BISTABLE ELECTROMECHANICAL RECEIVER FOR ULTRA-LOW FREQUENCY WIRELESS POWER TRANSFER

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ABSTRACT

In this article, we investigate a nonlinear electromechanical receiver for transmitting power with ultra-low frequency magnetic fields (1-10 Hz). The proposed nonlinear receiver is based on a bistable buckled-beam resonator that exhibits promising energetic behaviours when excited at ultra-low frequencies. After a numerical study of the receiver dynamics, an experimental prototype has been tested to validate the proposed concept. We demonstrate a transmitted power of 5.6 mW with a magnetic field frequency of (1 Hz).

KEYWORDS

Wireless Power Transfer, Electrodynamics, Nonlinear Dynamics, Frequency-up, Ultra-low frequency

INTRODUCTION

The performance of traditional Wireless Power Transfer (WPT) technologies, such as inductive, RF, and capacitive WPT, is often limited when the transmission medium is conductive. This is due to their high-frequency electric or magnetic fields (>100 kHz), which induce eddy currents in the medium, leading to significant energy absorption. Electrodynamic Wireless Power Transfer (EWPT) has been proposed as a low-frequency alternative (< 1 kHz), capable of transmitting power through conductive materials such as metallic walls, packaging, and water [1]. Such systems are based on a magnetic transmitter that generates a low-frequency magnetic field (typically 50 Hz to 300 Hz). The receiver generally consists of a cantilever beam with a magnetic mass, designed so that its resonant frequency aligns with the magnetic field frequency. The resonator's mechanical energy is then converted into electrical energy either through a piezoelectric material attached to the beam or by a coil wrapped around the moving magnet.

Over the past decades, various EWPT receivers have been developed. In their seminal work, Challah et al. designed an electrodynamic receiver of $10\,\mathrm{cm}^3$ and 38 Hz operation frequency [1]. Truong et al. designed a center-clamped piezoelectric receiver with a volume of $0.37\,\mathrm{cm}^3$ and a resonant frequency of 350 Hz [2]. Halim et al. proposed a miniaturized receiver that combines piezoelectric and electrodynamic transductions [3]. The proposed receiver exhbits a volume of $0.09\,\mathrm{cm}^3$ for a resonant frequency of 744 Hz. Ameye et al. also designed a dual-transduction receiver at centimeter-scale [4], exhibiting a volume of $23\,\mathrm{cm}^3$ and a resonant frequency of 38.5 Hz.

One key trade-off in these designs is that lowering the resonant frequency of the receiver typically results in a larger volume. This relationship can be explained by the fact that all the aformentioned receivers are linear resonators, where the resonant frequency is inversely proportional to the square of the mass. This inherently restricts the use of miniaturized receivers with ultra-low operation frequency (< 10 Hz), which could be particularly useful for applications involving highly conductive transmission media [5].

Nonlinear resonators do not follow the same rules as linear ones, and might exhibit promising behaviours under low-frequency forcing, even at small-scale [6]. As a matter of example, this behaviour has been leveraged for designing low-frequency vibration $(1-3)$ Hz energy harvesters [7]. This article proposes to exploit the dynamics of a nonlinear magneto-electromechanical receiver to transmit power using ultra-low frequency magnetic fields (1 Hz). The proposed nonlinear EWPT receiver is based on a bistable resonator featuring a mass fastened on a buckled-beam structure combined with an Amplified Piezoelectric Actuator (APA). The receiver's behaviour is initially studied through numerical simulations, demonstrating frequency multiplication behaviour under ultra-low frequency magnetic field. The concept is then experimentally validated by transmitting 5.6 mW of power at 1 Hz.

NONLINEAR RECEIVER UNDER ULTRA-LOW FREQUENCY MAGNETIC FIELD

Model of the receiver

Bistable electromechanical systems have already been studied for vibration energy harvesting [8], [9]. Here, instead of collecting an external vibration, the movement of the magnetic mass is the result of the varying magnetic field produced by a transmitter. It can be proven from Euler-Lagrange formalism [9] that the dynamics of the receiver is governed by Eq. 1:

$$\begin{cases} \ddot{x} = -\frac{\omega_0^2}{2}\left(\frac{x^2}{x_w^2}-1\right)x - \frac{\omega_0}{Q}\dot{x} - 2\frac{\alpha}{ML}xv + F_{\mathrm{mag}}(t) \\ \dot{v} = 2\frac{\alpha}{LC_p}x\dot{x} - \frac{1}{RC_p}v \end{cases} \tag{1}$$

With parameters defined in Table 1, and with:

$$\begin{cases} \omega_0 = \frac{x_w}{L}\sqrt{4\frac{K}{M}} \\ Q = \frac{x_w}{L}\frac{\sqrt{4KM}}{\mu} \\ k_m^2 = \frac{\alpha^2}{KC_p} \end{cases} \tag{2}$$

Table 1: Parameters list

Physical quantity	Symbol	Unit	Value
Magnetic force amplitude	F_m	[N]	3.72
Magnetic mass	M	[g]	30
Beams length	L	[mm]	35
Stable position	x_w	[mm]	1.93
Damping coefficient	μ	[mN.s/m]	26.4
APA stiffness	K	[N/m]	330000
APA piezoelec. capacitance	C_p	[µF]	1.1
APA piezoelec. force factor	α	[N/V]	0.144
APA coupling coefficient	k_m^2	−	0.057
Natural angular frequency	w_0	[rad/s]	370
Mechanical quality factor	Q	−	36.2
Electrical load resistance	R	[Ω]	1000

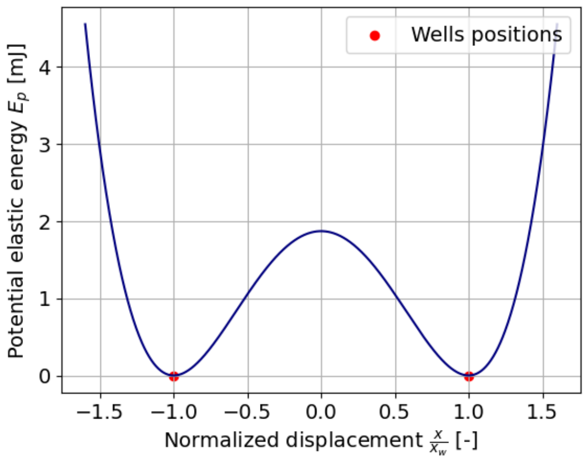

Figure 1: Potentials wells of the bistable receiver

The first ODE corresponds to the behaviour of the mechanical part of the receiver, while the second describes the electrical aspect. The two equations are coupled by the piezoelectric force factor α, which is intrinsic to the selected APA. The magnetic force applied on the receiver magnet is proportionnal to the magnetic field gradient $\frac{\mathrm{d}B}{\mathrm{d}x}$, and is given by $F_{\text{mag}}(t) = m\frac{\mathrm{d}B}{\mathrm{d}x}(t) = F_m \sin(\omega t)$, with m the magnetic moment of the magnetic mass [1].

The expression of the receiver's potential energy wells is derived from the non-linear elastic force as in (3) :

$$\begin{aligned} E_p(x) &= \int F_{\text{elastic}}\,\mathrm{d}x \\ &= \frac{M\omega_0^2}{8x_w^2}(x^2 - x_w^2)^2 \end{aligned} \tag{3}$$

Figure 1 shows the potential energy due to the non-linear elastic force, as a function of the displacement. The energy wells correspond to $\pm x_w$, the two stable positions of the receiver. In quasi-static regime ($\dot{x} = 0$), to get from a stable position to an other, the mechanical energy provided to the system must be equal or greater to the potential barrier $\Delta E = \frac{M\omega_0^2 x_w^2}{8}$. Increasing x_w and K will make the potential barrier higher and therefore allow more potential energy to be converted into kinetic energy, resulting in a greater transfer of energy if the barrier is crossed.

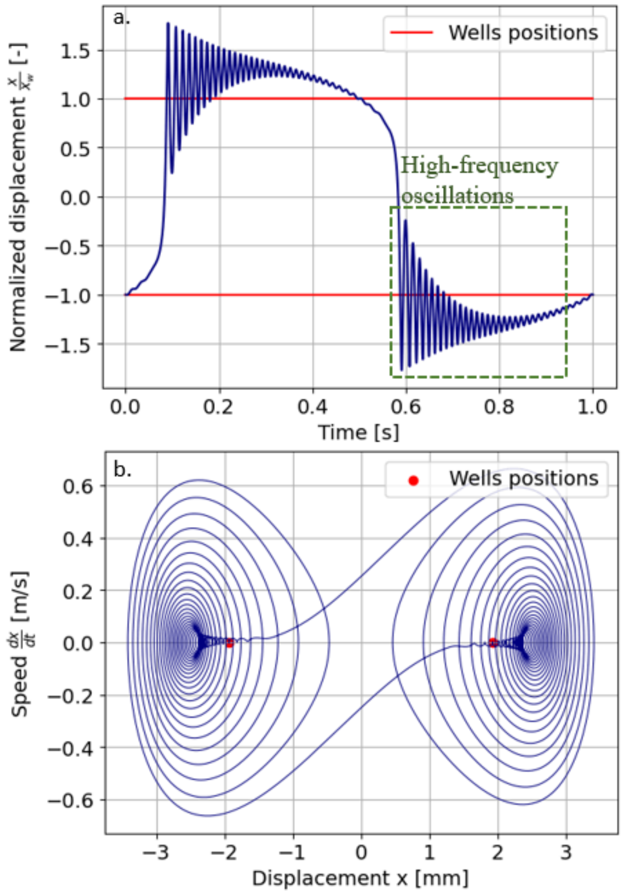

Figure 2: Behaviour of the bistable receiver. a. Time series of x, b. Phase portrait

Behaviour under ultra-low frequency B field

Equations (1) have been simulated in order to study the behaviour of the receiver under ultra-low frequency magnetic field (f = 1 Hz). Time series of the displacement of the receiver's magnet x are shown in Fig. 2(a) for a single period of excitation. Fig. 2(b) shows the phase portait of the receiver, illustrating the mass orbit in the $(x, \dot{x})$ plane.

Under such a low-frequency forcing, the mass follows the variation of the magnetic field and oscillates between the two stable positions $-x_w$ and $+x_w$ at a frequency of 1 Hz. However, everytime the mass crosses the central potential barrier, it starts oscillating in the wells at higher frequency. This frequency-up behaviour enables the system to accumulate kinetic energy under low-frequency forcing, improving the mechanical-to-electrical energy conversion.

EXPERIMENTAL VALIDATION OF THE ULTRA-LOW FREQUENCY BEHAVIOUR

The proposed ultra-low frequency EWPT receiver concept has been validated on a dedicated testbench illustrated in Figure 3. The home-made transmitter is made of copper wire wrapped around an iron core with 250 turns, powered at 1 Hz by a DC source and a two-leg inverter. The control signals of the inverter are generated by a dSpace console

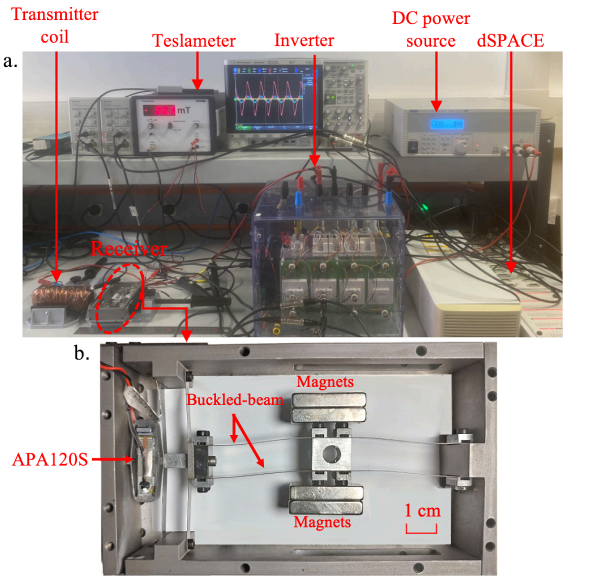

Figure 3: a. Experimental validation setup. and b. Bistable electromechanical receiver

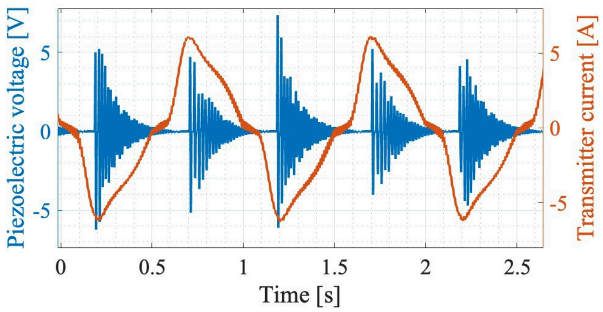

Figure 4: Experimental measurement of the piezoelectric voltage (blue) and transmitter current (red), for R = 330 Ω

that regulates the current amplitude to 6 A in the transmitter coil with a PI controller.

The receiver is a buckled-beam bistable electromechanical resonator with an inertial magnetic mass and an APA120S from Cedrat Technologies. The values of C_p, w_0, k_m^2, and Q have been identified from impedance analysis of the prototype. M and L have been directly measured on the prototype, and K is taken from the APA120S datasheet. The receiver's parameters values are summarized in Table 1. The APA electrodes are connected to a programmable resistor module piloted by the dSpace console. During the tests, the receiver was placed 5 cm away from the transmitter.

Voltages and currents time series have been recorded for various values of resistive load. Figure 4 shows an example of current and voltage time-series for a load resistance of 330 Ω. One can observe the 1 Hz emitter current, and the voltage across the APA. As shown in Figure 4, the APA voltage shows higher frequency oscillations due to the frequency-up behaviour of the receiver when it shifts from one stable position to the other one.

The average transmitted power to the load resistance has been determined from $P = \frac{<v^2>}{R}$, where $< v^2 >$ corresponds to the average of the squared time-series of the APA voltage. Measurements of the transmitted power are shown in Figure 5, and are compared with simulation results obtained from Eq. 1 and parameters in Table 1.

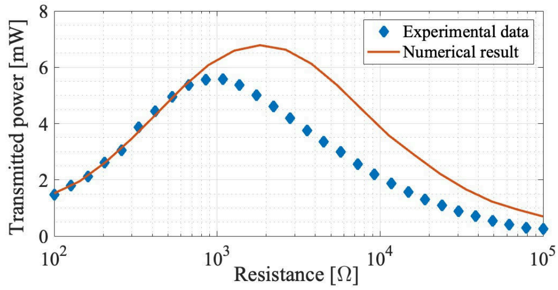

Figure 5: Transmitted power as a function of the load resistance

The experimental results are in relatively good agreement with the model prediction. The difference between numerical predictions and experimental data in Figure 5 are notably attributed to the quality factor of the receiver that was measured under low-signal excitation (impedance analysis) and might be smaller under large displacement amplitude. The maximum transmitted power, 5.6 mW, is obtained for a resistance of approximately 1 000 Ω.

EWPT RECEIVER OPTIMIZATION

Objective function

In order to increase the transmitted mechanical energy in the receiver, we focus on optimizing the parameters x_w, L, M. This approach is based on the fact that, to a first approximation, the mechanical-to-electrical conversion efficiency is independent of x_w, L, and M, as it primarily depends on the electromechanical coupling of the APA and the quality factor of the receiver. Therefore, we define the objective function as:

$$S : \max \left\{E_{\text{mag}}(x_w, L, M) \\ |(x_w, L, M) \in \Omega\right\} \tag{4}$$

Where Ω is the set of tuples (x_w, L, M) for which the constraints are respected.

Optimization constraints

The main constraints can be of three different natures:

- The maximum force applied to the APA during oscillations, F_{APA}, which should not exceed the recommended value provided by the manufacturer (32 N for the APA120S).
- The maximum bending constraint in the beam.
- Undesired higher buckling mode of the beams(Figure 6).

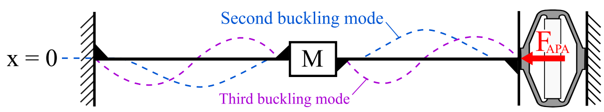

Figure 6: Representation of higher buckling modes

The expression of F_{APA} as a function of the mass displacement x is derived from geometrical considerations on the buckled-beam prototype,

$$F_{\text{APA}} = 2K\left(L - \sqrt{L^2 - x_{\max}^2}\right) \tag{5}$$

where $x_{\max}$ is the maximum displacement of the magnetic mass.

The maximum bending constraint in the beam is set following the model described in [10], given by:

$$\sigma_{\max} = \frac{E\pi^2}{2}\left(\frac{e^2}{3(2L)^2} + \frac{x_{\max}^2}{4(2L)^2}\left(1 + \frac{\pi^2 e^2}{6(2L)^2}\right)\right) \tag{6}$$

With E the Young modulus of a beam of thickness e. In our case, the model slightly overestimates the stress, nevertheless offering a safety margin for our design. Lastly, to avoid an upper degree of buckling of the beams, F_{APA} was applyed as the Euler's critical compressive load. In the case of the bistable receiver, the beams are in a clamped-clamped configuration, which leads to a higher critical load. Hence:

$$F_{\text{APA}} < \frac{4\pi^2 E\mathcal{J}}{L^2} \tag{7}$$

With $\mathcal{J}$ the quadratic moment of area of the beam.

Eq. 5 to Eq. 7 have been validated using COMSOL Multiphysics, and found to provide a good estimate of the strains in the beam, with a relative error of less than 20%.

Optimization results

The simulation results are shown in Figure 7, featuring:

- A heat map of the magnetic energy received by the system, which describe the performance of the receiver.
- Hatched areas, each of which represents the receiver failures when mechanical constraints are not respected.

The optimal operating point of the receiver tends to be a trade-off between maximizing x_w and minimizing L_p. It can be noted that an increase in magnetic mass or magnetic field results in stronger constraints. In this case, the optimal operating point is obtained for lower values of x_w and larger values of L_p, resulting in lower transmitted energy.

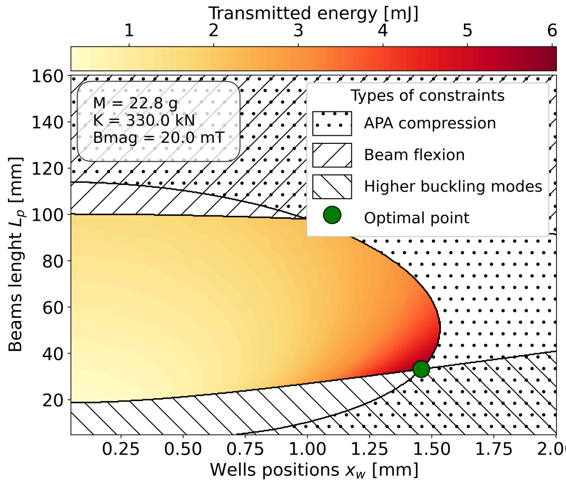

Figure 7: Optimization map of the receveir for an APA120S

CONCLUSION

An ultra-low frequency receiver based on a bistable electromechanical resonator has been proposed. We experimentally demonstrate a transmission of 5.6 mW with a magnetic field frequency of 1 Hz. Future works will focus on miniaturizing the receiver and optimizing its performance to maximize its power density with ultra-low frequency magnetic field.

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