Magnetic Pendulum Arrays for Efficient Wireless Power Transmission

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Abstract. In this paper we would like to propose an innovative electromechanical transmitter called Magnetic Pendulum Array (MPA), for efficient wireless power transmission at Ultra Low Frequencies (ULF). We take advantage of the high Quality (Q) factor and low dissipation in the electromechanical system to demonstrate efficient power transfer. It has been shown that using Magnetic Pendulum arrays leads to about 10dB% higher power transfer efficiency at the resonance frequency of 447 Hz as compared to a coil of similar dimensions.

1. Introduction

Wireless Power Transfer (WPT) has received considerable attention in the past decade due to its diverse applications such as charging of mobile and cellular devices, electric automobiles and biomedical implants. The most commonly used approach is inductive coupling of coils in which a transmitter coil produces alternating magnetic field which induces current and voltage in a receiver coil leading to wireless transfer of power. Most WPT systems work in the frequency range greater than 1 MHz. Previously low frequency electromechanical wireless power transfer systems have been demonstrated in [1-3] which use rotating magnets. However, those magnets are driven by motors where a low power conversion efficiency is expected as the motor is running with almost no load. This limits the overall system Quality factor and the power transfer efficiency. We would like to propose a near field WPT system which uses an electromechanical transmitter to transfer power at Ultra Low Frequencies (ULF) that can take advantage of the high-Quality(Q) factor and low dissipation in a mechanical system not consisting of rotating magnets but rather consists of an array of magnetic pendulums in oscillatory motion.

2. System Design

It is well known that the power transfer relation for a near field based wireless power transfer system is governed by the following link equation [4]:

\[ P_r = P_t \left( \frac{2}{1+k^2Q_1Q_2} \right)^2 k^2 Q_1 Q_2 \left( 1 - \frac{Q_1}{Q_1_{int}} \right) \left( 1 - \frac{Q_2}{Q_2_{int}} \right) \]  (1)

where \( Q_1 \) and \( Q_2 \) are the loaded quality factors of the transmitter and the receiver; \( Q_{1,int} \) and \( Q_{2,int} \) are the intrinsic quality factors of the transmitting and receiving antennas. \( k \) is the coupling coefficient.
determined by the distance between the antenna and the radius of the antenna [4]. It is evident from the above analysis that to achieve a high-power transfer efficiency, a high-Quality factor antenna system is essential. The higher Quality factor the antenna has, the further distance the power can be transferred wirelessly. The advantage of using Magnetic Pendulum Arrays is that they can achieve extremely high Quality factors and with low dissipation in a mechanical system, high efficiency power transfer can be achieved. To create the dynamic magnetic field required for power transmission, the Magnetic Pendulum Array consists of diametrically magnetized cylindrical magnets mounted on bearings excited by an RF coil as shown in figure 1. The array is self-biased as there is no need of a static external magnetic field and the magnets align themselves due to the field of the adjacent magnets. The RF coil creates a horizontally oriented magnetic field $B_{RF}$ that can physically rotate the magnets’ magnetic orientation toward the horizontal direction. The role of the RF coil is to inject the RF energy needed to build up the harmonic motion and replenish any losses, including the RF energy that is radiated and dissipated after the system reaches its steady state. The resonant frequency $f$ of such a system can be shown as:

$$f = \frac{1}{2\pi} \left( \frac{6M_s B_{ao}}{\rho} \right)^{\frac{3}{2}}$$

(2)

where $r$ is the radius of the cylinder, $M_s$ is the magnetization density of the magnet in the pendulum, and $\rho$ is the density of the magnet. $B_{ao}$ is the field between adjacent magnets. It is to be noted that the frequency is inversely proportional to the radii of the magnets and directly proportional to the square root of the field strength and magnetization density. The desired frequency can be obtained by controlling these parameters. Assuming no external bias and NdFeB magnets of radius 1.5 mm, we can calculate the expected resonant frequency from equation (2) as follows:

$$f = 447 \text{ Hz}$$

(3)

With $r = 1.5 \text{ mm}, \mu_0 M_s = 1.4 T, B_{ao} = 200G$ and $\rho = 7500 \text{ kg/m}^3$. 

![Figure 1. Self-biased Magnetic Pendulum Array.](image)

The limitation on the Q factor of the system because of friction losses can be shown to be
\[ Q = 2\pi \frac{W_{ME}}{W_{fr}} = \frac{3\pi M_B a_0 \theta_{max} V}{\mu F r} \]  

Where \( W_{ME} \) is the mechanical energy associated with the magnets and \( W_{fr} \) is the frictional losses associated with the bearings per cycle. \( \mu \) is the co-efficient of friction, \( F \) is the residual force on the bearings due to the imbalance of the system, \( V \) is the total magnetic volume and \( \theta_{max} \) is the maximum angular displacement of the pendulum. Hence to achieve higher Q factors we need to reduce the bearing radius and friction loss further and increase the volume fraction of the magnets.

3. Equivalent Circuit Model

In this section we derive an equivalent circuit model for the Magnetic Pendulum Array based on the physics of coupling between the coil and magnets as shown in figure.2. The magnet array can be modelled as a parallel RLC circuit. \( R_c \) and \( L_c \) represent the resistance and inductance of the coil, respectively. The resistance \( R_p \) is mainly attributed to the friction in the bearings. The Capacitor \( C_p \) represents the kinetic energy of the pendulum, and the inductance \( L_p \) represents the magnetic potential energy stored in the flux associated with the pendulum.

\[ Q_p = \frac{1}{\sqrt{L_p C_p}} \]  

At resonance, the imaginary part of the sum of the impedances can be equated to zero as

\[ \text{Im}ag \left( j \omega L_c + \frac{1}{j \omega L_p + j \omega C_p + \frac{1}{R_p}} \right) = 0 \]  

In a high Q system, we can assume there are no frictional and mechanical losses and ignore the \( \frac{1}{R_p} \) term. Simplifying for the series resonance \( \omega_s \) we get

\[ \omega_s = \sqrt{\frac{L_c + L_p}{L_c L_p C_p}} \]
4. Measured Results
A five-element prototype of the Magnetic Pendulum Array was fabricated and measured. The fabricated prototype is shown in figure 3. The Magnetic Pendulum Array consists of 5 diametrically magnetized cylindrical NdFeB N55 magnets attached to steel bearings in a plastic housing through aluminium brackets. Each magnet has a diameter of 3 mm and height 40 mm. The housing is made of plastic to prevent eddy current losses. A coil made of AWG26 copper wire with 125 turns is wrapped around the magnets to provide the excitation field. The input signal is generated from a signal generator and amplified using an audio power amplifier before being fed to the Magnetic Pendulum Array. A 45-turn loop antenna of radius 26 cm is used as a receiver, and the received signal is observed using a spectrum analyser.

The efficiency of the Magnetic Pendulum Array as compared to a bare coil is plotted in figure 4. The efficiency shows three distinct peaks corresponding to the three modes of oscillation of the Magnetic Pendulum Array. The efficiency is maximum in the in-phase mode at 447 Hz. The percentage efficiency of magnetic pendulum array is 10 dB better than a bare coil at 447 Hz. The spiking of the efficiency at resonance can be explained by the fact that, at resonance, the input current is decreased and the transmitted power peaks, whereas for the bare coil, input current increases with increase in frequency, leading to larger ohmic losses and a reduction in the efficiency.
5. Conclusion
In this paper an efficient and innovative method of wireless power transfer which utilizes mechanical resonance with high Q factor was presented. It was observed that a significantly higher fraction of power is transmitted at resonance with the pendulum array as compared to a bare coil. Future work involves improving the mechanical system to achieve higher Q factors resulting in more efficient transfer of power and obtaining a better model of the system. It can also be seen that the system has the potential to be used as an ULF antenna for a multitude of other applications.

6. References
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