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Modeling and Experiment of Terfenol-d Driven Composite Cantilever Beam

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Abstract: Vibration model of Terfenol-D composite cantilever beam is established by combining the transverse beam vibration theory with mechanics of composite materials. The structural natural frequency is simulated by COMSOL Multiphysics, Simulation results show that First-mode frequency is 54.30 Hz. The prototype experimental is done with the same parameters, First-mode frequency of the composite cantilever beam is 49.70 Hz. The simulation and experimental results show that quality of Terfenol-D patchs have little (only 7.72%) influence on natural frequencies.

Key words: Terfenol-D, composite cantilever beam, natural frequency

INTRODUCTION

Terfenol-D composite cantilever beam is a class of smart structure which mainly rely on the magnetostrictive strain of Terfenol-D slice actived cantilever beam bending. At presents, most of the smart cantilever structure are driven by piezoelectric material (Gu and Song, 2007), the films of GMM (Jia *et al.*, 2007) and Galfenol alloys (Shu *et al.*, 2011) but they share a characteristic of small driving force.

In 1973, Clark discovered $Tb_{0.27}Dy_{0.73}Fe_2$ and ordered the giant magnetostrictive material as Terfenol-D, its molecular formula is $Tb_xDy_{1-x}Fe_{1.95}$ (0.27<x<0.3). This material have a great magnetostrictive coefficient (strain value (1600-2000)$\times 10^{-6}$), its expansion strain 5-25 times than the Piezoelectric Material (PZT) and Galfenol alloy. The material also have properties of high energy density and low acoustic velocity. In submarine sonar, shock absorbers, robotics and other fields have a wide applications (He, 2006). The output power of Terfenol-D ten times higher than PZT but it brittleness and break easily (Jiang *et al.*, 2009). To solve this problem, we can effectively avoid the disadvantages by a small piece of adhesive-driven. This study firstly have theoretical towards the mode of beam and its frequencies without Terfenol-D film and then COMSOL Multiphysics numerical is used for simulation, the results showed that the simulation results are reliable. Finally, we computed Terfenol-D cantilever with COMSOL Multiphysics and analyzed data after experiment.

VIBRATION MODEL OF TERFENOL-D COMPOSITE CANTILEVER BEAM

Terfenol-D composite cantilever beam is elastic beam adhered with two Terfenol-D slices, The structure shown in Fig. 1 includes a sheel, a steel core, a skeleton, an end cover, coil and Terfenol-D composite cantilever beam.

The uniform and homogeneous Euler Bernoulli differential equation for transverse vibration:

$$EI\frac{\partial^4\omega(x,t)}{\partial x^4}+\rho A\frac{\partial^2\omega(x,t)}{\partial t^2}=f(x,t) \tag{1}$$

where, E is modulus of elasticity, I is moment of inertia of the beam face to Y axis, ω(x, t) is the lateral displacement of the beam,|Ñ is mass per unit volume of the beam, A is cross sectional area of the beam, f(x, t) is the external force per unit length.

When f(x, t) is 0, we can get the motion differential equation of free vibration. For one end fixed and the other end free,we can get vibration mode function:

$$W_n(x)=B_1[\sin\beta_n x-\sinh\beta_n x-\alpha_n(\cos\beta_n x-\cosh\beta_n x)] \tag{2}$$

The natural frequency of the beam:

$$f=\frac{\omega}{2\pi}=\frac{\beta^2}{2\pi}\sqrt{\frac{EI}{\rho A}}=\frac{(\beta L)^2}{2\pi}\sqrt{\frac{EI}{\rho AL^4}} \tag{3}$$

Frequency equation:

$$\cos\beta_n L\cosh\beta_n L+1=0 \tag{4}$$

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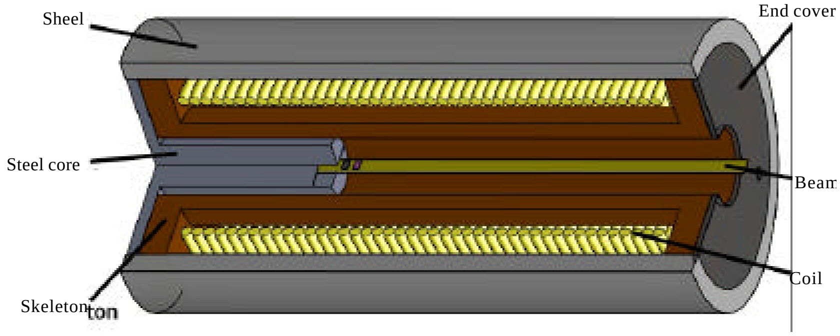

Fig. 1: Structure of terfenol-D composite cantilever beam

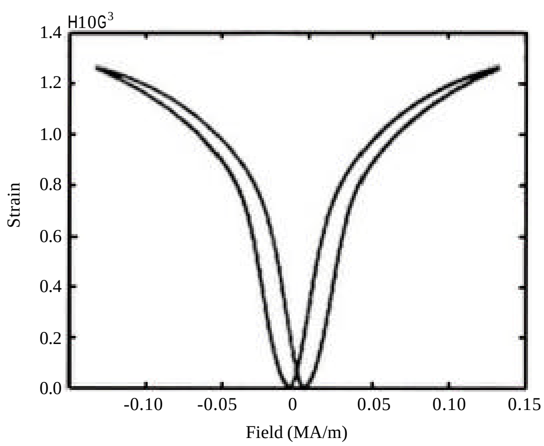

Fig. 2: Hysteresis curve

where, L is the length of the beam:

$$\beta^4 = \frac{\omega^2}{c^2} = \frac{\rho A\omega^2}{EI} \tag{5}$$

$$\alpha_n = \frac{\sin\beta_n L + \sinh\beta_n L}{\cos\beta_n L + \cosh\beta_n L} \tag{6}$$

Assuming the glue among Terfenol-D slices and beam is firm and ignore the adhesive layer influence on the vibration of cantilever beam. Total strain of Terfenol-D slices comprise elastic strain and magnetostrictive strain, as shown in Eq. 7 and Fig. 2:

$$\varepsilon = \frac{\sigma}{E} + \lambda(H, x) \tag{7}$$

The mechanical stress can be expressed as:

$$\sigma = E\left[\varepsilon - \lambda(H, x)\right] \tag{8}$$

Fig. 3: Geometric relation of terfenol-D beam

The strain of cantilever beam axial can be expressed as:

$$\varepsilon = -\frac{\partial^2\omega}{\partial x^2}y \tag{9}$$

Simplification results:

$$\sigma = -E\left[\frac{\partial^2\omega}{\partial x^2}y + \lambda(H, x)\right] \tag{10}$$

where, E is Terfenol-D elastic modulus, λ is Magnetostrictive strain, ε is Axial strain, σ is Mechanical stress.

As shown in Fig. 3, x_i is the distance between Terfenol-D slice and the beam end. Driving under the action of the magnetic field, The neutral axis of the cantilever beam will produce moments:

$$\begin{aligned} M_1 &= \int_{\frac{d_b}{2}}^{\frac{d_b}{2}+d_t} \sigma b y dy\left[U(x-x_1) - U(x-x_2)\right] \\ &= K(x)\left[U(x-x_1) - U(x-x_2)\right] \end{aligned} \tag{11}$$

$$\begin{aligned} M_2 &= \int_{\frac{d_b}{2}}^{\frac{d_b}{2}+d_t} \sigma b y dy\left[U(x-x_3) - U(x-x_4)\right] \\ &= K(x)\left[U(x-x_3) - U(x-x_4)\right] \end{aligned} \tag{12}$$

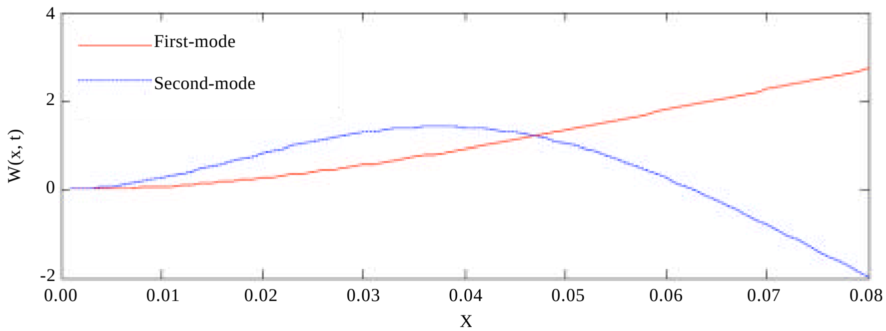

Fig. 4: Graph of vibration mode function W (x)

where, $U(x-x_i)$ is the step function:

$$K(x)=\int_{\frac{d_b}{2}}^{\frac{d_b}{2}+d_1}\sigma b y dy = -\int_{\frac{d_b}{2}}^{\frac{d_b}{2}+d_1} E\left[\frac{\partial^2\omega}{\partial x^2}y+\lambda(H,x)\right] b y dy \tag{13}$$

Ignoring damping and gravity of cantilever beam, the differential equation of the its vibration under driving force:

$$EI\frac{\partial^4\omega(x,t)}{\partial x^4}+\rho A\frac{\partial^2\omega(x,t)}{\partial t^2}=\frac{\partial^2 M_1}{\partial x^2}+\frac{\partial^2 M_2}{\partial x^2} \tag{14}$$

Gravity of Terfenol-D slices can be approximately equivalent to a force concentrated on its centroid. Putting the driving equation into the above equation, we obtain the vibration equation under the driving force and gravity of Terfenol-D slices:

$$EI\frac{\partial^4\omega(x,t)}{\partial x^4}+\rho A\frac{\partial^2\omega(x,t)}{\partial t^2}=\frac{\partial^2 M_1}{\partial x^2}+\frac{\partial^2 M_2}{\partial x^2}+G[\delta(x-\frac{x_1+x_2}{2})+\delta(x-\frac{x_3+x_4}{2})] \tag{15}$$

where, $\delta(x-x_i)$ is the pulse function, G is the gravity of Terfenol-D slice:

$$M_1=K(x)\left[U(x-x_1)-U(x-x_2)\right] \tag{16}$$

$$M_2=K(x)\left[U(x-x_3)-U(x-x_4)\right] \tag{17}$$

By the vibration function W(x), using the programming of Matlab draws out First-mode and Second-mode of the cantilever beam as shown in Fig. 4.

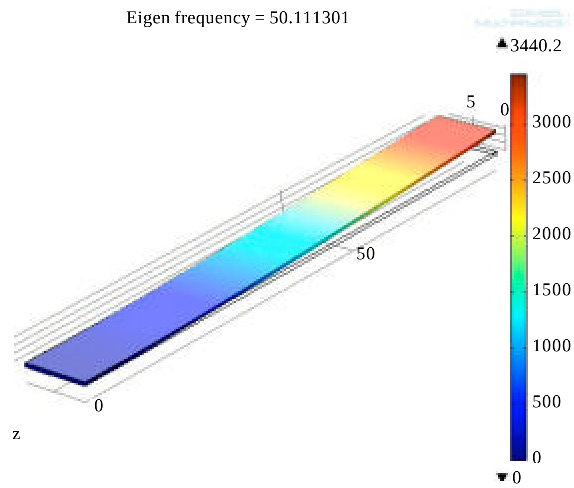

Fig. 5: First-mode of cantilever beam

SIMULATION

Now take a cantilever beam made of bronze as a research object.Its size is 80×9×0.5 mm and modulus of elasticity E is 128 Gpa, density ρ is 8300 kg m^{-3}. The data into the formula to obtain the first three natural frequencies:

$$f_1=49.580\text{ Hz},\ f_2=310.736\text{ Hz},\ f_3=870.158\text{ Hz}$$

Using the finite element software COMSOL Multiphysics, the mode analysis of cantilever beam was done and the results are given as Fig. 5, 6 and Table 1.

Easy to see that the simulation results of COMSOL Multiphysics is consistent to the output results of Matlab. The density is 9250 kg m^{-3}, modulus of elasticity is 26.5 GPa,establish the model and solving the results as below.

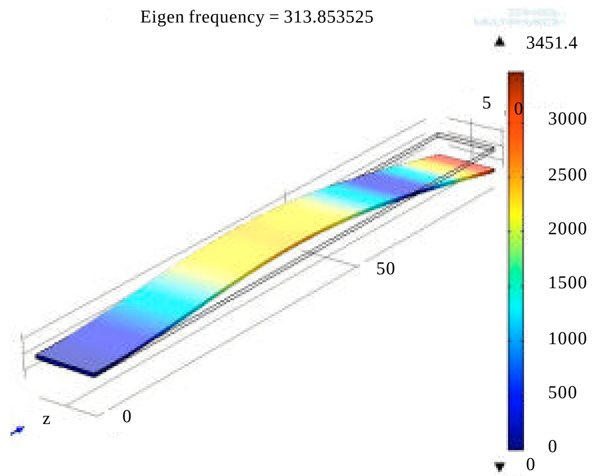

Fig. 6: Second-mode of cantilever beam

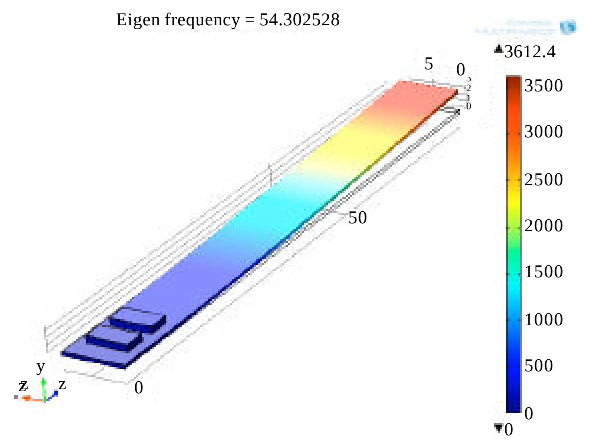

Fig. 7: Mode of Terfenol-D beam

Table 1: Theoretical value vs simulation result of COMSOL Multiphysics

Mode	Theoretical values (Hz)	Simulation values (Hz)	Deviation
First-mode	49.580	0.111	0.011
Second-mode	310.736	313.853	0.010

As shown in Fig. 7, simulation result of COMSOL Multiphysics show that first-mode frequency of Terfenol-D composite cantilever beam is 54.302 Hz.

EXPERIMENTS

According to the case of the resonance amplitude of the cantilever is the largest can determine first-mode frequency.

Experiment by the signal generator outputs a sinusoidal signal driving signal, the amplifier power is transported to the cantilever beam driving device and then cantilever swing will occurring.

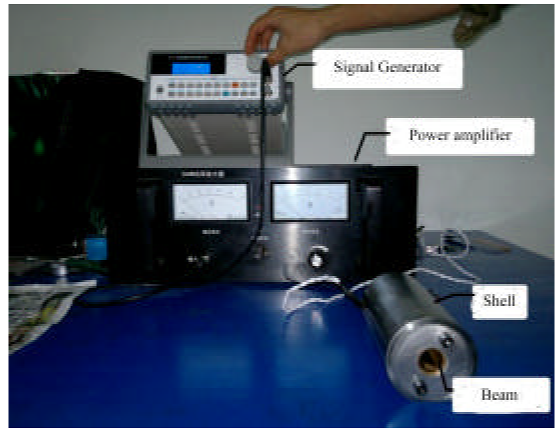

Fig. 8: Experimental test platform

Table 2: Simulation result vs experimental data

Beam	Simulation (Hz)	Experiment (HZ)	Deviation
Without terfenol-D slice	50.111		
With terfenol-D slice	54.302	49.70	0.084

We will find the maximum swing By adjusting devices and write down the frequency of the signal generator. The results and experiments are given in Table 2. The frequency of the signal generator around 24.85 Hz when the swing is largest. As magnetostrictive material has a multiplier effect, First-modal frequency of the composite cantilever beam is 49.70 Hz.

Define a function:

$$\varpi = \left| \frac{(m_N - m_Y)}{m_Y} \right| \times 100\%$$

$$= \left| \frac{(50.111 - 54.302)}{54.111} \right| \times 100\%$$

$$= 7.72\%$$

where, m_N is First-mode of beam without Terfenol-D slices, m_Y is First-mode of beam with Terfenol-D slices.

CONCLUSION

Simulation result of COMSOL Multiphysics have deviation of about 1% contrast to theoretical value,but about 8.4% to experimental data. Possible reasons are as follow: Doing the simulation, we ignore the epoxy adhesive layer on the Terfenol-D, air damping and other factors on the impact of the composite cantilever; During the experiment, the imperfections of the test equipment and error test results of the experimental resulting deviation; The two aspects can lead to a greater deviation, this may explain why the theory is in agreement with the simulation results. Overall, the simulation results and experimental test data are consistent. Numerical simulation can be a guidance for our analysis in some sense,but simulation results can't to be determining factor in the design. From experimental data we know First-mode frequency of Terfenol-D composite cantilever beam is 49.70 Hz, thus, the conclusions are given as follows:

- Terfenol-D slices have little effect on the beam,only 7.72%
- Many factors influence the test data output, Numerical simulation of COMSOL Multiphysicsresults can be used as a rough basis

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