Mechanism and Machine Theory 44 (2009) 1436–1449

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Mechatronic design of fault detection isolation and restoration systems for rotating machineries

Michał Manka *, Tadeusz Uhl

Department of Robotics and Mechatronics, Faculty of Mechanical Engineering and Robotics, AGH University of Science and Technology, Al. Mickiewicza 30, Cracow, Poland

ARTICLE INFO

Article history:
Received 2 November 2007
Received in revised form 25 September 2008
Accepted 24 November 2008
Available online 8 January 2009

Keywords:
FDI systems
FDIR system
Rotor balancing
Automatic balancing

ABSTRACT

This paper presents theoretical background and results of experimental research into fault detection, isolation and restoration (FDIR) system for rotating machineries created in Department of Robotics and Mechatronics, AGH University of Science and Technology in Cracow. The presented FDIR system solution concerns the problem of automatic balancing of rotating systems while in operation. Simulations and experimental results proved that application of the presented solution leads to a reduction in the vibrations caused by imbalance, without hindering service. A mechatronic approach to the design process makes this process more effective.

1. Introduction

In recent years the process of designing mechanical structures has evolved rapidly. Nowadays an engineer not only has to design a reliable mechanical system, but also predict what kind of faults may appear in a system and what steps should be taken to reduce their influence on performance. There are two methods used to fulfil this demand: robust design [11,15] and implementation of a special system that allows self-repair. In the following chapters the second method will be discussed.

Recent changes in the design of mechanical systems make fault detection and isolation one of the most important tasks [7]. The problem of fault detection and isolation is, in most cases, relatively easy to solve but problem of fault restoration is still a very challenging task [26,1]. Fault restoration can be performed in two ways: by reconfiguration of the system in a way that minimizes the influence of the fault, or by using a specially designed device for on-line repair. The typical structure of FDIR (fault detection, isolation and restoration) procedures is shown in Fig. 1 [2].

There are several definitions of FDIR procedures. The most popular and appropriate for rotating systems are given by Raich and Cinar [29]:

- *Fault detection* is determining whether a fault has occurred.
- *Fault identification* is identifying variables most relevant to diagnosing the fault.
- *Fault diagnosis* is determining the fault type, location, magnitude and time [13].
- *Process recovery*, also called *intervention*, is removing the fault or its influence on the system.

* Corresponding author. Tel.: +48 12 617 31 28; fax: +48 12 634 35 05.
E-mail address: mmanka@agh.edu.pl (M. Manka).

0094-114X/$ - see front matter
doi:10.1016/j.mechmachtheory.2008.11.011

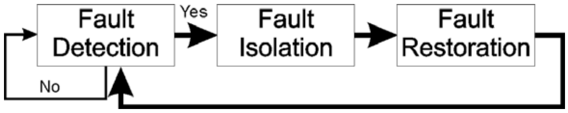

Fig. 1. Typical structure of FDIR system.

The main goal of monitoring the process is to maximize sensitivity of fault detection, identification and robustness to all possible faults. The best way to fulfil the goals mentioned above is to monitor multiple process parameters. Some of the parameters are more sensitive to certain faults and less sensitive to others. The disadvantage of taking multiple parameters into account in the monitoring and diagnostic process is the number of variables, which makes it impossible to detect a fault simply by observing the data. To improve the quality of diagnostic process several methods have been invented. They can be divided into three groups:

- *Data driven methods* are derived directly from measured data. These methods allow for transformation of high dimensional data into lower dimensions, with important data preservation. The main drawback of the data driven methods is that their accuracy depends on the quantity and quality of process data [2,5,17,19].
- *Analytical methods* use residual signals obtained from a mathematical model of the system and measured signals for fault detection. These methods can be used only in systems where an adequate mathematical model can be built. The quality of the model is crucial to the quality of the process [3,12,13].
- *Knowledge based methods* are used to imitate the reasoning of a human expert in the course of the diagnostic process. The expert's knowledge can be incorporated into a computer system as the rules. These methods are especially useful in fields where diagnostic associations are hard to translate into mathematical or causal models [25,34].

Most rotating systems are very complex and it would take a significant amount of time and resources to build an adequate model that could be used for analytical methods. Moreover it is impossible to build a universal mathematical model that can be used with different rotating devices. That is why the analytical methods are used only when other methods cannot achieve satisfactory accuracy of fault detection, or other aspects of the system indicate using this method. Both knowledge based and data driven methods can be used for universal systems. They can be easily adopted for different rotating machineries. Symptoms of faults in rotating machinery are well known [24,26] and most of them can be easily translated into mathematical rules. So there is no need to use a knowledge based system in this case. In the presented FDIR system solution, data driven methods have been chosen. The algorithms created are presented in the following sections.

The research presented in this paper concerns FDIR system for rotating machineries. The most commonly seen fault in this kind of mechanical structure is imbalance. In the classical approach to dealing with this problem, the rotating device is stopped during the balancing procedure and additional corrective masses are fixed in special balancing planes. In the vast majority of cases, balancing procedures have to be carried out several times in order to achieve a satisfactory level of vibration. Repeated starting and stopping of the rotating system may result in financial loss during stoppage or even in damage to some of the machine parts.

Increasing demands for higher rotation speeds, rotor sizes and higher requirements concerning vibration levels of the rotating machines make classical procedures insufficient. To match these new demands, active vibration control techniques were developed.

There are two main categories of active vibration control in rotating machineries:

– direct active vibration control (DAVC),
– active balancing methods.

The DAVC technique applies a control force directly to the rotor. A typical example of DAVC is systems with magnetic bearings [18]. The main advantage of the DAVC system is that the force generated can be changed rapidly. Rapid changes in the force can be used not only for suppressing synchronous (imbalance) vibrations but also for non-synchronous. The main disadvantage of the technique is force limitation – for high rotational speeds the force generated by the imbalance can easily exceed the maximum force that can be generated by the DAVC devices.

The alternative to the DAVC method is the active balancing system. This type of the system allows for the introduction of in-operational changes in mass distribution in the rotor in order to minimize the imbalance. The idea of in-operational balancing was originally proposed in 1960s by Van De Vegte [33], but his work mainly concerned theoretical problems of on-line automatic balancing. The first prototypes and experimental results were published at the turn of the 1970s and 1980s by Van De Vagte and Lake [31,32]. The proposed device was made of two concentric discs with corrective masses mounted on each disc, generating the desired reduction in mass eccentricity.

A different approach to automatic balancing has been presented by Furman [6]. This device was based on a non-contact local heating system to change the centre of gravity of a thermoplastic material in order to generate imbalance. Another solution was proposed by Jenkins [14], whose device was built of two discs with two chambers on each disc. Balancing was