Postprint of Optimal Design of Magnetic Shape Memory Alloy Sensors

Authors: Lu Jun, Su Chaofeng

Date: 2018-12-25T00:00:00+00:00

Abstract

Magnetically controlled shape memory alloy (MSMA) is a novel functional material with reversible characteristics. By exploiting these reversible properties, MSMA sensors can be developed. Based on theoretical analysis, finite element simulations were performed on each structural component of the MSMA sensor using the finite element analysis software AnsoftMaxwell, and an MSMA sensor with optimized structure and geometry was designed, achieving enhanced performance. The effectiveness of the MSMA sensor optimization was validated through experiments, establishing a technical foundation for the modeling and application of MSMA sensors.

Full Text

Optimized Design of Magnetically Controlled Shape Memory Alloy Sensor

Lu Jun, Su Chaofeng
School of Automation and Electrical Engineering, Shenyang Ligong University,
Shenyang 110159, China

Abstract

Magnetically controlled shape memory alloy (MSMA) is a novel functional material exhibiting reversible properties that can be exploited for sensor development. Based on theoretical analysis, this paper employs the finite element analysis software Ansoft Maxwell to simulate each structural component of the MSMA sensor separately, resulting in an optimized sensor design with improved structural configuration and enhanced performance. Experimental validation confirms the effectiveness of the optimization approach, establishing a technical foundation for MSMA sensor modeling and practical application.

Keywords: Magnetically controlled shape memory alloy, sensor, optimized design, experimental study

1 Introduction

Sensor technology has advanced rapidly in recent years, with new theories, sensing principles, materials, fabrication techniques, and information processing methods continuously integrated into sensor research and development. This progress has led to the emergence of novel sensor structures and applications, prompting investigation into magnetically controlled shape memory alloy (MSMA) sensors [1]. While existing literature extensively addresses MSMA actuator theory and applications [2-3], research on MSMA-based sensors remains limited [4-6]. This paper investigates the inverse effect of magnetically controlled shape memory alloys to optimize sensor structure through theoretical analysis and experimental study. Such sensors will play an increasingly important role in automated manufacturing, robotics, automotive systems, and related fields.

2 Mathematical Model of the MSMA Sensor

The sensor system model, composed of excitation coils, permanent magnets, and an iron core, is illustrated in Figure 1 [Figure 1: see original paper] [7]. In this equivalent magnetic circuit model, ΦP represents the magnetic flux from the permanent magnet; ΦS denotes the sum of magnetic flux from both the permanent magnet and excitation coil; ΦM is the magnetic flux passing through the MSMA element;   indicates the element’ s deformation; RmM( ) represents the magnetic reluctance generated by MSMA element deformation; RmG( ) is the air gap reluctance during deformation; Rm is the leakage reluctance through the MSMA material; and RmS is the internal reluctance of the excitation coil.

The magnetic flux ΦM in the induction coil is given by:

$$\Phi_M = \frac{\Phi_S R_{m\sigma}}{R_{m\sigma} + R_{mC} + \frac{[R_{mS}(\varepsilon)+R_{mM}(\varepsilon)]R_{mG}(\varepsilon)}{R_{mG}(\varepsilon)+R_{mM}(\varepsilon)+R_{m\sigma}}}$$

From the induced voltage differential equation and subsequent derivation, the induced voltage Ue can be expressed as:

$$U_e = k_1 B_M F_m \cos(\omega t) S_{MSMA} + k_2 F_m \sin(\omega t) S_{MSMA} + k_3 B_M + k_4$$

where BM is the bias magnetic field, Fm is the mechanical force amplitude, SMSMA is the cross-sectional area of the MSMA element,   is the angular frequency, and k1, k2, k3, k4 are coefficients.

3 Sensor Structure Design

3.1 Excitation Coil

The relationship between current I in the excitation coil and wire diameter d is given by [8-9]:

$$I = \frac{\pi d^2 J}{4}$$

which can be rearranged as:

$$d = 1.13\sqrt{\frac{I}{J}}$$

where J is the current density, typically ranging from 2-5 A/mm², with a maximum excitation current of 1 A.

To prevent excessive heat generation from coil power, Joule' s law dictates that higher resistance produces more heat. While J = 2 A/mm² yields minimum resistance, the resulting wire diameter would be excessively large. Therefore, this study selects J = 3 A/mm², yielding:

$$d \approx 0.65\text{mm}$$

The number of turns per unit length is:

$$n_1 = \frac{1}{d + e_f}$$

where ef is the thickness of interlayer insulation material. The number of layers per unit thickness is:

$$n_2 = \frac{1}{k_\eta k_\beta d}$$

The coil' s inner radius R1 is:

$$R_1 = R_t + e_1 + e_2 + e_3$$

where k is the winding arrangement coefficient, k is the stacking coefficient, Rt = 1/(2D) with D being the bare wire diameter, e1 is the gap for centering adjustment, e2 is the coil former thickness, and e3 is the required insulation thickness between coil and former.

The coil' s outer radius R2 and maximum outer radius R2m are:

$$R_2 = R_1 + e$$

$$R_{2m} = R_1 + e + e_f$$

where e is the coil thickness. The coil thickness is calculated by:

$$e = \sqrt{\frac{N}{n_1 n_2 \pi} + R_1^2} - R_1$$

where N is the total number of turns. The total number of turns is:

$$N = (n_1 L_c)(n_2 e)$$

where Lc is the coil length. Substituting the expressions for n1, n2, and e yields the total turns for the excitation coil. When the MSMA element' s deformation exceeds 3%, the bias magnetic field must increase accordingly. Within a reasonable range that avoids excessive heat, increasing coil turns enhances the output induced voltage. Based on calculations and electromagnetic simulation results, the excitation coil turns are selected as N = 1000.

The total coil resistance is:

$$R = \rho \frac{(R_1 + R_{2m})N}{S_d}$$

where Sd is the effective cross-sectional area of the wire and   is the resistivity of copper. The thermal power is:

$$P = I^2 R$$

The magnetic flux density BX produced by the excitation coil is:

$$B_X = \frac{\mu_0 n_1 n_2 I}{2} \left[(X + l) \ln \frac{R_2 + \sqrt{R_2^2 + (X + l)^2}}{R_1 + \sqrt{R_1^2 + (X + l)^2}} - (l - X) \ln \frac{R_2 + \sqrt{R_2^2 + (X + l)^2}}{R_1 + \sqrt{R_1^2 + (X + l)^2}} \right]$$

where l is half the coil length and X is the distance from the point on the coil axis to the center. With a maximum excitation current of 1 A, the calculated maximum excitation power is 6 W.

3.2 Iron Core

From the complete magnetic circuit Ohm’ s law, the iron core cross-sectional area S of the MSMA sensor is:

$$S = \frac{\Phi L}{\mu_0 \mu_r H}$$

where Φ is the magnetic flux, 0 is the vacuum permeability, r is the relative permeability (value of 700), H is the magnetic field intensity, and L is the total iron core length (excluding the permanent magnet section) in mm. Based on the dimensions of the MSMA material used in experiments, the iron core thickness is determined to be 20 mm and the cross-section width 16 mm.

3.3 Detection Coil

The MSMA sensor schematic is shown in Figure 2 [Figure 2: see original paper]. When DC current is applied to the excitation coil, deformation of the MSMA material in the air gap alters the magnetic flux in the iron core, and the induced voltage is output through the secondary coil. The induced electromotive forces are:

$$e_1 = -\frac{d\Phi_M}{dt} N_1$$

$$e_2 = -\frac{d\Phi_M}{dt} N_2$$

The voltage ratio k between excitation and detection coils is:

$$k = \frac{e_2}{e_1} = \frac{N_2}{N_1}$$

To achieve higher induced voltage output, the detection coil turns should exceed those of the excitation coil. Additionally, more detection coil turns provide better discrimination of harmonics and induced voltage. Therefore, the voltage ratio is selected as 1.5, giving detection coil turns of N2 = 1500.

4 Finite Element Analysis of Sensor Magnetic Field

As the MSMA sensor constitutes a nonlinear system involving coupled mechanical, electromagnetic, and thermal physical fields, finite element simulation [10-13] must replicate experimental conditions to achieve sensor optimization. Based on the structural design, the sensor configuration and optimization are illustrated in Figure 3 [Figure 3: see original paper].

With the iron core structure determined, either coil-only excitation or permanent magnet plus coil excitation can be employed. The magnetic field distribution and air gap flux density profile for coil-only excitation are shown in Figure 4 [Figure 4: see original paper]. With 1 A maximum current applied, the air gap magnetic flux density is only 345.04 mT, resulting in low induced voltage due to small MSMA material deformation. To reduce excitation power while increasing induced voltage, this study adopts the permanent magnet plus coil excitation method.

When permanent magnet 1 width is 20 mm and permanent magnet 2 width is 5 mm, the magnetic field distribution and flux density profile are shown in Figure 5 [Figure 5: see original paper]. The air gap magnetic flux density meets the required variation range and exhibits uniform distribution.

5 Experimental Study

5.1 Output Waveforms

The experimental parameters include: exciter frequency of 500 Hz, amplitude of 2 N, and bias magnetic field of 0.26 T. The induced voltage waveform is shown in Figure 6 [Figure 6: see original paper]. The results demonstrate that both the MSMA sensor’ s induced voltage and the exciter input vary sinusoidally with identical period and phase. Due to material frequency limitations, the exciter frequency cannot be too high, hence the frequency range is set to 200–1000 Hz.

5.2 Relationship Between Induced Voltage and Bias Magnetic Field

At an exciter input frequency of 250 Hz and amplitude of 1.5 N, the MSMA sensor’ s induced voltage is shown in Figure 7 [Figure 7: see original paper], where the induced voltage reaches 246 mV with significantly reduced waveform harmonics, confirming the sensor structure’ s correctness and stability. Figure 8 [Figure 8: see original paper] compares calculated values with experimental data under varying bias magnetic fields, showing good agreement. According to the MSMA inverse effect mechanism, the change in magnetic flux density at the material gap is proportional to the induced voltage, resulting in an approximately linear increase in peak-to-peak induced voltage with increasing bias magnetic field.

5.3 Relationship Between Induced Voltage and Exciter Frequency

When mechanical force frequency is too low, the induced voltage across the coil becomes too small for accurate measurement. Figure 9 [Figure 9: see original paper] compares calculated and experimental peak-to-peak induced voltage values at different frequencies. The induced voltage increases linearly with exciter frequency because higher frequencies increase the rate of magnetic flux density change, thereby increasing output voltage. The error between calculated and measured values is small.

5.4 Relationship Between Induced Voltage and Excitation Force Amplitude

With a magnetic field strength of 0.26 T and exciter frequency of 700 Hz, Figure 10 [Figure 10: see original paper] compares calculated and experimental peak-to-peak induced voltage values at different excitation amplitudes. The error between calculated and measured values falls within engineering tolerances. The induced voltage increases with exciter amplitude but exhibits a nonlinear relationship.

5.5 Comparison Before and After Structural Optimization

Figure 11 [Figure 11: see original paper] compares waveforms from MSMA sensors before and after optimization under identical experimental conditions. The optimized sensor clearly produces higher output voltage, validating the effectiveness of the optimization approach experimentally.

6 Conclusion

Based on electromagnetic theory, this paper designs the excitation coil, detection coil, and iron core of the MSMA sensor separately, performs finite element simulation of the sensor’ s magnetic field, and determines the optimized sensor structure and geometry, providing a design basis for MSMA sensor structural development. Experimental studies on the optimized MSMA sensor reveal the variation 规律 of peak-to-peak induced voltage output with changes in bias magnetic field, excitation force (amplitude and frequency), thereby verifying the sensor structure’ s rationality. Experimental results demonstrate that the optimized MSMA sensor achieves higher induced voltage output with improved waveform quality and reduced harmonics, meeting design requirements.

References

[1] Wang Fengxiang, Li Wenjun, Zhang Qingxin, et al. Experimental study on characteristics of NiMnGa magnetically controlled shape memory alloy[J]. Journal of Material Science & Technology, 2006, 22(1): 55-58.

[2] Zhang Qingxin, Wang Fengxiang, Li Wenjun, et al. Magnetic shape memory effect and external characteristic of NiMnGa alloy[J]. Rare Metal Materials and Engineering, 2005, 34(8): 1263-1266.

[3] Zhan Jianhui, Zhang Daiyuan. Sensor application, challenge and development[J]. Computer Technology and Development, 2013, 23(8): 118-121.

[4] Lu Jun, Li Min, Wang Fengxiang. Theoretical and experimental study on vibration sensor based on MSMA inverse characteristics[J]. Transactions of China Electrotechnical Society, 2014, 29(5): 233-237.

[5] Lu Jun, Yang Kuan, Wang Fengxiang. Model and experiment characteristic on vibration sensor of magnetically controlled shape memory alloy[J]. Journal

of Electric Machines and Control, 2014, 13(8): 20-24.

[6] Lu Jun, Li Xia, Wang Zhongma. Signal processing and fault detection of MSMA vibration sensors based on wavelet analysis[J]. Transactions of China Electrotechnical Society, 2015, 30(10): 354-360.

[7] Suorsa I. Performance and modeling of magnetic shape memory actuators and sensors[D]. Espoo: Teknillinen korkeakoulu, 2005.

[8] Jia Zhenyuan, Guo Dongming. Principle and application of giant magnetostrictive material micro-displacement actuator[M]. Beijing: Beijing Science Press, 2008.

[9] Wang Bowen, Cao Shuying, Huang Wenmei. Magnetostrictive materials and devices[M]. Beijing: Metallurgical Industry Press, 2008.

[10] Jiamu Studio. ANSYS finite element example analysis tutorial[M]. Beijing: Mechanical Industry Press, 2002.

[11] Wang Guoqiang. Practical engineering numerical simulation technology and its application in ANSYS[M]. Xi' an: Northwestern Polytechnical University Press, 2001.

[12] Tan Jianguo. Finite element analysis using ANSYS6.0[M]. Beijing: Peking University Press, 2002.

[13] Zhao Bo, Zhang Hongliang. Application of Ansoft 12 in engineering electromagnetic field[M]. Beijing: China Water & Power Press, 2010.

Note: Figure translations are in progress. See original paper for figures.