THE APPLICATION OF ADAPTIVE INVERSE CONTROL ALGORITHM IN SHAKING TABLES

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An adaptive inverse control (AIC) strategy is proposed in order to improve the control precision and reliability of shaking tables, and to eliminate the influences of disturbances on testing systems control. Based on the traditional AIC algorithm, an AIC algorithm in frequency domain is designed for the control of shaking tables. Because of the existence of disturbances and non-linear factors in shaking tables, the system transfer functions will change in the process of tests. The AIC algorithm can achieve an effective control on shaking tables by the accurate identification of the system impedance functions. The AIC algorithm is used for the control of PSD and time domain waveform replication tests on shaking tables and the practical results show that the AIC algorithm has good effects for the control of the shaking tables, and can achieve high-precision replications of reference waveforms such as PSD or time domain waveforms.

1. Introduction

Shaking tables have the features of large displacement and high load, so they are widely used in vibration tests in civil engineering, aerospace, vehicle engineering and so on. Waveform replication tests on shaking tables include PSD replication tests and time domain waveform replication tests. In PSD replication tests shaking tables make movements according to the required PSD spectrum, while in time domain waveform replication tests shaking tables make movements according to the reference time domain waveforms. In the waveform replication tests, specimens’ reliability against environment vibration is checked by generating the required waveforms on shaking tables, which has great significance on exposing specimens’ design defects and further improving their structure design in time1-5.

In waveform replication tests on shaking tables, different control strategies are adopted according to the reference waveforms (PSD or time domain waveforms). A PSD equilibrium strategy is used for PSD replication tests, and an iterative correction strategy is used for time domain waveform replication tests. In AIC strategy an adaptive algorithm is used for the identification of the inverse transfer function of the controlled system, and the identified inverse transfer function is connected in the system in series. By using the AIC strategy the system output response signal can precisely follow its required command signal. And strong robustness is achieved by adding a disturbance elimination circuit separating system disturbances from its command signal. In this paper, an AIC strategy is proposed to improve the control effect of shaking tables. PSD replication tests and time domain waveform replication tests show that the AIC algorithm has good control effects for shaking tables and can achieve high-precision waveform replication6-10.
2. Adaptive inverse control

Through control of a system transfer function, the AIC strategy can effectively make the system response signal keep track of its command signal rapidly and accurately. The AIC schematic diagram is shown in Fig. 1\(^{10-11}\). The system inverse transfer function serves as a feedforward controller and is in series with the system, while the command signal is directly input in the controller, which forms an open-loop control system. The reference model \(M(f)\) represents the required performance index of the controlled system, and usually it is a delay model. Connecting a delay model can ensure the stability of a delay system or a non-minimum phase system, and can ensure that the controller has enough control precision to achieve a precise and small-error response output. \(H(f)\) is the transfer function of the controlled system, and the inverse transfer function (impedance function) of controlled system serves as the controller transfer function \(Z(f)\). Their relationship can be expressed as:

\[
Z(f) = \frac{M(f)}{H(f)}.
\]

![Figure 1. AIC schematic diagram.](image)

For the AIC system in Fig. 1, the external disturbances will lead to a deviation solution for the system impedance function, which cannot satisfy the Eq. (1). In order to eliminate the noisy influence and use the adaptive LMS algorithm for the system control, the filtered-X LMS AIC algorithm is studied and applied for the control of shaking tables. The filtered-X LMS AIC schematic diagram is shown in Fig. 2, and its control process includes system modeling, system inverse modeling and adaptive inverse control\(^{12-15}\).
H1 method is used to identify the system initial transfer function in the system modeling process. To improve the precision of system identification, the system transfer function is identified and averaged for many times until the function achieves its identification precision. The filtered-X LMS AIC algorithm does not affect the controller’s Wiener solution even though identification errors exist between the real physical model $H(f)$ and the identification model $\hat{H}(f)$.

The system impedance function $Z(f)$ is identified using the copy of the system identification model $\hat{H}(f)$ and the adaptive LMS algorithm is applied in the system inverse modeling process.

The system impedance function $Z(f)$, identified by the AIC algorithm, serves as the transfer function of the controller and is used for the control of the actual physical model $H(f)$, which can achieve an effective control of the model $H(f)$.

3. PSD replication control

PSD replication tests on shaking tables are the main method for vibration simulation of random environment, and they are used in many military and civil products for reliability analysis. In PSD replication tests, the driving signals of shaking tables are controlled by a PSD equalization strategy. The PSD equalization strategy has a simple algorithm and a fast convergence speed, but the algorithm convergence and accuracy directly depend on the identification precision of the system transfer function. When nonlinear factors exist in the system, the system may be controlled divergently.

The PSD equalization strategy contains correction of the system impedance function, and real-time iteration and correction of the system driving PSD. The iteration equation for the system driving PSD is shown as:

$$G_{dd}(f)_{k+1} = G_{dd}(f)_k + \alpha_k Z(f)_k G_{xx}(f)_k Z(f)_k^T.$$  (2)
In Eq. (2), \( G_{ee}(f)_k \) is the PSD error between the reference PSD and the control PSD. And \( Z(f)_k^* \) is the conjugate function of the system impedance function \( Z(f)_k \).

The control process of PSD replication tests based on the filtered-X LMS AIC algorithm is shown in Fig. 3.

(1) Identify the system initial transfer function and get its inverse in H1 method. The identified initial transfer function and its inverse are expressed as \( \hat{H}(f)_0 \) and \( Z(f)_0 \).

\[
Z(f)_0 = \hat{H}(f)_0^{-1}.
\]  

(2) Calculate the initial driving PSD by the Eq. (4), and generate a driving signal to excite the system.

\[
G_{dd}(f)_0 = Z(f)_0 G_{rr}(f)_k Z(f)_0^*.
\]  

(3) Measure the system response signal \( x(t) \) and calculate its PSD \( G_{xx}(f)_k \), then further calculate the PSD error between the reference PSD and the control PSD by the Eq. (5).

\[
G_{ee}(f)_k = G_{rr}(f)_k - G_{xx}(f)_k.
\]  

(4) Correct the system impedance function according to the Eq. (6).

\[
Z(f)_{k+1} = Z(f)_k - \mu(f)_k X'(f)_k E(f)_k.
\]  

(5) Correct the system driving PSD \( G_{dd}(f)_{k+1} \) according to the Eq. (2), then generate a new driving signal to excite the system.

\[
G_{dd}(f)_{k+1} = G_{dd}(f)_k + \alpha Z(f)_k G_{xx}(f)_k Z(f)_k^* G_{ee}(f)_k.
\]

![Figure 3. Diagram of the PSD replication process.](image)

4. **Time domain waveform replication control**

Time domain waveform replication tests on shaking tables can truly simulate the specimen’s vibration environment, thus intuitively analyze its anti-vibration performance. Time domain waveform replication tests are mainly applied in the fields of civil engineering, vehicle engineering, aer-
ospace engineering, etc. An iteration algorithm is used for the driving signal control in time domain waveform replication tests. The algorithm mainly includes a direct iterative algorithm and a modified iterative algorithm. Considering of disturbance signals and nonlinear factors existing in the system, a filtered-X LMS AIC algorithm is designed to effectively control the time domain waveform replication tests and improve the stability of the testing system. The control process for a time domain waveform replication test by the filtered-X LMS AIC algorithm is shown in Fig. 4.

1. Identify the system initial transfer function and get its inverse in H1 method. $\hat{H}(f)_0$ and $Z(f)_0$ separately represent the identified transfer function and its inverse.

2. Calculate the initial driving frequency spectrum $D(f)_k$ when $k=0$ according to the Eq. (7), and then generate a driving signal $d(t)_k$ to excite the system.

$$D(f)_k = R(f)Z(f)_k.$$  \hspace{1cm} (7)

3. Measure the system response signal $x(t)_k$ and calculate its frequency spectrum $X(f)_k$. Then further calculate the spectrum error between the reference frequency spectrum and the control frequency spectrum by the Eq. (8).

$$E(f)_k = R(f) - X(f)_k.$$  \hspace{1cm} (8)

4. Correct the system impedance function $Z(f)_k$ to $Z(f)_{k+1}$ by the Eq. (6).

5. Repeat Step (2) using the system impedance function $Z(f)_{k+1}$, and then update the system driving signal $d(t)_k$ repeatedly. The driving signal is modified by correcting the system impedance function to ensure the system response signal $x(t)_k$ can replicate the reference signal $r(t)$ accurately.

![Diagram of time domain waveform replication process](image)

**Figure 4.** Diagram of time domain waveform replication process.
5. Tests

PSD replication tests and time domain waveform replication tests are conducted using the filtered-X LMS AIC algorithm. The shaking table as a testing object is chosen from the state key laboratory of fluid power transmission and control, Zhejiang University. And its relevant parameters are shown in Table 1.

![The shaking table for tests.](image)

**Table 1.** Parameters of the shaking table.

<table>
<thead>
<tr>
<th>Items</th>
<th>Technical parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>100Kg</td>
</tr>
<tr>
<td>Dimension</td>
<td>750mm×750mm</td>
</tr>
<tr>
<td>Load mass</td>
<td>100Kg</td>
</tr>
<tr>
<td>Max. speed</td>
<td>1000mm/s</td>
</tr>
<tr>
<td>Max. thrust</td>
<td>3000kgf</td>
</tr>
<tr>
<td>Stroke</td>
<td>120mm</td>
</tr>
</tbody>
</table>

The result of PSD replication test is shown in Fig. 6. In the figure, curve 1 stands for the control signal (or response signal), while curve 2 stands for the driving signal. The referential effective value is 0.1g, and the controlled effective value is about 0.100879g. The frequency bandwidth of the PSD replication test is 5-100Hz. The result shows that the AIC algorithm can achieve an effective control for the PSD replication test.

![The result of PSD replication test.](image)

To further analyze the control effect of AIC algorithm for shaking tables, a time domain waveform replication test is conducted using a typical seismic wave of El-Centro and the test result is shown in Fig. 7. The corresponding time history of the control waveform is about 18s, and the peak
of the acceleration signal is about 0.4g. In the test the replication accuracy (the correlation coefficient) is up to 95.7%, which indicates the filtered-X LMS AIC algorithm can achieve an accurate and stable control for the shaking table.

![Time Signal](image)

**Figure 7.** The result of time domain waveform replication test.

6. Conclusion

Shaking tables can simulate the vibration environment the specimen works in order to analyze its anti-vibration performance. The AIC algorithm has strong control abilities for the nonlinear system. Through research on the AIC algorithm and based on the servo control of shaking tables, an AIC method for waveform replication tests is designed, and the filtered-X LMS adaptive control is used in the AIC algorithm. The PSD and time domain waveform replication tests on the shaking table show that the AIC algorithm has strong control abilities for waveform replication tests, and it can help to achieve a high-precision waveform replication on the shaking table.

REFERENCES


