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Nonlinear effects of unbalance in the rotor-floating ring bearing system of turbochargers

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ABSTRACT

Turbocharger (TC) rotor-floating ring bearing (FRB) system is characterised by high speed as well as high non-linearity. Using the run-up and run-down simulation method, this paper systematically investigates the influence of unbalance on the rotordynamic characteristics of a real TC-FRB system over the speed range from 0 Hz to 3500 Hz. The rotor is discretized by the finite element method, and the desired oil film forces at each simulation step are calculated by an efficient analytical method. The imposed unbalance amount and distribution are the variables considered in the performed non-stationary simulations. The newly obtained results evidently show the distinct phenomena brought about by the variations of the unbalance offset, which confirms that the unbalance level is a critical parameter for the system response. In the meantime, the variations of unbalance distribution, i.e. out-of-phase and in-phase unbalance, can lead to entirely different simulation results as well, which proves the distribution of unbalance is not negligible during the dynamic analysis of the rotor-FRB system. Additionally, considerable effort has been placed on the description as well as discussion of a unique phenomenon termed *Critical Limit Cycle Oscillation* (*CLC Oscillation*), which is of great importance and interest to the TC research and development.

1. Introduction

To increase the output of internal combustion engines, turbochargers (TCs) are important auxiliary devices favoured by many automotive manufactures. Driven by the continuous desire for higher engine power, the speed of TC, which can climb up to over 200,000 rpm for a passenger car, firmly places it among the high-speed rotating applications. With a relatively simple structure, the rotating parts of a TC consist of a single overhung rotor, a compressor disk as well as a turbine disk (see Fig. 1). The compressor disk is usually attached to one end of the rotor by a loose or very light interference fit, while the turbine disk is commonly connected to the other end by friction welding or electron beam welding [1].

Usually sharing the same lubricating system with an engine, a TC rotor is normally supported by full floating ring bearings (FRBs) or semi-floating ring bearings (SFRBs) in the middle. In comparison with ball bearings and other structurally sophisticated bearing candidates, the considerable advantage of FRB and SFRB is that their plain bore geometry is inexpensive to manufacture for mass production. In addition, the structure of two fluid films connected in series by floating ring is capable of providing a better damping effect as well as fewer friction losses than single-film plain journal bearings [2]. In contrast with SFRB, FRB puts in a better performance in the oil contaminated and insufficient

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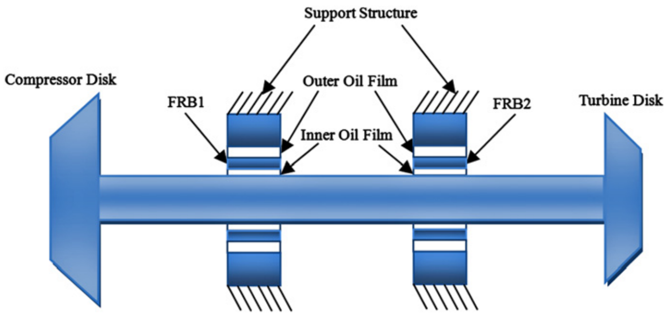

Fig. 1. TC rotor-FRB system assembly.

lubrication environment [3]. However, the well-known oil film instability phenomena of plain journal bearings, which have been thoroughly investigated and reported in many previous publications [4–10], can also be observed in rotor-FRB systems [1,3,11–21]. Based upon classical linear eigenvalue analysis and indicated by the positive real parts of the obtained complex eigenvalues, the high shaft speed can always lead to the instability of both inner and outer films. Surprisingly, resulting from the high non-linearity of the inner and outer oil films, it has been further observed that the loss of instability will usually induce the onset of stable limit cycles with subsynchronous frequency by a Hopf bifurcation [22–24], which can always ensure the safe operation of the TC [3]. With increasing rotor speed, the obtained stable limit cycle is possible to become unstable and further bifurcates into another limit cycle [3,20]. In the meantime, the ascending rotor speed may also lead to the collapse of limit cycles and the disappearance of the corresponding subsynchronous component on the frequency map, which means the system becomes stable again [3]. When the rotor speed is high enough, the most dangerous state named *Total Instability* or *Critical Limit Cycle Oscillation* (*CLC Oscillation*) is possible to occur, because of the synchronization of the inner and outer film limit cycles, which excites the rotor natural frequency. This phenomenon, which can cause the total failure of the TC, is only investigated and reported in Refs. [19,20,22,23,25]. Interestingly, according to the published simulation and experimental results [3,19–21,25,26], it has been that the proved the final occurrence of the above-mentioned possibilities is highly sensitive to the rotor-FRB system physical parameters, such as bearing structural parameters, oil feeding conditions and imposed unbalance values. The deep sensitivity clearly implies the possibility to optimize the TC rotor dynamic response and reduce the vibration level through adjusting the physical parameters. Nevertheless, accomplishing this objective through experimental prototype testing will be enormously costly and quite time-consuming, which makes the development of reliable computational tools more desirable than ever.

Despite the ability to predict the onset of oil film instability [27–30], the classical linear stability analysis is inadequate to be applied to investigate the inherently nonlinear characteristics of the rotor-FRB system, since the static equilibrium does not really exist unless the rotor speed is low enough and the rotor is in a perfectly balanced condition. Additionally, the analytical bifurcation and nonlinear stability analysis method can only be employed to analyse the bifurcation from static equilibrium to a stable limit cycle as well as further limit cycle bifurcations in a perfectly balanced rotor-FRB system [22–24,31]. There are currently no reliable tools to deal with the bifurcation of quasi-periodic motions, commonly resulting from the combination of limit-cycle oscillations and the unavoidable unbalance-force induced vibrations in TC rotor-FRB systems [31]. Under the circumstances, it is more convenient to employ the direct numerical simulation method to solve the nonlinear equations of motion of the investigated TC rotor-FRB system. Based upon the impedance bearing model given in Ref. [32], in the early 1980s, the results of direct numerical simulations of a TC rotor-FRB system have been, first, reported in Ref. [33]. However, owing to the lack of powerful computational tools, limited results have been shown, and the analysis is restricted to investigate the rotor orbits within the linearly predicted unstable region, in which the rotor speed is considerably smaller than the normal working speed of modern TCs. After more than 20 years, the stability analysis and the results of stationary nonlinear simulations for a TC rotor-FRB system are reported in Ref. [1]. It is shown that the nonlinear simulation can correctly predict the two unstable modes as compared to the experimental results presented in Ref. [12]. In order to replace the expensive experimental testing, the tribology group led by Andrés at Texas A&M University is making an effort to develop a comprehensive model for the TC rotor-FRB/SFRB system, in which significant attention has been paid on the bearing modelling [15–18,34]. Recently, with the oil film forces generated from the short bearing approximation, the transient modal analysis of a perfectly balanced TC rotor-FRB/SFRB system is shown in Ref. [35]. The thorough investigation into a TC rotor-plain journal bearing system by numerical modelling is given in Ref. [36]. After comparison with the experimental results, the oil film forces derived from the short bearing approximation are proved to be a good compromise over the more time-consuming finite bearing solutions, i.e. finite element method as well as finite difference method. Lately, also based upon the short bearing approximation and considering the thermal effect, the coupling analysis of a TC rotor-FRB system is presented in Ref. [37]. The nonlinear simulation results match the experimental results quite well, which validate the adoption of short bearing approximated models. Additionally, the foundation excitation effect is included and discussed in Ref. [38–41]. In the meantime, the run-up simulation method is employed by Schweizer to efficiently investigate the various bifurcation phenomena found in the rotor-FRB systems