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Optimization analysis of a magnetic-piezoelectric current sensor

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Abstract. In this paper, we reported an optimizing analysis for a magnetic-piezoelectric current sensor. The optimizing approach is conducted by investigating the magnetic force interaction between the sensor and the wire by changing the magnetization direction of the magnet and the relative orientations. Furthermore, we established a magnetic bending-moment based analysis and derive the governing equation to quantitatively correlate the magnetic force interaction to the mechanical bending moments. The analysis results show that the modelled results are highly consistent with the experimental results.

1. Introduction
To date, using wireless sensors network for electricity usage monitoring (i.e., wireless current sensing network) is general in smart grid applications. However, wireless current sensing network requires a large amount of current sensors with high sensitivity, linearity, and accuracy for precisely measuring the electricity use. Furthermore, for the need of long-term current monitoring, the current sensors have to own self-powered capabilities. To address this, some researchers recently proposed magnetic-piezoelectric self-powered current sensors [1]-[4] for monitoring electricity use. However, when the current carried by the wire is generally low in practical conditions, distinguishing the signals produced by the sensors from noises becomes difficult. Therefore, to increase the sensitivity of the sensors, an experimental-based optimizing approach was proposed (i.e., our previous work [4]). However, the experimental-based optimization in our previous work merely provides the optimizing concept in certain conditions, thus cannot be applied to more complete and complicated situations. Hence, to establish a complete optimizing approach, we present a magnetic bending-moment based optimizing approach for the piezoelectric current sensors.

2. Design
2.1. Piezoelectric current sensor
The design of the self-powered piezoelectric current sensor is shown in figure 1 (for design detail, please see [4]). The designs of the experiments are shown in figure 1(b)-(c). As shown in figure 1(b)-(c), we investigated magnetic force interaction by changing magnetization-direction of the magnet and the relative orientation between the sensor and the wire. Figure 1(d)-(e) is the illustration and photograph of the testing setup, respectively. Partial experimental results of three difference orientation cases of the sensor are shown in figure 1(f).
2.2. Optimization analysis of current sensor

To calculate the magnetic force interaction between the magnet and the wire, we establish the magnetic bending-moment based analysis and derive the corresponding governing equation to quantitatively correlate the magnetic force interaction to the mechanical bending moments. The general governing equation is shown as equation (1).

\[ \mathbf{M} = \mathbf{F} \times \mathbf{r} \propto \mathbf{B} \times \mathbf{H} \times \mathbf{r} \]  

(1)

In equation (1), a mechanical bending moment \( \mathbf{M} \) subjecting to the beam is estimated through the magnetic interaction force. Where \( \mathbf{B} \) is the magnetic flux density produced by the magnet, \( \mathbf{H} \) is the magnetic field intensity produced by the wire, and \( \mathbf{r} \) is the lever-arm distance from the subjecting location of the magnetic force to the pivot (note: the pivot is the fixing location of the sensor).

Based on the assumption of the 3-axial coordinate system shown in figure 2(a)-(c), equations (2)-(4) determine the 3-axial magnetic flux density at a location around a rectangular magnet in a 3-axial coordinate system [5]. In the 3-axial coordinate system, \( x_1, x_2, y_1, y_2, z_1, z_2 \) shown in figure 2(b) and 2(c) define the magnet’s two reference planes which are used in the equation (2), (3), and (4). Where \( B_x, B_y \) and \( B_z \) is the x-axial, y-axial, and z-axial magnetic flux density, respectively, \( \mu_0 \) is the vacuum permeability, \( M_s \) is the magnetization of the magnet, and \( (x_1, x_2), (y_1, y_2) \) and \( (z_1, z_2) \) denote the locations of the edges of the magnet respecting to the x-, y-, z-axes. For demonstration and comparison with the experimental results in our previous works [4], we set \( x_1 = -2.5, x_2 = 2.5, y_1 = -5, y_2 = 5, z_1 = -2.5, z_2 = 2.5 \text{ mm} \) (which are the dimensions of the magnet) and \( M_s = 9.95 \times 10^5 \text{ A m}^{-1} \).

The illustration of the magnetic field intensity produced by the wire is shown in figure 3. The 3-axial magnetic field intensity is derived from Biot-Savarts Law [2] and \( H_x, H_y, H_z \) are shown in equations (5), (6), and (7). Where \( H \) is the magnetic field intensity (A/m), \( I \) is the current in the wire (A) which is set as 8 A in the modeling, \( x \) and \( z \) is the x-axial and z-axial distance from the point P to the center of the wire.

Figure 1. The illustration of the magnetic-piezoelectric current sensor: (a) The design of the sensor. The design of experiment for investigating (b) the magnetization and (c) the orientation induced magnetic force interaction. (d) The illustration and (e) the photograph of the testing setup. (f) The partial results of three difference orientation cases of the sensor. [4]
Figure 2. The 3-axial x-y-z coordinate system of the rectangular magnet: (a) The illustration of x-y-z coordinate system. (b) The referenced x-y plane and (c) the referenced x-z plane from cross-sectional view of the magnet.

\[
\vec{B}_x(x, y, z) = \frac{\mu_0 M_s}{4\pi} \sum_{k=1}^{2} \sum_{m=1}^{2} (-1)^{k+m} \ln\left[ \frac{(y-y_m)^2 + (z-z_m)^2 + (z-z_m)^2}{(y-y_m)^2 + (z-z_m)^2 + (z-z_m)^2} \right]^{1/2} 
\]

\[
\vec{B}_y(x, y, z) = \frac{\mu_0 M_s}{4\pi} \sum_{k=1}^{2} \sum_{m=1}^{2} (-1)^{k+m} \ln\left[ \frac{(x-x_m)^2 + (y-y_m)^2 + (z-z_m)^2}{(x-x_m)^2 + (y-y_m)^2 + (z-z_m)^2} \right]^{1/2} 
\]

\[
\vec{B}_z(x, y, z) = \frac{\mu_0 M_s}{4\pi} \sum_{k=1}^{2} \sum_{m=1}^{2} (-1)^{k+m} \tan^{-1}\left[ \frac{(x-x_m)(y-y_m)}{(z-z_m)(x-x_m)^2 + (y-y_m)^2 + (z-z_m)^2} \right]^{1/2} 
\]

\[
\vec{H}_x = \frac{I}{2\pi x^2 + x^2} 
\]

\[
\vec{H}_y = 0 
\]

\[
\vec{H}_z = \frac{I}{2\pi x^2 + x^2} 
\]

Figure 3. The illustration and the derived equations for estimating the magnetic field intensity at any point located outside of the wire.

3. Modeling results and discussion

Through using equations (2)-(4), the partial modeled results of the x-axial and z-axial magnetic-flux-density (B_x and B_z) over the x-y and y-z plane surfaces of the magnet are obtained, as shown in figure 4(a), 4(b), 4(c), and 4(d), respectively. Base on the results shown in figure 4(a)-(d), the average magnetic-flux-density is calculated by using weighted average method (i.e., add up the products of value times weight to get the total value, and consequently divide the total value by the total weight) and subsequently converted to vector-form expression. In addition, above same method is used to calculate the magnetic field intensity produced by the wire.
Finally, by substituting the vectors of magnetic-flux-density and magnetic-field-intensity to equation (1), we can obtain the bending moment subjecting to the beam. The comparison of modeled results and experimental results [4] of four critical magnetization-direction ($\Phi = 0^\circ$, $\Phi = 45^\circ$, $\Phi = 90^\circ$ and $\Phi = 135^\circ$) at the relative-orientation $\Theta = 0^\circ$ are shown in figure 4(e). In figure 4(e), the modelled results are consistent with the experimental results.

Figure 4. The partial modeled results of the x-axial and z-axial magnetic-flux-density ($B_x$ and $B_z$) over the x-y and y-z plane surfaces of the magnet. (a) x-axial and (b) z-axial magnetic-flux-density over the x-y plane surface of the magnet. (c) x-axial and (d) z-axial magnetic-flux-density over the y-z plane surface of the magnet. (e) The comparison between the modeled and experimental results.

4. Conclusion
We proposed an optimizing approach for the magnetic-piezoelectric current sensor. The modelled results are consistent with the experimental results. By using the approach, the modeling-based approach can be used to further optimize the sensor performance.

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