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# Active Structural Control with Suppression of Absolute Acceleration Using Equivalent-Input-Disturbance Approach

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***Abstract*—This paper presents a new control system that suppresses not only the relative displacement, but also the absolute acceleration of a structure. It uses the modified-equivalent-input-disturbance (MEID) approach to design a control system. The control of the absolute acceleration is very important to protect properties and people from a large earthquake, and has been considered to be a difficult problem. To deal with this problem, this study constructed a modified EID control system to achieve satisfactory control performance.**

***Index Terms*—active structural control, equivalent input disturbance (EID), absolute acceleration**

## I. Introduction

Passive base isolation (PBI) has been installed in many buildings after the Kobe earthquake in 1995 to ensure the safe use of the buildings [1]. On the other hand, the active structural control (ASC) strategy has also been employed in many buildings to improve control performance [2]. While PBI is effective for high-frequency earthquakes, ASC can deal with earthquakes over a large frequency band by taking full advantage of control theory.

Many methods have been used to design an ASC system, for example, the modern control theory [3], the $H_\infty$ control [4], and preview control [5]. Most of the control systems use the structure of one degree of freedom (DOF). This may result in a trade-off among control performance. On the other hand, the equivalent-input-disturbance (EID) approach was developed for high-precision control of mechatronics systems [6], [7]. It uses the structure of two degrees of freedom for disturbance rejection. This allows us to design the input-output and the feedback characteristics independently.

The EID approach has also been applied to controlling seismic vibration for a three-story building with an actuator mounted on each story [8]. The results show that the control performance is better for EID than that for the linear-quadratic-regulator (LQR).

Miyamoto *at el.* introduced a gain factor in the low-pass filter of the EID estimator to improve vibration control performance for buildings caused by seismic shocks, and showed that tuning the gain factor improved the frequency response characteristics and reduced the energy for control [9]. They also showed that the EID approach improved the control performance for a low-frequency seismic wave. This is very important for the structural control of high rise buildings.

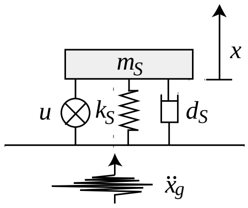


Fig. 1. 1-DOF model of structure with ASC.

The control of the absolute acceleration and displacement is of great importance for ASC to protect a building, properties and people inside. This paper presents a modified-EID (MEID)-based ASC system to suppress not only the relative displacement and the relative velocity, but also the absolute acceleration. The validity of the system is verified through numerical simulations using two accelerograms of earthquakes for a 1-DOF structure.

## II. Structural Model and Modified-EID-Based ASC System

The structural model is shown in Fig. 1 and its equation of motion is described

$$m_S\ddot{x}(t)+d_S\ddot{x}(t)+k_Sx(t)=-m_S\ddot{x}_g(t)+u(t). \quad (1)$$

The state space representation of (1) is

$$\dot{z}(t)=Az(t)+Bu(t)+B_dd(t) \quad (2)$$

where

$$\begin{cases} z(t)=\begin{bmatrix} x(t) \\ \dot{x}(t) \end{bmatrix}, \quad A=\begin{bmatrix} 0 & 1 \\ -\dfrac{k_S}{m_S} & -\dfrac{d_S}{m_S} \end{bmatrix} \\ B=\begin{bmatrix} 0 \\ \dfrac{1}{m_S} \end{bmatrix}, \qquad B_d=\begin{bmatrix} 0 \\ -1 \end{bmatrix}. \end{cases} \quad (3)$$

The state contains the relative displacement and the relative velocity of the structure. Many optimization methods have

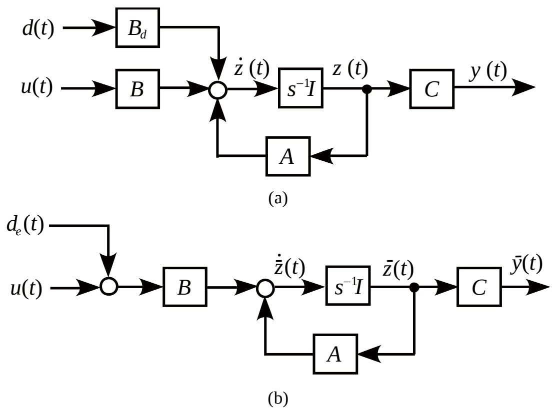

Fig. 2 Concept of EID: (a) original plant and (b) plant with EID.

been applied for the output

$$y(t) = Cz(t) \tag{4}$$

where $C$ is the output matrix indicating the places of sensors. If all states are available, then $C$ is an identity matrix.

Without loss of generality, the following two assumptions are made for the plant:

- *Assumption 1*: ($A$, $B$) is controllable.
- *Assumption 2*: ($A$, $C$) is observable.

Figure 2 is used to explain the concept of an EID. If the state of the original plant is $z(t)$, and the output is $y(t)$ for the input $d(t)$ [Fig. 2(a)], and if the state of a plant with EID is $\bar{z}(t)$ and the output is $\bar{y}(t)$ for the input $d_e(t)$ [Fig. 2(b)], then $d_e(t)$ is called an EID if $\bar{y}(t) = y(t)$. That is, an EID is an input signal on the control input channel that has the same effect on the output as an actual disturbance does [6]. Clearly, Taking full advantage of the EID improves the disturbance rejection performance for $d(t)$.

In the rest of this paper, we abuse the notation a bit, and only use the notation in Fig. 2 (b) for both. Since it is clear from the context, this should not cause confusion.

In this study, not only the state $z(t)$ but also the absolute acceleration is needed to be suppressed. To make this possible, we rewrote (1) as

$$\ddot{x}(t) + \ddot{x}_g(t) = -\frac{d_S}{m_S}\dot{x}(t) - \frac{k_S}{m_S}x(t) + \frac{1}{m_S}u(t) \tag{5}$$

that is,

$$\begin{cases} \ddot{x}(t) + \ddot{x}_g(t) = C_g z(t) + D_g u(t) \\ C_g = \begin{bmatrix} -\dfrac{k_S}{m_S} & -\dfrac{d_S}{m_S} \end{bmatrix}, \quad D_g = \dfrac{1}{m_S}. \end{cases} \tag{6}$$

Then, we define a new output

$$\begin{cases} y(t) = Cz(t) + Du(t) \\ C = \begin{bmatrix} C_c \\ C_g \end{bmatrix}, \quad D = \begin{bmatrix} 0 \\ D_g \end{bmatrix}, \quad C_c = [1 \quad 0]. \end{cases} \tag{7}$$

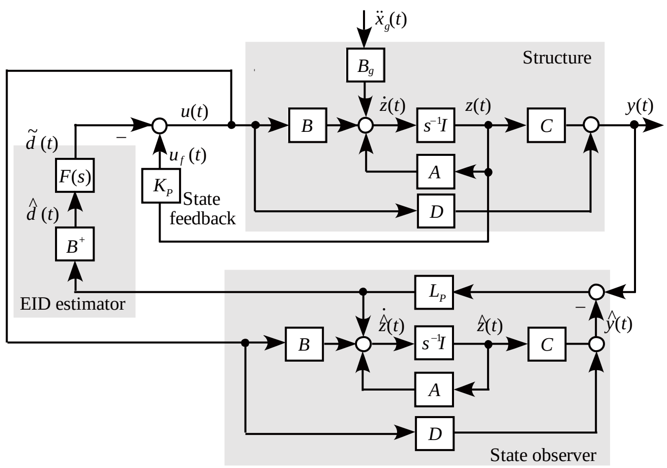

Fig. 3. Configuration of MEID-based ASC system.

Clearly, suppressing $y(t)$ achieves the goal of suppressing the relative displacement and the absolute acceleration of the structure.

The difference between the newly selected output, (7), and the output widely used in other studies, (4), is that the output of (7) has a direct-feedthrough term, $D$. The structure of the EID-based control system is modified to be the one shown in Fig. 3 so as to make it easy to implement an EID estimate for a plant with a direct-feedthrough term. For this MEID-based ASC system, we first show how an EID is produced.

In Fig. 3, $B^+$ is a pseudo-inverse of $B$ and is given by

$$B^+ = \frac{B^{\mathrm{T}}}{B^{\mathrm{T}}B}. \tag{8}$$

The state-feedback control law is

$$u_f = K_P z(t) \tag{9}$$

where $K_p$ is the state-feedback gain. A low-pass filter, $F(s)$, is used to select the angular frequency band for vibration suppression and to adjusting the control input. It has the form of

$$F(s) = \frac{N_F}{Ts+1} \tag{10}$$

where $s$ is the Laplace operator, and $T$ is used to select the maximum angular frequency for vibration suppression. The state space equation of the observer is

$$\begin{cases} \dot{\hat{z}}(t) = A\hat{z}(t) + Bu(t) + L_P C[z(t) - \hat{z}(t)] \\ \hat{y}(t) = C\hat{z}(t) + Du(t). \end{cases} \tag{11}$$

The state space representation of the plant with an EID is

$$\begin{cases} \dot{z}(t) = Az(t) + B[u(t) + d_e(t)] \\ y(t) = Cz(t) + Du(t) \end{cases}. \tag{12}$$

The estimate error of the state is given by

$$\Delta z(t) = z(t) - \hat{z}(t). \tag{13}$$

Assumption 1 ensures the existence of a control input, $\Delta d(t)$, that satisfies

$$\Delta\dot{z}(t) = A\Delta z(t) + B\Delta d(t). \tag{14}$$

Defining an EID estimate, $\hat{d}(t)$, to be

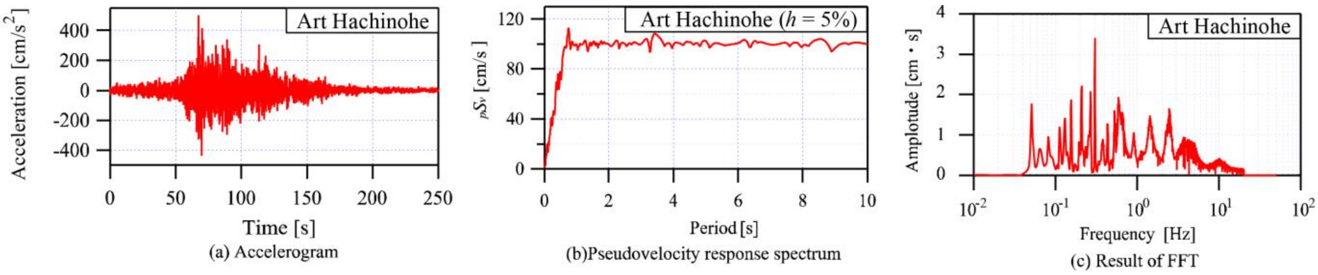


Fig. 4. Art Hachinohe wave

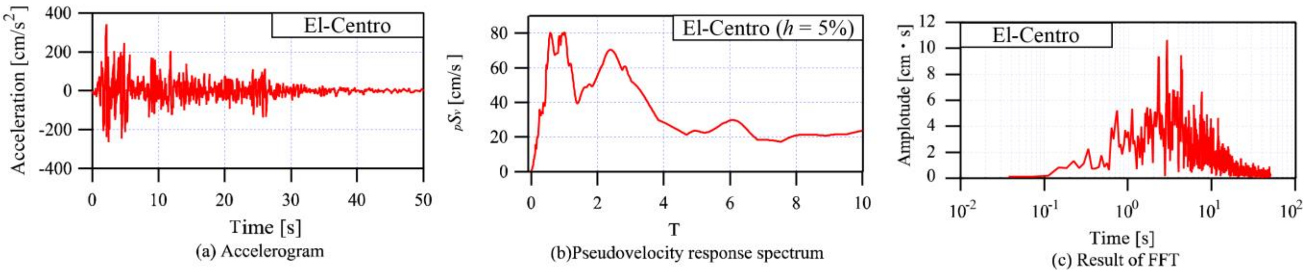


Fig. 5. El-Centro wave.

Table 1. Parameters of 1-DOF structure in (1).

| Parameter | Value | Unit |
|---|---|---|
| $m_S$ | $1.012\times10^4$ | kg |
| $k_S$ | $1.751\times10^5$ | N/m |
| $d_S$ | $2.066\times10^3$ | Ns/m |

Table 2. Selected low-pass filter and parameters for design of state-feedback and observer.

| | MEID | EID |
|---|---|---|
| $K_p$ | $Q=10^{4.5}I,\quad R=1$ | $Q=10^2 I,\quad R=1$ |
| $L_p$ | $\lambda_{1,2}=-30\pm10j$ | $\lambda_{1,2}=-20\pm20j$ |
| $F(s)$ | $\dfrac{0.7}{0.05s+1}$ | $\dfrac{0.8}{0.01s+1}$ |

$$\hat{d}(t)=d_e(t)-\Delta d(t) \tag{15}$$

where, $\Delta d(t)$ is estimation error.

Combining (11), (12), and (15) give an estimate of the EID:

$$\hat{d}(t)=B^{+}L_pC[z(t)-\hat{z}(t)]. \tag{16}$$

The filtered $\hat{d}(t)$, $\tilde{d}(t)$, is given by

$$\tilde{D}(s)=F(s)\hat{D}(s). \tag{17}$$

It is incorporated in the control law for vibration control. In (17), $\tilde{D}(s)$ and $\hat{D}(s)$ are the Laplace transforms of $\tilde{d}(t)$ and $\hat{d}(t)$, respectively.

## III. Design of MEID-based ASC System

The design of the MEID-based ASC system contains the design of the low-pass filter, $F(s)$, in (10), the state-feedback gain, $K_p$, and the observer gain, $L_p$.

Assume that $F(s)$ has been selected based on the requirements of design specification. This section discusses the design of $K_p$ and $L_p$.

The state-feedback gain is obtained by minimizing the performance index:

$$J=\int_0^{\infty}\left\{z(t)^{\mathrm{T}}Qz(t)+u(t)^{\mathrm{T}}Ru(t)\right\}dt \tag{24}$$

where $Q$ (> 0) and $R$ (> 0) are weighting functions, and $Q$ is set to be

$$Q=\begin{bmatrix} q_1 & 0 \\ 0 & q_2 \end{bmatrix}. \tag{25}$$

The gain is given by

$$K_P=-R^{-1}B^{\mathrm{T}}P \tag{26}$$

where $P$ is a positive symmetrical solution of the Riccati equation

$$A^{\mathrm{T}}P+PA+Q-PBR^{-1}B^{\mathrm{T}}P=0. \tag{27}$$

$L_P$ is designed using the pole placement method. For two selected poles of the closed-loop system, $\lambda_1$ and $\lambda_2$, $L_p$ is easily calculated using the algorithm presented in [10].

## IV. Numerical Example

The parameters in Table 1 were selected for the verification of the method. The designed low-pass filter, the state feedback gain, and the observer gain are shown in Table

2. Note that the parameters for the conventional EID-based ASC system are also shown in the same table.

### *A. Earthquake waves*

Two earthquake accelerograms are used to assess the control performance of the method:

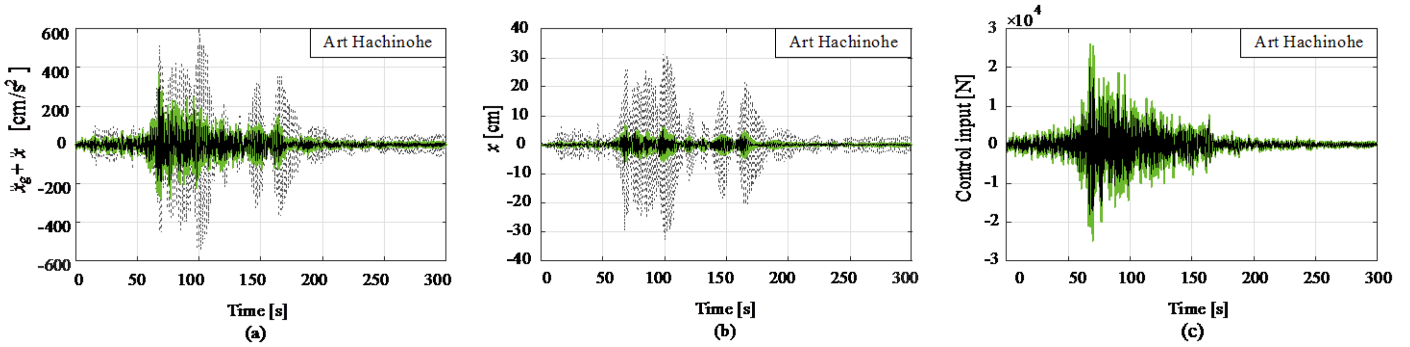


Fig. 6. Control results for Art Hachinohe.

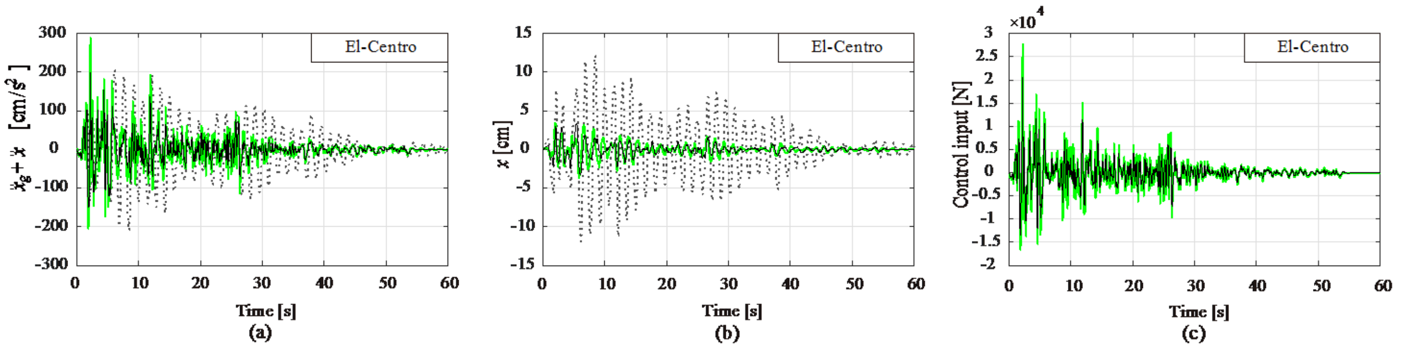


Fig. 7. Control results for El-Centro.

1. Art Hachinohe wave: the spectrum of the pseudo-velocity response, $_pS_v$, is 100 cm/s for a building with a damping ratio of 5%. The corner period is 0.64 s, and the phase characteristic is the same as the earthquake wave of the1968 Hachinohe EW.
2. El-Centro wave: El-Centro earthquake NS 1940.

The accelerogram, spectrum of the pseudo velocity and the Fourier transforms of these earthquakes are shown in Figs. 4 and 5.

### *B. Result of time response*

Figures 6 and 7 show the time responses of the displacement, the absolute acceleration, and the control inputs for the Art Hachinohe and El-Centro waves for no control, the conventional EID-based ASC system, and the MEID-based ASC system (they are abbreviated to NC, EID, and MEID in the rest for simplicity.). Figure 6 shows that the maximum displacement for NC is 33.2 cm at 100 s. It was reduced to 5.3 cm by EID. That is, it was reduced by 40%. On the other hand, the maximum absolute acceleration is the same for NC and EID. MEID yielded the same control performance for the displacement for the Art Hachinohe as EID did. However, it reduced the maximum absolute acceleration by 20% compared with EID did. Note that, in Table 2, $R$ was selected to be the same for both EID and MEID, but $Q$ was set to be larger for EID than for MEID. This means that we tried to suppress the control input for EID in the design. Even so, the control input of MEID is only 80% of that for EID.

Figure 7 shows the results for the El-Centro wave. It shows the same trend as that in Fig. 6. EID suppressed the maximum displacement to 60% of that for NC. However, the maximum absolute acceleration for EID is 140% larger than that for NC. This shows that the control performance of the absolute acceleration is not good for EID. In contrast, the maximum displacement of MEID is as good as the same for EID, and the maximum absolute acceleration is reduced to 30% of that for EID, and is almost the same as that for NC. Moreover, the control input of MEID is only 70% of that of EID. These results show that, while MEID suppresses both the displacement and the absolute acceleration, MEID also uses a small control input to yield good control performance compared with EID. This demonstrated the superiority of MEID over EID.

Unlike EID estimates a signal that suppresses the disturbance, MEID estimates a signal that is not only suppresses the disturbance, but also the absolute acceleration.

## V. Conclusion

This paper presented the MEID-base ASC system. Unlike other systems, it also takes the suppression of the absolute acceleration into consideration. The effectiveness of the method was examined through the time-response analysis of earthquake accelerograms. This study clarified the following points:

- The introduction of a direct-feedthrough term in the system made it possible to evaluate the absolute acceleration, and to estimate an EID signal to suppress the absolute acceleration.
- Numerical examples showed that the control performance of the absolute acceleration was better the MID-based ASC system than for the conventional EID-based ASC system, and the control input was also smaller for the MEID-based ASC system than for the conventional EID-based ASC system.

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