PIEZOELECTRODYNAMIC GYRATOR: ANALYSIS, EXPERIMENTS, AND APPLICATIONS TO WIRELESS POWER TRANSFER

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Abstract: We present theoretical analysis and experimental results of a device we call a *Piezoelectrodynamic Gyrator (PED-G)*, and discuss its applications to low-frequency wireless power transfer (WPT) and AC energy harvesting. A PED-G utilizes a resonating mechanical spring-mass system (receiver) containing a permanent magnet as its proof mass, which is excited to resonance by a sinusoidal magnetic field generated by a nearby coil (transmitter) on the primary side. The mechanical energy in the resonating spring-mass system is then extracted through a piezoelectric coupling to an electric circuit on the secondary side. We present experimental results of two PED-G prototypes. Electromechanical resonance enables WPT applications at frequencies orders of magnitude lower than that of purely inductively coupled WPT.

Keywords: Wireless Power Transfer, Piezoelectric, Electromagnetic, Gyrator

INTRODUCTION

Wireless power transfer (WPT) is a potentially promising technology for applications such as wirelessly powering distributed sensor nodes [1], body sensor networks or electrical vehicle charging. Traditional WPT systems employ coil–based approaches that require operations at high (several kHz) frequencies in order to achieve resonance at sufficiently high Q [2]. However, transduction to the mechanical domain enables the use of electromechanical components to achieve resonance at much lower frequencies [3,4,5], enabling efficient power-delivery mechanism for distributed wireless power-monitoring sensors [1].

In this work, we analyze and describe the operation of a *Piezoelectrodynamic Gyrator* (*PED-G*) as the electromechanical receiver for WPT. PED-G is a generalized version of the electromechanical AC energy scavenger [4] and is similar to the electrodynamic WPT [3,5] except that it uses piezoelectric transduction to transfer power from the mechanical domain to the secondary electric circuit. The piezoelectric transduction allows the system to operate as a gyrator [6] rather than a transformer. Implemented purely through the use of passive components, a PED-G offers an anti-reciprocal relationship between its two ports, relating the through-variable (current) in one port to the across-variable (voltage) in the other port. As it allows for load isolation and voltage amplification, a PED-G enables interesting applications in the domain of WPT and AC energy harvesting.

In the remainder of the paper, an analytical model describing the single-degree-of-freedom (1DOF) lumped-parameter representation of the PED-G system is presented. Experimental results validating the operation of the PED-G will be shown for two fabricated prototypes. Finally, the broad applications of PED-G to WTP and AC energy scavenging will be discussed.

PIEZOELECTRODYNAMIC GYRATOR

The schematic representation of the PED-G is shown in Fig 1. It consists of a transmitter coil on the primary side, and an electromechanical receiver at the secondary side. The receiver can be oriented either in force mode, or torque mode with respect to the transmitting coil.

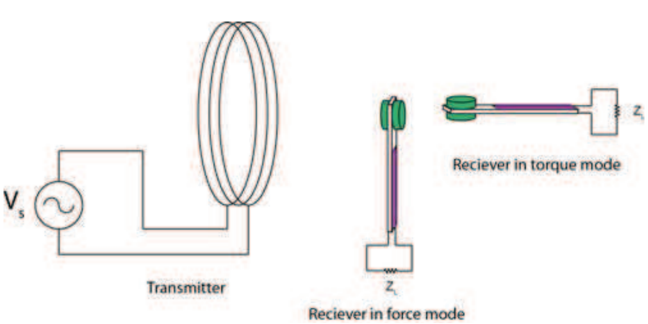

Fig. 1: Schematic representation of a PED-G system.

The 1DOF lumped-parameter equivalent circuit representation of the PED-G system is shown in Fig. 2.

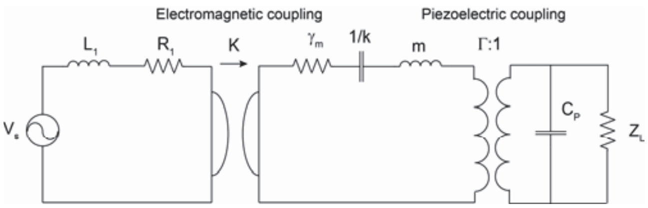

Fig. 2: Lumped-parameter circuit representation of a PED-G.

The input to the transmitter on the primary side of the PED-G is represented by a driven harmonic voltage source. The transmitting coil is represented by inductance L_s and resistance R_s. The electromagnetic coupling between the transmitting coil and the receiver is described by the ratio of gyration (transduction coefficient), K. Parameters γ_m, k, and m represents the mechanical damping, short-circuit stiffness, and the modal mass of the mechanical system, respectively. The piezoelectric coupling is represented by a transformer with the turn-ratio Γ. The electrical circuit on the receiver (secondary) side is modeled by the clamped capacitance C_p of the piezoelectric layers and a load Z_L across which the power is generated.

The ratio of gyration represents the coupling between the current in the transmitting coil and the induced force on the magnets in the mechanical domain. Assuming only one axis of compliance for the piezoelectric cantilever with a tip mass, the ratio of gyration K along the translation direction, x is given by [4],

$$K = \frac{\left| m \frac{dB_x(x)}{dx} \right|}{I_S} \tag{1}$$

in the force mode, and

$$K = \frac{3}{2l_{eff}} \frac{\left| mB_x(x) \right|}{I_S} \tag{2}$$

in the torque mode, where B_x is the magnetic flux density in the direction perpendicular to the coil, m is the magnitude of the magnetic moment, I_s is the source current, and l_{eff} is the distance between the foot of the cantilever and the center of the magnets.

Assuming a bimorph piezoelectric cantilever beam operating in 31-mode connected in parallel [6], the turn ratio Γ is.

$$\Gamma = -\frac{3d_{31}t_pY_pb_pC_p}{2\varepsilon_{33}(L-L_X)L}, \tag{3}$$

where t_p is the thickness of the piezoelectric layer, b_p is the distance from the center of the cantilever to the center of the piezoelectric layer, L is the length of the cantilever, and L_x is the length of the cantilever clamped by the magnets constrained against bending.

Reflecting mechanical impedance across the transformer onto the secondary electrical domain allows us to combine the gyrator and transformer to form a single equivalent gyrator with the ratio of gyration $K^*=K/\Gamma$. Consequently, this gyrator is instantiated using purely passive components.

PED-G PROTOTYPES

Two prototypes, referred to as prototype A and B, were developed to validate the feasibility of the PED-G concept. Both prototypes were constructed from bimorph piezoelectric cantilevers (Piezo Systems Inc.) with permanent magnets mounted on the tips. A photograph of prototype A and B is shown in Fig. 3.

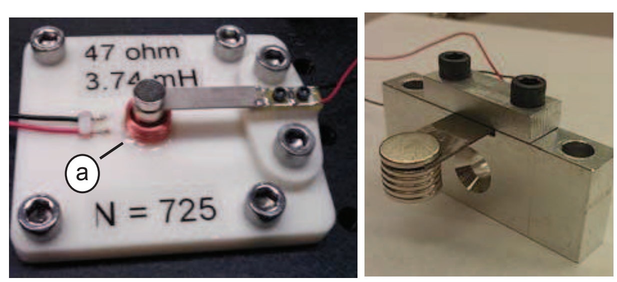

Fig. 3: PED-G prototypes A (left) and B (right). Prototype A is shown attached to the near-coil transmitter (a).

PED-G prototype A used a cantilever that is 6.35 mm wide, 28.58 mm long, and 0.51 mm in thick. The diameter of the magnets chosen for this prototype had the same dimension as the width of the cantilever. The upper and lower portions of the axially energized N52 cylindrical magnets used in the first prototype had thicknesses of 3.18 mm and 6.35 mm, respectively. Prototype B used a similar piezoelectric cantilever and magnets, except that its width was 12.7 mm. The upper and lower thicknesses of the magnets for the second prototype were 1.59 mm and 7.94 mm, respectively. From both prototypes, the magnets were placed such that their centers were aligned to the edges of the cantilevers in the longitudinal (axial) direction. Both cantilevers had a 0.13 mm brass center shim sandwiched by two 0.19 mm piezoelectric layers made of PZT-5A (see. Piezo systems catalog, Q220-A4).

EXPERIMENTAL RESULTS

Setup

The performance of the PED-G system was evaluated on a near-coil setup in force mode and on a far-coil setup in both the force and torque mode. In the near-coil setup (see Fig. 3 left), a small coil was fabricated between the coil and magnets in the regions of the greatest radial flux density for the two magnets below the cantilever. The self-inductance was known, and thus the AC voltage across the coil was measured with a multi-meter and the input current was calculated. The induced signal from the piezoelectric cantilever was measured across a resistor box with a custom op-amp buffered National Instruments DAQ.

In the far-coil setup, the PED-G was evaluated as follows. An AC voltage was supplied to the transmitting coil from an Agilent 33120A function generator, and the current in the transmitter coil was measured with a Tektronix TCP312 current probe. Both these signals were recorded using an Agilent DSO-X 2004A oscilloscope. The phase difference between the voltage and current in the transmitter was readily obtained from the oscilloscope. The far PED-G setup for prototype B in both the force and torque mode configurations is shown in Fig. 4.

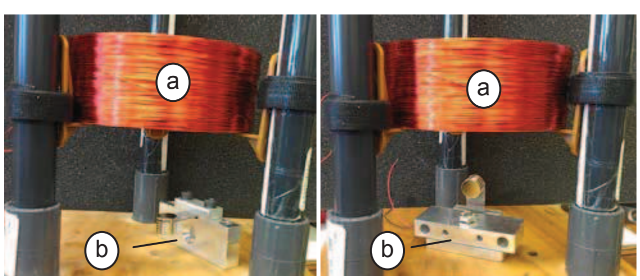

Fig. 4: Far-coil experimental setup for PED-G prototype B in force (left) and torque (right) configurations.

The voltage from the piezoelectric receiver was measured across a variable load potentiometer and was fed to the same oscilloscope. The resistance in the potentiometer was separately measured with a digital multimeter (Fluke 189). To determine WPT system performance with respect to the distance between the transmitter and receiver, the amplitude of the current into the transmitter was kept constant at 2 mA_{RMS}, and the separation distance between the transmitter and receiver was varied gradually from 0 cm to 12 cm. At each of the distances measured, the WPT system was tuned to resonance and the corresponding optimal load resistance and the resulting peak power output was determined. The input power to the transmitter was also recorded at each distance interval.

Results

The near-coil setup was operated in force mode only. As indicated by Table 1 the near-coil prototype achieved a maximum experimental efficiency of 0.52% (above 79 Hz the efficiency could not be measure because the minimum voltage output from the function generator was reached). The reduced efficiency at higher input currents was likely the result of the magnets impacting a hard mechanical stop that limited the beam deflection. A peak resonant frequency change of 17 Hz (softening) can be seen, and is most likely attributed to the non-linear interaction of the magnet with the field generated by the transmitter during the increasing stroke of the magnet.

Table 1: Near-coil setup results.

Resonant freq. [Hz]	Input current [A]	Efficiency [%]
62	0.0291	0.11
64	0.0194	0.12
69	0.0097	0.13
74	0.0048	0.43
77	0.0022	0.49
79	0.0010	0.52

Figs. 5 and 6 show plots of efficiency vs. distance for torque and force modes for the far coil system for both prototypes A and B. The peak efficiency in case of torque mode for prototype B was obtained at 0 cm and peak efficiency in force mode was obtained at a distance of 3.1 cm from the center of the transmitter coil. In the case of prototype B, it is to be noted that the resonant frequency in torque mode shifted from 69.3 Hz to 70.3 Hz as the distance was varied from 0 cm to 12 cm, but remained constant at 71.1 Hz in force mode, irrespective of the change in distance. The change in resonant frequency was attributed to the nonlinearity in the system, and is currently under investigation.

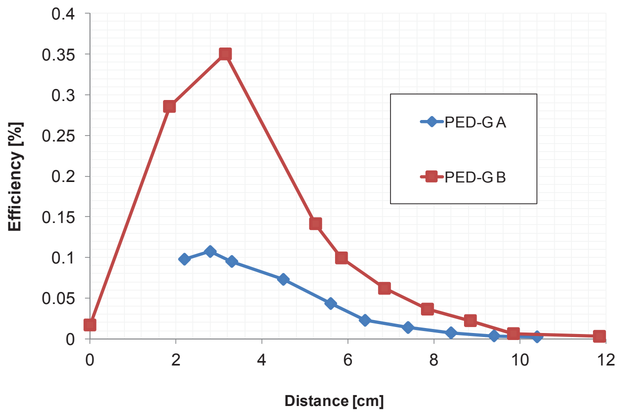

Fig. 5: The efficiency vs. distance of the far-coil setup for PED-G prototype A (blue) and B (red) operating in the force mode.

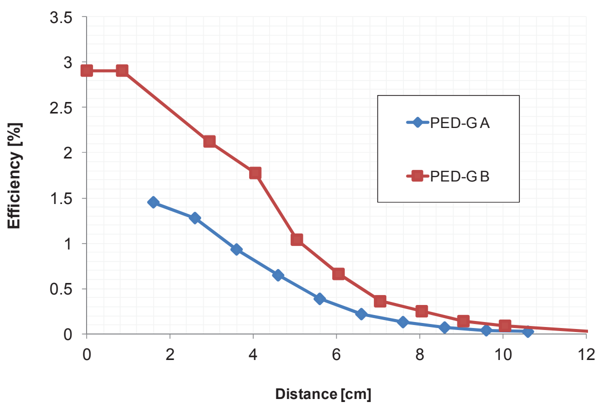

Fig. 6: The efficiency vs. distance of the far-coil setup for PED-G prototype A (blue) and B (red) operating in the torque mode.

CONCLUSION

In this paper, we have presented the concept of a Piezoelectrodynamic Gyrator (PED-G), and investigated its applications for wireless power transfer applications. PED-G is a generalized version of the AC energy scavenger. Implemented purely using passive components, PED-G, similar to an electrodynamical WPT allows resonant power transfer at frequencies orders of magnitude lower than what can be achieved with purely coil-based systems.

Data presented in this work validates that PED-G can indeed be used to achieve WPT. The output voltage of the PED-G tends to be higher than that of an electrodynamic WPT, due to a generally higher output voltage across the piezoelectric element. This is a benefit for connected power electronics, as higher output voltage can lead to a smaller loss in the attached power conditioning circuit. However, PED-G suffers from lower transfer efficiency than electrodynamical WPT. This can be attributed to a lower mechanical quality factor Q. This reduced Q is most likely attributed to inferior mechanical properties of the piezoelectric bimorph. However, improved design of the piezoelectric cantilever might improve the Q, and overall efficiency.

Fundamentally, the anti-reciprocity of a gyrator offers unique load transfer characteristics which may be useful in future WPT and AC energy harvesting applications, and should be explored further in future work.

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