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Kalman-based load identification and full-field estimation analysis on industrial test case

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ABSTRACT

The potential of the Augmented Kalman Filter algorithm is tested in this paper for joint state-input estimation in structural dynamics field. In view of inverse load identification, the filter is compared with the Transfer Path Analysis Matrix Inversion technique, commonly used for industrial applications. An existing Optimal Sensor Placement strategy for Kalman Filter is adopted and validated on real experimental data. The advantages of the proposed methods, through strain measurements information, are identified in the effort needed for data-acquisition and data-processing. The effectiveness of the filter and the quality of the results are demonstrated in this paper for an industrial test-case, such as a rear twistbeam suspension.

1. Introduction

Inverse load identification and full-field measurement technologies are very active fields of research in structural dynamics. Inverse load identification is generally linked to the solution of ill-conditioned systems of equations and it is notorious to be hard to solve in the case in which multiple loads are unknown on stiff structures [1–3]. The role of inverse load identification technologies is nonetheless of paramount importance. In fact engineers and analysts with different backgrounds often need an accurate knowledge of loads entering a structure or an electromechanical system. These input loads are often difficult to measure directly since dedicated sensors can be intrusive, expensive and can rarely be equipped during the operational life of the system. For these reasons, estimation of external loads represents a crucial task in many automotive, aerospace and manufacturing applications. If the loads are known, the design process of a component can be improved and the reliability and lifetime of a product can be increased. Within the last decades, several test-based and simulation-based technologies have been researched and developed aiming to deal with these issues. Inverse load identification were initially solved through off-line test-based strategies. One of such strategies relates to the field of Transfer Path Analysis (TPA), where the Matrix Inversion (MI) and Mount Stiffness (MS) [1,4–6] approaches are among the most commonly used methods, in particular for mechanical applications. The purely experimental nature of TPA and the low computational cost represent great advantages over other available inverse identification methods. The MS approach can be used when the external loads is acting on the structure through flexible mounts and if mount stiffness data is available. When this is not the case, the MI approach can be adopted. However, several numerical disadvantages might limit its usability. Over-determination of the matrix generally improves the robustness of the inversion and a large set of sensors is hence selected. This in turns leads

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to large measurement efforts and costs. Well-chosen measurement points around the loaded area of the structure are selected as sensors' locations [7], but an objective optimal criteria is not yet defined. A more time efficient-approach named Operational Path Analysis (OPA) is presented in [8], but its causal assumption among outputs limits the applicability in most industrial application cases. When going towards simulation-based methods, a common approach in the field of structural mechanics is the off-line estimations through Finite Element (FE) models. An example is reported by Adams [2] making use of a time domain approach in a deterministic setting. When the structural complexity of the system increases, the complexity of the proposed inverse method becomes a great disadvantage.

More recently, thanks to the advancement of computational performances of numerical strategies used to solve complex models, estimators such as Kalman-based filters [9–12] have been used to approach the problem of inverse load identification in an on-line fashion. The potential of on-line Kalman-based techniques was first tested on full-field response estimation (e.g. purely state estimation). A numerical and experimental application is reported in [13], performing the simultaneous usage of multiple types of measurements (e.g. accelerations and strains). If no direct measurements of the input are available but the input location is known, the estimation problem can be solved by using a joint state-input estimation algorithm. This Kalman-based approach gives the possibility to estimate full fields such as strains, displacements and accelerations concurrently with the unknown input. Gillijns and De Moor [14,15] studied the problem for linear discrete-time systems. A recursive filter was proposed, with the structure of a Kalman filter, except that the true value of the input is replaced by an optimal estimate. The numerical performances of this algorithm are investigated and applied to structural systems by Lourens et al. [16]. The feasibility of the method for industrial applications was demonstrated on a complex case for distributed load identification. Under certain conditions, inaccuracies of the response estimation occur and the effect of modelling errors is not compensated. A drift effect on the estimation of input and displacements is observed by Azam et al. [17,18]. That is linked to the integral nature of those quantities in the presence of acceleration information. A dual formulation of the simultaneous input and state estimation is hence proposed in [17] to prevent the mentioned numerical problems. The so-called Dual Kalman Filter (DKF) approaches the estimation of the input and states in two different stages. The effectiveness of this filter was tested on large industrial test cases [17,19]. Another way to perform joint state-input estimation is identified by the so-called Augmented Kalman Filter (AKF) [10]. Within this framework, the system state vector is augmented by including the unknown input variables. That defines a reduction of the computational cost needed for the execution of the DKF. One of the key points of both methods resides in the fact that a force model has to be introduced in the filter. This task is particularly challenging since mostly input loads have an erratic and a priory unknown distribution in time. The AKF was recently applied to structural dynamics in [20–22]. A detailed explanation regarding the applicability of this filter to dynamic mechanical systems is described in [23]. Lourens et al. [21] perform force identification through acceleration measurements. The results show that when measurements can only be performed at locations relatively far from the force identification, the AKF fails to predict the applied force. Naets et al. [20] propose an analytical analysis of the stability of the Kalman-based force estimation techniques and show that only using acceleration measurements inherently leads to unreliable results. That was also demonstrated with real data in [17,18]. Tamarozzi et al. [3] propose an Optimal Sensor Placement (OSP) strategy aimed to optimally define type (position/strain/acceleration) and location of sensors to be used in the joint state-input identification problem. The performance of the method is numerically tested. Significant reduction of sensors installation costs can be obtained.

Within the present work, the potential of the AKF through the OSP strategy was investigated on an industrial test case. In order to illustrate the effectiveness of the filter, the results about load identification are compared against the TPA MI technique and a direct force measurement through a 6 degrees of freedom force cell. Measurement acquisition and data processing will be analyzed and compared in details, including remarks on noisy experimental data and model accuracy. Furthermore, the applicability of the Kalman-based strategy for full strain field estimation is also analyzed. The paper presents the following structure. First, an overview of Kalman Filter applied to mechanical systems is reported together with the modelling techniques used within this work i.e. state-space formulation for structural dynamics problems and linear Model Order Reduction (MOR). Furthermore, the main principles of the OSP strategy are explained. In Section 2.2, a brief theoretical background about TPA Matrix Inversion is reported. In Section 3, the experimental setup of a rear twistbeam suspension is showed and the comparison between AKF and TPA is proposed for force identification. The potential of OSP for AKF applications is demonstrated on the acquired experimental data. In Section 4, the state estimation through Kalman Filter is performed in two conditions of known and unknown external loads. Finally, concluding remarks and future developments are discussed in Section 5.

2. Theoretical background

2.1. Augmented Kalman Filter for joint state-input estimation

This section addresses the Kalman-based strategy applied on a dynamic mechanical system. The governing equation of a second order model in a Finite Element [26] formulation is the following:

$$\boldsymbol{M}_z\ddot{\boldsymbol{z}}(t) + \boldsymbol{C}_z\dot{\boldsymbol{z}}(t) + \boldsymbol{K}_z\boldsymbol{z}(t) = \boldsymbol{B}_z\boldsymbol{u}(t) \tag{1}$$