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Dynamics of a geared parallel-rotor system subjected to changing oil-bearing stiffness due to external loads

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ABSTRACT

The variable critical speeds and resonances of a geared parallel-rotor system with five shafts effected by changing oil bearing stiffness due to different external loads are investigated in this paper. The rotor system of a modern centrifugal compressor is taken as the research object firstly. A finite element (FE) model of it is established by using rotating beam elements with 6 degrees-of-freedom (DOFs), and linear mesh stiffnesses of the engaged helical gears are involved. The changing stiffness and damping of the oil bearings effected by different loads are calculated based on traditional oil-film fluid formula. Then, the Campbell diagrams of the whole rotor system under different loads on three output shafts are calculated based on the above model. Finally, comparing the obtained critical speeds, the load ranges are revealed to lead possible resonances of the rotor system near the operating speeds.

1. Introduction

Integrally geared centrifugal compressor is one of the most attractive developed and important equipments in recent years and used in many patrol processing factories, which has merged the speed-increasing gearbox with the compression sections to create a compact and efficient package [1]. The rotor system of the integrally geared centrifugal compressor is always composed of some paralleled and geared shafts including one input shaft and three or even more output ones supported by the tilting pad journal bearing (TPJB). Due to the complicated dynamic characteristics, dynamic modeling of compression system has received significant attention over the years. However, the studies in this field are still inadequate because of its complexity. Among the limited modeling studies, most works in this field are done for axial compressors and fewer results are available from literatures on centrifugal compressors especially for the integrally geared ones. Morini et al. [2] developed a non-linear one-dimensional modular dynamic model of bio-gas compression system and which is used for the simulation of compression system transient behavior. Jiang [3] presented an analytical model for the centrifugal compressor which can be used to predict the compressor performance curves of outlet pressure, efficiency and losses and obtain surge line for defining stable operation range. Lee [4] conducted an investigation on the suppression of sub-synchronous vibrations due to aerodynamic response and surge in a two-stage centrifugal compressor with airfoil bearings. Gruntfest et al. [5] discussed the rotordynamic instability of an integrally geared compressor that initially had problems with high bearing pad temperatures and investigated its causes. Moore [6] conducted full-load, full-pressure rotordynamic stability measurements on a seven-stage, back-to-back centrifugal compressor. Kim [7] investigated the fundamental aeromechanics of compressor flow instabilities through experiments in a three-stage axial flow compressor, and pointed out that aerodynamically forced vibration in a centrifugal compressor should be considered.

Nowadays, many interesting papers on the dynamic analysis of geared rotor system have been presented. Choi [8] and Park [9] studied analytical modeling method for a helical geared system respectively and the dynamics of gears were investigated. Choi [10] presented a model of geared one-stage rotor bearing system by transfer matrix method where the gear mesh was modeled as a pair of rigid disks connected by a spring-damper. Baguet [11] applied an iterative Newmark scheme to a single stage geared system, and demonstrated the gear-bearing dynamic interactions through the analysis of dynamic gear loads, dynamic bearing loads and bearing displacements. Kang [12] investigated the dynamic behaviors of a two-shaft gear-rotor system with viscoelastic supports. Maliha [13], Eritenel [14] and Walha [15] analyzed the nonlinear behaviors of the geared rotors, and the dynamic gear loads and dynamic bearing forces were calculated. Lee [16] presented a 5-DOFs models for obtaining the unbalance response of a 600 kW turbo-chiller rotor-bearing system based on the finite element approach.

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To avoid the waste of the energy and the impact load on the starting process of the centrifugal compressor, the compressor is always speeding-up without load until stabilizing at the working speed firstly, which is beyond the first several critical speeds of its rotor system, and then increasing the load to the rated load. During the speeding-up process, it sometimes needs to accelerate through the critical points in order to avoid the increasing vibration. While during the load increasing process, it frequently occurs that the vibration of the system also increases as the rotor system speeding-up across critical speed. That is, when the load increases near to a certain value, the vibration increases significantly, while after this certain load, the vibration decreases to the normal range, which is often called “critical load” by the operations staff. Sometimes, the vibration is so violent that makes the operations staffs have to stop the compressor. This phenomenon is quite common, including the compressor designed by some well-known companies in the world, and confuse the users and designers.

Due to the nonlinear dynamics of the oil film bearing and gear mesh, there is no accurate critical speed for a gear-bearing-rotor system. Most researches focus on the nonlinear dynamics of rotor system, and few works focus on the changing dynamic characteristic caused by the load variation from the critical speeds perspective. But the critical speed of the geared rotor-system after linearization is useful, and the appropriate working speed of the high speed rotating machineries is also designed by critical speed analyzing. Meanwhile, many famous compressor manufacturing companies still treat the rotor system of the whole machine with many geared shafts as different single-rotor systems dividedly nowadays, and make the critical speed of the shaft diverge from the working speed at the design stage without considering the variable load. Sometimes, however, the vibration problems of the rotor system occur when increasing loads even though the rotating speed is steady in the start-up process of centrifugal compressor, which makes the compressor inoperable, or even causes dangerous risk in the machine operation. It is necessary to study the changing dynamic characteristic of the geared rotor system in the centrifugal compressor caused by the loads, and find out the possible cause of “critical load”, which would be a guidance in the integrally geared centrifugal compressor design.

In this paper, the dynamics of an integrally centrifugal compressor with five parallel shafts is investigated, where the changing parameters of TPJBs are considered as the main causes of the severe vibrations mentioned above. Admittedly, the “critical load” may not be caused only by the changing parameters of TPJB, but it is certain that it is one of the most important reasons. Based on the finite element (FE) model of the rotor system, the response reproduced the vibration phenomenon in the starting-up process. These results will provide guides for the integrally centrifugal compressor design.

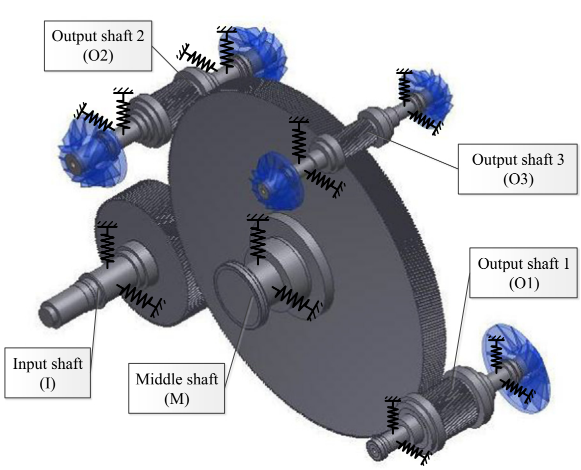

Fig. 1. A geared rotor system composed of five shafts.

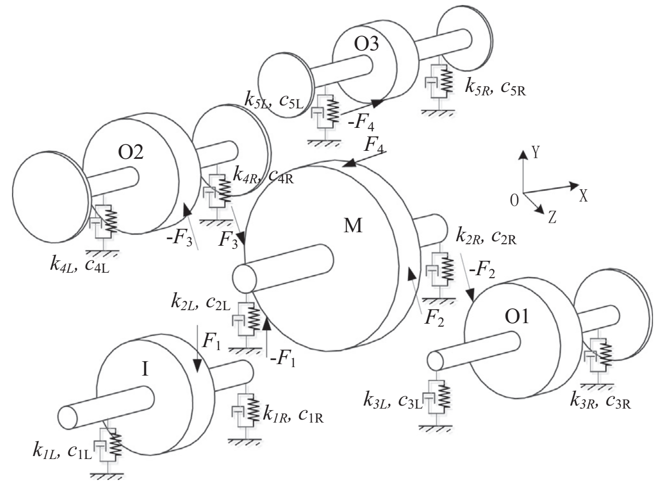

Fig. 2. The dynamic model of the five shaft geared rotor system.

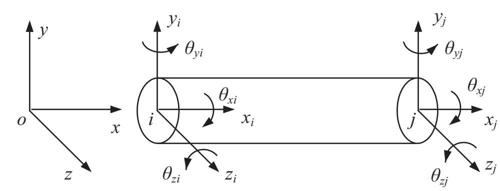

Fig. 3. Rotating beam element.

2. Geared rotor system in the integrally centrifugal compressor with five parallel shafts

A schematic of the geared parallel-rotor system is shown in Fig. 1, which is a prototype of an integrally geared centrifugal compressor with 5 shafts coupled by helical gears in parallel arrangement. Each shaft is supported by two TPJBs. The test rig is driven by an AC motor connected to the input shaft (I). The dummy impellers or discs are fixed on the three output shafts (O1, O2, O3). These shafts are all connected to a big main gear (M) by different gears. The transmission ratios of the three output shafts are 2.72 (I to O1), 3.25 (I to O2) and 5.10 (I to O3).

The dynamic model of the five shaft geared rotor system is shown in Fig. 2. k_{iL}, c_{iL} and k_{iR}, c_{iR} are the stiffness parameters and damping parameters of the left TPJBs and right TPJBs on the five shafts respectively, which are dependent on the loading characteristic. F_i is the meshing force. Unlike the traditional one-to-one gear pair's transmission, the geared system in Fig. 2 is consisted of a bull-gear (M) and four pinion gears, and the bull-gear meshes with the other four gears at the same time, which cause a much stronger coupling effect. This compact structure can offer several advantages such as smaller floor space, lower energy consumption, and higher power density. However, it also means that much more critical speeds must disperse in a certain interval of speed, which brings much more difficulties in critical speed designing.

3. 6-DOFs dynamic modeling method of geared rotor system

The finite element method is used to set up the dynamic model of the geared rotor system shown in Fig. 3, and the assumptions