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Effects of bearing outer clearance on the dynamic behaviours of the full floating ring bearing supported turbocharger rotor

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ABSTRACT

As a high speed rotating device, the modern turbocharger rotor is commonly supported by floating ring bearings (FRBs). The high nonlinearity there can always lead to quite complex and interesting phenomena rarely observed in other rotating applications. Using the run-up and run-down simulation method, this paper originally and systematically discusses the effect of bearing outer clearance on the rotordynamic characteristics of a realistic turbocharger rotor over the speed range up to 3000 Hz. The rotor is discretized by the Finite Element Method and supported by analytically calculated bearing forces. The linear analysis is proved to be effective in predicting the first two nonlinear jumps but inadequate to study the rotordynamic characteristics at higher rotor speeds. The nonlinearly simulated results show the appearances of distinct and interesting phenomena within the considered range of FRB outer clearance, which can be further divided into four groups. Within the same group, the simulation results are qualitatively similar to each other but quite dissimilar from the results from different groups. Moreover, the unwelcome *Critical Limit Cycle Oscillation* can be avoided by increasing the outer clearance size. Additionally, in some cases, the run-down simulations reveal distinct frequency maps as compared to the corresponding run-ups. Furthermore, it is seen that ring speed ratios can be considerably affected by the nonlinear jumps. Therefore, FRB outer clearance should be thoroughly examined to achieve the best rotordynamic performance.

1. Introduction

Turbochargers (TCs) are a typical kind of high-speed rotating machine widely employed in the automotive industry to meet the higher power output requirement with size-restricted internal combustion engines. The operating speed of a small size TC rotor for a passenger car can go to 200 krpm, which is much higher than many other rotating machines in the industry. Commonly, the TC rotating parts consist of a bearing supported single overhung rotor with compressor and turbine disks seated at the two ends (Fig. 1). Currently, full floating ring bearing (FRB) or semi-floating ring bearing (SFRB) is the dominant bearing candidate widely utilized in automotive TC applications, because they are inexpensive for mass production and can provide a better damping effect as well as fewer friction losses than the conventional plain journal bearings [1]. In contrast with FRB, SFRB demonstrates better stability characteristics at high rotor speeds [2], although FRB performs better in the oil-contaminated environment [3].

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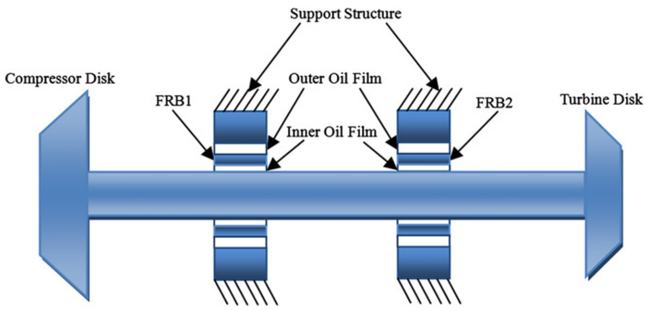

Fig. 1. TC rotor-FRB system assembly.

Available literature [4–9] shows that the high speed of TCs introduces a wide instability operating region, in which TC rotors are normally subject to serious subsynchronous vibrations produced by the instability of FRBs and SFRBs. Surprisingly, further observations reveal the high nonlinearity of FRBs is capable of producing stable limit cycles with acceptable amplitudes at rotor speeds higher above the linearly predicted threshold speed of instability, which can still ensure the safe operation of the supported TC rotor in usual situations [3,6,10–12]. Nonetheless, in some cases, due to the complexity and sensitivity of the TC rotor-FRB system, the wrongly designed bearing structural parameters can lead to catastrophic failure of TCs [13,14]. In addition, various kinds of frequency spectrum bifurcation or nonlinear jump phenomena are related to the emergence of uncomfortable noise found in TCs, and the undesired subsynchronous component can be suppressed by adjusting the bearing structural parameters [15,16]. Under the circumstances, it is pressing to develop reliable computational tools to carry out the parameter analysis of the TC rotor-FRB system on the drawing board to avoid the design defect and to improve the comfortability of passenger cars. At the early stage, in order to obtain the threshold speed of instability for the interested parameters, e.g. the ratio of bearing outer to inner clearance, the rotor-FRB systems have been mainly investigated by performing the linear eigenvalue analysis through linearizing the oil film forces to bearing stiffness and damping coefficients around the static equilibrium [4,5,17–20]. With a given dimensionless load parameter, it is observed that the bearing clearance ratio can considerably affect the threshold speed of instability. However, the extremely high speed of TC rotor is normally well above the linearly obtained stability border, which makes the relatively low-speed linear stability analysis useless. Nevertheless, recent researches show that the linearly predicted unstable modes over the considered TC speed range are in good agreement with the results from the nonlinear transient simulations and experiments [10,21–24]. This means that the linear eigenvalue analysis is possible to offer a valuable insight into the complex nonlinear behaviours of rotor-FRB system, but the nonlinear jump phenomena, i.e. the collapse of a limit cycle and the birth of another limit cycle, can hardly be linearly predicted. The analytical bifurcation method adopted in Refs. [25,26] is also an uphill struggle to be applied to the complex non-autonomous system with the unavoidable unbalance forces introduced during the manufacturing and using processes. Under the circumstances, solving the nonlinear equations of motion of the rotor-FRB system by direct numerical integration is an effective and feasible way to perform the nonlinear analysis. The advantage of the combination between this method and the comprehensively developed bearing model has been shown in Refs. [7,9,11,27,28]. Alternatively, less accurate bearing models based upon the short bearing approximation can also be adopted to carry out the nonlinear analysis, since they can ensure not only the efficiency but also sufficient accuracy [2,12,29,30].

Recently, the run-up simulation method has been presented by Schweizer in Refs. [3,8,13,31] to study the frequency spectrum bifurcation phenomena effectively in TC rotor-FRB systems. Through varying the TC rotor-FRB system physical parameters, for the first time, it has been observed that the synchronization of the inner and outer film instability will result in a situation called *Total Instability* [13], which can cause the failure of TC. However, the results of only limited number of run-up simulations have been presented and more than one bearing parameter is changed in each simulation. The so-called *Total Instability* phenomenon is also investigated by Boyaci et al. [26] in the analytical bifurcation analysis for a TC rotor-FRB system and is named *Critical Limit Cycle Oscillation*, which brings about unacceptable rotor vibration amplitudes and large inner as well as outer bearing eccentricities of FRBs. The onset speed of *Total Instability* or *Critical Limit Cycle Oscillation* determines the operation limit of FRB supported TCs, which is of great interest and significance to TC design and development. The utilization of the run-up and run-down simulation method for the parameter study of a commercial TC-SFRB system is shown in Ref. [16], although the bearing clearance effect is not included.

This paper aims to clarify the effect of FRB outer clearance on the rotordynamic characteristics of TCs by carrying out both run-up and run-down simulations of a realistic TC rotor-FRB system with varying FRB outer clearance sizes. As can be appreciated from the following sections, the obtained results systematically reveal some interesting phenomena, which have never been shown or reported in previous publications. The paper is structured as follows. Firstly, the TC rotor-FRB model is introduced in Section 2. The results of linear analysis are reported and discussed in Section 3 to get a deeper insight into the nonlinear simulation results presented in Section 4. In order to investigate the effect of FRB outer clearance purely, the simulated results under the perfectly balanced condition are presented first in Section 4.1 through Section 4.4, of which the range of application is further shown in Section 4.5 by considering the influence of unbalance. A short discussion is given in Section 4.6. Subsequently, the conclusions are reached in Section 5.