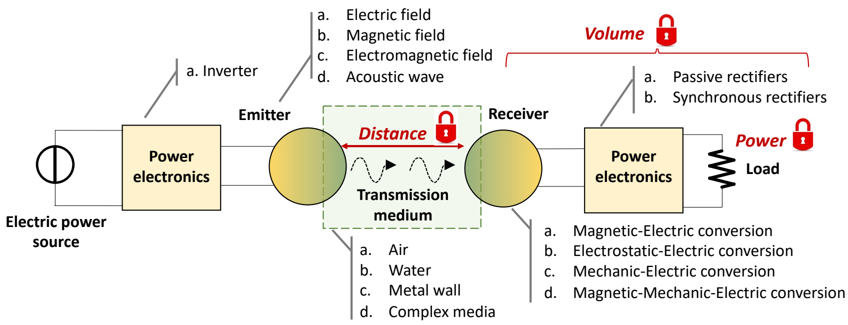
Low-frequency wireless power transfer based on nonlinear electromechanical antennas

Open PhD position in mechanical engineering and multiphysics

Context

Wireless power transfer (WPT) systems are used to transfer electrical energy without cables from a transmitter to a receiver to power an end-device (e.g., sensors, actuators, or low-power processing units). Such systems are particularly relevant for powering Internet of Things (IoT) devices when using cables appear too costly, complex, or hazardous [1]. The generic structure of a WPT system is shown in Fig.1. As depicted, the emitter converts electrical energy sent from the source to an intermediate form of energy (i.e., magnetic, mechanical, radiative, electrostatic …), in the aim of wirelessly transferring this energy through a transmission medium (i.e., air, metal, water …). On the receiver side, the energy is converted back to electricity to supply the load.



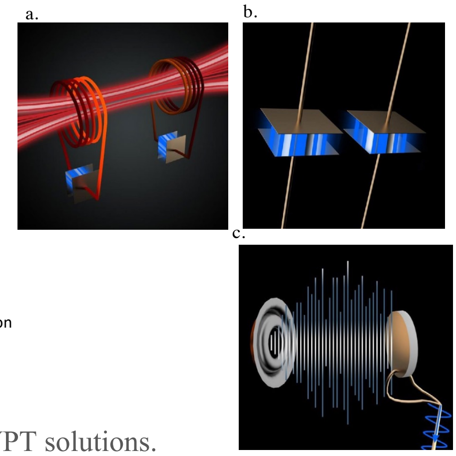


Fig.1 – Generic structure of a WPT system, and examples of WPT mechanisms [1]: a. inductive, b. capacitive and c. acoustic WPT solutions.

Various modern applications involve powering systems through conductive media, such as water, metal walls and boxes, and biological tissues. As an example, **implantable biomedical sensors and actuators developed for modern medicine purposes** (e.g., insulin pumps, glucose sensors, artificial neurotransmitters) require transmitting power through the human body, which is a complex medium mainly composed of water, and eventually through the package of the sensor which can be metallic and therefore conductive. In such applications, the **high frequency of traditional WPT systems has many drawbacks**: high absorption by the conductive media (water of the human body, metallic shell around the sensor) due to eddy currents leading to poor transmission distance and power, radiation hazard due to human tissue absorption of the high-frequency magnetic waves, large increase of the receiver size required to decrease the resonant frequency, etc. As an illustration, a 1mm thick aluminum sheet attenuates the amplitude of a 1MHz electromagnetic wave by a factor of about 10^6.

Objectives

ONEFOLD project, supported by the French national research agency, under grant number ANR-23-CE51-0007, aims at exploring an emerging solution for power transmission at very low frequencies, based on Electrodynamic wireless power transfer. Figure 2 illustrates an electrodynamic WPT system, where the emitter consists of a transmitting coil powered by a low-frequency current that generates a low-frequency (<100 Hz) magnetic field that is weakly absorbed by conductive media. This magnetic field sets in motion a moving magnet attached to a mechanical resonator with a low resonant frequency. The oscillation of this resonator is converted back into electrical energy using, for instance, a piezoelectric transducer. Electrodynamic WPT solutions offer high power density and low-frequency (50-1000 Hz) WPT options and are particularly effective for transmitting power through conductive media. They can achieve ten to hundreds of times higher power density than state-of-the-art low-frequency inductive WPT solutions for greater transmission distances through conductive media [2, 3].

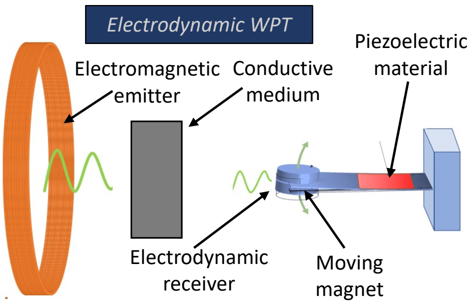


Fig.2 – Electrodynamic WPT system

In ONEFOLD, we propose to explore, size and optimize **nonlinear electromechanical receiver** for converting the magnetic field back to electricity. Nonlinear resonators will optimize receiver operation at **ultra-low frequencies**, with **small volumes** and low sensitivity to frequency shifts. **Various exotic behaviors** emerging due to the receiver nonlinearity, such as **superharmonics** regimes, **chaos**, or **softening resonances**, could be further exploited to design optimized receiver and propose new openings for efficient wireless power transfer through conductive media.

Objective 1 – **Explore nonlinear dynamics to maximize power transmission to nonlinear receivers.** We aim to investigate, both theoretically and experimentally, how nonlinear behaviors and resonances can be leveraged to maximize the power density of nonlinear receivers. In the first part of the project, we will analyze how various resonances and orbits of bistable nonlinear resonators can be exploited to achieve this goal. In the second part of the project, we will explore how other types of nonlinearities can be engineered to maximize the receiver power density. Fundamental questions, such as the relevance of exploiting nonlinear resonances, the optimality of softening and superharmonic behaviors, and the optimal potential well shapes for maximizing power density, will be answered.

Objective 2 – **Design and fabricate high power-density (>10 mW/cm^3) receivers for wirelessly transmitting power (10 mW – 1 W for distances between 1 cm to 30 cm) through conductive media at near-DC frequencies (< 20 Hz), with system-level constraints.** We will design and fabricate optimal receivers based on a global electromechanical optimization of the whole system, using nonlinear reduced-order models. This optimization will identify optimal geometrical dimensions for the resonator, the optimal emitting waveform, and the optimal circuitry connected to the receiver. To implement the optimal nonlinear resonator and shape its potential wells, we will fabricate new nonlinear prototypes based on mechanical buckling of beams or magnetic interactions. Finally, the optimal solutions proposed in this project will be compared against traditional WPT technologies described in the literature.

The long-term objective is to pave to way to a new category of nonlinear electrodynamics receivers for WPT systems, with reduced operating frequency, higher power density, and better efficiency for transmitting power through conductive media, compared to traditional WPT solutions. This will be allowed by bridging the gap between, on the one hand, nonlinear dynamics modeling and system optimization, and, on the other hand, mechanical design and fabrication.

Planning

1rst year:

- Literature review of wireless power transfer solutions, with a focus on electrodynamic solutions.
- Understanding and programing models of electrodynamic wireless power transfer systems, with linear and nonlinear receivers.
- Learning how to use lab materials, and developing an automated testbench for electrodynamic wireless power transfer.
- Design, fabrication and test of a low-frequency mechanical receiver.

2nd year:

- Optimization methodology of mechanical receivers, based on analytical and numerical tools, and on the experience with the first prototype.
- Design, fabrication, and test of an optimized mechanical receiver.
- Numerical and experimental exploration of nonlinear phenomena.
- Conference presentations, scientific article publications.

3rd year:

- Design, fabrication, and test of tunable mechanical receiver with optimal potential wells.
- Test of the system for powering a sensor through metal walls.
- Study of the scalability of the receiver (for possible miniaturization).
- Conference presentations, scientific article publications.
- PhD manuscript writing.

Tasks percentages estimation:
Literature review: 5%
Optimization with analytical and numerical tools: 25%
Mechanical fabrication: 20%
Experimental tests, measurements, and data processing: 20%
Nonlinear phenomena exploration: 15%
Scientific dissemination and manuscript writing: 15%

Candidate profile

The candidate should have or be about to obtain an Msc in Mechanical Engineering, dynamics, physics, or mechatronics. She/he must have an interest in **applied mathematics (**analytical modeling, optimization algorithms, nonlinear ODE analysis), **mechanical engineering (**linear and nonlinear resonators, FEM simulations, prototypes fabrication), and **multiphysics** (electromagnetism, electromechanical systems, piezoelectricity). It is obviously not required for the candidate to be already familiar with all of these topics, but she/he must be motivated and interested to investigate all aspects.

Analytical as well as experimental skills are mandatory. Knowledge of programming/computing language (MATLAB/Simulink, Mathematica and/or Python), FEM softwares (Comsol and/or Ansys) would be a plus. Excellent written and verbal communication skills in English is required. Fluency in French is also a plus, but is not mandatory.

PhD director and co-advisor

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Location

The PhD thesis will fully take place at SYMME (Systems and Materials for Mechatronics) laboratory, Annecy, France. The selected candidate will be integrated in the micro-energies team of the laboratory, that has expertise on micro energies transfer, conversion, and collection.

https://www.univ-smb.fr/symme/

Starting date

Budget is available to start any time. Starting by September 2024 would be ideal.

Salary and funding

The project is fully funded by the French ANR (Agence Nationale de la Recherche). PhD salary will be approx. 2000€/month (gross before taxes). Candidates in their final year of engineering school or master's degree can start with an internship in the second semester of the 2023-2024 academic year, before continuing with the PhD work from September 2024. If interested, the PhD student will have the possibility to teach at University Savoie Mont Blanc, for an additional remuneration.

References

[1] Song, M., Jayathurathnage, P., Zanganeh, E. *et al.* Wireless power transfer based on novel physical concepts. *Nature Electronics* 4, 707–716, 2021, doi: 10.1038/s41928-021-00658-x.
[2] N. Garraud, *et al*, “Modeling and experimental analysis of rotating magnet receivers for electrodynamic wireless power transmission,” *J. Phys. D: Appl. Phys., vol.* 52**,** 185501, 2019.
[3] E. Andersen, et al., "System Demonstration and Characterization of a Self-Biased Magnetoelectric Wireless Power Transfer System for Biomedical Implants," *2022 PowerMEMS*, 2022, doi: 10.1109/PowerMEMS56853.2022.10007081.