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Parametric output-only identification of time-varying structures using a kernel recursive extended least squares TARMA approach

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ABSTRACT

The problem of parametric output-only identification of time-varying structures in a recursive manner is considered. A kernelized time-dependent autoregressive moving average (TARMA) model is proposed by expanding the time-varying model parameters onto the basis set of kernel functions in a reproducing kernel Hilbert space. An exponentially weighted kernel recursive extended least squares TARMA identification scheme is proposed, and a sliding-window technique is subsequently applied to fix the computational complexity for each consecutive update, allowing the method to operate online in time-varying environments. The proposed sliding-window exponentially weighted kernel recursive extended least squares TARMA method is employed for the identification of a laboratory time-varying structure consisting of a simply supported beam and a moving mass sliding on it. The proposed method is comparatively assessed against an existing recursive pseudo-linear regression TARMA method via Monte Carlo experiments and shown to be capable of accurately tracking the time-varying dynamics. Furthermore, the comparisons demonstrate the superior achievable accuracy, lower computational complexity and enhanced online identification capability of the proposed kernel recursive extended least squares TARMA approach.

1. Introduction

Most structures in the real world are time-varying under a specific time scale and their intrinsic time-varying behavior is increasingly inevitable in industry. Typical examples include vibration absorbers with variable stiffness [1], bridges with

Abbreviations: AR, autoregressive; DPE, deterministic parameter evolution (method); EWKRELS-TARMA, exponentially weighted kernel recursive extended least squares TARMA (method); LTI, linear time-invariant; LTV, linear time-varying; MA, moving average; MAE, mean absolute error; PSD, power spectral density; RELS-TARMA, recursive extended least squares TARMA (method); RKHS, reproducing kernel Hilbert space; RPLR-TARMA, recursive pseudo-linear regression TARMA (method); RSS, residual sum of squares; SPE, stochastic parameter evolution (method); SPWV, smoothed pseudo Wigner-Ville; SSS, series sum of squares; SWKRELS-TARMA, sliding-window exponentially weighted kernel recursive extended least squares TARMA (method); TAR, time-dependent autoregressive (model); TARMA, time-dependent autoregressive moving average (model); TSS, time-dependent state space (model); UPE, unstructured parameter evolution (method).

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crossing vehicles [2], launch vehicles with varying fuel mass [3], airplanes with varying additional aerodynamic effects in flight [4], deployable space structures [5], rotating machinery [6] and many more. In contrast to linear time-invariant (LTI) systems producing stationary responses with time-invariant statistical characteristic [7], linear time-varying (LTV) systems exhibit time-varying/non-stationary characteristics, requiring time-dependent dynamic models and corresponding identification methods [8–10]. In the past, the time-varying nature of such systems was given limited attention. With the advances in theories and techniques of LTV systems [11–13], it is now possible to reconsider their time-varying dynamics and pursue more accurate modeling and analysis methods [14].

The problem of data-based modeling is referred to as an identification/inverse problem [15]. This paper focuses on the problem of output-only identification of time-varying structures in a recursive manner due to the following two reasons: Firstly, in many cases controlled testing may not be feasible or the excitation may be unobservable under realistic operating conditions. Hence, there exists a need to identify time-varying structures by exclusively using the available measured response signals. *Output-only* modal analysis aims at determining the dynamic characteristics of a system in operating conditions, without measuring the "natural" excitation forces [7]. Secondly, in many problems not all response signals are known in advance and the solution has to be recalculated as new observations become available. Hence, there also exists a need to identify time-varying structures in a *recursive* instead of batch manner.

LTV system identification methods are generally classified under the umbrella of time-frequency methods and further classified as non-parametric or parametric according to the type of model adopted [14], as shown in Fig. 1. Non-parametric methods are based on non-parameterized representations of the signal as a simultaneous function of time and frequency, and parametric methods are based on parameterized time-dependent representations, mainly of the time-dependent state space (TSS) and time-dependent autoregressive moving average (TARMA) types [9,10]. In the *frequency* domain, most identification methods employ non-parametric time-frequency analysis, such as the short time Fourier transform [16,17], the Cohen's class [18–22], wavelet-based methods [23,24], the Hilbert-Huang transform [25–27] and so on. In the *time* domain, most identification methods employ parameterized time-dependent representations. Based on the TSS representations, many efforts have been undertaken to extend LTI system identification approaches to the LTV case by using ensemble data from multiple experiments [28–34], leading these methods unable to operate recursively. Based on the TARMA representations and their extensions, many identification methods have been developed in recent years [8–10,35]. These methods are further divided into three main classes, as shown in Fig. 1, depending on the type of "structure" imposed upon the evolution of the time-varying model parameters [8–10]: unstructured parameter evolution (UPE) methods, stochastic parameter evolution (SPE) methods and deterministic parameter evolution (DPE) methods.

In this paper we propose to deal with the problem of output-only recursive identification of time-varying structures by using TARMA based parametric identification methods. Most of parametric output-only recursive identification methods are currently of the UPE type [8,9,15,36–38], which may not be suitable for fast varying structures as they impose no "structure" upon their model parameters [8–10]. In contrast with the UPE and SPE methods, the DPE methods are based on explicit models of parameter variation through approximating the parameter trajectory by a linear combination of known basis functions [8]. From this point of view the TARMA based recursive DPE methods are promising and are therefore investigated in this work.

Over the past decades many efforts have been undertaken to develop the recursive DPE methods. The method of exponentially weighted Legendre functions was first proposed by Xie et al. [39] and further explored by Li [40]. Tsatsanis et al. [41] extended this technique by expanding the time-varying parameters onto the basis set of complex exponentials. Niedzwiecki [8,42] investigated the time and frequency characteristics of basis function estimators and divided them into two categories: *running-basis* and *fixed-basis estimators*, as shown in Fig. 1. The polynomial recursive least squares method [43] can also be classified into the category of fixed-basis estimators. To reduce the computational complexity of the recursive basis function estimators, Niedzwiecki et al. [44,45] proposed some fast algorithms which have improved tracking capabilities with low computational requirements. It should be noted that the running-basis and fixed-basis estimators offer different computational and numerical advantages. The running-basis estimators are generally characterized by conceptual and algorithmic simplicity; unfortunately, they may be numerical unreliable when the basis sequences are not bounded (which is the case when the Legendre basis is used) [8]. The fixed-basis estimators do not suffer from those numerical problems at the price of relatively higher computational requirements; however, the available set of recursively computable basis functions for the fixed-basis estimators may be limited to Legendre and Fourier basis [8]. To some extent, these drawbacks limit the application of the above recursive DPE methods.

The recursive extended least squares TARMA (RELS-TARMA) method [9] further extends the recursive DPE methods by selecting basis functions from a broader family of orthogonal functions. However, the RELS-TARMA method, as a member of the running-basis estimators, encounters similar numerical problems in case that the basis sequences are not bounded. Hence, the RELS-TARMA method may be limited to the cases in which the length of samples is known and the basis functions can be scaled in advance. Yang [46] proposed a kernel-based time-dependent autoregressive (TAR) method by representing time-varying model parameters as a linear combination of kernel functions. However, the kernel-based TAR method does not apply well to the cases in which the signal-to-noise ratio of the measurements is low. In order to identify time-varying structures from noise-corrupted measurements with unknown sample length, the kernel-based TARMA method is considered in this paper.

The remainder of the paper is organized as follows: Section 2 briefly introduces the TARMA model. The kernelized TARMA model is proposed in Section 3. Section 4 proposes the kernel recursive extended least squares TARMA approach consisting