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Review

Mechanical model development of rolling bearing-rotor systems: A review

Hongrui Cao [a,*], Linkai Niu [a], Songtao Xi [a], Xuefeng Chen [b]

[a] Key Laboratory of Education Ministry for Modern Design and Rotor-Bearing System, Xi'an Jiaotong University, Xi'an 710049, China
[b] State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an 710049, China

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ABSTRACT

The rolling bearing rotor (RBR) system is the kernel of many rotating machines, which affects the performance of the whole machine. Over the past decades, extensive research work has been carried out to investigate the dynamic behavior of RBR systems. However, to the best of the authors' knowledge, no comprehensive review on RBR modelling has been reported yet. To address this gap in the literature, this paper reviews and critically discusses the current progress of mechanical model development of RBR systems, and identifies future trends for research. Firstly, five kinds of rolling bearing models, i.e., the lumped-parameter model, the quasi-static model, the quasi-dynamic model, the dynamic model, and the finite element (FE) model are summarized. Then, the coupled modelling between bearing models and various rotor models including De Laval/Jeffcott rotor, rigid rotor, transfer matrix method (TMM) models and FE models are presented. Finally, the paper discusses the key challenges of previous works and provides new insights into understanding of RBR systems for their advanced future engineering applications.

Contents

* Corresponding author.
E-mail address: chr@mail.xjtu.edu.cn (H. Cao).

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1. Introduction

Since the invention of the wheel, humans began to use rotors.[1] Rotor dynamic analysis plays an important role in designing, operating and troubleshooting rotors. The paper, 'On the centrifugal force on rotating shafts', published by Rankine in 1869, marked the beginning of rotor dynamics. Since then, the increasing importance and technical difficulties have led to a considerable growth of the new field. Nowadays, rotor dynamics is still a field of very active research. The authors recommend the readers to read excellent introductions on the history of rotor dynamics [1–5], and the representative books [6–18], which have detailed bibliographies.

In order to better understand rotor dynamics, we must turn to those laws of mechanics which determine rotor behavior. If we describe a physical system exactly or approximately by a set of equations, we call that set a model of the physical system [18]. In general, a rotor consists of shafts whose diameters change depending on their longitudinal position, disks with various shapes, and bearings situated at various positions. There are two primary issues in modelling the rotor system. The first issue focuses on the rotor. Many turbomachines have flexible rotors, where the shaft is designed in a relatively long and thin geometry to maximize the available space for components such as impellers and seals. Moreover, machines are operated at high rotating speeds in order to maximize the power output. The second issue is about the bearing modelling. The bearings support the rotating components of the system and provide additional damping to stabilize the system. Both plain bearings (fluid film bearings) and rolling element bearings are widely used in rotor systems. Due to the high stiffness and a wide range of load, speed, and operating temperature sustainability, rolling bearings applications have ranged from simple bicycles to very sophisticated gas turbine engines used in aircraft engines and cryogenic turbopumps that form critical parts of the space shuttle propulsion system [19]. In comparison with plain bearings, it is more difficult to model the rolling bearing as a whole due to the complicated coupling between the interactions of components (i.e., rolling elements, cages and rings) of rolling bearings. Furthermore, in order to investigate the dynamic behavior of the whole system, the coupled modelling between the shaft and rolling bearings is another difficult task. Up to now a long series of methods and studies related to the modelling of rolling bearing rotor (termed 'RBR' by the authors) systems have been proposed. However, to the best of the authors' knowledge, no comprehensive review on RBR modelling has been reported yet.

To address this gap in the literature, only rotor systems supported by rolling bearings are considered, and the current progress on the mechanical modelling of RBR systems are reviewed and critically discussed in this work. The rest of the paper is organized as follows. In Section 2, the rolling bearing models are reviewed. Section 3 presents the coupled modelling of rolling bearing rotor systems. Discussions on current limitations and future trends are given in Section 4. Finally, the paper is concluded in Section 5.

2. Rolling bearing models

Bearings constitute one of the most critical components in rotating machinery. Early investigators did not recognize the importance of the bearing properties, so many analytical rotor models (e.g., Jeffcott rotor [20]) had rigid supports at the bearing locations (infinite stiffness, no moment restraint). In fact, many problems we are facing with in rotating machinery today can be attributed to the improper design or application of the bearings. An understanding of how bearings work is therefore essential for making the proper choice for the particular design that best matches the performance requirements of the machine.

Although a rolling bearing consists of only four components (i.e., inner ring, outer ring, cage and ball), the static and dynamic behaviors of rolling bearings are very complicated in reality. The reason lies in the nonlinear contacts between different bearing components and the complex tribo-mechanical phenomena that occur during the bearing operation. Therefore, rolling bearing modelling is essential to gain the knowledge of basic principles. Over the past several decades, a number of models have become available for rolling bearing design and simulation. Rolling bearing models can be classified as the lumped-parameter model, quasi-static model, quasi-dynamic model, dynamic model and finite element (FE) model. A technical review of these models is given as follows.

[1] In this paper the word "rotor" is used to designate the assembly of rotating parts in a rotating machine, including the shaft, disk and other accessories.