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Unbalance detection in rotor systems with active bearings using self-sensing piezoelectric actuators

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ABSTRACT

Machines which are developed today are highly automated due to increased use of mechatronic systems. To ensure their reliable operation, fault detection and isolation (FDI) is an important feature along with a better control. This research work aims to achieve and integrate both these functions with minimum number of components in a mechatronic system.

This article investigates a rotating machine with active bearings equipped with piezoelectric actuators. There is an inherent coupling between their electrical and mechanical properties because of which they can also be used as sensors. Mechanical deflection can be reconstructed from these self-sensing actuators from measured voltage and current signals.

These virtual sensor signals are utilised to detect unbalance in a rotor system. Parameters of unbalance such as its magnitude and phase are detected by parametric estimation method in frequency domain. Unbalance location has been identified using hypothesis of localization of faults. Robustness of the estimates against outliers in measurements is improved using weighted least squares method.

Unbalances are detected in a real test bench apart from simulation using its model. Experiments are performed in stationary as well as in transient case. As a further step unbalances are estimated during simultaneous actuation of actuators in closed loop with an adaptive algorithm for vibration minimisation. This strategy could be used in systems which aim for both fault detection and control action.

1. Introduction

Rotating machinery could be found in many engineering systems and exists in different forms such as in electromechanical machines and turbomachines. Though it is not desired vibration is found in every machine. This could cause discomfort to users, affects performance of the process it drives and might also lead to its failure.

The reason for vibrations stem from faults in the system. This article focuses on unbalance faults affecting a rotor system. An unbalance might originate during the manufacturing of rotor where additional mass could be present or removed at a location of rotating shaft. Due to erosion between parts there could be loss of material leading again to an unbalanced condition. They are compensated during commissioning by placing balancing weights. It is not possible to completely balance a rotating system, as there is a small amount of residual unbalance. The system can only be brought to acceptable vibration limits [1]. This engineering problem has been explored over years by many researchers. Earlier work in [2] estimates unbalance by least squares approach which was later extended in [3] by an equivalent load minimisation approach. Both articles

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used modal expansion method to identify unbalance in time domain. A much simpler detection is possible in frequency domain as demonstrated by [4] using parameter estimation techniques. Because of its scope to conveniently extend to other fault types this method is used in this present article as well. Other faults which occur in a rotor system are misalignment, cracks, bearing failures, etc. A detailed review of different faults which occur in rotor systems along with the techniques used to identify them are presented in [5]. From these articles it can be inferred that fault detection in rotor systems has been attempted by many researchers since decades. Basic necessity of a condition monitoring unit is to sense the state of the system with the help of sensors. Unlike the studies which have been done previously this article explores the possibility of condition monitoring using virtually reconstructed sensor signals.

Conventionally sensors input information about a system to a control unit in which an algorithm or a controller is incorporated. It takes appropriate action on the system through actuators. Within the context of vibration in rotor systems the controller could perform an active vibration control. Commonly used actuators are active magnetic bearings [6] or piezoelectric actuators [7,8], both driven by auxiliary electric supply. In this article the functionality of a rotor test setup which is being investigated for vibration control is augmented to detect unbalance faults. Though both these problems have been solved only with physical sensors, the possibility to replace them with virtual signals has been explored in this article. This scientific work also forms an initial study towards simultaneous sensing of faults and actuation for vibration control in rotor systems.

Piezomaterials exhibit sensing and actuating capability due to the inherent coupling between their electrical and mechanical properties. Hence they are used to manufacture both sensors and actuators. Self-sensing in piezoelectric actuators eliminates the need for a sensor as the electrical signals could be reconstructed into mechanical signals with the help of an appropriate mechanism. These efforts began in 90s when capacitance of an actuator was estimated in [9,10] and approximated to be linear. If the working range of the actuators is more than 5% of its maximum operating voltage the capacitance is non-linear in nature [11]. In this present research work non-linear capacitance is estimated with the help of an experimental procedure. The procedure was suggested in [12], where self-sensing concept of piezoelectric actuators developed in [12] was applied to vibration control of a thin plate and simple beam structure. The reconstruction mechanism from it has been used in this study of a rotor system. In our present study displacement signals are reconstructed from electrical signals of actuators which are placed in bearings. The reconstructed displacement signals were used as control signals in a closed vibration control loop with the help of an adaptive algorithm [13]. This validates the simultaneous use of signals for actuation and sensing. However self-sensing concept in the above works was neither used in condition monitoring or for combined fault detection and vibration control.

The sensory signals used for fault detection in this article are displacement of bearings, reconstructed from actuators which are mounted there. In [14] multiple faults in a rotor were also detected using bearing displacement signals. However the displacement signals were integrated twice from accelerometer located at bearing, ultimately with the use of a sensor. In this article also displacement signal is used even without a sensor. In a previous work [15] faults were detected with self-sensing piezoelectric actuators where time domain methods are used. Because of computational complexity and requirement of a very accurate model time domain methods are not preferred. Instead faults are detected in frequency domain in the present article.

The novelty of this paper lies in the use of the virtual reconstructed signals in the field of fault diagnosis in rotordynamics. Conventional fault detection techniques need a sensor element which provides information about the system. In this research the sensor as a component is not needed, instead sensory signals are provided by actuator by an appropriate reconstruction mechanism. Another distinct topic is detection of faults in closed control loop. An integrated fault detection and vibration control is more close to a real implementation. Very few researchers such as [16] have investigated it. This research makes use of mechatronic system available for vibration control for simultaneous fault detection.

The rotor system subjected to fault diagnosis in this article is a test bench in our institute (Institute for Mechatronic systems in Mechanical Engineering). The test bench has been presented in Section 2. Apart from its construction its mathematical model has also been discussed based on which unbalance faults are detected. Signals to detect faults are reconstructed from electrical signals of piezoelectric actuators as explained in Section 3. The basic equations are presented and a two-step method of self-sensing reconstruction is described. The reconstructed virtual signals are also validated against physical sensors mounted in test bench. Section 4 explains the fundamentals of fault detection using parameter estimation which is then extended to a robust method by weighted least squares. The method is extended in this research to a case with simultaneous actuation and fault detection. Section 5 explains the different experiments performed in the actual test bench and the results are presented and discussed in Section 6.

2. Rotor test bench and its modelling

2.1. Structure and components

The test bench employed in this research work has a rotor shaft with a rotating mass and mounted in three bearing planes. The shaft with a length of 1.17 m weighs 22.5 kg together with the rotating mass. This mass represents a turbine of a turbopropeller aircraft engine. A schematic of the test bench is shown in Fig. 1 and its CAD diagram can be seen in Fig. 2. It can also be observed from the figures that the shaft on one side is mounted on a double bearing assembly where