System identification of buildings equipped with closed-loop control devices

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ABSTRACT

The purpose of this study is to provide a system identification tool to obtain dynamic structural properties of buildings when closed-loop control devices are in operation so that we will be able to detect possible damages or changes in the building structures without suspending the control devices. The difficulty associated with closed-loop systems, where noise, input and output signals are correlated, can be resolved using the output over-sampling approach. Using the approach, we were able to successfully obtain the open-loop properties of the building structures even when the control device is operated. Until now, it has been a common practice to temporarily suspend the closed-loop control circuits to measure the properties of the building without the influence of the control device. The control device is used as an exciter for the building structure with no feedback to the device. However, the true dynamic properties of the building when subject to control forces generated by the control devices that are operated as closed-loop systems may be different from those neglecting the control force. Thus, the output over-sampling approach was employed to overcome these difficulties. The employed approach was indeed able to estimate the properties of the building when the AMD, that is a typical vibration control device, is in operation under the condition that the control system can hold its control signal for the sampling period $T$.

Keywords: system identification, closed-loop, structural control, damage detection

1. INTRODUCTION

Vibration control devices for building structures have been studied for many years to mitigate the possible damage due to strong winds or and earthquakes. It is essential, however, to know the exact dynamic properties of a building to design any control device with excellent performance. It is further desired to obtain the dynamic behavior when the device is in operation. They are usually estimated from input and output signals for the building using the system identification technique. However, most system identification tools are only applicable to open-loop systems\textsuperscript{1}). They are not applicable to a system that has some feedback components such as a building with control devices. In this situation, feedback excitation due to the device always exists on the building. When the feedback components are included in the input signal, the conventional identification tools are no more effective.

In this paper, as an example of the control device, an active mass damper (AMD) is selected. The AMD has a feedback closed-loop with respect to vibration response of a building. The existence of the closed-loop components in a system makes the online identification very difficult. If we apply a method developed for open-loop systems directly to the closed-loop systems without careful consideration, the correlated noise, input and output signals would result in erroneous estimation. The output over-sampling approach employed here is known as a system identification tool for closed-loop systems developed for other engineering fields. Applicability of the approach was extensively examined by simulations and experiments for our target, building structures.

From our extensive study, it will be shown that the output over-sampling approach is indeed able to estimate the dynamic properties of the building when the AMD is in operation under the condition that the control system can hold the control signals for the sampling period $T$. It is found that, however, when the observation noise is higher than a threshold value, the method might fail. Thus, by keeping the observation noise lower than the threshold value, identification of buildings equipped with closed-loop devices becomes possible.

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2. SYSTEM IDENTIFICATION FOR CLOSED-LOOP SYSTEMS

2.1. Definition of the problem
System identification for the closed-loop systems is difficult due to correlation between noise and control signals. Their existence results in bias components in the estimation as well as lack of identifiability conditions$^{2,3)}$. Several methods have been proposed to keep away from this difficulty$^{4)}$. However, most methods require artificial noise or other inputs to achieve the process. The purpose of this study is to identify the dynamic properties of a building from the input and output signals when the control device is in operation without adding any other signals.

The state space representation of a building with an AMD is expressed by the equations as

\[
\begin{align*}
x_{k+1} &= Ax_k + Bu_k + Bv_k \\
y_k &= Cx_k
\end{align*}
\]

where \(x, y, u, v\) are the state vector, the output vector, the control force and the external force, respectively. The corresponding block diagram is shown in Fig. 1.

![Figure 1: Typical closed-loop system for a building with AMD.](image)

2.2. Over-sampling approach
An attractive approach$^{5)}$ has been proposed recently. The approach introduces open-loop subsystems intentionally by over-sampling the output signals. The mechanism is explained below.

The feedback system with sampling duration \(T\) is presented in Fig. 2. If it is possible to sample \(p\) data instead of just one during the period \(T\), the system can be represented by the block diagram as shown in Fig. 3 where \(\Delta = T/p\). In addition to this condition, if the control force can be constant for the period \(T\), the system can be modeled by the SIMO (single input multiple outputs) model as depicted in Fig. 4. From this figure, it is understood that only one subsystem becomes a closed-loop system while other subsystems are open-loop systems. Thus, this over-sampling approach enables us to identify the closed-loop system by artificially adding open-loop subsystems.

![Figure 2: Conventional closed-loop system.](image)

![Figure 3: Closed-loop system with output over-sampling.](image)
3. SIMULATIONS

3.1. Model description
A single degree of freedom system is considered to represent a building structure as shown in Fig. 5. An AMD is attached to the top of the building. The AMD is driven by an actuator whose feedback gains are given by

\[ u(t) = -G_k (x_d - x_s) - G_c (\dot{x}_d - \dot{x}_s) \]  

The AMD has linear feedback force with respect to its relative displacement and velocity. In fact, this control algorithm is equivalent to the TMD (tuned mass damper) with a spring and a dashpot. Thus, these gains were determined to emulate the optimum TMD6).

Table 1: Parameters used for simulations

<table>
<thead>
<tr>
<th>parameters</th>
<th>gains</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_s ) [kg]</td>
<td>2.54</td>
</tr>
<tr>
<td>( m_d ) [kg]</td>
<td>0.123</td>
</tr>
<tr>
<td>( f_s ) [Hz]</td>
<td>11.16</td>
</tr>
<tr>
<td>( h_s )</td>
<td>0.003</td>
</tr>
<tr>
<td>( G_k ) [N/m]</td>
<td>548</td>
</tr>
<tr>
<td>( G_c ) [Ns/m]</td>
<td>2.16</td>
</tr>
</tbody>
</table>

Figure 5: Simulation model.
3.2. Closed-loop system identification

The system identification was applied to the total system considering the random ground motion. The sampling frequency for driving the AMD was set at 500Hz. The MOESP algorithm was used for this identification. The identified two modes are summarized in Table 2. The transfer function between the displacement of the building and the ground motion is plotted in Fig. 6 compared with the building without the AMD. The effects of the optimized AMD are clearly understood from this figure.

<table>
<thead>
<tr>
<th>Mode number</th>
<th>Frequency</th>
<th>Damping ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.84</td>
<td>0.051</td>
</tr>
<tr>
<td>2</td>
<td>12.04</td>
<td>0.053</td>
</tr>
</tbody>
</table>

Table 2: Identified modal parameters.

To evaluate the over-sampling method, the sampling frequency was set in the range of 1,000Hz to 5,000Hz for the output signals while keeping the sampling frequency for the control system at 500Hz. This choice results in $p=2$,..,10. Two excitation cases, free vibration and the forced vibration considering the random ground motion, were considered. For the forced vibration, time histories of the ground motion and the control signal are plotted in Fig. 7 for $p=4$. The MOESP algorithm was used for identification. The singular values for an identification example are plotted in Fig. 8. Largest three singular values were used for deriving the modal information. The identified modal properties are summarized in Table 3. The transfer functions are plotted in Fig. 9. From these table and figures, it is clearly recognized that the direct system identification does not work and that the over-sampling algorithm works well for both free and forced vibration. The input signals used for identification were the ground motion acceleration and the control force. The output signal was the acceleration response of the building.

Figure 6: Transfer functions.

Figure 7: Ground motion and control signal. ($p=4$)
Table 3: Identified results for different inputs and sampling rates.

<table>
<thead>
<tr>
<th>Case</th>
<th>Frequency</th>
<th>Damping ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>True</td>
<td>11.16</td>
<td>0.003</td>
</tr>
<tr>
<td>Free vibration (p=1)</td>
<td>14.56</td>
<td>0.493</td>
</tr>
<tr>
<td>Free vibration (2 \leq p \leq 10)</td>
<td>11.16</td>
<td>0.003</td>
</tr>
<tr>
<td>Random vibration (2 \leq p \leq 10)</td>
<td>11.16</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Figure 8: Singular values.

Figure 9: Transfer functions.

4. EXPERIMENTS

The simulation models had no noise inputs and the control force was assumed constant until the next sampling step. However, the realistic system should have noise contamination. In addition, it is difficult to keep the control signal to be constant due to the noise. Thus, it is our purpose to test the over-sampling algorithm for realistic systems using a simple experiment system. The system is depicted in Fig. 10. A building consists of four columns and a floor system made of aluminum. The mass of the building is 2.54kg. This building is equipped with an AMD whose mass is 0.123kg. This AMD is driven by a linear actuator with its stroke of ±0.02m. The control system for the AMD is presented in Fig. 11. The identified transfer function of the total system is plotted in Fig. 12 compared with the transfer function for the system without AMD. These transfer functions were obtained considering the forced vibration using random inputs at the base.
Figure 10: Experiment model.

Figure 11: Control system for AMD.

Figure 12: Transfer functions identified from experiments.
The over-sampling approach was applied to the experiments to obtain the dynamic properties of the building when the AMD is in operation. In this case, the sampling frequency to drive the AMD was set at 500Hz. The sampling frequency for the output signal was 2,000Hz ($\nu=4$). The feedback gains were set to achieve the optimum TMD. Time histories for free and forced vibration are plotted in Figs. 13 and 14. A sample time history of the control force for the forced vibration is plotted in Fig. 15. Using the ground motion acceleration and the control force as the input signals and the acceleration response of the building as the output signal, the system identification using the MOESP algorithm was conducted. The modal properties obtained here are slightly deviated from the true values. However, the error in the modal frequency is less than 1% so that for most purposes this algorithm may provide satisfactory results. The control signal shown in Fig. 15 has a spike noise at the end. This is due to electrical noise in the control circuit. To improve the accuracy of the identification, it is essential to minimize the spikes.

<table>
<thead>
<tr>
<th>Case</th>
<th>Frequency [Hz]</th>
<th>Damping ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>True</td>
<td>11.16</td>
<td>0.003</td>
</tr>
<tr>
<td>Free vibration ($\nu=4$)</td>
<td>11.08</td>
<td>0.001</td>
</tr>
<tr>
<td>Random vibration ($\nu=4$)</td>
<td>11.16</td>
<td>0.072</td>
</tr>
</tbody>
</table>

Table 4: Identified results from experiments.

Figure 13: Free vibration
Figure 14: Random vibration
Figure 15: Control signal.
5. CONCLUDING REMARKS

It was shown that the over-sampling approach is a promising tool to obtain dynamic properties of a building when closed-loop control devices such as AMDs are in operation. In practical situations, the closed-loop control device has been used as an exciter by moving the system as an open-loop control system so that the conventional system identification tools should work fine. However, operation of the control devices may change the dynamic properties of the building so that there is a strong need to obtain the properties when the control device is in operation. The difficulty associated with the closed-loop systems, where noise, input and output signals are correlated, was removed by using the output over-sampling approach. By introducing the approach, we were able to successfully obtain the open-loop properties of the building structures. However, the success of the over-sampling approach relies on keeping the noise level as low as possible. For example, the spike noise in the control signal should be carefully avoided.

REFERENCES