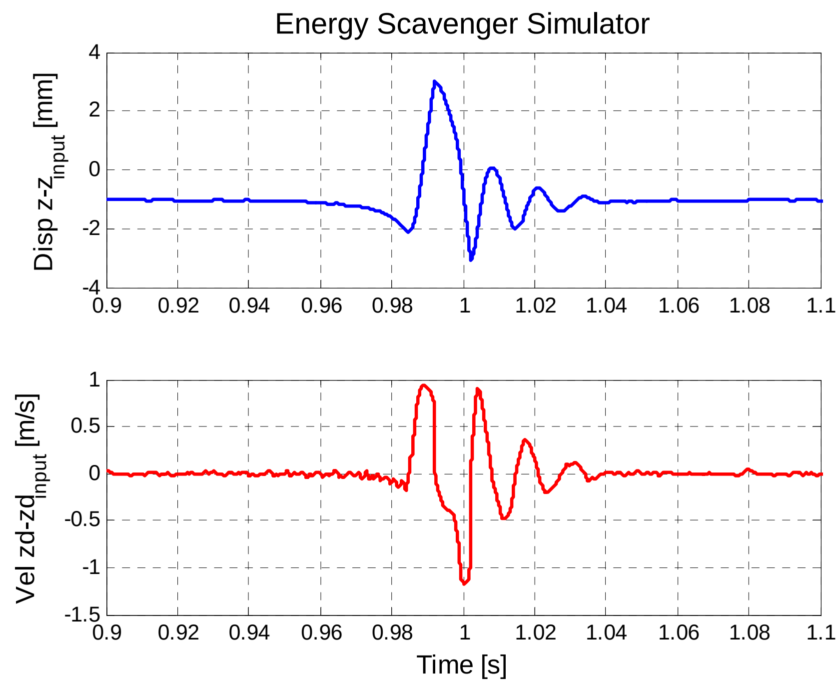


Simulated performance

Velocity of 40 km/h → full operative condition

- *Wide amplitude resonant motion*
- *Electric-magnetic coupling is equivalent to a viscous damping effect*

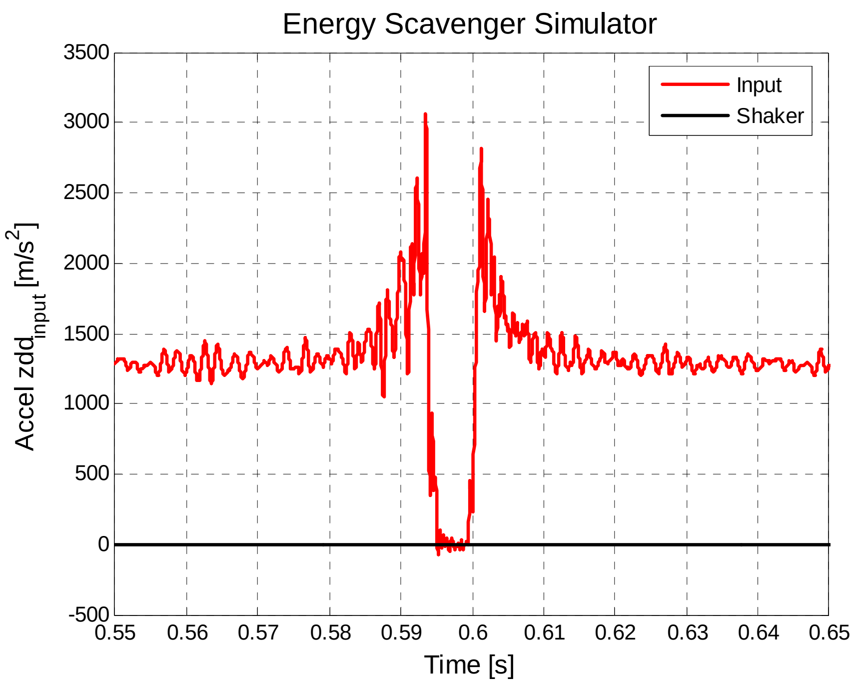


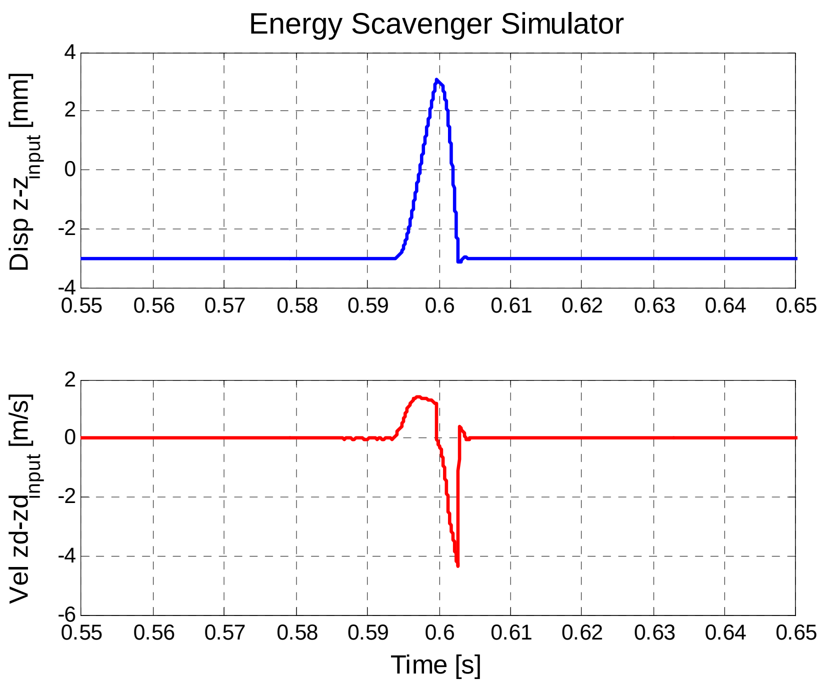


Simulated performance

Velocity of 80 km/h → full operative condition

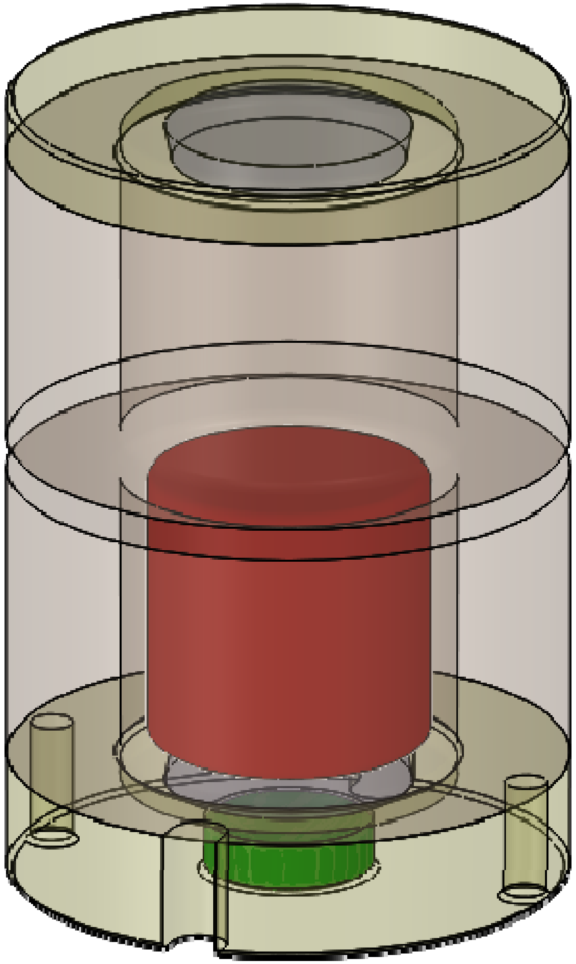
- ***Magnet presents an impulsive dynamic***
- ***Electric-magnetic coupling maintains a good power flow***
- ***At higher speed the power reduces because the moving mass does not have the time to reach the upper bumper***



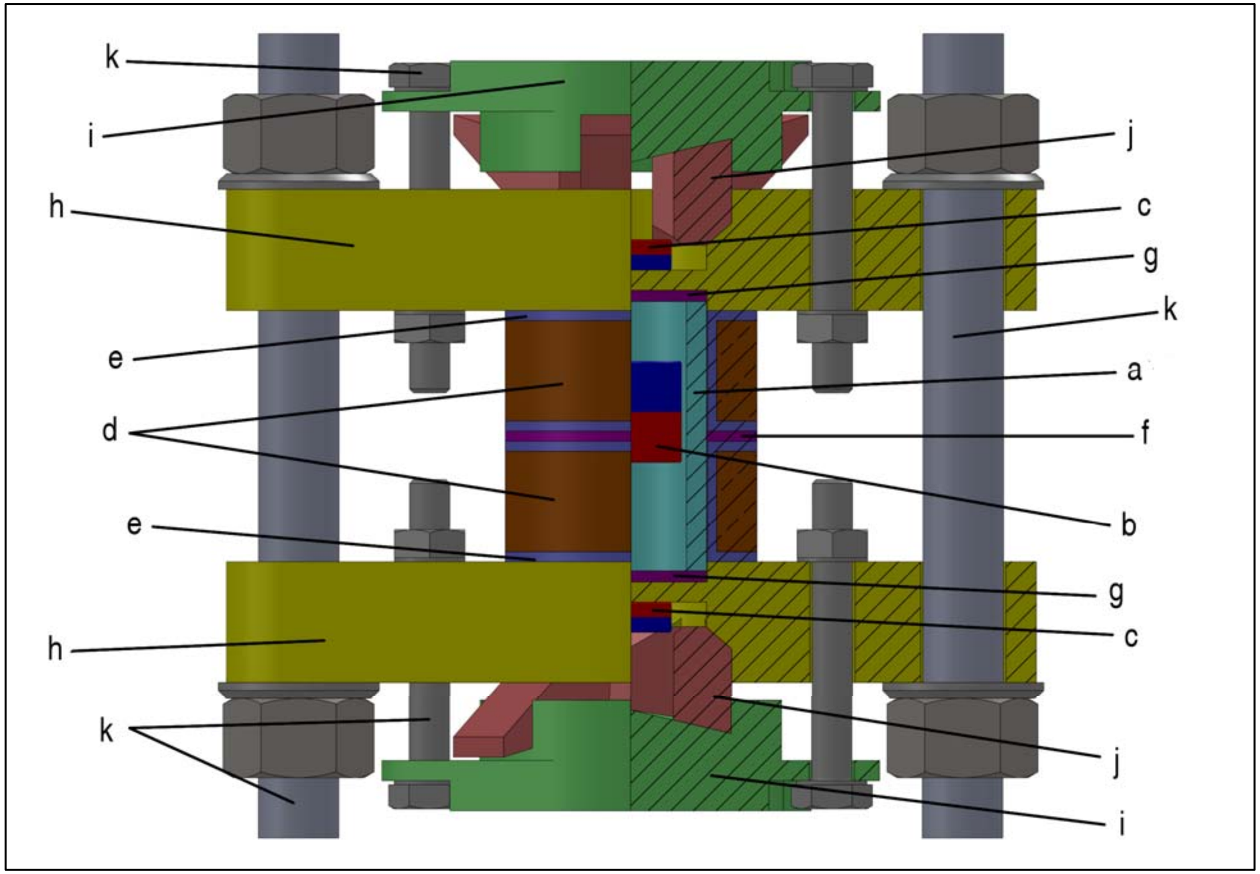


Device behaviour

20 km/h



Prototypes



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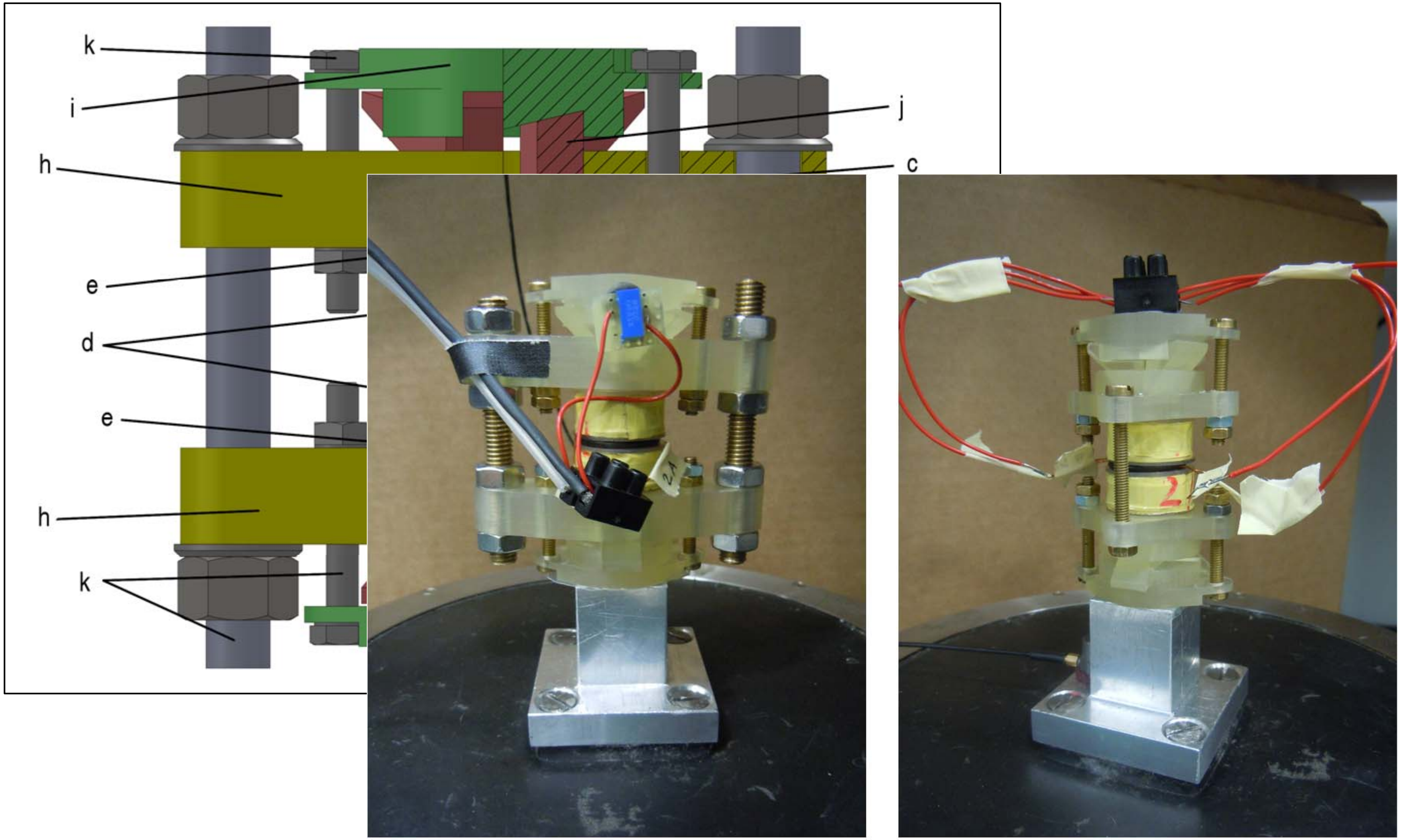
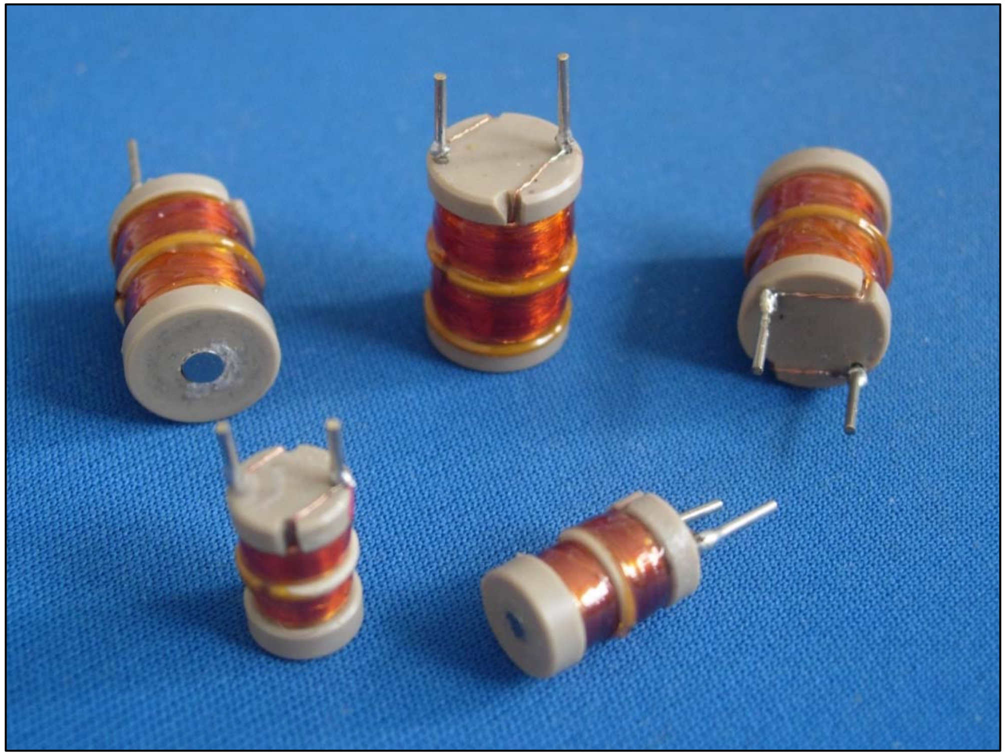
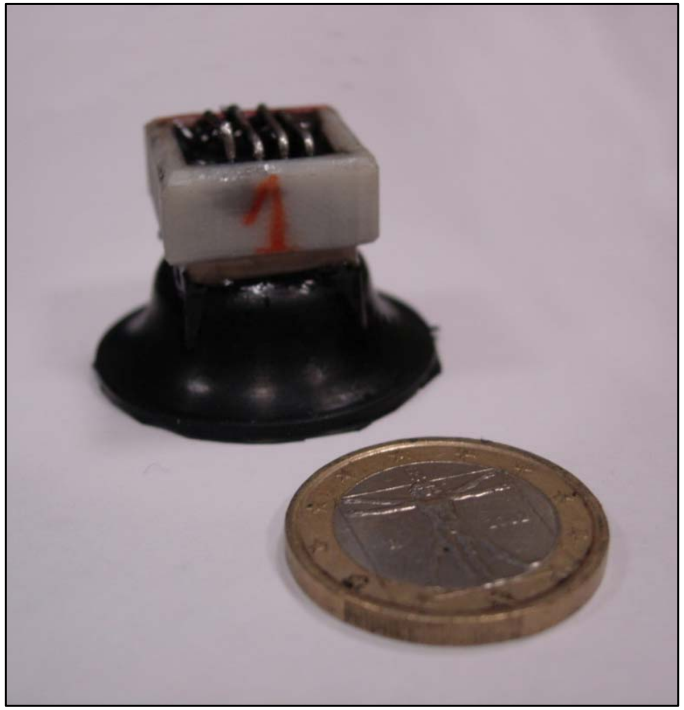


(a) (b)

Prototypes



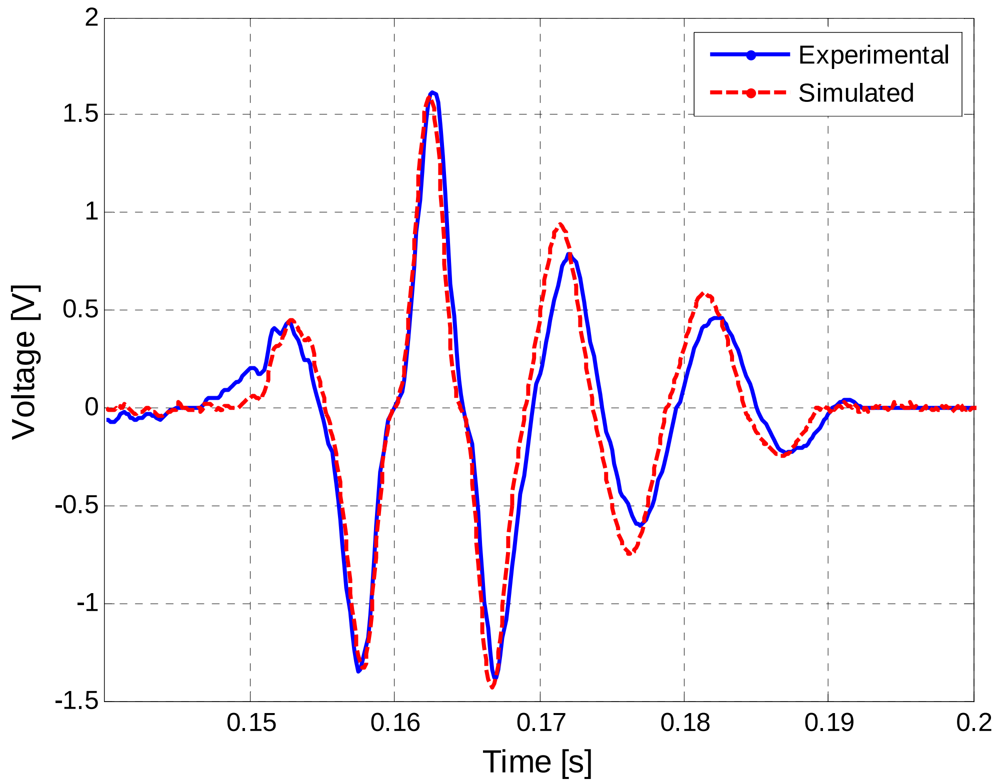


Test on shaker:

- ***Resonance detection and nonlinearity weight***
- ***Tests with sinusoidal and road profiles***

- ***Test with adapted load $R_l = 2 \times 210\ \Omega$:***

- ***road profile accelerations without radial component 60 km/h***



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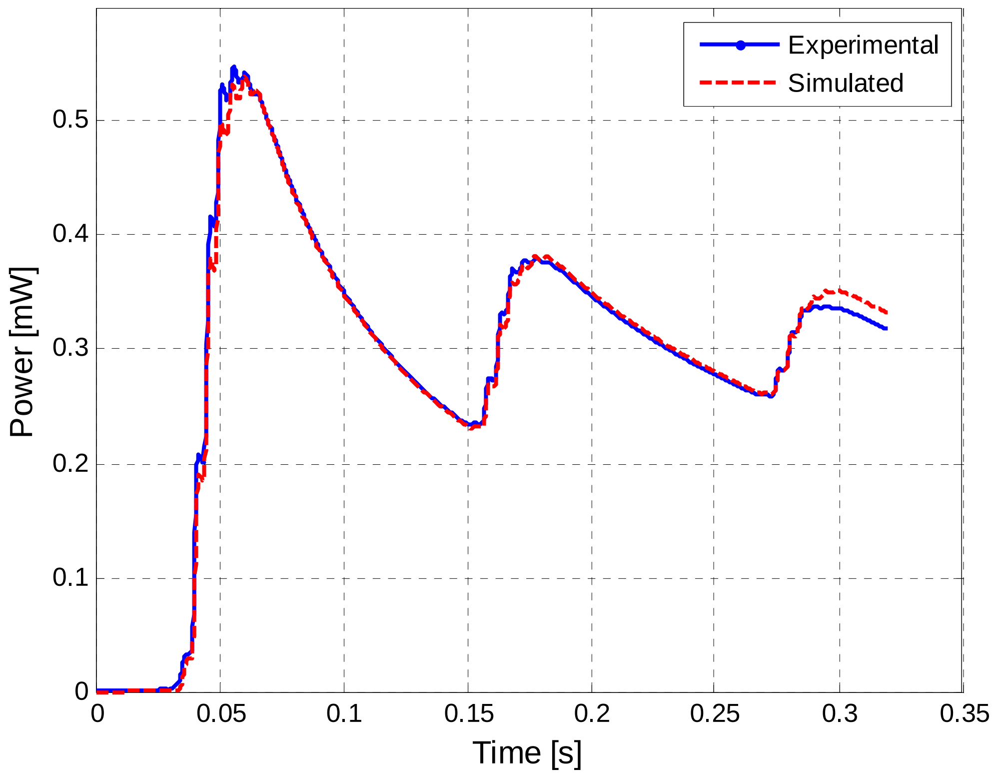
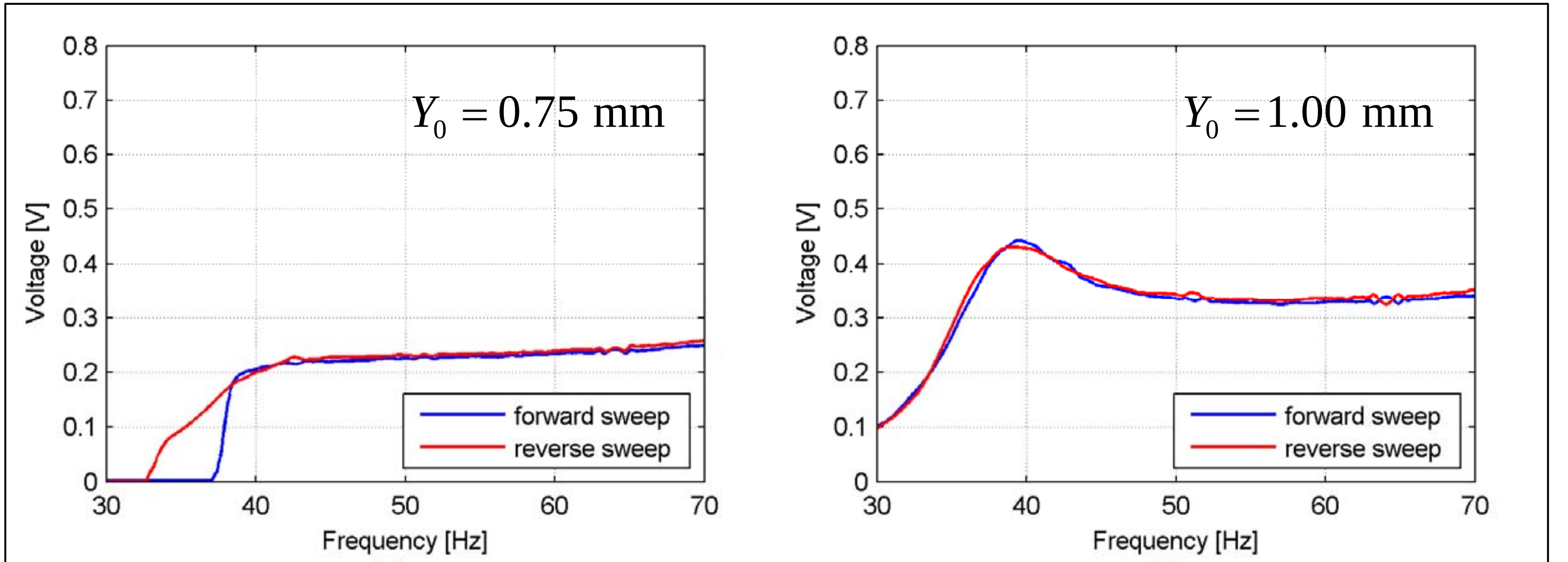


Experimental comparison



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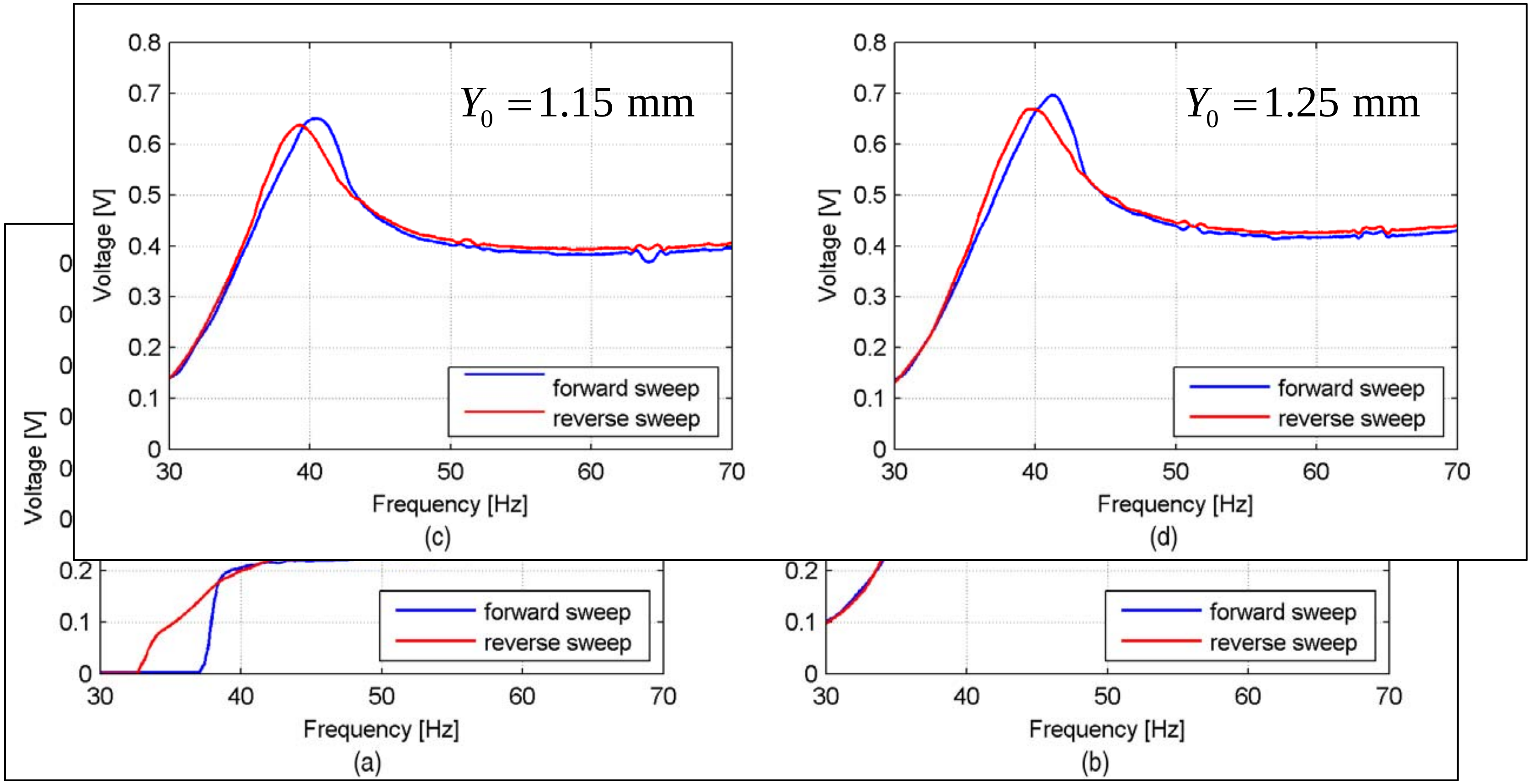

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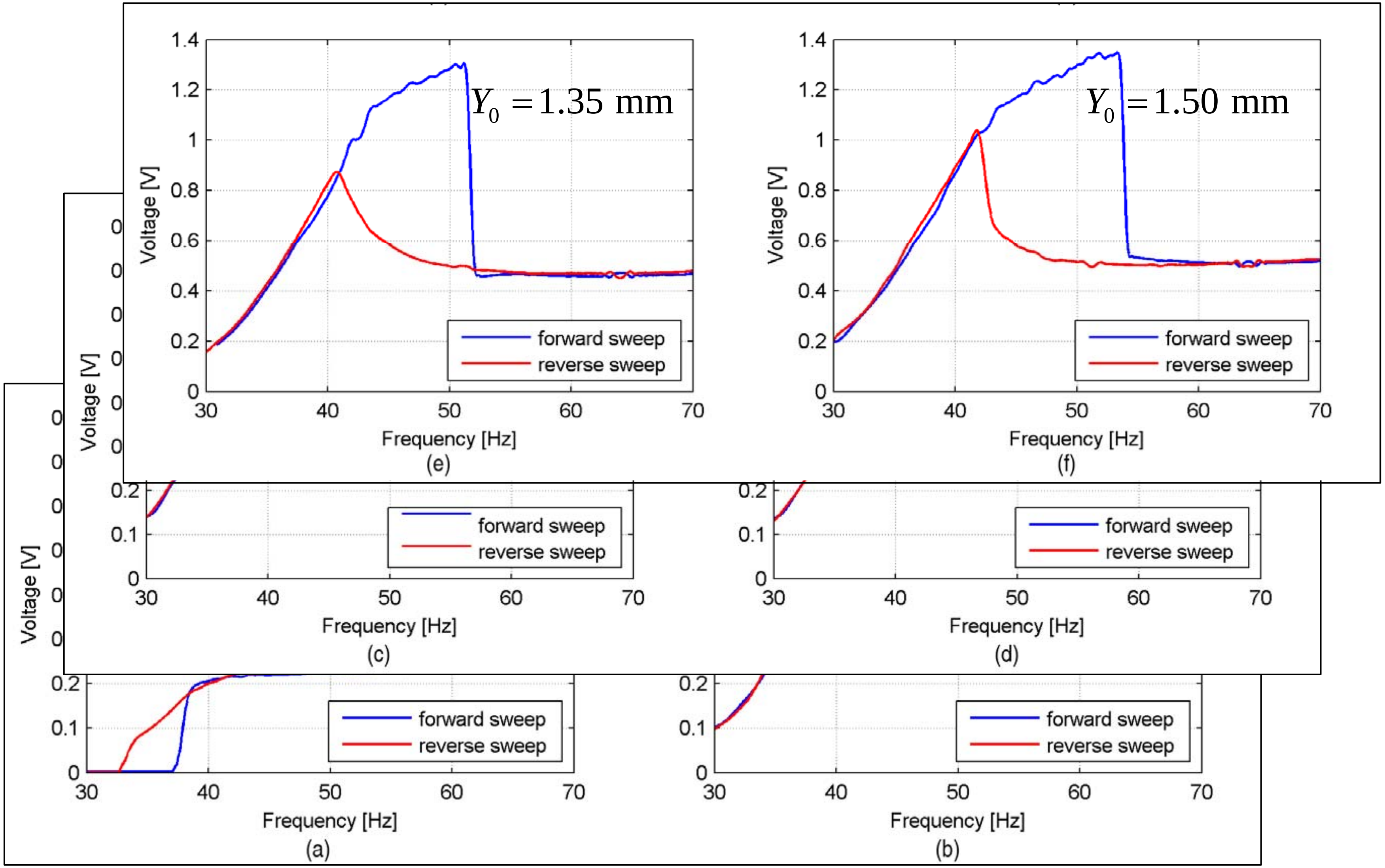
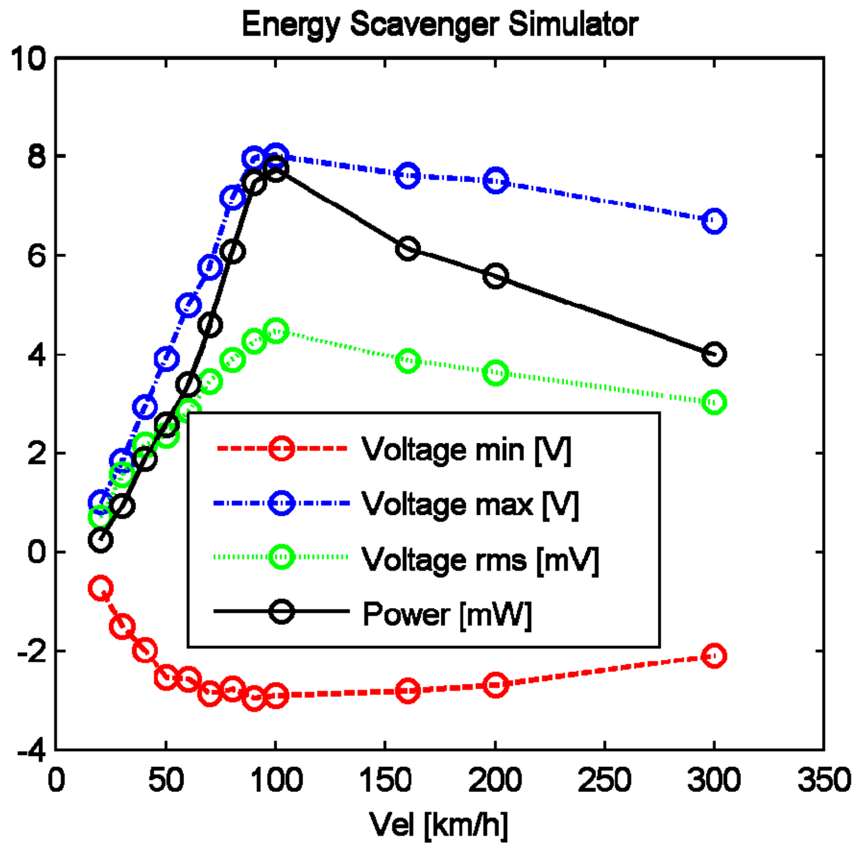


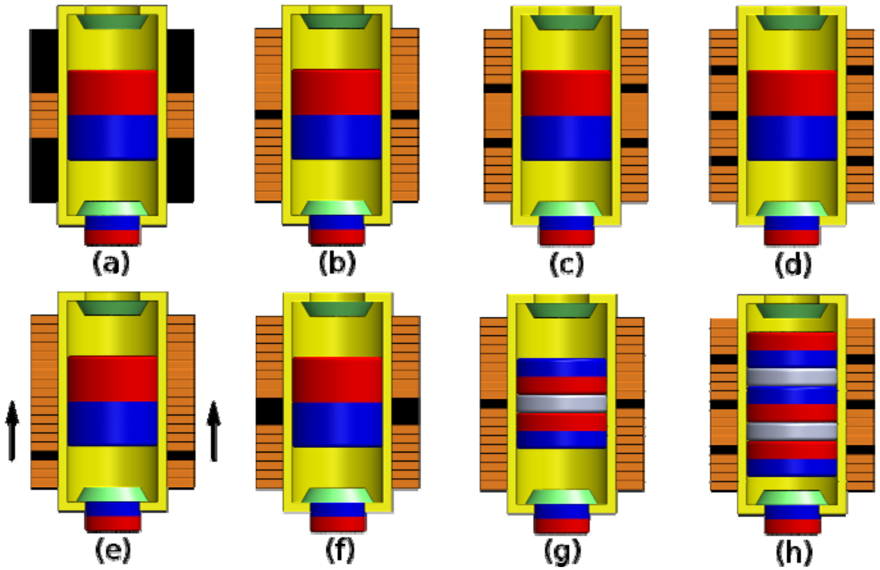
Goals:

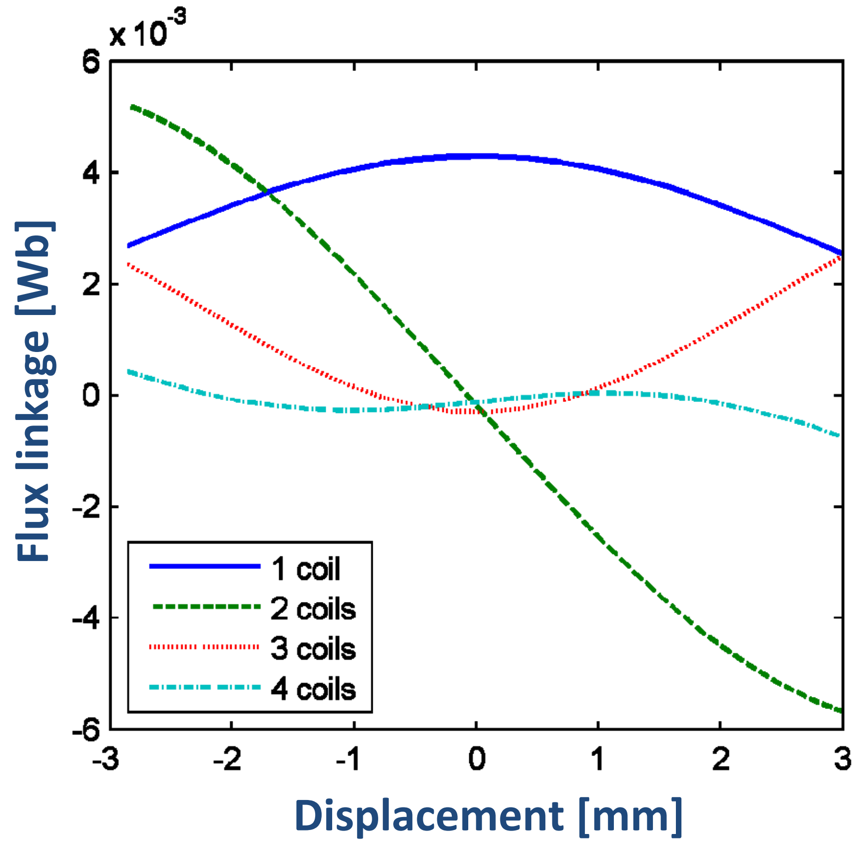
- *Verifying that the topology is optimal*
- *Improving the performance at low speed*
- *Optimization of components "weights"*



Coils optimization

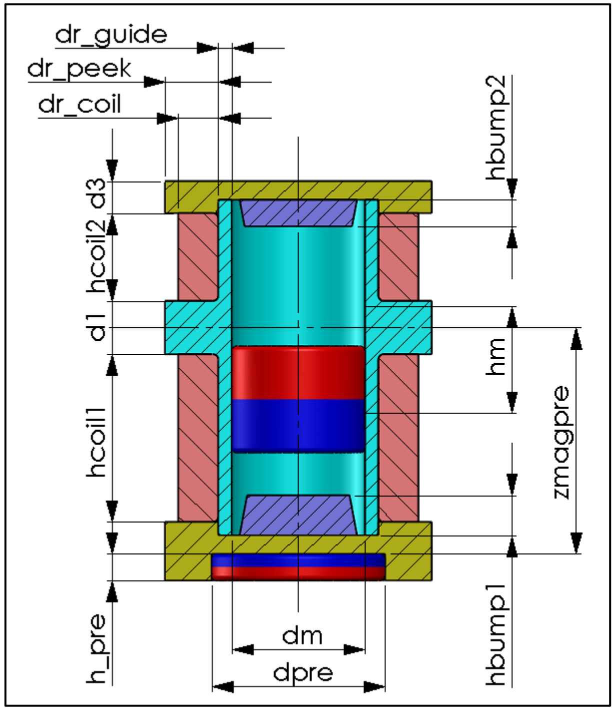
- *Multiple coils configurations*
- *Two (or more) spacers between coils*
- *One or more floating magnets*

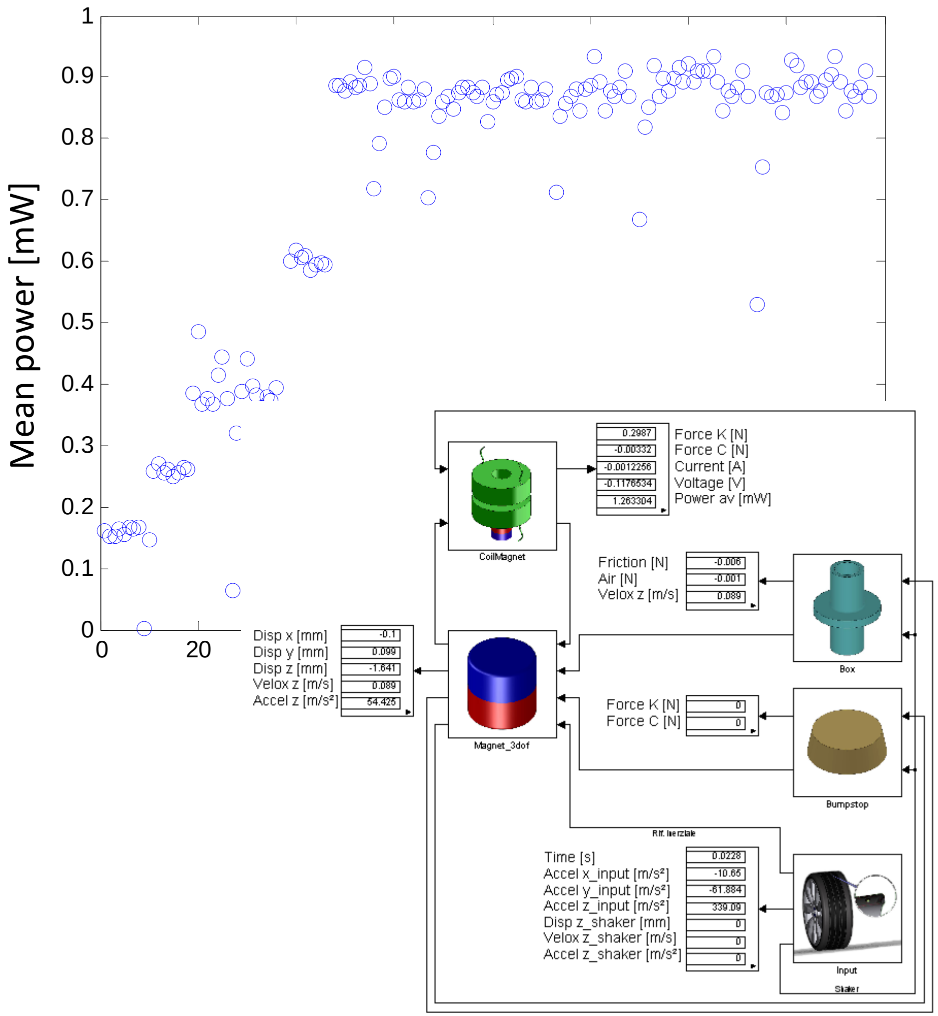




Global optimization

- *Full parametric model*
- *Volume constraints*
- *Gradient or genetic algorithms*



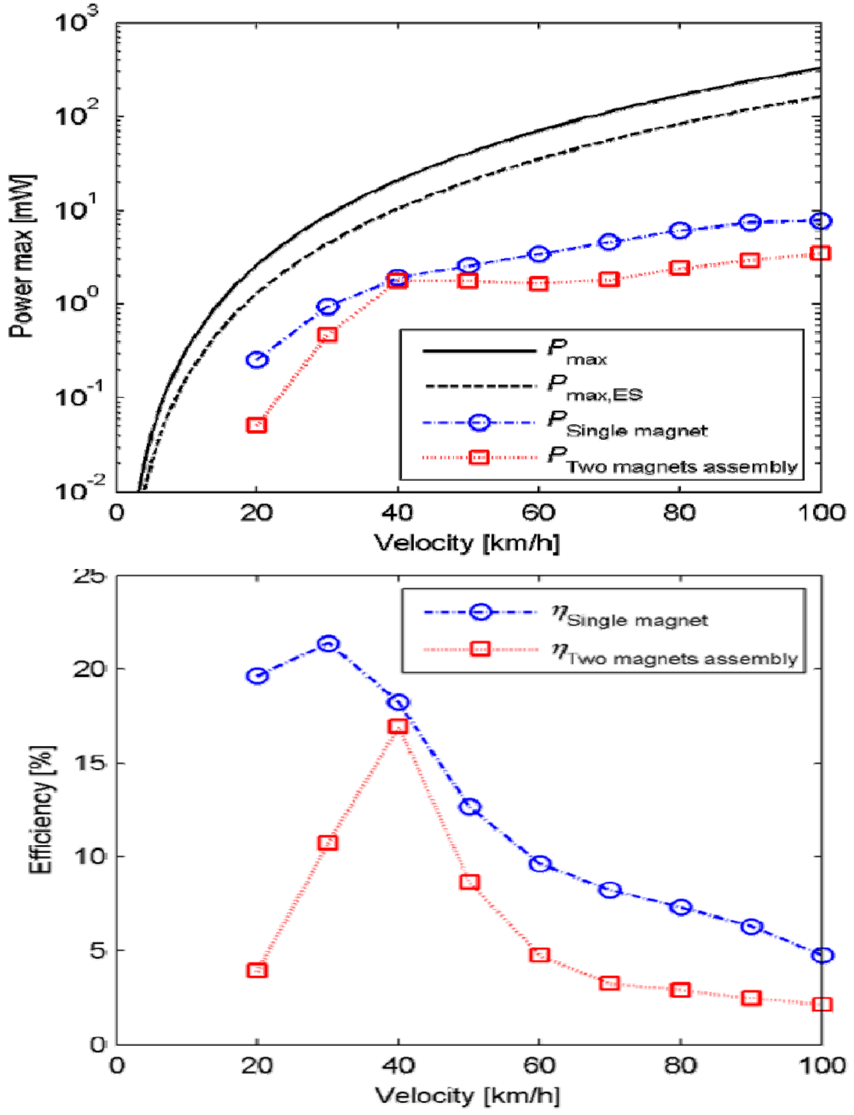


- ***Maximum available energy and power:***

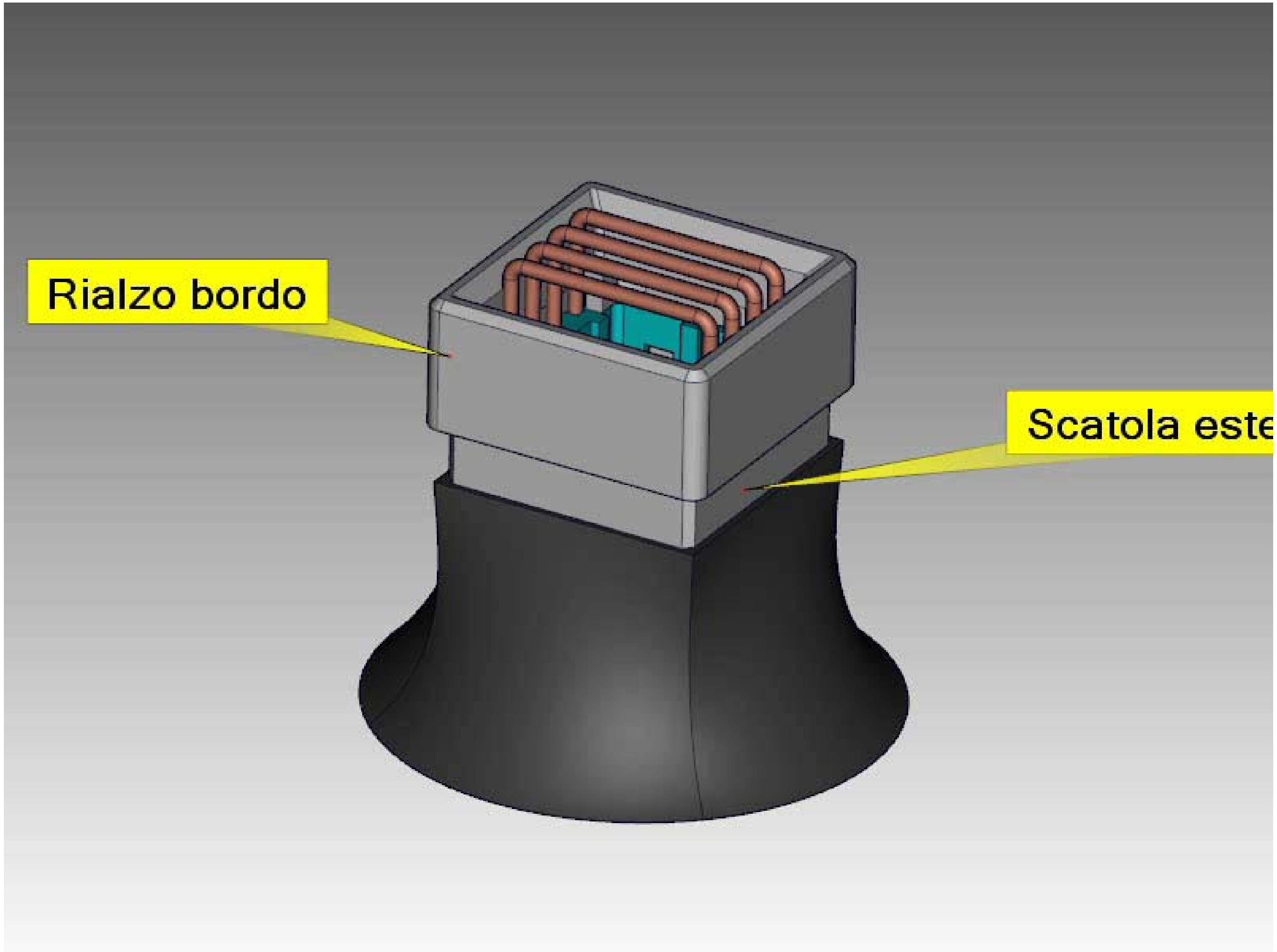
$$\Delta E_{\max} = L_{ext} = m \ \Delta a_r \ 2 \ s$$

$$P_{\max} = f \ m \ \Delta a_r \ 2 \ s = \frac{m \ s \ v^3}{\pi \ r^2}$$

- ***The system is more effective at low vehicle speed***



Work in progress …



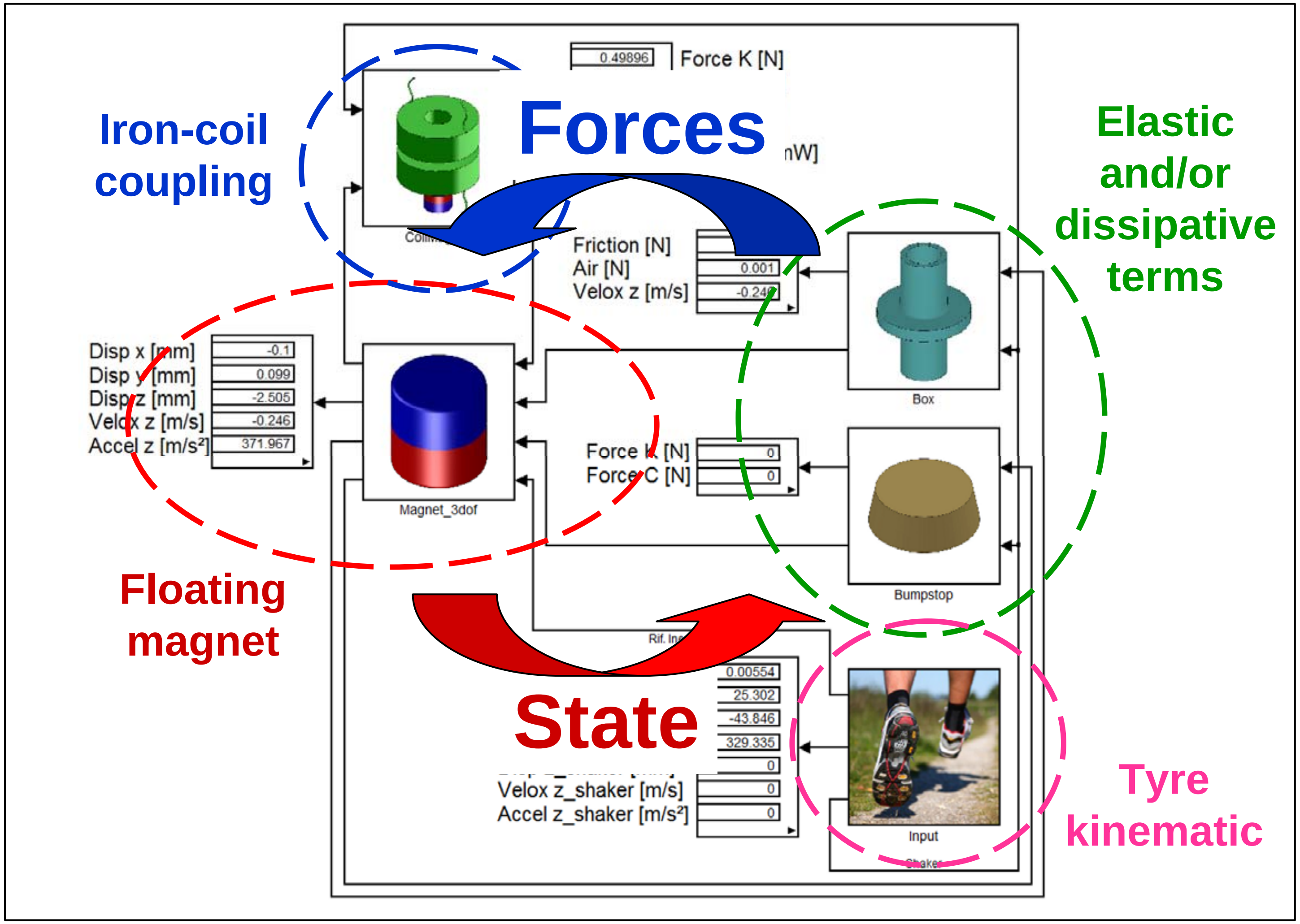
Work in progress …

PIRELLI

CYBER TYRE

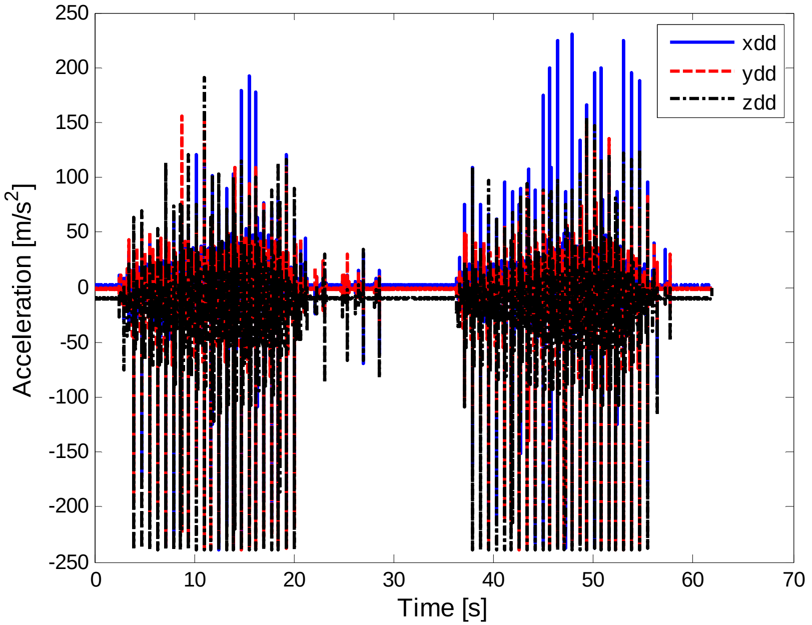
CYBER FLEET

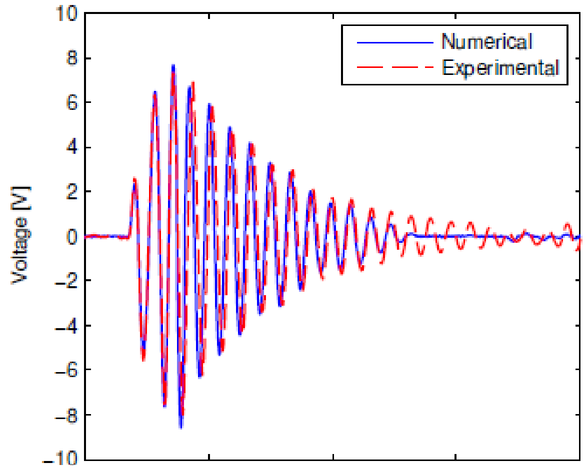
Simulated performance

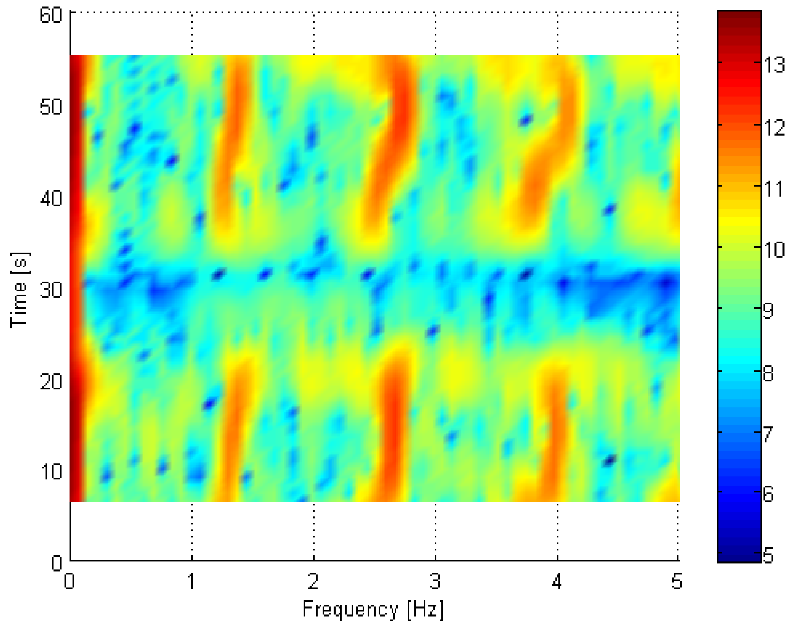


From tyre to … shoes

- *Time histories and frequency contents*

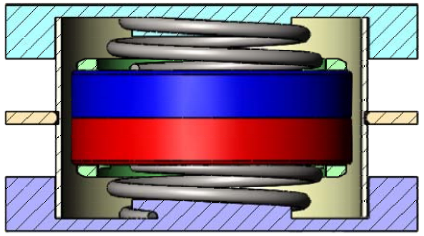


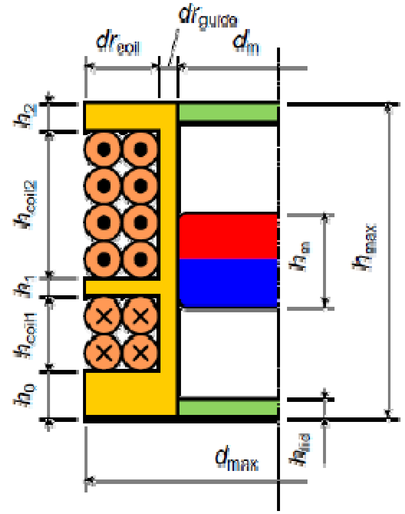


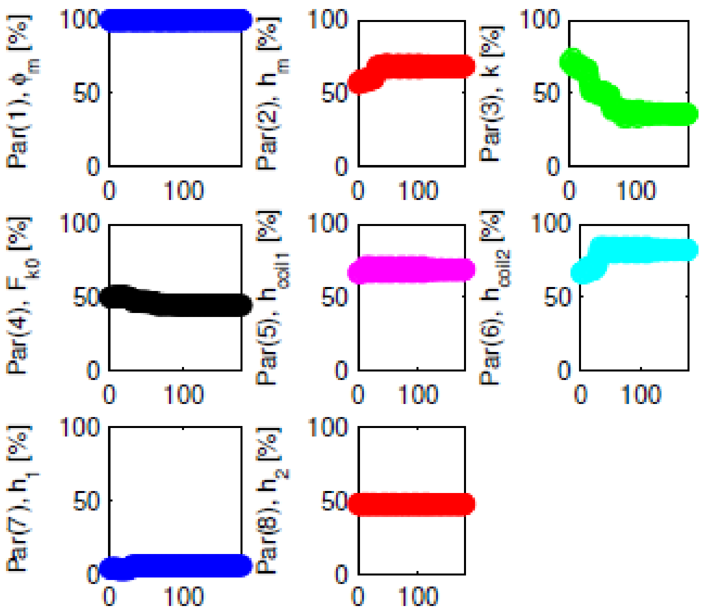


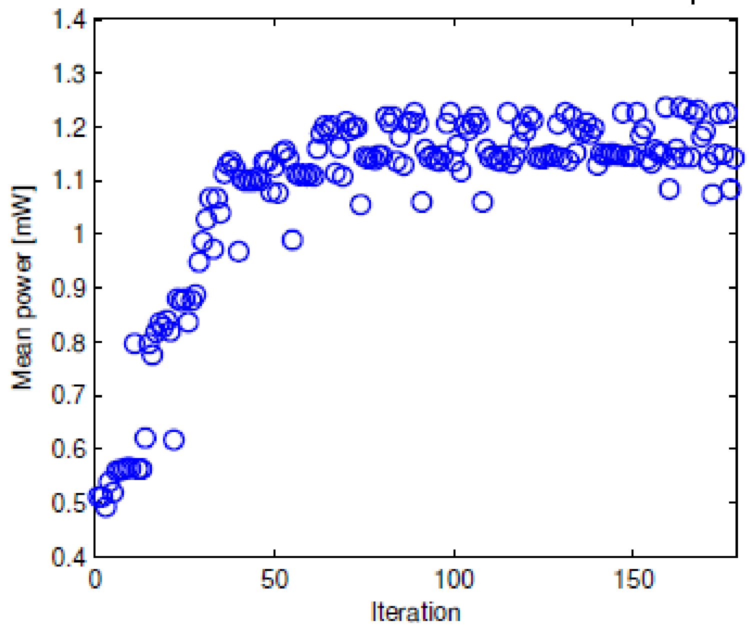
From tyre to … shoes

- *Optimization with conical springs*







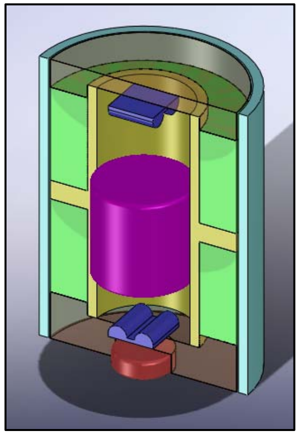


From tyre to … shoes

- ***Prototypes***

Energy Harvester for power supplier of wireless sensors

- Power density and suitability of sources
- Pirelli Cyber Tyre project
- Magneto-mechanical Energy Harvester
- Nonlinear dynamics, optimization and results
- From tyre to shoes and other device applications



Acknowledgements / People involved

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