A Resonant Pressure Sensor based on Magnetostrictive/Piezoelectric Magnetoelectric Effect

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Abstract. This study proposed a resonant pressure sensor based on magnetoelectric effect induced in magnetostrictive/piezoelectric materials. Due to the magnetoelectric effect, the resonant frequency of the sensor varies as the external applied pressure changes. By studying the nonlinear constitutive parameters of the magnetostrictive material and adopting the equivalent circuit method, the sensor is theoretically analysed and the relationship between the resonant frequency and applied pressure is determined. The prototype of the sensor is optimized based on theoretical model. Optimal parameters of the sensor are determined to ensure high sensitivity. The measurement range of the sensor is 0-360 kPa and experimental studies show that the sensitivity reaches to 11.63 Hz/kPa. The experimental result is in good agreement with theoretical analysis. It can be concluded that the pressure measurement method based on magnetostrictive/piezoelectric magnetoelectric effect is of robustness and accuracy. Analysis shows the proposed mechanism also has the potential in mass measurement.

1. Introduction

The magnetoelectric (ME) effect is the electric polarization induced by a magnetic field or the magnetization induced by an electric field [1]. A strong extrinsic ME effect is found in magnetostrictive/piezoelectric composites [2,3]. The high magnetoelectric coefficient at room temperature makes the ME composites be practically applied in sensing technology. The ME sensors are developed to measure magnetic field [3], current [4], rotational speed [5], crankshaft position [6] and susceptibility [7]. Given the high-precision measurement achieved by the ME sensors, they are promising in pressure sensing.

Pressure sensors are essential and widely applied in consumer electronics, medical, industrial, automotive and structural health monitoring [8,9]. Among them piezoresistive pressure sensors are of high linearity but with temperature drift and relatively low sensitivity. The capacitance pressure sensors are of high precision and rapid dynamic response. But the applied range of capacitance sensors is limited by the nonlinearity outputs and the strict environment requirement. Compared with above pressure sensors, resonant pressure sensors are of high signal-noise ratio, broad frequency bandwidth and high sensitivity [10].

This study proposed a resonant pressure sensor based on magnetostrictive/piezoelectric magnetoelectric effect. The magnetostrictive/piezoelectric composite structure works as the resonator and the resonant frequency varies with the applied pressure due to magnetoelectric effect. In this paper, Section 2 presents the sensing principle and theoretical model of the sensor. Section 3 introduces the
prototype and its optimization. Section 4 delivers experimental studies and determines the sensitivity of the sensor. Finally, conclusions are given in Section 5.

2. Modelling of the pressure sensor

2.1. Sensing principle

The configuration of the pressure sensor is shown in figure 1. The Terfenol-D bar is put inside the coil, which provides magnetic field. The magnetic yokes ensure the magnetic field a complete circuit. The stress generated by the magnetostriction of Terfenol-D applies on PZT-5 through mechanical coupling. An induced voltage is generated because of the piezoelectric effect in PZT-5. The measured pressure acts on the pressure applied plate. The resonant system consists of Terfenol-D, PZT-5, output rod and pressure applied plate. Due to the magnetoelectric effect, the resonant frequency of the system varies with the external pressure. Therefore the measurement of pressure is converted into measuring the resonant frequency of the system, which can be obtained by applying swept excitation to the coil.

Figure 1. Configuration of the sensor. 1. Pressure applied plate; 2. Output rod; 3. PZT-5; 4. Terfenol-D; 5. Coil; 6. Front cover; 7. Housing; 8. Magnetic yokes; 9. Rear cover.

2.2. Constitutive parameters of magnetostrictive phase

The magnetostrictive constitutive equations can be expressed as

\[
\begin{align*}
\varepsilon_m^3 &= e_{33e}^m \sigma_3 + d_{33e}^m H_3 \\
B_m^3 &= d_{33e}^m \sigma_3 + \mu_{33e}^m H_3
\end{align*}
\]

(1)

where \(\varepsilon_m^3\) and \(\sigma_m^3\) are the longitudinal strain and stress, \(B_m^3\) and \(H_m^3\) are the magnetic flux density and magnetic field, \(e_{33e}^H\), \(d_{33e}^3\) and \(\mu_{33e}^3\) are the nonlinear elastic compliance at constant \(H\), nonlinear piezomagnetic constant, and nonlinear magnetic permeability at constant stress. The subscript \(e\) denotes the parameters are derived from the nonlinear model of magnetostrictive phase and are equivalent to the parameters in linear constitutive equations. The nonlinear constitutive parameters are defined as

\[
\begin{align*}
\varepsilon_{33e}^H &= \frac{\partial \varepsilon_m^3}{\partial \sigma_m^3}, \\
d_{33e}^3 &= \frac{\partial \varepsilon_m^3}{\partial H_m^3}, \\
\mu_{33e}^3 &= \frac{\partial B_m^3}{\partial H_m^3}
\end{align*}
\]

(2)

Zhou Haomiao et al [11] derived the nonlinear constitutive parameters based on the nonlinear model for Terfenol-D [12]. The model is expressed as follows:
\[ H_e = mH_s + \alpha M + \left[ 2 \tanh \left( \frac{m \sigma_s}{\sigma_s} \right) \right] \frac{3m \sigma_s \lambda_s M}{2 \mu_0 M_s^2} \]

\[ M = M_s \left( \coth \frac{H_e}{a} - \frac{a}{H_e} \right) \]

\[ \lambda = \left[ \frac{1}{2} \tanh \left( \frac{m \sigma_s}{\sigma_s} \right) \right] \frac{M^2}{M_s^2} \]

\[ m \varepsilon_s = \frac{m \sigma_s - \sigma_0}{E_s} + \frac{\lambda}{2} \left[ \tanh \left( \frac{m \sigma_s}{\sigma_s} \right) - \operatorname{anh} \left( \frac{2 \sigma_s}{\sigma_s} \right) \right] + \lambda \]

where \( H_e \) and \( M \) are the effective magnetic field and magnetization respectively, \( \lambda \) is the magnetostriction coefficient, \( \alpha \) represents the effective field constant, \( a \) denotes the effective domain density, \( M_s, \lambda_s, \sigma_s \) and \( E_s \) are the saturation magnetization, saturation magnetostriction coefficient, saturation stress and saturation Young's modulus of the magnetostrictive material, and \( \sigma_0 \) is the prestress. The parameters are identified using hybrid niching coral reefs optimization algorithm (HNCRO) [13]. The results are shown in table 1.

**Table 1. Model parameters identified by HNCRO.**

| Parameters | Value |
|------------|-------|
| \( \alpha \) | 0.031 |
| \( a \) (kA/m) | 40 |
| \( M_s \) (kA/m) | 915 |
| \( \lambda \) | 0.0014 |
| \( \sigma_s \) (MPa) | 200 |
| \( E_s \) (GPa) | 110 |

In equation (3), \( m \sigma_3 \) is the pressure applied on Terfenol-D and can be expressed as

\[ m \sigma_3 = \frac{\sigma A_m}{A_m} + \sigma_0 \]

where \( \sigma \) is the measured pressure acting on pressure applied plate, \( A_m \) and \( A_m \) are cross section areas of pressure applied plate and Terfenol-D.

### 2.3. Magnetoelastic equivalent circuit analysis

The equivalent circuit method is adopted to model magnetoelectric effect [14]. At high frequency, equations of motion are established to study the magneto-elasto-electric coupling of the system. Assume the applied magnetic field is sinusoidal so the vibration of the system along the longitudinal or z axis is also sinusoidal (harmonic motion). The equations of motion are expressed as

\[ \frac{\Delta m}{\dot{c}} \frac{\sigma^2 u}{c^2} = \Delta \frac{\sigma_3 A_m}{m} \quad 0 \leq z \leq l_m \]

\[ \frac{\Delta m_p}{\dot{c}} \frac{\sigma^2 u}{c^2} = \Delta \frac{\sigma_3 A_p}{l_m} \quad l_m < z \leq l_m + l_p \]

\[ \frac{\Delta m_c}{\dot{c}} \frac{\sigma^2 u}{c^2} = \Delta \frac{\sigma_3 A_c}{l_m + l_p} \quad l_m + l_p < z \leq l_m + l_p + l_c \]

\[ \frac{\Delta m_a}{\dot{c}} \frac{\sigma^2 u}{c^2} = \Delta \frac{\sigma_3 A_a}{l_m + l_p + l_c} \quad l_m + l_p + l_c < z \leq l_m + l_p + l_c + l_a \]

where \( u \) is the displacement, \( \Delta m_m = \rho_m A_m \Delta z, \Delta m_p = \rho_p A_p \Delta z, \Delta m_c = \rho_c A_c \Delta z, \Delta m_a = \rho_a A_a \Delta z \). \( \rho_m \) and \( l_m \) are the density and length of Terfenol-D. \( \rho_p, A_p \) and \( l_p \) are the density, cross section area and length of PZT-5. \( \rho_c, A_c \) and \( l_c \) are the density, cross section area and length of output rod.
\( \rho_3 \) and \( l_a \) are the density and length of pressure applied plate. The constitutive equations of PZT-5 are written as

\[
\begin{align*}
\varepsilon_3^p &= \varepsilon_3^p \sigma_3^p + d_{33}^p E_3, \\
D_3 &= \varepsilon_3^p \sigma_3^p + e_{33}^p E_3,
\end{align*}
\]

(6)

where \( \varepsilon_3^p \) and \( \sigma_3^p \) are the longitudinal strain and stress, \( D_3 \) and \( E_3 \) are the dielectric displacement and electric field, \( \varepsilon_{33}^{p,e} \), \( d_{33}^p \) and \( e_{33}^p \) are the elastic compliance at constant \( E \), the piezoelectric constant, and the dielectric stiffness at constant stress. The impedance equations considering magneto-elasto-electric coupling are obtained as

\[
\begin{align*}
F_{1n} &= Z_{1n} \dot{u}_1 + Z_{3n} \left( \dot{u}_1 - \dot{u}_2 \right) + \varphi_{mn} H_3, \\
F_{2n} &= -Z_{1n} \dot{u}_2 + Z_{3n} \left( \dot{u}_1 - \dot{u}_2 \right) + \varphi_{mn} H_3 = Z_{1n} \dot{u}_2 + Z_{4n} \left( \dot{u}_2 - \dot{u}_3 \right) + \varphi_{mn} V, \\
F_3 &= -Z_3 \dot{u}_3 + Z_4 \left( \dot{u}_2 - \dot{u}_3 \right) + \varphi_0 V = Z_3 \dot{u}_3 + Z_6 \left( \dot{u}_3 - \dot{u}_4 \right), \\
F_4 &= -Z_4 \dot{u}_4 + Z_6 \left( \dot{u}_3 - \dot{u}_4 \right) = Z_4 \dot{u}_4 + Z_8 \left( \dot{u}_4 - \dot{u}_5 \right), \\
F_5 &= -Z_5 \dot{u}_5 + Z_8 \left( \dot{u}_4 - \dot{u}_5 \right)
\end{align*}
\]

where

\[
\begin{align*}
Z_{1n} &= j \rho_m v_{mn} A_{m} \tan \frac{k_{mn} l_m}{2}, \\
Z_{2n} &= j \rho_p v_{mn} A_{m} \tan \frac{k_{mn} l_m}{2}, \\
Z_3 &= j \rho_p v_{mn} A_{m} \tan \frac{k_{mn} l_m}{2}, \\
Z_4 &= j \rho_p v_{mn} A_{m} \tan \frac{k_{mn} l_m}{2}, \\
Z_6 &= j \rho_p v_{mn} A_{m} \tan \frac{k_{mn} l_m}{2}, \\
\varphi_0 &= \frac{A_p v_{333} d_{33}^p}{\rho_p}, \\
\varphi_{mn} &= \frac{A_p v_{333} d_{33}^p}{\rho_p},
\end{align*}
\]

(7)

\( F_{1n}, F_{2n}, F_3, F_4 \) and \( F_5 \) are forces at \( z = 0 \), \( z = l_m \), \( z = l_m + l_p \), \( z = l_m + l_p + l_r \) and \( z = l_m + l_p + l_r + l_a \) respectively. The subscript \( n \) denotes the forces at \( z = 0 \) and \( z = l_m \) are derived considering the nonlinearity of the magnetostrictive phase. \( V \) is the induced voltage. The wave velocities are defined as

\[
\begin{align*}
\nu_{mn} &= \sqrt{1/\rho_m v_{mn} s_{333}^m}, \\
\nu_p &= \sqrt{1/\rho_p v_{333}^p}, \\
\nu_r &= \sqrt{1/\rho_r r_{333}^r}, \\
\nu_a &= \sqrt{1/\rho_a},
\end{align*}
\]

\( v_{333}^p \) is the elastic compliance of output rod and \( a_{333}^p \) is the elastic compliance of pressure applied plate. The wave numbers are defined as

\[
\begin{align*}
k_{mn} &= \omega / \nu_{mn}, \\
k_p &= \omega / \nu_p, \\
k_r &= \omega / \nu_r, \\
k_a &= \omega / \nu_a,
\end{align*}
\]

where \( \omega \) is the angular frequency. The capacitance \( C_0 \) is defined as

\[
C_0 = A_p / \varepsilon_{333}
\]

The electromechanical coupling factor

\[
k_{33} = \frac{d_{33}^p}{\sqrt{\varepsilon_{333}^p p e_{333}^p}}.
\]

Considering the boundary conditions, one end of the system is clamped and the other end is applied by the external pressure \( \sigma \). The equivalent circuit of the system is shown in figure 2.
According to the Kirchhoff’s voltage law and current law, the equivalent circuit can be expressed as

\[
\varphi_{mn}^m H_3 - (Z_{tn} + Z_{2n} + Z_3) \dot{u}_2 - \left( Z_4 + \frac{\varphi_p^2}{j\omega C_0} \right)(\dot{u}_2 - \dot{u}_4) = 0
\]

\[
\begin{align*}
Z_4 + \frac{\varphi_p^2}{j\omega C_0} (\dot{u}_2 - \dot{u}_3) - (Z_3 + Z_5) \dot{u}_3 - Z_6 (\dot{u}_3 - \dot{u}_5) &= 0 \\
Z_6 (\dot{u}_3 - \dot{u}_4) - (Z_4 + Z_7) \dot{u}_4 - Z_8 (\dot{u}_4 - \dot{u}_5) &= 0 \\
\sigma A_s + Z_8 (\dot{u}_4 - \dot{u}_5) - Z_7 \dot{u}_5 &= 0 \\
(\dot{u}_2 - \dot{u}_3) - \frac{\varphi_p V}{\varphi_p^2 / j\omega C_0} &= 0
\end{align*}
\]

The output voltage \( V \) of the system is calculated as

\[
V(\sigma) = \frac{\varphi_{mn}^m H_3 - \left( \frac{Z_{tn} + Z_{2n} + Z_3}{(Z_3 + Z_5)(Z_5 + Z_6 + Z_7 + Z_8) - Z_8^2} \right) Z_{int}}{j\omega C_0 + \frac{Z_{int}}{Z_{int}}} + \frac{\varphi_p}{\varphi_p + Z_5}
\]

where

\[
Z_{int} = Z_1 + Z_5 + Z_6 - \frac{Z_6^2}{Z_5 + Z_6 + Z_7 + Z_8} - \frac{Z_8^2}{Z_7 + Z_8}
\]

According to equation (9), the resonant angular frequency of the system \( \omega_s \) under different \( \sigma \) can be derived as

\[
\omega_s(\sigma) = \omega \left[ V_{max}(\sigma) \right]
\]

where \( V_{max}(\sigma) \) is the maximum of \( V \) (resonant voltage) under \( \sigma \) and \( \omega_s(\sigma) \) is the corresponding angular frequency.

3. **Prototype of the sensor and optimization**

The prototype of the sensor is shown in figure 3. The PZT (PA4FKW) is supplied by Thorlabs China with dimensions of \( 5 \times 5 \times 3 \) mm\(^3\) and the Terfenol-D is supplied by Gansu Tianxing Co. Ltd with dimensions of \( 14 \times 2.5 \times 2.5 \) mm\(^3\). The parameter values of the prototype are listed in table 2. As part of the resonant system, the pressure applied plate largely affects the resonant frequency and performance of the sensor. By optimizing the design of the pressure applied plate, high sensitivity of the sensor can be achieved and corresponding optimal resonant frequency is determined.
Figure 3. Prototype of the sensor. (a) 1. Pressure applied plate; 2. Output rod; 3. Front cover; 4. Housing; 5 and 6. Magnetic yokes; 7. Rear cover; 8. PZT-5; 9. Terfenol-D and coil. (b) Assembly.

Table 2. Parameter values of the prototype.

| Parameters | Values       | Parameters | Values       |
|------------|--------------|------------|--------------|
| \( \rho_m \) | 9230 kg/m\(^3\) | \( l_p \) | 3 mm         |
| \( \rho_p \) | 7600 kg/m\(^3\) | \( l_r \) | 10 mm        |
| \( \rho_r, \rho_a \) | 2750 kg/m\(^3\) | \( p_{33}^f \) | 20.7×10\(^{-12}\) m\(^2\)/N |
| \( A_m \) | 6.25 mm\(^2\) | \( p_{d33} \) | 400 pC/N     |
| \( A_p \) | 25 mm\(^2\) | \( p_{E33}/\varepsilon_0 \) | 1750         |
| \( A_r \) | 28.3 mm\(^2\) | \( r_{33}, a_{33} \) | 14.5×10\(^{-12}\) m\(^2\)/N |
| \( l_m \) | 14 mm        |             |              |

Pressure applied plates with different dimensions are studied and the parameters are listed in table 3. Based on the theoretical model, the resonant frequency \( f_s \) under different \( \sigma \) can be obtained. For sensors with pressure applied plates of different dimensions, the output curves can be calculated and the results are shown in figure 4.

It is found as the diameter of the pressure applied plate increases, the variation of \( f_s \) increases. It is because \( \sigma A_3 \), i.e. the force applied on the sensor increases, thus the corresponding variation in the equivalent circuit increases. In addition, as the height of pressure applied plate increases, the variation of \( f_s \) decreases. The reason is that the mass of the resonant system increases so \( f_s \) decreases and its variation decreases as well. To ensure high sensitivity, considering the overall size of the sensor and the mechanical strength of the pressure applied plate, the optimal size is determined to be \( \varphi 20 \times 5 \) mm\(^2\).

Table 3. Pressure applied plates with different dimensions.

| Number | Dimensions (mm\(^2\)) | Mass (g) | Number | Dimensions (mm\(^2\)) | Mass (g) |
|--------|------------------------|----------|--------|------------------------|----------|
| 1      | \( \varphi 10 \times 5 \) | 1.08     | 7      | \( \varphi 15 \times 15 \) | 7.29     |
| 2      | \( \varphi 10 \times 10 \) | 2.16     | 8      | \( \varphi 15 \times 20 \) | 9.72     |
| 3      | \( \varphi 10 \times 15 \) | 3.24     | 9      | \( \varphi 20 \times 5 \) | 4.32     |
| 4      | \( \varphi 10 \times 20 \) | 4.32     | 10     | \( \varphi 20 \times 10 \) | 8.64     |
| 5      | \( \varphi 15 \times 5 \) | 2.43     | 11     | \( \varphi 20 \times 15 \) | 12.96    |
| 6      | \( \varphi 15 \times 10 \) | 4.86     | 12     | \( \varphi 20 \times 20 \) | 17.28    |
Figure 4. Output curves of sensors with pressure applied plates of different dimensions.

Based on the above results, it is found the resonant frequency of the sensor decreases as the mass of the plate increases. The resonant frequencies at $\sigma = 0$ with pressure applied plates of different masses are shown in figure 5. It is indicated that the proposed sensor has the potential to be applied in mass measurement.

Figure 5. Resonant frequency of the sensor as the mass of the pressure applied plate changes.

4. Experimental studies

With the configurations and parameters determined in Section 3, the performance of the sensor is tested by experiments. The experimental platform is shown in figure 6. The pressure sensor is clamped with a jig. A force gauge (HANDPI Instruments: HP-500) applies and measures the pressure $\sigma$ acting on the sensor. The input current is sent to the coil after being amplified by the power amplifier (NF: BP4610). The output signal $V_{out}$ is acquired using a lock-in amplifier (Zurich Instruments: MFLI) and sent to PC.
Figure 6. Experimental platform

The range of the applied pressure is 0-360 kPa where the output of the sensor is optimal. Based on theoretical analysis, the output tends to be saturated above 360 kPa. Under different $\sigma$, $V_{out}$ of the sensor is acquired by MFLI in sweep frequency mode and corresponding $f_s$ is obtained. The results of sweep frequency are shown in figure 7. Based on above results, the $\sigma$ vs. $f_s$ curve of the sensor is shown in figure 8.

Figure 7. $V_{out}$ vs. $f$ curves under different $\sigma$. (a) $\sigma = 0, 16, 32, 48, 64, 80$ kPa; (b) $\sigma = 96, 110, 128, 144, 160, 175$ kPa; (c) $\sigma = 190, 208, 222, 240, 255, 270$ kPa; and (d) $\sigma = 286, 302, 320, 334, 350, 360$ kPa.

Figure 8. $\sigma$ vs. $f_s$ curve of the sensor
The linear fit of the experimental curve is shown in figure 8 as well and the R-square value is 0.9724. The sensitivity of the sensor is determined to be 11.63 Hz/kPa. The experimental result shows good agreement with the theoretical one. The deviation might be caused by the assembly error of the sensor and the extra pretest applied by the front cover.

5. Conclusions
In this study, a resonant pressure sensor based on magnetostrictive/piezoelectric magnetoelectric effect is designed, fabricated and tested. The resonant system consists of Terfenol-D, PZT-5, output rod and pressure applied plate. The external pressure acting on the pressure applied plate changes the resonant frequency of the system. Nonlinear model of the magnetostrictive phase is established to evaluate the effect of pressure to the response of the system. Combining with the equivalent circuit method, the resonant frequency of the sensor under different pressure is obtained. The optimal parameters of pressure applied plate are determined to be $\phi 20 \times 5 \text{ mm}^2$ to improve the performance of the sensor. In the measurement range of 0-360 kPa, the sensitivity of the sensor is 11.63 Hz/kPa and the experimental result is close to the theoretical result. Future work is focused on further studying the performance of the sensor, reducing the dimensions and exploring the applications in Non-destructive Testing, mass measurement and other fields.

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