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Intelligent fuzzy weighted input estimation method for the multi-story buildings with unknown ground motion acceleration

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ABSTRACT

This paper presents a novel intelligent fuzzy weighted input estimation method which effiviently and robustly estimates the unknown ground motion accelerations. The new input estimation method includes the Kalman Filter (KF) and the recursive least square estimator (RLSE), which is weighted by the fuzzy weighting factor proposed based on the fuzzy logic inference system. By directly synthesizing the Kalman filter with the estimator, this work presents an efficient robust forgetting zone, which is capable of providing a reasonable compromise between the tracking capability and the flexibility against noises. The excellent performace of this inverse method is demonstrated by solving the earthquake-excitation estimation problem, and the proposed algorithm is compared by alternating between the constant and adaptive weighting factors. The results reveal that this method has the properties of better target tracking capability and more effective noise reduction.

1. Introduction

In recent years, there were many horrible earthquakes occurred in the seismic zones around the world, e.g., the Jawa earthquake in Indonesia (2007), the Chi-Chi earthquake in Taiwan (1999), the Kobe earthquake in Japan (1995), and the Northridge earthquake in California (1994). All these earthquakes caused severe damage to building structures and claimed quite a few lives [1]. The Chi-Chi earthquake was the greatest thrust event in the twentieth century to strike the Taiwan area (Ma et al., 2001). Owing to the strong shaking and extensive surface ruptures, more than 100,000 buildings were destroyed, and more than 2500 people lost their lives in this event [2]. The probability of occurring earthquakes increases on account that Taiwan is located on the seismic belt of the Pacific Ocean. The response characteristics and strength variation of structure systems based on the dynamic analyses are essential for the design of civil structures on the seismic belt. The reliability of structure security depends on the earthquake resistance design. It will influence the safety of civilian lives and properties directly. It costs a fortune to test the security of structure with the strong earthquake shock. For this reason, a seismometer can be installed on the building structure to collect the seismic data. According to the data, the dynamic characteristics of building structure can be determined by using the system identification method, and furthermore, the security of building structure can be evaluated. This is an approach to earthquake resistance evaluation of engineering structures.

Estimation of the responses of structure systems based on the dynamic analyses is essential for the design of civil structures on the seismic belt. In recent years, the utilization of time histories of earthquake ground motion has grown considerably in the field of earthquake engineering. For example, the time histories of ground motion are used in the design and analyses of civil structures. The strong motion prediction model, earthquake motion prediction model on rock surface (EMPR), was developed by Sugito et al. [3]. The simulated ground motion by the EMPR is adopted as the Green's function for the inversion of the fault process [4]. The method mentioned above was utilized to implement the simulation and calculation by applying the known earthquake acceleration. A simple off-line correction procedure is an adequate application for producing reasonable reproductions of historical earthquakes [5]. The approach to the compensation of the system dynamics is to apply a pre-filter to the command signal which accounts for the dynamics of the system [6]. Such an approach may be regarded as an inverse transfer function feed-forward compensation method. In practice, the earthquake motion may not be precisely determined because the transfer function is not well defined. Further improvements of the simulator performance may be obtained by converting the approach mentioned above to an iterative method [7]. The above researches used the off-line form to process the measurement data. The method is not a real-time procedure to estimate and control the unknown input.

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In the course of anti-vibration design, fatigue analysis, and reliability assessment of the structure system, the most important procedure is to obtain the values of active forces to the system. However, in the practical engineering problem, there are always difficulties in installing the force transducers used to measure the active forces to the structure system. Besides, the ground motion accelerations caused by the earthquake is sometimes overwhelming and transient so that the measurements will not be easy to obtain. Therefore, a real-time, indirect estimation for the excitation forces is frequently employed. Input force estimation is the process of determining the applied loadings from the measurements of system responses. The input estimation method has recently been applied to the structural dynamic problems. An inverse method to estimate the excitation forces from the dynamic responses of plate structure was presented in Ref. [8]. Ma et al. [9,10] proposed an inverse method to estimate the impulsive loads on the lumped mass structure systems. They first used the finite element method (FEM) to construct the system state equations of beam structures, and then used the inverse method to determine the unknown excitation forces. Liu et al. [11] and Ji et al. [12] used the Kalman filter with the recursive least square method to estimate the input force of a plate. However, the plate was simplified to the system with a single degree of freedom. Deng and Heh [13] presented the recursion relation algorithm to determine the input forces of beam structures and the individual node displacement. Lee and Chen [14] utilized the adaptive weighted input estimation method to inversely solve the burst load of the truss structure system. Chen and Lee [15] investigated the adaptive input estimation method applied to the inverse estimation of load input in the multi-layer shearing stress structure. The overall estimation performance is fine by utilizing the dynamic response of structure system to inversely estimate the load input. The input estimation method is using the recursive form to process data. As opposed to the batch process, using the recursive form is real-time and has higher effectiveness. There is no need to store all the data to implement the process, and the quantity of memory used can be reduced when dealing with more complex systems. The above studies are using the constant weighted estimator to estimate the unknown time-varying inputs. However, the access to the optimal constant weighting factor should go through complicated analyses of the estimation process [16].

In this work, an intelligent fuzzy weighting function is used to replace the weighting factor, $\gamma(k)$, of the recursive least square estimator (RLSE). Improving the weighting efficiency of the RLSE is essential, because the unknown input is time varying and changes continuously. Therefore, the inverse method with the rapider target tracking and more effective noise reduction capabilities is developed. The intelligent fuzzy weighted estimator is based on the fuzzy logic system. The robustness and efficiency of this method will be demonstrated through the simulation case study. The Chi-Chi earthquake ground motion data measured at the seismological station TCU056EW is used as the system input data. The results are compared with the ones using other weighted estimators. The case study verifies the reliability, adaptivity, and robustness of the proposed method.

2. Problem formulation

To illustrate the practicability and precision of the presented approach in estimating the unknown earthquake ground motion accelerations, the numerical simulations of the multi-story buildings structure are investigated in this research. As shown in Fig. 1, the structure is modeled as a lumped mass structure system undergoing the earthquake accelerations. The relative

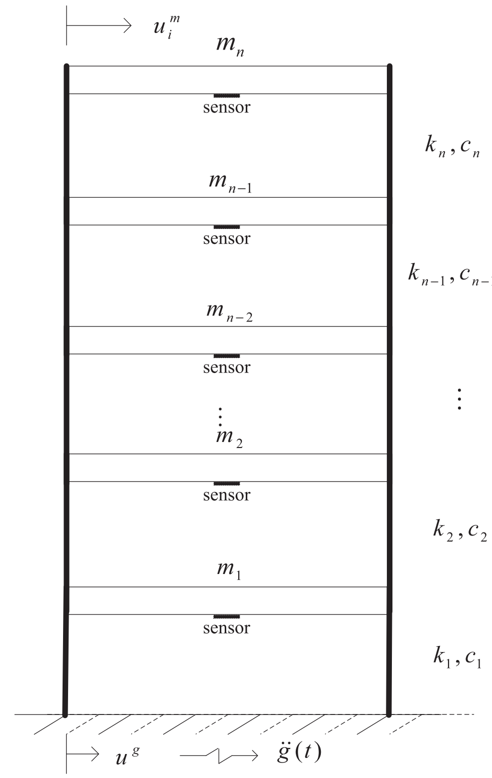

Fig. 1. The multi-story building structure model under the ground motion acceleration.

displacement between the lumped mass and ground is represented as the variable, $u_i = u_i^m - u^g$, where i is a index of the ith story. The movement equations of the structure system can be shown in the following equations:

$$M\ddot{U} + C\dot{U} + KU = -M1\ddot{g}(t) \tag{1}$$

where

$$M = \begin{bmatrix} m_1 & 0 & 0 & \dots & 0 \\ 0 & m_2 & 0 & \dots & 0 \\ 0 & 0 & m_3 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \vdots & m_n \end{bmatrix}_{n\times n}$$

is the diagonal mass matrix,

$$C = \begin{bmatrix} c_1 & -c_1 & 0 & \dots & 0 & 0 \\ -c_1 & c_1+c_2 & -c_2 & \dots & 0 & 0 \\ 0 & -c_2 & c_2+c_3 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & \ddots & -c_{n-1} \\ 0 & 0 & 0 & 0 & -c_{n-1} & c_{n-1}+c_n \end{bmatrix}_{n\times n}$$

is the damping matrix and

$$K = \begin{bmatrix} k_1 & -k_1 & 0 & \dots & 0 & 0 \\ -k_1 & k_1+k_2 & -k_2 & \dots & 0 & 0 \\ 0 & -k_2 & k_2+k_3 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & \ddots & -k_{n-1} \\ 0 & 0 & 0 & 0 & -k_{n-1} & k_{n-1}+k_n \end{bmatrix}_{n\times n}$$

is the restoring force vector.