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Gust factor approach to estimating maximum response and maximum control force for high-rise base-isolated buildings with active structural control on along-wind direction

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Abstract— **This paper extends the gust factor approach to include buildings combined with active structural control. Moreover, a design method for determining the isolated period, isolated damping ratio, and feedback gain that satisfies the restrictions on the maximum control force and maximum displacement response is developed. The efficiency of the estimation methods is confirmed via numerical examples.**

I. INTRODUCTION

Passive base-isolated (PBI) structures have been used to minimize the damage caused to superstructures and to help resume operations immediately after violent earthquakes. In recent years, PBI structures have been installed in many important facilities and high-rise buildings [1]. However, the wind load for high-rise buildings is extremely strong, and it directly acts on the superstructure. Therefore, the displacement response of high-rise PBI buildings is generally significantly high under such strong winds, thereby making it difficult to maintain suppressing the response within the standard limits. To solve this problem, the addition of active structural control (ASC) to the PBI story to suppress displacement responses is considered to be a feasible solution.

The duration of the wind event is long, and the response of buildings is calculated via the ensemble average using several cases, which leads to a prolonged simulation time. Moreover, the control system is generally designed via a trial-and-error approach, thereby increasing the complexity when determining a controller that can satisfies all design requirements. Above these reasons, the conventional design procedure of PBI buildings with ASC is very complex.

In this study, the analytical formulae for estimating the gust factor for the control force of multi-DOFs models is developed. The efficacy of the estimation methods is validated via numerical verifications.

II. MODELS AND WIND FORCE

A. Models

The study uses 11 degree-of-freedom (DOF) models (Fig. 1). The parameters of the model are shown in Table 1. The stiffness coefficient of the superstructure is determined by the method reported by Sato et al. [2], and the damping of the superstructure is determined using the stiffness-proportional damping model.

B. Along-wind Force

This study employs a wind force with a return period of 500 years. Wind force is determined using a wind tunnel experiment [3]. The airflow in the experiment is determined by referring to the building design load in Japan (terrain: III, directional angle: 0°). A total of 30 Cases of wind waves are used in this study. The responses of each model are calculated based on the ensemble average of the 30 Cases.

III. CONSTRUCTION OF CONTROL SYSTEM

The dynamics of the model is

$$M\ddot{X}(t) + C\dot{X}(t) + KX(t) = E_F F(t) - E_u u(t), \qquad (1)$$

where M, K, C are the mass matrix, damping matrix, and stiffness matrix, respectively; X, $\dot{X}$, and $\ddot{X}$ are displacement vector, velocity vector, and acceleration vector, respectively; F and u are wind force vector and control force, respectively; E_F and E_u are the input vectors for F and u, respectively.

The state-space representation of the dynamics of the model is

$$\dot{Z}(t) = AZ(t) + B_F F(t) - B_u u(t), \qquad (2)$$

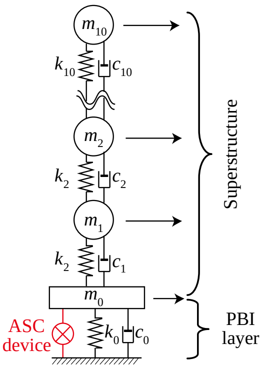

Fig. 1 Models

TABLE I
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	Parameters	
super structure	Height	100 m
	Fool area	20 m x 20 m
	DOF	10
	Density	175 kg/m^3
	1st period	2 s
	1st damping ratio	0.02
PBI story	DOF	1
	Density	2551 kg/m^2
	1st period	3, 4, and 5 s
	1st damping ratio	0.05

where Z is the state vector; A is the system matrix; B_F and B_u are the input matrix for F and u, respectively.

The feedback control law

$$u(t)=K_PZ(t)=[K_{PD}\quad K_{PV}][X\quad \dot{X}]^{\mathrm{T}}, \tag{3}$$

is used, where K_P is the feedback gain; K_{PD} and K_{PV} are the feedback gain for displacement and velocity, respectively. The feedback gain K_P is designed by the linear quadratic regulator (LQR) method in this paper and the LQR weighting matrices are set to the following equation:

$$Q=10^{\alpha}\mathrm{diag}\{1\cdots 1\,,0\ \cdots 0\},\text{and } R=1$$

where Q and R are the weights for the state and control force, respectively; α is the weighting entry in Q.

IV. GUST FACTORS

A. *Gust factor for displacement*

Figures 2(a) presents the comparison between the estimated and simulated values for the gust factor of displacement of the PBI story G_{D0}. The calculation procedure for the estimated values of the gust factor for displacement are referring to AIJ Recommendations for Loads on Buildings [5]. Note that Note that the value of the 1st natural period and 1st damping ratio of the model are calculated by the 1st eigenvalue of the control system (building with the controller).

B. *Gust factor for control force*

The gust factor for control force G u is defined as

$$G_u=\frac{\max\{u\}}{\bar{u}}\approx\frac{K_P\left[\max\{X\}\quad \max\{\dot{X}\}\right]^{\mathrm{T}}}{K_P[\bar{X}\quad \bar{\dot{X}}]^{\mathrm{T}}}. \tag{4}$$

As the velocity response of a control system does not contain the mean component [4], the mean component of velocity can be neglected:

$$G_u\approx\frac{K_P\left[\max\{X\}\quad \max\{\dot{X}\}\right]^{\mathrm{T}}}{K_P[\bar{X}\quad 0]^{\mathrm{T}}}. \tag{5}$$

Representing of (5) yields

$$G_u\approx G_D+\frac{K_{PV}(G_D\bar{X}-\bar{X})\omega_1}{K_{PD}\bar{X}}. \tag{6}$$

where G_D is the gust factor for displacement.

Fig. 2(b) presents the comparison between the values estimated using (6) and the simulation results of the gust factor for the control force.

V. DESIGN METHOD

Step 0. Specify the return period of the along-wind force and the parameters of the superstructure (i.e., structure shape, mass matrix, stiffness matrix, and damping matrix).

Step 1. Specify the parameters of the PBI story (i.e., mass of PBI story, isolated period, and isolated damping ratio).

Step 2. Specify the restrictions on the maximum displacement and maximum control force.

Step 3. Estimate the mean control force and the mean displacement response using [4].

Step 4. Use [5] and (6) to calculate the gust factor for the control force and displacement, respectively.

Step 5. Use the estimated values for the mean control force and mean displacement response calculated in Step 3 and the gust factor calculated in Step 4 to estimate the maximum control force and the maximum displacement response.

Step 6. If the restrictions on the maximum displacement response and maximum control force are satisfied, select the weighting entry α and proceed to the next step. If not, go back to Step 1, thereby decreasing the isolated period or increasing the isolated damping ratio or operating both of them.

Step 7. Design the control system using the isolated period T_0 and the isolated damping ratio ζ_0 determined in Step 1, and the weighting entry α selected in Step 6.

VI. CONCLUSION

This paper presents a method to estimate the gust factor for displacement and control force was developed. The numerical examples confirmed the validity of the estimation methods. Moreover, a design method for PBI buildings with ASC against an along-wind force, for determining the isolated period, isolated damping ratio, and feedback gain under restrictions on the maximum displacement response and maximum control force.

However, the design method presented in this paper is limited in the along-wind direction. The estimation for the across-wind and torsional direction is theoretically meaningful and will be performed in future works.

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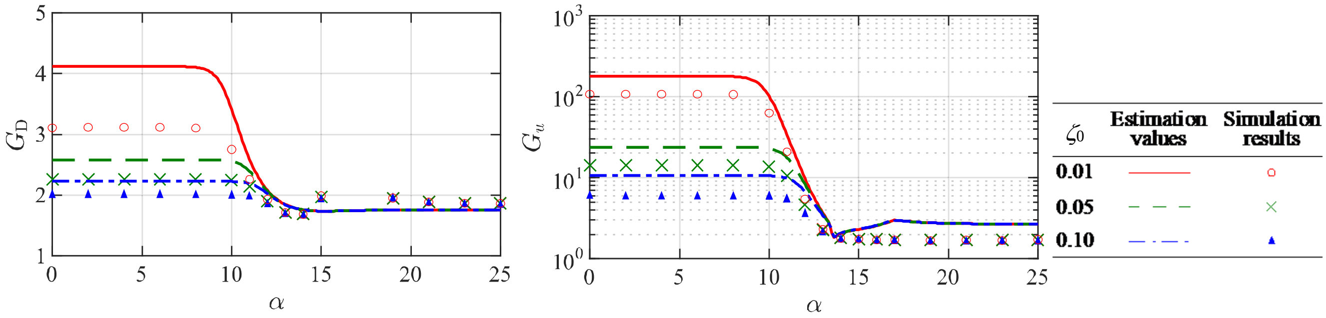

(a) Gust factor for displacement

(b) Gust factor for control force

Fig. 2 Gust factors