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Seismic response of offshore platform with TMD

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ABSTRACT: For any offshore structure located in a seismically active region, random sea waves and earthquake ground motions are two main design loads. An offshore structure will interact not only with the surrounding water and sea waves but also with the subsoil. The exact evaluation of dynamic response is important for the reliable design of structures. If the dynamic response of an offshore structure can be reduced by using TMD (Tuned Mass Damper) system which in some cases has the active control force, the reliability of the structure is enhanced. In the present research, the effects of TMD system on the dynamic response of an offshore platform are examined for seismic input. It is shown that the TMD system is effective in controlling the dynamic response of the offshore structure.

1 INTRODUCTION

Seismic force is one of the most important excitations for the dynamic response of an offshore structure. Numerous researches about the seismic response analysis of offshore structures have been carried out in the past (for example, Bea 1979, Penzien et al 1972, Venkataramana et al 1988). The random-vibration approach provides good evaluations of the responses because of the probabilistic properties of seismic motions. In order to perform the reliable design of offshore structure, it is important to carry out not only the exact evaluation of the dynamic response but also to examine the ways of reducing the response. The development of the system which can reduce the dynamic response gives important roles in enhancing the safety of offshore structures. The vibration control of structures is nowadays one of the most interesting and promising topics on civil engineering structures (Yang et al 1987, Sato et al 1990). In the present study, the seismic analysis of a jacket-type offshore structure with TMD system is carried out and the effects of active control force on the responses are examined using the time domain analysis.

2 DYNAMIC RESPONSE ANALYSIS METHOD

2.1 The governing equation of motion

Fig.1 shows the analytical model of an offshore structure with TMD system resting on the deck. The equation of motion is obtained by the substructure method in which the structure-pile-soil system is hypothetically divided into the superstructure and the pile-soil foundation system. The displacement of the structure can be expressed as the sum of the dynamic displacement of the structure on a fixed base, and the quasi-static displacement due to the interactions with the foundation. The dynamic displacements of the fixed-base structure with TMD system are represented with a linear combination of the first few vibrational modes which have significant effects on the response. The dynamic stiffness coefficients of the pile-soil foundation are expressed in simplified form using frequency-independent impedance functions. The equation of motion for the structure-pile-soil system is obtained by combining the equations of

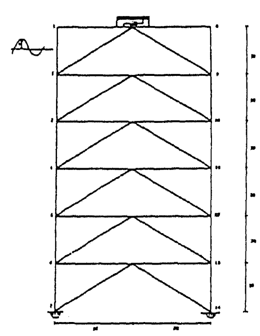

Fig.1 Analytical model of offshore structure

motion for the superstructure and the pile-soil foundation and by satisfying the compatibility conditions of the displacements and the equilibrium conditions of forces at the base nodal points. Finally the dynamic equation of motion for the offshore structure with TMD system subjected to active control force $u(t)$ is expressed as

$$\begin{bmatrix} [I] & [\tilde{M}_{ap}] \\ [\tilde{M}_{pa}] & [\tilde{M}_p] \end{bmatrix} \begin{Bmatrix} \{\ddot{q}\} \\ \{\ddot{x}_p\} \end{Bmatrix} + \begin{bmatrix} [\diagdown 2\beta_{fj}\omega_{fj}\diagdown] & [\tilde{C}_{ap}] \\ [\tilde{C}_{pa}] & [\tilde{C}_p] \end{bmatrix} \begin{Bmatrix} \{\dot{q}\} \\ \{\dot{x}_p\} \end{Bmatrix} + \begin{bmatrix} [\diagdown \omega_{fj}^2 \diagdown] & [0] \\ [0] & [\tilde{K}_p] \end{bmatrix} \begin{Bmatrix} \{q\} \\ \{x_p\} \end{Bmatrix} = -\begin{bmatrix} [P_a] \\ [P_b] \end{bmatrix} \{\ddot{z}_g\} + \{\tilde{B}\} u \quad (1)$$

where

$$\begin{bmatrix} [P_a] \\ [P_b] \end{bmatrix} = \begin{bmatrix} [\Phi]^T[\tilde{M}_{aa}][L][G] \\ [G]^T \left[[L]^T[\tilde{M}_{aa}][L] + [M_{bb}]\right][G] \end{bmatrix}$$

$$[\tilde{M}] = [M] + [C_A], \quad [\tilde{C}] = [C] + [C_D]$$

$$\{x_a\} = [\Phi]\{q\}, \quad \{\tilde{B}\} = [\Phi]^T\{B_f\}$$

in which $[I]$ is the unit matrix, $[L]$ is the quasi-static transformation matrix, $[\Phi]$ is the modal matrix of the undamped superstructure, $[\diagdown \beta_{fj} \diagdown]$ is the corresponding damping ratio which includes both the structural damping and the hydrodynamic damping, $[C_A]$ is the added mass matrix, vector $\{B_f\}$ denotes the locations where the control forces act, $\{\ddot{z}_g\}$ is the ground acceleration due to seismic motion and $[G]$ denotes the connection between the pile-heads and the base nodes of the superstructure.

2.2 Determination of the active control force

The governing equation of motion of offshore structure can be represented with the degrees of freedom of the first few vibrational modes of the superstructure and the pile-soil system as expressed in Eq.(1). This equation of motion can be solved by the mode superposition method. Using the eigenvalue analysis of the undamped system, Eq.(1) can be expressed as

$$\{\ddot{y}\} + [\diagdown 2\beta_j\omega_j \diagdown]\{\dot{y}\} + [\diagdown \omega_j^2 \diagdown]\{y\} = \{f\}\ddot{z}_g + \{B\}u(t) \quad (2)$$

in which

$$\begin{Bmatrix} \{q\} \\ \{x_p\} \end{Bmatrix} = [\Psi]\{y\}, \quad [\Psi]^T \begin{bmatrix} [I] & [\tilde{M}_{ap}] \\ [\tilde{M}_{pa}] & [\tilde{M}_p] \end{bmatrix} [\Psi] = [I]$$

$$[\Psi]^T \begin{bmatrix} [\diagdown 2\beta_{fj}\omega_{fj}\diagdown] & [\tilde{C}_{ap}] \\ [\tilde{C}_{pa}] & [\tilde{C}_p] \end{bmatrix} [\Psi] = [\diagdown 2\beta_j\omega_j \diagdown]$$

$$[\Psi]^T \begin{bmatrix} [\diagdown \omega_{fj}^2 \diagdown] & [0] \\ [0] & [\tilde{K}_p] \end{bmatrix} [\Psi] = [\diagdown \omega_j^2 \diagdown]$$

$$[\Psi]^T \begin{bmatrix} [P_a] \\ [P_b] \end{bmatrix} [\Psi] = \{f\}, \quad [\Psi]^T\{\tilde{B}\} = \{B\}$$

Assuming the diagonalization of the damping matrix, the equation of motion can be divided into each vibration mode and solved by the Wilson's θ method. Using this method, the responses of the jth mode at time t_{n+1} can be expressed with the responses at time t_n and excitation forces as follows

$$\begin{aligned} \dot{y}_{n+1} &= a_1 y_n + b_1 \dot{y}_n + c_1 \ddot{y}_n + d_1 g_\theta \\ y_{n+1} &= a_2 y_n + b_2 \dot{y}_n + c_2 \ddot{y}_n + d_2 g_\theta \end{aligned} \quad (3)$$

in which

$$g_\theta = \theta(f_{n+1} + Bu_{n+1}) + (1-\theta)(f_n + Bu_n)$$

The coefficients $a_1, b_1, \cdots, d_2$ are functions which are *determined with the damping ratio, natural* frequency and the time step parameter θ. Since Eq.(3) includes the control force at time t_{n+1}, it has to be determined in order to solve Eq.(3). The control force can be determined by the minimization of the functional as follows

$$\begin{aligned} H = &R_1 y_{n+1}^2 + R_2 \dot{y}_{n+1}^2 + R_3 u_{n+1}^2 \\ &+ \lambda_1(\dot{y}_{n+1} - a_1 y_n - b_1 \dot{y}_n - c_1 \ddot{y}_n - d_1 g_\theta) \\ &+ \lambda_2(y_{n+1} - a_2 y_n - b_2 \dot{y}_n - c_2 \ddot{y}_n - d_2 g_\theta) \end{aligned} \quad (4)$$

in which λ_1 and λ_2 are the Lagrange's parameters, and R_1, R_2, R_3 denote the weighting coefficients to the generalized displacement, the velocity and the control force. Now Eq.(4) can be minimized with the following conditions

$$\frac{\partial H}{\partial y_{n+1}} = 0 \qquad \frac{\partial H}{\partial \dot{y}_{n+1}} = 0 \qquad \frac{\partial H}{\partial u_{n+1}} = 0 \quad (5)$$

Finally the control force at time t_{n+1} can be determined by

$$\begin{aligned} u_{n+1} = &e_g[\{(a_1 d_1 R_1 + a_2 d_2 R_2) y_n \\ &+ (b_1 d_1 R_1 + b_2 d_2 R_2)\dot{y}_n \\ &+ (c_1 d_1 R_1 + c_2 d_2 R_2)\ddot{y}_n + (d_1^2 + d_2^2) \\ &\{\theta f_{n+1} + (1-\theta)(f_n + Bu_n)\}] \end{aligned} \quad (6)$$

in which

$$e_g = R_3 + \theta(d_1^2 R_1 + d_2^2 R_2)$$

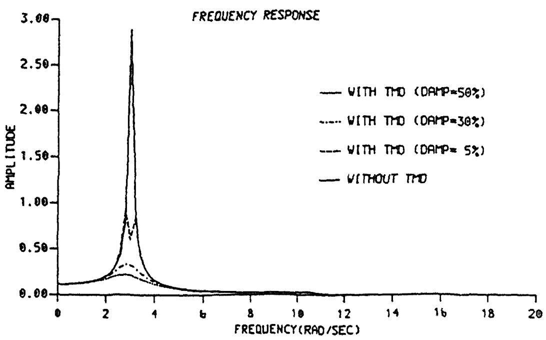

Fig.2 Frequency response function

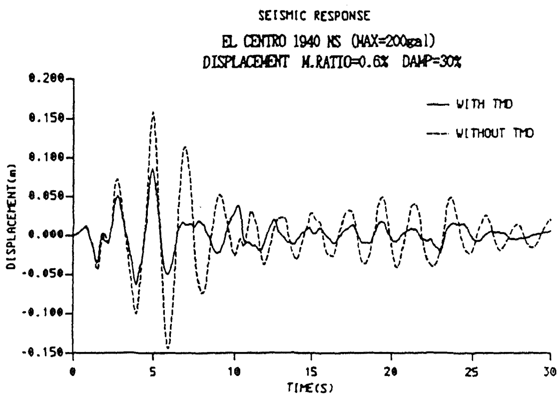

Fig.3 Time history of displacement responses

Given the input seismic motion, the dynamic response at each time step can be determined by Eq.(3) as the control force is given by Eq.(6).

3 NUMERICAL RESULTS AND DISCUSSIONS

Fig.1 shows the analytical model of the jacket-type offshore structure with the TMD system. The height of the structure is 120m and the water depth is 110m from the mean sea level. The main members have an outer diameter of 2.0m and a thickness of 20mm. The structure is discretized by lumping masses at selected nodal points. The vibration is in-plane and each node has 3 degrees of freedom. The base nodes are restrained from vertical movement. The shear wave velocity in the soil is assumed to be 100m/s. The governing equation of motion of the structure-pile-soil system can be obtained by the substructure method. The natural frequency of the first mode is 3.05rad/s. The structural responses are computed for the inputs of seismic motion records which are EL CENTRO 1940 NS and EW components, and TAFT 1952 N21E component. The maximum accelerations of these input motions are modified at 200gal.

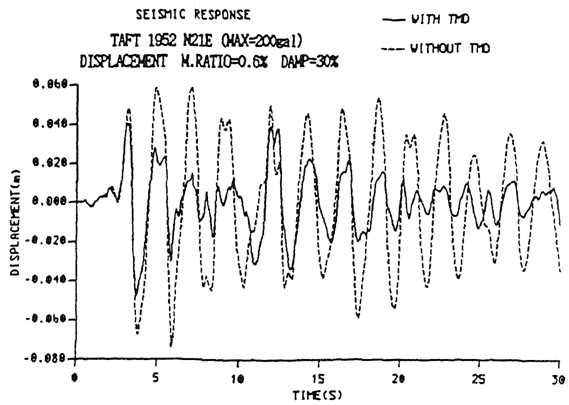

Fig.4 Time history of displacement responses

Fig.2 shows the frequency response functions of the horizontal response of nodal point 1 for different damping ratios of the TMD system. The mass of TMD is chosen as 0.6% of total mass of the superstructure including the added mass due to water. The stiffness of TMD is chosen such that the natural frequency of TMD is coincident to the first natural frequency of the total system. It is shown that the most dominating response at the natural frequency can be sufficiently reduced as the damping ratio of TMD increases.

Fig.3 shows the time histories of the displacement responses of the nodal point 1 to EL CENTRO 1940 NS components. The damping ratio of TMD is 30%. The solid line denotes the response without TMD and the dotted line the response with TMD. The response is generally reduced to about two thirds level over the duration of motion except for the first few seconds where probably transient responses dominate. The responses during the first five seconds which have the maximum value are enoughly reduced to about half when TMD is included. Since the dynamic response has maximum values at the natural frequency, the TMD system thus provides effective roles on the reduction of the response.

Fig.4 similarly shows the horizontal displacement responses of the nodal point 1 to TAFT 1952 N21E component. The TMD contributes to the reduction of the response values except for the first few seconds. The reduction of the response is generally larger for the increase of the duration time of the input seismic motion because the dynamic response is mainly controlled by the natural frequency of the structure. It is seen that the TMD system is very effective in reducing the dynamic response of offshore structure.

Fig.5 shows the response ratios of the maximum horizontal response without TMD system and that

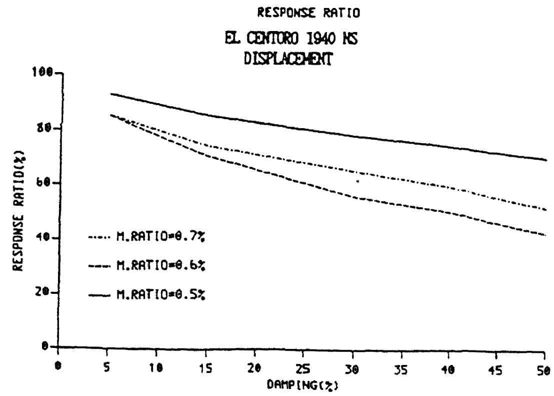

Fig.5 Response ratios of maximum responses

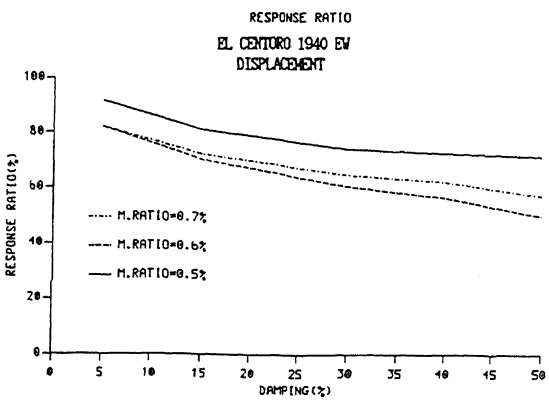

Fig.6 Response ratios of maximum responses

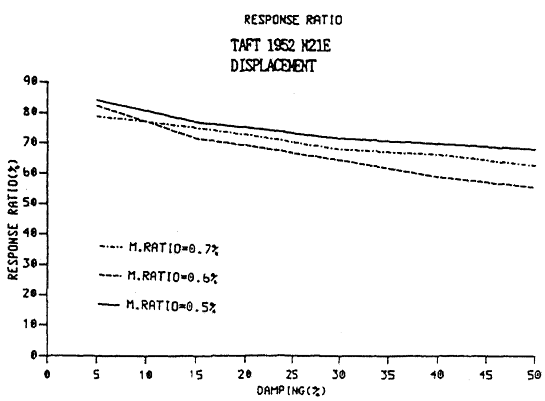

Fig.7 Response ratios of maximum responses

with TMD system subjected to EL CENTRO NS component. The abscissa denotes damping ratio of the TMD system. Since the amount of mass of the offshore structure is dependent upon the equipments of construction and operation, the variations of the

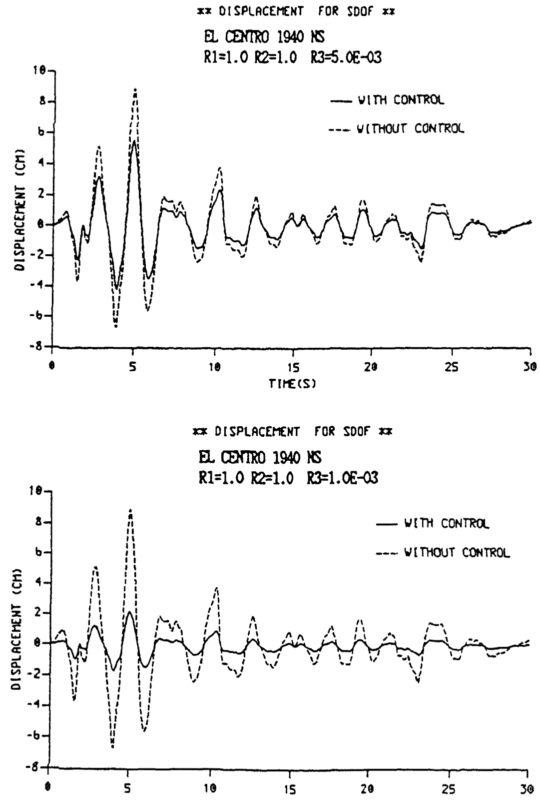

Fig.8 Active control effects on responses

responses due to different mass ratios are examined. Each curve denotes the response ratio which corresponds to a different mass ratio. The mass ratio of 0.6% gives the most effective roles on the reduction of the response. The response ratio which represents the reduction of the response due to the TMD system is very much affected by the mass ratio. Also, the response ratio generally decreases with the increase in the damping ratio of the TMD system.

Fig.6 similarly shows the response ratios of the maximum horizontal response without TMD system and that with TMD system subjected to EL CENTRO 1940 EW component. Each curve denotes the response ratios which correspond to different ratios. While the dynamic response is somewhat affected by the mass ratio of TMD, the TMD gives different contributions on the response reduction by the frequency characteristics of input motions.

Fig.7 shows the response ratios between the maximum horizontal response without TMD system and that with TMD system subjected to TAFT 1952 N21E. Each curve is represented for responses to different mass ratios. The mass ratio gives different value of

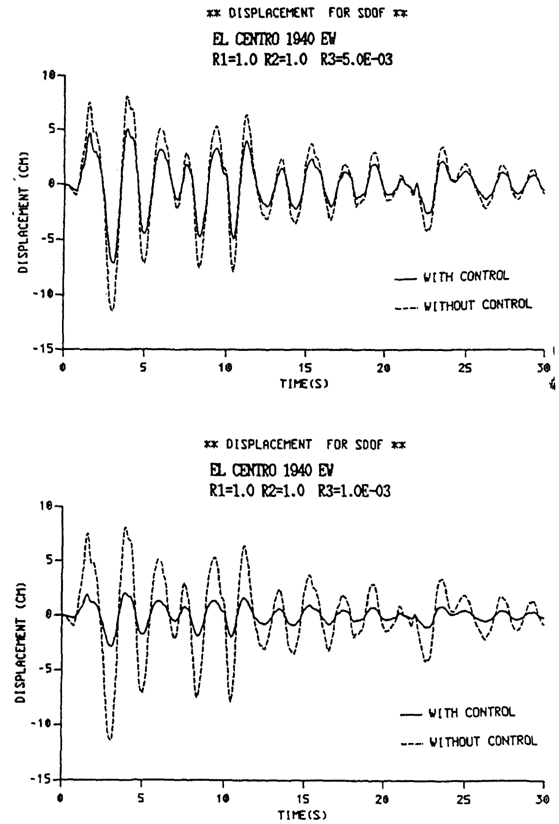

Fig.9 Active control effects on responses

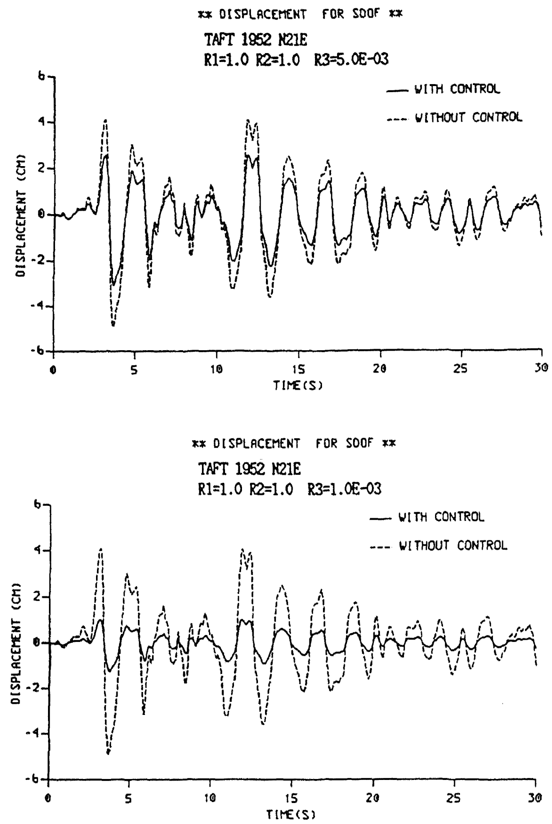

Fig.10 Active control effects on responses

the response reduction to these input motions. The response generally shows decreasing tendency as the damping ratio of TMD increases. The effects of TMD on the response reduction give different efficiencies due to the characteristics of the input seismic motions. This suggests the need to examine in more detail the active control effects on the seismic response of offshore structures.

Fig.8 shows the time histories of the horizontal displacement of the nodal point 1 subjected to EL CENTRO 1940 NS component. The dotted line denotes the response of the structure with TMD only and the solid line denotes the response with an active control force. The weighting coefficient of the control force, R_3, is 5×10^{-3} and 1×10^{-3} respectively. The dynamic responses of the structure to the active control force are much smaller than those with the TMD system only. The control force effects on the response increase as the weight coeffcient takes smaller value.

Fig.9 similarly shows the time histories of the horizontal displacement of the nodal point 1 subjected to EL CENTRO 1940 EW component. The dotted line represents the response with TMD only and the solid line denotes the response with an active control force. The dynamic response of the offshore structure is well controlled by control forces. While the dynamic response is affected by the frequency characteristics of input motions, the active control provides good reductions of the dynamic response.

Fig.10 shows similarly the time histories of the horizontal displacement responses subjected to TAFT 1952 N21E component. The dotted line denotes the response with TMD only and the solid line the response with active control force. The dynamic response is considerably reduced with the increase of the active control force which depends upon the value of the weighting coefficient, R_3. While the ratio of the response reduction is primarily dependent upon the extent of the control force, the characteristics of the input seismic motion have smaller effects on the reduction of the response. The active control gives us the problem of deciding the extent of the control force in order to achieve the reasonable reduction of dynamic responses.

Fig.11 shows the time histories of control force to the weighting coefficients of 5×10^{-3}. The time history of the control force to each seismic motion is entirely corresponding to the acceleration response.

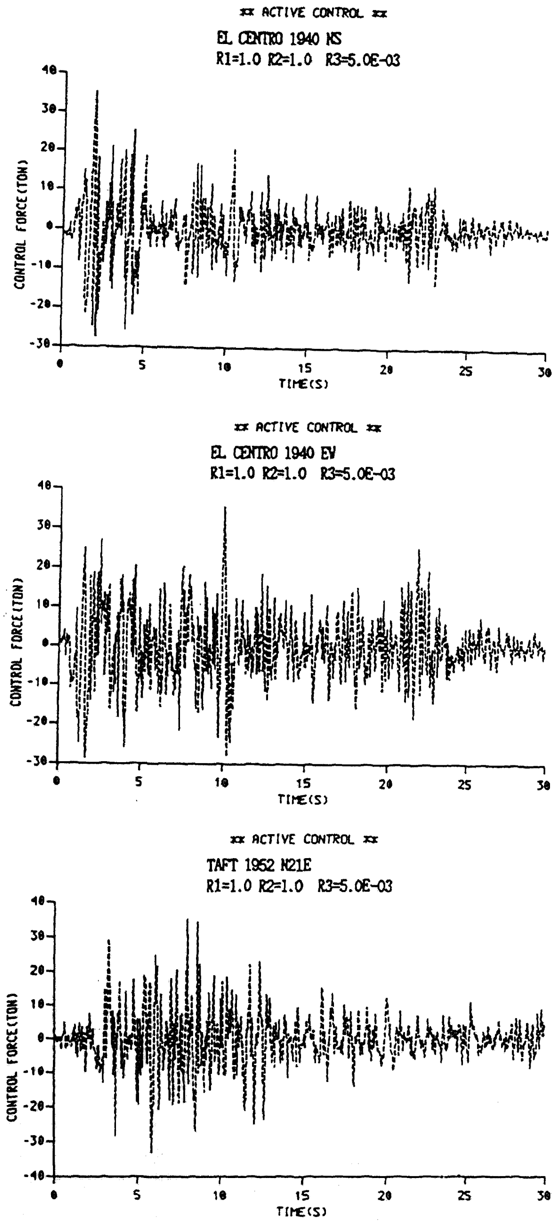

Fig.11 Time history of control force

The magnitude of the active control force seems to take somewhat larger values during the most severe input motion i.e., at the first ten seconds. While the dynamic response of the offshore structure can be greatly reduced with the active control, it requires large control forces. The active control is very helpful for the reduction of the response and the extent of reduction is more than that due to the passive control. Thus this research provides good informations on the dynamic response to understand the active control effects on the seismic response evaluation of offshore structures.

4 CONCLUSIONS

The control of the seismic response of the offshore structure using passive and active control forces is examined. The main results are summarized as follows:

1. Since the dynamic response of the offshore structure subjected to seismic motions is entirely dependent upon the first vibrational mode of the structure, the TMD system gives important roles on the reduction of the response.

2. The TMD system has different effects on the response evaluation due to the characteristics of the input seismic motions. The determination of the parameters of TMD and the characteristics of input motions is important to clarify the effects of TMD system on the dynamic response.

3. While the active control provides better reduction of the dynamic response, it is necessary to examine the active control effects on the seismic response evaluation of the offshore structure because severe active control force may be needed to adequately control the responses.

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