中國機械工程學刊第二十七卷第五期第501~506頁(民國九十五年)
Journal of the Chinese Society of Mechanical Engineers, Vol.27, No.5, pp.501~506 (2006)

Design Analysis of Voice Coil Motor for Active Vibration Isolation

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Keywords: Active vibration isolation, Voice coil motor, Optimal independent modal space control

ABSTRACT

With the progress of micro/nano technology, many miniature parts of ultrahigh precision requirement are produced. During the fabrication or measurement stage, we must consider the effect of environmental vibration. In this report, we propose an active-passive vibration isolation system. An accelerometer is used to detect the seismic vibration of the machine base. A voice coil motor (VCM) is used as the actuator for the active vibration isolation. The control algorithm employs optimal independent modal space control (Optimal IMSC) to obtain the optimal feedback force so that we can reduce the external influence of the system. The simulation results and the experimental results are in good agreement. The vibration amplitude can be suppressed to the amount of 85%. Furthermore, the VCM is taken from a market available loudspeaker, which not only reduces the cost but also obtains good vibration isolation effect..

INTRODUCTION

With the progress of the Hi-Tech industry, products have already been miniaturized to super-precision dimensions. During processing or measuring course, we must consider the effect of environmental vibration. If the environmental vibration sources cannot be eliminated completely, vibration control technology should be employed to solve the problem. Vibration control technology can be divided into active and passive controls. In general, passive vibration isolators have low pass filter properties and active ones have high pass filter properties. In this study, however, we need to apply an active vibration isolation technology to suppress the vibration that is near to the natural frequency of a passive vibration isolation system and the amplitude in micrometer level. The goal is to provide very stable machine base for micro/nano fabrication or measurement. .

The actuator of active vibration isolation can be classified into several types: piezoelectric actuator (Singh, et al., 2003, Jang and Tarng, 1999), electrorheological (ER) and magnetorheological (MR) fluid (Choi, et al., 2001, Yao, et al., 2002), pneumatic spring (Ahn, et al., 1996), and linear actuator (Chung, et al., 1999, Chen, et al., 2005). Nowadays, the most common type for active vibration control is the piezoelectric actuator. The main reason is to utilize its features of large thrust force and fine position resolution. The ER or MR fluid is the new smart material that achieved anti-vibration effect by changing the damping coefficient through applied electric or magnetic field to the fluid.

While the piezoelectric material, ER or MR fluid has good performance in vibration isolation, it fails to control the amplitude precisely due to the hysteresis effect. It also needs a complicated feed-back controller, so it increases the difficulty in the control. In contrast, the linear motor has some advantages, such as low hysterisis, low vibration, fast response time and great precision. Its simple structure and direct drive feature also make the system easy to maintain. The voice coil motor (VCM) is one of the linear motors. Today, VCM has many applications, such as in the servo control of the DVD (Chu, et al., 2004) and hard disc. Thus, in this experiment, the VCM is chosen to be the actuator.

In addition to the actuator selection, there are many related control theories and researches, for example, the PID control, independent modal space

Paper Received April 30, 2006. Revised June 15, 2006.
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control (IMSC) (Jang and Tarng, 1999, Meirovitch, and Baruh, 1981), Artificial Neural Network control (Ahn, et al., 1996, Zhang, et al., 2002), and so on. Since the active vibration control requires real-time phase, so the system process needs rapid response time. The advantage of the IMSC is transferred from the coupled dynamic equation to the de-coupled modal space, and then controls each de-coupled modal. This method can control the required modal, not only in reducing the difficulty caused by the modal in the tradition method, but also in saving the computation time. However, the independent modal control may lead to spillover and cause the system unstable. Therefore, Lin and Chu (Lin, and Chu, 1995) propose a new method that uses equivalent controlling weight matrix to solve it.

In this article, a low frequency accelerometer is adopted to detect the vibration, and a VCM is used as the actuator for the active vibration isolation. The control algorithm employs optimal independent modal space control (Optimal IMSC) to obtain the optimal reactive force so that we can reduce the external influence to the system.

THE MATHEMATICAL MODEL

The Thrust of the VCM

The VCM structure used in the experiment is shown in Fig. 1. In accordance with the Lorentz force equation, we can calculate the thrust on the coil when it is electrified in the magnetic field, and it can be expressed as follows:

$$f = klNIB \qquad (1)$$

where, f represents the thrust on the VCM, k is the constant, l denotes the effective length of the coil in the magnetic field, N indicates number of effective turns of the coil traveled by the electric current, I is the current in the coil, *and* B represents the flux density of the permanent magnets.

In general, the thrust force is proportional to the current applied to the coil. Therefore, K_f is the ratio of the thrust and current, called the force constant, Eq. (1) can be rewritten to:

$$f = klNIB = K_f I \qquad (2)$$

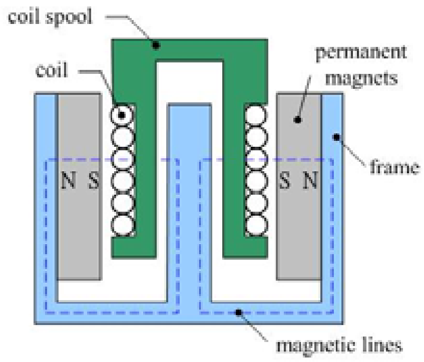


Fig. 1 The VCM structure.

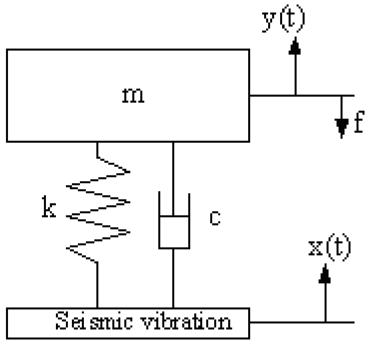


Fig. 2 Schematic of the active vibration isolation system.

Motion Equation of the Active Vibration Isolation

The system diagram of an active vibration isolation is depicted in Fig. 2, where m, c and k are the effective mass, effective damping coefficient and effective stiffness, respectively; x, y, z and f are base exciting displacement, the displacement of plate, the relative displacement of the plate to the base, and the control force, respectively. Therefore, the equation of the motion of the isolation system can be expressed by

$$m\ddot{z} + c\dot{z} + kz = F \qquad (3)$$

where, $z = y - x$, $F = f - m\ddot{x}$.

Dynamic Equation

In order to transform Eq. (3) to the dynamic equation and solve it by IMSC we define

$$e = \begin{Bmatrix} \dot{z} \\ z \end{Bmatrix} \qquad (4)$$

Substituting Eq. (4) into Eq. (3) yields to

$$M\dot{e} + Ke = Q \qquad (5)$$

where,

$$M = \begin{bmatrix} m & 0 \\ 0 & k \end{bmatrix}, \quad K = \begin{bmatrix} c & k \\ -k & 0 \end{bmatrix}, \quad Q = \begin{bmatrix} F \\ 0 \end{bmatrix}$$

Eq. (5) can be rewritten as a transfer representation of the dynamics by

$$\dot{e} = Ae + BQ \tag{6}$$

where, $A = -M^{-1}K$, $B = M^{-1}$

Independent Modal Space Control (IMSC)

IMSC can de-couple the coupled system and transform to a modal space. The goal of using IMSC is to find the modal control forces via each independent modal. The characteristic of the modal transfer matrix is obtained in the following form.

$$L^T R = I \ , \ L^T AR = \Lambda \tag{7}$$

where, Λ is block-diagonal matrix defined by

$$\Lambda = block - diagonal \begin{bmatrix} \sigma_s & \omega_s \\ -\omega_s & \sigma_s \end{bmatrix} ; s = 1,2,\ldots,k \tag{8}$$

where, σ_s and ω_s are the real and complex parts of eigenvalue λ_s of the controlled complex model.

Therefore, Eq. (6) can be simplified to

$$\dot{q} = \Lambda q + Q_u \tag{9}$$

$$Q_u = L^T M^{-1} Q \tag{10}$$

Eq. (10) defines the modal control force.

Optimal Control Method

This research uses optimal control method to make the design. In the first place, we find out the required control mode equation.

$$\dot{q}_s = \Lambda_s q_s + Q_{u,s} \ ; \ s=1,2,\ldots,k \tag{11}$$

The skill of the optimal control method is to minimize the performance index J in Eq. (12)

$$J = \sum_{s=1}^{k} J_s \tag{12}$$

where, J_s is the independent modal cost function defined as

$$J_s = \int_0^{\infty} \left(q_s^T \ q_s + Q_{us}^T \ E_s \ Q_{u,s} \right) \ dt \ ; s=1,2,\ldots,k \tag{13}$$

The factor E_s is the weight matrix with respect to the required control effort. In Eq. (13) the optimal modal controlling force may express as follows (Gardonio, et al., 1997)

$$Q_{u,s} = -E_s^{-1} S_s q_s \ ; s=1,2,\ldots,k \tag{14}$$

S_s is so-called Riccati matrix which is obtained in the form of

$$S_s \Lambda_s + \Lambda_s^T S_s - S_s E_s^{-1} S_s + I = 0 \ ; s=1,2,\ldots,k \tag{15}$$

However, the independent modal control may lead to spillover and cause the system unstable. Therefore, Lin and Chu Lin, and Chu, 1995) propose a new method that uses equivalent controlling weight matrix to solve it. Define

$$E_s^{-1} = \begin{bmatrix} E_{s11}^{-1} & 0 \\ 0 & E_{s22}^{-1} \end{bmatrix} \tag{16}$$

where $E_{s11}^{-1} = E_{s22}^{-1} = \overline{E}_s$ (17)

Because Eq. (15) is taken out from the requited control modal, it can avoid operating the large-scale matrix that creates the numerical computing time excessively long. This is the merit of optimal independent modal space control.

EXPERIMENT APPARATUS

The experimental system consists of an accelerometer, a platform, springs, a voice coil motor (VCM) and a granite base as shown in Fig. 3. Four springs are arranged symmetrically to support a high rigid plate. The accelerometer and the VCM are placed in opposite positions in the center of plate, respectively. The weight of the plate is about 6.9 kg. The effective stiffness is 17053.26 N/m.

The VCM is a popular actuator in the loudspeaker to generate various frequencies of sound. For the cost saving purpose, we adopt this type of VCM as the actuator in our system..

The accelerometer measures the vibration of the structure and the measured signals are digitized to a personal computer through an analog-to-digital (A/D) converter. The computer sends the voltage signal calculated by the optimal IMSC algorithm to the driver of the VCM through a digital-to-analog (D/A) converter to generate the required control force.

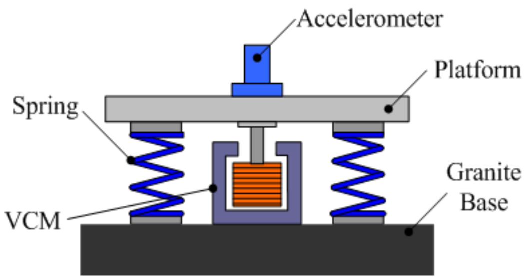


Fig. 3 The setup of the active vibration isolation system

EXPERIMENTAL RESULTS

The voice coil motor has output power of 100 W and resistance of 8 Ohm). The force constant of VCM can be obtained via experiment, the relationship between the thrust and the current is shown in Fig. 4, and the k_f is 3.33 N/A.

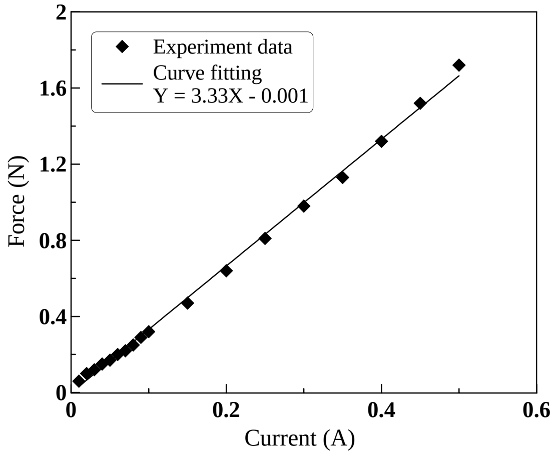
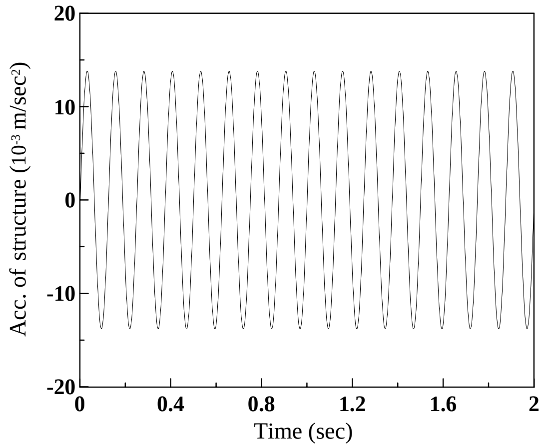
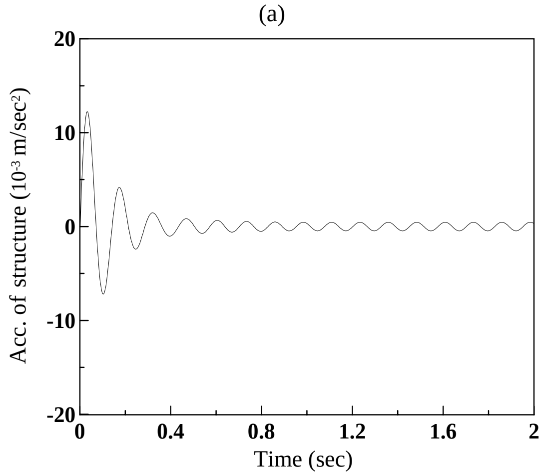


Fig. 4 The relation between the thrust of VCM and the applied current



(a)



(b)

Fig. 5 Response of the anti-vibration under an excitation at 8 Hz, (a) without control, (b) with control

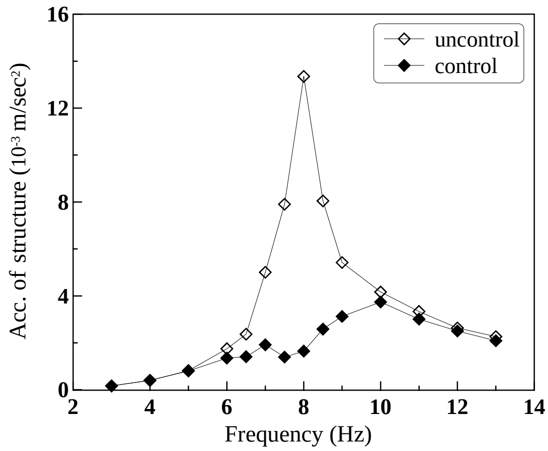
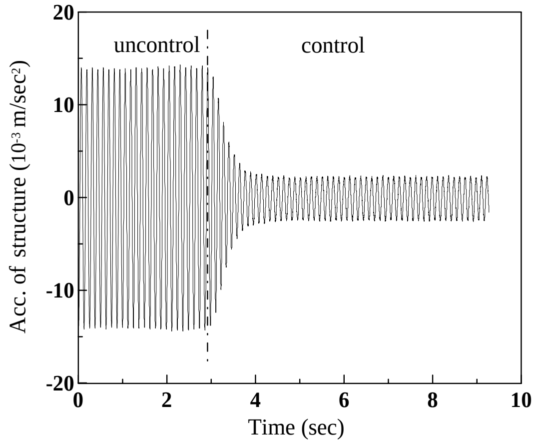
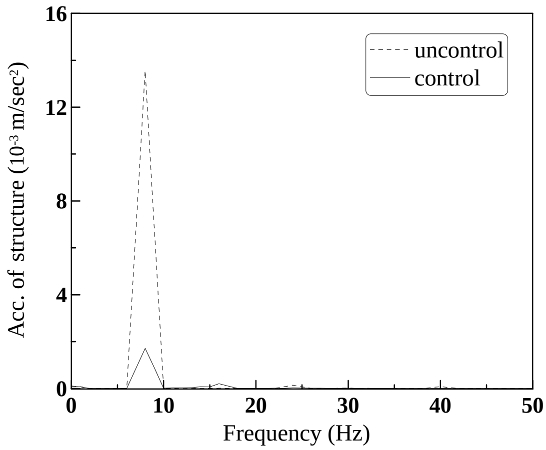


Fig 6 Performance test result under sinusoidal excitation.



(a)



(b)

Fig. 7 Response of the anti-vibration under an excitation at 8Hz, (a) time domain; (b) frequency domain.

From the finite element analysis and the experiment on the structure, the first natural frequency in the longitudinal direction is found to be 7.8Hz. The numerical simulation is carried out on the anti-vibration system with the MATLAB software. Given an excitation force of 8Hz a significant resonate signal is found, as shown in Fig. 5(a). Having applied the active vibration control the amplitudes are suddenly reduced to around 85%, as shown in Fig. 5(b). The transient time is about 0.6 seconds.

Performance tests of the active vibration isolation are carried out under sinusoidal excitation by changing frequencies form 3 Hz to 13 Hz with the interval of 0.5 Hz or 1Hz. As a result, the acceleration values of the active vibration isolation at each input frequency are shown in Fig. 6, for both the controlled and uncontrolled states. When a sinusoidal excitation with a frequency of 8 Hz applies to the system, the results are illustrated in Fig. 7 for time domain and frequency domain plots respectively. It is clearly seen that the acceleration level is reduced to the degree about 85%. The experimental results are in good agreement with the simulation results.

CONCLUSIONS

In this article, we propose an effective active-passive vibration isolation system. For the passive vibration isolation, four-spring isolators are arranged symmetrically to support a high rigid plate. The voice coil motor (VCM) is used as an actuator for the active vibration isolation. The VCM and springs are arranged in parallel. The control algorithm employs optimal independent modal space control (Optimal IMSC) to obtain the optimal feedback force so that we can reduce the external influence of the system. The performance test of the control system is validated by numerical simulation. Both results show good agreement, and the vibration can be reduced up to 85% Furthermore, the market loudspeaker is used as an actuator, this system not only reduces the cost but also obtains good vibration isolation effect.

ACKNOWLEGEMENT

The support provided by National Science Council of R.O.C. (NSC-94-2212-E-002-028) is greatly appreciated.

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音圈馬達於主動振動隔振器之設計分析

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摘　要

有鑑於微奈米技術的蓬勃發展，無論是加工或是量測過程都需要一個穩定的環境，來提高精度與良率。本文章中提出主被動隔振系統之研製，在主動隔振系統設計方面，將利用音圈馬達作為驅動器，並與被動隔振系統並聯使用，利用最佳化獨立模態控制法則求出最佳反饋值，藉此降低外界的振動對於系統的影響。藉由數值模擬與實驗結果可得到相同的結果。此外，本實驗設備中也以市售的喇叭當作驅動器，不僅可以降低成本，也能得到良好的隔振效果。