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Seismic response control by 'mode(s)-isolation' method
Part II: Control of a tall building by tuned multi-masses damper system

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ABSTRACT : This paper presents a new structure system to reduce responses of the system subjected to from weak earthquaks to severe ones. The system consists of main structure and sub-system, installed on the main structure, regulated by model following control rule. The sub-system consists of floor weights of plural stories from the uppermost floor of the structure utilized as an auxiliary mass, and the lever system connected between the both systems. The shaking table tests show that for severe earthquakes, the system can sufficiently reduce responses without active control energy, and for weak earthquakes, the behavior of the system is smoothed by actively controlling undesirable motion of the integrated sub-system due to inevitable frictional force generated in the lever system.

1. INTRODUCTION

This paper presents a new control system for tall building, reffered to as a tuned multi-masses damper (TMMD) system. It is very clear that conventional TMD systems can not effectively suppress seismic responses of tall buildings subjected to severe earthquakes, because auxirialy mass ratios to the main structures are very small. From the point of view, the method is proposed to increase the above ratios by taking advantage of floor weights of plural stories from the uppermost floor of the structure as a sub-system, i.e., TMD system. Furthermore, the sub-system is passively/actively controlled by providing the lever system with added masses introduced in Part I of the paper. Thus, the system is able to meet the demand that the smaller motions of sub-system is better without deteriorating the effect of seismic response reduction, because the sub-system is also utilized as resident space.

2. COMPOSITION OF TMMD STRUCTURES

Fig. 2-1 shows a schematic diagram to illustrate the concept of the proposed structure. The sub-system utilized as TMD consists of plural storied structure from

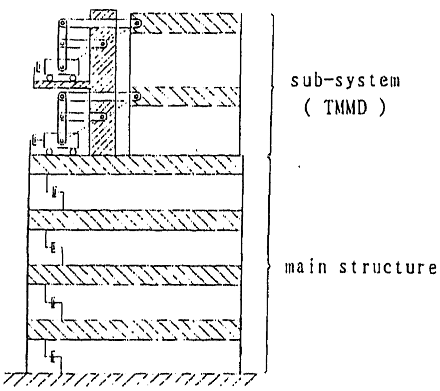

Fig. 2-1 Schematic diagram of TMMD

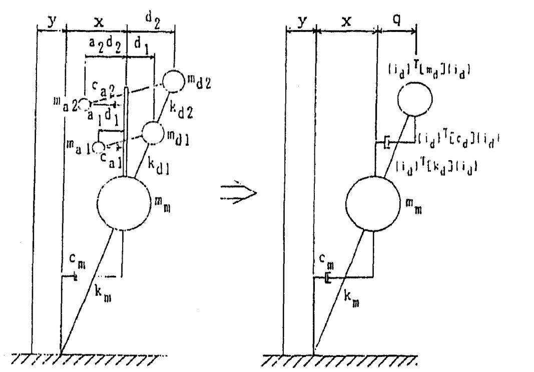

Fig. 2-2 Mathematical model

the uppermost floor, the wall system erected separetely from the previous multi-storied system and the lever systems with added masses which are pivotly connected between the wall and the floors. This sub-system is passively controlled by making use of the "mode(s)-isolation" method, so that the sub-system can behave as a pseudo SDOF structure. Therefore, the system is reffered to as a tuned multi-masses damper (TMMD) system, because of utilizing plural auxiliary masses as a TMD system.

Fig. 2-2 illustrates the mathematical model of the presented system. Taking care that the excitation introduced into TMMD system is the value $(\ddot{x}+\ddot{y})$ as shown in Fig. 2-2, the equation of motion of the system can be expressed by Eqs. (2-1)-(2-2), as illustrated in Part I. And the parameters of TMMD system are determined in the manner of satisfying Eqs. (2-3) and (2-4) to realize the "mode(s)-isolation".

Using the modal displacement q expressed by Eq. (2-5) with natural circular frequency w_d and damping ratio h_d, the behavior of TMMD system can be expressed by Eq. (2-6). Accordingly, the equation of motion of the integrated system can be expressed by Eqs. (2-7)-(2-13), because of the story drifts of the integrated system has two degrees of freedom, as expressed by Eq. (2-7).

Pay attention that these equations hold even if TMMD system consists of a SDOF system having the lever system, whose location vector becomes a scalar with $(m_{d1}+m_{a1}a_1)/(m_{d1}+m_{d1}a_1{}^2)$.

Thus, the natural circular frequency and damping ratio to reduce the response of the integrated system can be obtained by the conventional method such as "PQ points theory" presented by Ormondroyd (1928).

$$[m_d]\{\ddot{d}\}+[c_d]\{\dot{d}\}+[k_d]\{d\} = -[m_d]\{i_d\}(\ddot{x}+\ddot{y}) \quad (2\text{-}1)$$

$$\{d\}^T=\{d_2 \ , \ d_1\} \quad (2\text{-}2)$$

$$w_d{}^2[m_d]\{i_d\}=[k_d]\{i_d\} \quad (2\text{-}3)$$

$$[c_d]\{i_d\}=2h_d w_d[m_d]\{i_d\} \quad (2\text{-}4)$$

$$\ddot{q}+2h_d w_d \dot{q}+w_d{}^2 q=-(\ddot{x}+\ddot{y}) \quad (2\text{-}5)$$

$$\{d\} = \{i_d\}q \quad (2\text{-}6)$$

$$\{x\}=\begin{Bmatrix} d_1 \\ d_2 \\ x \end{Bmatrix} = \begin{bmatrix} \{i_d\} & \begin{matrix} 0 \\ 0 \end{matrix} \\ & 1 \end{bmatrix} \begin{Bmatrix} q \\ x \end{Bmatrix} \quad (2\text{-}7)$$

$$[m_c]\{\ddot{x}_c\}+[c_c]\{\dot{x}_c\}+[k_c]\{x_c\} = -[m_c]\{i_c\}\ddot{y} \quad (2\text{-}8)$$

$$\{x_c\}^T=\{q \ , \ x\} \quad (2\text{-}9)$$

$$\{i_c\}^T=[0 \ , \ 1] \quad (2\text{-}10)$$

$$[m_c]=\begin{bmatrix} \{i_d\}^T[m_d]\{i_d\}, & \{i_d\}^T[m_d]\{i_d\} \\ \{i_d\}^T[m_d]\{i_d\} & m_m \end{bmatrix} \quad (2\text{-}11)$$

$$[c_c]=\begin{bmatrix} \{i_d\}^T[c_d]\{i_d\}, & 0 \\ 0 & c_m \end{bmatrix} \quad (2\text{-}12)$$

$$[k_c]=\begin{bmatrix} \{i_d\}^T[k_d]\{i_d\}, & 0 \\ 0 & k_m \end{bmatrix} \quad (2\text{-}13)$$

3. OUTLINE OF MODEL FOLLOWING CONTROL RULE

The model following control rule is the algorithm to make the responses of a plant (i.e. system to be controlled) trace to the ones of a reference model. Although a theory including a optimal control rule was presented by Asseo (1970), a primitive style algorithm is adopted in this paper to reduce the computation load of controllers.

Fig. 2-3 illustrate the concept of the model following control rule applied to a SDOF system. Now, the plant is assumed to a gray-box system whose parameters can not be exactly identified. On the other hand, the

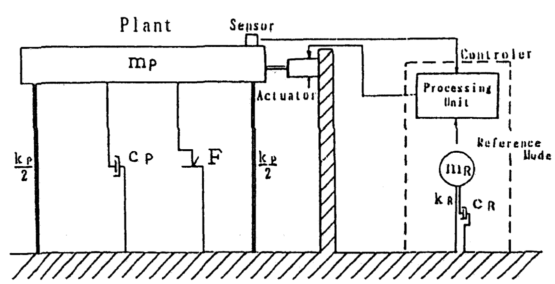

Fig. 2-3 Concept of the model following control rule

controller is constituted by two sytems, one of them is a simulator of the reference model which has desirable parameters, and the other is a part to compute control force from the difference between the responses of the plant and the ones of the reference model. The merit brought by the above constitution is that the decision of gains of controller depends only on the response-differences of both models, while in applying any other algorithms such as the pole assignment method or the optimal regulator method, etc., the gains for a gray-box can not be determined.

Fig. 2-4 illustrates the block chart ,in which the symbol "?" in the feedbackgains of the plant expresses a gray-box system. In this study, the control driver is designed in the manner of tracking the responses of the reference model by making use of the required control force, namely, by the so-called force control mechanism. In addition to this, for simplicity, the control driver is constituted by two gains, the feedback gain Hv and the feedforward gain Gv, which are designed to work propotionally to the response velocities.

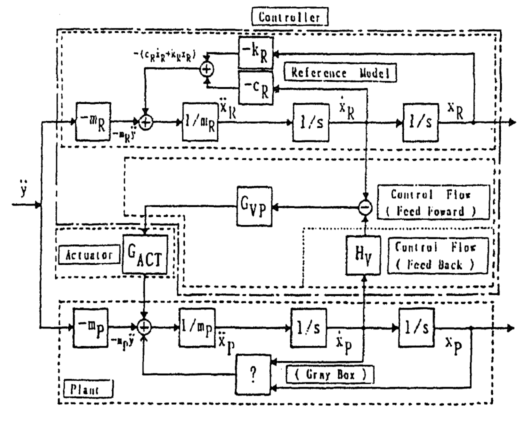

Fig. 2-4 Block chart of the model following control rule

4. SHAKING TABLE TESTS

The shaking table tests are carried out in order to verify the control effect and the robustness in the case of a not well-tuned TMMD system. The performace of the hybrid TMMD (HTMMD) is also examined, which is actively controlled by the model following control rule mentioned above.

Fig. 2-5 illustrates the specimen whose structural parameters are listed in Table 2-1. The specimen is a ten storied structure made of steel. TMMD sysyem consists of the three floors unified with braces and the control apparatus which is constituted by the levers with auxiliary mass and the actuator driven by the AC servo motor through ball screw as shown in Fig. 2-6. The dynamic characteristics of TMMD system are listed in Table 2-2.

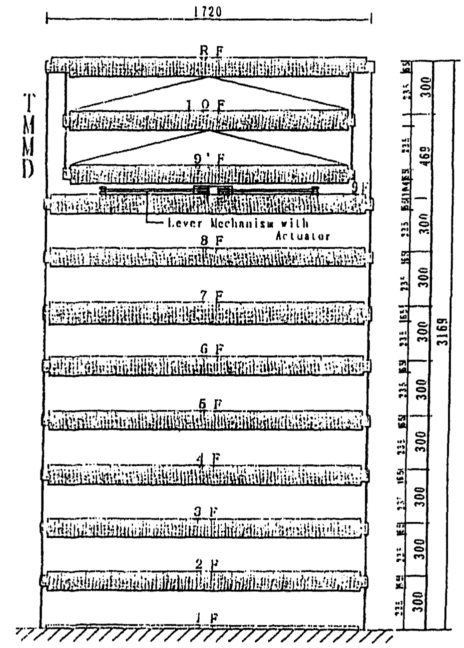

Fig. 2-5 Specimen of the shaking table tests

Prior to the shaking table tests, the frictional resistance of the control apparatus is identified as about 147[N] at the location of the auxiliary mass, which is equivalent to the restraining force of 0.04 times the weight of TMMD system. Table 2-2 indicates the optimal natural circular frequency and the optimal damping ratio of TMMD system, whose optimal frequency is samller about 60[%] than one of the real

Table 2-1 Structural parameters of the specimen of the shaking table tests

Story	Mass [Kg]	Stiffness [N/cm]	Story	Mass [Kg]	Stiffness [N/cm]
R FL	1.46	Fixed	6 FL	1.22	1800
10 FL	1.43	Fixed	5 FL	1.23	2900
9' FL	1.60	429	4 FL	1.24	2850
9 FL	3.53	1950	3 FL	1.24	2800
8 FL	1.22	1910	2 FL	1.24	2750
7 FL	1.22	1840			

system, which situation would lead the deterioration of control effect in the case of conventional TMD systems.

Table 2-3 lists the results of the shaking table tests forcusing on the maximum response displacements relative to base subjected to the 80[%] scale reduction of Hachinohe (1968), N-S. At the first, the no control structure is examined, which is constructed by fastening the TMMD to the main structure, and the passively controlled test is carried out for the system with the not well-tuned TMMD, and then, the hybridly controlled test is carried out for the above system controlling in the state of the optimal-tuned TMMD.

The both passively/actively controlled structures show the equivalent control effects of about 47[%] response reduction, which indicates that the active control is not necessarily required, even if the passive TMMD system is not well tuned. In other words, the tests approve the high robustness of TMMD systems.

Fig. 2-7 demonstrates the time histories of the displacement of the 9'th floor relative to 9th floor (the top floor of the main structure) in the cases of the passively controlled situation and hybridly controlled one, when the models are subjected to the 10[%] sacle reduction of the same accelerogram. The dash-dotted line is the result for the passive-control situation, and the solid line for the active-control one. It can be seen that the former is restrained due to the existence of frictional force, while the latter behaves smoothly because that the frictional resistance is eliminated by the control action.

5. CONCLUSION

TMMD system controlled by the "mode(s)-isolation" method is presented to provide high auxiliary mass ratio of TMD. The results of shaking table tests show that the proposed passive system has not only the sufficient effect of the response reduction for large amplitude vibration but also the the high robustness even if the system does not be well-tuned. Furthermore, utilizing active control with model following control rule, HTMMD system can behave smoothly for small amplitude vibrations even if frictional forces exist.

Table 2-2 Dynamic characteristics of TMMD

Auxiliary mass [Kg]	4.50
Added mass [Kg]	0.798
Arm-moment ratio of lever	2
Stiffness [N/cm]	429
Frequency (Optimal) [Hz]	1.19(0.72)
Rated thrust of actuator [N]	540

Table 2-3 Maximum displacements for the 80[%] scaled of Hachinohe (1968), N-S

Story	No con. Disp. [cm]	Passive con. Disp. [cm]	Passive con. Ratio* [%]	Hybrid con. Disp [cm]	Hybrid con. Ratio* [%]
R FL	13.5	9.49	29.7	10.8	20.4
9 FL	14.0	7.66	45.4	7.71	45.0
7 FL	10.3	5.82	43.4	4.78	53.5
5 FL	6.34	4.10	35.3	3.48	45.1
3 FL	3.64	2.45	32.7	2.09	42.6

Ratio=100{(No con.)-(With con.)}/(No con.)

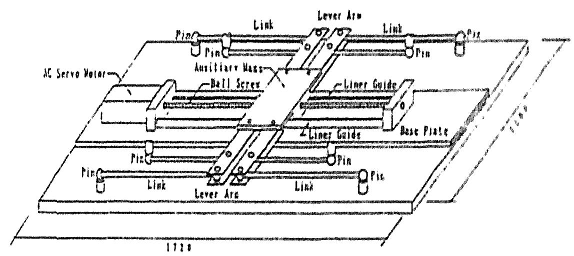

Fig. 2-6 Control apparatus

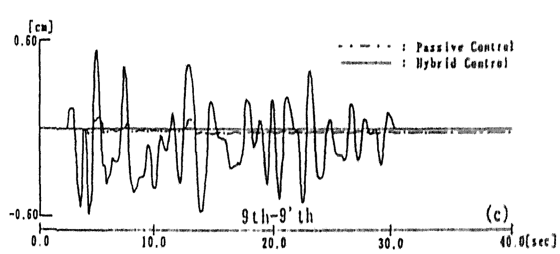

Fig. 2-7 Time histories of the displacement of 9'th floor relative to 9th floor for the 10[%] scaled Hchinohe (1968), N-S

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