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A dual Kalman filter approach for state estimation via output-only acceleration measurements

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ABSTRACT

A dual implementation of the Kalman filter is proposed for estimating the unknown input and states of a linear state-space model by using sparse noisy acceleration measurements. The successive structure of the suggested filter prevents numerical issues attributed to unobservability and rank deficiency of the augmented formulation of the problem. Furthermore, it is shown that the proposed methodology furnishes a tool to avoid the so-called drift in the estimated input and displacements commonly encountered by existing joint input and state estimation filters. It is shown that, by fine-tuning the regulatory parameters of the proposed technique, reasonable estimates of displacements and velocities of structures can be accomplished.

1. Introduction

This paper contributes to the problem of state estimation in the entire body of the metallic structures that undergo vibrations due to unknown input forces during their operational life, aiming at prediction of fatigue damage identification. The idea of using the estimated response of the structures for fatigue damage identification was first suggested by Papadimitriou et al. [1]; where a technique was introduced that uses the Kalman filter for estimating power spectral densities of the strain in the body of the structure thereby predicting the remaining fatigue life. To estimate the fatigue damage, a time history of the strains in the hotspot points of the structure is required. To estimate the strain in a point of interest, the displacement field around that point is needed; therefore, a reliable state estimate could lead to a reliable fatigue damage identification.

The subject of estimation of the states of a partially observed dynamic system in an stochastic frame has been studied by many scientists and there are well developed algorithms to manage both linear (e.g. the Kalman filter [2]) and nonlinear (e.g. the particle filter [3], the unscented Kalman filter [4]) state-space models. Dealing with structural systems, the states of the system are displacements and velocities of the response of the system at some points, namely degrees-of-freedom (DOF) on the structure. In practical cases, it is difficult or sometimes impossible to measure displacements and velocities of the system, hence when a knowledge of the displacements and velocities is required, a state estimation algorithm could be used to provide estimates of the whole state of the system. The Bayesian filters that exist in the literature, take advantage of the correlation between the observable part of the state of the system and the hidden part, and furnish an estimate of the whole

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state with the associated uncertainty of it. Within the context of the structural dynamics, over the continuous time the equations of motion, namely the dynamic model of the system define an intrinsic correlation between the states of the system. Dealing with discrete models, the kinematic relation between the accelerations, velocities and displacements of the system enters the dynamic model of the system and together with kinetics shape the discrete state-space model.

Within such a context, Ching and Beck [5] estimated the unknown states of a structure using incomplete output data from a structure excited by uncertain dynamic loading, to estimate the likelihood of any particular unobserved response of the structure exceeding a prescribed threshold. Hernandez [6] proposed an observer that possesses similar characteristics to the Kalman filter in the sense that it minimizes the trace of the state error covariance matrix. The main notion behind the algorithm is that the proposed observer can be implemented as a modified linear finite element model of the system, subject to collocated corrective forces proportional to the measured response. It has been used to estimate the number of threshold crossings in the bending moment history of a simulated tall vertical structure subject to turbulent wind load and fatigue damage [7]. The methodology has further been experimentally validated via a laboratory test [8]; where the measured stress at the locations of interest was compared to estimates obtained by well-established estimation methods such as Luenberger observers and the Kalman filter relying on the using a limited number of velocity measurements. Smyth and Wu [9] proposed a multi-rate Kalman filter for the online fusion of measured displacement and acceleration data sampled at different rates. The filter is designed to circumvent problems related to the integration of accelerometer or the differentiation of displacement data in situations where both these response quantities are collocated and available in different sampling rates. Gao and Lu [10] used the Kalman filter in combination with an ARX model for damage detection in linear structural systems where only accelerations at some degrees of freedom are measured. Reynders and De Roeck used the linear Kalman filter as part of the subspace identification technique for modal analysis [11] to directly estimate states from measured data without knowledge of the system model. The linear Kalman filter is also used by Bernal [12] in a damage detection scheme for linear systems based on the hypothesis test of whiteness of the innovations, taking advantage of the fact that correlations emerge when either the properties of the system or the process noise deviate from the values that the filter is formulated for. In very recent work, Bernal and Ussia [13] have proposed a sequential deconvolution method for input reconstruction in linear time invariant systems, and have presented a detailed study of the necessary conditions for identifying the input force as well as the stability conditions associated with a segmented implementation of the proposed method. Through theoretical derivations, it is shown that when the number of inputs is less than or equal to the number of observations the non-collocated inputs can be identified by performing deconvolution. Further, to facilitate continuous input reconstruction over time, a sequential implementation of the deconvolution method is proposed by authors. The method is an interesting alternative for the case where the aim is input reconstruction in the event where the input load locations are known and additionally the inputs to be reconstructed are fewer than the monitored outputs. In such a case one may solve for the inputs and then recast the problem into a standard Kalman filtering framework which would take care of the process and measurement noise involved, as well as the uncertain initial conditions. Instead, the method developed herein proposes a parallel carrying out of these tasks in one compact formulation.

For nonlinear state estimation and parameter identification in civil engineering, the extended Kalman filter (EKF) has been the de facto standard in the past mainly due to its ease of implementation, robustness and suitability for real-time applications. In recent years, however, many alternative techniques have been proposed. In a first extension for alleviating the issues that arise through linearization in the EKF, Julier and Uhlmann [4] have proposed the unscented Kalman filter (UKF), in which the evolution of the statistics of the state of the system is performed through a sampling scheme. It has been shown by Mariani and Ghisi [14] that at the price of a higher computational burden the UKF outperforms the EKF dealing with nonlinear parameter identification problems. To mitigate the issues pertinent to high computational costs, Eftekhar Azam et al. [15] proposed a parallel implementation of the UKF. Ching et al. [16] compared the performance of the EKF with that of the particle filter (PF) applied to identification of system matrices of a linear multi storey shear building. Chatzi and Smyth [17] and Eftekhar Azam et al. [18] compared the performance of the UKF and PF applied to identification of the parameters of nonlinear constitutive models. One of the advantages of the PF in comparison to the EKF is that it is applicable to highly nonlinear systems with non-Gaussian uncertainties. In turn, one major drawback of the particle filters is that when dealing with high dimensional state-space models, the computational burden of the generic particle filters increase exponentially. To alleviate this issue, recently techniques have been developed that improve the ensemble of the so-called particles. Chatzi and Smyth [19] have used evolutionary particle filters for structural health monitoring where, the use of the standard PF is combined with mutation operators to enhance the particles. Eftekhar Azam and Mariani [20] have used a hybrid extended Kalman particle filter for online damage detection of linear and nonlinear multi storey shear type buildings. In the abovementioned works, the process and observation noise covariances are always assumed as known parameters of the problem; however, in practice the covariances of the noise parameters should be appropriately estimated to ensure that an optimal prediction is furnished by the filters [21]. Moreover in practical implementations in online monitoring, the possible outliers contained in the observation process can have detrimental effects on the estimates including instability of the identified parameters. In treating this issue and for enabling online and continuous monitoring, Mu and Yuen have proposed a novel robust outlier resistant EKF for online parameter identification of linear time variant structural systems [22].

Although the joint state and parameter identification task is a subject frequently addressed in recent years, the joint identification of state and input information is a topic less treated so far in the literature. Structural systems are inherently characterized by uncertainty, relating to measurement errors, sensor noise, inefficacy of the numerical models and lack of a priori knowledge on the system and loading conditions. It this paper, the latter source of uncertainty, i.e. the lack of information