30th International Conference
ENGINEERING MECHANICS 2024
Milovy, Czech Republic, May 14 – 16, 2024

DYNAMICS OF ROTATING SYSTEMS FOCUSED ON INDUSTRIAL APPLICATIONS

Hajžman M.[*], **Bulín R.**[**], **Byrtus M.**[***], **Dyk Š.**[†], **Polach P.**[††], **Rendl J.**[†††], **Smolík L.**[‡]

Abstract: *This paper introduces the specific issues of dynamic behaviour and the possibilities of computational modelling in rotating systems. Initially, it revisits the basic properties of rotating systems supported by journal bearings. Subsequently, it explores the instabilities associated with various types of journal bearings. Three intriguing industrial applications are then presented. The first application explores the nonlinear dynamics of high-speed turbochargers, focusing on their specific floating ring bearings. Computational results are compared with experimentally obtained data for validation. Conversely, the second application concerns the dynamics of large turbine rotors used in power plants. Particular attention is given to addressing challenges related to stator and foundation considerations in computational models. Lastly, the third application aims to model a specific vertical rotor immersed in fluid and operating under extreme temperatures.*

Keywords: Rotordynamics, journal bearing, instability, turbocharger, turbine.

1. Introduction

Dynamics, a branch of mechanics, focuses on understanding the motion of mechanical systems in response to applied forces. When considering various types of motion, the inertia forces acting on specific bodies add complexity to dynamic analysis. Introducing rotation into the system reveals intriguing behaviours such as gyroscopic effects, spin softening, and centrifugal stiffening, e.g. Byrtus et al. (2010). Additionally, rotating components require support and coupling with non-rotating parts, achieved through various types of bearings. The main bearing groups consist of rolling element bearings and journal bearings. While journal bearings can feature a relatively simple design, they are versatile and can be effectively utilized in various applications, see Someya (1989). These journal bearings introduce additional complexities, including instabilities and qualitative changes in system properties summarized by Rendl (2021). In engineering and industry, the development of computational tools reflecting these dynamics is essential for properly and effectively designing rotating systems, see Friswell et al. (2010).

This paper focuses on selected interesting applications of rotor dynamics in industrial settings. Firstly, small-scale turbochargers, rotating at exceptionally high speeds and supported by specialized floating ring

---

[*] Assoc. Prof. Ing. Michal Hajžman, PhD.: Department of Mechanics, University of West Bohemia, Univerzitní 8; 306 00, Pilsen; CZ, mhajzman@kme.zcu.cz

[**] Ing. Radek Bulín, PhD.: NTIS – New Technologies for the Information Society, University of West Bohemia, Technická 8; 301 00, Pilsen; CZ, rbulin@ntis.zcu.cz

[***] Assoc. Prof. Ing. Michal Byrtus, PhD.: Department of Mechanics, University of West Bohemia, Univerzitní 8; 306 00, Pilsen; CZ, mbyrtus@kme.zcu.cz

[†] Ing. Štěpán Dyk, PhD.: NTIS – New Technologies for the Information Society, University of West Bohemia, Technická 8; 301 00, Pilsen; CZ, rbulin@ntis.zcu.cz

[††] Assoc. Prof. Dr. Ing. Pavel Polach: NTIS – New Technologies for the Information Society, University of West Bohemia, Technická 8; 301 00, Pilsen; CZ, ppolach@ntis.zcu.cz

[†††] Ing. Jan Rendl, PhD.: NTIS – New Technologies for the Information Society, University of West Bohemia, Technická 8; 301 00, Pilsen; CZ, rendlj@ntis.zcu.cz

[‡] Ing. Luboš Smolík, PhD.: NTIS – New Technologies for the Information Society, University of West Bohemia, Technická 8; 301 00, Pilsen; CZ, carlist@ntis.zcu.cz

doi: 10.21495/em2024-018

bearings that exhibit inherent instability, are introduced. Secondly, a contrasting application involving large turbine rotors utilized in power plants is examined. Lastly, a unique case study involving a vertical rotor submerged in a homogeneous mixture of Pb and Li at extreme temperatures is presented.

2. Stability analysis of a system with journal bearings

Journal bearings are well known for their low friction behaviour, low wear and mainly effective vibration-damping capabilities. Unfortunately, they can lead to fluid-induced instability resulting in undamped self-excited vibrations of a supported rotor commonly known as oil whirl, see Muszynska (2005). This behaviour has a dominant vibration frequency occurring at roughly 0.42X–0.49X of the rotor speed. Additionally, significant shaft flexibility can give rise to another phenomenon called oil whip developed from the oil whirl instability at the moment when the oil whirl frequency coincides and locks into the system's natural frequency. Rotor operation typically exhibits three phases: stable vibrations, fully developed instability and a transient state between the two. The speed at which the rotor becomes unstable is called the threshold speed. Interestingly, the threshold speeds identified during run-up and coast-down operations may vary.

A typical journal centre trajectory during the run-up with developed oil whirl is depicted in Fig. 1. The journal centre follows equilibrium locus until the threshold speed ω_t is surpassed. After surpassing this point, the rotor loses stability and oscillates with increasing lateral displacements. The hydrodynamic force stabilises this phenomenon until the second threshold speed ω_g. Here, the stabilising effect is lost and undamped orbital motion is significantly increased which leads to fully developed instability. Detailed behaviour during the oil whirl instability development is depicted in subfigures in Fig. 1.

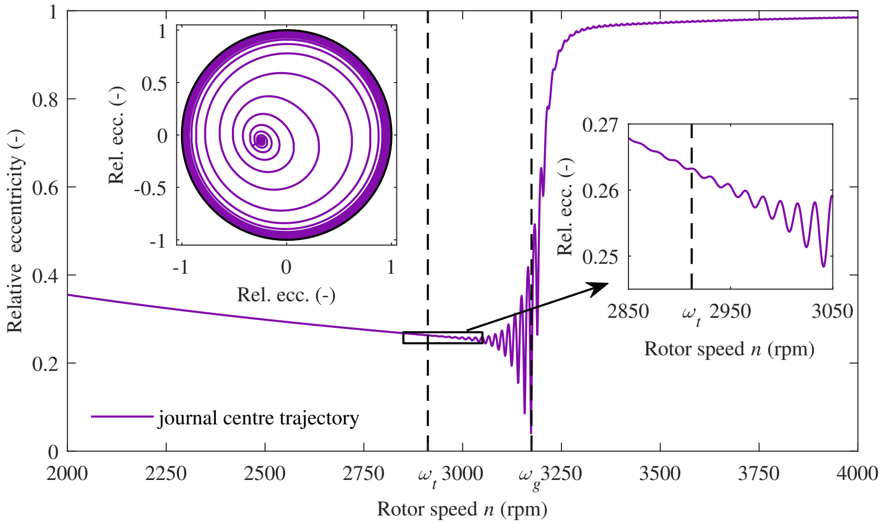

Fig. 1: Journal centre trajectory during the run-up with detected threshold speeds (adopted from Rendl (2021)).

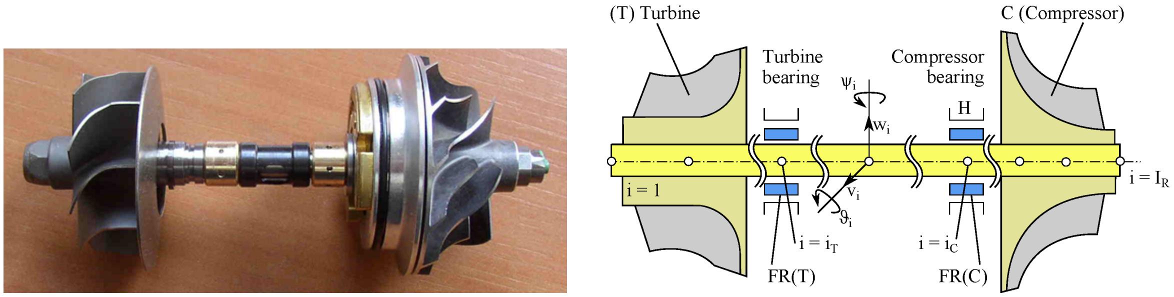

Fig. 2: Real turbocharger rotor (left) and its scheme (right).

3. Dynamics of turbochargers

Turbochargers are modern and highly dynamic systems integrated into various engines to boost their power output. Operating at speeds of hundreds of thousands of revolutions per minute, they are prone to fatigue and stability issues. Turbocharger rotors are usually supported by floating ring bearings (Fig. 2). Dyk et al. (2020) studied the possibilities of linearization of bearing forces in the turbocharges dynamic analysis. Used bearings feature two distinct bearing clearances: one between a journal and a floating ring, and another between the floating ring and its housing. These clearances vary based on temperature differences within the oil films and their effect was analyzed by Smolík et al. (2017). Modal analysis can conducted on a simplified linear model replacing each floating ring journal bearing with two linear springs, aiming to gain a deeper understanding of the system's dynamic properties (see Fig. 3).

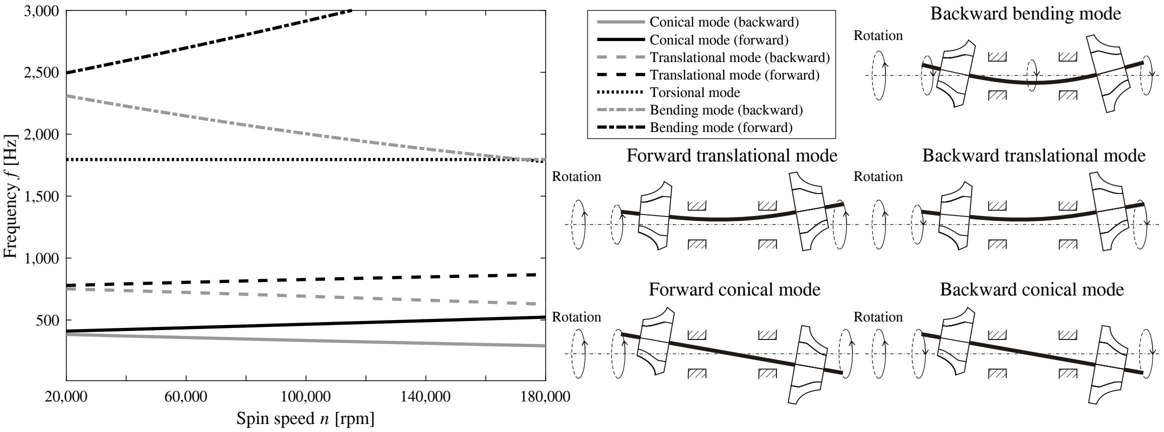

Fig. 3: Typical Campbell diagram of a turbocharger with dominant lateral mode shapes (adopted from Smolík et al. (2017)).

The turbocharger examined in this paper is modelled using flexible multibody dynamics methods. The behaviour of the bearings is characterized using the Reynolds equation, which is solved numerically in the time domain. Given the examination of the turbocharger across a speed range of 60 000 to 150 000 revolutions per minute (rpm), waterfall plots are employed to present the results visually (see Fig. 4 right). These plots illustrate the calculated response spectra as a function of the rotor's spin speed n. To validate the model, experimental measurements were performed and are shown in Fig. 4 on the left.

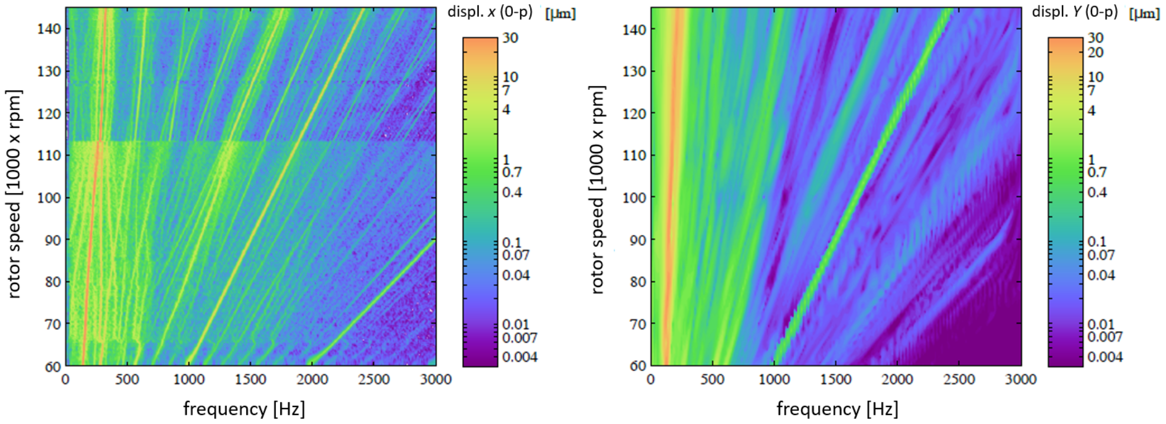

Fig. 4: Measured (left) and simulated (right) turbocharger dynamic response.

4. Large-scale rotor train dynamics

Turbines typically consist of two primary components and their connections (see Fig. 5). One major non-rotating component is the foundation, encompassing all stator parts of the turbogenerator. It can be fixed to the ground via viscous-elastic couplings, designed to provide appropriate stiffness and damping properties to enhance the overall dynamic behaviour of the turbine system. The second primary component is the rotor train, which varies in size and complexity depending on the specific type of turbine. The rotor train is linked to the foundation via bearings, commonly fluid-film bearings of various designs. The dynamics of turbines can experience significant influence from the presence of a rotor foundation. Consequently, the development of suitable modelling approaches is necessary to acquire accurate analysis tools. The method assessing the dynamic compliance of the foundation concerning the rotor's angular velocity is compared with the approach utilizing modal synthesis of rotor and foundation models. The overall methodology was introduced by Hajžman et al. (2022). The in-house computational tools in MATLAB were developed for the purpose of presented analysis.

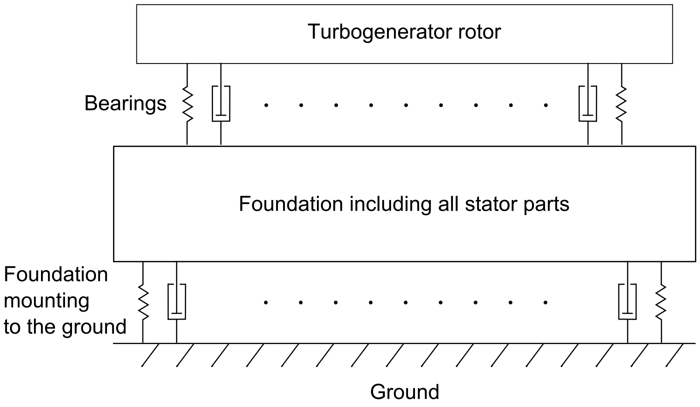

Fig. 5: General scheme of the turbogenerator rotor mounted to its foundation.

The rotor train (see Fig. 6 left), modelled using shaft finite elements with lumped rigid disks, consists of several parts: a high-pressure section (HP), an intermediate-pressure section (MP), two low-pressure sections (LP1 and LP2), a generator (G), and an exciter (E). The rotor support system comprises eleven oil-film bearings with frequency-dependent damping and stiffness properties. The relationship between particular eigenfrequencies of the rotor train with foundation effects (measured in revolutions per minute) and the rotor speed (also in revolutions per minute) is illustrated using the Campbell diagram (Fig. 6 right). Particular mode shapes are characterized by the dominant vibration of denoted rotors (HP to E).

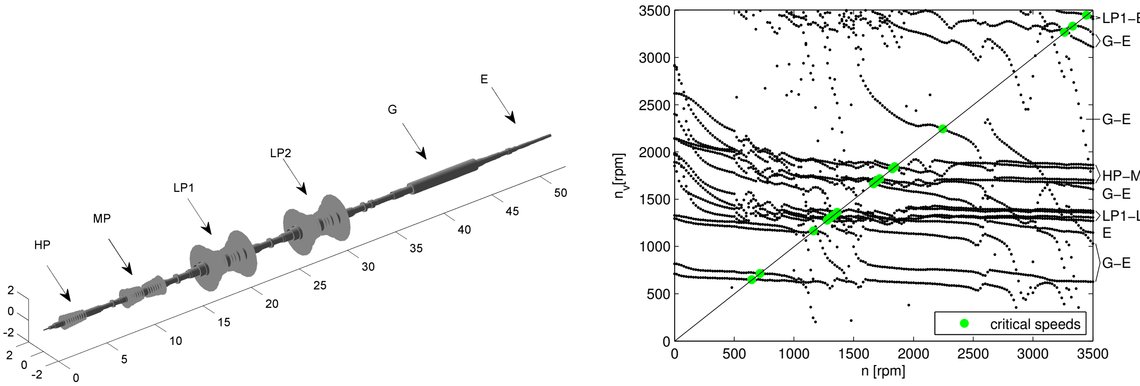

Fig. 6: Visualization of the turbogenerator (left) and a typical Campbell diagram (right), adopted from Hajžman et al. (2022).

5. Vertical rotor immersed in hot fluid

The device known as a saturator, utilized in fusion reactor research, can be designed as a vertical rotor featuring multiple thin discs. This apparatus is situated within a pressure vessel. The gap between the saturator and the vessel is filled with a lead-lithium mixture (PbLi), which undergoes mixing as it circulates through the vessel, facilitated by the rotation of the saturator. When the resulting mixture solidifies, it forms an *eutectic material*, a homogenous mixture of two solids produced under the laminar flow conditions.

Since the temperature of the PbLi mixture reaches 550 °C, the use of rolling element bearings or petroleum-based lubricants in journal bearings is impossible. The dynamic viscosity of the PbLi mixture is ca.

$1.28\ \mathrm{mPa\,s}$ at $550\,°\mathrm{C}$, and its density is ca. $9\,300\ \mathrm{kg\,m^{-3}}$. Therefore, it can be used as a lubricant in journal bearings but exerts significant forces on the rotor due to buoyancy and inertia effects. More concretely, a part of the fluid rotates together with the saturator, which causes a force that is proportional to the moving mass of the fluid and its acceleration and a force corresponding to the conservative gyroscopic force (Axisa and Antunes , 1992). In addition, the fluid can exert a viscous damping force and a conservative elastic force on the rotor (Axisa and Antunes , 1992).

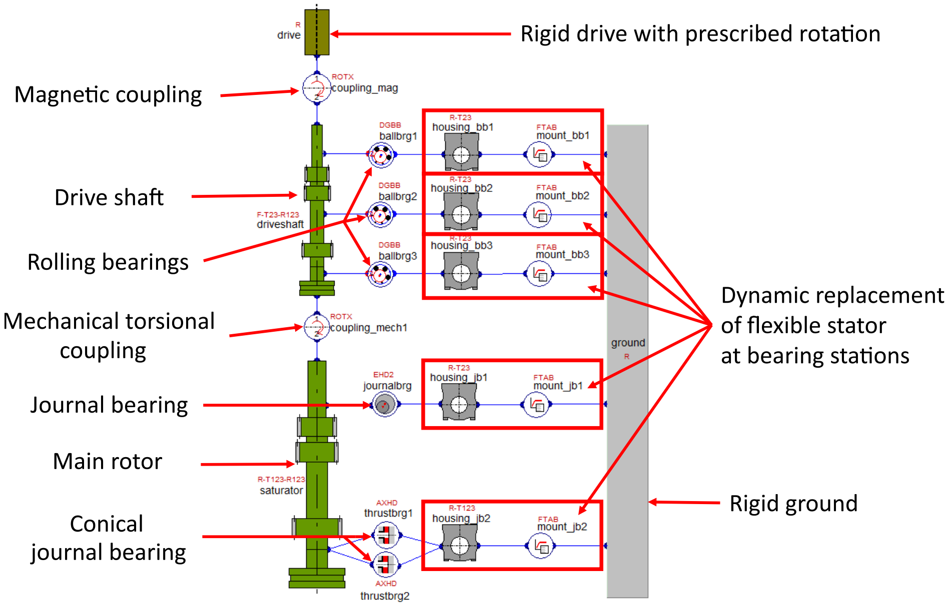

Fig. 7: Scheme of the model of a saturator assembly.

Fig. 7 depicts a saturator assembly comprising three flexible bodies (main rotor, drive shaft, and stator), a rigid drive, and couplings, including a radial journal bearing, a conical bearing supporting the main rotor both radially and axially, three deep groove ball bearings, and two torsional couplings. Due to the presence of multiple flexible bodies and nonlinear couplings in the assembly, its motion is described using the Newton-Euler equations for multi-body dynamics. The whole model was created in the AVL Excite software and numerically solved in order to verify the suitability of the bearing design with respect to instabilities, see Smolík et al. (2022).

Fig. 8 shows a simulated waterfall plot of absolute radial vibrations of the bearing housing that accommodates the upper bearing, see Fig. 7. Up to 600 rpm, the vibrations are caused by the rotating imbalance that causes a response synchronous to the rotor speed. However, as the speed exceeds 650 rpm, asynchronous vibration at ca. 45 Hz (2 700 rpm) becomes prominent. This frequency corresponds with the first stator eigenfrequency and the vibration can be linked with the lower conical bearing that supports both static thrust load and dynamic radial loads due to imbalance. At higher speeds, the conical bearing acts as a pump because of the low thrust load (remember that the thrust load is decreased by the buoyancy). This effect can be effectively mitigated by introducing an extra thrust load.

6. Conclusions

This paper presents some interesting applications of rotating systems related to various effects of rotation and employed bearings. Fluid-induced instability resulting in undamped self-excited vibrations (oil whirl) is introduced for a simple supported rigid rotor. Further, the paper shows how to deal with high-speed turbocharger modelling, with the analysis of large turbines in power plants and with design assessment of the vertical rotor immersed in the specific fluid. The development of appropriate computational approaches and the implementation of related software tools are necessary for the design and diagnostics of many rotating machines used in the industry. There are, naturally, many other topics and practical issues in rotor dynamics that haven't been covered in this paper. For instance, exploring the impact of rotor dynamics on tilting pad journal bearings and examining their detailed response presents an actual and interesting problem (Rendl et al. (2021)).

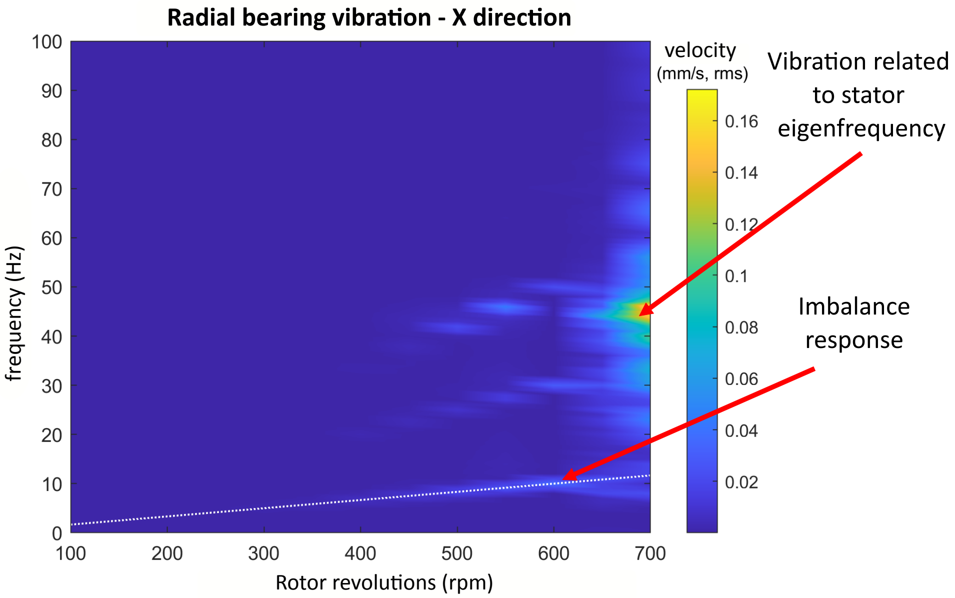

Fig. 8: Simulated waterfall plot of absolute stator vibrations at the upper journal bearing of the saturator.

Acknowledgment

This research work was supported by the Czech Science Foundation project 22-29874S. Chosen simulations were performed in the AVL Excite software which is available in the framework of the University Partnership Program of AVL List GmbH, and whose usage is greatly acknowledged.

References

Axisa, F. and Antunes, J. (1992) Flexural vibrations of rotors immersed in dense fluids, Part I: Theory. *Journal of Fluids and Structures*, 6, pp. 3–21.

Byrtus, M., Hajžman, M. and Zeman, V. (2010) Dynamics of rotating systems. University of West Bohemia, Pilsen.

Dyk, Š., Smolík, L. and Rendl, J. (2020) Predictive capability of various linearization approaches for floating-ring bearings in nonlinear dynamics of turbochargers. *Mechanism and Machine Theory*, 149, 103843.

Friswell, M. I., Penny, J. E. T., Garvey, S. D. and Lees, A. W. (2010) Dynamics of Rotating Machines. Cambridge University Press, Cambridge.

Hajžman, M., Balda, M., Polcar, P. and Polach, P. (2022) Turbine Rotor Dynamics Models Considering Foundation and Stator Effects. *Machines*, 10, 2, paper 77.

Muszynska, A. (2005) Rotordynamics. Taylor & Francis, Boca Raton.

Rendl, J. (2021) Nonlinear dynamics of rotating systems with journal bearings. PhD Thesis, University of West Bohemia, Pilsen.

Rendl, J., Dyk, Š. and Smolík, L. (2021) Nonlinear dynamic analysis of a tilting pad journal bearing subjected to pad fluttering. *Nonlinear Dynamics*, 105, pp. 2133–2156.

Smolík, L., Bulín, R., Hajžman, M., Byrtus, M. and Rendl, J. (2022) Vibration analysis of a vertical rotor immersed in fluid at extreme operating temperatures. In: *Proc. of Computational Mechanics 2022*, University of West Bohemia, Pilsen, pp. 141–144.

Smolík, L., Hajžman, M. and Byrtus, M. (2017) Investigation of bearing clearance effects in dynamics of turbochargers. *International Journal of Mechanical Sciences*, 127, pp. 62–72.

Smolík, L., Rendl, J., Omasta, M., Byrtus, M., Šperka, P., Polach, P., Hartl, M. and Hajžman, M. (2023) Comprehensive analysis of fluid-film instability in journal bearings with mechanically indented textures. *Journal of Sound and Vibration*, 546, paper 117454.

Someya, T. (1989) Journal-Bearing Databook. Springer-Verlag, Berlin.