Title: Cost Effective Computer Vision Based Structural Health Monitoring using Adaptive LMS Filters

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ABSTRACT

Structural health monitoring (SHM) algorithms based on Adaptive Least Mean Squares (LMS) filtering theory can directly identify time-varying changes in structural stiffness in real time in a computationally efficient fashion. However, the best metrics of seismic structural damage are related to permanent and plastic deformations. The recent work done by the authors uses LMS-based SHM methods with a baseline non-linear Bouc-Wen structural model to directly identify changes in stiffness (modelling or construction error), as well as plastic or permanent deflections, in real-time. The algorithm validated, *in silico*, on a non-linear shear-type concrete structure using noise-free simulation-derived structural responses.

In this paper, efficiency of the proposed SHM algorithm in identifying stiffness changes and plastic/permanent deflections under different ground motions is assessed using a suite of 20 different ground acceleration records. The results show that even with a fixed filter tuning parameters, the proposed LMS SHM algorithm identifies stiffness changes to within 10% of true value in 2.0 seconds. Permanent deflection is identified to within 14% of the actual as-modelled value using noise-free simulation-derived structural responses.

Accuracy of the proposed SHM algorithm mainly relies on providing high-speed structural responses. However, due to a variety of practical constraints, direct high frequency measurement of displacement and velocity is not typically possible. This study explores the idea that emerging high speed line scan cameras can offer a robust and high speed displacement measure required for the modified LMS-based SHM algorithm proposed for non-linear yielding structures undergoing seismic excitation, and can be used for more precise estimation of the velocity using measured acceleration and displacement data. The displacement measurement method is tested to capture displacements of a computer-controlled cart under 20

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different displacement records. The method is capable of capturing displacements of the cart with less than 2.2% error.

INTRODUCTION

Structural health monitoring (SHM) is the process of comparing the current state of a structure's condition relative to a baseline state to detect the existence, location, and degree of likely damage after a damaging input. Many current vibration-based SHM methods are based on the idea that changes in modal parameters; frequencies, mode shapes and modal damping, are a result of damage or decay. These methods are typically more applicable to steel-frame and bridge structures where vibration response is highly linear [1]. However, a major drawback of many approaches is their inability to be implemented in real-time, on a sample-to-sample basis as the event occurs. Further, their reliance on modal properties has potential problems. In some cases, modal properties are not robust in the presence of strong noise and insensitive to small amounts of damage [2]. Adaptive fading Kalman filters [3] and adaptive H_∞ filter techniques [4] which achieve real-time or near real-time results, provide identification of modal parameters in real time, but come with significant computational cost and complexity. Moreover, like other linear approaches they are not applicable to the typical nonlinearities found in seismic structural responses.

In contrast, direct identification of changes in stiffness and/or plastic deflection would offer the post-earthquake outputs desired by engineers. Adaptive Least Mean Squares (LMS) based SHM has been used for a benchmark problem [1], and also for a non-linear rocking structure [5], to directly identify changes in structural stiffness only. They are robust with fast convergence and low computational cost. However, they do not identify plastic and permanent deflections. The modified adaptive LMS-based SHM method with a baseline non-linear Bouc-Wen structural model to directly identify changes in stiffness (due to modelling or construction error) as well as plastic or permanent deflections in real-time in a computationally efficient fashion was introduced by the authors [6].

The adaptive LMS-based SHM methods require high-speed structural response measurement, but due to a variety of practical constraints, direct high frequency measurement of displacement and velocity is not typically possible. Displacement and velocity are often estimated by integration of measured acceleration and are subject to drift and error. However, this error can be corrected using low frequency displacement data obtained via a variety of sensors, such as ground-based GPS or fibre optics. The work described below explores the idea, which first was proposed by Lim et al. [7] for pile movements measurement, that emerging high speed line scan cameras can offer a robust and high speed displacement measure required for LMS-based SHM algorithms proposed for non-linear yielding structures undergoing seismic excitation.

Moreover, there is no reported result on performance of the adaptive LMS-based SHM algorithms under different ground motions or in other words, independency of the results from the external excitation.

This paper describes briefly the proposed modified LMS-based SHM algorithm capable of identifying stiffness changes and plastic or permanent deflections in real time, and presents the algorithm validation results and the results for performance analysis of the method under 20 different ground motions. Second part of the paper provides results for structural displacement measurement using a line scan camera and similar method explained in [7] under 20 different displacement records and evaluates the accuracy of the method for building displacement measurement.

In addition to the above mentioned issues, noise effect on performance of the proposed algorithm needs to be assessed at later stages of this study.

DEFINITION OF THE SHM PROBLEM

A seismically excited non-linear structure can be modelled at each time step using the incremental equations of motion:

$$\mathbf{M}\cdot\{\Delta\ddot{v}\}+\mathbf{C}\cdot\{\Delta\dot{v}\}+\mathbf{K}_{\mathbf{T}}(\mathbf{t})\cdot\{\Delta v\}=-\underline{\mathbf{M}}\cdot\Delta\ddot{x}_g \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K_T}$ are the mass, damping, and tangent stiffness matrices of the model, respectively, $\{\Delta v\}$, $\{\Delta\dot{v}\}$, and $\{\Delta\ddot{v}\}$ are the changes in displacement, velocity, and acceleration vectors, respectively, and $\Delta\ddot{x}_g$ is the change in the ground motion acceleration over the time step. The tangent stiffness matrix of a hysteretic structure can be represented using Bouc-Wen model assuming that bi-linear factor of each storey, which determines the change in slope between elastic and plastic regimes of that storey, and other Bouc-Wen model parameters described below are known. z_i, the dimensionless hysteretic component of the i^{th} storey is governed by the following first order non-linear differential equation [8]:

$$\dot{z}_i(t)=\frac{A_i\dot{r}_i(t)-\beta_i|\dot{r}_i(t)||z_i|^{n_i-1}z_i-\gamma_i\dot{r}_i(t)|z_i|^{n_i}}{Y_i},i=1,...,N \tag{2}$$

where A_i (usually 1.0), β_i (0.1 to 0.9), γ_i (-0.9 to 0.9), and n_i (1 to 3, usually 1) are stiffness, loop fatness, loop pinching, and abruptness parameters in a classical Bouc-Wen model, respectively. Further, n_i, the power factor, determines the curve from elastic to plastic force-deflection behaviour of each storey. $\dot{r}_i(t)$ is the velocity of storey i relative to storey i-1, Y_i is the yield displacement of i^{th} story, and N is the number of stories. The five dimensionless parameters, A_i, β_i, γ_i, n_i, and α_i determine the hysteresis loops shape. Neither degradation nor pinching of hysteresis is accounted for by the classical Bouc-Wen model. Over the years, this classical model has been modified to accommodate changes in hysteresis loops arising from deteriorating systems, and the contemporary model can be found in [9]. In this study, the classical Bouc-Wen model has been used, and only nonlinearities arising from the hysteresis behaviour of the building have been considered.

If damage occurs in the structure from an earthquake, or any other source of damaging excitation, structural properties, such as natural frequency and stiffness may also change, and may be time-varying. For the damaged structure, the equations of motion can be re-defined as:

$$\mathbf{M}\cdot\{\Delta\ddot{\bar{v}}\}+\mathbf{C}\cdot\{\Delta\dot{\bar{v}}\}+(\overline{\mathbf{K}}_{\mathbf{T}}+\Delta\overline{\mathbf{K}}_{\mathbf{T}})\cdot\{\Delta\bar{v}\}=-\underline{\mathbf{M}}\cdot\Delta\ddot{x}_g \tag{3}$$

where $\{\Delta\ddot{\bar{v}}\}$, $\{\Delta\dot{\bar{v}}\}$, and $\{\Delta\bar{v}\}$ are the measured changes in responses of the damaged structure, $\overline{\mathbf{K}}_{\mathrm{T}}$, is the tangent stiffness matrix of the damaged structure, and $\Delta\overline{\mathbf{K}}_{\mathrm{T}}$ contains changes in the tangent stiffness due to modelling or construction error damage and can be a function of time. $\Delta\overline{\mathbf{K}}_{\mathrm{T}}$ due to modelling or construction damage only appears in changes in initial stiffness of each storey.

Identifying the $\Delta\overline{\mathbf{K}}_{\mathrm{T}}$ term enables the structure's condition to be directly monitored without using modal parameters. To determine $\Delta\overline{\mathbf{K}}_{\mathrm{T}}$ using adaptive LMS, following the method proposed in [1], a new form of $\Delta\overline{\mathbf{K}}_{\mathrm{T}}$ is defined with time-varying scalar parameters $\hat{\alpha}_i$, representing stiffness of the i^{th} storey, to be identified using the LMS filter:

$$\Delta\overline{\mathbf{K}}_{\mathrm{T}} = \sum_{i=1}^{n} \hat{\alpha}_i \mathbf{K}_{\mathrm{i}} \tag{4}$$

where n is the number of degrees of freedom of the model, and $\mathbf{K_i}$ is the corresponding time-varying matrix to i^{th} degree of freedom [6]. Rewriting (3) for each time step using (4) yields:

$$\sum_{i=1}^{n} \hat{\alpha}_i \mathbf{K}_{\mathrm{i}} \cdot \{\Delta\bar{v}\}_k = -\mathbf{M}\cdot(\Delta\ddot{x}_g)_k - \mathbf{M}\cdot\{\Delta\ddot{\bar{v}}\}_k - \mathbf{C}\cdot\{\Delta\dot{\bar{v}}\}_k - \overline{\mathbf{K}}_{\mathrm{T}}\cdot\{\Delta\bar{v}\}_k = \{y\}_k \tag{5}$$

where $(\Delta\ddot{x}_g)_k$ is the change in the input ground acceleration over a given time step of k, and $\{\Delta\ddot{\bar{v}}\}_k$, $\{\Delta\dot{\bar{v}}\}_k$ and $\{\Delta\bar{v}\}_k$ are the measured changes in the acceleration, velocity, and displacement vectors of the damaged structure over the same time step, respectively. Matrices of $\overline{\mathbf{K}}_{\mathrm{T}}$ and $\mathbf{K_i}$ are calculated sample-to-sample using Equation (2) with the measured damaged structural responses. The elements of the vector signal $\{y\}_k$ can be readily modelled in real-time using an adaptive LMS filter so that the coefficients $\hat{\alpha}_i$, changes in linear elastic stiffness of each storey due to modelling or construction damage, can be readily determined [6].

INPUTS TO THE SHM PROBLEM

Inputs to this SHM problem are structural responses: acceleration, velocity, and displacement. Acceleration can be easily measured with low cost accelerometers at high sampling rates, but due to practical constraints, direct high speed measurement of displacement and velocity is not typically possible. A high speed displacement sensor would provide displacement, and could be used to derive a more precise estimation of the velocity at low added computational cost. To measure displacement of a real structure at high rates up to tens of kHz, line scan cameras can be used. This paper explores the similar method described in [7] to capture structural displacements caused by different ground motions to evaluate performance of the proposed method as a displacement sensor to capture structural displacements due to seismic excitations.

SIMULATED CASE STUDY STRUCTURE

The simulated structure is a single degree of freedom model of one of the moment-resisting frames in long-direction of a five-story concrete building. The floor system consists of 200 series precast hollow-core floor units having a 65 mm topping spanning on long direction of each floor. The seismic weight per floor is 1692 kN for roof level and 2067 kN for other levels. Each storey has 3.8 m height, and the frame system is designed according to the New Zealand Concrete Structures Standard [10] using the displacement-based design approach to sustain a target drift level of 2% under a 500-year return period earthquake. Ruaumoko [11] was used to perform push over analysis to determine the total linear stiffness (27300 kN/m), the bi-linear factor (0.065), and the yield displacement (46.5 mm) of the building.

Non-linear dynamic analysis using a Bouc-Wen hysteretic model was performed in MATLAB® to represent the non-linear hysteretic behaviour of the structure, and the simulated structural responses from MATLAB® were used to provide proof of concept and quantify the accuracy of the identified parameters, changes in linear elastic stiffness of each storey, plastic and permanent displacements. In simulating the structural responses, 5% constant damping was considered, and the building was given a shaping parameter of n=2, loop fatness and loop pinching factors of $\beta=\gamma=0.5$ to provide realistic non-linear structural behaviour.

The developed SHM algorithm was implemented in MATLAB® for the stiffness identification process, and identified values were used to recalculate structural responses using the Newmark-β integration method.

Plastic deflection is defined as to be the deflection of the structure if the elastic component of displacement were removed. It is a function of time, and is zero for an elastically responding structure. Moreover, permanent deflection is the final plastic deflection.

To assess how well the proposed adaptive filtering method is performing in modelling changes in stiffness and plastic or permanent deflections under different ground motions, the simulated structure was subjected to an ensemble of 20 different ground motions shown in Table I, with a 5% reduction in pre-yield stiffness applied to the structure at the 10 second mark. The adaptive identification process was performed with a fixed filter tuning parameter or step size (μ) for the whole records in Table I. This factor determines convergence of the filter as well as speed of the convergence. Simulation-derived data was recorded at 500 Hz.

More details about the selected records can be found in [12]. Although there are some studies which show that there is little evidence to support the need for a careful site-specific process of record selection by magnitude and distance for nonlinear seismic analysis of structures [13], this suite has been selected since it has been widely used for structural dynamic analyses in different studies and is a very popular suite among earthquake engineers.

To assess performance of the proposed high-speed displacement measurement method in [7] to capture seismic structural displacements, a single-degree-of-freedom case study structure with an undamped natural period of 0.5 seconds was considered, and displacements of the structure under different earthquakes shown in Table I were simulated in MATLAB® using Newmark-β integration method with 5% constant damping. This natural period was chosen to involve higher frequencies in frequency spectrum of the displacement data. Since there is no limit on amplitudes of the vibrations in the proposed displacement measurement method in [7], the records were used without scaling. Peak values for the derived displacement records are shown in Table I. Moreover, FFT analysis of the derived displacement suite for the simulated structure shows that there is no effective frequency in displacement data greater than 10 Hz, therefore, to avoid loosing data, displacement measurement was carried out at 100 Hz. Camera resolution and lens magnification were chosen to have 0.03 mm resolution in measurement data.

A computer controlled cart, which can be moved using dSPACE, was used to generate displacement patterns in front of the camera, and encoder counts for the actual position of the cart were used for comparison with the results from the imaging system for the cart displacements to avoid errors in the cart positioning process. Figure 1 shows the experimental set-up used for the cart displacement measurement.

Table II presents specifications of the measurement set-up. System settings such as resolution, frame rate, geometrical configurations, and magnification of the lens can be changed to accommodate the need for different measurement resolutions and speeds.

Table I. SELECTED GROUND MOTIONS

EQ	Event	Year	Station	R-Distance (km)	Soil Type	Duration (s)	Scaling Factor	PGA (g)	Peak Displacement (cm)
EQ1	Cape Mendocino	1992	Fortuna - Fortuna Blvd.	23.6	B	44.0	3.8	0.116	1.71
EQ2			Rio Dell Overpass - FF	18.5	B	36.0	1.2	0.385	3.78
EQ3	Landers	1992	Desert Hot Springs	23.2	B	50.0	2.7	0.171	1.5
EQ4			Yermo Fire Station	24.9	C	44.0	2.2	0.245	3.39
EQ5	Loma Prieta	1989	Capitola	14.5	C	40.0	0.9	0.48	4.85
EQ6			Gilroy Array #3	14.4	C	39.0	0.7	0.367	3.90
EQ7			Gilroy Array #4	16.1	C	40.0	1.3	0.417	5.26
EQ8			Gilroy Array #7	24.2	C	40.0	2.0	0.323	4.23
EQ9			Hollister Diff. Array	25.8	-	39.6	1.3	0.269	2.86
EQ10			Anderson Dam	21.4	B	40.0	1.4	0.244	3.8
EQ11	Northridge	1994	Beverly Hills 14145 Mulhol	20.8	B	30.0	0.9	0.617	3.77
EQ12			Canoga Park - Topanga Can	15.8	C	25.0	1.2	0.42	4.53
EQ13			Glendale - Las Palmas	25.4	C	30.0	1.1	0.357	3.09
EQ14			LA - Hollywood Stor FF	25.5	C	40.0	1.9	0.358	4.14
EQ15			LA - N Faring Rd	23.9	C	30.0	2.2	0.242	2.61
EQ16			N. Hollywood - Coldwater	14.6	B	21.9	1.7	0.298	2.03
EQ17			Sunland - Mt Gleason Ave.	17.7	B	30.0	2.2	0.157	2.76
EQ18	Superstition Hills	1987	Brawley	18.2	C	22.0	2.7	0.116	0.94
EQ19			El Centro Imp. Co. Cent.	13.9	C	40.0	1.9	0.358	3.83
EQ20			Plaster City.	21.0	C	22.2	2.2	0.186	3.52

Table II. MEASUREMENT SET-UP SPECIFICATIONS

Item	Description
Camera	DALSA P2-23-08K40
Max. line rate (kHz)	9.3
Pixel size (um)	7 x 7
Resolution (pixel)	8192
Frame grabber board	NI PCIe-1430
Light source	Halogen Lamb, 50W
Lens	Schneider Componon-S 4.0/80 with focusing mount and accessories
Image acquisition and processing software	LabVIEW™ 8.5

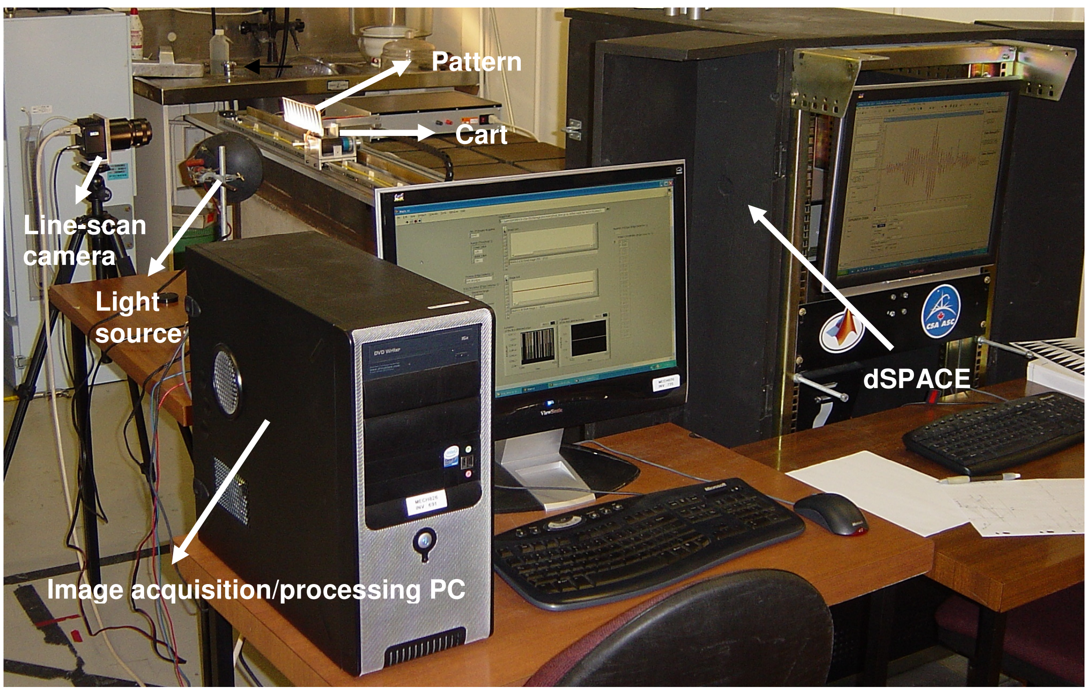

Figure 1. Experimental set-up used for displacement measurement

RESULTS

Identification Process Results

As shown in Figure 2, for the simulated case study structure, in a worst-case sudden failure situation, changes in pre-yield linear elastic stiffness of the structure converge to within 10% of the actual value in less than 2 seconds using a fixed step size and 10 taps at a 500 Hz sampling rate under all 20 different seismic excitations in Table I. The filter also approaches faster and smoother to the final values of the pre-yield stiffness changes after damage when higher sampling rates or a greater number of taps (prior time steps) are used to identify the stiffness changes [6].

Running the simulation with estimated values for changes in pre-yield stiffness of the structure to obtain identified responses of the damaged structure using the Newmark-β integration method and to get the plastic and permanent deflections of the structure, shows that as the filter approaches its final value for changes in stiffness, the plastic deflection approaches its actual final value and the error between actual and estimated values for plastic deflections becomes smaller. For the suite used in this study, as Figures 3(a) and (b) show, the ratio between norms of the error signal in estimating the plastic deflections and the actual plastic deflection signal is less than 12%, and the error in identifying the permanent deflection is less than 15% of the actual value for the whole records used in this study. As Figure 3 presents, records which cause permanent deflections less than 0.1% of the height of the case study structure have been excluded from the error evaluation process.

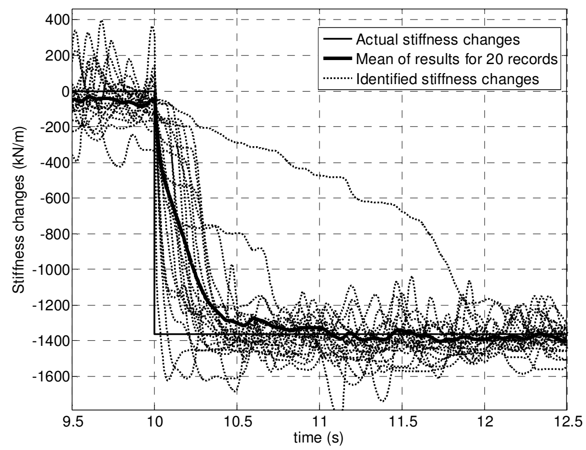

Figure 2. Identified changes in linear elastic stiffness of the simulated structure (10 taps with μ=25000)

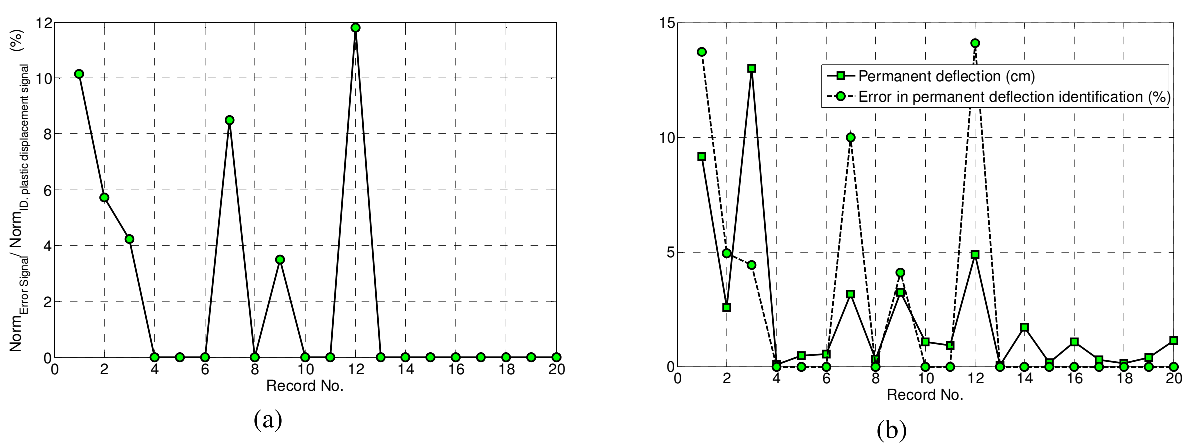

Figure 3. (a) Changes in the ratio of norms of the error in identifying plastic deflections and the plastic deflection signal, and (b) identified permanent deflections and changes in permanent deflection identification error over 20 different records in Table I

Moreover, as Figures 2 and 3 show, performance of the proposed SHM algorithm in identifying changes in stiffness and plastic or permanent deflections changes under different ground excitations, and even the best tune for the step size may result in large errors as high as 14% in identified permanent deflection. This clearly supports the need for a self-tuning LMS-based filtering algorithm, which begins with an initial value for the filter step size tuned based on past earthquake records, and adapts itself to the external load changes for the best identification results.

Displacement Measurement Results

Figure 4 presents the error in displacement measurement across 20 different displacement records derived from the earthquake ground accelerations described in Table I for a case study structure with a natural period of 0.5 seconds. Since the speed and resolution of the displacement measurement set-up is sufficient to capture movements of the cart, which represents a point on the structure, the error is mainly due to inaccurate cart position data from the encoder. These encoder errors are caused by backlash in a pinion coupled to the encoder which is moved on the rack by the cart movements.

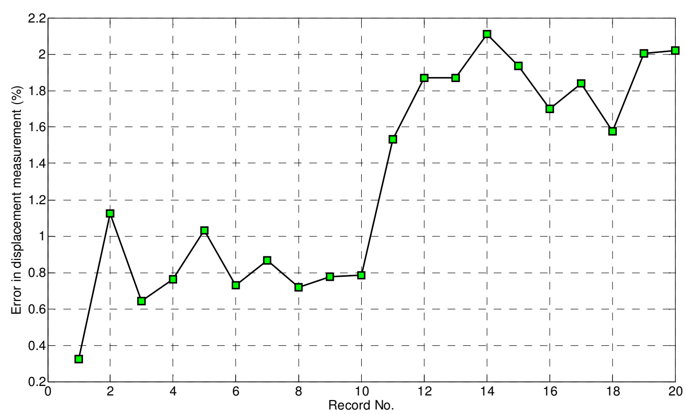

Figure 4. Changes in the displacement measurement error for the different records in Table I

CONCLUSION

The developed LMS-based SHM method with a baseline non-linear Bouc-Wen structural model can directly identify changes in stiffness (modelling or construction error) and plastic deflections, in real-time. The simulation results show that for the single-degree-of-freedom simulated structure under the suite of records used in this study, the algorithm identifies stiffness changes to within 10% of true values in less than 2.0 seconds, and permanent deflection is identified to within 14% of actual values using noise-free structural responses. Moreover, over the entire 20 different records used in this paper, norm of the error signal in identifying plastic deflections over the norm of the actual plastic deflection signal is less than 12%. These values for the error support the need for implementing an adaptive step size LMS filter in further studies.

In addition, effectiveness of the displacement measurement method proposed by Lim et al. has been investigated for seismic structural vibration measurement through carrying out some experiments, and the results for the case study structure under the 20 different studied records show less than 2.2% error.

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