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Authors	Kou Miyamoto, Daiki Sato, Jinhua She, Yinli Chen, Satoshi Nakano
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Wind-load estimation with equivalent-input-disturbance approach

Kou Miyamoto[1], Daiki Sato[2], Jinhua She[3], Yinli Chen[4], Satoshi Nakano[5]

***Abstract*— This paper presents a new method to estimate an along-wind load that contains a mean component using an equivalent-input-disturbance approach. An along-wind force contains both mean and fluctuating components. However, most studies estimate only fluctuating components. Moreover, these studies assume that the damping matrix is a Rayleigh one. In contrast, this paper presents a method that estimates both the mean and fluctuating components using velocity response. Furthermore, this method does not require that the damping coefficient is Rayleigh damping. The numerical verification verifies using an 11 degree-of-freedom(DOF) model of a seismic-isolated building. The results presented that the presented method accurately estimates an along-wind load.**

I. INTRODUCTION

In these few decades, buildings become taller and many skyscrapers are constructed, and not only the seismic loads but also wind loads are important for building designing. Recently, many wind-resistant design methods are studied such as [1], [2], [3], and some devices are devised to suppress responses of wind loads [4], [5]. Moreover, some studies consider both seismic and wind loads to design a building [6], [7], [8]. To investigate the responses of a building for strong wind, the results of wind tunnel tests or measured data are used. However, wind loads cannot be measured directly, and we need to estimate them. To date, many disturbance estimation methods have been devised to estimate wind loads. Maruta et al. presented a method to estimate a wind-load by using displacement [10]. Sato and Razelle et al. showed that the mean component of wind-loads can be yielded by using an inverse transform function and displacement of a structure.[11]. Amiri et al. applied the Tikhonov regularization, which is one of the method for an ill-posed problem to estimate a modal wind force [12].

On the other hand, a Kalman filter, which is one of the control engineering methods is also used to estimate modal wind loads such as [13], [14], [15]. Many studies have attempted to estimate wind loads. Most studies assume that a damping coefficient of a structural model is a stiffness or mass proportional one (Rayleigh damping), and focus on estimating the fluctuating component of wind loads.

In control engineering, they are many disturbance-estimation methods. The information of a disturbance is used to improve control performance. One of the common methods is a disturbance observer [16]. A disturbance observer uses an inverse transfer function of a system to estimate a disturbance. However, this cannot be used if a control system has unstable zeros or the transfer function is not a square one. To solve this problem, She et al. devised an equivalent-input-disturbance (EID) approach [17]. Since an EID approach does not use an inverse of the transfer function of a system, this method can be used for a system that the transfer function is a rectangle form or has unstable zeros. Moreover, an EID approach does not require any conditions for disturbance.

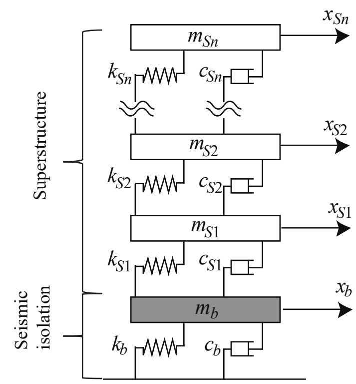

Fig. 1. Seismic-isolated building model

This paper estimates both mean and fluctuating components of wind-loads of a seismic-isolated building, which is one of the examples of a non-proportional damping structure, with an EID approach. Usually, structural displacements for wind-loads are not available, this paper uses velocity responses of a structure. Moreover, we assumed that the measured data contains white noise.

In this paper, we first explain the concept of an EID approach. Next, we show a system of estimation of wind-loads using an EID approach especially with velocity responses. Then, we verify our method through numerical examples with an 11 degree-of-freedom model of a seismic-isolated building.

II. EID APPROACH

This paper uses a shear building model of seismic-isolated building (Fig. 1). The dynamics of a building is shown as follows:

*This work was not supported by any organization
[1] Institute of Technology, Shimizu Corporation, Tokyo, 1350044, Japan kou_miyamoto@shimz.co.jp
[2]Tokyo Institute of Technology, FIRST, Kanagawa, 2268503, Japan sato.d.aa@m.titech.ac.jp
[3]Tokyo University of Technology, Dept. of Mechanical Engineering, Tokyo, 2268503, Japan sato.d.aa@m.titech.ac.jp

$$M_S\ddot{x}(t)+C_S\dot{x}(t)+K_Sx(t) = E_dF(t)+E_uu(t)M_S = \text{diag} \quad (1)$$

where M_S is a mass matrix, C_S is a damping matrix, K_S is a stiffness matrix, $F(t)$ is a wind force, E_d is a input channel of a wind force, and $u(t)$ and E_u are a control input and a control-input channel. Note that this model does not employ an active control, however, we use a virtual active control input and its channel to apply an EID approach. This paper uses a shear-building model and

The state space representation of (1) is

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

where

$$\begin{cases} A = \begin{bmatrix} 0 & I \\ -M_S^{-1}K & -M_S^{-1}C_S \end{bmatrix} \quad B_d = \begin{bmatrix} 0 \\ E_d \end{bmatrix} \\ B_d = \begin{bmatrix} 0 \\ E_u \end{bmatrix} \quad z(t) = \begin{bmatrix} x(t) \\ \dot{x}(t) \end{bmatrix} \\ d(t) = F(t). \end{cases} \quad (3)$$

In the above equations, A is a system matrix, B_d is a disturbance input matrix, B, $z(t)$ is a state of the system, and $d(t)$ is a disturbance. Now, we define the following output equation, $y(t)$:

$$y(t) = Cz(t), \quad (4)$$

where C is an output matrix that indicates that the placement or kind of sensors. For example, if C is an identity matrix, it means that the building employs displace and velocity sensors in every story. In other words, all displacements and velocities are available. Without loss of generality, we assume that (A,B) is controllable and (A,C) is detectable.

Next, we explain the concept of an EID. Figure 2(a) shows the block diagram of Eqs. 2 and 4. On the other hand, Fig. 2(b) shows the system (Eq. 2) with an EID, $d_e(t)$, and an output is defined as $\bar{y}(t)$. If $y(t) = \bar(y)$, then $d_e(t)$ is defined as an EID of the original disturbance, $d(t)$. To put it another way, an EID is a signal on a control input channel that outputs is the same as that of the original disturbance. Usually, the control input channel B_u, which is the placement of active control devices, and the distance input channel B_d are not the same. Thus, estimation of an EID is more useful than estimation of an original disturbance for active control systems. If we select $B_u = B_d$ and $u(t) = 0$, then the EID, $d_e(t)$, is identical to the original disturbance, $d(t)$. This paper applies an EID estimation problem for a disturbance estimation. Next section explains the system of wind-loads using an EID approach.

A. Estimation with displacements and velocities.

The disturbance estimation system is shown in Fig. 3. The full-state observer of Eq. (2) is

$$\begin{cases} \dot{\hat{z}}(t) = A\hat{z}(t) + LC[z(t) - \hat{z}(t)] \\ \hat{y}(t) = C\hat{z}(t), \end{cases} \quad (5)$$

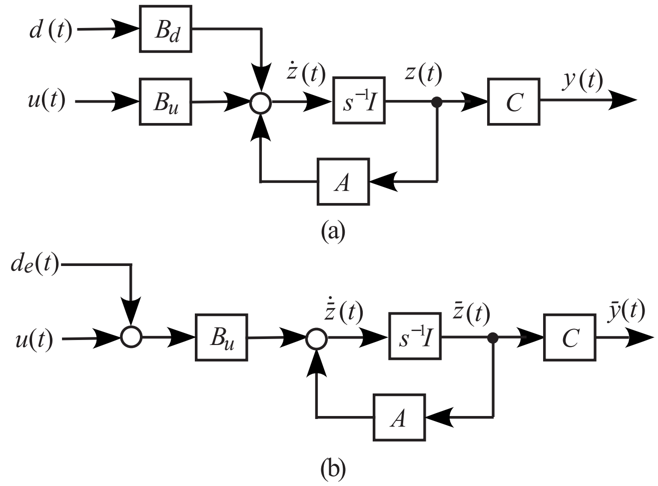

Fig. 2. Concept of EID

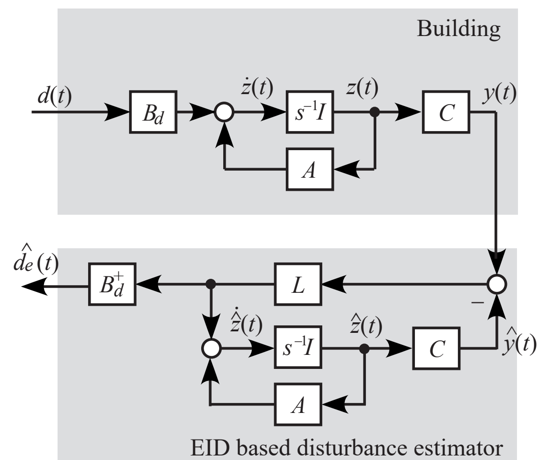

Fig. 3. Configuration of EID approach system for disturbance estimation

where $\hat{z}(t)$ is an estimated $z(t)$ and L is an observer gain. Substituting Eq. (2) into (5) yields that

$$\Delta\dot{z}(t) = (A - LC)\Delta z(t) + B_dd(t), \quad (6)$$

where $\Delta z(t)$ is an estimation error that is defined as

$$\Delta z(t) = z(t) - \hat{z}(t). \quad (7)$$

Since the system (2) is controllable, there is signal $\Delta d(t)$ that satisfies the following equation:

$$\dot{\Delta} z(t) = A\Delta z(t) + B_d\Delta d(t). \quad (8)$$

An estimated wind load, $\hat{d}_e(t)$, is given by substituting Eq. (8) into (7):

$$\begin{cases} \hat{d}_e(t) = B_d^+LC\Delta z(t), \\ \hat{d}_e(t) = d_e(t) - \Delta d(t), \end{cases} \quad (9)$$

where B_d^+ is a pseudo inverse matrix of B_d and it is given by

$$B_d^+ = (B_d^{\mathrm{T}}B_d)^{-1}B_d^{\mathrm{T}}. \quad (10)$$

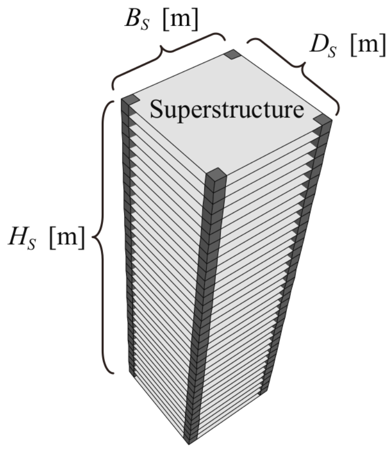

Fig. 4. Superstructure of building.

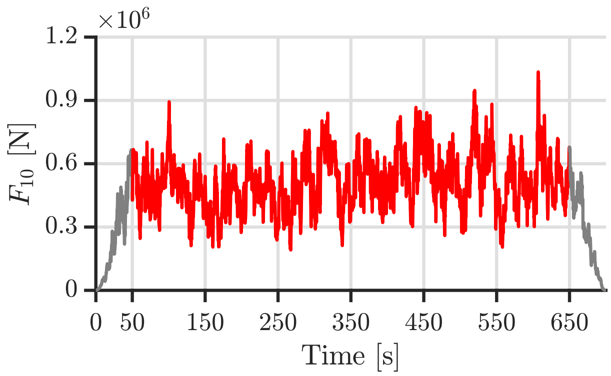

Fig. 5. Wind load of 10th floor.

III. Numerical verification

This section verifies the validity of our method. This paper uses an 11-DOF model of a seismic-isolated building, and the first story is the seismic-isolated story. The superstructure of the building is shown in Fig. 4.

The parameters of the building are as follows:

- Natural first-mode period of superstructure (T_S): 1.0 s
- Height of superstructure (H_S): $=T_S/0.02$ m
- Each story height of superstructure (h_{Si}): $H_S/10$
- Depth D_S and width B_S: 40 m
- Density of superstructure (ρ_S) (for all stories): 175 kg/m^3
- Each story mass of superstructure (m_{Si}): $B_S \times D_S \times \rho_S$
- Damping of superstructure: stiffness-proportional damping model $c_{Si} = 2\xi_S/\omega_i k_{Si}$ (damping ratio of the first mode, ξ_S: 0.02)
- Stiffness of superstructure [18]: The stiffness of the i-th story is

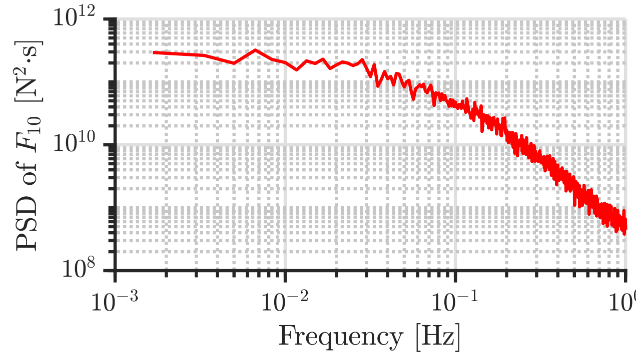

Fig. 6. PSD of Fig. 5.

$$\begin{cases} k_{S1} = \dfrac{\omega_S^2 m_{S1}\phi_{S1} + k_{S1}(\phi_{S2} - \phi_{S1})}{\phi_{S1}}, \\ k_{Si} = \dfrac{\omega_S^2 m_{Si}\phi_{Si} + k_{Si+1}(\phi_{Si+1} - \phi_{Si})}{\phi_{Si} - \phi_{Si-1}} \quad \{i = 2 \sim 9\}, \\ k_{S10} = \dfrac{\omega_S^2 m_{S10}\phi_{S10}}{\phi_{S10} - \phi_{S9}}, \end{cases} \tag{11}$$

where ϕ is an first eigen mode that is given as

$$\phi_{Si} = i - 1 \quad \{i = 2 \sim 11\}, \tag{12}$$

and ω_S is a natural frequency of the first mode of the superstructure. The parameters of the seismic isolation are

- Mass of the seismic-isolated story (m_b): $A_S \times \rho_b$, where ρ_b is a mass per unit area for the seismic-isolated story and is selected as 2551 kg/m^2.
- Stiffness (k_b):
$$k_b = \frac{2\pi \sum m_{Si}}{T_b}, \tag{13}$$
where T_b is a seismic-isolated natural period that assumes the superstructure is a rigid body. This paper selects $T_b = 4.0s$.
- Damping coefficient (c_{S1}):
$$c_b = 2\xi_b\sqrt{k_b \sum m_{Si}}, \tag{14}$$
where ξ_b is a damping ratio for the seismic-isolated period, T_b, that is selected as 0.2 in this paper.

The observer gain, L_p, is designed by solving the following Riccati equation:

$$\begin{cases} PA^{\mathrm{T}} + AP + Q - PC^{\mathrm{T}}R^{\mathrm{T}}CP = 0 \\ L_p = -R^{-1}C^{\mathrm{T}}P, \end{cases} \tag{15}$$

where P is a solution of the Riccati equation, and Q (> 0) and R (> 0) are weighting matrices. The Riccati equation is solved by minimizing the following performance index:

$$J = \int_0^\infty \{\Delta z_p^{\mathrm{T}}(t)Q\Delta z_p(t) + u_p^{\mathrm{T}}(t)Ru_p(t)\}\mathrm{d}t, \tag{16}$$

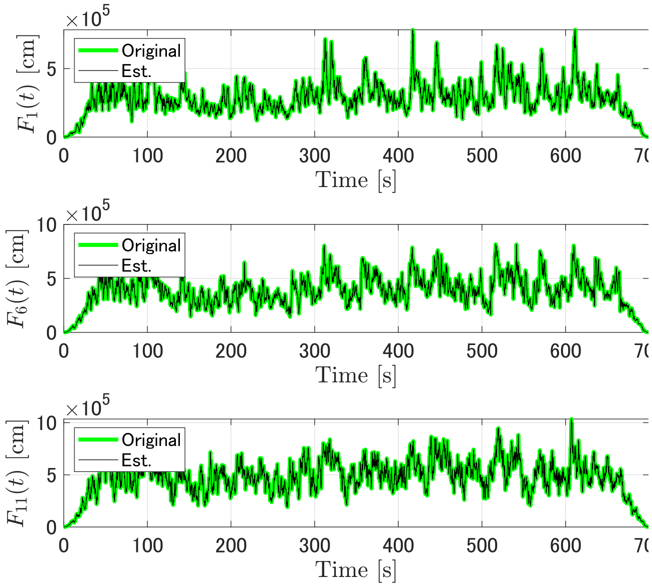

Fig. 7. Wind loads of 1st, 5th, and 10th floors.

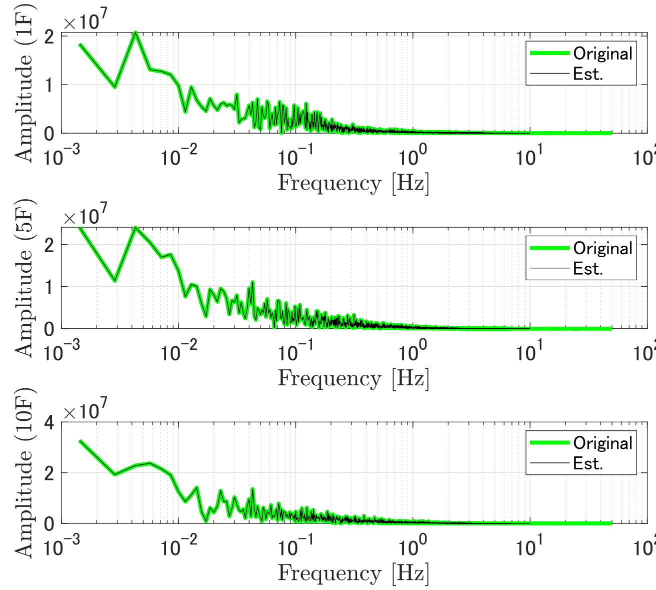

Fig. 8. FFT of Fig. 7.

where $u_p(t)$ is

$$u_p(t) = -PCR^{-\mathrm{T}} z_p(t). \tag{17}$$

Note that a dual system is used to design the observer gain. This paper select these matrices as follows:

$$\left\{ \; Q = \begin{bmatrix} 10^{-15} I_{11} & 0 \\ 0 & 10^{10} I_{11} \end{bmatrix} R = 10^{-10} I_{22}, \right. \tag{18}$$

where I_n is a $n \times n$ identity matrix.

This paper uses wind forces with a return period of 500 years. The wind force is determined by a wind tunnel experiment [19]. The airflow in the experiment is determined by referring to the building design load in Japan (terrain: III, directional angle: 0 degr)[20]. The design wind velocities of the 100-year and 500-year return periods are 54.9 and 63.8 m/s, respectively. Envelopes are set the first and the last 50 s for every case (Fig. 5), and the ensemble average of the power spectral density of the 10th floor is shown in Fig. 6.

The results of the estimation are shown in Fig. 7. In this paper, we show the results of the 1st, 5th, and 10th floors as an example. The results show that an EID approach estimates accurately the original wind loads. In particular, the EID approach estimates not only the fluctuating component but also the mean component of the wind load of a seismic-isolated building, which is a non-proportional damping.

Figure Fig. 8 shows the comparison of the fast Fourier transform (FFT), and the results show that an EID approach estimates the original disturbance in terms of a frequency domain.

An EID estimates the original disturbance using the states of the plant, and that is a key to for accuracy of estimation. Figures 9 and 10 show that the state observer estimates the displacements and velocity very accurately. In particular, the

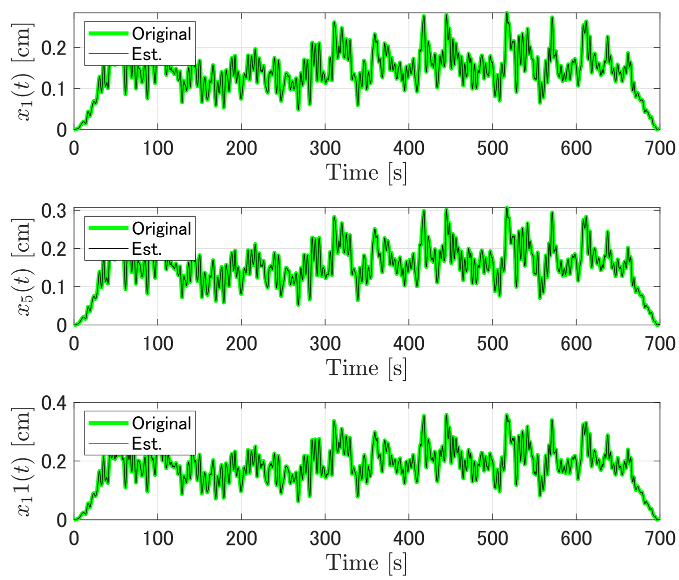

Fig. 9. Displacements of 1st, 5th, and 10th floors.

displacement includes the mean components. Thus, accurate estimation of displacements is important for disturbance estimation.

IV. CONCLUSIONS

This paper applies an equivalent-input-disturbance (EID) to estimate the wind loads of a building. An EID is a signal on the control input channel that gives the same output as an original disturbance. We apply this method to estimate the wind loads of a structure. First, we explain a concept of an EID method for active structural control. Next, we apply the EID approach for disturbance estimation. Then, a numerical example shows the validity of an EID approach for

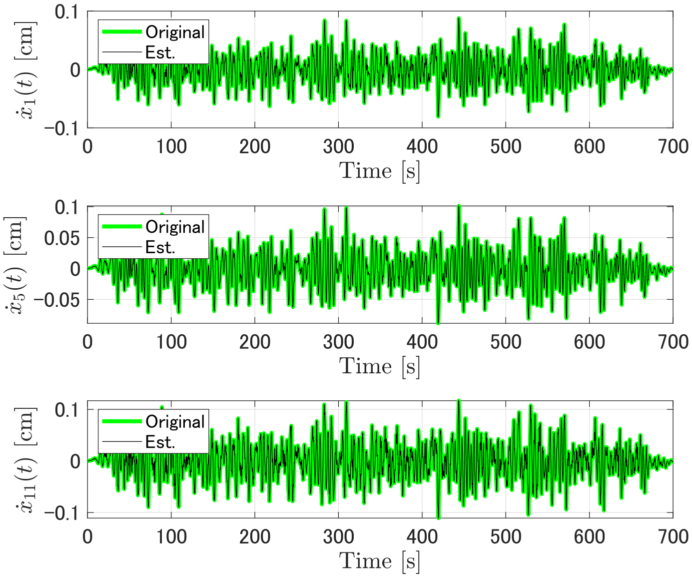

Fig. 10. Velocities of 1st, 5th and 10th floors.

estimating wind loads. A seismic-isolated building model is used in the numerical example. The results show that an EID approach estimates accurately the wind-loads of a building. This paper presents the following points:

- An EID estimates an original disturbance by setting the control input channel is the same as the disturbance input channel.
- Moreover, both the means and fluctuating components can be estimated using an EID approach.
- The numerical example shows that an EID approach estimates wind loads of a seismic-isolated building, which damping is a non-proportional one.

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