UDC 624.042.7: 534.015

RESPONSE OF BUILDING-MACHINE STRUCTURE SYSTEM SUBJECTED TO TWO DIFFRENT SEISMIC FORCES

2 入力をうける建築・機械系の地震応答

by SATO, Hisayoshi and SUZUKI, Kohei

佐 藤 壽 芳・鈴 木 浩 平

1. Introduction

We have investigated the dynamic behaviour and the aseismic design of a building-machine structure system which is considered as a simple two-degree-of-freedom system with small ratio as in Fig. 1.[1)]

However, the actual system, such as a piping system, a machine structure system as a crane and a civil structure as a bridge system, generally have more than one boundaries which introduce seismic forces to the system directly or indirectly.[2)]

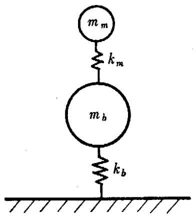

Fig. 1 A model of a simple building-machine structure system.

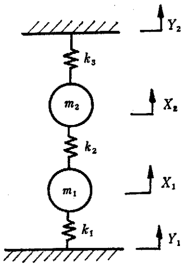

Fig. 2 A model of the machine structure system.

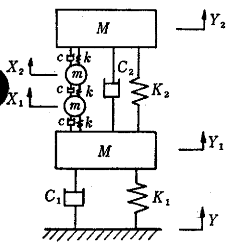

Fig. 3 A model of the building-machine structure system.

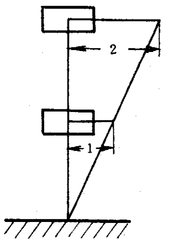

Fig. 4 Mode shape of the first natural frequency for building system.

We have paid attention to this fact and then proposed a model of the system shown in Fig. 3.

Having set up equations of motion, the response characteristics of the system to earthquake records are investigated by electronic analog computer.[3)]

2. Fundamental Equations

As a basic example, we propose the model of two-degree-of-freedom system as shown in Fig. 2. Neglecting damping effect for simplicity, the equations of motion are

$$\begin{cases} m_1\ddot{X}_1+k_1(X_1-Y_1)-k_2(X_2-X_1)=0 & (1) \\ m_2\ddot{X}_2+k_2(X_2-X_1)-k_3(Y_2-X_2)=0 & (2) \end{cases}$$

where X_1, X_2, Y_1, Y_2 are the absolute displacement, m_1, m_2 are the mass and k_1, k_2, k_3 are the stiffness.

(1) and (2) can be transformed as[4)]

$$\begin{cases} m_1(\ddot{X}_1-\ddot{Y}_1)+(k_1+k_2)(X_1-Y_1) \\ \quad -k_2(X_2-Y_1)=-m_1\ddot{Y}_1 & (3) \\ m_2(\ddot{X}_2-\ddot{Y}_1)+(k_2+k_3)(X_2-Y_1) \\ \quad -k_3(X_1-Y_1)=-m_2\ddot{Y}_1+k_3(Y_2-Y_1) & (4) \\ m_1(\ddot{X}_1-\ddot{Y}_2)+(k_1+k_2)(X_1-Y_2) \\ \quad -k_2(X_2-Y_2)=-m_1\ddot{Y}_2+k_1(Y_1-Y_2) & (5) \\ m_2(\ddot{X}_2-\ddot{Y}_2)+(k_2+k_3)(X_2-Y_2) \\ \quad -k_3(X_1-Y_2)=-m_2\ddot{Y}_2 & (6) \end{cases}$$

Then we have not only a term of the acceleration at ends, but also that is based on the relative displacement as the exciting force like $k_3(Y_2-Y_1)$ in (4) and $k_1(Y_1-Y_2)$ in (5). If damping effects exist, we have to add following terms, $c_3(\dot{Y}_2-\dot{Y}_1)$ and $c_1(\dot{Y}_1-\dot{Y}_2)$.

3. The Simple Example of The Building Machine System and Its Response Spectra[5)] to Real Earthquakes by Analog Computer

Now consider the system as shown in Fig. 3. For simplicity, let us make $m_1=m_2=m$, $k_1=k_2=k_3=k$, $c_1=c_2=c_3=c$, $M_1=M_2=M$. Assuming the first mode of the motion for the building as Fig. 4, the relations $K_2/K_1=2/3$, $C_2/C_1=\sqrt{2/3}$ are given.

The equations of motion can be given as

$$\begin{cases} (\ddot{Y}_1-\ddot{Y})+\left(\frac{C_1}{M}+\frac{C_2}{M}\right)(\dot{Y}_1-\dot{Y})+\left(\frac{K_1}{M}+\frac{K_2}{M}\right)(Y_1-Y) \\ \quad -\frac{C_2}{M}(\dot{Y}_2-\dot{Y})-\frac{K_2}{M}(Y_2-Y) \\ \quad =-\ddot{Y}+\gamma\cdot\frac{c}{m}(\dot{X}_1-\dot{Y}_1)+\gamma\cdot\frac{k}{m}(X_1-Y_1) & (7) \\ (\ddot{Y}_2-\ddot{Y})+\frac{C_2}{M}(\dot{Y}_2-\dot{Y})+\frac{K_2}{M}(Y_2-Y) \end{cases}$$

$$-\frac{C_2}{M}(\dot{Y}_1-\dot{Y})-\frac{K_2}{M}(Y_1-Y)$$
$$=-\ddot{Y}+\gamma\cdot\frac{c}{m}(\dot{X}_2-\dot{Y}_2)+\gamma\cdot\frac{k}{m}(X_2-Y_2) \quad (8)$$

$$(\ddot{X}_1-\ddot{Y}_1)+\frac{2c}{m}(\dot{X}_1-\dot{Y}_1)+\frac{2k}{m}(X_1-Y_1)$$
$$-\frac{c}{m}(\dot{X}_2-\dot{Y}_1)-\frac{k}{m}(X_2-Y_1)=-\ddot{Y}_1 \quad (9)$$

$$(\ddot{X}_2-\ddot{Y}_1)+\frac{2c}{m}(\dot{X}_2-\dot{Y}_1)+\frac{2k}{m}(X_2-Y_1)$$
$$-\frac{c}{m}(\dot{X}_1-\dot{Y}_1)-\frac{k}{m}(X_1-Y_1)$$
$$=-\ddot{Y}_1+\frac{c}{m}(\dot{Y}_2-\dot{Y}_1)+\frac{k}{m}(Y_2-Y_1) \quad (10)$$

$$(\ddot{X}_1-\ddot{Y}_2)+\frac{2c}{m}(\dot{X}_1-\dot{Y}_2)+\frac{2k}{m}(X_1-Y_2)$$
$$-\frac{c}{m}(\dot{X}_2-\dot{Y}_2)-\frac{k}{m}(X_2-Y_2)$$
$$=-\ddot{Y}_2+\frac{c}{m}(\dot{Y}_1-\dot{Y}_2)+\frac{k}{m}(Y_1-Y_2) \quad (11)$$

$$(\ddot{X}_2-\ddot{Y}_2)+\frac{2c}{m}(\dot{X}_2-\dot{Y}_2)+\frac{2k}{m}(X_2-Y_2)$$
$$-\frac{c}{m}(\dot{X}_1-\dot{Y}_2)-\frac{k}{m}(X_1-Y_2)=-\ddot{Y}_2 \quad (12)$$

(7) and (8) are as for the building, (9), (10), (11) and (12) are as for the machine structure. Both systems are connected with each other by only boundary conditions which are the second and third term of the right side in (7) and (8), and that in (10) and (11). $\gamma=m/M$ means mass ratio of the machine structure to the building. $\gamma=0$ means that the building system has no force reaction from the machine system. When $\gamma\neq0$, reactions with form of $\gamma(c/m)(\dot{X}-\dot{Y})$ and $\gamma(k/m)(X-Y)$, exist.

So these equations can be transformed into the normal coordinate. For example, (9) and (10) are

$$\ddot{\xi}_{m1}+\frac{c}{m}\dot{\xi}_{m1}+\frac{k}{m}\xi_{m1}$$
$$=\frac{\sqrt{2}}{2}\{-2\ddot{Y}_1-c(\dot{Y}_1-\dot{Y}_2)-k(Y_1-Y_2)\} \quad (13)$$

$$\ddot{\xi}_{m2}+\frac{3c}{m}\dot{\xi}_{m2}+\frac{3k}{m}\xi_{m2}$$
$$=\frac{\sqrt{2}}{2}\{c(\dot{Y}_1-\dot{Y}_2)+k(Y_1-Y_2)\} \quad (14)$$

where ξ_{m1} and ξ_{m2} are normal coordinate and

$$X_1-Y_1=\frac{\sqrt{2}}{2}\xi_{m1}+\frac{\sqrt{2}}{2}\xi_{m2} \quad (15)$$

$$X_2-Y_1=\frac{\sqrt{2}}{2}\xi_{m1}-\frac{\sqrt{2}}{2}\xi_{m2} \quad (16)$$

Building system can be also normalized independent of machine system.

This normalized form is effective to observe the first or second mode of motion separately.

Now we investigate the response characteristics to actual earthquake records for this system by the electronic analog computer. As the records, El Centro (May, 1940. NS, U.S.A.) and Taft (July, 1952. NS, U.S.A.) are used.[6] 0.33 g for El Centro and 0.3 g for Taft are taken for their maximum acceleration.

As the typical example of constants, $\gamma=0$, 0.01, 0.1, $h_b=0.05$, $h_m=0.007$, 0.02, 0.1, 0.2 are used, where the suffix m, b mean machine and building respectively, h_b, h_m are damping ratio to critical damping.

Now let T_b be the natural period for the first mode of the building system, T_m that of the machine structure system. So Fig. 5 through Fig. 7 show the displacement and the acceleration spectra to El Centro and Taft earthquakes.

About curves of the spectra $T_b=0.2$, 0.4, 0.6, 1.0, 1.6 sec in Fig. 7, the ratio of the maximum acceleration of the response to the maximum ground acceleration shows a sharp peak at every $T_b=T_m$. This tendency is conspicuous especially in shorter period as $T_b=0.2$, 0.4, 0.6 sec.

As for the relative displacement, $T_b=T_m$ also makes peaks in the spectrum. However, the peak value is greater in longer period as in Fig. 5 and Fig. 6.

These results show that the coincidence of both structure periods ($T_b=T_m$) should be evaded at first from the view point of the aseismic design of the machine-structure.

So Fig. 9 shows the response of acceleration and displacement connecting such the worst conditions $T_b=T_m$. h_m is selected as parameter. Let us call this graph "T_b-T_m response spectrum."

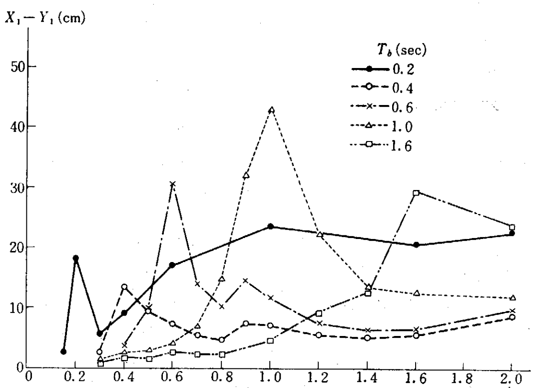

Fig. 5 Displacement response spectrum for El Centro ($h_b=0.05$, $h_m=0.02$, $\gamma=0$)

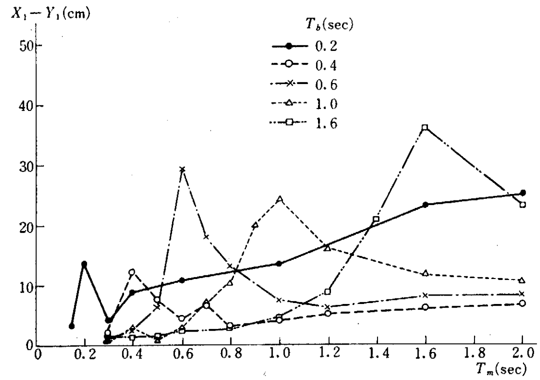

Fig. 6 Displacement response spectrum for Taft (h_b=0.05, h_m=0.02, γ=0)

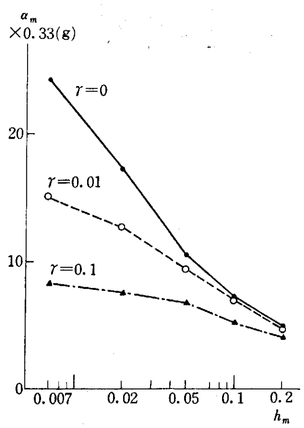

Fig. 8 Reration between α_m and h_m for $T_b=T_m$=0.4 sec (El Centro, h_b=0.05)

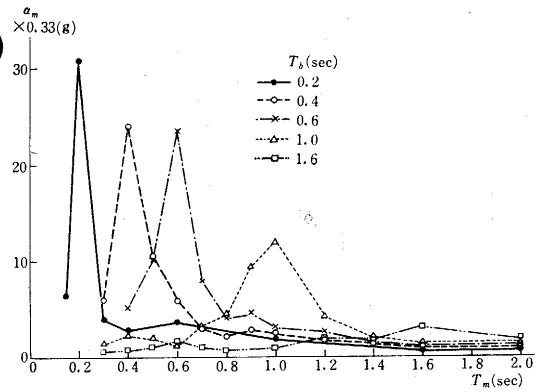

Fig. 7 Acceleration responce spectrum for El Centro (h_b=0.05, h_m=0.02, γ=0)

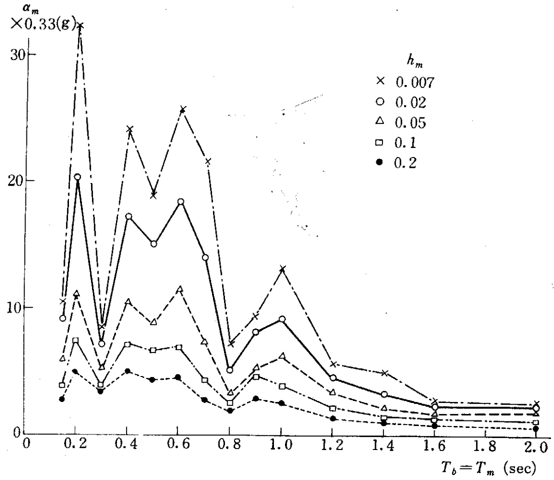

Fig. 9 T_b-T_m acceleration response spectrum (El Centro, γ=0.01, h_b=0.05)

4. Conclusion and Acknowledgement

So these analyses give us following results.

(1) The equations of motion for the building and machine systems can be analyzed by making terms based on the relative displacement and velocity as exciting forces.

(2) $T_b=T_m$ is the worst condition especially in shorter period about the acceleration, in longer period about the displacement.

(3) The T_b-T_m acceleration spectra have sharp peaks at $T_b=T_m$=0.2, 0.4, 0.6 sec and decrease with period as in Fig. 9, but that of the displacement response spectra increase with period.

(4) When h_m is large, the value of the response is small as in Fig. 8.

(5) With the large mass ratio, the response is small as in Fig. 9.

In closing the authors would like to express their sincere thanks to Professor Umemura who kindly allowed to use earthquake records for SERAC and to professors Fujii, Watari and Shibata for their fruitful advices and encouragements.

(Manuscript received July 19, 1968.)

Reference

1) H. Sato: On the Response Spectrum of the Machine Structure System to the Strong Motion Earthquake. Bull. of JSME. Vol. 9, No. 36, 1966.

2) K. Nakagawa and others: Preliminary Study on Modal Analysis of Response of a Structure Subjected to two Different Earthquake Motions at its Two Supporting Points. International Institute of Seism. and Earthq. Engg. Aug. 1967.

3) H. Sato and K. Suzuki: On the Response of Multi-Degree-of-Freedom System Subjected to Two Seismic Motions (In Japanese). A Report to the Sub-Committee of Studying the Method of Aseismic Design for Nuclear Reactor in JSME, Jan. 1968.

4) Y. Hayashi: Unpublished paper. Same equations are given and discussed independently,

5) G. W. Housner and others: Spectrum Analysis of Strong Motion Earthquakes. Bull. Seism. Soc. Am., Vol. 43, No. 2, April. 1953.

6) SERAC: Non-linear Response Analysis of Tall Buildings to Strong Earthquake and its Application to Dynamic Design No. 1～No. 6 (1962～1966)