doi: 10.21495/71-0-259

25th International Conference
ENGINEERING MECHANICS 2019
Svratka, Czech Republic, 13 – 16 May 2019

MULTIBODY SIMULATION OF TURBOCHARGER TRANSIENT ROTORDYNAMICS

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Abstract: *The paper introduces a multibody based computational model of the turbocharger rotor proposed for simulations of structural transient dynamics. Computational models of rotor components, fully floating ring radial bearings and thrust bearings are briefly introduced. The computational model of the turbocharger rotor is designed to allow an efficient solution to a rotor movement while retaining its high-level capability to describe the rotor dynamics and bearing tribology. The results help understand the vibration and noise issues of turbochargers. The computational models are verified using technical experiments on diesel engine turbochargers.*

Keywords: Turbocharger, rotor dynamics, hydrodynamics, vibrations.

1. Introduction

The turbocharging of internal combustion engines (ICE) incorporating modern technology improvements has potential to further increase powertrain efficiency and reduce emissions and CO_2 of future passenger, medium- and heavy-duty vehicles. However, fulfilling this potential requires a high degree of optimization of turbocharging technology to specific operating conditions. Thus, the turbocharger applications have to be sufficiently and accurately analysed for a wide range of operating conditions with subsequent optimization of design parameters. Future powertrains as well as powertrains based on hybrid powertrains have a promising turbocharging application potential.

Generally, the powertrains are always the dominant sources of noise and vibrations (NVH) of vehicles. The vibration and acoustic level of the ICE is mainly influenced by the working cycle running in the combustion chamber (Drápal et al., 2016), cranktrain unbalanced masses (Drápal et al., 2016) and often also by cranktrain torsion or bending vibrations (Novotny et al., 2016). Transmissions (Řehák et al., 2016), gear timing drives (Prokop et al., 2017), fuel injection systems (Novotny et al., 2016), valvetrains or balance units (Novotny et al., 2016) as powertrain subsystems contribute also to the overall vibration level, but their main impact is primarily on powertrain acoustic performance. In recent years, however, considerable emphasis has been placed on NVH generated by turbochargers. A computational model reflecting these issues is introduced in this paper.

2. Review of Turbocharger Rotor Computational Models

Historically, the first computational models used analytical solution to the rotor movement with only simplified linear assumptions. Nowadays, such models have become inappropriate for most of the applications. Introduction of locally linearized numerical models were an improvement. These generally nonlinear models are linearized under specified conditions. In principle, these models only allow one

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rotor steady state to be solved, and the model parameters must always be reformulated for another steady state. These models are presented, for example, by Nguyen-Schäfer (2015) or Tian (2011). 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 (2011) presents a certain improvement; he used the computational approach based on a commercial multibody system (MBS). Similarly, Wolff et al. (2008) or Knoll et al. (2004) present the use of MBS to solve vibration issues of turbochargers. These MBS approaches are now the most developed approaches 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, sealing ring dynamics and lubricant flow in the lubrication system. These MBS approaches can now be referred to as a virtual turbocharger (Novotný et al., 2018).

3. Solution Approach

3.1. Multi Body Dynamics

An advanced turbocharger computational model, the virtual turbocharger, designed to solve the long-lasting transient processes in the time domain, can be described in the MBS as a set of non-linear differential and algebraic equations (DAE). Solving of the DAE is realized thru numerical integration using α-method proposed by Hilbert at al. (1977).

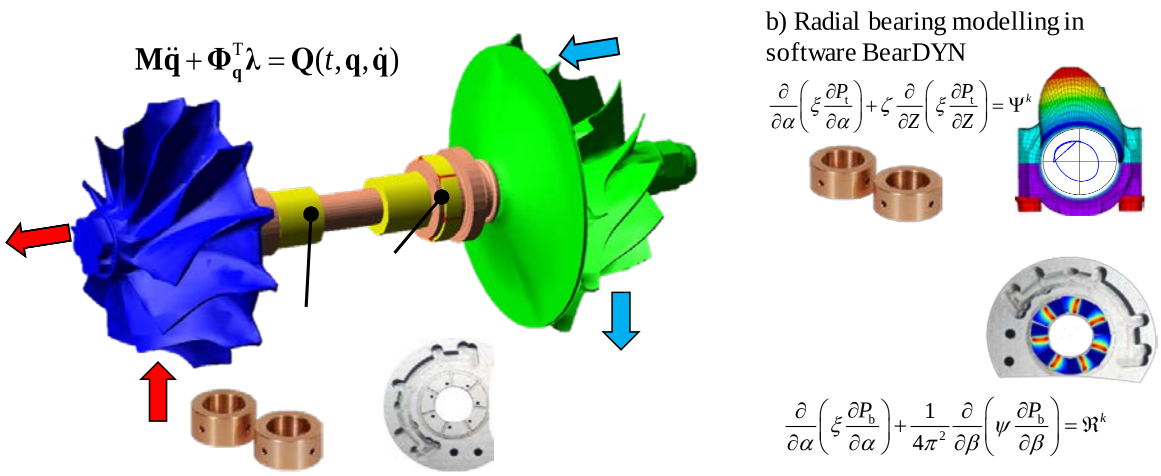

Fig. 1: *Overview of the virtual turbocharger computational model (a), radial bearing sub-module (b) and thrust bearing sub-module (c)*

The commercial MBS are designed for a general solution to body dynamics, but they do not primarily have the ability to solve some of the processes inherent in the interaction of individual components through lubricant thin films (e.g. bearings). Therefore, the virtual turbocharger assembled and numerically solved in commercial MBS ADAMS is extended by functions developed by the authors (Fig. 1).

3.2. Modelling of Radial Bearings

The virtual turbocharger incorporates sub-models of radial hydrodynamic bearings. These are the key models for simulations of rotor dynamics. The principle is based on numerical solution of Reynolds equation including turbulence and inertia effects introduced by Hori (2006). Detailed description of the radial floating ring bearing model is presented by Novotny et al. (2018).

Modelling of radial bearings requires a definition of lubricant properties, because they have a significant impact on the dynamics of the turbocharger rotor. Today's low viscosity multigrade oils are physically non-newtonian fluids in general, and show changes in lubricant properties depending on temperature, pressure and shear rate. Temperature and shear rate effects on lubricant properties are introduced by equations of Crouch (1961) and Cross et al. (1965).

3.3. Modelling of Rotor Body

The rotor computational model includes models of a rotor shaft and wheels. The rotor shaft is always modelled as a flexible body since rotor speeds in operating conditions move above the first natural bending frequency and the internal energy of the rotor therefore represents a notable share of the rotor total energy. Elastic deformations of the rotor shaft are modelled using component mode synthesis following principles introduced by Craig (1981). The rotor model also includes compressor and turbine wheels modelled as rigid bodies. The key feature of this relatively simple model is to ensure the dynamic behaviour of the wheels (including gyroscopic moments) without the impact of their deformations. This effect is particularly significant as the wheels generally present a relatively high moment of inertia and, in combination with the distance of the centre of gravity of the wheels from the bearings, have a significant effect on the rotor movement.

4. Result Examples

A basic type of simulation is a transient rotor run-up simulation over the entire operating range of its speed. The virtual turbocharger allows to determine a large range of results, such as kinematic quantities, component deformations, mass flow rates, gas blow-by and lubricant output temperatures. The presented results will only focus on quantities that can be experimentally verified.

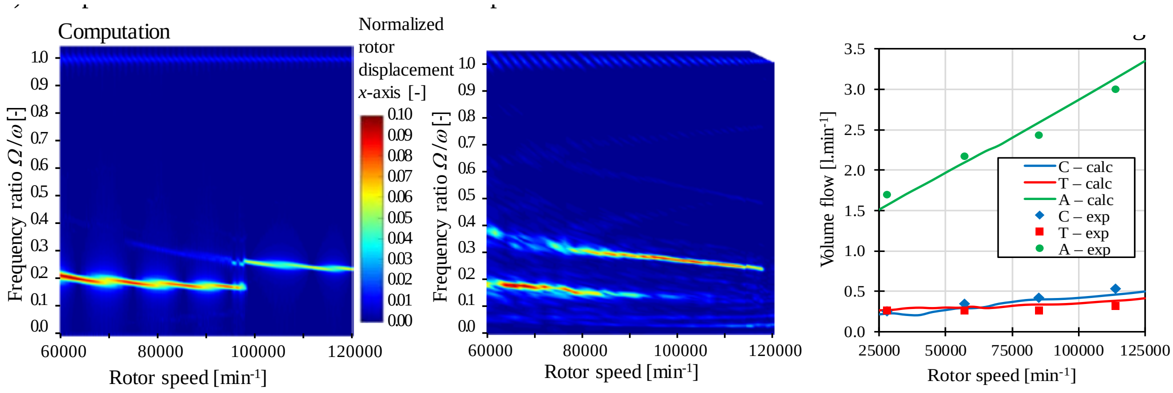

Fig. 2: *Frequency analysis of calculated and measured vibrations at turbocharger compressor nose (a) and oil volume flow rates of turbocharger bearings (b) (C – journal bearing on compressor side, T – journal bearing on turbine side, A – thrust bearing, calc – calculation, exp – measurement)*

The turbocharger compressor nose vibrations are the results that can be directly verified. Fig. 2a presents frequency analyses of calculated and measured vibrations at the nose of the turbocharger compressor wheel of the mid-size diesel engine. The run-up simulation of duration 10 s is presented. The results clearly show that the dominant source of vibrations are the journal bearings, and the vibrations are caused by self-excited sub-synchronous oscillations of the bearing in the inner and outer lubrication films (oil whirl). This sub-synchronous process represents the dominant source of vibration affecting the turbocharger rotor movement. The results presented in Fig. 2a show only a small synchronous vibration component caused by rotor unbalance.

One of the frequent questions of turbocharger developers is directed at lubricant flow rates and maximum temperatures in the lubricant layer of the bearing. In general, the loadings of the outer and inner lubrication layers of the floating ring bearing are almost identical, but due to the lower lubricant flow through the inner layer, there is a significantly higher layer warm-up. This effect is more evident on the turbine side, in addition to the heating of the lubricating layer from the housing and the rotor. The negative trend is complemented by a reduced bearing clearance caused by thermal deformations of components mainly on the turbine side. The calculated and measured turbocharger lubricant volume flow rates through the journal and thrust bearings are shown in Fig. 2b.

5. Conclusions

The nonlinear computational model is implemented in the MBS environment and forms the virtual turbocharger. This model allows for simulations of long-lasting transient mechanical processes in turbocharger rotors. Key advantage of this model is its computational efficiency, represented primarily by the reduced time-consuming solution to the journal and thrust bearing computational models. It is necessary to realize that the main source of inaccuracy of this computational model are the approximated solutions to Reynolds equation and isothermal fluid film model assumptions. The proposed computational model achieves acceptable compatibility with technical experiments and may be applied in development of modern turbochargers regarding vibration, noise and tribology.

Acknowledgement

The research leading to these results has received support from the specific university research program of Brno University of Technology, project No. FSI-S-17-4104.

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