Self-tuning of position feedback and velocity feedback of active vibration isolation system with 6 DOFs

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1. Introduction

Vibration isolation systems are widely used in high-precision motion systems such as IC stepper and high-precision measurement devices such as electron microscope [1-3, 4]. Ground vibration and direct disturbance force such as motion stages lead to payload vibration. Traditionally, passive isolators, such as air springs and Euler springs, are employed to isolate the vibrations above 10 Hz [5]. However, the passive isolator amplifies the vibrations near the resonance frequency which is normally in range of 2 ~ 6 Hz and greatly degrades the performance of precision equipment.

Unlike passive isolator, Active Vibration Isolation System (AVIS) can isolate both base vibration and direct disturbance without amplifying vibrations near resonance frequency. For a typical 6-DOF AVIS, position loop and velocity loop are both employed to achieve high anti-vibration performance and maintain position stability [1, 6-8]. Instead of velocity feedbacks, force feedbacks or acceleration feedbacks are used in pneumatic vibration isolation system and in aerospace vibration isolation system [9-11], in order to realize sky-hook damping [12-13]. Generally, loop-shaping tuning method is used to determine parameters of the sky-hook damping loop and the position feedback loop in sequence. However, there are 12 feedback loops, and at least 18 parameters in a 6-DOF AVIS. So the loop-shaping tuning method costs much time and greatly depends on the operator’s experience.

In this paper, a fast self-tuning procedure is presented to get optimal damping for the 6-DOF AVIS with sky-hook damping. Firstly, the dynamic model of the 6-DOF AVIS is built. Secondly, we propose the self-tuning procedure and simulate the performance. At last, the self-tuning controller is validated with an experiment.

2. Model of 6-DOF AVIS

2.1. Structure dynamics

A typical 6-DOF AVIS includes 3 vibration isolators, as shown in Fig. 1. The payload is supported by 3 vibration isolators displaced at the vertices of equilateral triangle on the base. We assume that the centre of equilateral triangle is the origin of the coordinate system OXYZ, the Z axis is in the gravity direction, and the X axis in the direction perpendicular to the connection line of Isolator 1 and Isolator 3. As is shown in Fig. 2, the displacement between each two isolators is L, and the three isolators distribute on the circle with the radius equates R.

Fig. 1 Layout of AVIS

Fig. 2 Geometry of AVIS \( \phi_i \)

The system geometry is depicted in Fig. 2. It shows both the sensor and actuator locations together with the centre of gravity, indicated with \( m \), with respect to the virtual reference point indicated with O. In the coordinates system OXYZ, the Cartesian coordinates of the system is defined as

\[
\theta = \begin{bmatrix} x \ y \ \phi_x \ \phi_y \ \phi_z \end{bmatrix}^T
\]

Six geophone sensors and six eddy sensors are used to measure the absolute velocity and the relative position of the payload. So the measurement results is written as

\[
A = \begin{bmatrix} A_{H1} \ A_{H2} \ A_{H3} \ A_{V1} \ A_{V2} \ A_{V3} \end{bmatrix}^T
\]

where \( V \) indicates the vertical direction and \( H \) indicates the horizontal direction, \( A_{Hi} \) and \( A_{Vi} \) \((i = 1, 2, 3)\) denotes the horizontal and vertical velocity (or displacement) signals.
for $i$-th isolator.

Because the angles $\varphi_x$, $\varphi_y$, and $\varphi_z$ are very small [1], the sensor output in terms of generalized position or velocity is given by

$$\theta = T_\theta A$$

where matrix $T_\theta$ is used to transform the measurement results of geophones and eddy sensors from physical axis into logical axis.

$$\begin{bmatrix}
\sqrt{3}/2 & 1/2 & R & 0 & 0 & 0 & 0 \\
0 & -1 & R & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & -1/2R & -1/2L & 0 \\
0 & 0 & 0 & 1 & R & 0
\end{bmatrix}^{-1}$$

$\theta$ is a symmetric stiffness matrix

$$K = \begin{bmatrix}
k_{11} & k_{12} & k_{13} & 0 & 0 & 0 \\
k_{21} & k_{22} & k_{23} & 0 & 0 & 0 \\
k_{31} & k_{32} & k_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & k_{44} & k_{45} & k_{46} \\
0 & 0 & 0 & k_{54} & k_{55} & k_{56} \\
0 & 0 & 0 & k_{64} & k_{65} & k_{66}
\end{bmatrix}$$

$$C = \begin{bmatrix}
c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\
c_{21} & c_{22} & c_{23} & 0 & 0 & 0 \\
c_{31} & c_{32} & c_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & c_{44} & c_{45} & c_{46} \\
0 & 0 & 0 & c_{54} & c_{55} & c_{56} \\
0 & 0 & 0 & c_{64} & c_{65} & c_{66}
\end{bmatrix}$$

$M$ is the matrix of the control force in logical axis $\theta$

$$F_M = \begin{bmatrix}
F_x \ F_y \ F_{rz} \ F_z \ F_{rx} \ F_{ry}
\end{bmatrix}^T$$

The actuator output $F_L$ in terms of physical coordinates is given by

$$F_L = T_s^{-1} F_M$$
2.2. Control strategies

As shown in Fig. 4, Six single input, single output (SISO) controllers with a velocity feedback and a position feedback are used to compensate the vibrations in six directions. The decoupling matrix $T_S$ is calculated from geometric relations. Sensor matrix $T_S$ is used to transform the measurement results of geophones and eddy sensors from physical axis into logical axis. Actuator decoupling matrix $T_A$ is used to transform the control signal from logical axis into actuator axis. With the coupling matrix and decoupling matrix, the 6×6 multiple input, multiple output (MIMO) controllers of AVIS are reduced to six SISO controllers in six logical axes. A velocity proportional-integral-derivative (PID) controller is used to increase the position stability. A vibration proportional gain $k_p$, position proportional gain $k_v$, and a position PID controller to maintain the damping. The decoupling matrix, the 6×6 multiple input, multiple output (MIMO) controllers of AVIS are reduced to six SISO controllers in six logical axes. A velocity proportional-integral-derivative (PID) controller is used to increase the position stability. The decoupling matrix, the 6×6 multiple input, multiple output (MIMO) controllers of AVIS are reduced to six SISO controllers in six logical axes. A velocity proportional-integral-derivative (PID) controller is used to increase the position stability.

3. Self-tuning method for SISO feedback

The payload vibration is caused by both base vibration and direct force disturbance. As shown in Fig. 4, the transfer function $H_x^w(s)$ from base $x_b$ to payload $x_m$ and transfer function $H_x^f(s)$ from direct disturbance force $F$ to payload $x_m$ can be deprived and normalized as

$$H_x^w(s) = \frac{cs^2 + (k + k_p)s + k_i}{ms^3 + (c + k_v)s^2 + (k + k_p)s + k_i}$$

$$H_x^f(s) = \frac{X_m(s)}{F(s)} = \frac{1}{ms^2 + (c + k_v)s + k + k_p + \frac{1}{k_i}}$$

Normalizing Eq. 2 and Eq. 3 with respect to $\omega_n$, $s_n$, $\zeta$, $\xi$, $m$, and $\eta$, we can get

$$H_x^w(s) = \frac{2\zeta s_n^2 + s_n + \eta}{s_n^3 + 2\zeta s_n^2 + s_n + \eta}$$

$$H_x^f(s) = \frac{1}{\omega_n^2 m s_n^2 + 2\zeta s_n^2 + s_n + \eta}$$

with

$$\frac{1}{m}(k + k_p) = \omega_n^2, \frac{1}{m}(c + k_v) = 2\zeta \omega_n$$

$$\frac{c}{m} = 2\zeta \omega_n, \frac{k_i}{m} = \eta \omega_n, s_n = \frac{s}{\omega_n}$$

It should be noted that the parameters $k_n$, $k_v$, and $k_i$ do not appear in Eq. 4 and Eq. 5, and the mechanical parameters $\omega_n$ and $m$ only appear as gains. These imply that only the parameter $\zeta$ is needed to determine the optimum control parameters for the feedback control parameters $\zeta$ and $\eta$. The parameter $\zeta$ must be very small to achieve high vibration isolation performance in high-frequency band. Its typical value is set to 0.02. As the parameters $\zeta$ and $\eta$ are determined, the parameter $\omega_n$ can be optimized by minimizing the vibration of the payload.

So we can follow the following procedure: first determine the damping rate $\zeta$ and integration rate $\eta$, and then determine the $\omega_n$.

3.1. Damping rate $\zeta$ and integration rate $\eta$

a) Stability

Fig. 6 is root locus with different integration rate $\eta$. The damping rate $\zeta$ and integration rate $\eta$ are limited into the stable area shown in Fig. 7.
b) Base vibration isolation

Fig. 8 denotes the vibration transmissibility from base at resonance frequency according to the integration rate $\eta$ and the damping rate $\zeta$. In order to limit the vibration transmissibility resonance into 5 dB, $\eta$ and $\zeta$ are limited into the area of “Resonance < 5 dB” as shown in Fig. 8.

Fig. 9 Step response of $H^a_{F}(s)$

To limit the setting time into $T_0$, $\eta$ and $\zeta$ are restricted into the area of “Setting time $1T_0$” area, as shown in Fig. 10.

Above all, the optimal $\eta$ and $\zeta$ should set into $1T_0$ range. Damping $\zeta = 0.7$ and $\eta = 0.36$ are recommend to achieve maximum damping rate.

3.2. Resonance frequency $\omega_n$

The resonance frequency affects the vibration level of the payload. By minimization of accumulate acceleration PSD (Power Spectral Density) on the payload, the resonance frequency $\omega_n$ is achieved. The accumulate acceleration PSD on the payload is defined as follows

$$J = \int_{\omega_n}^{\omega} [S_F(\omega)|H^a_{F}(j\omega)|^2 + S_b(\omega)|H^b_{S}(j\omega)|^2]d\omega$$

where $H^a_{F}(j\omega)$ is the acceleration response of disturbance force $F$, $H^b_{S}(j\omega)$ is the vibration transmissibility from base, $S_b(\omega)$ is the base vibration PSD, and $S_F(\omega)$ is the disturbance force PSD.

By minimization of $J$ in Eq. 7, the optimal resonance frequency $\omega_n$ can be calculated.

4. Simulation on self-tuning controller

4.1. Self-tuning procedure for AVIS:

a) calculation of the sensor decoupling matrix and actuator decoupling matrix, based on the geometry relations;

b) estimation of system parameters in six logical axes, such as relative damping $c$, stiffness $k$, mass $m$.

This parameter estimation approaches are divided into indirect and direct techniques who work together to use online [2, 15, 16].

c) Determination of the optimal controller parameters.

Follow the procedure of chapter 3, we can calculate the feedback control parameters.

$$\begin{align*}
    k_p &= m\omega_n^2 - k \\
    k_c &= 1.4m\omega_n - c \\
    k_i &= 0.36m\omega_n^2
\end{align*}$$

4.2. Calculation

We take a metrology frame as an example. The
payload mass is 1300 kg, and the moments of inertia are: 
\( I_x = 184.6 \text{ kgm}^2, \quad I_y = 193.7 \text{ kgm}^2, \quad I_z = 373.9 \text{ kgm}^2. \) From
the following parameters: 
\( R = 0.65 \text{ m}, \quad k_{h1} = k_{h2} = k_{h3} = 6.7 \times 10^4 \text{ N/m}, \quad k_{v1} = k_{v2} = k_{v3} = 8.2 \times 10^4 \text{ N/m}, \)
\( c_{h1} = c_{h2} = c_{h3} = 500 \text{ N/m}, \quad c_{v1} = c_{v2} = c_{v3} = 600 \text{ Ns/m}, \)
the damping matrix \( \mathbf{C} \) and Stiffness matrix \( \mathbf{K} \) are determined.

There are two primary vibrations, vibration from base floor and direct disturbance acoustics, the acceleration PSD of base vibration is depicted in Fig. 11 while the random disturbance force caused by acoustics noise below the level of 0.01 N.

The resonance frequencies \( \omega_n \) for each SISO loop are optimized based on the Eq. 7. All three parameters are then calculated based on the Eq. 8. The results are depicted in the Table.

<table>
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<th>Axis</th>
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<tr>
<td>X</td>
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<tr>
<td>Rz</td>
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<td>Rx</td>
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<td>Ry</td>
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<table>
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<th>Controller parameters</th>
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<td>Rx</td>
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Compared with the base vibration, the effects of acoustics noise can be ignored. The self-tuning controller of AVIS is turned on with the parameters listed in Table. Both the base and payload vibration are measured by accelerometers, which are shown in Figs. 15 and 16.
Fig. 15 Base acceleration PSD

Fig. 16 Payload acceleration PSD with active control

Fig. 16 shows that the PSD level of payload acceleration is satisfied and Fig. 16 shows that the acceleration PSD value is below the level of $10^{-10}$ (m/s$^2$/Hz) in the frequency range of 10 Hz to 100 Hz. These imply that the self-tuning controller can achieve high vibration isolation performance and shorten the tuning time.

6. Conclusion

A self-tuning procedure is proposed for 6-DOF AVIS with position feedback and velocity feedback, which aims at optimal damping of AVIS with Sky-hook. As the structure coupling is weak in six orthogonal coordinates, self-tuning is realized in three steps: calculation of the decoupling matrix, identification of the structure parameters based on the dynamic model of the AVIS, optimization of the feedback controller by minimizing the vibration of the payload. An experiment is implemented to verify the self-tuning method and the performance of AVIS with a metrology test platform. The acceleration PSD value is below the level of $10^{-10}$ (m/s$^2$/Hz) in range of 10 Hz to 100 Hz by using the self-tuning controller. Compared with the traditional loop shaping method, this self-tuning procedure can quickly and efficiently determine the feedback control parameters and doesn’t depend on operator’s experience.

References


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**Summary**

Active Vibration Isolation Systems (AVIS), which are composed of position feedback loop and velocity feedback loop, are widely used in IC equipments and high precision metrology devices to achieve high vibration isolation performance and maintain position stability. However, the performance of AVIS is always affected by both position feedback loop and velocity feedback loop. Traditionally, the control parameters of the velocity loop and feedback loop are determined in sequence. But these tuning procedures are time-consuming and the performance of AVIS greatly depends on operator’s experience. Further more, AVIS controlled with these parameters can not attain the best performance. In this paper, we propose a self-tuning procedure for the AVIS with velocity feedback and position feedback, which aims at optimal damping of AVIS with Sky-hook. As the structure coupling is weak in six orthogonal coordinates, the self-tuning procedure is realized in three steps: calculation of the decoupling matrix, identification of the structure parameters based on the dynamic model of the AVIS, optimization of the feedback controller by minimizing the vibration of payload. A simulation and an experiment are implemented to verify the self-tuning method and the performance of AVIS.

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