Hybrid Genetic Algorithm to Parameter Identification of Structural Systems with Added-Damping-and-Stiffness Device

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Abstract

The structural parameters may be deviated from the design values due to the yielding or the fatigue of the material strength. In this regard, the dynamic characteristics may also be changed due to the damage of the structure. In order to realize the dynamic behavior of structural systems, we can determine the dynamic models and parameters by system identification techniques. The method proposed for the parameter identification of nonlinear systems in this paper is the hybrid genetic algorithm combining Wen's model as the restoring force model for each story shear. The process of exploring this algorithm is demonstrated by the simulated single-degree-of-freedom system. Finally, the method was applied to the three-story structural models with added-damping-and-stiffness devices mounted on the shaking table. The ground motion records used for these models are time histories of El Centro earthquake adjusted to different intensities. The results showed that the D20H100 model of added-damping-and-stiffness devices experienced slight damage when subjected to the excitation of the El Centro earthquake with PGA values equal to 500 gal and received more damage when the excitation increased to 600 gal.

Keywords: *system identification, hybrid genetic algorithm, Wen's model, restoring force, added-damping-and-stiffness device*

1. Introduction

Structural properties can deteriorate and degrade with time in an unexpected way as a result of randomness in the environment and loadings over its lifetime. When a structure is attacked by strong earthquakes, the properties of the structure may be altered, and its behavior after an earthquake can be different from that before the earthquake. In order to realize the dynamic behavior of structural systems, we can determine the dynamic models and parameters using system identification techniques.

Many applications of genetic algorithms are applied to various optimization problems such as system identification. Koh et al. [1], proposed a hybrid strategy to exploit the strengths of genetic algorithm (GA) and local search operators Two local search methods have been studied: the existing SW method and the proposed MV method. The numerical study showed that hybrid strategies performed better than GA alone. Wang et al. [2] applied real GA codes to structural identification problems. The validity and effectiveness of the GA strategy proposed was investigated for systems with simulation input/output measurements. Moreover, this strategy was also applied to the real structures.

Genetic algorithms (GAs) are global search algorithms for optimization. However, they are inherently slow and are not good for climbing hills. To accelerate convergence to the best solution, Wang [3] proposed and tested a GA hybrid identification strategy that combined the Gauss-Newton method as the local search technology.

The parameters of some real buildings can be altered with the change in the amplitude of vibration, and the identified parameters may not reflect the real state of the structure if we only use a model of a linear system to represent the structure. The method proposed for the identification of parameter for nonlinear systems in this paper is the hybrid GA that combines Wen's model as the restoring force model of story shear. A full-scale 3-story steel space frame with diagonal bracing in the Y direction was designed by the National Center for Research on Earthquake Engineering (NCREE) for structural control research. This full-scale 3-story steel space frame was installed with two circular added-damping-and-stiffness devices on the two frames for each floor in the X direction for structural control research. To capture the behavior of the control devices, it is intended to implement the identification techniques to the structures equipped with those devices. The method will be applied to three-story structural models with added-damping-and-stiffness devices mounted on the shaking table. The ground motion records used for these models are time histories of El Centro earthquake adjusted to intensities of 200 gal, 300 gal, 400 gal, 500 gal and 600 gal.

2. Hybrid Genetic Algorithm and Wen's Model

2.1 Genetic Algorithm

Genetic algorithms are stochastic search techniques based on natural selection and genetics developed by Holland [4]. Genetic algorithms model natural processes such as selection, recombination, mutation, migration, and competition. The algorithms work on a population of individuals instead of a single solution. In this way, the search is performed simultaneously. At the beginning of the calculation, a number of individuals are generated randomly. The objective function for these individuals is then evaluated. If the termination criteria are not met, a new generation will be created. Individuals are selected depending on their ability to produce offspring. The parents are recombined to produce offspring. All offspring will be muted with a certain probability. Then the fitness of the offspring is calculated. The offspring are incorporated into the population, replacing their parents, producing a new generation. This cycle continues until the optimization criteria have been met. Such a single population GA is powerful and performs well in various problems. However, better results can be obtained by introducing multiple subpopulations. Each subpopulation evolves over a few generations separated (like the single population GA) before one or more individuals are exchanged between subpopulations using migration and competition mechanisms. Multi-population GA models the evolution of a species more naturally than in a single population.

2.2 Gauss-Newton method

Since Gauss-Newton method has been demonstrated to be an efficient method in the nonlinear least square problems, it is appropriate to use it for the optimization of the prediction error in system identification problems. For the problem of system identification, an objective function $E(\tilde{x})$ minimized is a sum of squares as

$$E(\tilde{x}) = \frac{1}{2}\sum_{i=1}^{N}[f_i(\tilde{x})]^2 = \frac{1}{2}\sum_{i=1}^{N}[y_i - v_i(\tilde{x})]^2 \tag{1}$$

where $\tilde{x}$ is the vector of the parameters which will yield the minimized least square error between the measured response y_i and the predicted response $v_i(\tilde{x})$, and N is the number of measurement sequence. According to the quasi-Newton method, a new iterated parameter $\tilde{x}_{m+1}$ can be evaluated in terms of the current parameter vector $\tilde{x}_m$ as

$$\tilde{x}_{m+1} = \tilde{x}_m - H(\tilde{x}_m)G(\tilde{x}_m) \tag{2}$$

where $G(\tilde{x})$ is the gradient vector of $E(\tilde{x})$, and $H(\tilde{x})$ is the Hessian matrix of $E(\tilde{x})$. Denoting the Jacobian matrix of $E(\tilde{x})$ as $J(\tilde{x})$ and using the definition in Equation (1), we have

$$\tilde{x}_{m+1} = \tilde{x}_m - [J^T(\tilde{x}_m)J(\tilde{x}_m)]^{-1} J^T(\tilde{x}_m)[f_i(\tilde{x}_m)] \tag{3}$$

Equation (3) is the iterative formula for the Gauss-Newton method.

2.3 Hybrid GA Method

GA is a parallel global search technique that searches for multiple points without making any assumptions about search space. However, GAs are inherently slow and are not good at climbing hills. To compensate for the computational inefficiency of hill climbing when the solution obtained by GA approaches the optimal value, a GA-compatible local search operator is integrated into the GA strategy. When merging the Gauss-Newton method to GA, the efficiency and effectiveness can be affected by the following elements:

- Where to add the local search operator
- Who to carry out the local search operator
- The maximum number of iterations for local search
- When performing the local search operator

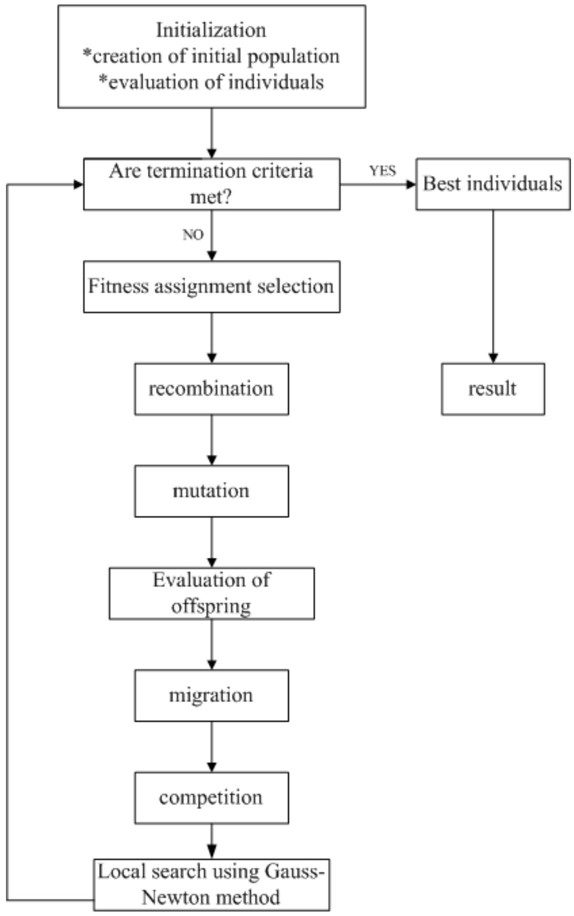


Fig. 1. Structure of hybrid GA

In order to realize these effects of these elements, the parameters of a single degree of freedom (SDOF) system are searched using different combinations of merging strategy by Wang [3]. The results obtained from the tests are as follows: (1) The Gauss-Newton method is performed after the evolution process is completed; (2) the best individuals of each subpopulation are used to perform the local search; (3) the maximum number of iterations for each local search is 5; and (4) the Gauss-Newton method is performed every 10 generations. In this regard, a hybridization of GA with the Gauss-Newton method was formed. Figure 1 shows the structure of this hybrid GA using the Gauss-Newton method as a local search operator.

2.4 Wen's Models

Structural systems often show nonlinear behavior under severe excitations. Accordingly, the restoring force becomes highly nonlinear, and shows significant hysteresis. Many hysteretic restoring force models has been developed to incorporate the time-dependent nature using a set of differential equations. Among them, the Wen's model [5] has been proven to be a versatile nonlinear hysteretic model because it can capture a wide range of shapes of hysteresis loops that represent the properties of real nonlinear structural systems in a continuous function.

The motion equation for such a single-degree-of-freedom (SDOF) system when excited by a uni-directional earthquake ground acceleration is

$$m\ddot{u} + c\dot{u} + \alpha k u + q(u,t) = -m\ddot{u}_g \tag{4}$$

where m = mass, c = damping coefficient, k =stiffness, and $\ddot{u}_g$ = ground acceleration in one direction. q is the restoring force defined by

$$q = \alpha \cdot K \cdot u + (1-\alpha)\cdot K \cdot z \tag{5}$$

z is the hysteretic component (displacement) of the restoring force governed by

$$\dot{z} = \dot{u} - (\beta \cdot |\dot{u}| \cdot |z|^{n-1} \cdot z + \gamma \cdot \dot{u} \cdot |z|^{n}) \tag{6}$$

Typically, α may be taken as the ratio of preyield to postyield stiffness. The shape of the hysteretic loop is controlled by parameters α, β, γ and *n* where the value of n set at 1. The measured response is the relative acceleration and can be represented as

$$y = \ddot{u} = -\ddot{u}_g - C\dot{u} - K[\alpha u + (1-\alpha)z] \tag{7}$$

where *C*=*c/m* and *K*=*k/m*

3. Application to symulated SDOF System

This section illustrates the application of hybrid GA to the simulated nonlinear SDOF system where the nonlinear restoring force of each floor is described by the Wen's model. The hybrid GA strategy is applied to identify the parameters *C, K,* α, β, γ in this case. To account for the effect of initial condition, initial displacement u_0, initial velocity $\dot{u}_0$, and initial hysteretic component z_0 are also implemented as parameters to be identified in addition to the system parameters.

In order to optimize the system, the error function is defined in such a way that it is quadratic in terms of the parameters and is denoted as the error index, *E.I.*, for the system.

$$E.I = \left[\frac{\sum_{i=1}^{Ns}(y_i - v_i)^2}{\sum_{i=1}^{Ns} y_i^{\,2}}\right]^{1/2} \tag{7}$$

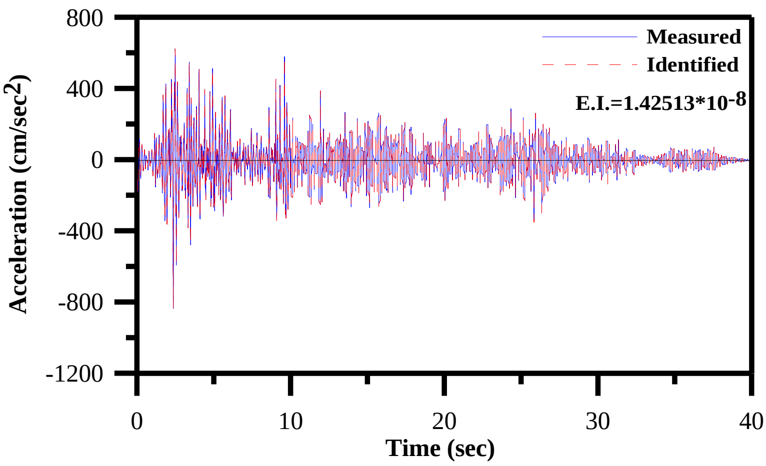


Fig. 2. Comparison of the measured response with the identified one of simulated SDOF system

The response used for the simulated system is generated by substituting the value of the system parameter and initial condition into Equation (7) to obtain the acceleration response. The parameters used are *C*=1.526、*K*=1325、 α =0.01, β=2.78, γ=-0.25,

u_0 =3, $\dot{u}_0$ =5, and z_0 =0.02. The ground excitation used is the time history of the El Centro earthquake with the PGA level scaled to 550gal. Then, the proposed strategy is implemented to identify the system parameters and the initial parameters. The identified parameters are the same as the true ones, and the error index is approximating 0. Figure 2 illustrates the comparison of the true acceleration with the identified one. There is a good agreement between the identified response and the measured one. Consequently, the strategy is demonstrated to be able to identify the system parameters for the nonlinear SDOF system.

4. Identification of A C the with circular added-damping-and-stiffness devices

The National Center for Earthquake Engineering (NCREE)has designed a full-scale three-story steel space frame with a diagonal Y-direction bracing in Figure 3 for structural control research. This three-story full-scale steel structure is designed and built at the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan. As shown in Figure 3, the three-story structure consists of a single bay with a floor area of 3m by 2m and with a height of 3m for each story. The structure is constructed using an H150x150x7x10 steel I beam for beam elements and column elements. Each beam-column connection is designed as a bolted joint. Concrete blocks are added and connected to the floor diaphragm until the total mass of each floor is precisely 6,000 kg. The entire structure is tested on a large-scale shaking table capable of applying base motion. Then, the full-scale 3-story steel space frame was installed with two circular added-damping-and-stiffness devices, called D20H100 dampers, on the two frames in the X direction for each floor. This device can be used to dissipate the energy produced by an earthquake. The V-shaped bracing system can be added to each story to support the installation of the added devices. The mass for the first two floors becomes 7150kg, and that of the third floor becomes 7000kg. Figure 4 shows the image of the frame with circular added-damping-and-stiffness devices taken from the NCREE Laboratory. Figure 4 also shows the scale of the D20H100 damping device and the image of the devices mounted on the frame. The height and diameter of the device are 100mm and 20mm, while the minimum diameter of the neck is 8.32mm. The device is made of stainless steel S304. The structural behavior is modeled using a lumped mass shear-building type of structural model defined by 3 degrees-of-freedom.

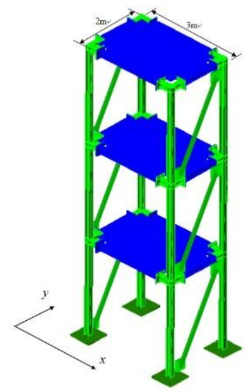
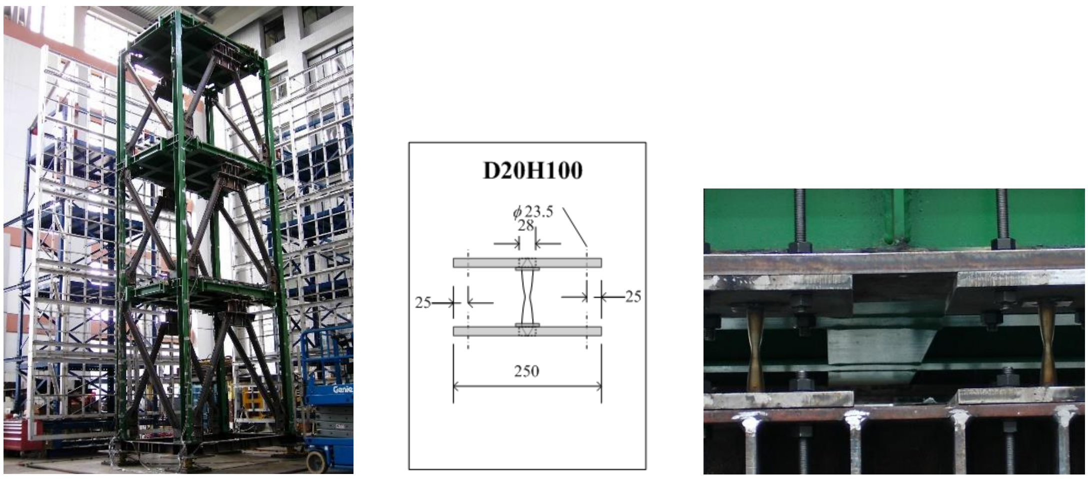


Fig. 3. 3-story steel frame [6]



(a) (b) (c)

Fig. 4. (a) Photo of the frame with circular added-damping-and-stiffness device (b) Scale of the device (c) Photo of the devices mounted on the frame.3-story steel frame [6]

This frame with added-damping-and-stiffness devices was tested on the shaking table. El Centro waves are selected as seismic excitation for the shaking table test. This excitation is scaled from the peak ground acceleration (PGA) value of 50gal to the value of 600gal with an increment of 50gal. In this paper, the system parameters of the frame will be identified using the response associated with the PGA value of 200gal, 300gal, 400gal, 500gal and 600gal. The ground excitation with PGA value equal to 200gal is denoted as EL200, etc. We can apply the hybrid genetic algorithm combining Wen's model as the restoring force model for each story shear to the records collected from the test with El Centro excitation of different PGA value and study the variation of the identified parameters.

First look at the changes in the story stiffness K_i. Table 1 shows that when the intensity of the earthquake is 200gal, K_1=4730, K_2=1448.9 and K_3=2701.2; when the intensity of the earthquake increases to 300gal, K_1=4854.2, K_2=1420.7 and K_2=2687.4; when the intensity of the earthquake increases to 400gal, K_1=4718.2, K_2=1497.9 and K_3=2659.2; when the intensity of the earthquake increased to 500gal, K_1=4545, K_2=1417.3 and K_3=2770.4; when the intensity of the earthquake finally increased to EL600, K_1=3718, K_2=1353.7 and K_3=2641.1. According to the above results, when the PGA value increases from 200gal to 600gal, K_1 decreases from 4730 to 3718, K_2 decreases from 1448.9 to 1353.7, and K_3 decreases from 2701.2 to 2641.1. Figure 5 shows a comparison of the identified story stiffness subjected to excitation of different PGA values. From the above results, it can be seen that when the intensity of the excitation becomes larger, the story stiffness of the first story will tend to become smaller, while decrease of the story stiffness of the second and third story are not very obvious.

Then compare the changes in α_i for each story, where α_i represents the post-yielding stiffness ratio, and the closer to 1, the closer to linearity. Table 1 shows when the excitation is EL200, the values of the three floors from the bottom to the top is 0.678, 0.899 and 0.986; if the excitation is EL300, the value of the three floors is 0.327, 0.873 and 0.996; if the excitation is EL400, the value of the three floors is 0.241, 0.844 and 0.995; if the excitation is EL500, the value of the three floors is 0.195, 0.636 and 0.931 respectively; finally if the excitation is EL600, the values of the three floors is 0.154, 0.831 and 0.952. As can be seen from the above identification results, when PGA value increases from 200gal to 500gal and then to 600gal, α_1 drops from 0.678 to 0.636 and then to 0.154, α_2 from 0.899 to 0.636 and then increases to 0.831, and α_3 from 0.986 to 0.931 and then to 0.952. Figure 6 is a comparison diagram of the three α_i values corresponding to all the identified results associated with different PGA values. From the above results, it can be seen that the value α_1 will decrease with the increase in the PGA value, indicating that inelastic response portion of the bottom floor becomes apparent. However, the figure shows that when the PGA value is 500gal, there is an increase trend for α_2; when the PGA value rises to 600gal, there is also an increase trend for α_3.

Therefore, we consider that the possible reason is that the first and second floors of the structure were slightly damaged by an excitation with PGA value of 500 gal and energy was dissipated through these two floors. The energy received on the third floor was reduced, resulting in an increase in the value α_3. When the value of the PGA value increased to 600 gal, the damage to the first floor became more serious. Most of the energy was dissipated on the first floor, reducing the energy transmitted to the second and third floors, thereby allowing both the α_2 and the α_3 values to rise.

Figure 6 illustrate the comparisons of true acceleration measurement with the identified response of the three floors for PGA values of 600gal.

Tab. 1. Identified parameters of three-story steel space frame

Excitation	dof	K_i	α_i	β_i	γ_i	E.I.
	1	4730	0.678	8.495	-2×10^{-5}	
EL200	2	1448.9	0.899	12.094	-1×10^{-6}	26.78%
	3	2701.2	0.986	82.997	-7×10^{-4}	
	1	4854.2	0.327	3.272	2.758	
EL300	2	1420.7	0.873	6.181	1.271	24.73%
	3	2687.4	0.996	0.493	-2.745	
	1	4718.2	0.241	3.210	2	
EL400	2	1497.9	0.844	6.127	1.991	26.42%
	3	2659.2	0.995	0.252	-3.483	
	1	4545	0.195	2.640	2.313	
EL500	2	1417.3	0.636	1.867	0.329	27.67%
	3	2770.4	0.931	5.170	7.832	
	1	3718	0.154	3.963	-4.5×10^{-8}	
EL600	2	1353.7	0.831	5.800	-2.383	28.55%
	3	2641.1	0.952	0.500	-2.690	

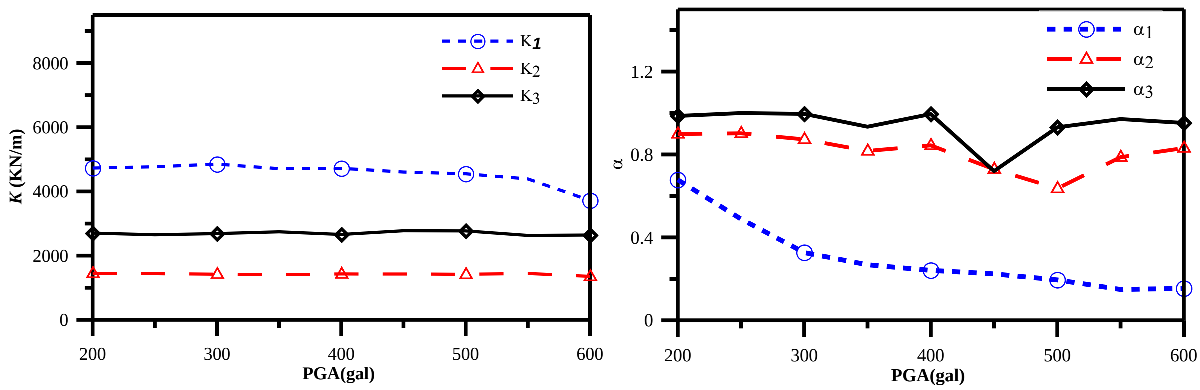


Fig. 5. Variation of identified story stiffness and post-yielding stiffness ratio

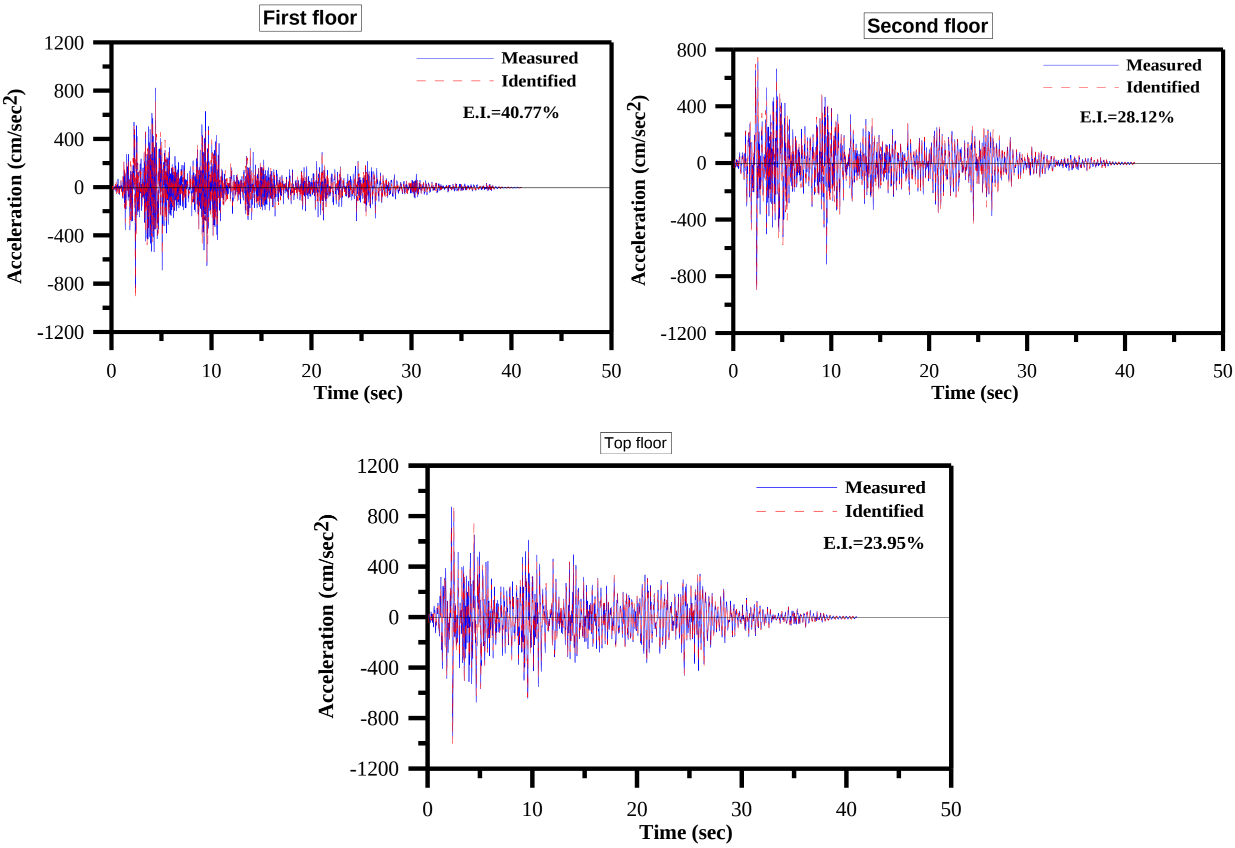


Fig. 6. Comparison of the measured response with the identified one of 3-Story frame (PGA level=600gal).

5. Conclusion

In this paper, a hybrid genetic algorithm combining Wen's model as the restoring force model is proposed. It changes the elastic restoring force of the original hybrid genetic algorithm to Wen's inelastic restoring force model, so it can effectively identify the dynamic parameters of structures equipped with dampers. This article first applied the new identification method proposed in the parametric identification of simulated single-degree-of-freedom system. Then, the new identification method was also applied to a real three-story steel frame equipped with circular added-damping-and-stiffness devices on each floor. Therefore, the following conclusion can be made:

1. Using the hybrid genetic algorithm combined with Wen's model to identify the response of the single-degree-of-freedom nonlinear numerical simulation system, it is observed that the parameter values identified are consistent with the true values. The identified response is also consistent with the measured response. Consequently, the applicability of the proposed strategy to the parametric identification of nonlinear dynamic systems is proved.
2. Based on the identification results of using the hybrid genetic algorithm to identify the full-scale three-story frame structure equipped with D20H100 circular added-damping-and-stiffness devices, it can be found that the stiffness corresponding to the three degrees of freedom will decrease slightly as the PGA value of the excitation increases.
3. From the results of the the post-yielding stiffness ratios, it can be seen that the value α_1 decreases with the increase in the PGA value, indicating that the inelastic response portion of the bottom floor becomes apparent. However, when the PGA value increased to 500gal, there was an increase trend for α_2; when the PGA value rose to 600gal, there is also an increase trend for α_3. When the first and second floors of the structure were slightly damaged under an excitation with a PGA value of 500gal, energy was dissipated through these two floors. The energy received on the third floor was reduced, resulting in an increase in the value α_3. When the PGA value of the excitation increased to 600 gal, the damage to the first floor becomes more serious. Most of the energy was dissipated on the first floor, reducing the energy transmitted to the second and third floors, thereby allowing both the α_2 and the α_3 values to rise.

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