WIRELESS POWER TRANSMISSION VIA MAGNETIC COUPLING TO AN ELECTRODYNAMIC RECEIVER

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Abstract: This paper demonstrates a wireless power transmission system that exploits magnetic coupling and electromechanical resonance for safe, spatially distributed, low-frequency power delivery to sensors, consumer electronics, or implantable medical devices. The system uses one or more power transmitting coils and an electrodynamic receiver. An alternating magnetic field from the transmit coil(s) excites a magnet in the receiver into mechanical resonance. The vibrating magnet then functions like an energy harvester to induce voltage/current on an internal coil. In a preliminary demonstration, with only 1 A of current at ~100 Hz, an estimated 5 mW of power is delivered to a compact receiver (1 cm^3 in size) over a distance of 6 cm.

Keywords: wireless power transfer, electrodynamic transduction, magnetic coupling

INTRODUCTION

Wireless power transmission (WPT) aims to completely free electronic devices from direct wire connections. WPT was originally explored by Nikola Tesla in 1893 for long-range power transmission even before the existence of the wired power grid [1]. The effort ceased because of the undesirably large electric field involved. Recent research has focused on near-field power transfer using inductively coupled coils [2-5]. The operating principle of these systems is similar to air-core transformers. Due to the weak mutual inductance between the air-coupled coils, the operating frequency of such systems is usually in the RF range (1-100 MHz) to achieve reasonable efficiency. However, there are strict safety limits on magnetic and electric fields for RF power transmission that greatly restrict the range, efficiency, and thus application of these systems.

In order to transfer Watts of power in an inductively coupled WPT system, the magnetic flux density that permeates the media may be on the order of 10^{-4} T [5]. Such strong flux density is only safe when the operating frequency is lower than 100 kHz [6]. For even lower frequencies, the flux density safety limit is higher. For example, flux density up to 10^{-3} T can be tolerated when the frequency is lower than 760 Hz [7], and up to 0.4 T of static flux density can be tolerated by general public [8]. However, according to Faraday's law, the voltage induced on a receiving coil is proportional to the time rate change of magnetic flux. For sinusoidal excitation, this is proportional to the product of angular frequency, magnetic flux density, and the coil area. Since the power is proportional to the square of the voltage, this means that in order to deliver certain amount of power, either the frequency or the flux density in the receiving coil (the area of the receiving coil is usually predetermined) needs to be sufficiently high, which is possibly not achievable without violating the safety limits.

This paper presents an electrodynamically coupled solution that aims to address this problem. In the proposed system (Fig. 1), a permanent magnet is allowed to oscillate in the vicinity of the receiving coil, providing a large flux density in the coil. The receiving coil and the magnet are in the same package, forming an electrodynamic transducer. The transmitting coil outside the package is connected to the power source and carries an alternating current. The field generated by the transmitting coil activates the motion of the magnet through magnetic force. Power is generated on the receiving coil in a manner similar to an electrodynamic vibrational energy harvester, except the system excitation is provided by the magnetic force rather than an external vibration.

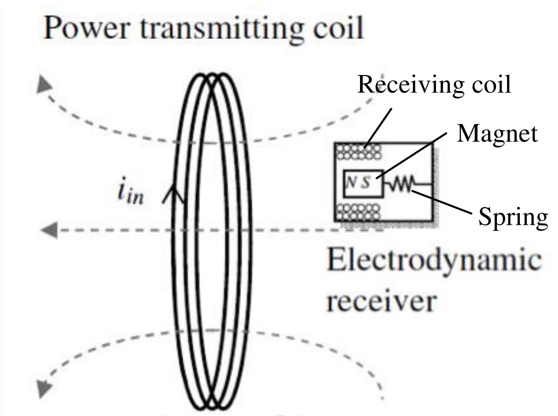
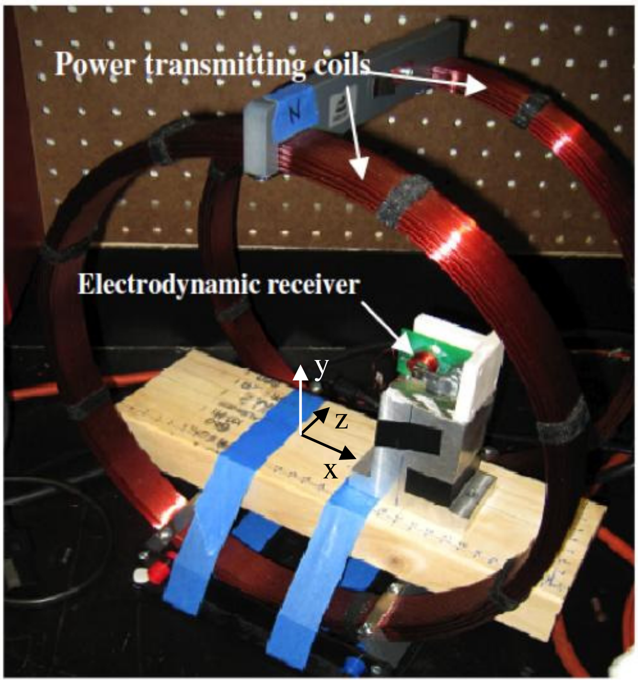


Fig. 1: Schematic of the proposed WPT system.

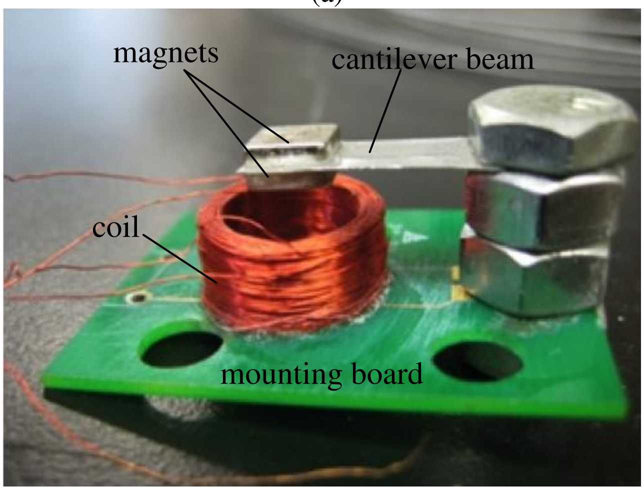
Unlike inductively coupled WPT systems, where strong electric and magnetic fields permeate the transmitting media, the strong magnetic field in the electrodynamically coupled system (from the magnet) is limited to the region close to the receiving coil. This will greatly reduce the exposure of human body to strong magnetic fields. Due to the high magnetic field experienced by the receiving coil, not only can the operating frequency be reduced, but also the receiving coil size. This results in low-frequency operation and a much smaller (possibly integrated) receiver.

EXPERIMENTAL

A simple experiment is performed to prove the concept. In the experiment, a Helmholtz coil-set is used as the transmitting coil, and an electrodynamic energy harvester is used as the receiver (Fig. 2). The Helmholtz coil-set consists of two 295 mm diameter, 124-turn circular coils (AWG 15) with 150 mm spacing. The resistance and inductance of each coil are 1.2 Ω and 800 μH, respectively. The electrodynamic receiver consists of two attracting block magnets (NdFeB N50, 6.4 x 6.4 x 1.6 mm^3) clamped on a cantilever beam (17 x 7.5 x 0.2 mm^3). The other end of the cantilever beam is clamped by a bolt and a nut (aluminum) fixed to the mounting board (FR4 PCB). A circular coil (AWG 36, outer diameter x inner diameter x height: 15 mm x 11 mm x 7.2 mm) is glued to the mounting board underneath the magnets. The receiver is positioned near the transmitting coil using an aluminum holder and a wooden block with gratings.



(a)



(b)

Fig. 2: Pictures of the setup: (a) the whole system, (b) electrodynamic receiver.

The transmitting coils are supplied with counter directional ac current (counter directional currents are used to create a large uniform field gradient) generated by a signal analyzer (Stanford Research Systems, SR785) and amplified by a power amplifier (Techron 7540), creating a time varying gradient field (Fig. 3). The current amplitude is measured with a current probe (Tetronix TCP312) and regulated by the signal analyzer. The induced voltage on the receiving coil is measured with the signal analyzer.

Initially the receiver is positioned midway between the two coils, but radially offset 80 mm (location as shown in Fig. 2a and indicated by the dot in Fig. 3). The excitation frequency is swept around the natural frequency of the receiver for a fixed current amplitude of 1 A. The open-circuit voltage frequency response is plotted in Fig. 4. A peak voltage of ~0.35 V is generated at ~103 Hz, which is the natural frequency of the receiver. Based on the output impedance of the receiver at this frequency (~15 Ω, almost purely resistive), the maximum power delivery to a resistive load is estimated to be ~1 mW, which is sufficient to power sensors or other low-power electronics. Although the input power on the transmitting coil is measured to be ~1.2 W, and the efficiency is only 0.1%, great potential improvement is discussed later.

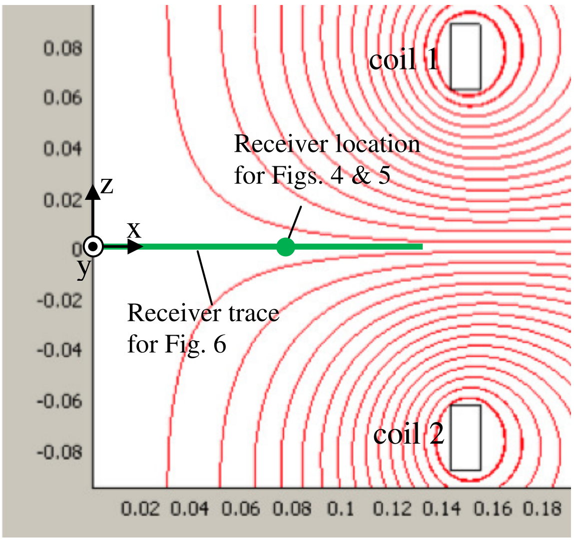


Fig. 3: Streamline plot of the flux density generated by the counter-directional coil currents using 2D axi-symmetric FEM simulation on COMSOL Multiphysics.

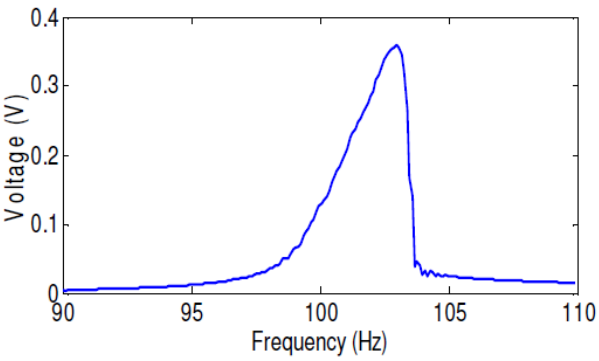


Fig. 4: Open-circuit voltage amplitude vs. frequency at 1 A excitation.

With the frequency fixed at the natural frequency (103 Hz), the transmitting coil current amplitude is then varied from 0 to 1 A, and the open-circuit voltage is recorded (Fig. 5). The relationship between the open-circuit voltage and the input current amplitude is almost linear.

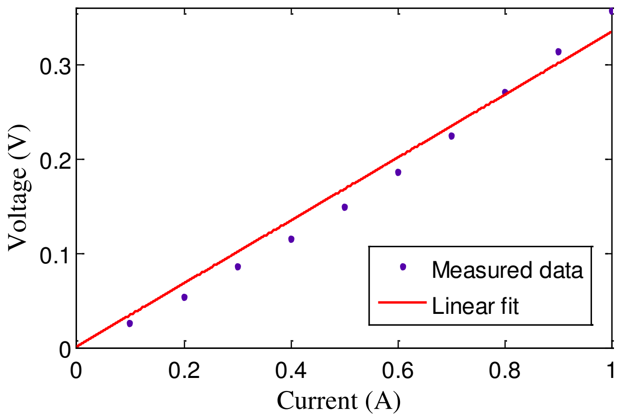


Fig. 5: Open-circuit voltage vs. input current amplitude at 103 Hz excitation.

Next, the magnets on the receiver are removed, so that the system resembles an inductively coupled WPT system between the transmitting coils and the receiver coil. With 1 A input current, the frequency is swept within the same range as the previous test. The results show that the induced open-circuit voltage is two orders of magnitude lower than the electrodynamically coupled system. The estimated power is ~5000x lower. The open-circuit voltage of the inductively coupled system increases to a level similar to the electrodynamically coupled system only when the frequency is increased to greater than 10 kHz.

In the last experiment, the position dependency is investigated by moving the receiver radially along the green trace shown in Fig. 3. The open-circuit voltage vs. radial position is plotted in Fig. 6. The data shows the voltage increasing to a maximum of ~0.75 V as the receiver moves to the radial position of 110 mm. At this peak voltage location, ~5 mW of power is estimated, a 5x improvement over the prior discussed results.

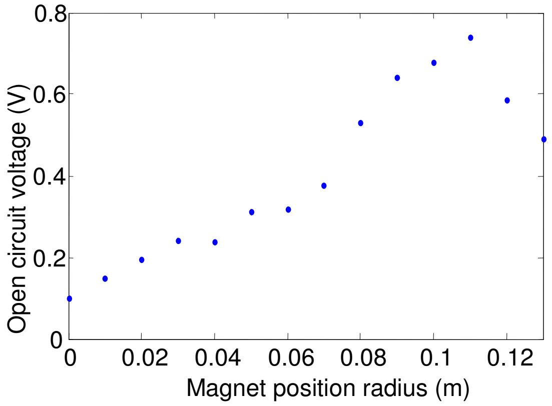


Fig. 6: Open-circuit voltage amplitude vs. magnet position for 1 A current at 103 Hz.

THEORY

The experiments show that the electrodynamically coupled WPT concept is promising for low-frequency applications. However, significant improvements can be made to increase the power transfer efficiency.

An equivalent circuit model of the WPT system is developed and analyzed using the lumped element method [9]. As shown in Fig. 7, the model consists of three parts: the transmitting coil, the receiver mechanical structure and the receiving coil. The transmitting and receiving coils are both modelled with a series R-L network (R_1 & L_1 and R_2 & L_2). V_S and R_L are the source voltage and the load resistance attached to the transmitting coil and receiving coil, respectively. The mechanical structure is modelled using a mass-spring-damper system with mass m (kg), spring constant k (N/m) and viscous damping coefficient b (N·s/m). The electrodynamic coupling between each of the coils and the mechanical structure is modelled with two gyrators with gyration ratios K_1 and K_2 (V·s/m) representing the transduction coefficients. The transduction coefficient is given as

$$K = \oint_{l_{coil}} \vec{B} \cdot d\vec{l}\,, \tag{1}$$

where $\vec{B}$ is the flux density generated by the magnets, and l_{coil} is the length of the coil.

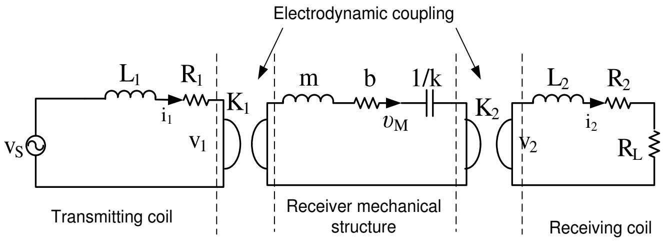


Fig. 7: Equivalent circuit model of the electrodynamically coupled WPT system.

The circuit can be simplified by assuming that the operating frequency under consideration is sufficiently low, so that the inductance of both transmitting and receiving coils can be ignored. With this assumption, the maximum efficiency is obtained at the natural frequency, when the load resistance is given by

$$R_L = \sqrt{\frac{(\gamma_1 + \gamma_2 + 1)(\gamma_2 + 1)}{\gamma_1 + 1}} R_2\,, \tag{2}$$

where

$$\gamma_i = \frac{K_i^2}{R_i b}, \; i = 1, 2 \tag{3}$$

is the unitless coupling strength [10] of the electrodynamic coupling. The maximum power efficiency is given by

$$\eta_{max} = \frac{\gamma_1 \gamma_2 \beta}{\left[(\gamma_2 + \beta + 1)(\gamma_1 + 1) \right] (\gamma_2 + \beta + 1)}, \tag{4}$$

where

$$\beta = \sqrt{\frac{\gamma_1 + \gamma_2 + 1 \quad \gamma_2 + 1}{\gamma_1 + 1}} \tag{5}$$

For a well-designed WPT system, it is reasonable to assume that the electrodynamic receiver is strongly coupled [10]:

$$\gamma_2 \gg 1. \tag{6}$$

Also, since the transmitting coil is much farther away from the magnet than the receiving coil, the transmitting coupling strength γ_1 is much smaller than the receiving coupling strength γ_2:

$$\gamma_1 \ll \gamma_2. \tag{7}$$

Substituting (6) and (7) into (2) and (4), the maximum efficiency condition can be simplified to

$$R_L = \gamma_2 \sqrt{\frac{1}{\gamma_1 + 1}} R_2, \tag{8}$$

and the maximum efficiency is given by

$$\eta_{max} = \frac{\gamma_1 \sqrt{\frac{1}{\gamma_1 + 1}}}{\left[1 + \sqrt{\gamma_1 + 1}\right]\left(1 + \sqrt{\frac{1}{\gamma_1 + 1}}\right)} \tag{9}$$

A plot of the maximum efficiency vs. transmitting coupling strength is shown in Fig. 8. Note that the plot is subject to the assumptions given by (6) and (7). It can be concluded that the key to high efficiency is the transmitting coupling strength. However, the coupling strength in the demonstrated system is estimated to be on the order of 10^{-3}, which explains the low efficiency.

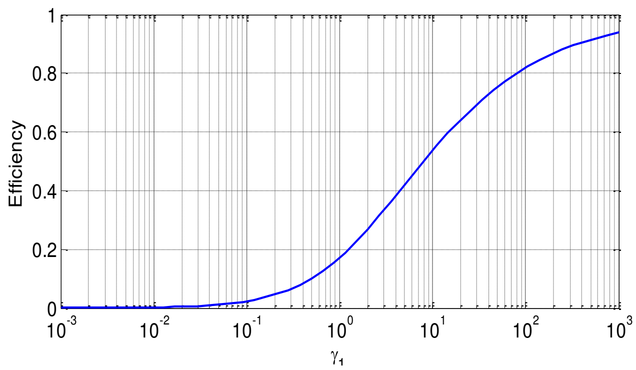


Fig. 8: Maximum efficiency vs. transmitting coupling strength, when $\gamma_2 \gg 1$ and $\gamma_1 \ll \gamma_2$.

There are generally four ways to increase the coupling strength [10]: increase the average radial flux density at the coil conductor; increase the conductor volume of the coil; use highly conductive material for coil conductor; and reduce the mechanical damping coefficient. All of these may be effective means for increasing the overall WPT efficiency.

CONCLUSION

The demonstrated electrodynamically coupled WPT system provides a safe, low-frequency and potentially small-size solution for broad range of WPT applications. The system model reveals that by increasing the transmitting coupling strength, the efficiency can be significantly increased. Future work will be done to verify the model and further optimize the system for specific application.

ACKNOWLEDGEMENT

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