Electrodynamic wireless power transmission to a torsional receiver

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Abstract. This paper presents a wireless power transmission (WPT) concept that uses electrodynamic coupling and torsional motion of a permanent magnet in the receiver. The system is shown to transfer an average power of 3.09 mW (power density equal to 143 μW/cm³) over a distance of 1 cm, an average power of 1.98 mW over a distance of 2 cm, and an average power of 126 μW over a distance of 7 cm. We also demonstrate unaltered power transmission through conductive media, including a human hand and an aluminum plate, highlighting a key advantage of the electrodynamic wireless power transmission approach.

1. Introduction

Many groups currently research the use of inductively coupled coils to achieve wireless power transmission (WPT) [1-5]. Inductively coupled WPT utilizes an alternating magnetic field from a transmitter coil to induce a current in a receiver coil some distance, $d$, away via electromagnetic (inductive) coupling. Electrodynamic WPT is an alternative method, in which the magnetic field induces mechanical motion in a permanent magnet situated above a receiver coil [6-7]. The motion of the magnet induces a current through the receiver coil, and if a load is connected to the receiver coil, WPT from the transmitter coil to the load is realized. Inductively coupled WPT solutions typically operate in the MHz range [1-4], with the exception of [5], which uses frequency control circuitry to transmit at a frequency around 72 kHz. Conversely, the electrodynamically coupled approach allows for much lower frequencies in the range of 10’s of Hz [6-7]. This lower operation frequency facilitates WPT through electrically conductive media, such as the human body or metal walls, which have been shown to attenuate signals in the MHz range [1]. Additionally, the limit placed by IEEE on the magnetic field a person’s head or torso may be exposed to for frequencies of 20-759 Hz is 0.904 mT, whereas for frequencies 3 kHz to 5 MHz, the allowable magnetic field exposure is limited to 0.205-0.229 mT [8-9]. The use of lower frequency range may therefore be advantageous for biomedical and consumer applications, since higher fields can be safely used to transmit power within a populated environment (e.g. a room), or potentially even to receivers located inside a patient’s body (e.g. for implanted medical devices).

Previously, our group has experimented with a prototype electrodynamically coupled WPT system that yielded power transmission of 0.15 mW over a distance of 2.2 cm [6], and 0.9 mW over a distance of 1 cm [7]. The system employed a cantilever beam with a magnet as a tip mass and had two operating modes: force mode and torque mode in which the field from the transmitter induced a force

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or torque, respectively, on the magnet. Both modes induced vibration of the cantilever beam, but efficiency and maximum power transmitted were both higher in the torque mode of operation. This prompted the question: what if the receiver was built with an architecture to better capitalize on torsional motion of the magnet? Hence, the system presented in this paper was designed with torsion as the desired vibrational mode, with hopes of increasing the power output and/or efficiency.

2. WPT System Design

The torsional electrodynamic WPT system has two distinct parts: a transmitter coil and a receiver, as illustrated in figure 1. The transmitter coil has an outer diameter of 63 mm, an inner diameter of 49 mm, and a height of 12.3 mm. It consists of approximately 435 turns of AWG 28 copper wire, estimated from the resistance of the wire. The receiver comprises a disc-shaped permanent magnet suspended over a compact receiver coil by rubber bands that function as torsion springs (figure 2). The magnet used is an N45 grade NdFeB diametrically magnetized ring magnet with an outer diameter of 6.35 mm, an inner diameter of 3.17 mm, and a thickness of 3.17 mm. The receiver coil’s outer diameter is 26.5 mm, inner diameter is 13 mm, and height is 8.4 mm and comprises approximately 187 turns of AWG 25 copper wire, estimated from the resistance of the wire. The distance \( d \) between the transmitter and receiver is defined as the distance between the center of the transmit coil and the center of the receiver coil.

To transmit power, an alternating electric current is input to the transmitter coil, which induces a time-varying magnetic field. When in range of the receiver, the magnetic field from the transmitter applies an alternating torque on the receiver magnet, causing the magnet to rotate back and forth over the receiver coil. The resulting time-varying magnetic flux from the magnet motion induces a current in the load, and hence power delivery. Compared to a translational motion, the torsional motion of this architecture has the potential to induce a higher rate of change in magnetic flux through the coil, since the magnet alternates between completely in-plane (zero flux) and out-of-plane (maximum flux) with respect to the receiver coil in just one quarter of a period. When the transmitter frequency equals the resonant frequency of the torsional resonator, a very large response is observed (mechanical quality factor of 47).

3. Test Setup

The test setup used in the characterization of the wireless power transmission system is as follows. An Agilent 33120A function generator was used to supply the AC input power to the transmitter coil. The rms voltage supplied was measured via an Agilent DSOX2004A 4-channel oscilloscope, while the
current supplied was measured with a Tektronix TCPA312 current probe. The probe was connected to a Tektronix TCPA 300 current probe amplifier, which was in turn connected to the oscilloscope to display the rms current measurement. Additionally, the rms output voltage was measured across the leads of the receiver coil via the oscilloscope. A 100 Ω potentiometer was used as a resistive load. A Keithley 2400 SourceMeter was used to measure the resistance of the load potentiometer.

4. Results
Using the test setup described in the previous section, first the open-circuit voltage was measured over varying input current and frequency, at a fixed transmission distance of 1 cm. Additionally, the power transmitted was measured over varying load resistance, frequency, and distance. Finally, the output power was measured under the same input conditions while transmitting through three different media.

4.1. Open-circuit voltage
At a transmission distance of 1 cm, for constant-amplitude current inputs of 1 mA\textsubscript{rms}, 5 mA\textsubscript{rms}, and 10 mA\textsubscript{rms}, the open-circuit voltage was measured across the output of the receiver coil for different excitation frequencies. For each excitation level, the current amplitude was held constant to ensure a constant amplitude magnetic field from the transmitter, since the impedance of the transmitter was frequency dependent. As a consequence, changes in the receiver output voltage were due only to changes in the frequency of the alternating magnetic field, and not changes in the magnetic field amplitude. As can be seen in figure 3, a resonant dynamic response was observed with peak output at 53-56 Hz. However, the peak voltage amplitude did not scale proportionally with the input current, and a “spring softening” type behavior was noted, both indicating non-linear behavior.

To prove the output from the receiver was caused by the magnet’s torsional motion relative to the receiver coil and not simply due to inductive coupling between the transmitter coil and receiver coil, the magnet was removed from the receiver, and the open-circuit rms output voltage was measured for the same distance, frequencies, and input excitation as before. From figure 4, it is clear that the contribution from inductive coupling between the coils (~1 mV) is negligible when operating at resonance.

4.2. Maximizing output power
For the same transmission distance of 1 cm, the output power was then measured across a potentiometer connected with the receiver coil’s terminals. The optimal load resistance was measured by tuning the resistance until maximum time-average output power was achieved. As shown in figure 5 below, for a 5 mA\textsubscript{rms} input current and a fixed 1 cm transmission distance, operating at a frequency of 54 Hz, the optimal load resistance was found to be 4.65 Ω, yielding an output power of 141.8 μW. However, it must be noted that this load resistance was only optimal at this distance and for this input
current. The same process was repeated to find the optimal load resistance for 20 mA\textsubscript{rms} and 100 mA\textsubscript{rms} input currents at the same fixed distance of 1 cm, which were found to be 2.63 $\Omega$ and 1.20 $\Omega$, respectively. The system’s output power was also measured over varying frequency, in order to determine the optimal operating frequency of the system. For a 5 mA\textsubscript{rms} input and a load resistance of 4.65 $\Omega$, the system transmitted a maximum power of 161.6 $\mu$W at an optimal frequency of 55 Hz, as can be seen in figure 6.

4.3. Power vs. distance
The maximum transmission distance between the transmitter and receiver is paramount in many practical wireless transmission implementations. Hence, the system was characterized for transmitter currents of both 20 mA\textsubscript{rms} and 100 mA\textsubscript{rms} using the optimal load resistances found in the previous section. The transmitter and receiver were set a certain distance apart, and then the excitation frequency was tuned to achieve the maximum output for that distance. This process was repeated for distances ranging from 1 cm to 10 cm. As expected, the power decays with distance as shown in figure 7. At a distance of 1 cm, the transmitted power was 1.04 mW for a 20 mA\textsubscript{rms} input current and 3.09 mW for an input current of 100 mA\textsubscript{rms}. For many low-power sensing applications, 100 $\mu$W is sufficient power. With this benchmark in mind, an output power of 100 $\mu$W was achieved at a distance of 4.3 cm for an input current of 20 mA\textsubscript{rms} and at a distance of 7.4 cm for an input current of 100 mA\textsubscript{rms}.

4.4. Transmission through solid media
To demonstrate this system’s ability to transmit power through conductive media, measurements were taken both with and without solid objects obstructing the path between the transmitter and receiver. The solid media tested are two media likely to come in between a transmitter and receiver if used in commercial or industrial applications: a human hand and a 6.75 mm thick plate of aluminum.
As seen in figure 8 below, the power transmission hardly differs when compared with transmission through air. For a 100mA current in the transmitter coil and a transmit distance of 8 cm, output powers of 94.1 μW, 93.6 μW, and 93.6 μW were measured for transmission through air, a human hand, and the aluminum, respectively. The variation between these three measurements is small enough to be attributed to experimental error.

\[\text{Figure 8. Average output power at a transmission distance of 8 cm for a 100 mA current input through three media: air, a human hand, and aluminum.}\]

5. Conclusions

The results from this initial prototype are promising, with a maximum observed output of over 3 mW. Furthermore, an output power of 126 μW was achieved over a distance of 7 cm. It was demonstrated that power transmission with our device is virtually unimpeached through both a human hand and a plate of aluminum, illustrating a key potential advantage of the electrodynamic WPT approach for real-world applications. This is especially true for bio-applications in which the transmitted power needs to pass through the skin to reach the receiver(s) inside the body.

Ongoing work is focused on shrinking the receiver’s size and increasing the maximum transmission distance; all this while keeping the maximum transmittable power at a practical, usable level. Additional work is also being done on experimenting with different suspension materials, with the hopes of achieving higher efficiency, since rubber elastic produces a highly damped response.

Acknowledgements

This work was supported in part by a National Science Foundation Graduate Research Fellowship for Kelly McEachern.

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