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Analysis and control for transient responses of seismic-excited hysteretic structures

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ABSTRACT

The semi-analytical solution of transient responses and the bounded control strategy to minimize the transient responses for seismic-excited hysteretic structures are investigated in this manuscript, the hysteretic behavior is described by Duhem model while the seismic excitations by random processes with Kanai–Tajimi spectrum. The averaged Fokker–Planck–Kolmogorov equation with respect to the probability density of amplitude response is firstly derived by utilizing the stochastic averaging technique based on the generalized harmonic functions. The probability density is approximately expressed as a series expansion in terms of a set of specified basis functions with time-dependent coefficients which are determined through the Galerkin procedure. The quasi-optimal bounded control strategy to minimize the transient response is proposed based on the averaged system with respect to amplitude response and an appropriate performance index. The quasi-optimal control is derived from the minimum condition in the dynamic programming equation. The application and effectiveness of the proposed analytical procedure and control strategy are illustrated through one representative example.
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1. Introduction

Strong earthquakes are frequently occurred nowadays, some of them, such as those in Wenchuan, Fukushima and Yaan, induced catastrophic consequences. Casualty caused by devastating earthquakes mainly attributes to the collapse of constructions subjected to severe dynamical loadings. Undoubtedly, the analysis and control of seismic responses of civil structures are crucial to reduce earthquake hazards. Response analysis helps to thoroughly understand the influence of earthquake motions on constructions and constitutes the fundamental of response control, while response control to minimize seismic responses is the ultimate objective to reduce casualties. Careful observation indicates that the analysis and control of seismic responses of civil constructions include the following properties: the hysteretic behavior of structures, the transient feature of responses and the randomness of excitations. The hysteretic behavior introduces strong nonlinearity factor in system considered while the transient feature is relatively seldom investigated in traditional random theory, both of these two properties raise the difficulties to determine the seismic response and control strategy.

Structures subjected to severe dynamical loadings always exhibit hysteretic behaviors [1–3]. The hysteretic force not only depends on the instantaneous state but also the past states. Many models, such as bilinear model, distributed-element model, Bouc–Wen model, Duhem model, Preisach model and so on, have been proposed to describe the hysteresis behavior [4–9]. In the above models, Duhem differential model is versatile to describe hysteretic behavior and widely adopted in structural engineering. Exact random responses of hysteretic structures are extremely difficult to be obtained directly and current investigations focus on approximate techniques. The bilinear model, the distributed-element model, the Bouc–Wen model and the Preisach model have been investigated through the equivalent linearization method [10–12], the stochastic averaging method [13–16] and a probability density evolution technique [17]. The stationary response of the Duhem hysteretic system subjected to non-white random excitation is investigated through the stochastic averaging of energy envelope [18,19]. In these research works, the Duhem hysteretic force is decomposed to the conservative and the dissipative components, and the former is described by the derivative of system potential energy while the latter by a quasi-linear damping with energy-dependent coefficient. The stationary responses of the equivalent system can be obtained through the stochastic averaging of energy envelope, and that is the approximate evaluation of the stationary responses of the original hysteretic system. Compared to the research works on stationary response of hysteretic system, the studies on transient response aspect are relatively seldom. Some approximate techniques established for calculating the transient responses of nonlinear stochastic systems have been applied to hysteretic systems [20–23]. The non-stationary response of

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Bouc–Wen hysteretic structure is calculated by the probability density evolution technique [17]. The response evolutionary power spectrum and survival probability density of Preisach hysteretic system under evolutionary stochastic excitation are determined by analytical methods based on stochastic averaging treatment [24,25].

The response control of random-excited hysteretic systems has been investigated and some control strategies to reduce the system response have been proposed. An instantaneous optimal control algorithm for hysteretic structures is presented, where the optimal control vector is obtained by minimizing time-dependent quadratic performance index subjected to the constraint of the equations of motion [26]. An optimal polynomial control strategy to reduce the peak response of seismic-excited hysteretic structures has been proposed, where the performance index is minimized based on the Hamilton–Jacobi–Bellman equation using a polynomial function of nonlinear states [27]. In essence, these control strategies possess deterministic property. By using a stochastic linearization technique and adopting an energy performance index, an optimal passive control for an adjacent structure interconnected by nonlinear hysteretic devices has been studied [28]. Recently, the nonlinear stochastic optimal control strategy based on the stochastic averaging technique and stochastic dynamic programming principle [29,30] has been applied to Bouc–Wen hysteretic systems [31] and Preisach hysteretic systems [16], and this strategy possesses good control performance and high control efficiency. The nonlinear stochastic optimal control strategy, however, is confined to the response control in infinite time interval due to the difficulty of searching the optimal strategy for that in finite time interval.

The semi-analytical solutions of transient responses and the optimal bounded control strategy to minimize transient responses for seismic-excited hysteretic structures are investigated in this manuscript. The seismic-excited hysteretic structure is modeled as a Duhem hysteretic system subjected to random excitations with Kanai–Tajimi spectrum. The averaged Fokker–Planck–Kolmogorov (FPK) equation with respect to the probability density of system amplitude is derived through the stochastic averaging technique based on the generalized harmonic functions, and the solution is approximately expressed as a series expansion in terms of a set of specified basis functions with time-dependent coefficients. The quasi-optimal bounded control strategy to minimize the transient response is derived based on the averaged system, an appropriate performance index and the dynamic programming principle. Also, the extension of the proposed procedure to the case with time-modulated Kanai–Tajimi excitation is briefly illustrated. A representative example is investigated to verify the accuracy of response analysis and the effectiveness of control strategy to the cases with non-modulated or time-modulated excitations.

2. Duhem hysteretic model and the equivalent nonlinear system

A hysteretic column with one concentrated mass at the top is a typical model in civil engineering, which can describe the one-story building, elevated water tank, pergola with a heavy concrete roof supported by light-steel-pipe columns [32]. The system subjected to both horizontal and vertical earthquake motion excitations is depicted in Fig. 1(a). The general non-dimensional equation of the hysteretic column-mass model is described as follows:

$$\ddot{X}+2\zeta\dot{X}+Z\left(X,\dot{X}\right)=f_j\left(X,\dot{X}\right)\xi_j \quad j=1,\cdots,n \tag{1}$$

where, X,ζ and Z are the system displacement, the viscous damping coefficient and the hysteretic force, respectively; $f_j\left(X,\dot{X}\right)$

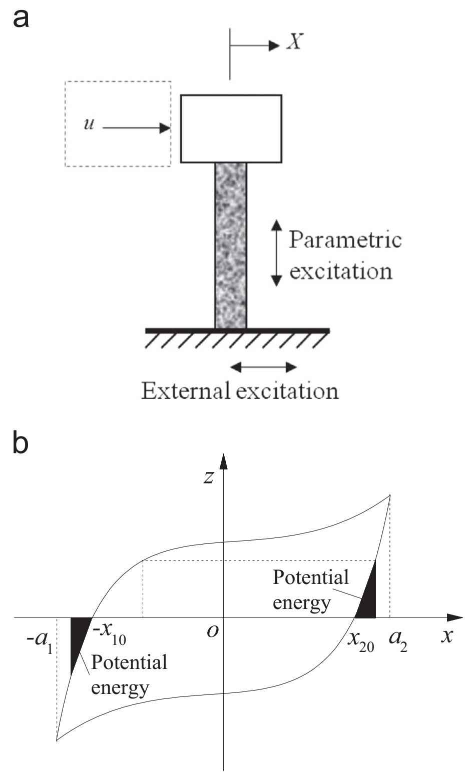

Fig. 1. Hysteretic column-mass system and Hysteresis loop. (a) A schematic diagram of a simple beam system; (b) a representative of Duhem anti-symmetric hysteresis loop.

denote the amplitudes of external and/or parametric random excitations; ξ_j are independent stationary random processes with zero mean and Kanai–Tajimi spectrum,

$$S_{\xi_j}(\omega)=\frac{\omega_{g_j}^4+4\zeta_{g_j}^2\omega_{g_j}^2\omega^2}{\left(\omega^2-\omega_{g_j}^2\right)^2+4\zeta_{g_j}^2\omega_{g_j}^2\omega^2}S_{0j} \tag{2}$$

The Duhem hysteretic model is adopted to describe the hysteretic behavior, and the hysteretic force Z is governed by the following first-order differential equation [19]:

$$\dot{Z}=g\left[X,Z,\mathrm{sgn}\left(\dot{X}\right)\right]\dot{X}=g_1(X,Z)\dot{X}_+-g_2(X,Z)\dot{X}_-$$
$$\dot{X}_+=\left(|\dot{X}|+\dot{X}\right)/2,\dot{X}_-=\left(|\dot{X}|-\dot{X}\right)/2 \tag{3}$$

where both g_1 and g_2 are continuous functions of displacement and hysteretic force. It can be found that the hysteretic force is determined by g_1 when $\dot{X}>0$ and g_2 when $\dot{X}<0$. The corresponding hysteresis loop in the plane (x,z) consists of two parts, i.e., ascending line $z_1(x)$ for $\dot{x}>0$ and descending line $z_2(x)$ for $\dot{x}<0$. Both ascending and descending lines are independent of the magnitude of velocity $\dot{x}$. The hysteretic force on ascending line or descending line depends on both the instantaneous displacement and the local displacement history since the last change in velocity direction, but is independent of the displacement history before the change.

The potential energy deposited in a hysteresis component for $\dot{x}>0$can be expressed as,

$$U(x,a)=\begin{cases}\int_{-x_{10}}^{x} z_1(x_1)\mathrm{d}x_1, & -a_1\le x\le -x_{10}\\ \int_{x_{20}}^{z_2^{-1}[z_1(x)]} z_2(x_1)\mathrm{d}x_1, & -x_{10}\le x\le a_2\end{cases} \tag{4}$$

where a_1 and a_2 are negative and positive displacement amplitudes, respectively; x_{10} and x_{20} are residual hysteretic

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