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# Time-varying stiffness characteristics of roller bearing influenced by thermal behavior due to surface frictions and different lubricant oil temperatures

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ABSTRACT

In this paper, the time-varying stiffness of the cylindrical roller bearing due to the thermal behavior, i.e. warm-up process and different lubricant oil temperatures are experimentally investigated. Firstly, a special test rig that can measure the bearing stiffness is built. Then, a bearing stiffness identification method is proposed, which can avoid the influence of the clearance and deformation on measurement results. Finally, a series of measurements are carried out at different operational conditions. Results reveal that the bearing stiffness shows strong nonlinearity and time-varying characteristics due to the variation of structure and oil performance. In startup (quasi-isothermal condition) and thermal balance states (combined with the frictional heat generation), the influence of the rotational speed on stiffness is opposite.

## 1. Introduction

Rolling bearing is the important component of the rotating machinery, which is in the vibration transmission path between the shaft and the bearing housing. The stiffness characteristics of the bearing determine the critical speed, vibration response, noise, deformation, component stress, wear and stability of the machine [[1–4]]. The heat is generated due to the surface frictions when the bearing operates, and some bearings work in thermal environment. The thermal effects have significant impact on the bearing stiffness. The bearing stiffness shows strong thermal time-varying characteristics, which are often the main source of mechanical nonlinear vibration [5,6].

The research of the bearing stiffness characteristics has a long history. Earlier studies on the stiffness of rolling bearings were carried out by Harris [7], Jones [8] and Palmgren [9]. They studied the nonlinear relationship between the elastic deformation of bearings and external load. At present, plenty of research results have been reported on the influence of the clearance [10], assembly [11], preload [12], speed [13], load [14], contact angle [15], angular misalignment [16] and manufacturing error [17] on the bearing stiffness. The stiffness matrix [18,19], finite element model [2,20] and rotor-bearing system model [1,21] of different types of the bearings were established to analyze the bearing stiffness characteristics.

The bearing needs lubrication when it operates. The main function of the lubricant oil is to provide an elastohydrodynamic lubrication (EHL) oil film between the friction surfaces, which can reduce friction. The lubricant oil film formed between the friction surfaces leads to the increase of the bearing stiffness [22,23]. Zhang et al. [24] studied the oil film stiffness characteristics of the line contact. The results showed that the oil film stiffness increases with the increase of the load. Huang et al. [25] studied the influence of the thermal EHL on the stiffness of the angular contact ball bearing. It was concluded that the thermal effects reduces the oil film thickness, which leaded to the decrease of the radial stiffness. Zhang et al. [26] found that the lubrication had great influence on the stiffness coefficient of the deep groove ball bearing. Similar work for angular contact ball bearing was done by Bizarre [27].

Early experimental studies on the bearing stiffness were to understand the dynamic characteristics of the spindle. Goodwin [3] gave a detailed overview of the measurement approaches of the bearing stiffness. Stone [28] pointed out that the main parameters influencing the stiffness of rolling bearings were the load, assembly, rotational speed and lubrication. Li et al. [29] measured the dynamic stiffness of the angular contact ball bearing, and the relationship between the preload and stiffness was analyzed. Hao et al. [30] measured the nonlinear stiffness of the roller bearing. It was concluded that the stiffness measurement results were obviously smaller than the calculation results

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which were based on the rigid body assumption. Jacobs et al. [31] experimentally investigated the influence of the oil on the stiffness characteristics of the ball bearing. It was found that the bearing stiffness decreased gradually due to the frictional heat generation. García et al. [32] observed that the load and oil viscosity had certain influence on the ball bearing stiffness, and the stiffness was also sensitive to the temperature difference of the components.

In summary, there are many previous theoretical studies focused on the influence of the structural size, speed, load, assembly, lubrication and other combined factors on the stiffness of rolling bearings. In terms of the stiffness measurement, there are mainly two methods. One is to apply load (constant load or excitation load) directly to the bearing and determine the bearing stiffness by measuring the elastic deformation, and the other is to determine the bearing stiffness by analyzing the dynamic response of the rotor-bearing system. However, most of the existing experimental research focus on the influences of the load, rotational speed and preload on the bearing stiffness. There are few experimental research on the influence of the thermal behavior (heat generation due to surface frictions and thermal lubricant oil) on the bearing stiffness.

In this paper, the time-varying stiffness of the cylindrical roller bearing due to the thermal behavior, i.e. warm-up process and different lubricant oil temperatures are investigated based on a series of experimental measurements. A special test rig is built to measure the bearing stiffness. The sliding guides matched with the bearing housing are designed to avoid the influence of the relative movement of the rings on the measurement accuracy. A bearing stiffness identification method is proposed by applying incremental loads to the bearing and measuring its deformation. The time-varying stiffness characteristics of the bearing during the warm-up and at different lubricant oil temperatures are both discussed. Some parameters, such as radial load, rotational speed, are varied to investigate their influences on the bearing stiffness in startup state (quasi-isothermal condition) and thermal balance state (combined with the frictional heat generation). The presented results in this paper focus on the rotational speed range from 1200 to 3000r/min, the load range from 400 to 800 N, and the lubricant oil temperature range from 20 to 80 °C.

## 2. Test rig

In this section, a special test rig for measuring the cylindrical roller bearing stiffness is designed, and the N1013 M cylindrical roller bearing is chosen for research. The oil injection system, data measurement and acquisition system used in the current research are all described.

### 2.1. Description of apparatus

The main concept of the bearing stiffness test rig is shown in Fig. 1. It consists of a motor, a coupling, a shaft, two support bearings, a tested bearing, a bearing box, two sliding guides and a loading device. The support bearings are mounted at both ends of the shaft, which forms a flexible spindle. In the middle of the shaft, the tested bearing is mounted.

The bearing stiffness determines the dynamic characteristics of the rotor system. Generally, the clearance of the cylindrical roller bearing is relatively large. When it is loaded, only a few rollers are loaded, and other rollers are unloaded. This will lead to large bending of the rings and variation of the lubrication characteristics, which will have an obvious influence on the bearing stiffness. In addition, it is relatively difficult to measure the stiffness of the cylindrical roller bearing because of the large order of magnitude. Therefore, the stiffness characteristics of the cylindrical roller bearing are studied in this paper. The N1013 M cylindrical roller bearing is used for the stiffness measurement due to its representativeness, convenient installation and arrangement of the sensors. The structural parameters are summarized in Table 1. The material of the bearing is E52100 (AISI), and the material of the shaft, bearing housing and sliding guide is C1045 (AISI).

The bearing box fixed on the frame is used to collect and remove the oil. The applied load is controlled by a hydraulic cylinder. It is mounted in the bearing box and can apply accurate and stable upward radial load to the bearing. In order to avoid unnecessary offset load, the load should be imposed to the bearing center. The oil injection system as shown in Fig. 2 is used for the tested bearing lubrication, which can heat the oil temperature (up to 120 °C) and flow rate. The oil is ISO VG 46#.

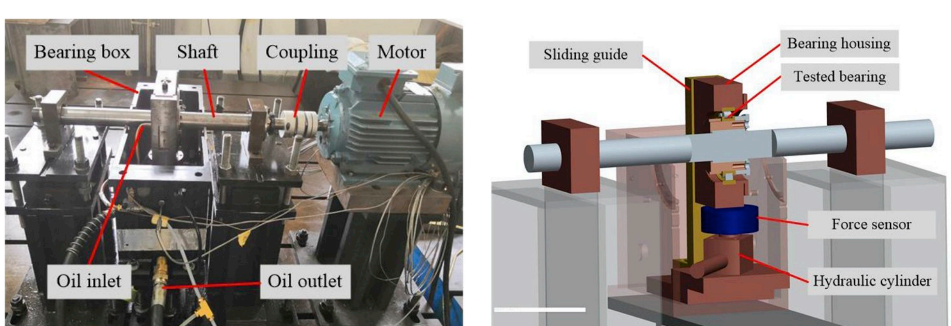
When the radial load is applied, two sliding guides are designed in the current research to avoid the axial relative movement of the bearing rings. They are solid structures, located on both sides of the bearing housing and fixed in the bearing box, as shown in Fig. 3. The clearance fit is adopted between the sliding guides and the bearing housing. The contact surface is very smooth. The bearing housing and outer ring have one degree of freedom (displacement $z$).

### 2.2. Measurement system

The measurement system is composed of sensors, data acquisition modules, signal acquisition controller and PC, as shown in Fig. 4. In this study, the bearing stiffness is measured by two eddy current sensors and a force sensor. In addition, a thermocouple sensor is attached on the

**Table 1**
The structure parameters of N1013 M cylindrical roller bearing.

| Parameters | Value |
|---|---|
| Bore diameter (mm) | 65 |
| Inner raceway diameter (mm) | 74.5 |
| Outer raceway diameter (mm) | 90.5 |
| Outside diameter (mm) | 100 |
| Roller diameter (mm) | 8 |
| Roller length (mm) | 10 |
| Roller number | 21 |



(a) Physical drawing (b) Cutaway view

**Fig. 1.** Concept of test rig.