

# Vibration analysis and experiment of giant magnetostrictive force sensor

Zhiwen Zhu <sup>1</sup>, Fang Liu <sup>2</sup>, Xingqiao Zhu <sup>2</sup>, Haibo Wang <sup>2</sup> and Jia Xu <sup>2,\*</sup>

<sup>1</sup>School of Mechanical Engineering, Tianjin University, Tianjin, China

<sup>2</sup>Tianjin Key Laboratory of Nonlinear Dynamics and Control, Tianjin, China

\*Corresponding author e-mail: xujiatju@163.com

**Abstract.** In this paper, a kind of giant magnetostrictive force sensor is proposed, and its magneto-mechanical coupled model is developed. The relationship between output voltage of giant magnetostrictive force sensor and input excitation force is obtained. The phenomena of accuracy aggravation in high frequency and delay of giant magnetostrictive sensor are explained. The experimental results show that the model can describe the actual response of giant magnetostrictive force sensor. The new model of giant magnetostrictive sensor has simple form and is easy to be analyzed in theory, which is helpful to be applied in measuring and control fields.

## 1. Introduction

Giant magnetostrictive material (GMM) is a kind of smart material. It can be used to convert mechanical energy into magnetic energy, which is known as the inverse magnetostrictive effect or the Villari effect. Based on the Villari effect, giant magnetostrictive sensors used in MEMS can be designed. Compared with other kinds of sensor, giant magnetostrictive sensor has many advantages, such as small size, rapid response, long service life, and wide range of measurement, which make it be applied in vibration measurement fields widely.(1)

Many scholars studied giant magnetostrictive sensors. Jia designed a novel force sensor based on giant magnetostrictive material.(2) Yan developed the dynamic model of giant magnetostrictive acceleration sensors including Eddy-Current effects.(3) Huang developed a novel sensors based on magnetostrictive/piezoelectric laminations.(4) Pacheco and Bruno studied the effect of shape anisotropy in giant magnetostrictive fiber Bragg grating sensors.(5) Although many advances were obtained, the modeling problem of giant magnetostrictive sensor limits its application in industry fields.(6) In order to optimize giant magnetostrictive sensors effectively, it is necessary to build its model in high accuracy.

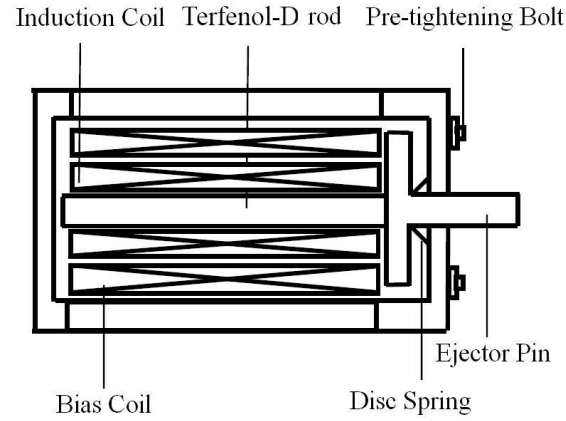
In this paper, nonlinear difference term was introduced to present the hysteresis phenomena of the strain-magnetic field intensity (MFI) curves of giant magnetostrictive material (GMM), and the dynamic characteristics of giant magnetostrictive sensor are studied.

## 2. Dynamic model of giant magnetostrictive sensor

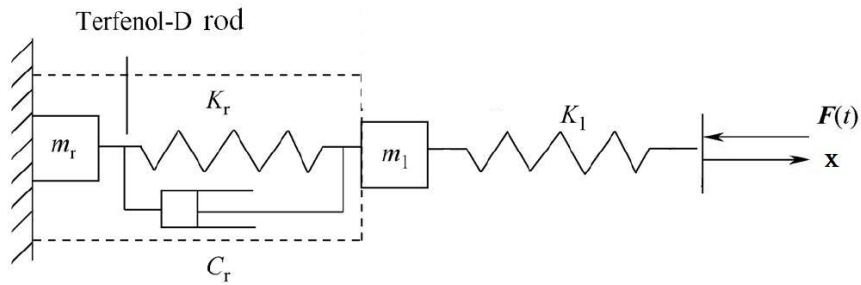
A typical structure of giant magnetostrictive sensor is shown in Fig. 1, and the mechanical model of giant magnetostrictive sensor is shown in Fig. 2, where  $m_r$  is mass of Terfenol-D rod,  $m_l$  is equivalent mass of load,  $C_r$  is structural damping of sensor,  $k_r$  is stiffness of Terfenol-D rod,  $k_l$  is



equivalent stiffness of load,  $F(t)$  is excitation force. The aim of the force sensor is measuring the force. The excitation force  $F(t)$  is added on the sensor, it will lead to the displacement of the ejector pin, and then cause the strain of the Terfenol-D rod. According to Villari effect, the varying magnetic field will be created around the Terfenol-D rod, and finally the coil will create induced currents. Based on the amplitude of induced currents, we can obtain the value of the excitation force  $F(t)$ .



**Figure 1.** Structure of giant magnetostrictive sensor.



**Figure 2.** Mechanical model of giant magnetostrictive sensor with load.

In this paper, we introduce the following model to show the nonlinear characteristics of Terfenol-D:

$$H = a_1 \varepsilon + a_2 \varepsilon^2 + a_3 \varepsilon^3 + a_4 \varepsilon \dot{\varepsilon} + a_5 \varepsilon^2 \dot{\varepsilon} + a_6 \varepsilon^3 f \quad (1)$$

The dynamic model of giant magnetostrictive sensor under excitation force can be shown as follows:

$$\begin{bmatrix} m_r & 0 \\ 0 & m_l \end{bmatrix} \begin{bmatrix} \ddot{x}_r \\ \ddot{x}_l \end{bmatrix} + \begin{bmatrix} c_r & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}_r \\ \dot{x}_l \end{bmatrix} + \begin{bmatrix} k_1 + k_r & -k_1 \\ -k_1 & k_1 \end{bmatrix} \begin{bmatrix} x_r \\ x_l \end{bmatrix} = \begin{pmatrix} 0 \\ F(t) \end{pmatrix} \quad (2)$$

where  $x_r$  is giant magnetostrictive sensor,  $x_l$  is displacement of load.

To constant excitation force  $\tilde{F}$ ,  $x_r = \frac{\tilde{F}}{k_r}$ ;

If  $F = F(t) = \bar{F} \cos \omega t$ , we obtained:

$$x_r = L\varepsilon = \frac{\sqrt{[k_1(m_1 + m_r) - \omega^2 m_1 m_r]^2 + \omega^2 c_r^2 (m_1 + m_r)^2}}{\sqrt{a^2 + b^2}} \bar{F} \cos \omega t = n_1 \bar{F} \cos \omega t \quad (3)$$

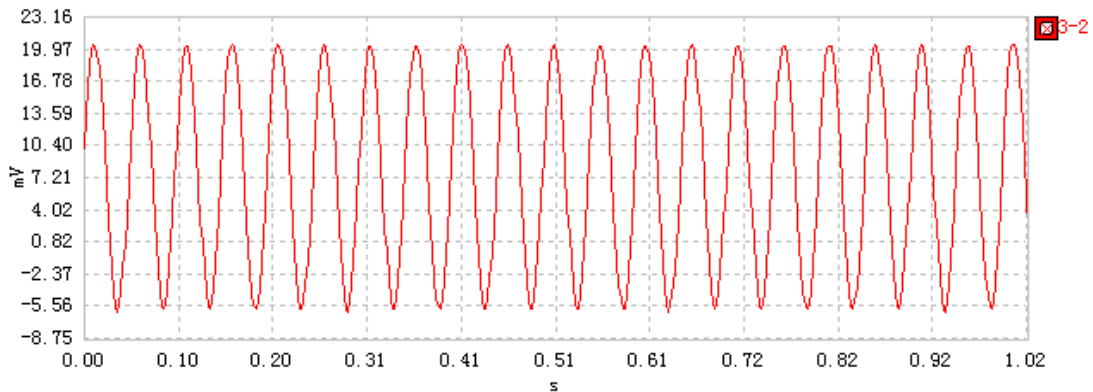
According to eq. (1), the relationship between output voltage  $U$  of giant magnetostrictive sensor and excitation force  $F = \bar{F} \cos \omega t$  can be shown as follows:

$$U = \delta H = \delta(a_1 \varepsilon + a_2 \varepsilon^2 + a_3 \varepsilon^3 + a_4 \varepsilon \dot{\varepsilon} + a_5 \varepsilon^2 \dot{\varepsilon} + a_6 \varepsilon^3 f) \quad (4)$$

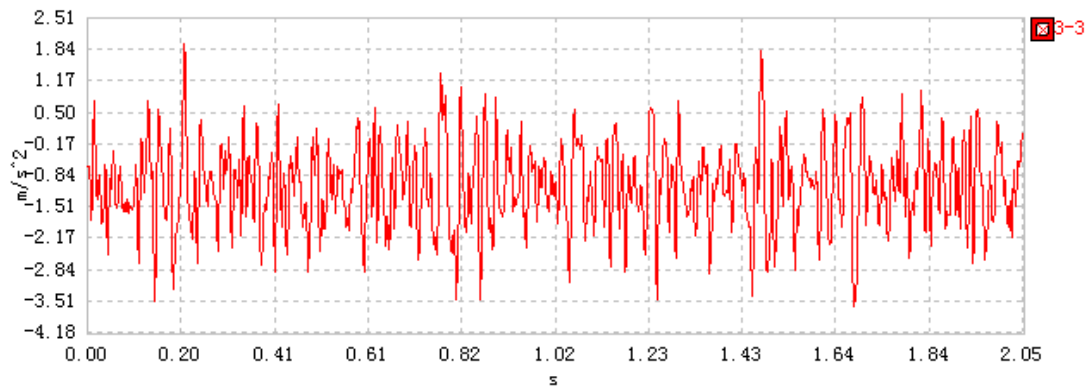
where  $\delta$  is magnification coefficient,  $\varepsilon = \frac{x_r}{L}$ ,  $L$  is the length of Terfenol-D rod.

From eq. (4), we can see that there are the term  $\varepsilon \dot{\varepsilon}$  and  $\varepsilon^2 \dot{\varepsilon}$  in the expression of output voltage  $U$ . When  $x_r = n_1 \bar{F} \cos \omega t$ ,  $\varepsilon = \frac{n_1 \bar{F} \cos \omega t}{L}$ , and  $\dot{\varepsilon} = -\frac{n_1 \bar{F} \omega \sin \omega t}{L}$ . Thus,  $\varepsilon \dot{\varepsilon} = -\frac{n_1^2 \bar{F}^2 \omega \sin 2\omega t}{2L^2}$ , and  $\varepsilon^2 \dot{\varepsilon} = -\frac{n_1^3 \bar{F}^3 \omega \sin 3\omega t}{4L^3} - \frac{n_1^3 \bar{F}^3 \omega \sin \omega t}{4L^3}$ . It means that there are many kind of frequencies in the output voltage  $U$ , which cause the phase delay of output voltage. On the other hand, there are the term  $\varepsilon^3 f$  in the expression of output voltage  $U$ , which implies the accuracy aggravation in high frequency.

The experimental results of giant magnetostrictive sensor system are shown in Figs. 3 and 4. we can see that the output voltage  $U$  is harmonic when  $f = 20\text{Hz}$ , and becomes chaotic when  $f = 100\text{Hz}$ . It proves that our theoretical analysis result is effective.



**Figure 3.** Output voltage curve of giant magnetostrictive sensor when  $f = 20\text{Hz}$ .



**Figure 4.** Output voltage curve of giant magnetostrictive sensor when  $f = 100\text{Hz}$ .

### 3. Conclusion

In this paper, a kind of giant magnetostrictive force sensor is proposed, and its magneto-mechanical coupled model is developed. The relationship between output voltage of giant magnetostrictive force sensor and input excitation force is obtained. The phenomena of accuracy aggravation in high frequency and delay of giant magnetostrictive sensor are explained. The experimental results show that the model can describe the actual response of giant magnetostrictive force sensor. The new model of giant magnetostrictive sensor has simple form and is easy to be analyzed in theory, which is helpful to be applied in measuring and control fields.

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