WIRELESS POWER TRANSMISSION TO AN ELECTRODYNAMIC ENERGY HARVESTER USING LOW-FREQUENCY MAGNETIC FIELDS

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Abstract: Near-field, magnetically-coupled systems transmitting power from a coil to an electrodynamic vibration energy harvester are presented. Mechanical resonances below 100 Hz in the receiver allow efficiencies above 10%. In contrast, inductively-coupled wireless power transmission requires higher frequencies. Furthermore, low frequency fields may allow transmission through conductive media, such as metal or saline water. Depending on the system configuration, the receiver responds to the magnetically induced force or torque. A torque-coupled validation system has a peak efficiency of 14% at 42.5 Hz. The system delivers 0.9 mW across 1 cm and 15 μW across 10 cm from a 6.3 mW input.

Keywords: Wireless power transmission (WPT), electromechanical device, energy harvester, magnetic coupling.

INTRODUCTION

The increase in wireless sensors and portable electronics for personal and industrial applications has greatly increased the use of batteries. Most battery-powered systems are constrained in size or weight. As a result, the lifespan of such devices is limited by the energy capacity of the battery. In many cases, these batteries need to be replaced or charged in order to provide a sufficiently long period of operation. This maintenance procedure might be inconvenient, expensive, or even impossible for applications involving inaccessible locations or harsh environments.

Current research efforts to address the need for ubiquitous power are ambient energy harvesting and wireless power transmission (WPT). Energy harvesters typically have low power densities, and their dependence on the environment results in variable performance. In contrast, WPT systems actively transfer power from a source to a receiver, allowing total control of the power transfer.

WPT systems can be classified as either near-field or far-field systems depending on the distance between the source and receiver. If the distance is much larger than the electromagnetic wavelength, it is far-field; if it is shorter, it is near-field. This paper focuses on near-field WPT.

Most near-field WPT systems consist of inductively coupled coils. For example, Kurs et. al, has demonstrated a WPT system where 60 W of power are sent over a distance of about 2 m [1]. In another work, Wang et al., use metamaterials to improve the efficiency of a WPT system consisting of coupled resonators [2]. While these systems are able to successfully transfer power from the source to the receiver, the operating frequency is in the range of 1-100 MHz. The high operating frequency limits the magnitude of the magnetic field that can be safely used according to human exposure safety standards [3]. Also, absorption and attenuation of high frequency electromagnetic energy makes such systems unable to transmit power through conductive media. Additionally, such systems may create a source of unwanted high-frequency electromagnetic interference (EMI).

To address this challenge, a low-frequency, magnetically-coupled WPT system was presented by Cheng et al. [4]. A similar work has been reported recently by Zhang et al., where they employed a multiferroic energy harvester as a receiver in their WPT system [5]. This work builds upon prior work [4] to present force- and torque-coupled systems for the receiver, along with experimental results for a torque-coupled validation system.

The presented WPT system consists of a coil serving as a transmitter and an electromechanical vibration energy harvester as a receiver. The receiver is configured as a spring-mass-damper resonator with a permanent magnet as the vibrating mass. The transmitter coil generates a sinusoidal magnetic field. As a result, the magnet experiences a sinusoidal force and torque, as shown in Fig. 1. The resulting kinetic energy on the magnet can be converted into electrical energy using various energy harvesting techniques, including electrodynamic (electromagnetic), piezoelectric and electrostatic. The damper b_m in Fig. 1 represents the parasitic mechanical damping, and the damper b_e represents the electrical damping corresponding to the generation of electrical energy.

This magnetically coupled electromechanical receiver methodology offers several advantages over inductively coupled WPT approaches. First, the relatively low resonance frequency of the mechanical structure eliminates the need to operate at high frequencies, thereby allowing a higher permeable magnetic flux density than inductively coupled WPT.

Another advantage is the reduction of the receiver size, since a large-area coil is no longer required.
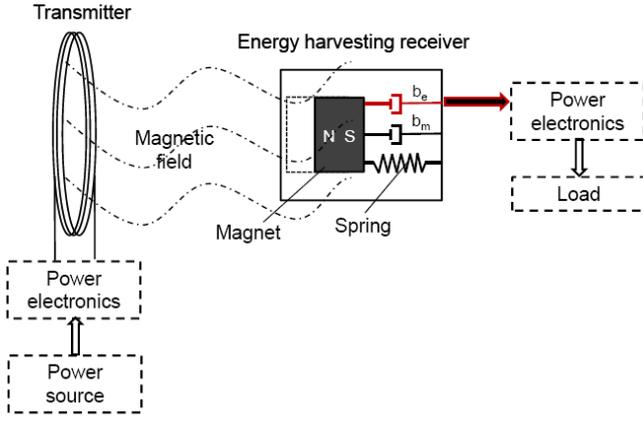

Fig. 1: Schematic of the proposed WPT system.

THEORY

The construction of the receiver in the proposed magnetically coupled WPT system is similar to a conventional vibrational energy harvesting device. In this work, the vibrating structure is a cantilever beam with a permanent magnet at the tip, as shown in Fig. 3. At any location, the force and torque acting on the magnet due to the sinusoidal magnetic field from the coil is given as

$$\vec{F}(t) = \vec{m} \cdot \nabla \vec{B} \sin \omega t \tag{1}$$

$$\vec{\tau}(t) = \vec{m} \times \vec{B} \sin \omega t \tag{2}$$

where $\vec{m}$ is the net magnetic moment of the permanent magnet and is given by

$$\vec{m} = \vec{M}_R V_R. \tag{3}$$

The net magnetic moment depends on the magnet magnetization $\left|\vec{M}_R\right|$, where $\left|\vec{M}_R\right| = B_R / \mu_0$, B_R is the residual flux density, and μ_o is the permeability of free space. The volume of the magnet is V_R. B and ∇B are the magnetic flux density and magnetic flux density gradient along the transmitter coil axis, respectively, and ω is the frequency of the current in the transmitter. Fig. 2 shows a simulated example plot of B and ∇B as a function of distance from the transmitter (1,000 turns, 10 mA current, and 5 cm coil radius).

The position of the receiver with respect to the transmitter determines whether force, shown in Fig. 3(a), or torque, shown in Fig. 3(b), dominates the response of the magnet. In order to maximize the power conversion, an electrodynamic energy harvester must maximize the velocity $v_M(t)$ of the tip of the vibrating cantilever beam. At resonance, the magnitude of the velocity in response to an induced force $F(t)$ and torque $\tau(t)$ are given by

$$\left|v_M(t)\right| = \frac{|\tau(t)|L^2 \omega}{2EI} \cdot Q \tag{4}$$

and

$$\left|v_M(t)\right| = \frac{|F(t)|L^3 \omega}{3EI} \cdot Q, \tag{5}$$

where L, E, I and Q are the length, elastic modulus, moment of inertia, and quality factor of the vibrating cantilever beam, respectively. The quality factor Q is equal to $1/2\zeta$, where ζ is the mechanical damping ratio.
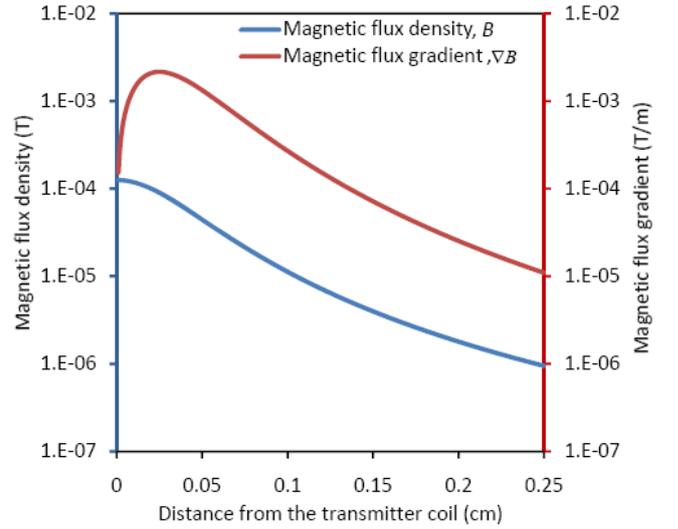

Fig. 2: Magnetic flux density and gradient of magnetic flux density along the normal axis of the transmitter coil with respect to distance.
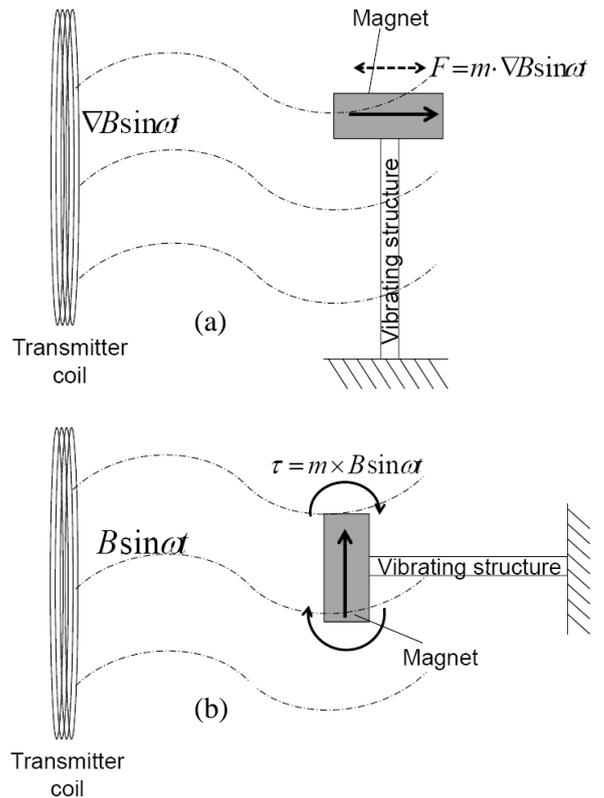

Fig. 3: System configuration for (a) force coupling and (b) torque coupling.

According to Faraday's law, the voltage induced in the receiver coil is given by

$$V_2(t) = NlB_{radial,average} \cdot \left|v_M(t)\right| \tag{6}$$

where $B_{radial,average}$ is the average radial magnetic flux density induced in the receiver coil by the permanent magnet and Nl is the total length of the receiver coil. The average power extracted across a matched load resistance R_L is given by

$$P_{load} = \frac{|V_2|^2}{8R_L} \qquad (7)$$

The preceding analysis can be generalized from the particular geometry of the vibrating beam using generalized lumped elements. Fig. 4 shows this model for the entire WPT system, including the transmitting coil, the receiver vibrating beam and the receiver coil. The transmitter and receiver coils are represented as R_1 and L_1 in series, and R_2 and L_2 in series, respectively. V_S is the voltage applied to the transmitter, and R_L is the load resistance at the receiving coil [4]. The vibrating beam is represented as a series spring-mass-damper with spring constant k (N/m), mechanical damping coefficient b (N·s/m), and mass m (kg). The mass is given by magnet at the tip of the beam.
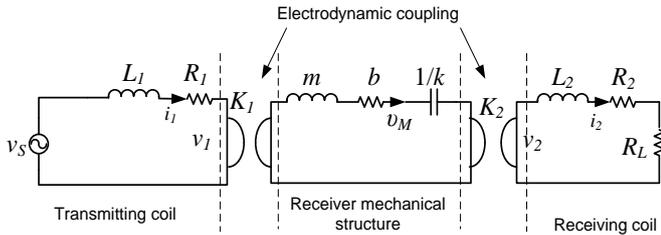

Fig. 4: Equivalent circuit model of the magnetically coupled WPT system.

Assuming the inductance of the coil is negligible, the power generated at the load resistor R_L is given by

$$P = \frac{1}{2}(K_1 \cdot \frac{v_s}{R_1} \cdot \frac{K_2}{Z_m})^2 \frac{R_L}{\left(K_2^2 / Z_m + R_2 + R_L\right)}, \qquad (8)$$

where the transduction coefficients K_1 and K_2 (V·s/m) represent the coupling between each of the circuits, and are given by [4]

$$K_i = \oint_{l_{coil_i}} \vec{B} \cdot d\vec{l} \,, \, i = 1, 2. \qquad (9)$$

$\vec{B}$ is the flux density generated by the magnet, and l_{coil} is the length of each coil. Z_m corresponds to the total effective impedance in the mechanical structure due to the mass, stiffness and mechanical damping. At resonance, the mechanical impedance simplifies to the mechanical damping ($Z_m = b$). Assuming the system is strongly coupled ($K_2^2 / Z_m >> R_2$), and the resistance is optimized ($R_L = K_2^2 / Z_m + R_2$), the power output is given by

$$P \approx \frac{1}{8} \frac{(K_1 v_s / R_1)^2}{b}. \qquad (10)$$

The power (for a cantilever beam) can also be expressed as

$$P \approx \frac{1}{4}\left(\frac{B_r}{\mu_o}\right)^2 \frac{B^2}{\rho^2} \sqrt{\frac{m^3}{Eth^3 L}} Q, \qquad (11)$$

where ρ is the density of the beam, m is the effective mass of the beam, E is the Young's modulus, t is the thickness, h is the height, L is the length, and Q is the quality factor of the cantilever beam. The corresponding maximum efficiency of the system with the optimal load is given by

$$\eta_{max} = \frac{1}{4}(\frac{K_1^2 / Z_m}{R_1} \frac{K_2^2 / Z_m}{\left(K_2^2 / Z_m + R_2\right)}. \qquad (12)$$

EXPERIMENT

A force-coupled system was reported in [4]. A different setup is used to demonstrate a torque-coupled system here, and the corresponding results are presented. The experimental setup consists of a transmitter coil with a 100 mm diameter made of AWG 25 (0.45 mm thickness) wire, and an electrodynamic energy harvester as the receiver, as shown in Fig. 5. The electrodynamic receiver consists of two cylindrical magnets (NdFeB N50, 6.3 x $\pi(9.4/2)^2$ mm^3 volume) attached at the tip of the vibrating cantilever beam (23 x 13 x 0.15 mm^3). The magnetic moment of the magnets must be aligned such that the resulting moment is in the same direction. The cantilever beam is clamped by a bolt and a nut (plastic, 10-24) to a plastic piece custom made using a rapid prototyping machine (Spectrum Z510). The receiver coil (AWG 32, outer diameter x inner diameter x height: 26.6 mm x 12.5 mm x 5.5 mm) is glued to the mounting board underneath the magnets. The receiver is mounted on a wooden plank using a plastic bolt and nut (ANSI 10-32), as shown in Fig. 5. The transmitter is mounted on movable holders placed on three long plastic pipes that are glued on the wooden base such that the center of the transmitter coil is aligned with the length axis of the vibrating beam in the receiver as shown in Fig. 5.
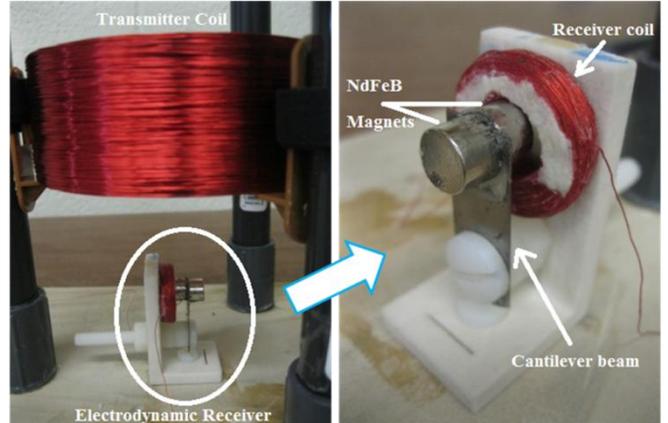

Fig. 5: Pictures of the setup: (a) the WPT system, (b) electrodynamic receiver.

The resistance and inductance of both the transmitter and receiver coils were measured using a DC multimeter (Fluke 189) and an impedance analyzer (Agilent 4294A) and are 32 Ω, 89 mH and 20 Ω, 6.4 mH, respectively. The damping coefficient b is equal to 0.02 Ns/m, and was determined from an amplitude decay plot [6]. An AC current is supplied to the transmitting coil from an Agilent 33120A function generator, which creates a time-varying gradient field. The current is measured with a Tektronix TCP312

current probe and fed into an Agilent DSO-X 2004A oscilloscope along the voltage across the coil. The induced voltage on the receiving coil is measured across a Bourns 3296 4.7 kΩ potentiometer using the same oscilloscope.

RESULTS AND DISCUSSION

The natural frequency of the receiver is determined by sweeping the frequency of the AC current fed to the transmitter and monitoring the open circuit voltage of the receiver. The peak voltage corresponds to a natural frequency of 42.5 Hz. An optimal load resistance of 309 Ω is determined by adjusting the resistive load. The peak power is 0.9 mW for an input power of 6.3 mW, which generates a magnetic field of 0.2 mT at a distance of 1 cm from the receiver. The power output as a function of frequency is shown in Fig. 6, indicating the importance of operation at resonance.
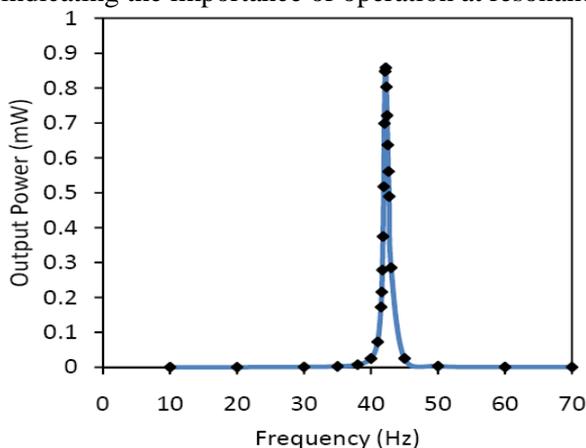

Fig. 6: Receiver output power as a function of driving frequency of the transmitter.
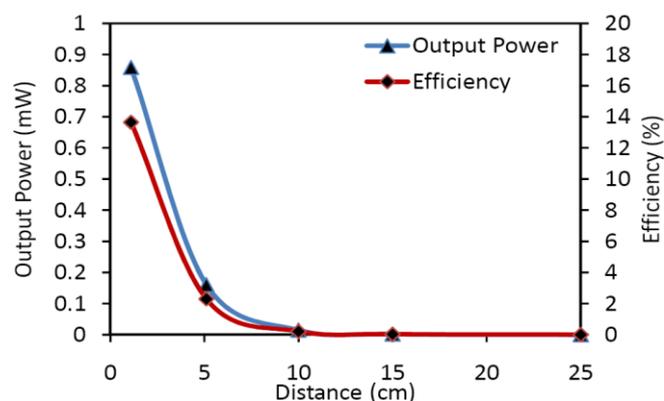

Fig. 7: Output power and efficiency of the WPT system as a function of distance between transmitter and receiver.

Fig. 7 shows the decrease in output power and efficiency with the increase in distance between transmitter and receiver, indicating the range limit of the WPT system. Fig. 8 shows the open voltage of the receiver exhibiting the nonlinear behavior resulting from the spring softening effect of the system with increasing input voltage to the transmitter. This suggests that, for higher input voltages and higher

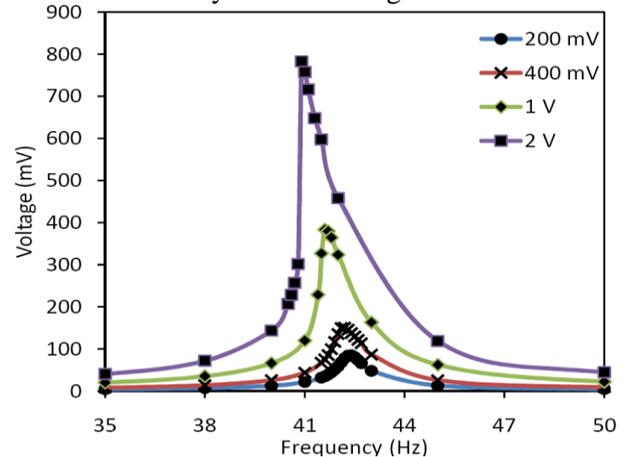power transmission, a nonlinear model is needed. This model is currently under investigation.

Fig. 8: Open circuit voltage at the receiver for various transmitter input voltages.

In conclusion, the presented WPT system should allow power transmission through any obstructing media such as walls, conducting plates and under water, enabling a wide range of applications. The torque-coupled system presented in this paper showed a considerable increase in efficiency (14%) with respect to the force-coupled system (0.1%) presented in prior work [4]. However, the dimensions of the magnet and the cantilever beam will determine if force or torque-coupling would be more effective in a WPT system. Additionally, the efficiency of the WPT system can be further enhanced by increasing the coupling strength in the receiver.

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