Engineering Structures 32 (2010) 3616–3628

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Control strategy for mitigating the response of structures subjected to earthquake actions

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ARTICLE INFO

Article history:
Received 13 December 2008
Received in revised form
30 July 2010
Accepted 9 August 2010
Available online 9 September 2010

Keywords:
Structural control
Dynamic control strategy
Semi-active control
Pole placement
FFT
Structural dynamics
Earthquake engineering

ABSTRACT

On-line control strategy for structures subjected to earthquake actions is investigated. The general control strategy consists of monitoring the incoming signal, analyzing it and recognizing its dynamic characteristics, applying the control algorithm for the calculation of the required action, and finally applying this action. Thus, the way in which the structure is controlled, and the algorithm that is used, are based on the dynamic characteristics and the frequency content of the applied dynamic signal. The procedure of selection of poles of the controlled structure, which is critical for the success of the algorithm, is proposed in this paper. The proposed methodology transforms each consecutive part of the signal, as well as the uncontrolled structure, to the complex plane and, depending on their relative positions, and following specific rules, the desired poles of the controlled structure are calculated and adjusted during the earthquake. According to those locations of poles, and using the pole placement algorithm, the feedback matrix is estimated, and then the equivalent forces that should be applied to the structure by the control devices, which are installed on the building, are calculated. Parametric simulations for different dynamic loads and seismic actions are performed, for both single and multi degree of freedom systems. From the numerical results it is shown that the above control procedure is efficient in reducing the response of building structures, with a small amount of required control forces.

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1. Introduction

Innovative means of enhancing structural functionality and safety against natural and manmade hazards are currently in various stages of research and development. They can be grouped into the following broad areas: passive control systems and active, semi active, or hybrid control systems. The main subcategories of passive control systems are the base isolation and the passive energy dissipation systems. In general, such systems are characterized by frequency shift and their capability to enhance energy dissipation in the structural system, in which they are installed. These devices generally operate on principles such as frictional sliding, yielding of metals, deformation of visco-elastic solids or fluids and fluids orificing. Active, semi active, and hybrid control systems are a natural evolution of passive control technologies. The use of active, semi-active and the combination of passive, active or semi-active systems as a means to protect the structures against seismic loads has received considerable attention in the last few decades. The devices of this category are part of an integrated system, with real time processing controllers (control algorithms) and sensors, all installed to the structure. They act simultaneously with the excitation to provide enhanced structural behavior for improved service and safety.

Over the past few decades various control algorithms and control devices have been developed, modified and investigated by various groups of researchers. The work of Yao, Yang, Soong, Housner, Spencer, Symans, Kobori, Lu, Kurata, Renzi, Reigles [1–21], is representative. While many of these structural control strategies have been successfully applied, challenges pertaining to cost, reliance on external power and mechanical intricacy during the life of the structure have delayed their widespread use.

One of the most suitable algorithms for controlling the structure is the pole placement algorithm. Pole placement algorithms have been studied extensively in the general control literature Sage, Kwakernaak, Brogan, Ogata, Kwon, Kautsky, Laub [22–29]. The application of the algorithm in structural control can be found in the work of Martin, Wang, Meirovotch, Soong, Utku, and Preumont [30–34].

In [35] a pole placement algorithm where the poles of the structure are estimated based on the complex Fourier characteristics of the incoming earthquake is proposed. In this paper the procedure for estimation of the poles of the control structure is extended and improved. The poles are calculated on-line based on the important frequencies of seismic loading

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doi:10.1016/j.engstruct.2010.08.006

Nomenclature

The following symbols are used in this paper:

$\mathbf{M}$	Mass matrix of the structure;
$\mathbf{C}$	Damping matrix of the structure;
$\mathbf{K}$	Stiffness matrix of the structure;
$\mathbf{E}$	Location matrix for the earthquake;
$\mathbf{E}_f$	Location of control forces on the structure;
$\mathbf{F}$	Control forces on the structure;
t_d	Time delay;
$\mathbf{F}_{\text{allowable}}$	Maximum capacity of the control device;
$\mathbf{X}$	Matrix of states of the system;
$\mathbf{Y}$	Matrix of the output states;
$\mathbf{C}$	Output matrix;
$\mathbf{D}$	Feed forward control force matrix;
$\mathbf{v}$	Noise matrix;
λ_i	Eigenvalues or poles of the uncontrolled system;
$\lambda_{c,i}$	Eigenvalues or poles of the controlled system;
f_i	Eigenfrequencies of the uncontrolled system;
ξ_i	Damping ratio of the uncontrolled system;
$\mathbf{G}$	Feedback or gain matrix;
$\omega_{s,i}$	Bandwidth of the unsafe zone;
a_p	Percentage of maximum value of the Fourier power spectrum above which the frequencies are taken into consideration;
I_p	Percentage of participation of selected frequencies to the power of the signal;
$I_{p,d}$	Design percentage of participation of those selected frequencies to the power of the signal;
ω_o	Eigenfrequency of single degree of freedom system;
$u_{o,\max}$	Maximum response of single degree of freedom system at resonance;
$u_{1,\max}$	Maximum response of single degree of freedom system moving its pole along a line with constant damping;
$u_{2,\max}$	Maximum response of single degree of freedom system moving its pole along a cycle sector with constant ω;
$u_{\max}$	Maximum response of single degree of freedom system for every location of its pole out of resonance;
x	The ratio $u_{\max,1}/u_{o,\max}$;
ξ_c	Equivalent damping ratio;
$u_{1,R,\max}$	The maximum response at point R;
x_d	The desired ratio of further reduction of the maximum response, $u_{2,\max}/u_{1,R,\max}$.

and equivalent damping. Furthermore, a dynamic control strategy based on pole placement technique is proposed for application to active or semi-active control systems installed in buildings designed against seismic actions.

2. Control strategy of structures by a pole placement algorithm

The general control strategy consists of the following stages: (i) the monitoring of the incoming signal, (ii) its FFT or wavelet analysis for recognition of its dynamic characteristics, (iii) the selection of poles of the integrated controlled system, (iv) the application of the pole placement algorithm for the calculation of the required actions, and finally, (v) accounting for the limitations of the devices that are used, the application of these actions, considering saturation effects and time delay. A flow chart of this integrated control strategy is shown in Fig. 1.

The equation of motion of a controlled structural system with n degrees of freedom u_i, subjected to an earthquake excitation a_g, is given by Eq. (1).

$$\mathbf{M}\ddot{\mathbf{U}}(t) + \mathbf{C}\dot{\mathbf{U}}(t) + \mathbf{K}\mathbf{U}(t) = -\mathbf{M}\mathbf{E}a_g(t) + \mathbf{E}_f \,\mathrm{sat}\,\mathbf{F}(t - t_d) \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$ denote the mass, damping and stiffness matrices of the structure, respectively, $\mathbf{E}$, $\mathbf{E}_f$ are the location matrix for the earthquake and the control forces on the structure, and sat $\mathbf{F}$ is the saturated control force matrix, which is applied to the structure with time delay t_d and is given by:

$$\mathrm{sat}\,\mathbf{F}(t-t_d) = \begin{cases} \mathbf{F}(t-t_d), & \mathbf{F}(t-t_d) < \mathbf{F}_{\text{allowable}} \\ \mathbf{F}_{\text{allowable}}, & \mathbf{F}(t-t_d) \geq \mathbf{F}_{\text{allowable}}. \end{cases} \tag{2}$$

$\mathbf{F}_{\text{allowable}}$ is the maximum capacity of the control device. In the state space approach the above Eq. (1) can be written as follows:

$$\begin{aligned} \dot{\mathbf{X}}(t) &= \mathbf{A}\mathbf{X}(t) + \mathbf{B}_g a_g(t) + \mathbf{B}_f \,\mathrm{sat}\,\mathbf{F}(t-t_d) \\ \mathbf{Y}(t) &= \mathbf{C}\mathbf{X}(t) + \mathbf{D}_f \,\mathrm{sat}\,\mathbf{F}(t-t_d) + \mathbf{D}_g a_g(t) + \mathbf{v}. \end{aligned} \tag{3}$$

The matrixes $\mathbf{X}$, $\mathbf{A}$, $\mathbf{B}_g$, $\mathbf{B}_f$ are given by:

$$\begin{aligned} \mathbf{X} &= \begin{bmatrix} \mathbf{U} \\ \dot{\mathbf{U}} \end{bmatrix}_{2n\times 1}, \qquad \mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}_{2n\times 2n}, \\ \mathbf{B}_g &= \begin{bmatrix} \mathbf{0} \\ -\mathbf{E} \end{bmatrix}_{2n\times 1}, \qquad \mathbf{B}_f = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\mathbf{E}_f \end{bmatrix}_{2n\times 1}. \end{aligned} \tag{4}$$

The matrixes $\mathbf{Y}$, $\mathbf{C}$, $\mathbf{D}_f$, $\mathbf{D}_g$, and $\mathbf{v}$ are the output states, the output matrix, the feed forward control force matrix, the excitation matrix and the noise matrix, respectively. We consider the case where the output variables are the same as the states of the system and there is no application of the control forces to the output variables, so the matrixes $\mathbf{C}$, $\mathbf{D}$ are the identity and zero matrix, respectively. The noise matrix depends on the sensor we use to measure the response of the system. The above equation can be solved by the technique of delay differential equation, Shampine and Thompson [36], or one can use the following transformation, which is described by Cai et al. [37]:

$$\mathbf{Z}(t) = \mathbf{X}(t) + \int \mathrm{e}^{-\mathbf{A}(\eta+t_d)}\mathbf{B}_f\mathbf{F}(t+\eta)\mathrm{d}\eta. \tag{5}$$

Then:

$$\begin{aligned} \dot{\mathbf{Z}}(t) &= \mathbf{A}\mathbf{Z}(t) + \mathbf{B}_g a_g(t) + \mathbf{B}(\mathbf{A})\mathbf{F}(t) \\ \mathbf{B}(\mathbf{A}) &= \mathrm{e}^{-\mathbf{A}t_d}\mathbf{B}_f. \end{aligned} \tag{6}$$

The eigenvalues or poles of the uncontrolled system are given by:

$$\lambda_i = -\xi_i\omega_i \pm j\omega_i\sqrt{1-\xi_i^2} \tag{7}$$

where f_i and ξ_i are the eigenfrequencies and the damping ratio, respectively, which are obtained from the solution of the eigenvalue problem. If a state space formulation is adopted, then these eigenvalues are obtained directly from the eigenvalues of matrix $\mathbf{A}$:

$$\det[\lambda\mathbf{I} - \mathbf{A}] = 0 \rightarrow \lambda_i = \alpha_i \pm j\beta_i. \tag{8}$$

The representation of the poles in the complex plane is shown in Fig. 2.

It is assumed that the control force $\mathbf{F}$ is determined by linear state feedback:

$$\mathbf{F} = -\mathbf{G}_1\mathbf{U} - \mathbf{G}_2\dot{\mathbf{U}} = -\begin{bmatrix}\mathbf{G}_1\mathbf{G}_2\end{bmatrix}\begin{bmatrix}\mathbf{U} \\ \dot{\mathbf{U}}\end{bmatrix} = -\mathbf{G}\mathbf{X}. \tag{9}$$

$\mathbf{G}$ is the gain matrix, which will be calculated according to the desired poles of the controlled system. Replacing the force $\mathbf{F}$ into

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