Active Vibration Control in a Rotor System by an Active Suspension with Linear Actuators

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ABSTRACT
In this paper the problem of modeling, analysis and unbalance response control of a rotor system with two disks in an asymmetrical configuration is treated. The Finite Element Method (FEM) is used to get the system model including the gyroscopic effects and then, the obtained model is experimentally validated. Rotordynamic analysis is carried out using the finite element model obtaining the Campbell diagram, the natural frequencies and the critical speeds of the rotor system. An asymptotic observer is designed to estimate the full state vector which is used to synthesize a Linear Quadratic Regulator (LQR) to reduce the vibration amplitudes when the system passes through the first critical speed. Some numerical simulations are carried out to verify the closed-loop system behavior. The active vibration control scheme is experimentally validated using an active suspension with electromechanical linear actuators, obtaining significant reductions in the resonant peak.

Keywords: Active vibration control, rotor system, active suspension.

1. Introduction

Rotating machinery plays an important role in modern industry due to the wide range of applications of these kind of machines (i.e. turbomachinery, compressors, generators, etc.). The presence of mechanical vibrations is an inherent phenomenon in rotating machinery. Mass unbalance and dynamic interaction between the stator and rotating parts are the main causes for vibrations. The trend in industry has been to move towards high speed, high power, lighter and more compact machinery, which has resulted in machines operating above their first critical speed and increasing the vibrations problem [1-4]. In spite of the fact that the total elimination of the mass unbalance is impossible, it is very important to control the vibration amplitudes within acceptable limits for a safe operation of the machines. To do this, machinery designers have to understand and predict the rotordynamic behavior of machinery taking advantage of the improvements in computing technologies and modeling techniques, nowadays finite element techniques are widely used to model and to analyze rotor systems (see e.g. [2,3,5,6,7]). However, we must keep in mind that any model is only an approximation of a real system and its experimental validation has to carry out. The prototypes in laboratories are very important in the study of rotordynamics because by these, the analytical models and the control schemes proposed can be experimentally validated.

Nowadays, many machines must operate to high rotating speeds which yields a supercritical operation, that is, during the running up the machine has to cross one or more critical speeds causing large vibration amplitudes and more complex dynamic effects [2,3]. Some authors have presented important results about rotordynamics analysis such as [8,9], or fault diagnosis in rotor-bearing systems [10-12], but they do not include control schemes to attenuate the vibration amplitudes. On the other hand, rotating machines increasingly incorporate transducers, actuators and control systems, in order to attenuate vibration amplitudes, to improve the machines performance and to extend their useful life. One of the most important issues of this tendency is the use of active bearings. Active vibration control has been an area of theoretical and experimental research in rotordynamics, providing many advantages for the attenuation of vibration amplitude, during run-up and coast-down through critical speeds, and minimization of sudden transient behavior due to rotor unbalance or parametric uncertainty. In literature many control strategies to reduce the unbalance response in the classical Jeffcott rotor have been published, but using very simple models [13,14]. Other authors have proposed the use of active bearings to control the unbalance response in rotor systems with more than a disk. Nicoletti and Santos [15] show a methodology to design an active control of vibrations in a rotor system using actively lubricated bearings, they employ two control strategies, in the first one the control system reduces the vibration amplitudes at the desired position of the shaft, at the expense of increasing displacement at the ends of the flexible rotor and, in the second one, significant reduction of vibration amplitude along the whole rotor is achieved, and finally, they found that the actuator must operate in a linear range and the excitation frequency must be less than the natural frequency of the servo valve, otherwise, the control system does not properly operate, the results are presented by numerical simulations. Active Magnetic Bearings (AMB) and piezoelectric actuators are other devices used to control actively vibrations in rotor systems. Bi et al. [16] propose an automatic learning control for unbalance compensation using two AMB in a small rotor of around 1.5kg obtaining an important reduction in vibration amplitudes crossing the first critical speed. Couzon and Der Hagopian [17] combine neural networks to identify and fuzzy logic to control the flexible modes of a rotor suspended on active magnetic bearings and working under the first critical speed, they obtain the system finite element model by software to design the control scheme and then, they validate experimentally this control law proving that it is possible to use artificial intelligence in the active control of a flexible structure. Lei and Palazzolo [18] present the design and analysis of a rotating system with magnetic bearings including dynamics, control and simulation results, by rotordynamic analysis they find that the first bending mode is above the maximum operating speed which permits the controller design to ignore the flexible mode; they do not present experimental results, but they show the importance of a multidisciplinary design. Simoes et al. [19] show an active vibration control for unbalance compensation using piezoelectric actuators and show that important reductions in the vibration amplitudes are possible using active bearings with linear actuators. However, AMB and piezoelectric actuators are rather expensive, exhibit physical limitations and sometimes they are not easily available (see e.g. [20]). All of the works mentioned above use a reduced order model obtained by finite element techniques, but only some of them use experimental results to validate the mathematical models and control schemes.

In this work a reduced order model for a rotor system with two disks is obtained by the finite element method. The system model includes the gyroscopic effects and it is experimentally validated and used to get the Campbell diagram, the critical speeds and the mode shapes. An asymptotic observer is designed to estimate the full vector of system states and then, with the estimated states, a Linear Quadratic Regulator (LQR) with state feedback controller is synthesized to attenuate the resonant peak in vibration amplitudes when the rotor passes through the first critical speed. Some numerical simulations to validate the control scheme proposed are presented. The experimental test rig described in [21] was used to carry out some experiments to validate the closed loop system behavior. This experimental results show important reductions in the unbalance response of the overall system.

2. System modeling and analysis

2.1 Description and finite element model of the rotor system

First, we consider a rotor-bearing system shown in Figure 1. The rotor system is driven by an AC motor, which is connected to a steel shaft by a flexible couple. The shaft is supported by a traditional journal bearing on its ends. Two unbalanced disks are mounted in an asymmetrical way along the shaft, and the disks are fixed to the shaft by bridles. The motor and both bearings are fixed on a thick metallic base in order to give high stiffness to the system.