Journal of Sound and Vibration 418 (2018) 184–199

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

# Estimation of single plane unbalance parameters of a rotor-bearing system using Kalman filtering based force estimation technique

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ARTICLE INFO

*Article history:*
Received 13 August 2017
Revised 10 November 2017
Accepted 11 November 2017
Available online XXX

*Keywords:*
Kalman filter
Model-based fault diagnosis
System equivalent reduction expansion process
Unbalance identification

ABSTRACT

This paper proposes a model-based method to estimate single plane unbalance parameters (amplitude and phase angle) in a rotor using Kalman filter and recursive least square based input force estimation technique. Kalman filter based input force estimation technique requires state-space model and response measurements. A modified system equivalent reduction expansion process (SEREP) technique is employed to obtain a reduced-order model of the rotor system so that limited response measurements can be used. The method is demonstrated using numerical simulations on a rotor-disk-bearing system. Results are presented for different measurement sets including displacement, velocity, and rotational response. Effects of measurement noise level, filter parameters (process noise covariance and forgetting factor), and modeling error are also presented and it is observed that the unbalance parameter estimation is robust with respect to measurement noise.



## 1. Introduction

Unbalance is the most common fault and source of vibration in a rotating machinery [1]. Rotating unbalance can be categorized into single and multi-plane based on the unbalance present in single and multi-disks, respectively. Single plane unbalance occurs in gear wheels, single stage turbine wheels, compressor, pump impellers etc. The present work aims to propose an on-line estimation technique for single plane unbalance parameters, i.e., amplitude and phase angle.

Unsupervised fault diagnostic techniques of rotor systems mainly rely on signal processing based techniques. These techniques are helpful only for the qualitative understanding of machine's condition. Furthermore, signal processing based techniques detect faults at a late stage of machinery operations, however for better machinery condition monitoring, incipient fault detection is necessary. Model-based fault diagnostic techniques utilize all the information obtained from the measured signal. In comparison to signal processing based techniques, model-based monitoring system is cost effective [2]. Model-based approaches for rotor system fault diagnosis have been used for the identification of common machinery faults e.g. unbalance [3,4], misalignment [4], and cracks [5,7] based on load estimation. Full system states are required for equivalent load estimation, which can be calculated by an observer [5] or modal expansion [4]. It is observed that the modal expansion has a major influence on the identification results [3]. In model-based techniques, use of the reduced-order technique can limit the use of modal expansion or full state estimation.

Signal processing based techniques identify faults by their corresponding characteristic frequencies in the measured vibration signal [6]. However, this technique proves ineffective when different faults show similar characteristics. For example, Pen-

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https://doi.org/10.1016/j.jsv.2017.11.020

nacchi and Vania [7] have analyzed real gas turbine vibration data and used a model-based approach to detect actual fault where shaft bow caused by crack induced 1× vibration which also occurs in the case of unbalance or misalignment. It was concluded that the model-based approach for fault diagnostic could confirm the occurrence of an actual fault.

A major disadvantage of conventional techniques of balancing is the requirement of a number of runs which is always not convenient for large machines. Therefore, researchers from the field of machinery vibrations are looking for a balancing technique that requires less number of runs. The quantification of the amount of unbalance and misalignment present in rotating machines has been an active area of research. Lees and Friswell [8] presented a technique for estimating bearing parameters and state of unbalance using a numerical model of the rotor and measured vibration. They verified their technique with a numerical example of a single plane unbalance for a two bearing system. It was found that a good numerical model for the rotor is required for the estimation of unbalance. Later, this technique was verified on a small experimental rig [9]. Sinha et al. [10] proposed a model-based technique for unbalance (amplitude and phase) and misalignment estimation of a rotating machine from a single run-down/run-up. The method was verified on a small experimental rig, and it was observed that with modeling errors phase estimation is robust as compared to unbalance amplitude. Tiwari and Chakravarthy [11,12] presented an identification technique using impulse response measurement and least-square method for the identification of residual unbalances and bearing dynamic parameters. Frequency domain force and vibration response are used in the identification algorithm.

The occurrence of faults changes the system's dynamic behavior which is detected via model-based fault diagnostic approach [13]. Residual generation is one such technique where equivalent forces corresponding to different faults are calculated using residual vibrations. Then, using a fitting technique such as least-square the phase and residual of a particular fault type can be estimated either in time-domain [4] or in frequency-domain [14,15]. Usually, fault is identified when a change in vibration vector exceeds a threshold. In model-based fault diagnostic approach, it is assumed that this change is caused by the fault which is to be characterized.

Meanwhile, some deterministic-stochastic techniques have been developed in structural dynamics for unknown input force estimation [16–24]. These techniques consider modeling and measurement errors and provide a better estimate of the inputs. One such technique has been applied to an inverse heat conduction problem, by developing an on-line estimation technique based on Kalman filter and a recursive least square estimator [16,18]. The methodology of input estimation based on Kalman filtering was later implemented on input force estimation of structural systems. Ma et al. [19] have applied this technique for impact load estimation of single and multi-degree-of-freedom system. Later, this technique was applied to a beam, modeled as a single-degree-of-freedom system [20] and using finite element method [21]. The response at the tip of the cantilever beam was measured experimentally to estimate input forces. The calculated normalized root mean square error between true and estimated forces verifies the effectiveness of the proposed technique. This technique requires only displacement and/or velocity as the measured response. Eigenvalue realization technique with Markov parameters is used by Liu et al. [22] to obtain system matrices and then to model a cantilever plate in state-space form. In Ref. [23], this technique was applied for force estimation of rotating machines where numerical simulations were presented with a rigid rotor model, transverse and radial displacements. In Ref. [24], Kalman filter based input estimation technique was integrated with fuzzy logic inference system. To the best of authors' knowledge, this technique has not been employed in rotating systems for the purpose of fault diagnosis.

Optimal state estimation technique has been an active area of research in the field of fault identification under model-based approach. Kalman filter and its variants for linear and nonlinear systems are applied to rotordynamics for various purposes e.g. crack detection [25], parameter identification [26], fault identification [27], etc.

The major challenge of the previous model-based approaches is the estimation of full system response prior to force identification because of the limited response measurements. Furthermore, measurement noise and modeling error also affect force identification. Kalman filter-based force estimation technique is capable of dealing with measurement noise and modeling error. In this paper, Kalman filter and recursive least square based force identification technique is used for unbalance parameter estimation in a rotor-disk-bearing system. Here, single plane unbalance is considered, and thus the location of unbalance force is known. Finite element modeling is used for mathematical modeling of the system. The reduced-order model using modified system equivalent reduction expansion process (SEREP) technique is obtained for selected master degrees-of-freedom (DOFs) and number of modes. The measured displacement/rotational responses are chosen as master states. Effect of different measurement sets (including displacement, velocity, and rotations) are shown and discussed. Results are presented for different shaft speeds and measurement noise levels. Errors of estimated parameters are calculated for different values of filter parameters.

## 2. Mathematical modeling of rotor system

### 2.1. Full-order model

Finite element model of a rotor system is used in the present work. The shaft element consists of two nodes with 4 DOFs (two translational and two rotational) each. The bearings are modeled as linear springs with same stiffness as in the two lateral directions.

The linear equation of motion at a defined rotational speed is described by:

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}_\mathrm{d}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{S}_\mathrm{F}\mathbf{F}(t) \tag{1}$$

where $\mathbf{M}$ is the matrix containing mass and inertial, $\mathbf{C}_\mathrm{d}$ is the damping matrix and $\mathbf{K}$ is the stiffness matrices. $\mathbf{F}(t)$ is the force vector, $\mathbf{S}_\mathrm{F}$ is a binary matrix with entries 1 correspond to DOFs where forces are acting and 0 for remaining DOFs, $\mathbf{x}(t)$ is a vector