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Influence of hydrodynamic thrust bearings on the nonlinear oscillations of high-speed rotors

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ABSTRACT

This paper investigates the effect of hydrodynamic thrust bearings on the nonlinear vibrations and the bifurcations occurring in rotor/bearing systems. In order to examine the influence of thrust bearings, run-up simulations may be carried out. To be able to perform such run-up calculations, a computationally efficient thrust bearing model is mandatory. Direct discretization of the Reynolds equation for thrust bearings by means of a Finite Element or Finite Difference approach entails rather large simulation times, since in every time-integration step a discretized model of the Reynolds equation has to be solved simultaneously with the rotor model. Implementation of such a coupled rotor/bearing model may be accomplished by a co-simulation approach. Such an approach prevents, however, a thorough analysis of the rotor/bearing system based on extensive parameter studies.

A major point of this work is the derivation of a very time-efficient but rather precise model for transient simulations of rotors with hydrodynamic thrust bearings. The presented model makes use of a global Galerkin approach, where the pressure field is approximated by global trial functions. For the considered problem, an analytical evaluation of the relevant integrals is possible. As a consequence, the system of equations of the discretized bearing model is obtained symbolically. In combination with a proper decomposition of the governing system matrix, a numerically efficient implementation can be achieved.

Using run-up simulations with the proposed model, the effect of thrust bearings on the bifurcations points as well as on the amplitudes and frequencies of the sub-synchronous rotor oscillations is investigated. Especially, the influence of the magnitude of the axial force, the geometry of the thrust bearing and the oil parameters is examined. It is shown that the thrust bearing exerts a large influence on the nonlinear rotor oscillations, especially to those related with the conical mode of the rotor. A comparison between a full co-simulation approach and a reduced Galerkin implementation is carried out. It is shown that a speed-up of 10–15 times may be obtained with the Galerkin model compared to the co-simulation model under the same accuracy.

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1. Introduction

The application area of hydrodynamic thrust and journal bearings in turbomachinery ranges from small turbocharger rotors to large steam turbogenerators. The type of the thrust bearing used in a rotor system depends on the specific application. Fluid-film thrust bearing can be subdivided into hydrodynamic and hydrostatic bearings. Additionally, one can distinguish between tilting- and fixed-pad thrust bearings. An overview on different bearing geometries and a discussion of their advantages and disadvantages can be found in Refs. [1–3]. In Ref. [4], for instance, the characteristics of fixed- and titling-pad thrust bearings are discussed.

In Ref. [5], the performance of a large hydrodynamic thrust bearing was compared with experimental results. In the current manuscript, high-speed turbocharger rotors are considered, which are usually equipped with taper-flat thrust bearings, see Ref. [6]. Taper-flat thrust bearings were studied experimentally in [7].

Considering run-up simulations of high-speed rotor systems, the thrust bearings are normally not incorporated into the analysis. The exclusion of thrust bearings from transient rotor calculations is mainly attributed to the fact that the Reynolds equation needs to be solved at each time-integration step for every bearing pad separately. Efficient run-up simulations could be achieved with analytical thrust bearing models. However, only for special thrust bearing geometries, the solution of the Reynolds equation can be derived analytically. In [6], an analytical solution for a step thrust bearing is proposed. A set of analytical solutions for rectangular fixed-incline pads is presented in [8]. These solutions are available only in simplified cases and only for an aligned shaft, however, the importance of the shaft misalignment for thrust bearings was shown in [9]. For radial (journal) bearings analytical solutions for simplified forms of the Reynolds equation (short and long bearing approximations) can be found in [2,10]. In most applications, the geometry of the thrust bearing pads is such that the respective formulas of the short or long bearing approximations are not applicable. Analytical solutions for finite length journal bearings and their evaluation in stationary and transient simulations are given in [11,12]. Since for a thrust bearing with misaligned runner, no such analytical expression of the solution of the Reynolds equation exists, approximate solutions in terms of Finite Difference, Finite Element, Finite Volume or Spectral methods are used for the calculation of the thrust bearing forces and moments. The computational burden of solving the Reynolds equation in each time-integration step can be avoided by calculating the linearized stiffness and damping coefficients [13]. The effect of a hydrodynamic thrust bearing in connection with rotor/bearing simulations based on linearized bearing coefficients has, for instance, been investigated in [14].

Different numerical approaches and techniques can be used to reduce the costs for solving the Reynolds equation. For the reduction of the simulation times, meshless methods may be applied very advantageously. In [15], radial basis functions were used in context with a collocation method to find approximate solutions of finite bearings for stationary problems. As has been shown in the reference, a small number of basis functions can create a good approximation of the solution of the Reynolds equation. A similar approach was followed in [16] for foil-air bearings. In the paper at hand, an efficient hydrodynamic thrust bearing model is implemented, suitable for transient simulations of high-speed rotors. A global Galerkin approach is applied for finding an approximate solution of the Reynolds equation. Transient simulations under thrust-load and thrust-free operations are performed where the effect of thrust bearings on the amplitudes and frequencies of the subsynchronous rotor oscillations is evaluated. A turbocharger rotor/bearing system is selected for the implementation of the thrust bearing.

Considering the radial support, turbochargers are usually equipped with full- or semi-floating ring bearings mainly due to their advantage of mutual damping between the oil-films [17]. The oil whirl/whip phenomena were analyzed in detail in Refs. [18–20]. Simulation and experiments have shown that the nonlinear response of turbochargers with floating ring bearings is enriched when compared with the rotors supported by single oil-film bearings [21,22]. The stability analysis of turbochargers using the classical linear analysis [23] is not adequate. The dynamics and stability of rotors supported by floating ring bearings were investigated analytically in [24] and through numerical simulations in [25]. Run-up simulations for automotive turbocharger were presented in [26,27]. In [28,29] a methodology was applied for the case of a turbocharger rotor with full-floating ring bearings that allows the quantification of the subsynchronous vibrations during run-up simulations.

The main contributions of this manuscript are summarized below:

- A numerical model for an accurate determination of the transient pressure fields in hydrodynamic thrust bearings in run-up simulations is presented.
- An efficient approximation of the Reynolds equation using a global Galerkin approach is introduced and detailed comparisons with a well-established Finite Difference approach in stationary and run-up simulations are performed.
- A physical explanation of the influence of thrust bearings on the nonlinear rotor oscillations of high-speed turbocharger systems is suggested.
- A detailed study is performed on the influence of the external axial force, the oil-viscosity and the number of bearing pads on the self-excited rotor vibrations and bifurcation behavior.

This work is organized as follows: In Section 2, the Reynolds equation, the kinematics of the runner and the axial forces and moments for thrust bearings are discussed. In Section 3, a time-efficient approximate solution of the Reynolds equation using the global Galerkin approach is presented. Its numerical accuracy is compared with a Finite Difference implementation. Numerical simulations showing the influence of a thrust bearing on the radial oscillations of a turbocharger rotor are presented in Section 4. Here, also the effect of the number of bearing pads, the viscosity of the oil and the externally applied axial force on the subsynchronous oscillations of the rotor is investigated. A detailed comparison with respect to