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Seismic response control by 'mode(s)-isolation' method
Part I: Control method and its verification experiments

S. Ishimaru & T. Niiya
College of Science and Technology, Nihon University, Tokyo, Japan

N. Yamaguchi
Office of New Frontier Engineering, Takenaka Corporation, Tokyo, Japan

M. Kawakubo
Technological Research Center, Tokyo Construction Co., Ltd, Kanagawa, Japan

ABSTRACT : A design method is proposed to make a MDOF structure to be controlled in the state of the selected single mode of vibration during earthquakes. Then, in order to verify the method, the experiment for the steel model designed by the proposed method is carried out by shaking table test and the method is verified to be proper. In general, a MDOF structure complicately behaves in the state superposed by the modal response values for various modes of vibration, which gives difficulty in designing actively/passively controlled structures. This paper is made in order to overcome this problem.

1. INTRODUCTION

Over the last decade, information-oriented society has been becoming bigger and bigger, which situation causes an urgent social demand for developing seismic design methods which can not only gurantee human lives but also keep such important equipments as computer in good conditions. Because the conventional seismic design methods pay attention for nothing but the safety of structures. Therefore, it is natural that control problems of structures to reduce seismic responses have attracted increasingly interest and importance. Thus, a lot of approaches for structures with passive and/or active devices have been conducted in simulations and experiments, which were reviewed by Izumi (1988) and Kobori (1988), respectively, However, most of them have focused control systems subjected to weak but frequent earthquakes and wind disturbance, because of extraordinaly energy required in the case of severe earthquakes.

This study was made in order to solve this problem. The control strategy is a new method refered to as the "mode(s)-isolation" which can be achieved by taking advantage of the characteristics that earthquake energy is always inputed from the base of building structures.

2. CONCEPT OF MODE(S)-ISOLATION

The main objective of the presented design algorithm is to make MDOF systems behave as SDOF systems during earthquakes. A brief explanation is given, as an exact proof was given in the paper by Ishimaru (1990). The equation of motion for a MDOF system subjected to seismic excitations is expressed as follows ;

$$[m]\{\ddot{d}\}+[c]\{\dot{d}\}+[k]\{d\}=-[m]\{i\}\ddot{y} \qquad (1\text{-}1)$$

where [m], [c], [k] are the mass matrix, the viscous damping coefficient matrix and the stiffness matrix, respsectively. {d} is the vector of story drifts relative to the base and {i} is the location vector of seismic excitation $\ddot{y}$. And the modal displacement q_j for the j-th mode is expressed as follows ;

$$\ddot{q}_j+2h_jw_j\dot{q}_j+w_j{}^2q_j=-\ddot{y} \qquad (1\text{-}2)$$

where h_j and w_j are the viscous damping ratio and natural circular frequency for the j-th mode, respectively.

Assuming that the system can be controlled to behave as a SDOF structure, holding the mode shape {i} which equals to the j-th mode shape $\{r_j\}$, the vector of story displacement {d} can be described as follows ;

$$\{d\}=\{i\}q_j \quad (1-3)$$

where $\{r_j\}$ is the j-th mode shape normalized by the participation factor.

Substituting Eq. (1-3) into Eq. (1-1), then multiplying the both sides of the equation by $[m]^{-1}$ gives

$$\{i\}\ddot{q}_j+[m]^{-1}[c]\{i\}\dot{q}_j+[m]^{-1}[k]\{i\}q_j = -\{i\}\ddot{y} \quad (1-4)$$

Equating Eq. (1-4) to the equation multiplyed Eq. (1-2) by the vector {i}, the following equations can be obtained under the condition that Eq. (1-7) holds.

$$2h_jw_j[m]\{i\}=[c]\{i\} \quad (1-5)$$

$$w_j{}^2[m]\{i\}=[k]\{i\} \quad (1-6)$$

$$\{i\}=\{r_j\} \quad (1-7)$$

If the matrices [m], [c], [k] and {i} are adjustable and Eq. (1-7) holds, the participation factors can be computed by taking account of Eq. (1-7) as follows.

$$\left.\begin{aligned} \alpha_j &= \frac{\{r_j\}^T[m]\{i\}}{\{r_j\}^T[m]\{r_j\}} = 1 \\ \alpha_m &= \frac{\{r_m\}^T[m]\{i\}}{\{r_m\}^T[m]\{r_m\}} = 0 \quad (j \neq m) \end{aligned}\right\} \quad (1-8)$$

The above results mean that the other vibration modes except the j-th mode do not be generated. Namely, a pseudo SDOF structure with "mode(s)-isolation" except the specified j-th mode, can be achieved.

3. APPLICATION OF PRESENTED ALGORITHM

In the conventional structures, the elements of vector {i} have the constants 1.0, namely, $\{i\}^T=\{1,1,\cdots,1,1\}$ which does not coincide with the j-th mode shape unless controlling passively and/or actively.

It is the simplest method, taking no account of required control energy, to actively control in realizing the pseudo SDOF structures.

Let describe the equation of motion of the target structure as follows.

$$[m_u]\{\ddot{d}\}+[c_u]\{\dot{d}\}+[k_u]\{d\}-\{f\} = -[m_u]\{i_u\}\ddot{y} \quad (1-9)$$

where {f} is the control force vector.

Now, express the equation of motion for the ideal model which an engineer wants to control as follows.

$$[m_c]\{\ddot{d}\}+[c_c]\{\dot{d}\}+[k_u]\{d\} = -[m_u]\{i\}\ddot{y} \quad (1-10)$$

where the vector {i} is assigned desirable values. Furthermore, the elements of matrices $[m_c]$ and $[c_c]$ are decided in the manner of satisfying Eqs. (1-11) and (1-12), in which the damping ratio h is also specified by the engineer.

$$2hw[m_c]\{i\}=[c_c]\{i\} \quad (1-11)$$

$$w^2[m_c]\{i\}=[k_u]\{i\} \quad (1-12)$$

Thus, the control force can be obtained by subtracting Eq. (1-9) from Eq. (1-10).

$$\{f\}=([m_u]-[m_c])\{\ddot{d}\}+([c_u]-[c_c])\{\dot{d}\} \\ ([m_u]\{i_u\}-[m_c]\{i\})\ddot{y} \quad (1-13)$$

It is needless to say that the amounts of the required control force depend on the assigned values for the vector {i}.

Fig. 1-1 demonstrates an example of the passively controlled system. This consists of a nominal four storied structure and a rigid core wall which is erected in the manner of structurally separating from each floor. This can be changed into two DOF structure and controlled to make the structure behave as the SDOF system as follows. As shown in the figure, the even number floors are supported by the columns, and the odd number floors are suspended from the just above even number ones, which combination makes 2 structural pairs composed of 2 floors. The paired floors are connected by the lever which is pivotally attached on the core wall through the links. And viscous dampers are equiped between the odd number floors and core wall.

Accordingly, the odd number floors are moved by the quantity $a_i d_i$ which is propotional to the displacement of the 2i-th floor relative to the base, d_i, in which a_i means the arm-moment ratio of the i-th lever. When the masses of floors are indicated as m_{d1}, m_1, m_{d2}, m_2, the stiffness of columns as k_1, k_2 and the viscous damping coefficients of the dampers as c_1, c_2, the equation of motion become as follows ;

$$[m]\{\ddot{d}\}+[c]\{\dot{d}\}+[k]\{d\}=-[m]\{i\}\ddot{y} \qquad (1\text{-}14)$$

where

$$[m]=\begin{bmatrix} m_2+m_{d2}a_2^2 & \\ & m_1+m_{d1}a_1^2 \end{bmatrix} \qquad (1\text{-}15)$$

$$[c]=\begin{bmatrix} c_2a_2^2 & \\ & c_1a_1^2 \end{bmatrix} \qquad (1\text{-}16)$$

$$[k]=\begin{bmatrix} k_2 & \\ & k_1 \end{bmatrix} \qquad (1\text{-}17)$$

$$\{i\}=\begin{Bmatrix} (m_2+m_{d2}a_2)/(m_2+m_{d2}a_2^2) \\ (m_1+m_{d1}a_1)/(m_1+m_{d1}a_1^2) \end{Bmatrix} \qquad (1\text{-}18)$$

It can be seen that the elements of Eqs. (1-15), (1-16) and (1-18) are the functions with respect to a_1 and a_2. Therefore, tuning these elements in the manner of satisfying Eqs. (1-5) and (1-6), the mode(s)-isolation except the specified mode is realized without any active control energy.

The vector {i} cannot be arbitrarily decided, because the vector {i} is not independent from the matrix [m]. However, the elements of {i} can be confined within less than 1, which situation leads the response reduction.

4. THE SHAKING TABLE TESTS TO VERIFY THE PRESENT DESIGN ALGORISM

Fig. 1-2 shows the specimen of passively controlled system. The almost all parts of the specimen are steel, but suspenders are

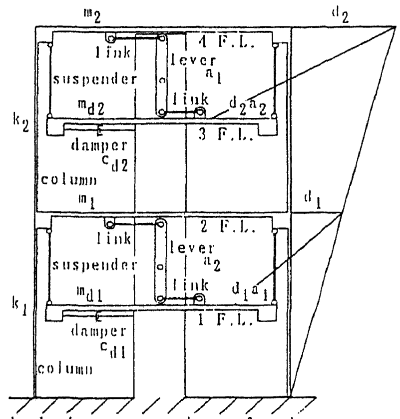

Fig. 1-1 An example of the passively controlled structure utilizing the presented method

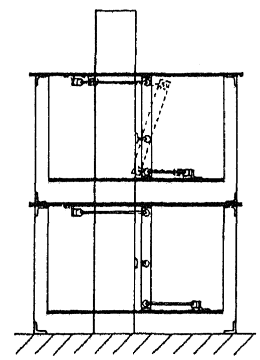

Fig. 1-2 Specimen of the passively controlled system

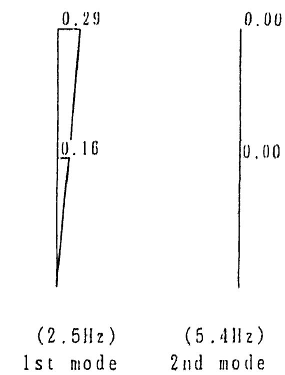

Fig. 1-3 participation vectors of the passively controlled system excited by seismic motions

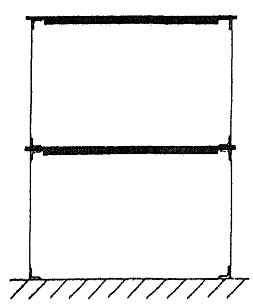

Fig. 1-4 Specimen of the no control system

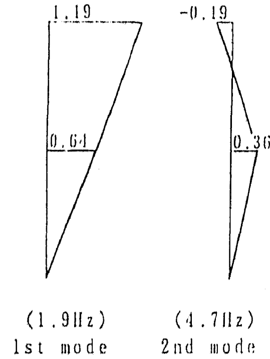

Fig. 1-5 participation vectors of the no control system excited by ground motions made of the vinyl plastic sheet. The physical properties of the specimen are listed in the Table 1-1 and the mode shapes excited by seismic motions are indicated in Fig. 1-3.

Fig. 1-4 shows the no control specimen which is constructed by fixing the odd number floors to the just above even number floors. Table 1-2 is the list for the no-control system and Fig. 1-5 expresses the 1st and 2nd mode shapes of the system.

Fig. 1-6-(a) and (b) are the result of the shaking table test for the 50[%] scaled El Centro (1940), N-S on the passively controlled structure and the one of no control structure, respectively. They show the relationships between the values of $\ddot{d}_2$ and $\ddot{d}_1$. Comparing both diagrams, it is clear that the result for the no control structure has complicate motions, and this fact means that the first mode vibration and the second one are simultaniously excited. On the contrary, the result of the passively controlled structure is formed by simple linear line. This means that the structure behaves as the SDOF system holding the specified mode.

Moreover, comparing the maximum response values of both models, it is evident that the passively controlled structure have the sufficient effect to reduce the seismic response.

5. CONCLUSIONS

The "mode(s)-isolation" control algorithm was proposed so as to realize such the structure that behaves in the state of the SDOF system with the specified mode. And the shaking table tests verified that the present method precisely holds and the reducing effect of seismic responses depends on the tuning values for the elements of location vector {i}.

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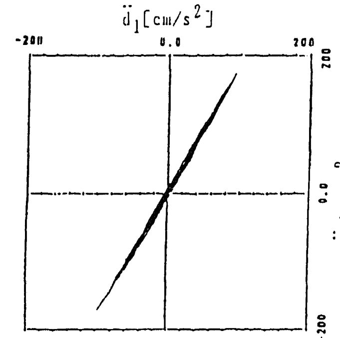
Table 1-1 physical properties of the passively controlled system

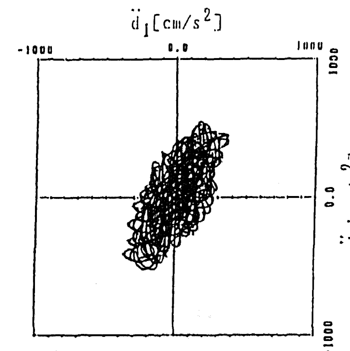
Properties	1st story	2nd story
Main mass [Kg]	5.00	5.00
Aux. Mass [Kg]	5.00	5.00
Stiffness [N/cm]	55.1	36.8
Arm-moment ratio	-0.749	-0.600

Table 1-2 physical properties of the no control system

Properties	1st story	2nd story
Mass [Kg]	10.0	10.0
Stiffness [N/cm]	43.7	33.1



(a) passively controlled system



(b) no control system

Fig. 1-6 Relationships between the response accelerations of $\ddot{d}_2$ and $\ddot{d}_1$ of the shaking table tests