Earthquake Response Estimation and Control of Equipment Supported by Frames*

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Dynamic interaction between industrial equipment and its supporting frames should be taken into account in the aseismic design of complex industrial structures such as blast furnaces, chemical reactor vessels, towers, or stacks. This paper aims to examine the effects of dynamic interaction on the maximum base shear distribution between two kinds of structural components, that is, the equipment and its supporting frames, and on the vibratory energy consumption of the damping devices placed between these two structural components. The random vibration theory is applied to obtain the average peak responses of simplified interaction models placed on a base which is stimulated by ground acceleration having the standard power spectrum. The expected ratio of the maximum rocking moment shared between the two structural components of the dynamic model is obtained as a function of the dynamic characteristics of each constituent component and the interaction spring, and the maximum response is reduced by the intermediate damping devices. These results are presented graphically for convenience so as to determine the rational aseismic design forces for each structural component.

Key Words: Machinery, Damping, Vibration Control, Coupled Vibration, Earthquake Response, Gaussian Random Process, Base Shear, Rocking Moment

1. Introduction

Huge blast furnaces in modern iron-making plants and tall reactor vessels or stacks in complex chemical plants are often supported laterally by steel or reinforced concrete frames so as to withstand earthquakes. The current aseismic design of these structures starts with the calculation of the distribution of the base shear to be transmitted to the constituent structural components, equipment and its supporting frames during earthquakes, and is then followed by precise stress analysis of these components. It is very important, therefore, to provide a well-grounded base shear distribution considering the dynamic interaction between them in place of the conventional values which are determined via a static analysis.

The total base shear caused in these structural components may be effectively reduced by installing dampers between these components, because the

dynamic interaction between them during earthquakes will give substantial relative velocity or displacement.

This paper aims to examine the effects of dynamic interaction on the base shear distribution between the equipment and its supporting frames, and on the energy consumption by the dampers installed between them. The random vibration theory is applied to obtain the average peak responses of simplified interaction models placed on a base which is excited by ground acceleration having the standard power spectrum.

2. Simplified Structural Model of Supported Equipment

The supported equipment can be divided from the structural viewpoint into two categories as shown in Fig. 1.

The vessel in Fig. 1 represents equipment which cannot stand by itself even under no-earthquake conditions and the stack represents free-standing equipment that needs lateral supports to endure earthquakes. Simplified models for dynamic analysis are presented in Fig. 2 by assuming rigid bodies for the

* Received 2nd March, 1993.

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vessels and the stack in Fig. 1⁽¹⁾.

Taking the rocking motion of the equipment around the pin support as " θ " and the relative displacement of the frames from the ground as " U_s ", both interaction models in Fig. 2 give us the same differential equation which is directly derived from d'Alembert's principle. We thus write

$$\begin{bmatrix} M_s & 0 \\ 0 & I_E \end{bmatrix} \begin{Bmatrix} \ddot{U}_s \\ \ddot{\theta} \end{Bmatrix} + \begin{bmatrix} K_s + K_I & -K_I H_1 \\ -K_I H_1 & K_I H_1^2 + K_\theta \end{bmatrix} \begin{Bmatrix} U_s \\ \theta \end{Bmatrix} = - \begin{bmatrix} M_s & 0 \\ 0 & M_0 H_0 \end{bmatrix} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix} \ddot{U}_G \quad (1)$$

where

M_s : mass of the supporting frames

I_E : moment of inertia of the equipment around the pin support which is given by Eq. (2) as $I_E = I_0 + M_0 H_0^2$ (2)

I_0 : moment of inertia of the equipment around the center of gravity

M_0 : mass of the equipment

K_s : lateral spring constant of the supporting frames

K_θ : rotational spring constant of the equipment

K_I : interactional spring constant of intermediate elements

$\ddot{U}_G$: earthquake acceleration on the ground

" $\ddot{\cdot}$ " denotes second derivative

The terms of damping forces in Fig. 1 will be considered later.

Equation (1) can be changed into Eq. (4) by using the following variable translation.

$$\begin{Bmatrix} U_s \\ \theta \end{Bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1/H_1 \end{bmatrix} \begin{Bmatrix} U_s \\ U_E \end{Bmatrix} \quad (3)$$

where " U_E " is lateral displacement of the point at which the equipment is supported laterally by the

Fig. 1 Structural models of supported equipments

Fig. 2 Interaction models for dynamic analyses

interaction springs.

$$\begin{bmatrix} M_s & 0 \\ 0 & M_E \end{bmatrix} \begin{Bmatrix} \ddot{U}_s \\ \ddot{U}_E \end{Bmatrix} + \begin{bmatrix} K_s + K_I & -K_I \\ -K_I & K_E + K_I \end{bmatrix} \begin{Bmatrix} U_s \\ U_E \end{Bmatrix} = - \begin{bmatrix} M_s & 0 \\ 0 & M_E \end{bmatrix} \begin{Bmatrix} 1 \\ f \end{Bmatrix} \ddot{U}_G \quad (4)$$

where

$$M_E = I_E / H_1^2 = M_0 \frac{i_0^2 + H_0^2}{H_1^2} \quad (5)$$

$$K_E = K_\theta / H_1^2 \quad (6)$$

$$f = (M_0 H_0 H_1) / I_E = \frac{H_0}{H_1} \frac{H_1^2}{i_0^2 + H_0^2} \quad (7)$$

$$i_0^2 = I_0 / M_0 \quad (8)$$

Equation (4) represents the typical matrix equation which is given for the two-degree-of-freedom system standing parallel to each other as presented in Fig. 3.

In Fig. 3, the point mass " M_E " has the equivalent mass defined by Eq. (5), which is excited by lateral ground acceleration with an efficiency of " f " defined by Eq. (7). Equivalent mass " M_E " decreases and efficiency " f " increases when " H_1/H_0 " increases and " I_0 " decreases.

Analyzing the dynamic responses of the two-degree-of-freedom system shown in Fig. 3, we obtain the peak displacement of each point mass during an earthquake. Denoting these peak displacements of the equipment and the frames as " $|U_E|_{\text{peak}}$ " and " $|U_s|_{\text{peak}}$ ", respectively, peak value of the shared rocking moment of each component, " $|T_E|_{\text{peak}}$ " or " $|T_s|_{\text{peak}}$ ", can be calculated using the following equations.

$$\begin{Bmatrix} |T_E|_{\text{peak}} = K_\theta |\theta|_{\text{peak}} = H_1 K_E |U_E|_{\text{peak}} \\ |T_s|_{\text{peak}} = H_1 K_s |U_s|_{\text{peak}} \end{Bmatrix} \quad (9)$$

Peak value of the total rocking moment, " $|T_{\text{ALL}}|_{\text{peak}}$ ", is

$$\begin{aligned} |T_{\text{ALL}}|_{\text{peak}} &= |K_\theta \theta + H_1 U_s K_s|_{\text{peak}} \\ &= H_1 |U_E K_E + U_s K_s|_{\text{peak}}. \end{aligned} \quad (10)$$

Then the sharing ratio of rocking moment between two components becomes

$$\begin{Bmatrix} \frac{|T_E|_{\text{peak}}}{|T_{\text{ALL}}|_{\text{peak}}} = \frac{K_E |U_E|_{\text{peak}}}{|U_E K_E + U_s K_s|_{\text{peak}}} = \frac{|Q_E|_{\text{peak}}}{|Q_E + Q_s|_{\text{peak}}} \\ \frac{|T_s|_{\text{peak}}}{|T_{\text{ALL}}|_{\text{peak}}} = \frac{K_s |U_s|_{\text{peak}}}{|U_E K_E + U_s K_s|_{\text{peak}}} = \frac{|Q_s|_{\text{peak}}}{|Q_E + Q_s|_{\text{peak}}} \end{Bmatrix} \quad (11)$$

where " $|Q_E|_{\text{peak}}$ " and " $|Q_s|_{\text{peak}}$ " are the peak values of the base shears induced during an earthquake in

Fig. 3 Equivalent two degree of freedom system

masses M_E and M_S in Fig. 3, respectively.

3. Statistical Response Analysis

Introducing the following nondimensional notation into the differential equation for the equivalent two-degree-of-freedom system,

$$m_E = \frac{M_E}{M}, m_S = \frac{M_S}{M}, k_E = \frac{K_E}{K}, k_S = \frac{K_S}{K}, \\ k_I = \frac{K_I}{K_E + K_S}, \omega_0^2 = \frac{k_S}{M_S}, m_S = k_S = 1.0, \gamma = \frac{M_E}{M_S}$$

Equation (4) becomes

$$\begin{bmatrix} 1 & 0 \\ 0 & \gamma \end{bmatrix} \begin{Bmatrix} \ddot{U}_S \\ \ddot{U}_E \end{Bmatrix} + \omega_0^2 \begin{bmatrix} 1+k_I(1+k_E) & k_I(1+k_E) \\ k_I(1+k_E) & k_E+k_I(1+k_E) \end{bmatrix} \begin{Bmatrix} U_S \\ U_E \end{Bmatrix} \\ = \begin{bmatrix} 1 & 0 \\ 0 & \gamma \end{bmatrix} \begin{Bmatrix} 1 \\ f \end{Bmatrix} \ddot{U}_G \quad (12)$$

Natural circular frequencies are obtained from Eq. (12) as follows:

$$\frac{\omega_1^2, \omega_2^2}{\omega_0^2} = \frac{1}{2\gamma} \left[\gamma + k_E + k_I(1+k_E)(1+\gamma) \right. \\ \left. \mp \sqrt{\{\gamma + k_E + k_I(1+k_E)(1+\gamma)\}^2 - 4\gamma\{k_E + k_I(1+k_E)\}^2} \right] \quad (13)$$

in which suffixes "1" and "2" denote the first and second modes taking signs of "-" and "+" in Eq. (13), respectively.

Mode shape " X_p " and participating factor " β_p " of the p -th mode are

$$X_p = \left(\frac{X_E}{X_S} \right)_p = \frac{k_I(1+k_E)}{k_E + k_I(1+k_E) - \gamma(\omega_p/\omega_0)^2} \quad (14)$$

$$\beta_p = \frac{1 + \gamma f X_p}{1 + \gamma X_p^2} \quad (15)$$

On the other hand, the mean squares of responses of linear systems in the time domain can be obtained by Eq. (16), assuming that the earthquake motion is a stationary random process.

$$\overline{U_u^2} = \int_0^\infty S_u(i\omega) G^2(\omega) d\omega \quad (16)$$

where " $S_u(i\omega)$ " is the frequency transfer function of the u -th mass displacement against the ground acceleration, and is given in Eq. (17).

$$S_u(i\omega) = \sum_{p=1}^n (\Phi_{up}) \frac{\frac{1}{\omega_p^2}}{1 - \frac{\omega^2}{\omega_p^2} + 2h_p \frac{i\omega}{\omega_p}} \quad (17)$$

where

Φ_{up} : p -th participation function

h_p : p -th modal damping coefficient

ω_p : p -th natural circular frequency

n : total mode number to be applied

" $G^2(\omega)$ " is a power spectrum of the ground acceleration. Following Kanai's formula⁽²⁾, the standard power spectrum of the ground acceleration is represented as follows:

$$G^2(\omega) = \frac{1 + 4h_g^2 \frac{\omega^2}{\nu_g^2}}{\left(1 - \frac{\omega^2}{\nu_g^2}\right)^2 + 4h_g^2 \frac{\omega^2}{\nu_g^2}} B \quad (18)$$

where " ν_g " and " h_g " are the parameters determining the shape of the power spectrum function. Referring the previous study⁽¹⁾, we choose the values of " ν_g " and " h_g " as 8π and 0.4, respectively. " B " is a constant. Using Eq. (17),

$$|S_u(i\omega)|^2 = \sum_p^n \Phi_{up}^2 Z_{pp}^2(\omega) + \sum_{\substack{p, q \\ (p \neq q)}}^n \Phi_{up} \Phi_{uq} Z_{pq}^2(\omega) \quad (19)$$

where

$$Z_{pp}^2(\omega) = \frac{\frac{1}{\omega_p^4}}{\left(1 - \frac{\omega^2}{\omega_p^2}\right)^2 + 4h_p^2 \frac{\omega^2}{\omega_p^2}} \\ Z_{pq}^2(\omega) = \frac{\left\{ \left(1 - \frac{\omega^2}{\omega_p^2}\right) \left(1 - \frac{\omega^2}{\omega_q^2}\right) + 4h_p h_q \frac{\omega^2}{\omega_p \omega_q} \right\} \frac{1}{\omega_p^2 \omega_q^2}}{\left\{ \left(1 - \frac{\omega^2}{\omega_p^2}\right)^2 + 4h_p^2 \frac{\omega^2}{\omega_p^2} \right\} \left\{ \left(1 - \frac{\omega^2}{\omega_q^2}\right)^2 + 4h_q^2 \frac{\omega^2}{\omega_q^2} \right\}} \quad (20)$$

The transmissibilities are expressed as follows:

$$\left. \begin{aligned} \lambda_{pp}^2 &= \int_0^\infty Z_{pp}^2(\omega) G^2(\omega) d\omega \\ \lambda_{pq}^2 &= \int_0^\infty Z_{pq}^2(\omega) G^2(\omega) d\omega \end{aligned} \right\} \quad (21)$$

Finally, the mean squares of the u -th mass displacement can be written in the form

$$\overline{U_u^2} = \sum_p^n \Phi_{up}^2(\omega) \lambda_{pp}^2 + \sum_{\substack{p, q \\ (p \neq q)}}^n \Phi_{up} \Phi_{uq} \lambda_{pq}^2 \quad (22)$$

Tajimi has shown that the average peak value is proportional to the root mean square of the response in the time domain, when the earthquake motion can be assumed as a stationary random process following the probability rule of the normal distribution⁽²⁾. Using this Tajimi's formula, the following equation is derived.

$$\frac{E[|Q_E|_{\text{peak}}]}{\sqrt{Q_E^2}} = \frac{E[|Q_S|_{\text{peak}}]}{\sqrt{Q_S^2}} = \frac{E[|Q_E + Q_S|_{\text{peak}}]}{\sqrt{(Q_E + Q_S)^2}} \quad (23)$$

where " $E[-]$ " denotes averaging.

Therefore, the sharing ratio of rocking moment between the equipment and the frames, which is defined by Eq. (11), becomes

$$\left. \begin{aligned} \frac{E[|T_E|_{\text{peak}}]}{E[|T_{\text{ALL}}|_{\text{peak}}]} &= \sqrt{\frac{Q_E^2}{(Q_E + Q_S)^2}} = \sqrt{\frac{k_E^2 \left\{ \sum_p^n \Phi_{Ep} \lambda_{pp}^2 + \sum_{\substack{p, q \\ (p \neq q)}}^n \sum_q^n \Phi_{Ep} \Phi_{Eq} \lambda_{pq}^2 \right\}}{\sum_p^n (k_E \Phi_{Ep} + \Phi_{Sp})^2 \lambda_{pp}^2 + \sum_{\substack{p, q \\ (p \neq q)}}^n \sum_q^n (k_E \Phi_{Ep} + \Phi_{Sp})(k_E \Phi_{Eq} + \Phi_{Sq}) \lambda_{pq}^2}} \\ \frac{E[|T_S|_{\text{peak}}]}{E[|T_{\text{ALL}}|_{\text{peak}}]} &= \sqrt{\frac{Q_S^2}{(Q_E + Q_S)^2}} = \sqrt{\frac{\left\{ \sum_p^n \Phi_{Sp} \lambda_{pp}^2 + \sum_{\substack{p, q \\ (p \neq q)}}^n \sum_q^n \Phi_{Sp} \Phi_{Sq} \lambda_{pq}^2 \right\}}{\sum_p^n (k_E \Phi_{Ep} + \Phi_{Sp})^2 \lambda_{pp}^2 + \sum_{\substack{p, q \\ (p \neq q)}}^n \sum_q^n (k_E \Phi_{Ep} + \Phi_{Sp})(k_E \Phi_{Eq} + \Phi_{Sq}) \lambda_{pq}^2}} \end{aligned} \right\} \quad (24)$$

Using Bigg's method⁽⁴⁾, the p -th damping coefficient " h_p " in Eq.(17) can be given as follows:

$$\begin{aligned} h_p &= \frac{\sum_j \{\phi_{pj}\}^T [h_{pj} K_j] \{\phi_{pj}\}}{\sum_j \{\phi_{pj}\}^T [K_j] \{\phi_{pj}\}} \\ &= \frac{h_{pE} k_E X_p^2 + h_{pS} + h_{pI} k_I (1 + k_E) (1 - X_p)^2 \left(\frac{\omega_0}{\omega_p} \right)^2}{1 + \gamma X_p^2} \end{aligned} \quad (25)$$

where " ϕ_{pj} " represents the j -th factor in the p -th mode shape function, and " h_{pj} " is the damping coefficient of the j -element at the p -th natural frequency, which is assumed here to be constant at all frequencies. The notation " T " denotes matrix transposition.

4. Parameter Variation

We have confirmed in the previous study⁽¹⁾ that the ratio of the peak response between the two structural components, that is, the equipment and its supporting frames, tends to gather around a certain value which is unique to the dynamic characteristics of the tested structure, and that this value is stable whatever the ground motion may be, for example having much different frequency characteristics which may scatter each peak response value itself in a wide range. We also found the most suitable combination of parameters in the standard power spectrum of the ground as shown in Eq.(18), which gives excellent agreement between the average peak ratio obtained from a total of 15 actual earthquakes and the analytical one derived from the random vibration theory. These suitable parameters are adopted in this study as shown in Eq.(18).

The parameters which define the dynamic characteristics of the structural model are determined in such a manner that they cover the range of the actual industrial structures.

$$\left. \begin{aligned} \omega_0 &= \omega_s = 2\pi \quad (T_0 = T_s = 1.0 \text{ sec}) \\ \omega_E/\omega_0 &= 0.1 \sim 10.0, \quad k_I = 0.04 \sim 10.0 \\ f &= 0.1 \sim 10.0, \quad \gamma = 0.1 \sim 10.0 \end{aligned} \right\} \quad (26)$$

The range of " H_I/H_0 " and " M_0/M_S " correspond to those of " f " and " γ " which are 0.1~10.0, and the range of " i_0/H_0 " is 0.1~1.0.

The damping coefficients of actual furnaces and steel frames are reported⁽¹⁾ to be almost the same as

those of reinforced concrete buildings and steel buildings, respectively. So we adopted the constant values of $h_E=0.02$ and $h_S=0.01$ for the equipment and its supporting frames, respectively, as the most common values⁽⁴⁾ for buildings.

5. Dynamic Interaction and Maximum Rocking Moments

The peak rocking moments caused in the equipment and its supporting frames are calculated, and the sharing ratio of each peak rocking moment to the total peak is plotted against the natural frequency ratio between both structural components, using the interaction spring constant k_I . Several sets of curves of these sharing ratios are shown in Figs. 4-1 and 4-2 with the combinations of parameters " γ " and " f ".

In general, the summation of these two sharing ratios does not necessarily become unity, but

$$\frac{|T_E|_{\text{peak}}}{|T_{\text{ALL}}|_{\text{peak}}} + \frac{|T_S|_{\text{peak}}}{|T_{\text{ALL}}|_{\text{peak}}} \geq 1.0 \quad (27)$$

Figures 4-1 and 4-2 show the relations of Eq.(24), and in case of smaller " k_I ", this summation tends to be greater than unity.

Upon itemizing the obvious features from these curves of sharing ratios against frequency ratios, the following are noted.

(a) The sufficiently rigid interaction spring of $k_I=10$ gives almost proportionally shared rocking moments with lateral rigidity of each component. In the case of $k_I \leq 0.3$, the dynamic interaction between both components influences the sharing ratios, and the proportionally shared rocking moment, which has been conventionally used so far, is recognized as no longer being correct⁽⁵⁾.

(b) Deviation of the actual sharing ratio from the proportional one increases when the product of " γ " and " f " becomes smaller in the region of $\omega_E/\omega_S > 1.0$, while it also increases when this product become larger in the region of $\omega_E/\omega_S < 1.0$.

(c) The value deviating from the proportional one finally approaches the constant value which is produced when each component is mutually independent, that is, in proportion to its own mass. However, it is important to notice that the minute interaction spring constant, such as $k_I=0.04$ may cause a

considerable effect in the sharing ratio as shown in these figures.

(d) The dynamic interaction is marked in the vicinity of $\omega_E/\omega_S=1.0$ when $k_l < 0.3$. In this region, the sharing ratio may change considerably for a small variation of the frequency ratio. Mutually connected twin structures, the components of which have a

similar natural frequency, should be inspected if the intermediate spring has not an adequate lateral rigidity not to cause severe interaction phenomena like so-called "pounding"⁽⁶⁾.

Figures 4-1 and 4-2 may be used in the following manner for the aseismic design of industrial equipment supported by frames. The total lateral

Fig. 4-1 Relations between the shared ratios of average peak rocking moment and the frequency ratio (part 1)

earthquake force is usually given by seismic coefficients of “ α_i ” which are designated in the standard codes⁽⁷⁾. The rational maximum rocking moment of the equipment “ $(T_E)_{\max}$ ” and that of the supporting frames “ $(T_S)_{\max}$ ” are given by using the aforementioned sharing ratios,

$$\left. \begin{aligned} (T_E)_{\max} &= \frac{E[|T_E|_{\text{peak}}]}{E[|T_{\text{ALL}}|_{\text{peak}}]} \left\{ \sum W_i H_i \alpha_i \right\} \\ (T_S)_{\max} &= \frac{E[|T_S|_{\text{peak}}]}{E[|T_{\text{ALL}}|_{\text{peak}}]} \left\{ \sum W_i H_i \alpha_i \right\} \end{aligned} \right\} \quad (28)$$

where “ W_i ” and “ H_i ” are the weight and the height of the i -th component, respectively, the maximum base shear can be estimated from this maximum rocking moment considering the equivalent height of the

Fig. 4-2 Relations between the shared ratios of average peak rocking moment and the frequency ratio (part 2)

component.

6. Response Control Using Intermediate Damping Devices

The damping devices would be most effective if they were installed between two points which have a

fairly large relative velocity of displacement during earthquakes. The supported type equipment may largely interact with its supporting frames under some conditions, causing substantial relative velocity or displacement.

Figures 5-1 and 5-2 represent damping effects on

Fig. 5-1 Relations between the damping effect by the dynamic interaction and the frequency ratio (part 1)

the earthquake responses of such structures which have damping devices installed parallel to the interaction springs. The maximum total base shears which appear in the aforementioned analytical models with a variable damping coefficient of " h_i ", are computed and plotted against frequency ratios of each compo-

nent. The maximum total base shears are expressed relative to a standard base shear, which is obtained from a model with a very rigid interaction spring.

Upon itemizing the features of these curves indicating the damping effect based on the adopted range of parameters " γ ", " f ", and " h_i ", the following

Fig. 5-2 Relations between the damping effect by the dynamic interaction and the frequency ratio (part 2)

are noted.

(a) Damping effect is recognized over a wide range of frequency ratios except in the narrow region centered by $\omega_E/\omega_S=1.0$. The width of this non-effective region becomes smaller as the interaction spring becomes weaker.

(b) Damping becomes more effective when the damping coefficient of the damper becomes larger, but there seems to be an upper limit to reduce the maximum total base shear by using intermediate dampers. We consider that this upper limit is around 0.15.

(c) Damping effect becomes apparent when the interaction spring is rather weak; however extremely weak springs do not achieve effective damping. From Fig. 5-1 and 5-2, we see that the optimum rigidity of the interaction spring is around 0.3.

(d) Parameters " γ " and " f " do not substantially influence the damping effect, but when their product is far from unity, the damping effect decreases.

7. Conclusions

Equipment supported by frames like large furnaces, vessels, or towers, is commonly found in modern heavy-industry plants. For the aseismic design of these combined structures, the maximum rocking moments or base shears distributed between these structural components must be precisely determined.

This paper proposes the maximum shared rocking moments induced during earthquakes via a statistical approach which is based on the assumption that a stationary random process follows the probability rule of the normal distribution. The results are presented graphically for several combinations of parameters which determine the dynamic characteristics of each component and the intermediate spring.

Using the same analytical method, the damping

devices installed between the two components is optimized so as to reduce the maximum total response by changing the damping capacity together with the dynamic interaction behavior. These results are also presented graphically and the optimum combination of damping coefficients and spring constants to reduce the total response is found for the combination of each structure.

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