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Highly coupled hybrid transduction for low-frequency electrodynamic wireless power transfer

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Abstract — In this paper, we report a hybrid low-frequency near-field electrodynamic wireless power transfer (EWPT) system. The power receiver is designed as a vibrating cantilever, with two mechanical-to-electrical transducers: a piezoelectric transducer and an electrodynamic transducer. The use of a hybrid system increases the converted power for the same mechanical system when the quality factor is reduced under high oscillation. We propose an analytical model, combined with admittance measurements, to determine the physical parameters of the system. This model allows a good prediction of the performance (efficiency, resonance frequency and output power) as a function of the input power and the resistive loads connected to the two transducers of the transmitter.

Keywords— Hybrid wireless power transfer, piezoelectric, electrodynamic, low frequency, electrodynamic power transfer

I. INTRODUCTION

Wireless power transfer (WPT) is an alternative to the constraint of power supply cables. For many applications, the deployment or use of these cables can be complicated or even impossible (moving sensors/actuators systems, medical devices). The use of batteries could also not be suitable when the system is difficult to access or in harsh conditions (high temperature...). Different WPT technologies were developed, such as inductive coupling, far-field RF or capacitive power transfer [1]. However, the use of high-amplitude and high-frequency magnetic or electric fields could be detrimental, especially when metal elements are in the vicinity of the transmitter or for human safety.

We proposed to further develop a recent technology, the electrodynamic WPT (EWPT), which operates at very low frequency (<1 kHz). The transmitter, either an ac-powered coil or a rotating magnet, creates a time-varying magnetic field around itself. The compact receiver, placed in its vicinity, consists of a moving permanent magnet attached to a mechanical suspension and one or several electromechanical transducers to generate power. The permanent magnet is subjected to a magnetic force or torque because of the time-varying field and therefore translates or rotates. Its mechanical energy is converted back into electrical energy by a transducer, using either piezoelectric, electrodynamic, or capacitive elements.

Designing a transducer that is robust and maximizes energy transfer is difficult. A decrease in the quality factor of the system, due to the system ageing or due to an increase of the input magnetic field and the amplitude of vibration, can

lead to a loss of coupling. A solution could be to implement a hybrid system with several transducers using both piezoelectric (PE) and electrodynamic (ED) transductions. [2] has demonstrated an energy gain by using two weakly coupled transducers for energy harvesting. [3] has also shown the integration of a hybrid transduction (ED and PE) on a multimodal energy harvester. For WPT applications, [4] has realized a weakly coupled hybrid system integrated in a chip-sized micro-receiver.

In this paper, we present a hybrid system combining both highly coupled piezoelectric transducer and electrodynamic transducer. The system modelling is described in Section 2, a prototype and its characterization are presented in Section 3 and the system performances are detailed in Section 4.

II. HYBRID EWPT MODEL

The transmitter coil, emitter of power, is supplied by an ac-current and generates a time-varying magnetic field around it. The receiver, placed nearby, consists of a high quality factor resonant electromechanical system made of permanent magnets attached at the tip of a piezoelectric cantilever beam (Fig. 1). The beam strain and the magnet motion are converted back into electrical energy thanks to the piezoelectric layer (PE transduction) and one or several receiver coils wound around the magnets (ED transduction).

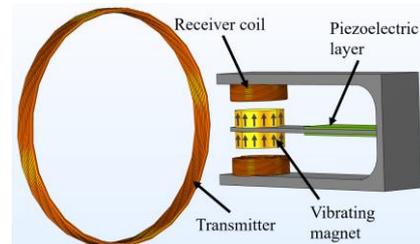


Fig. 1. Principle of the proposed hybrid EWPT system.

A. Equivalent Input Force and Best Configuration

The torque τ and the force F applied on the permanent magnets depends on their total magnetic moment m , the on-axis magnetic field B_x and field gradient dB_x/dx generated by the coil and the angle θ between the magnetic field B_x , as given in (1) and (2).

$$\tau = m B_x \sin(\theta) \quad (1) \quad F = m \frac{dB_x}{dx} \sin(\theta) \quad (2)$$

At the first mode of resonance, the dynamic deformation of the resonant beam is similar to the one resulting from a localized equivalent force F_{eq} acting on the magnet [2]:

$$F_{eq} = \frac{3\tau}{2L} + F \quad (3)$$

with L the length of the beam.

A first study was made to compare different configurations of the receiver, by changing the type of efforts applied on the magnets (i.e. force or torque), the cantilever direction (i.e. on-axis or transverse), and the magnet magnetization direction (i.e. parallel or perpendicular to the beam). The power receiver is considered in different positions at the center of Helmholtz coils (Fig. 2): in case A, the force mode, the uniform field gradient generates a force on the magnet; in case B, the torque mode, the uniform field generates a torque on the magnet.

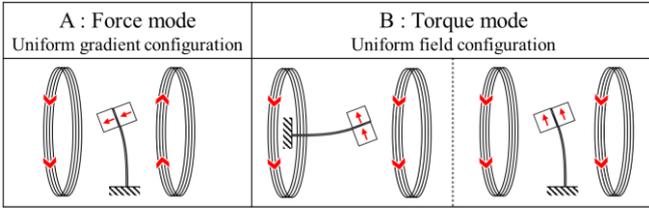


Fig. 2: Comparison of two modes of power transmission to the beam: force mode and torque mode.

In a pre-study, considering the receiver presented later, the equivalent force on the magnets F_{eq} is found to be 4.74 times larger in case B than in case A (121.9 mN vs. 25.7 mN) when 1 A is injected into the Helmholtz coil. Therefore, the torque mode is more efficient in transmitting mechanical energy to the receiver and only this configuration is considered thereafter.

B. Receiver Modelling

The mechanical structure of the receiver can be described as a mass-spring-damper system, with two electrical dampers created by the two mechanical-to-electrical transducers (Fig. 3). The system behavior can be described by the coupled equations from the mechanics (4), the electrical circuit of the piezoelectric transducer (PE) (5), and the electrical circuit of the electrodynamic transducer (ED) (6) [5]

$$\begin{cases} F_{eq} = M \ddot{v} + K v + D \dot{v} + \alpha_{PE} u_{PE} + \beta_{ED} i_{ED} \end{cases} \quad (4)$$

$$\begin{cases} \alpha_{PE} \dot{v} = -u_{PE}/R_{L,PE} - C_p \dot{u}_{PE} \end{cases} \quad (5)$$

$$\begin{cases} \beta_{ED} \dot{v} = -L_c \dot{i}_{ED} - (R_{L,ED} + R_c) i_{ED} \end{cases} \quad (6)$$

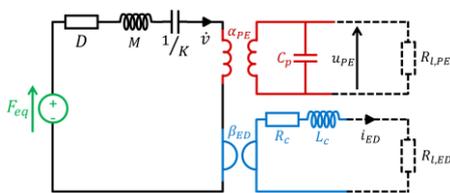


Fig. 3: Equivalent electrical circuit representation of a hybrid electrodynamic vibrational energy harvester.

M , D and K are the effective dynamic mass, the damping coefficient and the stiffness of the beam without electrical effects, respectively. α_{PE} and C_p are the piezoelectric transduction coefficient and the piezoelectric capacitance. β_{ED} , L_c and R_c are the electrodynamic transduction coefficient, the receiver coil inductance and the receiver coil

resistance. v , u_{PE} and i_{ED} are the center of mass displacement, the piezoelectric voltage, and the electrodynamic current. This model does not take into account the dielectric losses in the piezoelectric material, which can be neglected. For resistive loads connected to the output of the transducers, the powers dissipated in the loads are given by:

$$P_{PE} = \frac{U_{PE}^2}{2R_{L,PE}}, \quad (7) \quad P_{ED} = \frac{I_{ED}^2 R_{L,ED}}{2}. \quad (8)$$

$R_{L,PE}$ and $R_{L,ED}$ are the electrical resistances connected to the piezoelectric layer and the receiver coil, and U_{PE} and I_{ED} are the amplitudes of u_{PE} and i_{ED} .

This model allows to predict the outputs of the two transducers as a function of the amplitude and frequency of the magnetic field generated by the transmitter coil, and the electrical loads applied.

C. Parameters Determination by Admittance Fitting

M , C_p and L_c can be directly measured. Other parameters, as the effective mechanical damping or the transduction coefficients, are difficult to estimate. An analysis of the admittance of each of the two transducers can be performed to identify these parameters. From the previous model, the admittance of the piezoelectric layer Y_{PE} is given by (9) when the receiver coil is open-circuited, and the impedance of the receiver coil Z_{ED} is given by (10) when the piezoelectric layer is short-circuited.

$$Y_{PE} = \frac{j\omega \alpha_{PE}^2}{M_a \omega^2 - K - j\omega D} - j\omega C_{PE} \quad (9)$$

$$Z_{ED} = \frac{j\omega \beta_{ED}^2}{-M_a \omega^2 + K + j\omega D} + j\omega L_{Or} + r_{tr} \quad (10)$$

III. RECEIVER PROTOTYPE

The receiver is built with a 54 mm×25.4 mm×1.32 mm beam from MIDE (S452-J1FR-1808XB) consisting of four thin piezoelectric layers embedded in FR4. The NdFeB magnets volume is 1.1 cm³. The 4164-turn receiver coil made with 0.18 mm diameter copper wire has an inner dimension of 22 and 27 mm, an outer dimension of 40 and 33 mm, and a height of 2*0.9 mm. The volume of the smallest cube enclosing the receiver is 67.3 cm³. For characterization purposes, the receiver is placed at the center of 30-cm diameter Helmholtz coils in order to better control the magnetic field (Fig. 4).

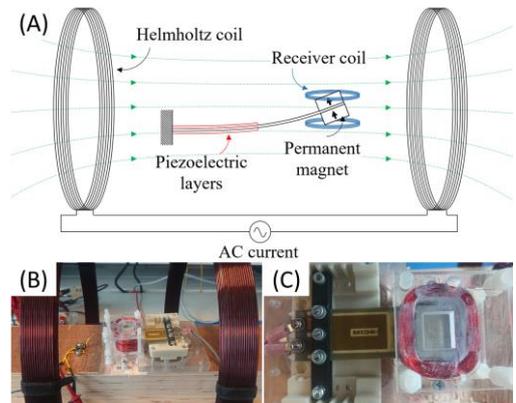


Fig. 4. (A) Schematics of the EWPT hybrid system. (B) Picture of the full system. (C) Picture of the piezoelectric beam, and the ED transducer.

A. Parameters Identification

The admittance measurements on both the receiver coil (Fig. 5 A) and the piezoelectric transducer (Fig. 5 B) were performed with the same maximal motion amplitude, monitored by a laser vibrometer. Equations (9) and (10) are fitted on measurements by identifying all parameters reported in Table 1, except for the effective dynamic mass that was directly measured.

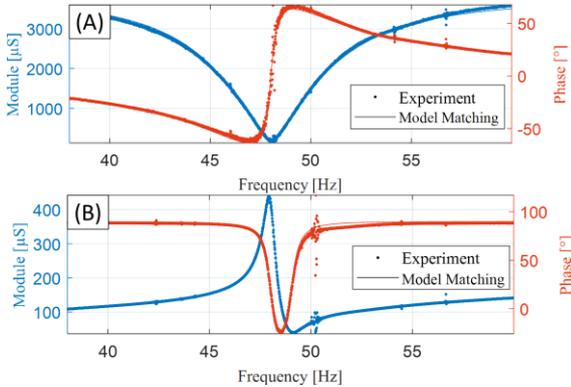


Fig. 5. Admittance measurement and model matching with identified parameters on the ED transducer (A) and on the PE transducer (B).

TABLE I. IDENTIFIED SYSTEM PARAMETERS

Parameters	Value
Receiver coil inductance, L_c	14.4 mH
Receiver coil resistance, R_c	264 Ω
Piezoelectric capacitance, C_p	404 nF
Effective mass, M	35.3 g
Spring constant, K	3212 N/m
Damping coefficient, D	126 mN/m/s
Piezoelectric transduction coefficient, α_{PE}	7.36 mN/V
Electromagnetic transduction coefficient, β_{ED}	22.7 N/A

B. Electromechanical Coupling and Quality Factor

Mechanically, the ability of a transducer to convert mechanical energy into electrical energy or electrical energy into mechanical energy is represented by the electromechanical coupling. For vibratory receivers, in order to optimize the amount of energy converted, the electrical damping of the receiver must be equal to the mechanical damping. The maximum amount of energy that can be converted P_{lim} is given by:

$$P_{lim} = \frac{F_{eq}^2 Q}{8 M \omega_0}, \quad (11)$$

with Q and ω_0 the quality factor and the natural resonant pulsation of the resonant system, respectively. The definition of the electromechanical coupling of a system depends on the transducer used. For a piezoelectric transducer, a strong coupling is often defined thanks to the Figure of Merit (FoM) $k_m^2 Q$ [5], with k_m^2 the coupling factor defined by (12).

$$k_m^2 = \frac{\alpha_{PE}^2}{K C_p}. \quad (12) \quad \gamma = \frac{\beta_{ED}^2}{D R_c} = \frac{\beta_{ED}^2}{R_c} \frac{Q}{M \omega_0}. \quad (13)$$

The system is strongly coupled if $k_m^2 Q > 2$. In such case, if dielectric losses are neglected, the amount of power that the transducer is able to convert from the mechanical side is equal to P_{lim} . For an electrodynamic transduction, such a criterion differentiating strong and weak coupling cannot be found. Indeed, the resistive losses can't be neglected and the system

cannot fully convert P_{lim} . Instead, a FoM describing the coupling can be given by the coefficient γ defined by (13).

In this case, the amount of power that the transducer is able to convert from the mechanical side is given by $P_{max} = \frac{\gamma}{1+\gamma} P_{lim}$. Even if the maximum power cannot be reached with an electrodynamic system, a strong coupling can be arbitrarily defined as a coupling γ of at least 9, allowing to convert 90 % of the maximum theoretical power.

It can be noted that both coupling, as well as the maximum power P_{lim} , depend on the quality factor. Therefore, the quality factor is a critical parameter that heavily influence the performance of the system.

Fig. 6 shows the evolution of the quality factor identified from admittance analyses while increasing the amplitude of the excitation. Increasing the excitation voltage amplitude leads to an increase in vibrations and to a decrease in quality factor. For cantilever tip displacement above 300 μm , the quality factor becomes too low (≈ 40) and both transducers are no longer highly coupled (red range). However, the combination of piezoelectric and electrodynamic transductions (hybrid configuration) enable to reach the maximum power despite a low quality factor.

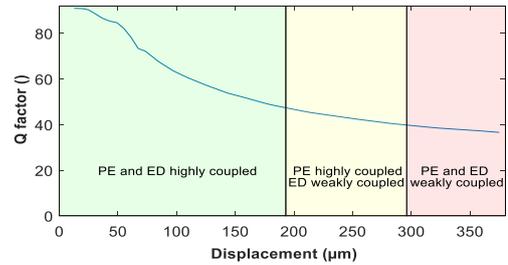


Fig. 6. Measured quality factor vs. displacement of the center of mass. PE and ED transducers are highly coupled or weakly coupled depending on the quality factor.

IV. RESULTS

Our hybrid system is characterized for two levels of magnetic field B_x (90 μT and 948 μT) corresponding to 109 mA pk and 1150 mA pk in the Helmholtz coils. The powers extracted by the piezoelectric and the electrodynamic transducers are measured while changing both resistive loads $R_{L,PE}$ and $R_{L,ED}$. The loads variations affect the equivalent stiffness of the beam and consequently the resonance frequency of the system. Therefore, for each load value, the input frequency is set to the resonance of the system before each measurement. For the two amplitude levels, the maximum recoverable power P_{lim} are 147 μW and 8.10 mW.

A. Low Amplitude Excitation

For low amplitude excitation (90 μT), Fig. 7 gives the power maps from each transducer and the total power from the two transducers for different output loads according to the analytical model (A) and according to experimental measurements (B). The maximum amplitude of the cantilever tip is 76 μm . There is a good agreement between the analytical and the experimental output powers, validating the process.

The maximum measured power from the ED transducer is 152.9 μW , while the maximum measured power from the PE transducer is 150.6 μW . A maximum electrical power of

154 μW is measured when both transducers are connected to their respective optimal electrical loads. The maximum electrical power is equal to the ED and PE maximum measured power within the uncertainties. In this low input excitation case, the extracted power is maximized for two optimal loads on the PE transducer since the transducer is highly coupled ($Q \approx 70; k_m^2 Q = 3.12 > 2$). Alternatively, the electrodynamic coupling γ is 13.0, which allows the ED transducer to recover 92.3 % of the maximum power. The measurement was performed with a quality factor corresponding to in the green zone of Fig. 6. The efficiency of power transfer at this amplitude is 2 %.

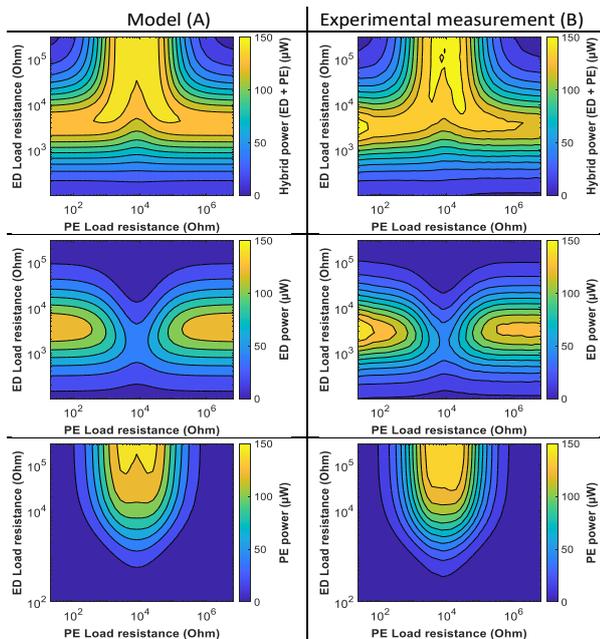


Fig. 7. Comparison of the analytical and experimental output powers for the PE and ED transducers and the total output power at the resonant frequency with low input excitation (90 μT).

B. High Amplitude Excitation

Fig. 8 shows the power maps for a higher amplitude excitation (948 μT , $\times 10.5$ more than previously). The maximum amplitude of the cantilever tip is 443 μm . The quality factor of the model (A) has been adjusted according to the admittance analysis corresponding to this level of motion amplitude ($Q \approx 35$, $\times 2$ less than previously).

The maximum energy transfer for high amplitudes occurs only when the two transducers are recovering energy. Indeed, a maximum power of 7.55 mW is measured, while the maximum power recovered from the purely electrodynamic transducer is 6.50 mW, and the maximum power recovered from the purely piezoelectric transducer is 7.01 mW. The extracted power by a piezoelectric transduction is maximized for a unique optimal load, which is characteristic of a weakly coupled piezoelectric transducer. Indeed, the piezoelectric FoM $k_m^2 Q$ is 1.54, now lower than the criterion of 2. Alternatively, the electrodynamic coupling γ is 6.44, which allows to recover 86.5 % of the maximum power. The quality factor is not sufficient to recover the maximum power separately from each transducers. This phenomenon would be increased for higher magnetic field amplitudes. However, the hybrid configuration allows the maximum energy to be converted. The measurement was performed with a quality

factor corresponding to in the red zone of Fig. 6. The efficiency of power transfer at this amplitude is 0.9 %.

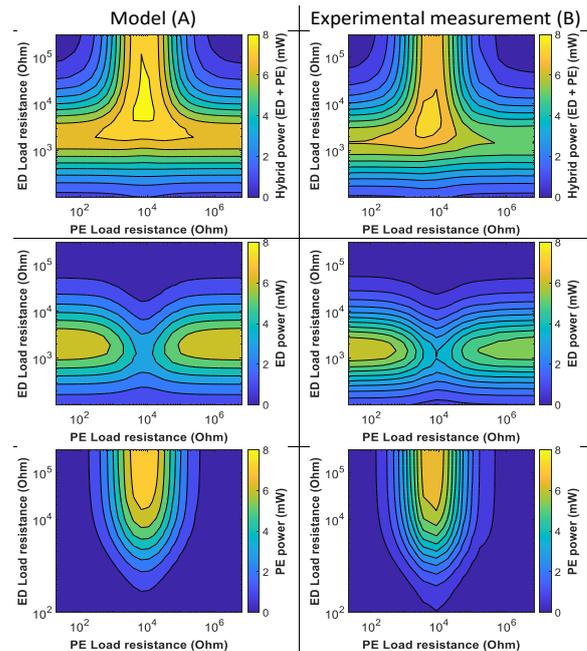


Fig. 8. Comparison of the analytical and experimental output powers for the PE and ED transducers and the total output power at the resonant frequency with high input excitation (948 μT).

V. CONCLUSION

This paper presents further developments of the EWPT technology with a hybrid transduction system. The model studied in this paper is suitable to determine the system parameters with admittance analysis and to predict the output power of a resonant EWPT with both piezoelectric and electrodynamic transducers. The model has been experimentally validated either for strongly coupled transducers or for weakly coupled at high amplitude with optimal resistive loads. We showed that a hybrid system can be of interest when the motion amplitude is high or when the mechanical quality factor is low in order to recover the maximum of the power. Further research on the subject of hybrid receivers will be led, notably on frequency tuning and detuning to increase the system robustness.

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