ATTITUDE CONTROL FOR AIR SPRING ISOLATION SYSTEM WITH ELECTROMAGNETIC ACTUATOR

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Active-passive isolation technology is applied in ship equipment to achieve higher isolation efficiency both in broadband vibration and low-frequency harmonic vibration. A hybrid vibration isolation system (HVIS) is designed with active-passive vibration isolators, which consist of electromagnetic actuator and air spring. In order to obtain expected effect for vibration line-spectra isolation, the air gap of actuator need maintain in a fairly small range. As low and nonlinear stiffness characteristics, the air gap is more susceptible to some disturbance, such as temperature variation and air spring pressure change. So how to control attitude of the isolation system to ensure air gap in appropriate range is a challenge for designers. In this paper, the factors affecting air gap are analyzed, and an attitude control algorithm is designed to achieve high control precision and stability. The experiment results show the algorithm meet the air gap requirement for electromagnetic actuator.

Keywords: active-passive isolation, electromagnetic actuator, air spring, air gap, attitude control

1. Introduction

Due to low natural frequency characteristic, air spring isolation system can achieve high-performance vibration isolation effect for marine power equipments[1]. But low-frequency harmonic vibration from equipments is hard to be attenuated further. Passive-active vibration isolation system has more optimal performance in decreasing low-frequency harmonic vibration.

This paper presents a hybrid vibration isolation system (shown in Fig. 1) in which the hybrid isolator consists of air spring and electromagnetic actuator. A little variation of air gap is permissible for the
electromagnetic actuator to ensure stably and desired effect. Accordingly, air spring’s pressure should be adjustable to keep the magnetic gap within the desired range. The variation of gap can be measured by the displacement sensors, and the pressure of air spring can be detected and adjusted by the pressure control unit[2]. The stiffness nonlinear characteristic of the isolator is analysed; the main influence factors are analysed; a method of attitude control is proposed and the effect of controlling magnetic gap is tested.

![Figure 1: Schematic of HVIS](image)

### 2. Stiffness Characteristic Analysis of Hybrid Isolator

The schematic structure of hybrid isolator is shown in Fig. 2, an electromagnetic actuator is integrated inside an air spring which bears the equipment weight. The actuator consists of iron core, coil, permanent magnet, magnetic conductive rubber and armature[3]. The permanent magnet generates attraction force to the armature, and the force increases with the air-gap decreasing. Accordingly, the actuator shows characteristic of equivalent negative stiffness. The magnetic conductive rubber is filled between the permanent magnet and actuator armature to reduce the air-gap reluctance and increase contact stiffness of the isolator[4].

![Figure 2: Internal Structure of Hybrid Isolator](image)

When air spring height varies in a small range, its stiffness $k_s$ is linear relation with its pressure and can be expressed as:
\[ k_s = \mu_r p \] (1)

where \( p \) is the air spring pressure, \( \mu_p, \mu_q, \mu_r \) are constants related to air spring’s structure parameters.

The attraction force caused by permanent magnet can be approximately expressed as[5]:

\[ F_p = \eta_p \frac{4H_c^2 h_m^2}{(z + h_m)^2} \] (2)

where \( h_m \) is the thickness of permanent magnet; \( z \) is the air-gap height; \( H_c \) is the coercive force of permanent magnet; \( \eta_p \) is a constant related to material and structure parameters of actuator. Accordingly, the equivalent negative stiffness of actuator can be calculated:

\[ k_p = -8\eta_p \frac{4H_c^2 h_m^2}{(z + h_m)^3} \] (3)

The total stiffness of hybrid isolator can be expressed as:

\[ k = k_s + k_p + k_r \] (4)

where \( k_r \) is the stiffness of magnetic conductive rubber.

For an air spring of the hybrid isolator, the rated load is 8.3kN which corresponding 0.65MPa pressure. At the rated pressure, the static stiffness of the hybrid isolator is measured on a material testing machine and the test results are shown in Fig. 3 under different air-gap height. When the height of air-gap varies in the range from 0mm~0.4mm, the rubber and armature not touch, the total stiffness of the hybrid isolator is \( k = k_s + k_p \). Within this range, the negative stiffness of actuator is larger, total stiffness behaves zero stiffness characteristic. When the height of air-gap is negative, the rubber is compressed by the armature, the static stiffness swiftly increased to about 1750N/mm; When the height of air-gap is larger than 0.4mm, the negative stiffness of actuator decreases rapidly and the total stiffness of the isolator increases to 250N/mm. Accordingly, the total stiffness can be linearized by three-segment.
3. Attitude Control algorithm

3.1 Motion Equations of System

As shown in Fig. 1, the frame of reference is established at ship hull. At rated height of hybrid isolators, the center-of-gravity (C.G) of raft was considered as original point and initial value of air-gap is \( z_0 \). The variation of air-gap can be expressed as:

\[
\begin{align*}
    z_j &= g_j^T x_c \\
    \text{where } z_j &\text{ is the height of air-gap of } j\text{th hybrid isolator, } x_c = [x_c, y_c, z_c, \alpha, \beta, \gamma]^T \text{ refers to rotation and translational motion of the raft. } g_j = [0, 0, 1, s_{jx}, s_{jy}, s_{jz}]^T, s_{jx}, s_{jy}, s_{jz} &\text{ refer to the coordinate components of } j\text{th hybrid isolator.}
\end{align*}
\]

The motion of the raft \( x_c \) can be expressed as:

\[
    x_c = K^{-1} F
\]

where \( F \) is disturbance force applied on the raft. \( K \) is system stiffness matrix, and varies with the heights of air-gap. Apparently, in order to ensure the stability of HVIS, the heights of air-gap must be larger than 0.4mm.

3.2 Influence of Temperature on Air-gap

When actuator works, the control current is input to the coil. As the actuator is sealed in air spring, inner temperature will increase with the actuator working, and the pressure of air spring will increases. Considering volume of air spring is invariable, the pressure can be expressed as:
\[ p_j' = \frac{T'}{T_j} p_j \]  

(7)

Test results show that the inner temperature of air spring will rise at most 20℃ with the actuators working. According to Eq. (7), the air spring pressure will rise about 5%. The disturbance force caused by temperature variation can be expressed as:

\[ F_j = \Delta p_j A_j g_j \]  

(8)

where \( \Delta p_j = p_j' - p_j \), \( A_j \) is the effective area of the air spring. Fig. 4 shows the influence of temperature on the air-gap. It can be seen that with inner temperature of air spring rising about 20℃, the height of air-gap increases from 1.8mm to 2.3mm.

3.3 Attitude Control Algorithm

Considering the influence of temperature and zero stiffness characteristic, appropriate static equilibrium point \( z_0 \) is set to 2mm. Too large or too small value of \( z_0 \) will cause active control performance and stability of HVIS degradation. In order to achieve high attitude control precision with rapid convergence, an attitude control method is proposed. According nonlinear stiffness characteristic of hybrid isolator, the control process can be divided into three phases.

In the initial phase, the raft is supported by the air springs and magnetic conductive rubbers with \( \max z_j < 0, j = 1, 2, L, N \). The air spring with smallest pressure should be chosen to charge.

In the second phase, the armature begins to depart from the magnetic conductive rubber, and the condition \( z_j > 0, j = 1, 2, L, N \) is met. Here, the system stiffness of HVIS sharply decreases, and air-gap
is sensitive to the pressure. Little variation of pressure causes significant fluctuation in air-gap. Therefore, minimum adjustment of pressure is required to avoid over control.

In the final stage, a prediction algorithm is proposed[6]. At k-step control, \( j \) th air spring is chosen to charge or deflate. Substituting Eq. (8) into Eq. (6) and Eq. (6) into Eq. (5), the height vector of air-gap can be expressed as:

\[
\hat{z}^{(k+1)} = \Delta p_j A_j g_j^T K^{-1} g_j + \hat{z}^{(k)}
\]  

(9)

where \( G = \{g_1, g_2, \ldots, g_N\} \), \( \hat{z}^{(k+1)} \) is the predicted height of air-gap after k-step. \( \Delta p_j \) is pressure variation of \( j \) th air spring caused by charge or deflate.

\[
(j, \mu)^{(k)} = \left\{ (j, \mu) \mid |\bar{p} - p_j| = \max_{i=1}^{N} |\bar{p} - p_i|, \mu = \text{sgn}\left(\bar{p} - p_j\right) \right\}
\]  

s.t. \( \left\| \hat{z}^{(k+1)} \right\|_c - \left\| \hat{z}^{(k)} \right\|_c \leq \delta \)  

(10)

where \( j \) is the serial number of target air spring to be controlled at \( k \)-step. \( \delta \) is the allowed convergence rate of air-gap control. \( \bar{p} \) is the average pressure of all air spring. \( \mu \) is a control parameter, \( \mu = 1 \) for charge control and \( \mu = -1 \) for deflate.

4. Experiments

On a test rig of HVIS, a series experiments were carried out to validate the effect of the attitude control algorithm (shown in Fig. 5). It can be seen that the duration of control process is about 200s. Before 100s, the magnetic conductive rubbers were compressed and height of air-gap almost unchanged with the air spring pressure rising. When air spring pressure reached about 0.4MPa, the armature departs from the magnetic conductive rubber, the total stiffness of system decrease sharply, and the heights of air-gap have obvious changes. All heights of air-gap have been converged to the static equilibrium point 2mm round. The control precision of air-gaps reaches \( \pm 0.5 \)mm.

![Figure 5(a): air-gaps during control process](image1)

![Figure 5(b): pressures control curves](image2)
5. Conclusion

In the HVIS, it is important to keep stable air-gap of electromagnetic actuator. In this paper, the non-linear stiffness characteristics of hybrid isolator is analysed in detail, the total stiffness can be simplified by piecewise linear method. The disturbance force caused by temperature variation should be considered in design phase and control process. According to the stiffness characteristics of HVIS, an attitude control algorithm is presented by dividing control process into three-phase is presented. Test results verified the attitude control algorithm, and control precision satisfies with the HVIS requirement.

REFERENCES


