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Increasing the robustness of electrodynamic wireless power receivers with hybrid transduction

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Abstract — Electrodynamic wireless power transmission (EWPT) is a technique for transmitting power based on an electromechanical system operating at very low frequency. The power receiver converts a time-varying magnetic field first into mechanical power through the motion of a permanent magnet, and then into electrical power through an electromechanical transducer. One issue of electrodynamic WPT receivers is that they can be over-excited and break when subjected to strong magnetic fields. In this paper, we show that the simultaneous use of piezoelectric (PE) and electrodynamic (ED) transducers in a hybrid receiver allows taking advantage of both transductions to recover high levels of energy while limiting wear at higher magnetic field amplitudes.

Keywords— *Wireless power transfer, hybrid receiver, piezoelectric, electrodynamic, low frequency.*

I. INTRODUCTION

Various wireless power transmission (WPT) technologies are used to transmit power between a transmitter and a receiver [1]. Inductive coupling WPT is an efficient technique at short distances through the air, but the high frequency magnetic field can be screened in the presence of metal objects. Electrodynamic wireless power transmission (EWPT) is a technique operating at very low frequency (< 1 kHz) which is less sensitive in the vicinity of conductive media or through seawater.

EWPT system consists of a power transmitter generating a time-varying magnetic field around itself, usually an AC powered coil or a rotating magnet, coupled with a compact power receiver. This receiver comprises a moving permanent magnet that can be attached to a mechanical suspension, and one or more electromechanical transducers to convert mechanical energy into electrical energy. Two types of motion can be used:

- the continuously rotating motion, which consists of rotating a permanent magnet in the center of a coil, offering high power close to a transmitter but with a complex control and a greater proximity to the transmitter,
- the resonating mode, which consists of making a mechanical system with a magnet as mass resonate, with a high quality factor, offering a high sensitivity to weak magnetic fields to harvest power farther from the transmitter. In this paper, we focus on the resonating mode.

Such resonant mechanical systems usually implement a mechanical suspension to set the restoring force. One issue is the low mechanical robustness of such suspension: an increase in the magnitude of the magnetic field (for example by approaching the receiver too close to the transmitter) can lead to the breakage or premature wear of the system. In order to limit the mass movement in amplitude, those systems usually implement mechanical stops, however leading to low energy output and shocks that may damage the structure. Another method is to use specific characteristics of the electromechanical transducers to either overdamp or detune the mechanical system to reduce its motion amplitude.

In the state of the art, piezoelectric transducers (PE), electrodynamic transducers (ED) or triboelectric transducer (TE) are primarily used [2]–[4]. PE have a high power density, the ability to tune their resonant frequency but they often suffer from ageing since they are made of brittle material. ED have a high capacity to overdamp the motion but they are more bulky because of the use of a coil. Hybrid systems using both transducers have already been presented, and have shown a power gain with weakly electromechanically coupled transducers [5], [6].

In this paper, we propose to compare resonant hybrid transduction systems (PE or ED) to a hybrid system (PE and ED) in terms of i) power recovery and ii) ability to limit the mobile mass's displacement. First, we present a mechanical study on the impact of detuning and overdamping on the electrical output power and the displacement amplitude. Then, we use a complete hybrid model to compare the performances of the two transducers alone or together. Finally, we analyze the effects of the transducer electromechanical coupling and the magnetic field amplitude on the performances of hybrid receivers.

II. HYBRID ELECTRODYNAMIC WPT

In this paper, we study theoretically a hybrid receiver already reported in a previous article [7]. The receiver consists of a high quality factor resonant electromechanical system made of a piezoelectric cantilever beam, two NdFeB magnets attached at its tip, and two receiver coils wound around the magnets (Fig. 1). The transmitter, made of 30-cm-diameter Helmholtz coils supplied by ac-currents (not illustrated in Fig. 1), is generating a uniform time-varying magnetic field of amplitude B_0 exciting the magnets with a magnetic torque. The beam strain and the magnet motion are converted back into electrical energy thanks to PE and ED transductions.

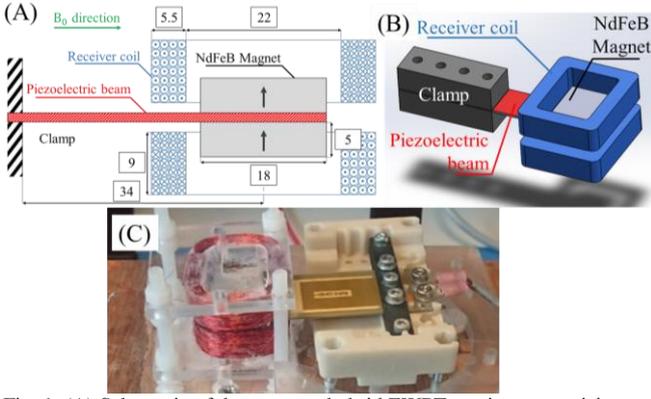


Fig. 1. (A) Schematic of the resonant hybrid EWPT receiver comprising both piezoelectric (PE) and electrodynamic (ED) transducers (dimensions in mm). (B) 3D representation of the receiver. (C) Picture of the experimental setup.

The piezoelectric beam (MIDE S452-J1FR-1808XB) has four piezoelectric layers embedded in FR4. This design results in a high PE coupling, but also makes the beam more prone to wear for high displacements due the risk of delamination. The coils are made of 4150 turns of 0.18-mm-diameter copper wire, with outer dimensions of $40 \times 33 \times 9 \text{ mm}^3$. This design results in a high ED coupling, but its volume is significantly larger compared to the PE transducer.

The system is represented to scale in Fig. 1.A, and its mechanical parameters are summarized in Table I. In a first approach, the mechanical quality factor is considered constant and independent from the displacement amplitude of the mass.

TABLE I. PHYSICAL PARAMETERS OF THE HYBRID EWPT RECEIVER

Parameters	Units	Value
Effective mass, M	[g]	35.3
Spring constant, K_m	[N/m]	3212
Mechanical damping coefficient, D_m	[mN/m/s]	126
Magnet magnetic moment, m	[A.m ²]	3.2
Length of the beam, L	[mm]	34

III. ELECTRICAL DAMPING AND DETUNING

We first study a general case with a theoretical electromechanical transducer. The resonant EWPT receiver can be modelled by the equivalent model in Fig. 2, with mass, damper and spring, plus electrical damper (introducing over-damping) and electrical spring (introducing frequency detuning) resulting from the electromechanical coupling and the electrical load.

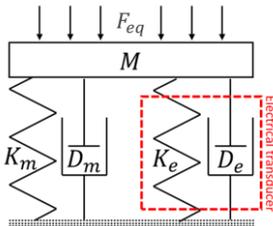


Fig. 2. Equivalent mechanical representation of a EWPT receiver.

The equivalent force F_{eq} acting on the magnetic mass at the first resonant frequency is derived from the magnetic torque, and depends on the magnetic moment of the permanent magnet m , the length of the beam L , and the magnetic field amplitude B_0 generated by the transmitter at the receiver location:

$$F_{eq} = \frac{3mB_0}{2L} \quad (1)$$

The system can be described by the equation of motion (2), where M is the effective dynamic mass, K_m is the stiffness of the beam, D_m is the mechanical damper, D_e and K_e are respectively the stiffness and damper electrically induced by the electromechanical transducer. They will further be called electrical stiffness and electrical damper.

$$F_{eq} = M\ddot{x} + (D_m + D_e)\dot{x} + (K_m + K_e)x \quad (2)$$

The mechanical quality factor of the structure Q when no electrical effect acts on the structure is then equal to :

$$Q = \frac{\sqrt{K_m M}}{D_m} \quad (3)$$

Considering a sufficiently high Q factor, the resonant angular frequency ω_r is given by:

$$\omega_r \approx \sqrt{\frac{K_m + K_e}{M}} \quad (4)$$

The theoretical maximum power that can be recovered from any damper is defined by (5) and the maximum displacement without electromechanical transduction action is defined by (6), where $\omega_r = \omega_t$ with ω_t the pulsation of the transmitter.

$$P_0 = \frac{F^2 Q}{8M\omega_r} \quad (5) \quad X_0 = \frac{FQ}{M\omega_r} \quad (6)$$

Fig. 3 presents the effects of the electrically induced damping (variation of D_e) and of the detuning (addition of a positive or negative K_e which implies a variation of ω_r) on the amplitude of the motion X and the output power P .

In Fig. 3A, the amplitude that allows the maximum power P_0 is when $X = X_0/2$. This case is reached when the resonant frequency of the system is equal to the resonant frequency of the transmitter (no detuning), and the electrical damping is equal to the mechanical damping.

Fig. 3B shows the normalized power output as a function of the normalized amplitude in the case of pure detuning in blue (K_e varying, $D_e = D_m$) and pure overdamping in red (D_e varying, $\omega_t = \omega_r$). When limiting the tip amplitude to $X < 0.5 X_0$, it is shown that it is preferable to use transducers that can overdamp rather than transducers that can detune the mechanical system to maximize the power output.

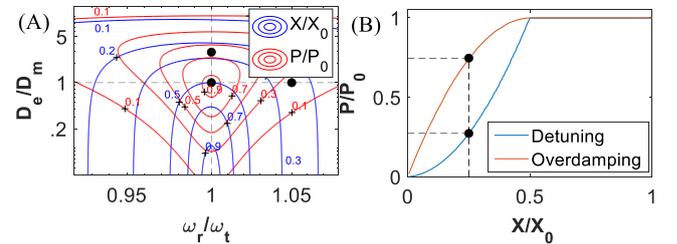


Fig. 3. (A) Effect of the electrical stiffness K_e and damping D_e on the output power P and the amplitude of motion X . (B) Comparison of the detuning effect and the overdamping effect on the maximal output power and the amplitude of motion.

IV. ELECTRODYNAMIC AND PIEZOELECTRIC EFFECTS

We are now focusing on the two transducers ED and PE. The receiver is able to operate either with the PE or ED only, or with both transducers (hybrid mode), depending on the electrical loads connected to the two transducers. In this work we limit the study to resistive output loads.

The equivalent electrical circuit of the hybrid system is presented in Fig. 4, with the mechanical structure described as a mass-spring-damper $\{M, K_m, D_m\}$ system, and with the two electromechanical transducers.

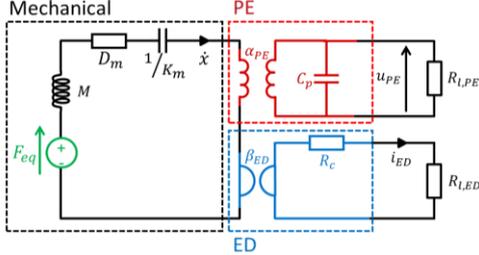


Fig. 4: Equivalent electrical circuit representation of a hybrid electrodynamic receiver.

The behavior is described by three coupled equations (8), with α_{PE} and C_p the PE transduction coefficient and the piezoelectric capacitance respectively, and β_{ED} and R_c the ED transduction coefficient and the receiver coil resistance respectively. x , u_{PE} and i_{ED} are the displacement of the center of mass, the piezoelectric voltage, and the electrodynamic current. $R_{l,PE}$ and $R_{l,ED}$ are the electrical resistances connected to the piezoelectric layer and the receiver coil, respectively.

$$\begin{cases} F_{eq} = M \ddot{x} + K_m x + D_m \dot{x} + \alpha_{PE} u_{PE} + \beta_{ED} i_{ED} & (8a) \\ \alpha_{PE} \dot{x} = -u_{PE}/R_{l,PE} - C_p \dot{u}_{PE} & (8b) \\ \beta_{ED} \dot{x} = -(R_{l,ED} + R_c) i_{ED} & (8c) \end{cases}$$

A. Electrodynamic transducer

Considering the receiver with the ED transducer only (PE short-circuited, i.e. $u_{PE} = 0$), the mechanical effect of the transducer can be decomposed into an electrical damper D_{ED} and an electrical stiffness K_{ED} :

$$\beta_{ED} i_{ED} = D_{ED} \dot{x} + K_{ED} x \quad (9)$$

The inductance of the ED coil is considered negligible at the resonant frequency, so $K_{ED} = 0$, and the damping depends on the load $R_{l,ED}$.

$$D_{ED} = \frac{\beta_{ED}^2}{R_{l,ED} + R_c} \quad (10) \quad K_E = 0 \quad (11)$$

The resonant frequency ω_r therefore only depends on the mechanical parameters K_m and M .

The transducer's ability to overdamp Γ_{ED} is defined as the maximum damping that can be induced by the ED transducer (i.e. when $R_{ED} = 0$) compared to the mechanical damping, which is also linked to the well-known ED coupling coefficient γ :

$$\Gamma_{ED} = \frac{D_{ED}}{D_m} \Big|_{max} = \frac{\beta_{ED}^2}{D_m R_c} = \gamma \quad (12)$$

The maximum power recoverable with the transducer is also related to the coupling:

$$\max\left(\frac{P_{ED}}{P_0}\right) = \frac{\gamma}{\gamma + 1} \quad (13)$$

B. Piezoelectric transducer

Considering the system with the PE transducer only (ED open-circuited, i.e. $i_{ED} = 0$), the mechanical effect of the transducer can also be decomposed into an electrical damper D_{PE} and an electrical stiffness K_{PE} .

$$\alpha_{PE} u_{PE} = D_{PE} \dot{x} + K_{PE} x \quad (14)$$

Unlike the ED transducer, the PE transducer induces an electrical stiffness:

$$\frac{D_{PE}}{D_m} = \frac{R_{l,PE} \alpha_{PE}^2}{(1 + R_{l,PE}^2 \omega^2 C_p^2) D_m} \quad (15)$$

$$K_{PE} = \frac{R_{l,PE}^2 \alpha_{PE}^2 C_p \omega^2}{1 + R_{l,PE}^2 \omega^2 C_p^2} \quad (16)$$

By varying the output load, it is possible to vary the resonant frequency of the system. The maximum variation of the resonant frequency ω_r depends on the piezoelectric coupling factor k_m^2 :

$$\omega_r \in \left[\omega_0, \omega_0 \sqrt{1 + k_m^2} \right] \text{ with } k_m^2 = \frac{\alpha^2}{K_m C_p} \quad (17)$$

In order to reach the maximum power P_0 , the electrical damper D_{PE} and the resonant angular frequency ω_r must be equal to the mechanical damper D_m and transmitter's ω_e . It is therefore necessary to adapt the transmitter's frequency taking into account the change of stiffness due to the piezoelectric effect. The optimal frequency has already been described in [8].

The transducer's ability to overdamp Γ_{PE} is defined as the maximum damping of the PE transducer at its resonant frequency (i.e. when $R_{PE} = 1/C_p \omega_r$) compared to the mechanical damping, which is also linked to the well-known PE coupling coefficient k_m^2 :

$$\Gamma_{PE} = \frac{D_{PE}}{D_m} \Big|_{max} = \frac{\alpha_{PE}^2 Q}{2 K_m C_p} = \frac{k_m^2 Q}{2} \quad (18)$$

As the electric losses of the PE transducers have been neglected, it is possible to obtain the maximum energy if the coupling is sufficiently high [8]:

$$\max\left(\frac{P_{PE}}{P_0}\right) = 1 \text{ if } k_m^2 Q \geq 2 \quad (19)$$

C. Effects of PE and ED coupling

The relationships between the coupling factors γ and $k_m^2 Q$ and the maximum output power or the maximum damping are summarized in the table II.

TABLE II. IMPACTS OF γ AND $k_m^2 Q$ ON NORMALIZED POWER AND DAMPING

	ED	PE
$\max(P/P_0)$	$\frac{\gamma}{1 + \gamma}$	1 if $k_m^2 Q \geq 2$
$\max(D_e/D_m)$	γ	$\frac{k_m^2 Q}{2}$

Considering the ED transducer, an increase in γ corresponds to an increase in power output, however with a saturation effect. For the PE transducer, the maximum recoverable power is reached if $k_m^2 Q$ is greater than 2. Therefore, there is no need to have stronger piezoelectric

coupling above a certain level of $k_m^2 Q$. Considering maximizing the damping to limit the displacement, both γ and $k_m^2 Q$ are related to the ability of the transducers to dampen the mechanical system: the greater they are, the greater the damping.

We will compare two case studies with three sets of parameters for PE and ED. Case #1 corresponds to the actual parameters of the experimental system presented in [7] and illustrated in Fig. 1. These parameters correspond to strongly coupled electromechanical transducers. However, this results in oversized coils (lowering the power density) and oversized piezoelectric layers (making the system less robust). Case #3 corresponds to a theoretically degraded coupling system, resulting in a more compact, cheaper and more robust receiver. Case #2 corresponds to an intermediate case. Parameters are summarized in Table III.

TABLE III. IDENTIFIED TRANSDUCTION PARAMETERS

Case study		#1	#2	#3
PE coefficient, α_{PE}	[mN/V]	12.1	8.7	6.1
Piezoelectric capacitance, C_p	[nF]	404		
Equivalent Γ_{PE}	[]	2.0	1.0	0.5
ED coefficient, β_{ED}	[N/A]	28.2	19.9	14.1
Receiver coil resistance, R_c	[Ω]	264		
Equivalent Γ_{ED}	[]	10	5.0	2.5

The effects of a variation of the resistive load on the mechanical system are different depending on the considered transducer. For each case study, a variation of the load on the ED transducer results in a change in electrical damping and therefore in amplitude of motion. A variation of the load on the PE transducer leads to a variation in both the electrical damping and the resonant frequency, both contributing to the drop in amplitude.

The Fig. 5(A-B-C) shows the impact of the variation of the load R_l on the electrical damping D_e , the resonant pulsation ω_r and the resulting displacement amplitude X in the case study #1 with strong couplings. These parameters have been normalized by the load resistance R_0 allowing the optimal damping, the mechanical damper D_m , the natural frequency ω_0 , and the unloaded amplitude X_0 .

In this case, the ED transducer has a stronger capacity to reduce the amplitude (10 fold reduction) compared to the PE transducer (4 fold reduction).

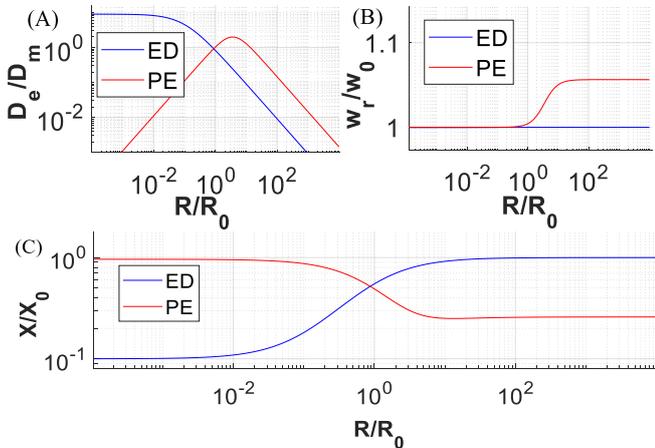


Fig. 5: For case study #1: (A) Electrical damping of ED and PE transducer vs resistive loads (B) Variation of resonant frequency vs resistive loads. (C) Variation of the mass displacement amplitude vs resistive loads.

V. HYBRID SYSTEM WITH STRONG MAGNETIC FIELD

In the case of strong excitation magnetic fields, it is important to limit the displacement amplitude X to ensure the durability of the receiver while operating. Fig. 6(A-B-C) shows the ability of the three different receivers (case #1, #2 or #3) to recover power as a function of the amplitude of the mass motion normalized by the unloaded displacement X_0 for a given field amplitude of $B_0 = 2 \text{ mT}$.

In all three cases, the hybrid system does not recover much more power than single transducer systems for the optimal amplitude $X_0/2$, but it does allow a significant output power while reducing a lot the amplitude of the mass. This effect is more noticeable with weakly coupled transducers (case #2 and #3) than for strongly coupled transducers (case #1).

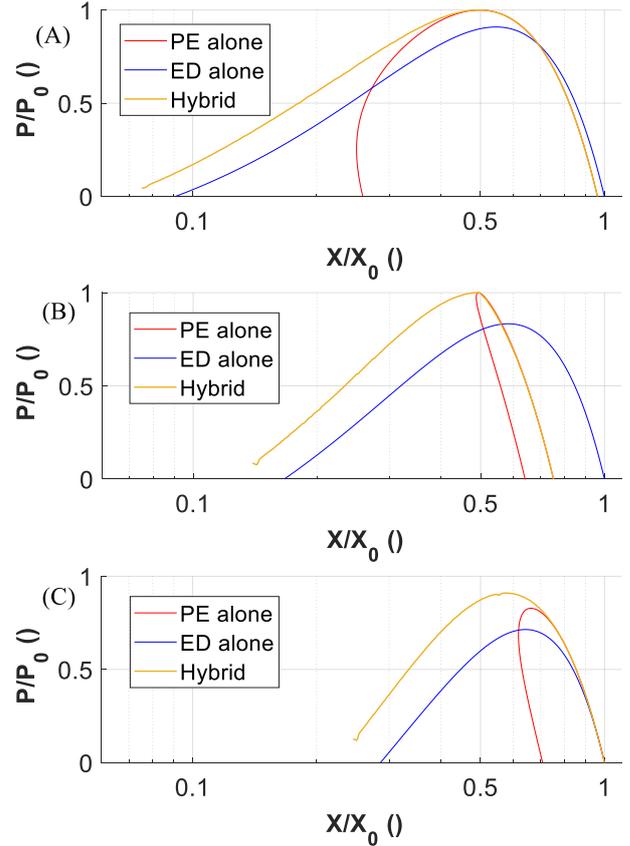


Fig. 6: Maximal output power as a function of the mass displacement amplitude, for (A) case #1 “strongly coupled”, (B) case #2 “intermediate coupling” and (C) case #3 “lowly coupled”.

When designing a receiver, it is necessary to fix a maximum amplitude that the mass should not exceed. If this limit is exceeded, the receiver will come into mechanical contacts (e.g. stoppers) which could stop the resonance, or may break or damaged the system. Therefore, limiting the mass displacement by overdamping or detuning makes it possible to operate at larger input magnetic field B_0 (i.e. closer from the source) without breaking and while still harvesting enough power. Fig. 7(A-B-C) shows the output power as a function of the field amplitude B_0 generated by the transmitter, with an amplitude of motion of the mass electrically limited at 1 mm.

VI. CONCLUSION

This paper presents the benefits of a hybrid piezoelectric and electrodynamic receiver for EWPT under strong magnetic fields. By taking advantage of the different characteristics of these two transductions, a hybrid system can reduce wear and tear on the mechanical component by limiting the amplitude of movement during operation, making it more robust while still recovering power. The hybrid system also allows an increase in power at maximum displacement, which allows to design more compact systems with almost the same performances for high input field. The hybrid system we present here can recover 51 mW under a field strength of 7 mT with a 1 mm mass displacement amplitude, whereas a PE only system or ED only system would not be able to limit its displacement amplitude at this field strength. As a result, designing hybrid systems allows to take advantage of both PE and ED transductions, making it possible to make power receivers more robust to strong fields while reducing their size.

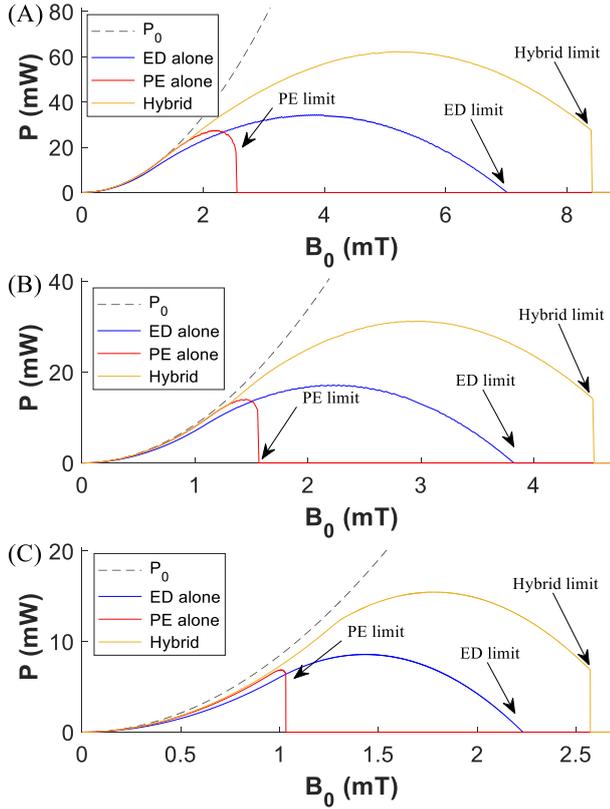


Fig. 7: Maximal output power with a maximum allowed displacement of 1 mm as a function of the magnetic field for (A) case #1, (B) case #2 and (C) case #3.

With our parameter sets and with an electrically limited amplitude, a hybrid system accepts input magnetic fields 2.5 times higher than the PE system alone and is also able to recover twice as much power at high magnetic fields. This effect is as important for strong couplings (case #1) as for weaker couplings (case #2 and #3). It can also be seen that the stronger the couplings, the more robust the receiver is for high magnetic field. The maximum power of the hybrid system is 62.2 mW for 1 mm of amplitude, compared to 31 mW and 28 mW for the PE and ED system respectively (case #1).

Table VI shows the recoverable power for each system if they had to withstand a magnetic field of $B_0 = 2$ mT. In the case of strong couplings, the maximum power is almost recovered in each case, and the hybrid system is not necessary. Furthermore, thicker piezoelectric patches would further limit the maximum allowed displacement, and the receiver coils would increase the receiver volume. In the case of weaker couplings, the PE alone case can no longer operate, while the ED alone case does not recover significant power (32 % P_0). However, the hybrid receiver can recover a significant power level (72 % P_0) while being more robust (thinner piezoelectric material) and less voluminous (smaller coil) than the system of case #1.

TABLE VI. OUTPUT POWER FOR 1 mm MAXIMUM DISPLACEMENT AT 2 mT (For $B_{max} = 2$ mT)

		Case #1	Case #2	Case #3
Electrodynamic only ED	[mW]	23.2	16.7	4.2
Piezoelectric alone PE	[mW]	26.1	N/A	N/A
Hybrid system	[mW]	28.81	25.0	14.8

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