Design and experimental study of magnetically controlled shape-memory alloy sensor

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Abstract. Magnetically controlled shape-memory alloys (MSMA) are smart materials with shape-memory function and such advantages, as large strain, high response speed and high energy conversion efficiency. This lucrative combination provides a theoretical basis for the design of MSMA sensor, which is also experimentally validated in this study. Based on the inverse effect of MSMA, the overall design of MSMA sensor is carried out. The structure of the sensor is optimized by finite element simulation. The input and output characteristics of the sensor are experimentally verified. Finally, the coil excitation power is reduced, and the output induction voltage of the sensor is increased. The correctness of sensor structure and rationality of optimization are verified.

1. Introduction

Functional materials are the core of the field of new materials and play an important role in promoting and supporting the development of high and new technologies. The use of functional materials can make precise sensors, so it is widely studied. Representatives of such materials include piezoelectric/electrostrictive ceramics; shape memory materials; magnetostrictive materials; electrorheological and magnetorheological materials [1].

Magnetically controlled shape-memory alloys (MSMA) have the advantages of large output strain and stress, fast response speed, and high energy conversion rate [2, 3]. Under the action of external stress field and magnetic field, it can produce stress-induced and magnetic field-induced martensitic transformation [4-6]. It is suitable for the research of new sensors, so the sensor based on the inverse characteristics of magnetically controlled shape memory alloy has broad application prospects.

In this paper, by studying the inverse effect characteristics of MSMA materials, the structure of MSMA sensor is designed and optimized, which makes the structure of the sensor more reasonable, reduces the excitation power of the coil, and increases the value of the output induction voltage of the sensor.

2. Design of MSMA sensor

2.1. Mathematical model of MSMA sensor

According to the inverse effect mechanism of magnetically controlled shape memory alloy and Faraday electromagnetic induction principle. The magnetic circuit of MSMA sensor is analyzed, and the mathematical model of magnetically controlled shape memory alloy sensor is established.

Parameter $\Phi_M$ represents flux passing through the MSMA material, whose magnetic field direction...
is normal to the deformation direction of the material; N is the number of coil turns, which is related to the magnetic field required for excitation; F_m is the amplitude of excitation force; B_M is the bias magnetic field of MSMA material; \( \varepsilon \) and S_{MSMA} represent the deformation and cross-sectional area of MSMA, respectively, while \( a, b, h, k, \alpha, \beta, \) and \( \gamma \) are unknown parameters.

The general expression is as follows:

\[
\varphi_M = \alpha B_M \frac{\varepsilon + \beta}{\varepsilon + \gamma}
\]

(1)

According to the differential equation of induced voltage:

\[
U_e = N \frac{d\varphi_m}{dt} = N \frac{d\varphi_m}{d\varepsilon} \frac{d\varepsilon}{dt}
\]

(2)

After derivation, the peak-peak value expression of induced voltage can be obtained as follows:

\[
U_e = N \frac{k \alpha (\gamma - \beta) B_M F_m \omega}{S_{MSMA} (a B_M - b \sigma_0 - h + \gamma)^2}
\]

(3)

2.2. Basic composition of MSMA sensor

There are three basic components of the sensor:

One is the preloading system, which consists of an exciter, an ejector pin, an adjusting nut, a baffle and a force sensor.

The second is the magnetic circuit system, which consists of the excitation coil and the permanent magnet to produce the bias magnetic field to excite MSMA material.

The third is the detection coil. When the input sinusoidal signal acts on the ejector pin through the exciter, the MSMA material is continuously deformed in the magnetic field, and the magnetic flux density of the material changes, so that the magnetic induction intensity in the magnetic circuit also changes, thereby generating an induced voltage in the detecting coil. And the waveform of the induction voltage is displayed by the oscilloscope.

The schematic diagram of the preloading system is shown in figure 1.

Figure 1. Structural sketch of experimental platform.

2.3. Excitation mode selection

When the sensor is working, it is necessary to apply a bias magnetic field to the MSMA material, that is, to excite the MSMA. At present, there are mainly three excitation modes, one is the permanent magnet excitation alone, the other is the excitation coil excitation alone, and the third is the permanent magnet excitation together with the excitation coil excitation. When the third excitation method is adopted, the biased magnetic field is composed of permanent magnet and excitation coil. The flux
density in the air gap of MSMA sensor can be changed by adjusting the magnitude and direction of excitation current.

2.4. Size and turn number of excitation coil

The relationship between the diameter D of the coil bare wire, the magnitude of the current I allowed to pass, and the coil current density J in the exciting coil [7,8]:

\[ D = 1.13 \sqrt{\frac{I}{J}} \]  

(4)

where D is the coil bare wire diameter, mm; I is permissible current, A; J is the coil current density, A/mm².

The maximum current density J=2-5A/mm² can be allowed for long-time electrified coils under poor heat dissipation conditions.

Presupposed that the current allowed to enter the coil is 1A, the bare wire diameter of the required excitation coil is 0.65 mm, and the number of winding turns N = 1320.

According to formula (4), taking J=3 A/mm² and current of 0.7A, the bare wire diameter of excitation coil D=0.54 mm is calculated. Within the range of 0.25T-0.6T bias magnetic field, the variation of deformation produced by MSMA material is linearly related to the variation of magnetic induction intensity. The permanent magnet provides a magnetic field of 0.25T and the excitation provides a magnetic field of 0.35T. According to the Ampere loop law:

\[ NI = H_c \delta_l \]  

(5)

\[ B_i = \mu_0 H_c \]  

(6)

where N is the number of excitation winding; I is the current value of excitation winding, A; Hc is the bias magnetic field strength generated by the field winding at the air gap, A/m; \( \delta_l \) is the air gap width equal to 4.5 mm; \( B_i \) is the magnetic flux density at the air gap; \( \mu_0 \) is the permeability in vacuum, \( 4\pi \times 10^{-7} \) H/m.

When two N35 permanent magnets with a thickness of 2.5 mm each are used for excitation, the ampere turn number of excitation coil is determined to be 1320 by the calculation of the above formula. After using N45 permanent magnet with stronger magnetism, the thickness of two permanent magnets can be reduced due to the magnetic enhancement of the permanent magnet. When the thickness is 2 mm, the ampere turn number of the excitation coil is determined to be 1140 by the calculation of the above formula.

According to the size of the coil skeleton, the relationship between the number of coil turns N and the thickness T of the coil wound can be obtained as follows (7)

\[ N \approx \frac{IT}{C^2} \]  

(7)

where L is height of the coil skeleton section, 0.04 m; C is diameter of enamelled wire, m. The coil material is copper, and the resistivity of copper is \( \rho = 0.172 \times 10^{-7} \Omega \cdot m \). According to (8), the total resistance of the exciting coil can be calculated as follows:

\[ R = \rho \frac{l}{S} = \frac{N \times 2 \times (\frac{M}{2} + T + T) \times 0.172 \times 10^{-7}}{\pi (\frac{D}{2})^2} \]  

(8)

where M is the circumference of coil (0.08 m); \( \rho \) is the resistivity of excitation coil, \( \Omega \cdot m \);

When a 2.5 mm-thick permanent magnet is used to excite the coil, and the current in the coil is 1A,
the bare wire diameter of the coil is 0.65 mm, and the number of winding turns \( N = 1320 \). The total resistance of the coil is about 9.59 \( \Omega \). According to the Ohm power relationship \( P = I^2 R \), the maximum excitation power is about 9.59 W.

When the current into the coil is 1 A and the thickness of N45 permanent magnet is 2 mm, the bare wire diameter of the coil is 0.65 mm, and the number of coils to be wound is \( N = 1140 \). The total resistance of the coil is about 7.7 \( \Omega \). to the Ohm power relationship \( P = I^2 R \), the maximum excitation power is about 7.7 W.

When the current into the coil is 0.7 A, the bare wire diameter of the excitation coil is 0.53 mm, and the number of winding turns \( N = 1629 \). The total resistance of the coil is about 15.6 \( \Omega \). the maximum excitation power is calculated to be about 7.64 W.

According to the above calculation results, when the thickness of N45 permanent magnet is reduced, its excitation power decreases by about 20\%, and when the current in the coil is 0.7 A and 1 A, the difference of excitation power is not significant. The selection of smaller input current has no effect on the bias magnetic field. Therefore, in this experiment, it is expedient to use a 0.53 mm-diameter coil as excitation coil.

In order to provide a higher induction voltage, it is necessary to have more coil turns, and the more turns, the better the discrimination. The initial selection of the coil turns is 1,500 turns.

3. Simulation experiment

The size of MSMA material is 2.5 mm x 5 mm x 20 mm. In order to make MSMA material completely in a uniform magnetic field, the thickness of core material is 20 mm.

When N35 permanent magnet provides stable magnetic field for MSMA sensor alone, the magnetic circuit is simulated by the Ansoft software [9,10]. When the thickness of two permanent magnet materials is 2.5 mm, the three-dimensional static magnetic field distribution and air gap flux density profile are shown in figures 2 and 3.

![Figure 2](image1.png)

**Figure 2.** Three-dimensional static magnetic.

![Figure 3](image2.png)

**Figure 3.** Air gap flux density profile field distribution.

The air gap flux density profile shows that the air gap flux density is about 0.26T.

Cut the four corners of the core into rounded corners. When the thickness of permanent magnet is 2.5 mm, the three-dimensional static magnetic field distribution and air gap flux density profile are shown in figures 4 and 5.
According to the air gap flux density profile, the magnetic induction intensity of air gap magnetic field is about 0.27T.

When the four corners of the core are made into rounded corners, the magnetic flux leakage at the rounded corners decreases due to the refraction principle, so the magnetic field intensity at the air gap is enhanced, and the magnetic field intensity at the air gap is increased by about 10 mT after optimization. When the magnetic induction strength of MSMA is in the range of 0.25T-0.6T, the deformation of MSMA is linear, so the thickness of permanent magnet can be reduced appropriately.

When the thickness of N45 permanent magnet is 2 mm, the air gap flux density profile is shown in figure 6.

As shown in figure 6, the magnetic induction intensity of the magnetic field in the air gap is about 0.25T, which meets the experimental requirements.

Because of the compact structure of the sensor, in order to increase the space, the length of the sensor is lengthened by 20 mm, which increases the spacing between excitation coils and leaves more space for detection coils.

By increasing the detection coil from 1500 to 2000 turns, the MSMA material will generate larger induced voltage under the same deformation. Because the magnetoresistance of silicon steel sheet is very small, the change of magnetoresistance can be neglected after elongation.

4. Experimental study

4.1. Construction of the experimental platform
The physical diagram of MSMA sensor experimental platform is shown in figure 7.
The signal generator and power amplifier in the figure provide the input signal as the exciter. The exciter outputs a sinusoidal signal with adjustable frequency and amplitude. The regulated power supply provides stable voltage for MSMA sensor, force sensor and eddy current sensor. The exciter acts on the MSMA element through the ejector rod. Under the action of excitation signal, the induction voltage, force and displacement signals produced by sensor coil can be observed by using oscilloscope. Force sensor, displacement sensor and Tesla meter are used to detect the excitation force, displacement of MSMA element and magnetic field passing through MSMA element respectively.

4.2. The Relationship between sensor induced voltage and input signal frequency
When the magnitude of exciting force is 0.1 N and the bias magnetic field is 0.32T, other conditions remain unchanged, only the frequency of the input signal is changed, and the experimental data are obtained. The output waveforms of signal generator, force sensor and induced voltage are shown in figure 8. The frequency of exciting force is 200 Hz. The output waveform of force sensor is about 5 mV and the output amplitude of induced voltage is about 22 mV.

The output waveforms of the force sensor and the output waveforms of the induction voltage all change according to the sinusoidal law. When the frequency of the input signal increases, the flux density change rate of the magnetic field of MSMA material increases, and the peak value of the output induced voltage also increases. When the vibration frequency is too low, the sensor output is seriously disturbed by the external environment. At the same time, due to the limitation of the material itself, the vibration frequency cannot be too high. The frequency of the input signal is changed by the signal generator, and the peak value of the output induction voltage is recorded. According to the experimental data and the calculated data, the data comparison figures of different frequency induction voltage are drawn, as shown in figure 9. It can be seen from the graph that the peak value of induced
voltage increases with the increase of input signal frequency, and the relationship between them is approximately linear.

**Figure 9.** Comparison of induced voltage data with different frequencies.

**Figure 10.** Comparison of induced voltage data of different biased magnetic fields.

### 4.3. The relationship between sensor induced voltage and bias magnetic field

When the exciting force frequency is 200 Hz, the amplitude is 0.1N and the bias magnetic field is 250 mT, only the magnitude of the bias magnetic field of MSMA material is changed.

According to the experimental data and the calculated data, the comparative figures of the induced voltage under different bias magnetic fields are drawn, as shown in figure 10.

As can be seen from figure 10, when the bias magnetic field of the material is high, the strain of MSMA element increases, so that the peak value of induced voltage increases.

The peak value of induced voltage increases with the increase of biased magnetic field, and the relationship is basically linear.

### 4.4. The relation between sensor induced voltage and input signal amplitude

When the input signal frequency is 300 Hz, the amplitude is 0.08 N and the bias magnetic field is 0.32T, the peak value of the output induced voltage signal is recorded only when the magnitude of the exciting force is changed.

Using different amplitudes as independent variables and output signals as dependent variables, the data comparison diagrams between them are drawn, as shown in figure 11.

**Figure 11.** Comparison of induced voltage data of different exciting force amplitude.

**Figure 12.** Comparison of induced voltage before and after optimization.
From figure 11, it can be seen that the amplitude of induction voltage increases with the increase of input signal amplitude. The larger the input signal amplitude, the larger the deformation rate of MSMA material, the larger the induction voltage signal.

4.5. Sensor optimization comparison
The same experimental conditions are provided for the sensors before and after optimization. When the bias magnetic field is 320 mT, the amplitude of excitation force is 0.1N and the frequency is 200 Hz, the experimental analysis is carried out before and after optimization, and the comparative figure of the output induced voltage waveform is obtained, as shown in figure 12.

The peak induced voltage of the optimized structure is obviously larger than that of the original structure, which is more suitable for the experimental study of magnetically controlled shape-memory alloy sensors.

5. Conclusion
In this paper, based on the theory of electromagnetism, the structure and size of MSMA sensor are designed, and the experimental platform is built by studying the inverse characteristics of MSMA material. The parameters of the sensor are optimized by simulation experiment, which reduced the optimized excitation power and increased the output induction voltage. According to the experimental data, the relationships between the frequency, amplitude, and biased magnetic field of the input signal and the output induced voltage were analyzed. The correctness of sensor structure and rationality of optimization were proved.

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References
[1] O’Handley R C C 1998 Model for strain and magnetization in magnetic shape memory alloys J. Appl. Phys. 83 3263-70
[2] Zhang J, Zhang Q X and Yang M 2009 Dynamic modeling and simulation of magnetically controlled shape memory alloys Journal of Shenyang Institute of Aeronautical Engineering 26 42-5
[3] Sozinov, Likhachev A and Ullakko K 2002 Crystal structures and magnetic anisotropy properties of Ni-Mn-Ga martensitic phases with giant magnetic-field-induced strain IEEE Trans. Magn 38 2814
[4] Suorsa, Tellinen J, Ullakko K and Pagounis E 2004 Voltage generator induced by mechanical straining in magnetic shape memory materials J. Appl. Phys 95 8054-8
[5] Lu J, Yu Q Y and Su C F 2017 Study on multi-parameter variation characteristics of MSMA sensors Journal of Electrical Engineering 12 16-20+41
[6] Zhan J H and Zhang D Y 2013 Sensor application, challenge and development Computer Technology and Development 23 118-21
[7] Zhang Q X, Wang F X, Li W J et al 2004 Linear actuator of magnetically controlled shape memory alloy China Mechanical Engineering 15 1787-90
[8] Lu J, Li M and Wang F X 2014 Vibration sensor theory and experiment based on inverse characteristics of MSMA Journal of Electrical Engineering 29 233-8
[9] Lu J and Su C F 2018 Optimum design of magnetically controlled shape memory alloy sensor Journal of Electrical Engineering 13 1-6
[10] Lu J, Yang K and Wang F X 2014 Model and experimental characteristics of magnetically controlled shape memory alloy vibration sensor Journal of Electric Machines and Control 3 20-4