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Structural parameters and dynamic loading identification from incomplete measurements: Approach and validation

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ABSTRACT

System identification is becoming more important in structural dynamic applications including structural model update, damage detection primarily due to the rapid increase in the number of damaged or deteriorated engineering structures, and load identification for remaining service life forecasting. Time-domain identification techniques based on measured vibration data, e.g. the least-squares estimation (LSE), have been studied for a relatively long time and shown to be useful. However, the traditional least-squares techniques require that all the external excitation measurements should be available, which may not be the case for many practical applications. In this paper, by introducing a weighted positive definite matrix to the objective function and a learning coefficient using the information in the previous iterations in the identification approach to improve the convergence performance, an alternative iterative approach for both structural parameters and dynamic loading identification, referred to as weighted adaptive iterative least-squares estimation with incomplete measured excitations (WAILSE-IME), was proposed. The accuracy, convergence, and robustness of the proposed approach was demonstrated via numerical simulation on a six-story shear building model with noise-free and different levels of noise-polluted structural dynamic response measurements. The effects of the positive weight matrix, the learning coefficient, and the sampling duration on the convergence and the accuracy of the proposed approach were discussed and the results were compared with available related literature results. Results show that the proposed approach can simultaneously identify structural parameters and unknown excitations within very limited iterations with high accuracy and shows its robustness even noise-polluted dynamic response measurements are utilized. Furthermore, the approach was validated via available experimental measurements for a four-story frame structure excited by impact excitations. The results show that the proposed approach is capable of identifying both structural parameters and the unmeasured excitations with acceptable accuracy and improved convergence.

1. Introduction

In structural dynamic applications, system identification (SI) has received considerable attention recently primarily due to the rapid increase in the number of damaged or deteriorated structures and the needs to forecast structural remaining

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service life considering the load profile. Most of the conventional vibration based structural identification approaches are frequency domain methods mainly based on the change in the natural frequencies, mode shapes, and their derivatives such as extracted curvatures and modal flexibility [1–3]. In particular, time domain analysis techniques, including the methods of least-squares estimation (LSE) [4–6], extended Kalman filter [7,8], and sequential nonlinear least-squares estimation [9], have been used for the identification and tracking of structural parameters and their variations. In the conventional approaches above, all external excitations should be available for structural parameters identification. Frequently, however, from a practical point of view, either sensors may not be installed to measure all the external excitations or some external excitations are un-measurable. Consequently, it is highly desirable to extend the traditional SI algorithms for the purpose of identifying structural parameters and external excitations simultaneously utilizing structural vibration response measurements and incomplete measured external forces. Moreover, for the purpose of both structural damage prognosis, it is strongly needed to develop efficient approaches for the simultaneous identification of structural physical parameters and unknown external excitations (inputs), because the load profile analysis plays key role in structural remaining service life estimation for structural damage prognosis, which is the future of structural health monitoring (SHM) [10].

In the past years, SI with incomplete excitation measurements has been attempted and much progress has been made. When some external excitations are not measured or not available, numerical iterative procedures based on the classical LSE or extended Kalman filter (EKF) have been proposed to identify the constant structural parameters. Wang and Haldar [11] proposed an iterative least-squares technique with unknown inputs to evaluate large structural systems at element level. In the proposed approach, the iteration can be started by assuming the inputs at a number of sequential time steps are zero. From a practical point of view, since it is not correct to assume zero input excitation at all times, the number of the time steps, which inputs are assumed to be zero should be kept to a minimum to obtain a nonsingular solution of the optimization equations and without compromising the convergence or the accuracy of the proposed method. It was elaborated in the above study that the number of time steps can be only two if the structure was excited at any degrees of freedom (DOFs) and only four if the structure was excited at the base representing seismic motion. In subsequent years, based on the EKF method [12], Wang and Haldar [13] extended their work to present a combination approach for SI with limited observations and without the use of input. Using the Taylor series approximation, Ling and Haldar [14] presented a modified iterative least square approach with unknown input for the element level SI with Rayleigh damping. Yang et al. [15] proposed a recursive least-square estimation with unknown inputs (RLSE-UI) approach to identify the structural parameters, such as the stiffness, damping, and other nonlinear parameters, as well as the unmeasured excitations. Cattarius and Inman [16] used the time histories of vibration response of the structure to identify damage in smart structures. Majumder and Manohar [17,18] proposed a time domain approach for damage detection in beam structures using vibration data with a moving oscillator as an excitation source. More recently, the force induced by a vehicle moving on the bridge was taken to be the source of excitation. Zhu and Law [19] proposed an approach for damage detection in a simply supported concrete bridge structure in time domain using the interaction forces from the moving vehicles as excitation. The vehicle–bridge interaction forces and the structural damage in the bridge deck were identified from the measured responses in sequence of iteration without prior knowledge of the moving loads and the simulation results showed that the method was effective and noise insensitive to damage detection in the concrete bridge structure under moving vehicular loads. Lu and Law [20] presented a system parameters and input force identification method only using output based on sensitivity of structural responses.

Li and Chen [21] proposed a method, called the statistic average algorithm, to identify the structural parameters under unknown ground motion. Moreover, different from the approach proposed by Wang and Haldar [11,13], Chen and Li proposed iteration procedures under incomplete measured excitations to estimate the stiffness and damping coefficients as well as the unmeasured excitations [22,23]. In the approaches, the known input information was employed to update the excitation vector once during each iteration process before solving the optimal estimation on structural parameters by LSE. Moreover, the iteration approaches proposed by Chen and Li stopped when the difference of identified structural parameters between two sequential iterations reached a predetermined accuracy [22,23]. Shi et al. [24] and Chen and Li [25] presented updated methods to identify structural parameters and input time history from output-only measurements iteratively. Most recent advances in the time domain identification of structural parameters and input time history includes the substructural identification approach, the adaptive quadratic sum-squares error methods, soft computation algorithms such as fuzzy logic, genetic algorithms, and neural networks [26–31]. Neural network was widely recognized as a nonparametric modeling approach. Xu et al. [32] proposed a time domain structural parameters identification approach with the direct use of structural vibration measurements without the extraction of structural frequencies and mode shapes. The approach was then adopted to identify structural parameters using spatially incomplete measurements by Xu [33]. For large-scale structural system, Xu and Wu [34] proposed a decentralized and localized identification method using structural response measurement time series.

In this paper, an alternative iterative approach for both structural parameters and load identification, referred to as weighted adaptive iterative least-squares estimation with incomplete measured excitations (WAILSE-IME), was proposed. The structural parameters e.g. the stiffness and damping coefficient, and the time series of the unknown dynamic loading were identified. The iteration process started at an initial assumption of the unknown external excitation time series and structural parameters were estimated based on a weighted objective function using adaptive algorithm in order to improve the convergence and accuracy of the identification approach. Here, in the proposed approach the estimated external excitations were firstly updated by utilizing the excitation time history measurements corresponding to the DOFs,