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Unbalance identification using the least angle regression technique

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ABSTRACT

The present investigation proposes a robust procedure for unbalance identification using the equivalent load method based on sparse vibration measurements. The procedure is demonstrated and benchmarked on an example rotor at constant speed. Since the number of measuring positions is much smaller than the number of possible fault locations, performing unbalance identification leads to an ill-posed problem. This problem was tried to be overcome previously with modal expansion in the time domain and with several linear regressions in the frequency domain. However, since the solution to the problem is a sparse equivalent force vector, these methods cannot provide a robust identification procedure. A robust identification can only be achieved by providing a-priori information on the number of unbalances to be identified. The presently proposed procedure achieves more precise unbalance identification without the need of a-priori information by incorporating a regularization technique. A well-known technique for producing sparse solutions is the Least Absolute Shrinkage and Selection Operator (LASSO). The proposed procedure is based on the generalized technique Least Angle Regression (LAR) which finds all the solutions of LASSO. A comparison of the time-domain approach, the frequency-domain approach and the proposed technique is made and the superiority of the latter technique in identifying the number of possible fault locations is highlighted. The selection of the threshold of the convergence algorithm of LAR as well as the selection of the value of the Lagrangian multiplier is discussed in some detail.

1. Introduction

1.1. Vibration-based Identification Methods

Fault identification techniques using vibration measurements follow two general approaches, the signal-based and the model-based approach. The signal-based approach extracts qualitatively features of the acquired signals that may enable the analyst to identify the underlying fault. As the name indicates this approach is based on the vibration signal only, which is then combined with a statistical model of the expected fault. Fault identification in rolling element bearings is a characteristic example of signal-based fault identification techniques. The analysis of data in time domain, frequency

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domain and time-frequency (or scale) domain, as well as the analysis of specific features emerging from intuitive or statistical models, like spectral kurtosis, may give information about the fault [1]. Techniques similar to the above, as well as parametric methods like the well-known ARMA [2] are used for fault diagnosis of gears. The signal-based identification techniques are generally used when the physical model of the fault is difficult to obtain or when a statistical model is sufficient to describe the fault. These techniques are generally easier with respect to their implementation but their accuracy and capabilities of fault localization are much lower than those of model based methods.

Model based fault identification techniques can be considered as more robust methods, however, the accuracy of the results is highly sensitive to the model accuracy. Numerous faults were identified by using model based techniques in the past: The unbalance as well as the parameters of the elastic support structure were identified by Edwards et al. in [3]. Sinha et al. in [4] identified also the misalignment at the couplings together with unbalance and the parameters of the elastic support structure. Chasalevris and Papadopoulos in [5] identified two transverse cracks in a beam under bending loads. Chu and Lu in [6] used the dynamic stiffness in order to identify the axial position of rotor–stator contact. Residual unbalance and the bearing dynamic parameters were identified by Tiwari and Chakravarthy in [7]. They used both simulation and experimental data for performing two identification methods: In the first step impulse response measurements of the bearings were used and in the second step several sets of unbalance configurations. Sawicki et al. in [8] used auxiliary harmonic excitation to detect a crack in a rotor. The authors stated that a robust identification method is still under investigation. Darpe et al. in [9] used a simply supported Jeffcott rotor in order to investigate the motion of a cracked rotor with a bow. The breathing behavior of the crack under various bow intensities was studied and qualitative suggestions were made for the detection of these faults. Patel and Darpe in [10] considered simultaneously rotor unbalance, crack and rotor–stator contact both theoretically and experimentally in a simple test-rig with a single disk. The faults were first tested independently and the contribution of each fault to the full-spectrum was assessed. Qualitative characteristics of each fault were suggested only for detection and not identification and estimation of the faults.

From all these investigations and approaches it is clear that no unifying approach is capable of investigating different kind of faults. A quite general approach was developed recently for on-line diagnosis of multiple faults [11,12]. This method considers the faults as equivalent loads that act on the undamaged nominal system.

The present paper reviews the equivalent load method in the time and the frequency domain. The main literature considering fault identification using this approach is discussed. In Section 2, the problem is stated and a small example is introduced. Regularization techniques and the current approach using LASSO are outlined and a short introduction to LAR for fault identification is given. In Section 3 the already existing time domain and frequency domain techniques will be benchmarked to the proposed approach. The drawbacks of the existing methods are illustrated for example using simulation data. Finally, in Section 4 the LAR is discussed. The influence of the threshold of the coordinate descent algorithm but mainly the selection of the tuning parameter and their effect on the identification results is discussed.

1.2. The method of equivalent loads

Several investigations in the literature have addressed the problem of fault identification considering the faults as fictitious forces that act on the linear undamaged system, avoiding therefore non-linearities introduced by the fault models. The proposed approaches can be classified into two kinds of procedures. The first kind of procedures performs the identification in the time domain, for which non-linear least square techniques were used for fitting model parameters to measured data [11]. The second procedure considers the fault identification in the frequency domain, for which the minimum solution of an overdetermined system (the force vector is sparse) is needed [12].

The present study is based on the equivalent load method that is described in the following according to [11]. The undamaged model of a nominal rotor system with N degrees of freedom can be linearized in the vicinity of its operating conditions and can be described by

$$M_0\ddot{r}_0(t)+B_0\dot{r}_0(t)+K_0r_0(t)=F_0(t), \tag{1}$$

where $r_0(t)$ is the N-dimensional vector of displacements and M_0, B_0 and K_0 the inertia, damping and stiffness matrices of the undamaged rotor system, which may include the rotor, the bearings and the foundation and may also change with rotor speed due the bearing characteristics and due to the gyroscopic effect. Once a fault is present in the system, the displacement vector $r_0(t)$ changes to $r(t)$. The difference of these two vectors is the residual vector Δr and can be considered as the result of a virtual force acting on the undamaged system. Therefore, the equation of motion for the rotor system with faults becomes

$$M_0\Delta\ddot{r}(t)+B_0\Delta\dot{r}(t)+K_0\Delta r(t)=\Delta F(\beta,t), \tag{2}$$

where β is a vector containing the fault parameters. It should be highlighted that in order to apply the equivalent load method an initial measurement of the intact system is necessary.

1.2.1. Time domain approach

The time domain approach was used for the identification of unbalance, of rotor–stator contact and of rotor cracks. The equivalent load method applied in the time domain was described in [13]. In addition, fault models for rotor–stator contact, for rigid coupling misalignment and for transverse cracks were discussed. A simultaneous unbalance and rotor–stator