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Nonlinear model for condition monitoring of non-stationary vibration signals in ship driveline application

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ABSTRACT

Condition monitoring of mechanical systems is an important topic for industry since it improves machine maintenance and reduce the total associated operational cost. In this sense, vibration analysis is a useful tool for failure prevention in rotating machines, and its main challenge is to perform on-line estimation of dynamic behavior, due to non-stationary operating conditions. To this, estimation of both, amplitude and instantaneous frequency, holding most of process information should be carried out. Nevertheless, approaches for estimating those parameters require to have the shaft speed reference signal, which is not always provided in several industrial applications. In this paper, a novel Order Tracking (OT) scheme of estimation is proposed that is based on the state space model that avoids the shaft speed reference signal. The nonlinear oscillatory model designed as frequency tracker is adapted for estimating the phase and the amplitude of each particular harmonic component. Specifically, nonlinear filtering (namely, the Square-Root Cubature Kalman Filter) is used to estimate the spectral components from the vibration signal. The proposed approach is tested and compared with baseline Vold–Kalman Filtering over four different datasets. The obtained results show that proposed approach is robust and it performs with high accuracy estimation of the order component and the instantaneous frequency under different operating conditions; both allow capturing machine dynamic behavior.

1. Introduction

Vibration analysis of rotating machines is one of the most used techniques for fault diagnosis and condition monitoring due to its high performance and low implementation cost. Nowadays, one of the main challenges in vibration analysis is to track and reduce influence of changes during time-varying operating conditions and loads. In this regard, techniques grounded on order tracking (OT) had been proposed, which are devoted to obtaining fundamental component features of the shaft reference speed (called *basic order*) and capture dynamics of measured vibration signals. The OT technique has shown to be useful mostly within the analysis of non-stationary vibration signals, condition monitoring, and fault diagnosis [1]. OT allows identifying the rotation speed and the spectral/order components, being both fundamental to describe the

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Nomenclature

List of symbols

$y(\cdot)$	measured vibration signal
$a(\cdot)$	order component amplitude
$\varphi(\cdot)$	order component phase
$\omega(\cdot)$	angular frequency
$\boldsymbol{x}(\cdot)$	state variable vector
$v(\cdot)$	measurement noise
$\boldsymbol{M}(\cdot)$	state transition matrix
$\boldsymbol{H}(\cdot)$	measurement matrix
$\boldsymbol{Q}(\cdot)$	covariance matrix of process noise
$\boldsymbol{h}(\cdot)$	measurement vector
$\boldsymbol{\vartheta}(\cdot,\cdot)$	state transition nonlinear function
n	discrete-time domain index
k	subscript to denote an order component
η	rotational speed in rpm
f	rotational speed or frequency (Hz)
$\boldsymbol{\xi}$	process noise vector
K	total amount of order components
q	initial value of process noise
r	variance of measurement noise
$\boldsymbol{\Gamma}$	vector of tracked order components
α	maximum value in $\Omega(\cdot,\cdot)$
$\Omega(\cdot,\cdot)$	time–frequency representation

Variables in Square-Root Cubature Kalman Filter

$\boldsymbol{P}$	error covariance matrix
$\hat{\boldsymbol{x}}$	predicted state (time update)
W	Kalman gain
χ	evaluated cubature points (time update)
$\hat{\boldsymbol{y}}$	predicted state (measurement update)
$\boldsymbol{S}$	square-root matrix
$\boldsymbol{\phi}$	cubature points
m	amount of cubature points
χ^*	propagated cubature points (time update)
$\boldsymbol{\psi}$	propagated cubature points (measurement update)

machine state as well as its conforming mechanisms during changing loads and speed regimes (e.g. start and stop of the machine) [2,3].

Mostly, OT is based on estimation of the instantaneous frequency (IF) that in turn can be extracted from a given time–frequency representation [2,4]. For instance, the Gabor transform is employed in [5], where the shaft speed reference signal is not required allowing to analyze rotating machines with less quantity of sensors or when the reference signal is not available at all. Nevertheless, the windowed Fourier-based transforms have limited resolution in both, time and frequency, axes and they suffer from increased computational burden [6]. To overcome this issue, OT technique is carried out grounded on parametric modeling including adequate estimation of spectral/order components.

Particularly, an OT approach based on Kalman filtering is suggested in [1]. Its improved version with increased precision, termed *Vold–Kalman filtering* (VKF-OT), is proposed in [3,6]. Yet, either of them needs for measuring the shaft speed, which makes the order analysis more complex since tracking performance must rely on the synchronization process between vibration signal and its reference speed. Furthermore, shaft speed measurement implies installing additional equipment close to the machine, which in not all situations may be feasible. To cope with this trouble, indirect measurement of shaft speed, based just on the instantaneous frequency, is also discussed in [7,8], where a frequency tracker is introduced using the oscillatory model. Parameters of the model are calculated employing the Extended Kalman Filtering (EKF), which supplies amplitude, phase, and mainly frequency of harmonic signal, for de-noising in non-stationary environments. Nonetheless, tuning of the above approach is heuristic and relies to some degree on expertise. In this regard, better estimation of amplitude and frequency using a non-linear least minimum square algorithm is suggested in [9].

On the other hand, an improved version of the EKF frequency tracker for non-stationary harmonic signals is presented in [10], where the time-varying amplitude is another state variable included in the oscillatory model, i.e., the standard state space model of a measured signal takes into consideration amplitude variations of harmonic data, which can be assumed as time-variant or even corrupted. In many real applications, however, the number of harmonic signals to track can increase remarkably, and consequently the needed amount of state variables implies more computational cost affecting the on-line tracking task implementation.

This paper discusses a nonlinear model-based OT approach for condition monitoring of non-stationary vibration signals that reduces the computational burden by decreasing the model order. Particularly, time-varying amplitude is estimated assuming the state variables as the in-phase and quadrature components from the input signal, and then computing the quadratic mean between those components. As a result, the amount of state variables required to track the signal becomes lower and hence the model order itself also decreases. Besides, to avoid numerical precision errors that are implicit during derivative calculation within the EKF framework [11], the use of Square-Root Cubature Kalman Filter is considered [12,13]. The proposed scheme is tested over several experiments: first, a synthetic signal is used aiming to distinguish between closed-order components; second, a test rig is employed under two different regimes, permanent and non-stationary, to track main order components and extract them; finally, a real-world application is used to validate the proposed scheme.

The paper is organized as follows: Section 2 presents estimation fundamentals of both, parametric instantaneous frequency and order, by using Kalman filtering. Section 3 discusses a simulation study to validate performance of considered OT schemes for the closed-order component identification. Further in Section 4, a set of test rig experiments is rendered