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An online coupled state/input/parameter estimation approach for structural dynamics

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Abstract

In many practical structural applications, unknown states, inputs and parameters are present. However, most methods require one or more of these variables to be known in order to estimate the other(s). In this research an estimation technique which employs physical models is proposed to perform coupled state/input/parameter estimation. In order to obtain a modeling technique which allows the estimation of a wide range of parameters in a generic fashion at a minimal computational cost (even real-time), the use of a parametric model reduction technique is proposed. The reduced model is coupled to an extended Kalman filter (EKF) with augmented states for the unknown inputs and parameters. This leads to a very efficient framework for estimation in structural dynamics problems. Special attention is also given to the measurement requirements in order to obtain an adequate observability of all unknown quantities and the necessity for at least one displacement level measurement is shown. The proposed methodology is validated numerically and experimentally. The approach is shown to be easy to tune and provides good results with different measurement methods.

Keywords: Structural dynamics; State estimation; Parameter estimation; Input estimation; Kalman filter

1. Introduction

Condition monitoring and control applications require the online knowledge of both the states and parameters of (structural) systems. However many applications exist in which it is impossible to directly measure the required variables. This could be because the direct measurements require very expensive sensors, because the integration in the machine is unfeasible or in many cases there does not even exist a specific sensor. In these cases, other approaches have to be adopted in order to obtain the required variables. The classical approach in this case, is to measure another variable which is related to the required one and perform a calibration assuming a constant relation. This happens for example when strain gauges are used to measure the forces on a structure. Unfortunately this is not a robust approach because small system changes or other operating conditions can considerably affect the calibration. Therefore it is clear that a robust approach which can take parameter variation into account is required. Furthermore it might even be of specific interest to retrieve an estimate of the unknown parameters as well (e.g. damage accumulation for condition monitoring).

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In structural dynamics applications, both machine applications and civil structures, the variables of interest for estimation could be states (deformation and acceleration mainly), input forces or parameters. In practice one is often even interested in all these variables.

Unfortunately there is no straightforward way to measure input forces on a general structure because the introduction of (expensive) dedicated force cells requires alteration to the structure to locate the sensor in the force path, which is unwanted and unpractical. Obtaining force values from indirect measurements, like calibrated strain gauges, requires a good knowledge of the system parameters, which might be unknown as well. The same issue appears when forces are estimated through a Kalman filtering approach and strain or acceleration measurements [1–3].

On the other hand techniques for estimating physical parameters in structural dynamics typically require known inputs [4–9]. The measurement of inputs might be infeasible in operational conditions, especially when online monitoring is the goal. In order to circumvent this issue, several approaches have been proposed for parameter estimation with unknown inputs. The iterative least squares with unknown input (ILS-UI) technique offers a time domain estimation method for finite-element parameters from unknown input measurements [10,11]. This technique is aimed specifically at element level parameters and is particularly suitable for localized damage detection. However, due to the element level approach, this approach is too computationally expensive for online applications. *Kolmanovsky* et al. [12] proposed the coupling of an input observer and set-membership parameter estimation, but this method requires fully known states, which is rarely the case in structural applications.

Another important issue in estimation problems, is the high computational load associated with the model evaluation of physical dynamical models. In order to circumvent this issue, model order reduction (MOR) is employed to reduce the computational load of the model. Moreover, in the case of parameter estimation, the parameter dependency has to be taken into account explicitly in the model reduction scheme, which leads to parametric model order reduction (pMOR) techniques. Benner et al. provides a clear overview of the current state-of-the-art in pMOR [13]. The techniques can also be exploited for inverse problems like parameter estimation. Lieberman et al. [14] and De Sturler et al. [15] have proposed interpolation based pMOR for parameter identification, while Bechtold et al. [16] proposed multivariate moment matching techniques. In each case the reduced models were coupled with an optimization approach to extract the unknown parameter values.

This work proposes the use of the augmented discrete extended Kalman filter (A-DEKF) coupled to a first principle physical model in order to meet the requirements of coupled state/input/parameter estimation with online applicability. The extended Kalman filter (EKF) is a nonlinear variation on the regular Kalman filter, based on a linearization for a given configuration [17]. In order to estimate the inputs and parameters, these are considered as additional states to be estimated, they are typically called *augmented states*. This allows a simultaneous estimation of both the inputs and the parameters. In the past this augmented approach has been adopted for either state/input [3,18] or state/parameter [6,9] estimation for structural dynamics, but to the authors' knowledge this is the first work where these two domains are coupled. The Kalman filter exists in a continuous time version and the discrete time version, of which the latter is better suited for efficient computer implementation. An essential factor in the development of the estimation methods is an appropriate modeling approach, especially when online performance is the goal. This work focuses on exploiting physical models rather than data-driven models. This allows a much closer connection between the different quantities which have to be estimated. In order to guarantee real-time performance, parametric model order reduction is exploited. This is discussed further in Section 2.

Due to the pMOR approach, the Jacobians of the equations of motion can easily be obtained, which allows for a very efficient computational scheme with the EKF. A typical drawback of the EKF is the necessity to compute the, often complex, Jacobians of nonlinear systems, which is conveniently circumvented by this reduction approach. Special attention is also given to the time-discretization scheme for the equations of motion. The discrete time EKF (DEKF) is the most efficient way to implement the Kalman filter on digital hardware. In this case an exponential integrator is used to allow stable simulation even at larger time-steps, as might be dictated by the measurement equipment.

In estimation problems, special attention should be given to the observability of the problem. The observability conditions determine whether the estimates can be obtained and whether the estimation algorithm is stable. However, in general terms it is not straightforward to interpret these observability conditions. Therefore the observability conditions are discussed in Section 3 for the coupled estimation problem presented here and several measurement methods are evaluated.

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