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The effective computational model of the hydrodynamics journal floating ring bearing for simulations of long transient regimes of turbocharger rotor dynamics

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ABSTRACT

The paper presents an efficient and numerically stable calculation model of a journal plain floating ring bearing. The computational model is based on the numerical solution of the Reynolds equation in combination with the analytical description of the resulting variables. This model is used in a virtual turbocharger assembled in multibody systems. This approach allows to effectively solve transient events, such as turbocharger run-up, considering issues of rotor dynamics, tribology of bearings, flows of lubricant in the channels and potentially also gas flow through the sealing system. The model of the bearing includes the influence of the inlet and outlet channels and the non-cylindrical shape of the bearing surfaces. Influence of lubricant and structure temperature changes caused by shear stresses in lubrication film and related changes in the lubricant properties is also considered. The paper also presents the numerical implementation of the computational models and the verification of these models using technical experiments with the turbocharger of a diesel engine.

1. Introduction

Vibration and noise caused by transport, that is by means of transport and their powertrains, have negative impact on the environment and cannot be avoided in principle. Transport noise is one of the most widespread environmental problems in the European Union (EU) and also in the world [1]. The powertrain is often a major contributor to noise emissions. Looking back on the history of powertrains, which is in most cases the history of internal combustion engines, it is obvious that development was not mostly formed by step changes or thanks to revolutionary breakthrough technologies, but by gradual improvements. The introduction of a direct fuel injection combined with a turbocharging technology was one of the rare and visible exceptions to this trend.

The automotive industry is constantly under high legislative pressure to reduce pollutant production, as well as under pressure from customers to increase vehicle performance, reduce fuel consumption and increase passengers' comfort. These parameters are often defined for transient operating conditions and therefore development work requires simulations of transient processes. These simulations logically have to include simulations of the turbocharger dynamics, as the noise caused by the turbochargers can be very negatively perceived by the vehicle crew.

A transient regime simulation requires fast and effective computational models. For example, the turbocharger's run-up takes several seconds, during that time the turbocharger of a small vehicle engine will run from tens of thousands of revolutions to hundreds of thousands of revolutions. Thus, this transition process contains tens of thousands of revolution cycles and therefore the run-up solution is extremely time-consuming and requires a suitable choice of computational models to address issues of vibration and noise, rotor stability, bearing tribology and sealing systems.

2. Aim of the work

The aim of the work is to develop a computational model of a journal floating ring bearing which can be directly integrated into the advanced mechanical computational model of the turbocharger. This advanced turbocharger model, the virtual prototype of the turbocharger, then enables to simulate turbocharger rotor dynamics, tribology of journal and thrust bearings, rotor stability, rotor component strength and gas and oil leakage through sealing system. The basic requirements for a new computational model of the journal floating ring bearing include:

- Solution time efficient and numerically stable model using the principles of multibody dynamics for transient simulations.
- Floating ring changing speed ratios and interactions among inner and outer lubrication films.
- Influences of lubricant inlet/outlet on bearing lubrications.

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- Influence of non-cylindrical shape of bearing surfaces.
- Influences of heat convection in the lubricant films.
- The possibility to be included in larger models represented by the turbocharger model or even the entire powertrain model.

3. Rotor dynamics and fluid journal bearing solution

3.1. Review of the rotor dynamics solution approaches

The computational model for solutions of turbocharger rotor dynamics includes at least a rotor model, journal bearing models and a thrust bearing model. The rotor model can be approximately considered as linear problem since its material properties are linear and the rotor deformations are small. It is quite different in case of hydrodynamic bearing properties which are strongly nonlinear not only because of the bearing journal movement but also due to the properties of the lubricant used. For example, the basic lubricant property, which is the dynamic viscosity, is dependent at least on pressure, temperature and shear rates. Similarly, the density of the same oil depends on temperature and pressure for modern low-viscosity oils. The computational model has to appropriately reflect the substantial physical properties of the real turbocharger.

Historically, the first calculation models used analytical solution of the rotor dynamics with bearings with only linear assumptions. Nowadays, such models have become inappropriate. Introduction of locally linearized numerical models has been an improvement. These generally nonlinear models are linearized for some conditions. In principle, these models only allow one steady state to be solved, and the model parameters must be reformulated for another steady state. These models are presented, for example, by Nguyen-Schäfer [2] or Tian [3]. These single-purpose models often prefer the speed of solution and simplicity of the description and principally cannot be used to solve other turbochargers' issues. Schweizer [4] presents a certain improvement; he used the computational approach based on a commercial multibody system (MBS). For example, Smolík [5] also used the MBS approach to study influence of bearing clearance on rotor behaviour. Similarly, Wolff [6], Knoll [7] and Novotný [8] present the use of MBS to solve vibration issues and the associated mechanical noise of turbochargers. This MBS approach is now mostly developed for simulations of turbocharger rotor dynamics.

Regarding more advanced nonlinear numerical models assembled in MBS, it is possible to solve not only the problems of rotor dynamics, but also problems of gas leakage through the sealing system, movements of sealing rings and lubricant flow in the lubrication system. These approaches can now be referred to as a virtual turbocharger. Virtual turbochargers are then numerically resolved in the time domain for any transient state. A more precise description of body motion (shaft or turbocharger housing) requires the assumption of deformable bodies, often in the form of their elastic properties discretised and obtained by Finite Element Method (FEM). This results in models with a high number of degree of freedom. Most of the time in simulation modelling involving virtual prototypes is consumed to express external functions (interaction between bodies, for example) and it is necessary to thoroughly consider the physical accuracy of the computational model of the hydrodynamic journal bearings. Still, the use of MBS-based computational models is a very efficient way of dealing with the structural dynamics of turbochargers, and this approach is chosen for the simulation modelling of rotor dynamics proposed in this article.

3.2. Effective model of hydrodynamic journal floating ring bearing

The key issue of the research on fluid lubrication is the study of dynamic characteristics of hydrodynamic forces. From a mathematical point of view, the primary research task of the fluid lubrication is the solution of Reynolds equation. Linearization is the most popular method for the analysis of nonlinear hydrodynamic forces. Linear models are generally adequate to describe the static characteristics of the rotor systems supported by hydrodynamic bearings. However, linearization is insufficient to describe the nonlinear dynamic behaviour. Therefore, the nonlinear model should be developed for the analysis of nonlinear behaviour of the rotor dynamics.

The common approach to the solution is to simplify Reynolds equation under the assumption of the infinitely long or short bearings. The simplified equation is integrated with respect to the eccentricity and attitude angle and then the results are modified, if necessary, by the coefficients of the turbulent flow and leakage. This approach shows a medium accuracy and great convergence in case of small eccentricity, whereas under large eccentricity, the calculation error may appear to be very obvious. Such models are presented, for example, by Nguyen-Schäfer [2] or by Qihang et al. [9].

Computationally more advanced approaches to solutions use different forms of impedance methods, such as Butenschon [10] and Novotný [11]. These solve the given hydrodynamic problem separately from the mechanical problem. The results of this solution are used, for example, in the form of pre-calculated dimensionless Sommerfeld numbers. These approaches are not sufficient for high-speed rotor bearings because they do not account for some significant effects, such as impact of lubricant inlet or outlet channels or grooves and the effect of centrifugal forces on the lubricant flow.

Modern highly advanced computational models of hydrodynamics bearings are employed in simulation modelling of fluid-structure interactions of cranktrain components. These models consider elastic deformations of structures, local thermal processes in the lubricating film and surrounding structures, or non-Newtonian lubricant properties. Such a physically highly detailed commercially available model applied to the cranktrain journal bearings is presented, for example, by Bukovnik [12]. However, typical turbocharger run-up simulation may include tens of thousands of rotor revolutions (cycles), and the resulting solution time would be totally unacceptable for physically highly advanced computational bearing models. There are different physical processes preferred in simulations of turbocharger rotor dynamics. A scheme of a typical hydrodynamic journal floating ring bearing is shown in Fig. 1.

The suggested approach for journal bearing model assumes generally known simplification assumptions, thin film theory assumptions, such states presents for example Hori [13]. In general, the ratio of the thickness to radius varies between 10^2 and 10^3 for the journal bearings considered allowing all second order terms to be neglected for a solution. The fluid flow is assumed to be incompressible and also laminar. Reynolds number remains in the lower range of the laminar to turbulent transition. All external forces are negligible and there is no slip of the fluid at the walls.

Attention is required to define the dynamic viscosity of the lubricant. The first simplification is the assumption that the dynamic viscosity of the lubricant is independent of the pressure. This assumption is not, in principle, limiting as the maximum pressures in the lubricating film of the turbocharger bearings are mostly few MPa and do not cause a significant increase in the lubricant dynamic viscosity. The other assumption is the temperature of the lubricating film which is considered as a variable in time and constant throughout the lubricating film.

The computational model proposed in this work is based on the principle of the superposition of the partial hydrodynamic solutions (solution components) of the Reynolds equation supplemented by suitable boundary conditions. It should be noted that Reynolds Eq. (1) is a nonlinear partial differential equation, where the main source of nonlinearity is cavitation phenomena and the dependence of dynamic viscosity on pressure, temperature and shear rate. Many authors neglect the influence of these nonlinearities and then consider this equation to be linear. This approach is formally incorrect, but for the rotor dynamics solution, it appears to be sufficiently precise and especially fast.

It is also believed that the lubricant inlets and outlets influence the flow of lubricant in the lubricating film. The influence of the lubricant inlet is important, as the inlet pressure of the lubricant often reaches values close to the maximum lubricant pressure in the lubricating film. The lubricant flow in the journal plain bearing can be described according