Research on Simulation for Dynamic Characteristics of Giant Magnetostrictive Actuator

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Abstract. The mathematical model of Giant Magnetostrictive Actuator is established. The simulation of the model for its dynamic performance with Simulink shows the curve of its characteristics under continuous current and frequency. It is shown that under continuous AC excitation amplitude, the greater the excitation frequency is, the smaller the output displacement is, and the greater the output force is; under continuous AC frequency excitation, as the excitation amplitude increases, the output displacement and output force are increased, and under fixed excitation, as the AC excitation frequency increases, the output displacement decreases. The conclusion establishes the theoretical basis to the following experiment on dynamic characteristic of the actuator and the active control of vibration of submarine mechanical equipment.

Introduction

With some control strategy, the influence of the vibration produced by the actuator to the protected object counteracts that produced by the main vibration source of the influence of vibration on the influence of the protected object offset each other, so as to achieve the purpose of vibration isolation. Therefore, the actuator is one of the core component of active vibration isolation, which is used to accordance with the control objects by determined control law, system accuracy and performance directly affect on vibration isolation, but the existing of the actuator whose output, output force and displacement response speed can hardly meet the design requirements. Compared with other actuators, giant magnetostrictive actuators (GMA for short) has a lot of advantages in response speed, bearing capacity and using conditions, especially for GMA structure, the model and the control theory of in-depth research.

The dynamic characteristic of actuator refers to the displacement response and output force response under AC excitation. The model of GMA should be able to describe of the relationship input current and output strain, displacement and force. The model of GMA is used commonly:

1. Model of the electromechanical equivalent circuit: Using electromechanical equivalent circuit of the active components and each component vibration, establish the one-dimensional longitudinal vibration model of GMA [1-2].

2. Finite element model of magnetic-mechanical coupling: establish weak coupling or strong coupling model with the finite element method [3-4];

3. Double-end network model: with the typical electromechanical linear transformation equation, relationship of GMA electromechanical is get. It is identified by operating electromechanical undetermined parameters in linear transformation equation: electrical impedance, electrical machinery, mechanical electric coefficient and the mechanical impedance [5-6];

4. Hysteresis model. This issue about establishment of GMA hysteresis model, hysteresis model of numerical simulation, establishment and implementation of inverse hysteresis model, and establishment of nonlinear compensation control system is carried out extensive and in-depth research both here and abroad [7-11].

At present, the dynamic characteristics of GMA description have explored greatly in experiments, but it is still lacking in terms of the simulation, which makes the experimental data cannot be validated and applied completely. In order to develop the best performance of GMA, the simulation of dynamic characteristics of GMA is essential.
Structure and Principle of GMA

GMA is composed of end cover, displacement amplification mechanism, giant magnetostrictive rod, the output shaft, shell, temperature control system and the base, etc. Prestressing force is act on giant magnetostrictive rod by adjusting bolt, disc spring, and the output plunger. The pre-tightening force of direction of the plunger can make the interior of the giant magnetostrictive rod magnetic domain at zero magnetic field arrange along a direction perpendicular to the axial stress as much as possible. Permanent magnet is adopted to act on giant magnetostrictive rod with bias magnetic field of fixed intensity, which can make the magnetic of giant magnetostrictive rod deform in linear region. Current is act on the drive coil, which produce surplus drive magnetic field, and make the giant magnetostrictive rod obtain larger axial magnetostrictive strain. Magnetic field generated by coil can be adjusted by the drive current so as to adapt to different working condition. GMA structure is shown in Figure 1.

![Figure 1. Structure diagram of GMA.](image)

The Mathematical Model of GMA

The movement of Giant magnetostrictive material under plus magnetic field is a complex process. Therefore, the system is simplified, principle diagram of model of GMA is as shown in Figure 2, and the assumptions are made as follows:

1. The internal magnetic field of excitation coil keeps uniform and constant;
2. The characteristic parameters of the telescopic rod are constant, which is not zero drifting with the temperature;
3. The inductance of excitation coil is constant, which does change with the temperature;
4. The influence of the coil magnetic field is ignored at the top of the telescopic rod;
5. Ignore movement the phenomena of the short separation of the giant magnetostrictive rod and driving plunger which may occur in the process;
6. Regardless of the eddy current loss and temperature variations [12-14].
In general, axial strain $\varepsilon$ and axial magnetic induction intensity $B$ of the inside of the giant magnetostrictive rod can be represented as the linear piezomagnetic equation:

$$
\begin{align*}
\varepsilon &= S^\sigma \sigma + dH \\
B &= d\sigma + \mu^\sigma H
\end{align*}
$$

(1)

in which, $\varepsilon$, $S^\sigma$, $\sigma$, $d$, $H$, $B$, $\mu^\sigma$ are the axial strain of the giant magnetostrictive rod, soft coefficient, stress and piezomagnetic coefficient, magnetic field intensity and magnetic induction intensity and magnetic permeability. With the consideration of the quality and damping effect of the giant magnetostrictive rod [15], the equation (1) should be rewritten as:

$$
\varepsilon = S^\sigma \sigma + dH - CS^H \dot{\varepsilon} - \frac{\rho L^2}{3} S^H \ddot{\varepsilon}
$$

(2)

in which, $C$, $\rho$, $L$ are the damping coefficient of inside of giant magnetostrictive rod, density and length. In addition, the magnetic field intensity of solenoid can be represented as:

$$
H(t) = c_0 I(t) + H_0
$$

(3)

in which, $c_0 = n/l = n/(L+x)$ is the coil factor, $I(t)$ is plus drive current, $H_0$ is plus bias magnetic field intensity, $n$ is number of turns of the drive coil, $l$ is the actual length of the giant magnetostrictive rod. Considering giant magnetostrictive rod as the research object, its output force can be represented as:

$$
F = \sigma A
$$

(4)

in which $A$ is cross sectional area of giant magnetostrictive rod. Because of output force $F$ and output plunger effect of the giant magnetostrictive rod which is reaction and reaction with force of giant magnetostrictive rod, the following formula can be developed according to the second law of Newton:

$$
F = \sigma A = -(M_2 x + C_2 x + K_2 x + \sigma_2 A)
$$

(5)

Because $\varepsilon = \frac{\Delta l}{L} = \frac{x}{L}$, $\dot{\varepsilon} = \frac{1}{L} \dot{x}$, $\ddot{\varepsilon} = \frac{1}{L} \ddot{x}$, unit(2),(3),(5):

$$
(M_1 + M_2) x + (C_1 + C_2) x + (K_1 + K_2) x = \frac{A}{S^L} d\sigma + \frac{A}{S^0} dH - \sigma_1 \frac{A^2}{S^L}
$$

(6)

in which, $M_1 = \rho LA/3$, $C_1 = CA/L$, $K_1 = A/L$. Is respective as equivalent mass equivalent damping and equivalent stiffness of giant magnetostrictive rod, $M_2$, $C_1$, $K_1$ is respective as equivalent mass of load (including spring, the output end of the plunger, quality), damping, and stiffness. Type (6) shows that when the drive current $I = 0A$, the output displacement of the plunger equilibrium position is:

$$
x_0 = \frac{AdH}{S^H(K_1 + K_2)} - \frac{\sigma_1 A^2}{S^H L(K_1 + K_2)}
$$

(7)

In practical applications, pre-tightened stress is always acting on the giant magnetostrictive rod,
the actual measuring displacement is relative to the equilibrium position, that is \( x_1 = x - x_0 \), united (6), type (7) can be said as follows:

\[
(M_1 + M_2)x_1 + (C_1 + C_2)x_1 + (K_1 + K_2)x_1 = \frac{A}{S^2} \, d\theta
\]  

(8)

Laplace transform of type (8), its transfer function is:

\[
G_{n_1} = \frac{X_{n_1}}{I_{n_1}} = \frac{Adn}{S^2L} \frac{1}{(M_1 + M_2)s^2 + (C_1 + C_2)s + (K_1 + K_2)}
\]  

(9)

Transmitting the force by the plunger can be represented as:

\[
f = M_2 \frac{d^2x_1}{dt^2} + C_2 \frac{dx_1}{dt} + K_2x_1
\]  

(10)

Laplace transforms type (10):

\[
G_{n_1} = \frac{f_{n_1}}{X_{n_1}} = M_2s^2 + C_2s + K_2
\]  

(11)

So the transfer function between output force and the input current:

\[
G_{n_1} = \frac{f_{n_1}}{I_{n_1}} = G_{n_1}G_{n_2} = \frac{Adn}{S^2L} \frac{(M_1s^2 + C_2s + K_2)}{(M_1 + M_2)s^2 + (C_1 + C_2)s + (K_1 + K_2)}
\]  

(12)

**Simulation of Dynamic Performance of GMA**

By the mathematical analysis mentioned above, the MATLAB/Simulink transfer function model of GMA is built, which is shown in Figure 3:

![Simulink model of transfer function of GMA](image)

Figure 3. Simulink model of transfer function of GMA.

Set equivalent stiffness, damping, young's modulus, diameter, length, density of telescopic rod, and calculate quality of the telescopic rod \( m_1 \) is 71.8639g. Set the equivalent mass of load \( m_2 = 0.5 \) g, stiffness coefficient and damping coefficient, the coil number of turns is 1800, and simulation calculation is carried out in accordance with the transfer function model of GMA. Dynamic performance curve of GMA can be obtained.

With frequency respectively for 20Hz, 40Hz, 60Hz and 80Hz, and amplitude of 1A–4Acontinuous AC excitation, output displacement and output force of GMA are obtained with the simulation. As is shown in Figure 4, 5.
According to Figure 4 and 5, with 1A–4A continuous amplitude, 20HzAC excitation, output displacement is the biggest, 80HzAC excitation, output displacement is minimum, but output force is opposite to the output displacement; besides, in 20HzAC excitation, current and output displacement is linear proportion, other frequency from 1.5A, current keep a good linear relationship with the output displacement, which makes the control of the GMA is relatively simple.

With the current amplitude is 1A, 2A, 3A, 4A, the frequency of 10Hz-80Hz inspired continuous AC excitation, the output displacement and output force of GMA is concluded, which is as shown in Figure 6, 7.

According to figures 6 and 7, with 10Hz - 80Hz continuous frequency AC excitation, the excitation amplitude increases, the output displacement and output force are increased following; with excitation of fixed amplitude, output displacement decreases with the increase of excitation frequency, the reason is that in order to make the output displacement amplitude of GMA remain unchanged, the drive current cannot be changed, and the impedance of drive coil increases with the increase of excitation frequency.

\[
Z = R + jX = R + jωL = R + j2πfL
\]  

(13)

When the input voltage is constant, the driving current of the coil decreases, so the output displacement amplitude decreases as the driving frequency increases.

Summary

This paper established the mathematical model of GMA, and concludes the dynamic characteristic curve of GMA with simulation. The analysis shows that with 1A-4A continuous AC excitation, the greater the excitation frequency, the smaller the output displacement, and the greater the output force; with 10 Hz-80 Hz AC excitation of continuous frequency, the excitation amplitude is increased with the output displacement and output force increased. The conclusion provides the certain theoretical basis to next experiment of dynamic characteristic of the GMA.
Reference


