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Application of MR Damper in Real-time Structural Damage Detection Using Extended Kalman Filter

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ABSTRACT
The current condition and performance of infrastructure systems in the US is in urgent need of improvements. Maintaining civil engineering structures in good condition through structural health monitoring has become an increasingly viable option. Real-time damage detection capability is desirable in order to determine the status of the structure online, and send out an early damage alarm to prevent loss of life and property. In this paper, a novel approach using extended Kalman filter is proposed to detect structural damage for structural dynamic systems containing MR damper. Based on measurement of accelerations of each degree-of-freedom and damper force, the EKF algorithm can identify state variables and parameters for both structure and MR damper in real time. The extended Kalman filter based approach is tested using simulation response data of a magneto-rheological damper controlled linear building structure under earthquake excitation. The numerical results show that this adaptive extended Kalman filter based method is capable of tracking the state variables and approximating structural parameters online with high confidence.

KEYWORDS: *Structural damage detection, Structural control, MR damper, Extended Kalman filter, System identification*

1. INTRODUCTION

Structural health monitoring for civil structures has received great interests in the past decades. The goal of structural health monitoring system is to determine the status of the structure and detect the damage when it occurs. Generally damage detection methods can be divided into two categories: frequency domain method and time domain method. Frequency domain method detects structural damage based on the changes of structure's mechanical properties, such as natural frequency. [1] However, it is not sensitive to tiny damages. In addition, the post-processing approach is expensive and slow, thus is not adaptive to online damage detection. On the other hand, time-domain system identification method detects structural damage based on online measurement data of dynamic responses from in-service structures, thus can overcome the above difficulties. Extended Kalman filter (EKF) is one of the representative techniques [2].

The extend Kalman filter (EKF) is an effective method to identify system parameters, and it has been adapted to solve various damage detection problems in structural engineering [2]-[7]. The EKF linearizes the nonlinear equation by using Tylor series expansion, and predicts structural parameters based on approximating state prediction with real measurement. Different from frequency domain method that only uses modal parameters to represent key characteristics of a structure, EKF-based method can estimate structural parameters directly, thus it is more accurate for structural damage detection and damage localization. Furthermore, it is feasible for building a real-time automatic structural damage detection system for in-service structures. Many successful applications of EKF-based structural damage detection method have been reported. Yang et al. developed an adaptive extended Kalman filter (AEKF) method to track changes of structural parameters, and tested in numerical simulations for both linear and nonlinear structures [2]. The capacity of AEKF in identifying the structural damage is verified using lab-scale structural dynamic experiments [3]. Soyoz et al. presented an experimental verification of EKF method using a three-bent concrete bridge model subjected to seismic damage on a large-scale shaking table, which showed that EKF was also useful to provide quantification of structural damage and post-event capacity evaluation [4].

The magneto-rheological (MR) fluid damper is a promising device in structural control to reduce structural damage due to dynamic loadings. The MR damper can also be used as an ideal component in structural dynamic experiments. Changing the current inputs and settings of the damper can result in significant difference in the force response of the damper and structure. The MR damper has nonlinear and rate dependent properties, thus a challenging problem for structural damage detection is to develop an accurate and effective model to identify structural properties for structures that equipped with MR damper components.

2. LARGE SCALE MR DAMPER

The MR damper considered in this study is large-scale MR damper which is used for seismic reduction for building structures. The schematic of the MR damper manufactured by the Lord Corporation is shown in Fig. 2.1. The damper is 1.47 m (57 inches) in length, weights approximately 2.734 kN (615 lbs), and has an available stroke of 584 mm (23 inches). The damper's accumulator can accommodate a temperature change in the fluid of 80 ºF (27 ºC). The damper can provide control forces of over 200 kN (25 kip). The dynamics of the MR damper is controlled by commanded variable current. Details about the dynamic models of the current driver and magnetic coils used in this study can be found in Jiang and Christenson (2012) [8].

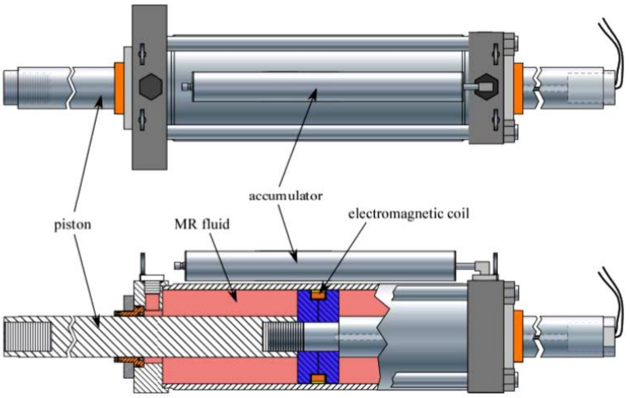

Figure 2.1 Schematic of large scale MR damper [8]

3. HYPERBOLIC TANGENT MODEL FOR MR DAMPER

Four numerical models have been proposed and verified to determine the values of MR damper force as a function of current, displacement and velocity of the damper: hyperbolic tangent model, Bouc-Wen model, viscous plus Dahl model and algebraic model [9]. The hyperbolic tangent MR damper model can be described in a state space form, thus can be estimated by extend Kalman filter and applied in this study. The hyperbolic tangent model used in this paper is based on the model proposed by Bass and Christenson (2007) [10]. The schematic of this model is shown in Fig. 3.1.

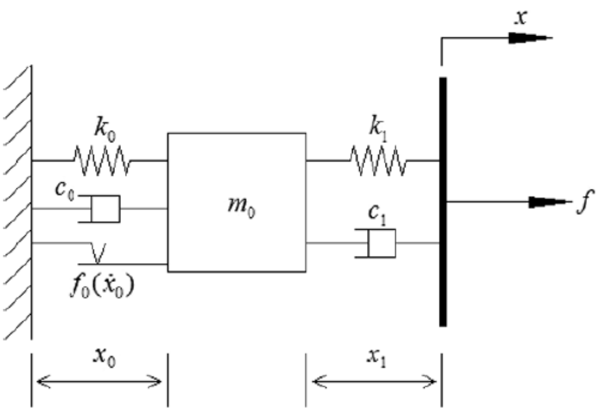

Figure 3.1 Schematic of the MR damper hyperbolic tangent model

The state space model for the dynamic system of the MR damper hyperbolic tangent model can be described as Eq. 3.1 and Eq. 3.2.

$$\begin{bmatrix} \dot{x}_0 \\ \ddot{x}_0 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ (-k_0 - k_1)/m_0 & (-c_0 - c_1)/m_0 \end{bmatrix} \begin{bmatrix} x_0 \\ \dot{x}_0 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ k_1/m_0 & c_1/m_0 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \end{bmatrix}$$
$$+ \begin{bmatrix} 0 \\ 1/m_0 \end{bmatrix} \times f_0 \tanh(\dot{x}_0 / V_{ref}) \tag{3.1}$$

$$f = \begin{bmatrix} -k_1 & -c_1 \end{bmatrix} \begin{bmatrix} x_0 \\ \dot{x}_0 \end{bmatrix} + \begin{bmatrix} k_1 & c_1 \end{bmatrix} \begin{bmatrix} x \\ x \end{bmatrix} \tag{3.2}$$

where x_0 and $\dot{x}_0$ are the displacement and velocity of the inertial mass relative to a fixed end, x_1 and $\dot{x}_1$ are the displacement and velocity of the damper piston end relative to the inertial mass. The k_1 and c_1 model the pre-yield visco-elastic behavior, and k_0 and c_0 model the post-yield visco-elastic behavior. The m_0 represents the inertia of both fluid and the moving piston. In the Coulomb friction function term, f_0 is the yield force and V_{ref} is a reference velocity.

The hyperbolic tangent model has seven parameters (k_0, k_1, c_0, c_1, m_0, f_0, V_{ref}), each of them can be expressed through a function of current. The functions of these parameters with current are shown in Table 3.1. More details about how these functions are determined can be found in Bass and Christenson (2007) [10].

Table 3.1 Parameters in the hyperbolic tangent model.

Parameters as a function of damper current, *i* (A)	**Units**
$k_0 = (0.10i^4 - 1.00i^3 + 1.30i^2 + 2.30i + 6.20) \times 10^{-4}$	kN mm^{-1}
$k_1 = -2.43i^4 + 23.76i^3 - 80.70i^2 + 110.62i + 55.08$	kN mm^{-1}
$c_0 = (-0.98i^4 + 9.33i^3 - 29.96i^2 + 35.80i + 12.64) \times 10^{-2}$	kN s mm^{-1}
$c_1 = (-0.62i^4 - 6.73i^3 + 29.96i^2 - 46.06i + 35.67) \times 10^{-2}$	kN s mm^{-1}
$m_0 = (0.16i^4 - 1.62i^3 + 5.48i^2 - 7.05i + 4.85) \times 10^{-3}$	kg
$f_0 = 1.52i^4 - 10.27i^3 + 2.79i^2 + 94.56i + 6.19$	kN
$V_{\mathrm{ref}} = -0.12i^4 + 1.36i^3 - 6.19i^2 + 13.12i + 0.76$	mm s^{-1}

4. EXTENDED KALMAN FILTER BASED DAMAGE DETECTION

The extended state vector of the dynamic system is defined as

$$x(t) = \left[u(t), \dot{u}(t), \alpha(t)\right]^T \tag{4.1}$$

where $\alpha(t) = \left[\alpha_1(t), \alpha_2(t), \cdots, \alpha_n(t)\right]^T$ is a vector of the unknown parameters for building structure and damper.

The state equation and measurement equation of Kalman filter can be written as:

$$\dot{x}(t) = f\left(x(t)\right) + v(t) \tag{4.2}$$

$$y(t) = h\left(x(t)\right) + w(t) \tag{4.3}$$

where $v(t)$ and $w(t)$ are process and observation noises, respectively, and $y(t)$ is measurement vector. For simplification, both of process noise and measurement noise are assumed white, zero-mean, and Gaussian noise, with process covariance matrix $Q(t)$ and measurement noise covariance matrix $R(t)$.

Since the state equation is in a continuous-time form, it is required to convert into the discrete time when applying linearization is on both state and measurement equations. State equation can be linearized to obtain state matrix F_k , which is the partial derivative of $f(x(t))$ with respect to $x(t)$ at the estimated weights, i.e., a Jacobian matrix,

$$F(t) = \frac{\partial f\left(x(t)\right)}{\partial x} \tag{4.4}$$

$$F_k = F\left(\hat{x}\left(k|k-1\right)\right) \tag{4.5}$$

Similarly, linearized measurement matrix H_k can be obtained as the partial derivative of $h(x(t))$ with respect to $x(t)$ at the estimated weights, i.e., a Jacobian matrix,

$$H(t) = \frac{\partial h\left(x(t)\right)}{\partial x} \tag{4.6}$$

$$H_k = H\left(\hat{x}\left(k|k-1\right)\right) \tag{4.7}$$

The first-order Taylor series expansion is used to obtain the state transition matrix of the linearized system,

$$\Phi(t_k, t_{k-1}) = I + \Delta t \times F_{k-1} \tag{4.8}$$

Given the initial values of state $x(0)$, discrete process noise covariance matrix $Q(0)$, the measurement noise covariance matrix $R(0)$, and the initial estimation error covariance matrix $P(0|0)$, the EKF procedure can be recursively implemented. The key steps of EKF are summarized as time-update equations Eq. 4.9-4.10, and measurement-update equations Eq. 4.11-4.14.

$$\hat{x}(k+1|k) = \Phi(k)\hat{x}(k|k) \tag{4.9}$$

$$\hat{y}(k+1|k) = H(k+1)\hat{x}(k+1|k) \tag{4.10}$$

$$S(k+1) = H(k+1)P(t)H(k+1)^T + R(k+1) \tag{4.11}$$

$$G(k+1) = P(k+1|k)H(k+1)^T S(k+1)^{-1} \tag{4.12}$$

$$P(k+1|k+1) = P(k+1|k) - G(k+1)H(k+1)P(k+1|k) \tag{4.13}$$

$$\hat{x}(k+1|k+1) = \hat{x}(k+1|k) + G(k+1)\left(y(k+1) - \hat{y}(k+1|k)\right) \tag{4.14}$$

where $G(k)$ is the Kalman gain, and $P(k|k)$ is the weight covariance matrix. The variance of output can be obtained from the diagonal elements of the covariance matrix $S(k+1)$.

5. NUMERICAL SIMULATION

EFK based method has been applied in structural damage detection for both linear and non-linear structural problems [5] [6]. For this study considering MR damper, the numerical testing is performed using Simulink in Matlab. The testing structure is a three story one bay steel frame building, with total weight of 596 kN. As shown in Fig. 5.1, the structure is a linear, in-plane, three degree-of-freedom model with an MR damper installed at the first story. The MR damper is controlled by a constant 2A current. The time history data of acceleration for each floor, MR damper force and ground acceleration are obtained from simulation tests, and then are fed into EKF algorithms to estimate the states and parameters of structure and MR damper. To achieve the goal of real-time damage detection, this method is expected to demonstrate the capacity to identify system states for both structure and MR damper.

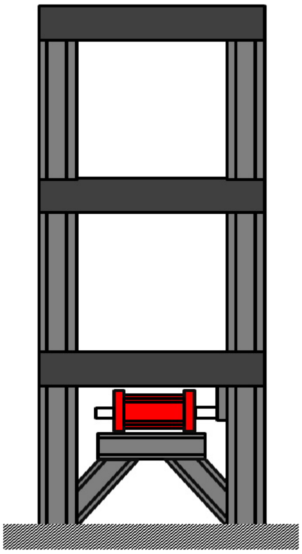

Figure 5.1 Three story building structure with MR damper

The equation of motion for the simulated structure can be represented as:

$$M\ddot{x}+C\dot{x}+Kx=-Gf-ML\ddot{x}_g \tag{5.1}$$

where $x = [x_1; x_2; x_3]^T$ is the relative displacement of each story, $\dot{x}$ and $\ddot{x}$ are the relative velocity and acceleration of each story. The relative displacement and velocity of first story is assumed equal to the MR damper. $\ddot{x}_g$ is the ground acceleration and f is the damper force. The influence vectors of MR damper force $G = [1; 0; 0]^T$, and ground excitation matrix $L = [1; 1; 1]^T$. The mass matrix M, stiffness matrix K and damping matrix C, are as:

$$M=\begin{bmatrix} 20.253 & 0 & 0 \\ 0 & 20.253 & 0 \\ 0 & 0 & 20.253 \end{bmatrix}\times 10^{-3} kN\cdot s^2/m \tag{5.2}$$

$$K=\begin{bmatrix} 9.933 & -5.662 & 0 \\ -5.662 & 11.340 & -5.662 \\ 0 & -5.662 & 5.662 \end{bmatrix} kN/m \tag{5.3}$$

$$C=\begin{bmatrix} 7.243 & -2.069 & 0 \\ -2.069 & 4.139 & -2.069 \\ 0 & -2.069 & 2.069 \end{bmatrix}\times 10^{-3} kN\cdot s/m \tag{5.4}$$

To estimate the state variables and parameters with considering the MR damper force, the state vector in EKF contains displacement and velocity of structure and inertial mass of damper (x, $\dot{x}$, x_0, $\dot{x}_0$), structural parameters (stiffness matrix K, damping matrix C) and parameters in hyperbolic tangent damper model (k_1, k_0, c_0, c_1, m_0, f_0, V_{ref}). The measurements are the accelerations of each floor and damper force ($\ddot{x}$, f). For simplicity, the new state-space model incorporating hyperbolic MR damper model (Eq. 3.1, 3.2) and equation of motion (Eq. 5.1) is formed as shown in Eq. 5.5 and 5.6:

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dot{x}_0 \\ \ddot{x}_0 \end{bmatrix} = \begin{bmatrix} 0 & I & 0 & 0 \\ -M^{-1}K-M^{-1}GG^Tk_1 & -M^{-1}C-M^{-1}GG^Tc_1 & M^{-1}GG^Tk_1 & M^{-1}GG^Tc_1 \\ 0 & 0 & 0 & 1 \\ (k_1/m_0)\times G^T & (c_1/m_0)\times G^T & (-k_1-k_0)/m_0 & (-k_1-k_0)/m_0 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ x_0 \\ \dot{x}_0 \end{bmatrix}$$

$$+\begin{bmatrix}0\\M^{-1}\\0\\0\end{bmatrix}u+\begin{bmatrix}0\\0\\0\\1/m_0\end{bmatrix}\times f_0\tanh(\dot{x}_0/V_{ref}) \tag{5.5}$$

$$\begin{bmatrix}\ddot{x}\\f\end{bmatrix}=\begin{bmatrix}-M^{-1}K-M^{-1}GG^Tk_1 & -M^{-1}C-M^{-1}GG^Tc_1 & M^{-1}GG^Tk_1 & M^{-1}GG^Tc_1\\ k_1 & c_1 & -k_1 & -c_1\end{bmatrix}\begin{bmatrix}x\\\dot{x}\\x_0\\\dot{x}_0\end{bmatrix}$$

$$+\begin{bmatrix}M^{-1}\\0\end{bmatrix}u \tag{5.6}$$

The El Centro earthquake recorded at the Imperial Valley, California on May 19, 1940 is utilized as the ground excitation in the testing, as shown in Fig. 5.2. The measurement and estimation for displacement responses of three floors are plotted in Fig. 5.3 and 5.4. The first floor has a relatively smaller displacement due to the fact that the damper force counterweights the external force at the first floor due to ground motion. The reason for the estimation variance in the displacement of first floor is due to its complexity introduced by MR damper force, and the amplitude of the displacement of the first floor is very small compared with other two stories. As it can be seen from the damper force history plots in Fig. 5.5 and 5.6, the EKF algorithm has a good approximation capability and the estimation results are very close to values of simulation. The stiffness of each floor are estimated and compared with actual simulation with high accuracy, as shown in Fig. 5.7.

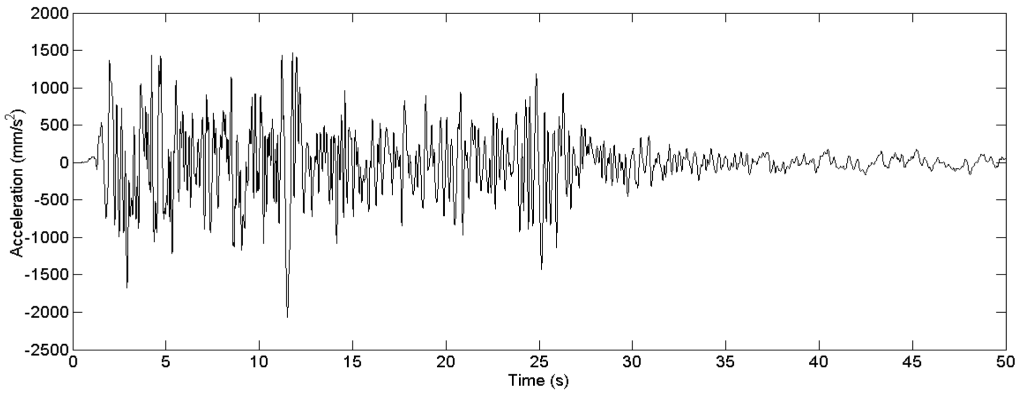

Figure 5.2 Ground acceleration of El Centro Earthquake

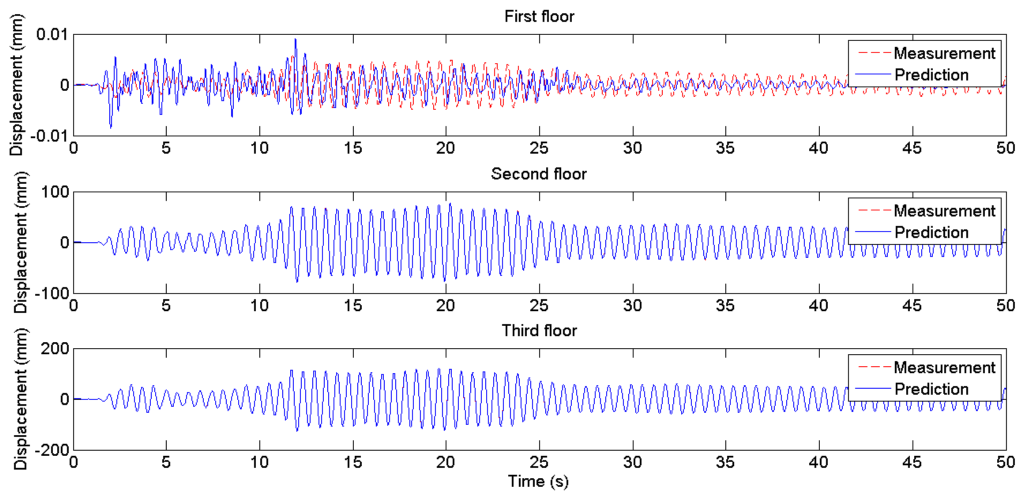

Figure 5.3 Simulation comparison: response of three stories

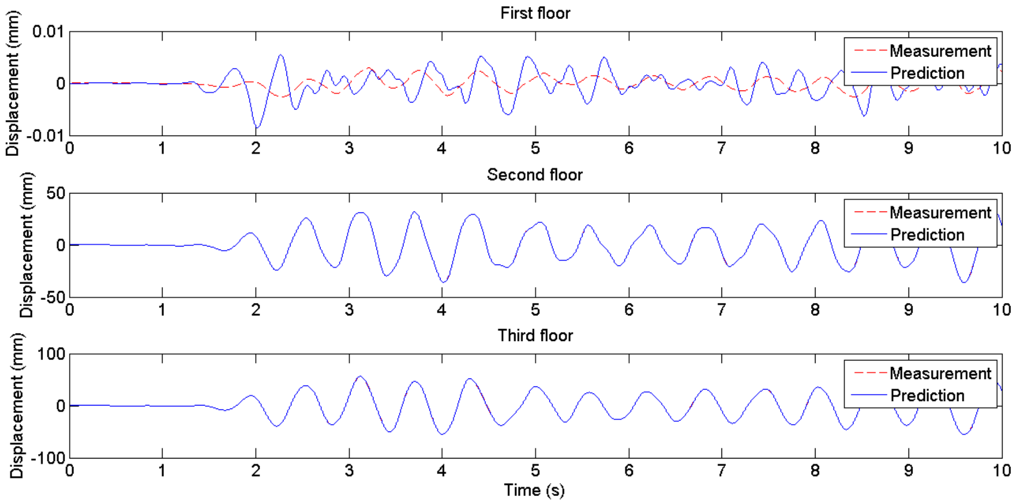

Figure 5.4 Simulation comparison: response of three stories (Zoom-in)

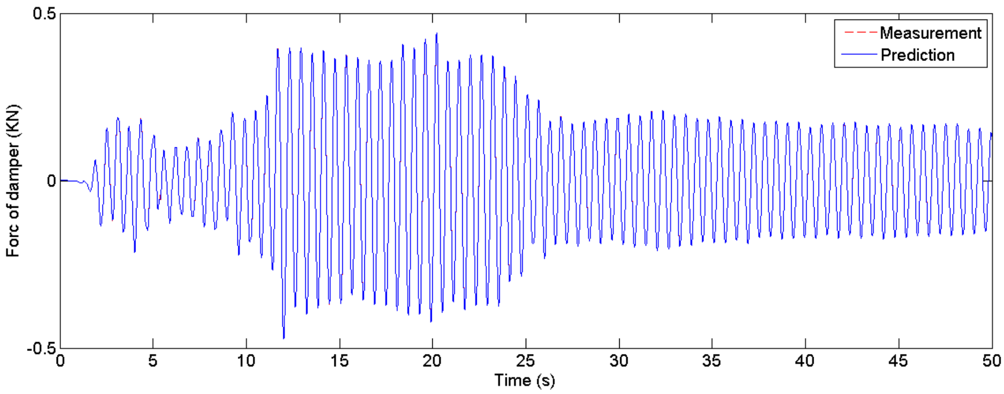

Figure 5.5 Simulation comparison: damper force time history

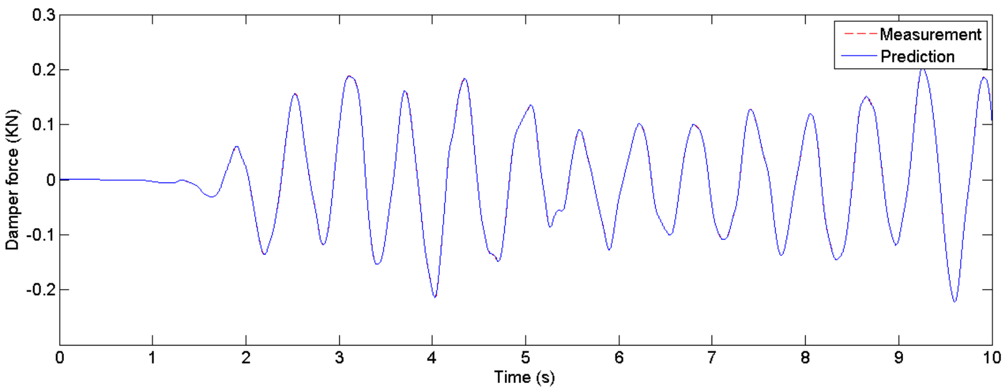

Figure 5.6 Simulation comparison: damper force time history (Zoom-in)

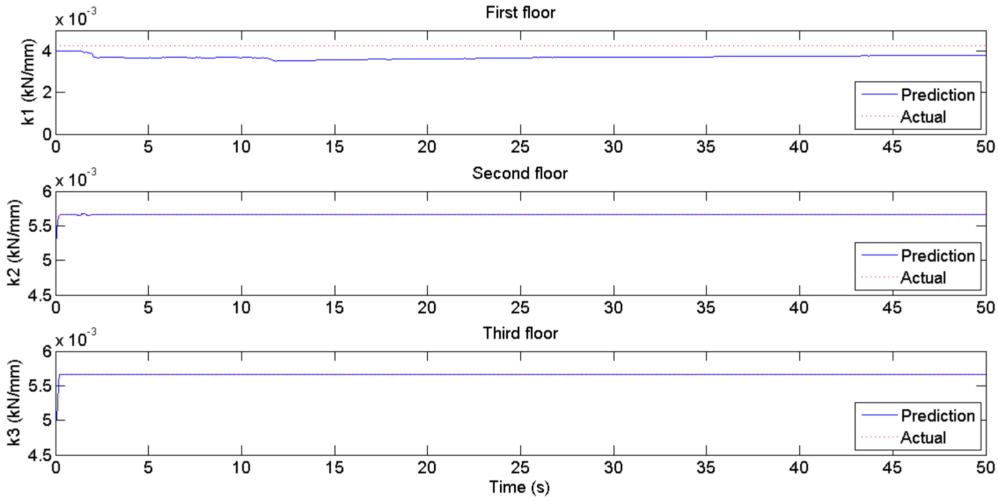

Figure 5.7 Simulation comparison: stiffness of each floor

6. CONCLUSION

In this paper, a new damage detection method based on extended Kalman filter was developed to incorporate MR damper in structural dynamic problems. To estimate the structure variables and parameters, a new state-space model is established including all variables in the structural equation of motion and hyperbolic tangent model of MR damper. Based on measurements of accelerations of three stories and damper force, the EKF algorithm can produce real-time estimation for the structural parameters and state variables. The EKF based method is tested using simulated data of a three stories linear building with MR damper under earthquake excitations, and numerical results demonstrate high estimation accuracy and light computation of this presented method. The developed EKF based method can be easily replicated to other damage detection or health monitoring problems for structures attached with MR damper. Future work of this study will include developing dynamic control limits based on Statistical Process Control theory for damage detection, and validating this method using real-time hybrid simulation tests considering various damage scenarios.

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