Active control simulation based on an active vibration isolator

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Abstract. We studied an active vibration isolator’s performance for vibration suppression in this article. A modified FxLMS control method is presented by replacing the weights update law of FxLMS with NR-LMS algorithm and its reference signals is got from the sensors’ output. Control simulation is performed by employing the models identified and the modified FxLMS method, the results indicate that the modified FxLMS method can suppress the vibration effectively and the control performance can be improved by minimizing the divergence between the secondary plant model and the practical second plant.

1. Introduction
Reaction wheel assembly (RWA) and control moment gyroscopes (CMGs) used for attitude Reaction wheel assembly (RWA) and control moment gyroscopes (CMGs) used for attitude control and pointing at scientific targets are important equipments in spacecrafts and satellites, whereas they are also the primary disturbance sources which degrade the pointing precision and camera’s image quality[1,2]. The primary feature of these disturbances is that they have very small amplitude of vibration (called micro-vibration) but the degradation of image quality caused by them is serious[3,4]. Therefore attenuating these micro-vibrations would enhance the performance of the optical payloads effectively[5,6]. The vibration isolation is a feasible way and there have been many researchers provided their methods for vibration attenuation [7].

In this paper, an active vibration isolator and active control simulation based on which is proposed. The feed-forward algorithm requiring the disturbance source information to attenuate the vibration, but the source of vibration is impractical or expensive to measure. So the feedback control frame of FxLMS algorithm is used in section 2. Further, the NR-LMS algorithm is also used to replace the update law of general FxLMS algorithm. In section 3, active control simulations are carried out for studying the relationship between the secondary model error and the controller’s performance. The conclusion is given out in section 4.

2. Model of active vibration isolator
The active vibration isolator (AVI) is presented in Figure 1, it contains a load board, four piezoelectric folded-beams, and a base. The disturbance source, especially the RWA, is fixed on the load board. Piezoelectric folded beams with piezoelectric patches glued on their surfaces as sensors and actuators are orthogonal to each other, and they are the primary components of control platform.
Figure 1. The active isolator model. (a) sketch map of AVI, (b) 3D model, (c) the real active isolator.

This AVI can measure the vibration level of disturbances from the source and generate control forces to attenuate vibration under the commands of controller. The base is the connector between the platform and the plant (satellite or spacecraft). In Figure 1(a), the vertical elements are normal space beam elements, the horizontal elements are piezoelectric beam elements which have piezoelectric layers glued on their upper and lower surfaces. The actuator and the sensor on the same beam construct a actuator/sensor pair. Each actuator/sensor pair and the controller can constitute a SISO closed loop control system, and all the actuator/sensor pairs constitute a 8-input-8-output active multi-free vibration control system. The dynamic model of this AVI has been given in reference [8] by employing state space theory and NR-LMS identification method based on experiment data. Here this 8-input-8-output dynamic model is used to study AVI’s performance.

3. Active control method

In this paper, we use the FxLMS control method to perform the active control simulation. The MIMO FxLMS control method is represented in Figure 2. We assume there are \( M \) actuators and \( L \) sensors. The reference signal \( x(k) \) passes through a “primary plant” before being sensed at the system output as \( d(k) \). The plant model is a \( J \)-th order Finite Impulse Response (FIR) filter \( C \) which is used to filter the reference signal, and the resulting filtered signal \( r(k) \) includes \( L \times M \) elements indicated by \( r_{lm}(k) \) [9]. The \( M \) control signals in \( g(k) \) are generated by filtering the reference signal with the \( I \)-th order FIR filter \( W \). The error signal from the \( l \)-th sensor is indicated as \( e_l(k) \), and its expression is

\[
e_l(k) = d_l(k) + \sum_{m=1}^{M} \sum_{j=0}^{J-1} C_{lmj} \sum_{i=0}^{I} w_{mi}(n-i)x(n-i) - f_{lm}(k)
\]  

where \( w_{mi} \) is the coefficients of filter \( W \), \( d_l(k) \) is the disturbance sensed by the \( l \)-th sensor, \( C_{lmj} \) indicates the \( j \)-th coefficients of the filter \( C \) which models the dynamics between the \( m \)-th actuator and the \( l \)-th sensor. Based on the principle of minimum mean square root, we get the update law of coefficients \( w_{mi} \) is

\[
w_{mi}(k + 1) = w_{mi}(k) - 2\mu \sum_{l=1}^{L} e_l(k)r_{lm}(k - l)
\]  

where \( \mu \) is the adaptation rate. To maintain stability, \( \mu \) must be chosen in the domain below [10]:

\[0 < \mu < \frac{1}{\sqrt{2\pi^2 I}}\]
The FxLMS control method includes two important portions, one is the coefficients update law and the other is the reference signal’s acquisition [11]. In this article we use the normalized robust LMS method to replace the normal LMS method, and the update law of coefficients \( w_{mi} \) becomes

\[
w_{mi}(k + 1) = w_{mi}(k) - 2\mu \left[ \gamma_1 \frac{E(k)^T R_m(k - i)}{\|R_m(k - i)\|^2} + \gamma_2 \frac{E(k - 1)^T R_m(k - i - 1)}{\|R_m(k - i - 1)\|^2} + \gamma_3 \frac{E(k - 2)^T R_m(k - i - 2)}{\|R_m(k - i - 2)\|^2} \right]
\]

where \( R_m(k - i) = \begin{bmatrix} r_{1m}(k - i) & r_{2m}(k - i) & \cdots & r_{Lm}(k - i) \end{bmatrix}^T \), \( E = \begin{bmatrix} e_1(k) & e_2(k) & \cdots & e_L(k) \end{bmatrix}^T \).

The coefficients \( \gamma_1, \gamma_2, \gamma_3 \) are used to control the contribution of the product at current time step and the two previous time steps. To keep stability, the coefficients must be in the range below [9]:

\[
\begin{cases}
0 \leq \gamma_i \leq 1, (i = 1, 2, 3) \\
\gamma_1 + \gamma_2 + \gamma_3 = 1 \\
0 < \mu < 2/\lambda_{\text{max}}
\end{cases}
\]

where \( \lambda_{\text{max}} \) is the largest eigenvalue of the correlation matrix \( R \), after normalized \( \lambda_{\text{max}} = 1 \).

In the FxLMS control algorithm, the reference signal \( x(k) \) must be dependent with the disturbance response signal. Generally one more sensor is used to measure the disturbance and the measured signal is employed as reference, but this method would make the AVI structure presented here more complex. Another way to get the reference signal is to identify the frequencies of disturbance from the error signals, and then by employing these frequencies the reference signal could be constructed. This method needs added signals identification processes which make the system complex too. In this article, we construct the estimator of disturbance response signal by using the error signals and control response (output from the second path). In the control system, control signal \( u(k) \) is supported by the controller and it is can be stored in PC, the secondary path \( H \) has been identified and the error signals can be measured. So in z-domain the estimator of disturbance response \( \hat{d}(k) \) is

\[
\hat{d}(z) = e(z) - H(z)u(z)
\]

It is concluded the more accurate the secondary path model identified, the closer estimator \( \hat{d}(z) \) get to the real disturbance response \( d(z) \).

The vibration isolator presented has eight sensors, so \( d(k) \) is a 8×1 vector, we use the eight disturbance response signals’ mean as reference \( x(k) \):

\[
x(k) = \frac{1}{L} \sum_{n=1}^{L} d_n(k)
\]

where \( L \) is the number of sensors.

Figure 2. The block diagram of FxLMS algorithm.
4. Active control simulation

The SIMULINK diagram describing the active control is shown in Figure 3. There are five main function blocks in the diagram: the disturbance block, the primary path block, the secondary path block, the secondary path 1 block and the FxLMS controller block. Three source blocks are included in disturbance block, the inner structure of which is shown in Figure 4(a). Two sine source blocks are used to generate the disturbance signals, and the random source block represents the environmental noises. There are three sub-blocks in the FxLMS controller block whose inner structure is shown in Figure 4(b). The reference adjust block is used to get the reference signal at history sample periods, the filter is the model of secondary path in AVI and it is equivalent to the secondary path 1 block. The weight update block receives the signals from the reference adjust block and the filter, then it composes reference matrix R and outputs control signal at the end. All the functions supported by weight update block are carried out by employing the S-function LMS_update in SIMULINK environment[10].

![Figure 3. The SIMULINK diagram for active control.](image)

![Figure 4. (a) Inner structure of disturbance block (b) Inner structure of FxLMS controller block.](image)

The sampling time of all the modules in Figure 3 must be equivalent to that value of SIMULINK settings. We use the high order dynamic model passed to the secondary path block and low order dynamic model to the secondary path 1 block. Filter block is in accordance with the real situation. All the models except the control filter \( W \) employed in simulations are employing state space form instead of FIR form. Such a changing takes advantages to the active control, which has studied in reference [12].

In the first simulation, we set the sine block outputs sinusoidal signal with amplitude 3 and frequency 46 Hz, while the second sine block outputs zero. The random signal from the random block is set with max amplitude being \( \pm 0.03 \). The sampling time \( \Delta t \) is 0.001s and the simulation time is 5s. The parameters of FxLMS controller are set as: \( \mu = 1.5 \), \( \gamma_1 = 0.50 \), \( \gamma_2 = 0.3 \), \( \gamma_3 = 0.2 \). Simulation is carried out and the controller begins working after 1 second. The output of piezoelectric sensors can be seen in Figure 5. It can be seen all eight sensors’ outputs voltage dropped initiated at approximately 1 second. The 1-st and 5-th sensors’ signals are shown in Figure 6 and Figure 7 in the frequency domain, and it is seen clearly that the energy in 46Hz has been removed from the signals. We can
judge the control performance by comparing the RMS level of the steady state outputs of sensors before and after using controller, and the comparing results are shown in Figure 8. The max drop scope is at sensor 1 with 34dB, and the minimal drop is at sensor 7 with 20.6dB. Here we define the background noise is the system response to the random signal block’s input. It is clear that the 46Hz disturbance has been attenuated absolutely by employing this FxLMS controller which indicates this control method is effective in controlling single frequency disturbance. The control signals for the eight actuators are shown in Figure 9.

Figure 5. Sensors outputs before and after control with one disturbance (46Hz).

Figure 6. Spectral comparison of output from sensor 1.

Figure 7. Spectral comparison of output from sensor 5.

Figure 8. Steady state RMS and background noise level.

Figure 9. Control signals.
In the second simulation, two disturbances are employed. The frequency of one disturbance is 46Hz which is the same as before and the amplitude of it is 1.5. Another disturbance with frequency 120Hz and amplitude 1.5 is added. The amplitude of holistic disturbance is still 3. The other settings of the SIMULINK environment and the FxLMS controller keep the same as before. Simulation is carried out and at the beginning there is no control. From 1s time on the controller works, and Figure 10 shows the results of the eight sensors’ output signals. It is clear that this AVI can substantially suppress disturbance with two frequencies, and the control effects looks the same as the first simulation. For evaluating the performance of AVI the RMS level of the steady state outputs of sensors before and after using controller are compared and the results are shown in Figure 11, it is clear the RMS of the outputs after controlling is down to the level equal to the level of background noise. The max drop scope is at sensor 1 with 33.5dB, and the minimal drop is at sensor 7 with 20.5dB. We can find out that the FxLMS controller proposed can attenuate the vibration under disturbances with two different frequencies.

![Figure 10. Sensors outputs before and after control with two disturbance (46Hz and 120Hz).](image)

![Figure 11. Steady state RMS and background noise level.](image)

5. Conclusions
In this paper, an active vibration isolator (AVI) and an active control model is proposed. The modified FxLMS control method, which get the reference signal from the sensors’ output and replace the LMS update algorithm with NR-LMS algorithm, was proposed here. Active control simulations employing the modified FxLMS algorithm and the AVI’s identified model were carried out under sinusoidal disturbance.

In the first active control simulations with one sine disturbance, the performance of modified FxLMS controller is validated and the overall sensors’ RMSs are reduced to nearly equivalent to the level of background noise. The first sensor’s output after control drops 34dB. In the second simulation,
there are two sine disturbances whose frequencies are 46Hz and 120Hz. The simulation results indicate the controller can attenuate the vibration under disturbances with two different frequencies and the control effect is the same as the first simulation. Both the simulation results show the AVI with modified FxLMS controller can suppress effectively sine disturbance. So it is useful for machines which produce primarily sine disturbance.

Acknowledgments
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