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SYNOPSIS: Safety requirements for structures built in seismic regions have led to techniques for absorbing the energy induced to these structures by earthquakes. Passive isolation systems such as base isolators are suitable for low-rise structures but they provide only a partial solution to the problem. This paper presents three active control techniques for reducing the dynamic response of machine supporting foundations. The concept of active control is discussed and various control strategies are presented. The active tendon system (ATS), active mass damper (AMD), and active base control (ABC) mechanisms are examined. Both optimal and non-optimal control algorithms are described and numerical simulations are performed. It is shown that active control can reduce the dynamic response of turbomachines and their foundations under both normal operation, and emergency conditions such as earthquakes.

INTRODUCTION

The design of structures to resist forces induced by earthquakes has advanced considerably. Recent earthquakes in Mexico, Armenia, and California have shown that when design codes are followed and aseismic techniques are applied, damage can be controlled to a certain level. However, considerable research is underway to ensure integrity of important structures under seismic loading.

Three approaches can be used to achieve reduction of damage and enhancement of reliability of important structures in seismic regions. The first approach is to stiffen the structure and thus enable it to resist the earthquake induced forces. The second method employs special structural elements such as energy absorbers and isolators to limit the magnitude and frequency of seismic forces experienced by the structure. These elements are called passive since no external energy is required for their operation. The third method is directed at reducing seismic forces by using active control devices such as the ATS, AMD or ABC mechanisms. Active control devices require external energy for their operation.

Period lengthening devices such as soft springs, rubber and friction plates, and rubber bearings can reduce the structure's accelerations to very small values; however, they permit large displacements which are not acceptable in most applications. Energy absorbing devices such as viscoelastic dampers have been used in the World Trade Center in New York. In each of the twin towers approximately 10,000 viscoelastic damping units were employed to decrease wind-induced sway. Viscoelastic dampers dissipate energy in the form of heat and friction. Another example of a passive device is that of the Tuned Mass Damper (TMD). The Citicorp building in New York City is equipped with a TMD-a floating 400-ton concrete block - installed on the 59th floor to limit sidesway. The TMD utilizes the fact that its energy dissipating mechanism (vibration of the concrete block) can be activated by the motion of the building itself. However, the TMD is limited to controlling only the fundamental mode of vibration.

Active control is the most recent method for vibration control. The first AMD system has been installed on the roof of the Kyobashi Seiwa building in Japan (Rosenbaum and Usui, 1990) to resist seismic forces. Preliminary results indicate that the system is very effective (Kobori and Soong, 1990). Recently, two mechanisms of active control were installed in a six-story building built for experimental use only (Reinhorn, et al. 1990). A pendulum type AMD was installed on the top floor. In the bottom floor four diagonals were fitted with hydraulic actuators, to form an ATS. The system has performed well during some moderate earthquakes.

ACTIVE CONTROL CONCEPT

The concept of active control is explained using the King-post truss shown in Fig. 1. The beam is loaded with a dynamic load P(t). A gauge at midspan (point B) records the midspan deflection $\delta(t)$. An operator can maintain the deflection $\delta(t)$ within prescribed limits by applying the necessary force u(t) in the cable. The basic components of an active control system are the control device (operator and cable), the sensor (gauge), and the control force (tensile force exerted by the operator). Since the operator expends energy to produce the force u(t), this is an active control system. The system contains feedback information (deflection), which is used as input to an equation or algorithm that determines the magnitude of the force u(t). A block diagram of the beam and control system is shown in Fig. 2. This technique of implementing active control is termed closed-loop.

Instead of measuring the deflection $\delta(t)$, one could measure the load P(t) and determine the magnitude of force u(t) that would limit $\delta(t)$ within prescribed limits. This technique of implementing active control is termed open-loop. A third technique of implementing active control is the open-closed-loop control scheme. In this case both the deflection $\delta(t)$ and the load P(t) are measured in order to determine the magnitude of the force u(t) that would limit $\delta(t)$ within prescribed limits. This technique is very useful when P(t) is a random force.

ACTIVE CONTROL SYSTEMS

Three active control systems are suggested for reducing dynamic response of machine supporting foundations. The first system (ATS) uses the tendon to exert the active control force as shown in Fig. 3a. The technique of applying the active control force in Fig. 3a is the closed-loop scheme. Note that in Fig. 3a the difference is that now instead of an operator, an electrohydraulic actuator is used, the excitation is the ground acceleration $\ddot{X}_g(t)$, and a computer is required to perform on-line calculations to determine the control force u(t).

The second system (AMD) consists of a block mass, a spring, and a dashpot connected to the foundation as shown in Fig. 3b. Unlike the TMD this is an active system as can be observed from the presence of the actuator. The third system is that of active base control (ABC) as shown in Fig. 3c. It is necessary to decouple the base of the foundation from the ground when the ABC is installed. One possibility is to use lead rubber bearings to achieve this. The active system consists of the actuator as shown in Fig. 3c.

All three control systems can also use the open-loop or open-closed-loop techniques. For earthquakes the closed and open-closed-loop techniques are the most promising.

ACTIVE CONTROL ALGORITHMS

An active control system requires an on-line computer to evaluate the required control force. The algorithm to be used depends on the control scheme, i.e. whether it is open, closed, or open-closed-loop (Pantelides, 1987). Two types of algorithms are available: (a) Optimal (Yang et al., 1987), and (b) Non-optimal (Samali et al., 1985). Optimality refers to efficiency of the control force with respect to the power required to produce it, and the reduction of response it achieves. Nonoptimal control algorithms can achieve response reduction but the control forces required may be larger than those for optimal algorithms. Optimal control algorithms can be divided into continuous and discrete-time algorithms. The distinction is based on the degree of computational efficiency (Pantelides, 1990a). The continuous Ricatti optimal control algorithm is used in this paper, but discrete algorithms can also be used (Pantelides, 1990b).

Ricatti Optimal Control

Consider the structure with the ATS of Fig. 3a. The floor relative displacement x(t) is taken

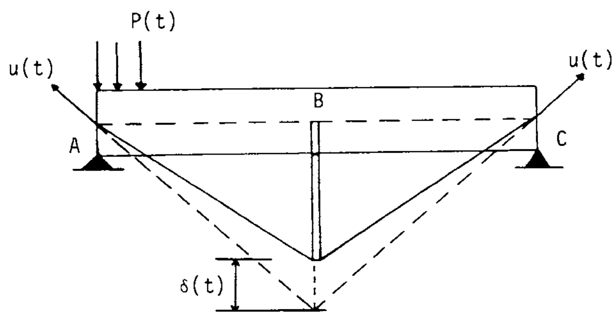

Fig. 1. King-post truss

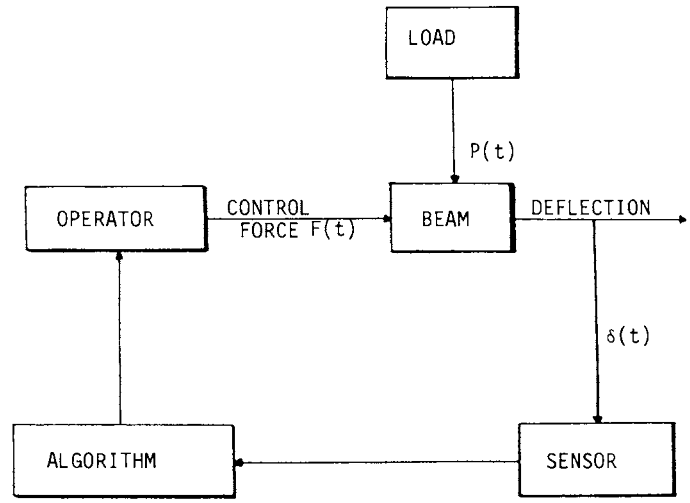

Fig. 2. Block diagram of active control system using closed-loop control

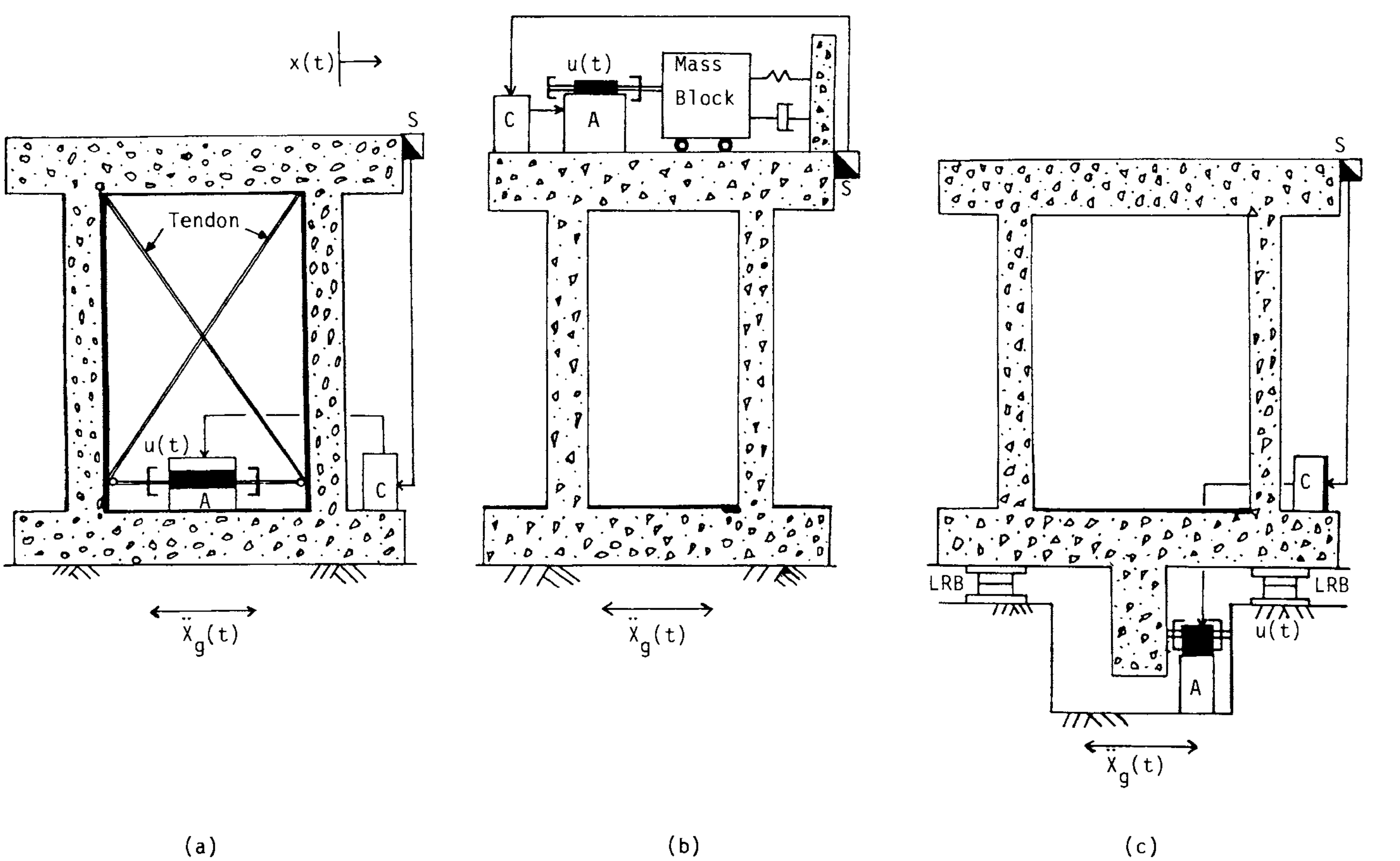

Fig. 3. Active control systems: (a) ATS, (b) AMD, and (c) ABC; (S=Sensor, A=Actuator, C=Computer, and LRB=Lead Rubber Bearing)

as the generalized coordinate. The motion equation of the structure-control system under an earthquake acceleration $\ddot{X}_g(t)$ is

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = -u(t) - m\ddot{X}_g(t) \quad (1)$$

where m,c, and k are the mass, damping and stiffness of the structure, and

$$x(t) = X(t) - X_g(t) \quad (2)$$

Rewriting eqn (1) in state-form

$$\{\dot{z}(t)\} = [A]\{z(t)\} + \{B\}u(t) + \{G\}\ddot{X}_g(t) \quad (3)$$

in which the state is defined by

$$\{Z(t)\} = \begin{Bmatrix} x(t) \\ \dot{x}(t) \end{Bmatrix} \quad (4)$$

$$[A] = \begin{bmatrix} 0 & 1 \\ -k/m & -c/m \end{bmatrix}; \{B\} = \begin{Bmatrix} 0 \\ -1/m \end{Bmatrix}; \{G\} = \begin{Bmatrix} 0 \\ -1 \end{Bmatrix} \quad (5)$$

The optimal control problem consists of finding the optimal force u*(t) which minimizes the following performance index

$$J = \frac{1}{2}\int_{to}^{tf}(\{z(t)\}^T[Q]\{z(t)\} + Ru^2(t))dt \quad (6)$$

and satisfies the equality constraint of eqn (3). The [Q] and R weighting matrices are chosen by the designer. Variational calculus yields (Pantelides, 1990a)

$$u^*(t) = \frac{1}{R\,m}[P_{21}\,x(t) + P_{22}\,\dot{x}(t)] \quad (7)$$

where P_{21} and P_{22} are solutions of the algebraic matrix Ricatti equation

$$[P][A]+[A]^T[P]-[P]\{B\}(\tfrac{1}{R})\{B\}^T[P]+[Q]=[0] \quad (8)$$

$$[P] = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \quad (9)$$

<u>Simplified Model</u>

The Ricatti control algorithm is implemented for the reinforced concrete frame foundation shown in Fig. 4 equipped with an ATS. A simplified single-degree-of-freedom (SDOF) model is used for the analysis. The stiffness (k_T) and mass (m_T) of the SDOF are evaluated using the following equations (Prakash and Puri, 1988)

$$k_T = \sum_i k_i \quad (10a)$$

$$k_i = \frac{12EI_c}{h^3}\left(\frac{6K+1}{3K+2}\right) \quad (10b)$$

$$m_T = (\sum_j w_j + W_{ds})/g \quad (11)$$

where k_i = lateral stiffness of individual transverse frame, w_j = vertical point loads from machinery, W_{ds} = weight of deck slab, g = acceleration due to gravity, h = effective height of foundation, E = Young's modulus of concrete, I_c = moment of inertia of the column and K is defined as

$$K = \frac{I_b}{I_c}\left(\frac{h}{\ell}\right) \quad (12)$$

where I_b = moment of inertia of beam and ℓ = effective span.

Assume unit weight of concrete is 2.24 t/m³, E = 3X10⁶ t/m², point loads #1 and 2 = 10t each, #3, 4, 5, and 6 = 5t each and g = 9.81 m/sec². Using eqs 10-12, one obtains: k_i = 1258 t/m and since there are two transverse frames k_T = 2516 t/m; m_T = 10.62 tons-sec²/m. Damping is assumed to be 1% of critical. The simplified model is analyzed with and without the ATS system. The horizontal ground acceleration $\ddot{X}_g(t)$ is assumed to be

$$\ddot{X}_g(t) = 0.3\,g\,\sin(5\pi t) \quad (13)$$

The displacement response of the SDOF model to the ground acceleration is shown in Fig. 5 for a duration of ten seconds. The displacement response for the foundation equipped with the ATS control is also shown in Fig. 5. The weighting matrices used are diagonal with Q(1,1)=Q(2,2)=1.0, and R=0.01. As can be seen from Fig. 5 the displacement is reduced appreciably. The maximum displacement is reduced to approximately 24% of the uncontrolled value. Acceleration response is compared in Fig. 6, with the same [Q] and R

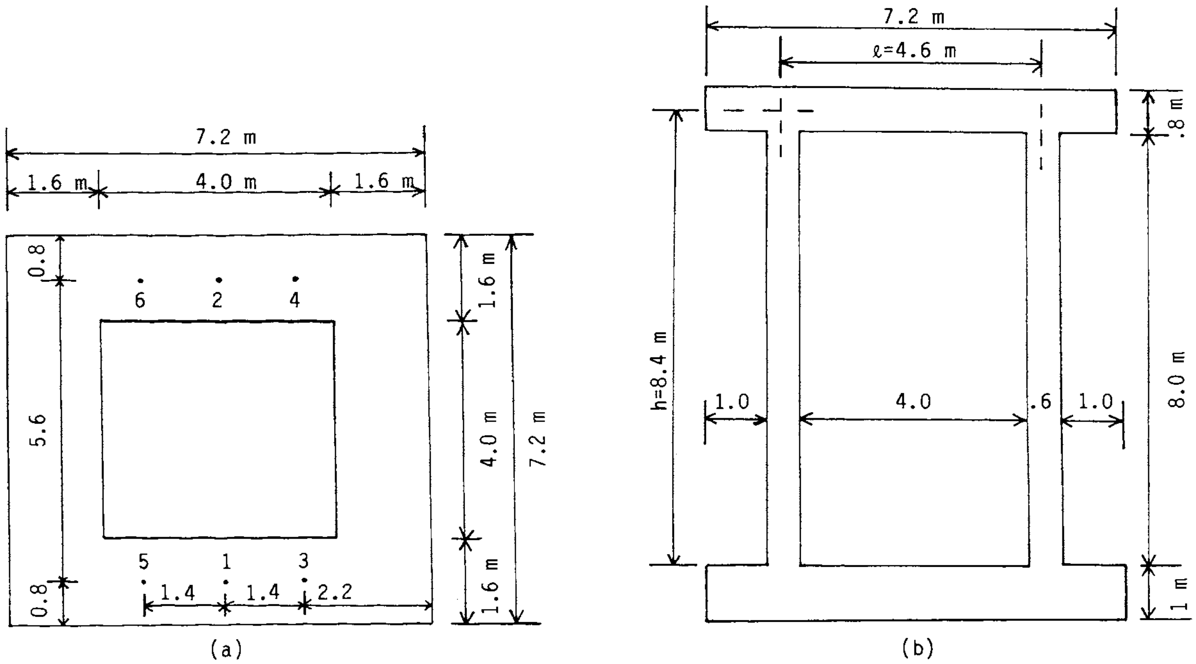

Fig. 4. Machine Frame Foundation: (a) plan of the deck slab; (b) longitudinal section

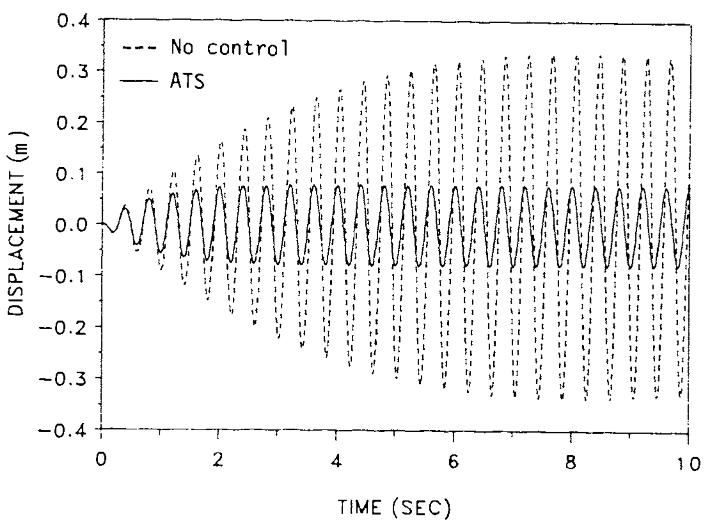

Fig. 5. Displacement response of SDOF model

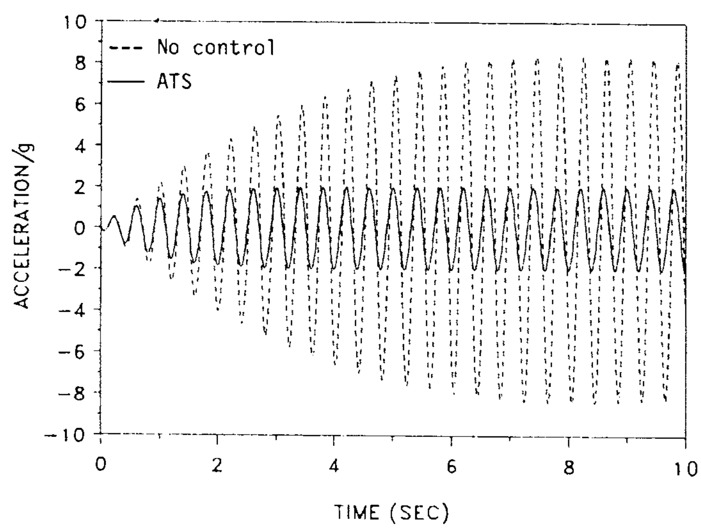

Fig. 6. Acceleration response of SDOF model

matrices for the controlled case as above; it is expressed in nondimensional form in terms of g's. The maximum acceleration is reduced to approximately 25% of the uncontrolled maximum value. The control force required to produce this response reduction is shown in Fig. 7. The maximum control force is approximately 7% of the total weight of the foundation.

The same SDOF model with the ATS, subjected to the ground acceleration of eqn (13) is simulated for various weighting matrices. Matrix [Q] is fixed to be diagonal with elements Q(1,1)=Q(2,2)=1.0, and R is varied. The maximum values of displacement, velocity and acceleration response are shown in Table I, for three cases. In addition, Table I shows the maximum control force required in each case, both in absolute value and in nondimensional form in terms of the foundation's total weight. For comparison, the maximum quantities for the response of the foundation without controls are also given in Table I. It is observed that as the control force increases the response is reduced. This is a consequence of the optimal control scheme as seen from eqn (6).

TABLE I. Comparison of Response for Various Weighting Matrices

Quantity	R=0.10	R=0.05	R=0.01	No Control
x_{max}(m)	0.226	0.177	0.080	0.338
$\dot{x}_{max}$(m/s)	3.542	2.780	1.261	5.282
$\ddot{x}_{max}/g$	5.659	4.448	2.091	8.413
u_{max}(t)	7.83	10.90	15.79	—
u_{max}/Fd.Wt	3.5%	5.0%	7.0%	—

It is obvious from the results of Table I that the designer has the option of limiting the foundation's response by providing different levels of control force. The ground acceleration of eqn (13) simulates a strong earthquake and its frequency is very close to the foundation's natural frequency. Even under these conditions, the ATS control limits the foundation's maximum displacement to less than 0.01 h; in addition, the maximum acceleration is reduced to only 0.25 times that of the uncontrolled foundation. This is achieved at a reasonable level of control force of 7% of the foundation's total weight.

CONCLUSIONS

Active control devices can be used for reduction of seismic response of machine foundations. The active device can be designer to activate if excessive vibrations occur during normal operation, and in addition help reduce vibrations to nearby structures. In emergency conditions, such as earthquakes, it has been shown that active systems can be used to ensure that foundation members do not suffe. appreciable damage. In addition, active control systems can help in maintaining operation of the machines the foundation supports in emergency situations.

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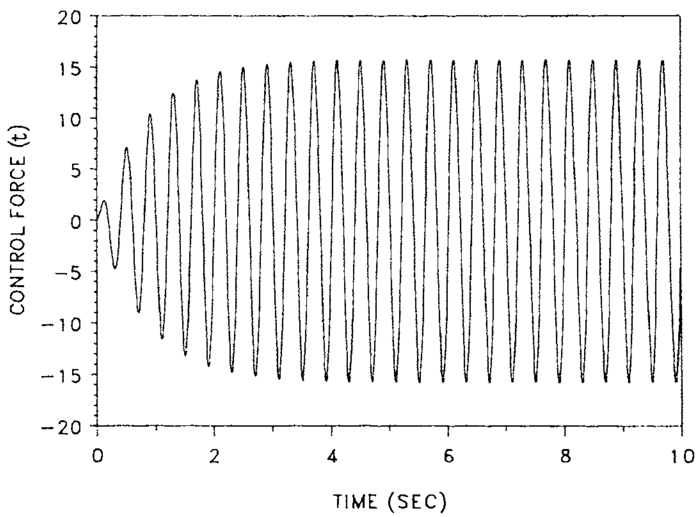

Fig. 7. Control force for SDOF equipped with ATS