Self-tuning of Hybrid Position and Velocity Feedback of 6-DOF Vibration Isolation System

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Abstract

Active Vibration Isolation System (AVIS) is widely used in precision metrology devices and IC equipments. It is composed of a position feedback and a velocity feedback to achieve high vibration isolation performance and maintain position stability. However, its performance is always affected by the combination of position feedback loop and velocity feedback loop. Traditionally, the parameters of velocity controller and position controller are determined step-by-step. The tuning procedure is time-consuming and greatly depends on the experience, so it can not attain the best performance. In this paper, we proposed a self-tuning procedure for the AVIS with a velocity feedback and a position feedback. The procedure aims at optimal damping by means of Sky-hook. In case the structure coupling is weak in six orthogonal coordinates, self-tuning is realized in three simple steps: (1) calculation of the decoupling matrix, (2) identification of the structure parameters based on the dynamic model of the AVIS and (3) optimization of the feedback controller by minimizing the vibration of the payload. The numerical simulation is employed to implement the self-tuning method and validates the performance of AVIS.

1 A 6-DOF AVIS model

1.1 Structure dynamics

A typical 6-DOF AVIS includes 3 vibration isolators displaced at the vertices of an equilateral triangle on the base. The mechanical dynamics of each vibration isolator can be equivalent to three mutually orthogonal springs and dampers.

The load dynamic equation is expressed as

$$\mathbf{M}\ddot{\boldsymbol{\theta}} + \mathbf{C}\dot{\boldsymbol{\theta}} + \mathbf{K}\boldsymbol{\theta} = \mathbf{F_M} \quad (1)$$

where **M, C, K, F_M** are mass matrix, damping matrix, stiffness matrix, and control force vector in logical axis $\boldsymbol{\theta}$ separately.

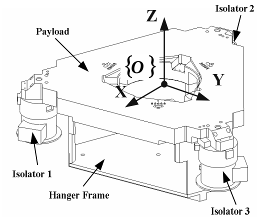

Fig1: A schematic of 6-DOF AVIS

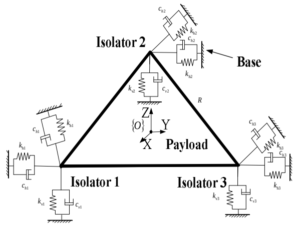

Fig.2 Structure dynamics model

1.2 SISO feedback controller

Six SISO controllers, hybrid of velocity and position feedback, are used to compensate the vibrations in six Cartesian directions by utilizing of the sensor decoupling matrix [T_S] and actuator decoupling matrix [T_A]. The decoupling matrix can be calculated with geometry relations.

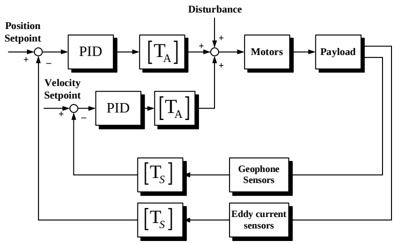

Fig.3 Control block of AVIS

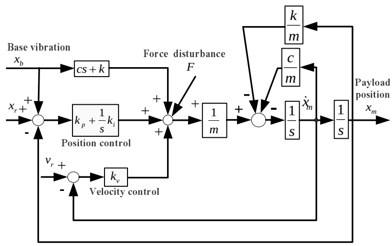

Fig.4 SISO control block

2 Self-tuning method with optimal damping

In case the structure coupling is weak in six orthogonal coordinates, six SISO feedback controllers can be self-tuned separately. For a typical SISO controller, there are only 3 parameters, velocity proportional gain kv, position proportional gain kp and integral gain ki. They must be determined with a self-tuning procedure.

The transfer function from base x_b to payload x_m and the transfer function from direct disturbance force F to payload x_m can be normalized as

$$H_{x_b}^{x_m}(s) = \frac{2\xi_1 s_n^{\ 2} + s_n + \eta}{s_n^{\ 3} + 2\xi s_n^{\ 2} + s_n + \eta} \qquad (2)$$

$$H_F^{x_m}(s) = \frac{1}{\omega_n^2 m}\frac{s_n}{s_n^3 + 2\xi s_n^2 + s_n + \eta} \tag{3}$$

with

$$\frac{1}{m}(k+k_p) = \omega_n^2, \frac{1}{m}(c+\mathrm{k}_v) = 2\xi\omega_n, \frac{c}{m} = 2\xi_1\omega_n, \frac{k_i}{m} = \eta\omega_n^3, s_n = \frac{s}{\omega_n} \tag{4}$$

It should be noted that the parameters kp, ki and kv do not appear explicitly in Eq.2 and Eq.3, and the parameter ω_n and m only appear as gains. This implies that in order to determine the optimum control parameters for the feedback controller parameters ξ and η, only ξ_1 is needed. The parameter ω_n can be optimized by minimizing the vibration of the payload if the parameters ξ and η are determined.

a) Determination of the damping rate ξ and integration rate η

- Stability

As shown in Fig.5, the parameters ξ and η must be limited into the ‘Stable area’ in order to keep the system stable,.

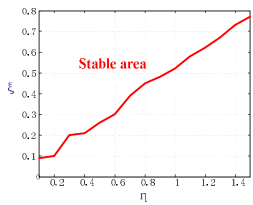

Fig.5 Stable area

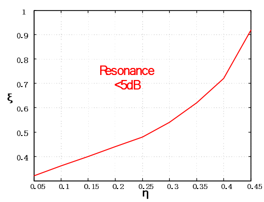

Fig.6 Resonance vibration transmissibility

- Base vibration transmissibility <5dB

In order to limit vibration level transferred from the base, the resonance of the vibration transmissibility $H_{x_b}^{x_m}(s)$ must be restricted below 5dB, and the parameters η and ξ are limited in the area of ‘Resonance<5dB’ shown in Fig.6.

- Setting-time $T_s \le T_0$

Step response of $H_F^{x_m}(s)$ is depicted in Fig.7, and the parameter P_0 and T_0 are the position response amplitude and resonance period without active control.

To limit the setting time $T_s \le T_0$, η and ξ need to be restricted into the area of ‘$T_s = 1T_0$’ in Fig.8.

By compromising of base vibration transmissibility and setting-time, an optimal damping rate $\xi = 0.7$ and integration rate $\eta = 0.36$ is achieved.

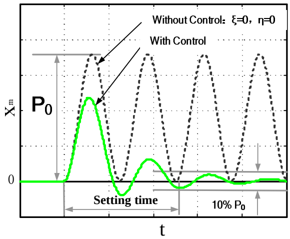

Fig.7 Step response of $H_F^{x_m}(s)$

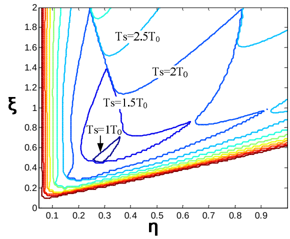

Fig.8 Setting time contour

b) Determination of the resonance frequency ω_n

The cost to minimum vibration on the payload can now be defined as follows:

$$\min J = \int_{\omega=\omega_1}^{\omega=\omega_2} \left(S_F(\omega) \cdot \left| H_F^{a_m}(j\omega) \right|^2 + S_B(\omega) \cdot \left| H_{a_b}^{a_m}(j\omega) \right|^2 \right) d\omega, \quad \omega_n \geq \omega_{n1} \quad (5)$$

where $H_F^{a_m}(j\omega)$ is the acceleration response of disturbance force F, $H_{a_b}^{a_m}(j\omega)$ is the vibration transmissibility from base, $S_B(\omega)$ and $S_F(\omega)$ are the base vibration PSD and the disturbance force PSD.

With the Eq.5, the optimal resonance frequency ω_n can be calculated.

c) Calculation of the feedback control parameters kp, ki and kv

$$k_p = m\omega_n^{\ 2} - k, \quad \mathrm{k}_v = 1.4m\omega_n - c, \quad \mathrm{k}_i = 0.36m\omega_n^{\ 3} \quad (6)$$

In Eq.6, the parameters damping c, mass m and stiffness k can be identified in-situ[1].

References:

[1] H. Kato, S. Wakui, T. Mayama, et al. System identification of anti-vibration units in semiconductor exposure apparatus. Proc. IEEE. International Conference on Control Applications. 1999. Kohala Coast-Island of Hawai'i. USA.