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Physical parameter identification of nonlinear base-isolated buildings using seismic response data

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ABSTRACT

Base isolation is an increasingly applied earthquake-resistant design technique in highly seismic areas. Examination of the actual performance of isolated structures in real earthquake has become a critical issue. In this paper, a new computational method for system identification is proposed for obtaining insight into the linear and nonlinear structural properties of based-isolated buildings. A bilinear hysteresis model is used to model the isolation system and the superstructure is assumed linear. The method is based on linear and nonlinear regression analysis techniques. Response time histories are divided into different loading or unloading segments. A one-step multiple linear regression is implemented to simultaneously estimate storey stiffness and damping parameters of the superstructure. A two-step regression-based procedure is proposed to identify the nonlinear physical parameters of the isolation system. First, standard multiple linear regression is implemented to deduce equivalent linear system parameters. Analysis of the varying equivalent linear system parameters with displacement is used to distinguish linear and nonlinear segments. Second, nonlinear regression is applied for the nonlinear segments to obtain nonlinear physical parameters. A 3-storey base-isolated building was simulated to real earthquake ground motions and recorded responses were used to demonstrate the feasibility of the proposed method. Superstructure and isolation bearing properties were identified to within 6% those of actual model value even with a SNR 30 dB signal noise level. The overall method allows the simple, effective analysis of nonlinear base isolated structures. The approach to multi-degree of freedom nonlinear structures could be readily generalised to nonlinear, fixed-base, multi-storey structures.

1. Introduction

The goal of seismic isolation is to shift the fundamental natural period of a building away from the dominant frequency components of the ground motion. Isolators are placed at the base of the structure to physically decouple it from the foundation and provide flexibility and energy dissipation capability. Base isolation systems have been effective in protecting structures from strong motion earthquakes and are used with increasing popularity [1–4]. However, their effectiveness is dependent on isolator performance. If isolators degrade or fail due to aging, temperature cycles or exceeding their design capacity during extreme events, structural safety is no longer guaranteed. In another case, the isolators were too stiff and no isolation was provided, leading to structural damage [5]. Therefore, the identification and monitoring of the building isolation performance is increasingly important in civil engineering.

Recorded seismic responses contain a lot of information about the dynamic properties of the structures and isolators. A number of studies to identify the actual performance of the base-isolated structures subjected to seismic excitation have been conducted. The four base-isolated buildings affected by the 1994 Northridge earthquake were identified as equivalent linear dynamic systems characterised by time-invariant or time-variant modal parameters in [6]. Nagarajaiah and Sun [7] investigated the seismic response and performance evaluation of the base-isolated USC Hospital Building. Both parametric and non-parametric system identification methods were applied to estimate the equivalent linear system periods and damping. The same method was then used to identify the base-isolated Los Angeles Country Fire Command and Control building in [8]. In a later work, a time segmented least squares technique was proposed for the building and time-variant linear system properties were obtained in [9]. Recently, Yoshimoto et al. [10] proposed a multiple-input multiple-output (MIMO)

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subspace identification method for damage detection of the base-isolated buildings. Time piecewise system parameters, such as the lateral stiffness and damping coefficient, were identified as damage indices. Loh et al. [11] developed a recursive subspace identification method to identify the time-variant periods and damping of the mid-story isolation buildings using earthquake records. Yao and Pakzad [12] proposed time and frequency domain linear regression methods to identify interstory stiffness of a shear frame structure subjected to white noise excitation.

However, these studies are all based on an assumed linear equivalent system over the whole time history or piecewise linear systems over different time segments. Nonlinear physical parameters of the structural system, which are more attractive for understanding the actual dynamic characteristics of base-isolated buildings, and which are critical to structural control and health monitoring, cannot be directly obtained. Equally, it is these parameters, linear and nonlinear, which are used to specify isolators and in design. Thus, directly identifying these parameters would best suit designers and practitioners.

A limited number of methods addressed nonlinear physical parameter identification of base-isolated structures, have been developed. Tan and Huang [13] proposed an iterative trial and error optimisation procedure to identify the physical parameters of the linear superstructure and bilinear hysteretic isolators. The essence of the study is the application of a Masing criterion to transform the multi-value hysteretic restoring force into a single-value function such that ordinary identification processes can be used. The method needs complex iterations and is computationally costly. Similar identification methods were then extended to different base-isolated structures in [14–17]. Furukawa et al. [18] proposed a least squares prediction-error minimisation method to identify a base-isolated building in Kobe City affected by the 1995 Hyogoken-Nambu earthquake. The isolation system was identified based on three different models: a linear equivalent model, a bilinear model and a tri-linear model. Results show that the nonlinear model parameters can be reasonably estimated and the tri-linear model best fit the actual isolator hysteretic behavior and response time histories. Ahn and Chen [19] proposed a nonlinear model-based system identification method for a three-span continuous base-isolated bridge. It used the Mengotto-Pinto model to model hysteresis behaviour of the lead-rubber bearings. Nonlinear model parameters were pulled out by a two phase output-error optimisation algorithm to address ill-conditioning issues. Xie and Mita [20] presented a method to estimate the restoring force of an isolation layer using component mode synthesis (CMS). The amplitude-dependent equivalent system stiffness and damping coefficients were identified to characterise the nonlinearity of the isolation layer. Oliveto et al. [21] developed a time domain nonlinear system identification procedure to determine the physical parameters of the hybrid seismic isolation system of a base-isolated building. The method used a bilinear hysteretic model and a constant coulomb friction model to model the high damping rubber bearings and low friction sliding bearing respectively. The model parameters were estimated by a nonlinear least squares output-error minimisation method using free vibration test data. The Covariance Matrix Adaptation-Evolution Strategy (CMS-ES) algorithm was proposed for identification of nonlinear base isolation system from earthquake records in [22].

Hence, nonlinear isolation system parameters can be identified. However, most of these methods belong to classes of output-error algorithms that depend on a specific mechanics model, which may or may not fully match the measured response due to material nonlinearities, degradation or variability in construction. Furthermore, these methods are applied after the whole time history data are obtained and cannot be applied in real-time, near real-time, or in situ. In particular, an optimisation iteration algorithm is needed to derive model parameters, as well as added algorithm control parameters that are often manually adjusted to get a good result given the complex optimisation algorithm applied. Thus, there is a major need for a much simpler, more efficient approach to capturing nonlinear behaviours that is amenable to real-time or near real-time results and requires no specific model and less operator input.

It should also be noted that structural control arena there have been some simpler real-time approaches. In particular most have dealt with strictly linear structure stiffness or/and modal parameters [23–25], which is not the case here. Amongst relatively simpler nonlinear structural identification methods in the control arena, Wu and Smyth [26] used a non-parametric unscented Kalman filter to identify five of fourteen parameters in one generalised hysteretic model with minimal noise, while Smyth et al. [27] used a similar adaptive filtering approach for a Bouc-Wen modelled hysteretic structure. All of these are mechanics model dependent and identify some parameters that would allow a nonlinear elasto-plastic stiffness to be identified for a record, but not cycle to cycle.

In this paper, a new computational method for identification of physical parameters of nonlinear base-isolated buildings is developed and validated. The algorithm is based on linear and nonlinear statistical regression analysis techniques. It yields nonlinear physical parameters of the isolation system, as well as linear stiffness and damping parameters of the isolated structure. The proposed method can be generalised to various forms of nonlinearity in the isolation layer. A proof-of-concept case study was performed to demonstrate and prove the method.

2. Structural model

Consider the base-isolated N-storey shear building in Fig. 1. Let m_i, k_i, c_i denote the mass of the i-th level, the stiffness and the viscous damping coefficient of the i-th storey, respectively. Let u_i denote the displacement of the i-th ceiling in relation to the

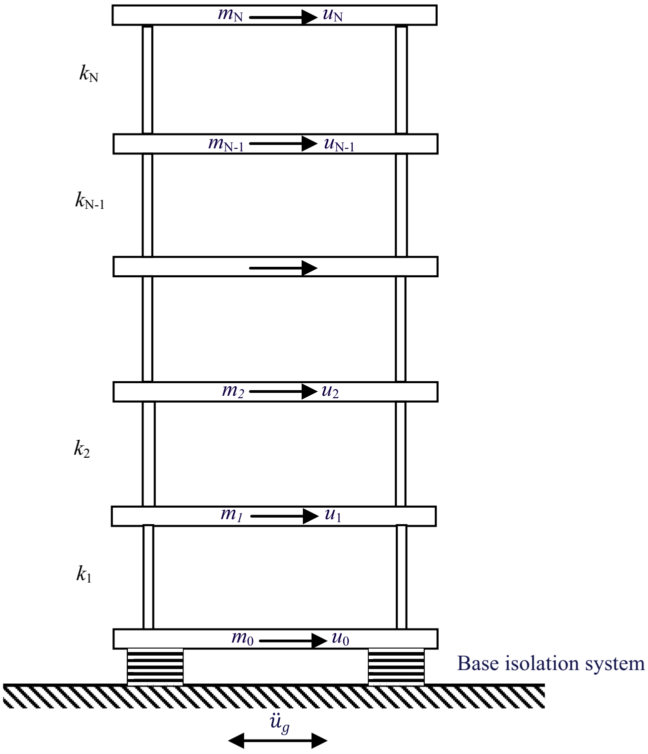

Fig. 1. *N*-storey base-isolated shear building model.