DESIGN OF A MEMS PASSIVE, PROXIMITY-BASED AC ELECTRIC CURRENT SENSOR FOR RESIDENTIAL AND COMMERCIAL LOADS

E.S. Leland[1], P.K. Wright[2], R.M. White[3]
[1]Department of Mechanical Engineering, Univ. of California, Berkeley
[2]Center for Information Technology Research in the Interest of Society, Univ. of California, Berkeley
[3]Berkeley Sensor and Actuator Center, Univ. of California, Berkeley

Abstract: We present new considerations in the design of a MEMS passive, proximity-based electric current sensor for residential and commercial AC electric loads such as appliances and office equipment. The sensor device consists of a permanent magnet mounted to the end of a piezoelectric cantilever. The magnet couples to the alternating magnetic field surrounding an electric power cord, forcing the cantilever sinusoidally. Piezoelectric coupling produces a sinusoidal voltage proportional to the current in the power cord. This design requires no external power source and remains electrically isolated from the current carrier. Models predicting sensor behavior are presented and compared to experimental data. Meso-scale prototypes show sensitivites of 74 mV/A, while simulations suggest MEMS-scale devices will have sensitivities of 2-3 mV/A.

Key Words: MEMS, current sensor, piezoelectric cantilever, permanent magnet

1. INTRODUCTION

Motivated by concern over global energy use and the need for better energy end-use monitoring technology, this research seeks to develop a novel design for a passive, proximity-based MEMS electric current sensor for residential and commercial AC electric loads.

The sensor design studied in this research consists of a piezoelectric cantilever with a permanent magnet mounted to its free end (see Fig. 1). When placed near a wire carrying AC current, magnetic coupling induces a sinusoidal force on the sensor magnet. This force deflects the piezoelectric cantilever, resulting in a sinusoidal voltage signal proportional to the current being measured. This sensor design is advantageous in that it requires no external power source (passive) and because it can accurately measure current while remaining electrically isolated from the current carrier (proximity-based).

Several types of integrable current sensors are in use [1] including some using magnetic materials [2]. All of these designs either require a power source or they must encircle the current carrier. Neither is necessary for the design presented herein. This research also relates to magnetic field sensors using magnetic materials [3,4] and magnetic microactuators [5,6].

Early work on this sensor design was presented previously [7]. This paper introduces new models describing both the force on a permanent magnet placed near an appliance cord and the voltage developed in a piezoelectric cantilever resulting from a sinusoidal tip force. These models are validated by comparing their output to experimental data obtained from a meso-scale prototype. Also presented are simulations predicting the performance of a MEMS-scale device.

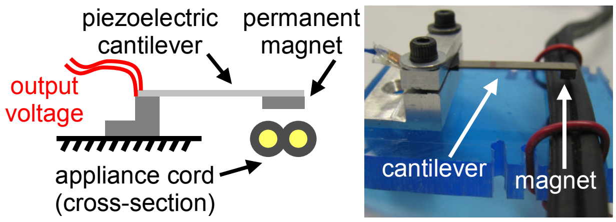

Fig. 1: Diagram and photo of current sensor prototype

2. THEORETICAL BACKGROUND

2.1 Force on a magnet near an AC current-carrying wire

The force on a permanent magnet in a magnetic field is proportional to the integral of the field gradient over the magnet's volume [5]. Considering the case of a magnet near a long current-carrying wire, the vertical forces on the magnet in the plane normal to the wire are described by equation 1.

$$F_y = B_r \int \frac{d}{dy}\left(H_y\right) dV \qquad (1)$$

In this equation, F_y is the vertical force on the magnet, H_y is the y-component of the magnetic field in amperes per meter, B_r is the remanence of the permanent magnet in Tesla, and V is the magnet's volume. We assume that the remanence of the permanent magnet is uniform and aligned in the positive y-direction.

As the intended application of this research is to monitor residential and commercial electricity use, we will focus on the case of a two-wire "zip-cord" common to many appliances (see Fig. 2).

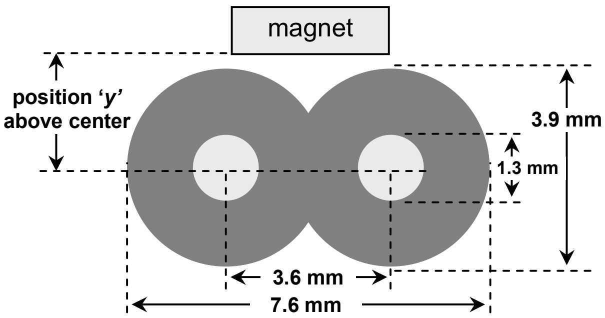

Fig. 2: Cross-section of 16AWG appliance cord

The basic equations for the magnetic field surrounding an appliance cord are developed in [7]. The gradient of this field was computed numerically and plotted using MATLAB. Figure 3 shows the y-direction gradient of the y-component of the magnetic field surrounding the cord, as well as the possible placement of the current sensor's magnet.

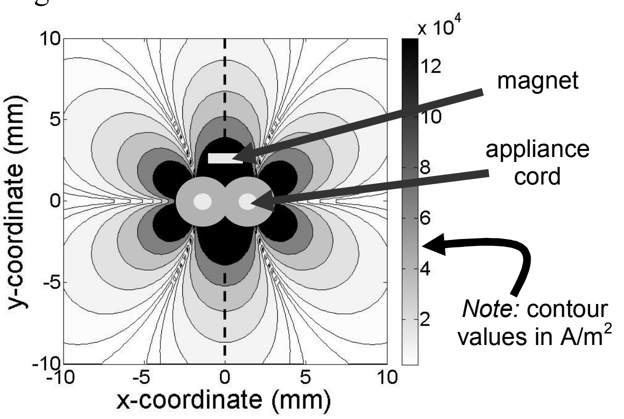

Fig. 3: Plot of magnitude of the magnetic field gradient around an appliance cord, 10 A current

The darker regions of Figure 3 indicate larger gradient magnitude, and hence large magnetic force. Magnet placement along the vertical dashed line that bisects the appliance cord's cross section is particularly advantageous. It corresponds to a region where significant force is developed and it has the added benefit that any horizontal forces are balanced due to symmetry. Equation 1 was evaluated numerically to predict the force on the sensor magnet.

2.2 Voltage developed in a piezoelectric cantilever as a result of tip deflection

Roundy and Wright developed an analytical model for the power output of a piezoelectric cantilever when used for vibration energy scavenging [8]. Using Laplace analysis, their state equations can be manipulated to produce the frequency response function shown in equation 2.

$$V_{oc} = F_{in} \frac{c_p d_{31} t_p a_3}{\varepsilon k_2 m a_2} \cdot \frac{1}{\omega_n^2\left(1 - \frac{c_p d_{31}}{\varepsilon}\right) - \omega^2 - j\left(2\zeta_m \omega_n \omega\right)} \qquad (2)$$

This equation describes the frequency and magnitude of the piezoelectric cantilever's open-circuit voltage in response to the sinusoidal force on the tip magnet when placed near an AC current carrier. V_{oc} is the open-circuit voltage, F_{in} and ω are the amplitude and frequency of the sinusoidal force on the tip-mounted sensor magnet ($\omega = 2 \times \pi \times frequency$--mains current is generally 60 Hz in North America and 50 Hz in Europe). The thickness of the piezoelectric layer appears as t_p, c_p is its elastic modulus, d_{31} is the piezoelectric coupling coefficient, and ε is the dielectric permittivity of the piezoelectric material. Continuing, m is the mass of the sensor magnet, ω_n is the natural frequency of the system, k_2 is a geometric term relating tip displacement to average strain in the piezoelectric layer, and ζ_m is the dimensionless mechanical damping coefficient of the cantilever. Finally, j is the imaginary number and a_2 and a_3 are constants determined by whether the piezoelectric cantilever is a unimorph, or a series- or parallel-poled bimorph.

3. EXPERIMENTAL RESULTS

Experiments were undertaken to validate the theoretical models for magnet force and piezoelectric voltage presented in the previous section. A meso-scale prototype current sensor was constructed from a piezoelectric lead zirconate titanate (PZT) model T215-A4-103X bimorph from Piezo Systems, Inc. and a neodymium magnet from K&J Magnetics. Table 1 presents the specifications of the prototype sensor.

Cantilever length (mm)	25.8
Magnet dimensions (mm)	0.32 x 0.32 x 0.16
Magnet mass (g)	0.12
Magnet remanence (T)	1.3
Sensor resonance frequency (Hz)	166

Table 1: Properties and dimensions of the meso-scale sensor prototype

In order to measure the sensor prototype's voltage response to a known input force, the sensor was first mounted on a vibrometer shake table and excited with 60 Hz vibrations of varying acceleration amplitude. Vibration acceleration was measured with a PCB Piezotronics accelerometer, and sensor voltage output was measured using an oscilloscope. Figure 4 shows the sensor's response to vibration excitation.

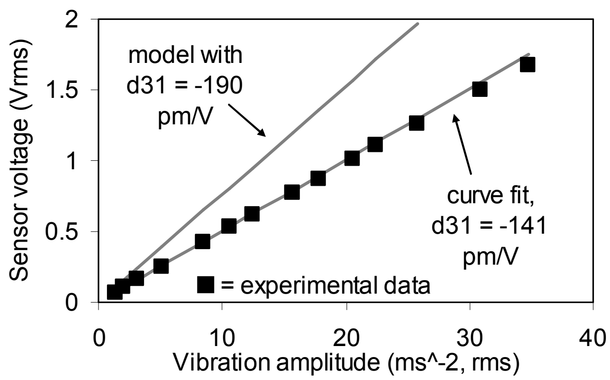

Fig. 4: Sensor response to vibration excitation

It should be noted that equation 2 can be used to model the sensor's response to vibration excitation. In this case the magnitude of force input F_{in} is equal to the mass of the tip magnet multiplied by the vibration acceleration magnitude rather than the force experienced by the magnet in an AC magnetic field. Curve fitting was used to determine an experimental value for the piezoelectric coupling coefficient d_{31}. The experimental value was determined to be d_{31} = -141 pm/V, which is about 26% below the datasheet value of -190 pm/V.

The prototype current sensor was then mounted with the magnet's height y = 3 mm (see Fig. 2) above a 16AWG appliance cord connected to a space heater capable of drawing varying levels of 60 Hz AC current. The sensor's voltage response was measured against a range of currents in the appliance cord. The AC current was measured independently using a Veris AC current transformer. Figure 5 plots the prototype's performance as an AC current sensor.

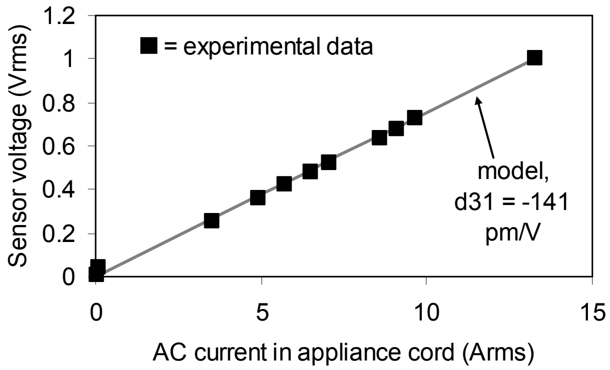

Fig. 5: Sensor response to AC current in a nearby appliance cord

The plot shows the prototype current sensor's response to be highly linear, with a sensitivity of 74 mV/A. Also shown in Figure 5 is the predicted performance of the sensor prototype using the analytical models for magnet force and piezoelectric voltage response (eqns. 1 and 2), using the experimentally-determined value of d_{31} = -141 pm/V. The close correspondence to the experimental data suggests the model offers a good prediction of the current sensor's behavior.

4. MEMS DESIGN AND FABRICATION

Numerical simulations were performed using the models presented in this paper to predict the performance of MEMS-scale versions of this current sensor. As aluminum nitride (AlN) and PZT are two materials commonly used in piezoelectric MEMS, the simulations were constructed to compare the performance of both materials for devices of the same dimensions. Table 2 displays the results of these simulations.

Piezoelectric layer	**Aluminum Nitride**		**PZT**	
d_{31} (pm/V)	-3		-141	
ε_r	9		1800	
c_p (GPa)	350		66	
Cantilever length (μm)	1000	500	1000	500
Resonance freq. (Hz)	434	1425	281	927
Sensitivity (mV/A)	**2.4**	**1.2**	**0.6**	**0.3**

Table 2: Simulated performance of MEMS current sensors. Simulations assume cantilever unimorphs, 1 μm thick piezoelectric, 1 μm thick platinum structural layer, 100 μm width, 100 x 100 x 100 μm^3 magnet with B_r = 0.4 Tesla

It is initially surprising that the AlN devices are predicted to have better sensitivity than those made using PZT, which has a larger piezoelectric coupling coefficient. Closer examination of equation 2 reveals that, with all other variables held equal, the sensor's voltage response is roughly proportional to the ratio of piezoelectric material properties d_{31}/ε. While PZT has greater piezoelectric coupling, it also has much greater dielectric permittivity. The result is that this ratio for AlN is roughly four times that of PZT (see Table 2), which explains the disparity in predicted MEMS sensor performance.

MEMS-scale AlN cantilevers are currently under development using a four-mask process developed in the UC Berkeley microfabrication facility [9].

5. CONCLUSION

The behavior of this new design for a passive, proximity-based electric current sensor has been characterized by analytical models and experimental data. Simulations suggest MEMS-scale devices will be feasible. Ongoing research focuses on developing released aluminum nitride piezoelectric cantilevers as well as fabricating composite micromagnets using a new dispenser printing process [10].

ACKNOWLEDGEMENTS

The authors thank the California Energy Commission for supporting this research under award DR-03-01, as well as the ASEE/NDSEG graduate research fellowship program. Thanks also to Mike Koplow and Padraic Shafer.

REFERENCES

[1] C. Xiao, et al., An Overview of Integratable Current Sensor Technologies, *Proc. 38th IAS Annual Meeting*, Oct. 2003, pp. 1251-1258

[2] P. Ripka, Current Sensors using Magnetic Materials, *J. Optoelectronics and Adv. Matls.*, vol. 6 no. 2, pp. 587-592, 2004

[3] H.H. Yang, et al., Ferromagnetic micromechanical magnetometer, *Sensors and Actuators A*, vol. 97-98, pp. 88-97, 2002

[4] J. Liu, X. Li, A piezoresistive microcantilever magnetic field sensor with on-chip self-calibration function integrated, *Microelectronics Journal*, vol. 38, pp. 210-215, 2007

[5] B. Wagner, W. Benecke, Microfabricated actuator with moving permanent magnet, *Proc. MEMS'91*, Nara, Jan.30-Feb.2, 1991, pp. 27-32

[6] L. Lagorce, et al., Magnetic Microactuators based on Polymer Magnets, *J. of MEMS*, vol. 8, no. 1, pp. 2-9, 1999

[7] E. Leland, et al., Energy scavenging power sources for household electrical monitoring, *Proc. PowerMEMS 2006*, Berkeley, Nov. 29–Dec. 1, 2006, pp. 165-168

[8] S. Roundy, P. Wright, A piezoelectric vibration based generator for wireless electronics, *J. Smart Materials and Structures* vol. 13, pp.1131-1142, 2004

[9] P. Stephanou, et al., Mechanically coupled contour mode piezoelectric aluminum nitride MEMS filters, *Proc. MEMS '06*, Istanbul, Jan. 22-26, 2006, pp. 906-909

[10] Steingart D. et al., Dispenser Printing of Solid Polymer – Ionic Liquid Electrolytes for Lithium Ion Cells, *Proc. IEEE Polytronic 2007*, Tokyo, Jan. 16-18, 2007, pp. 1-5