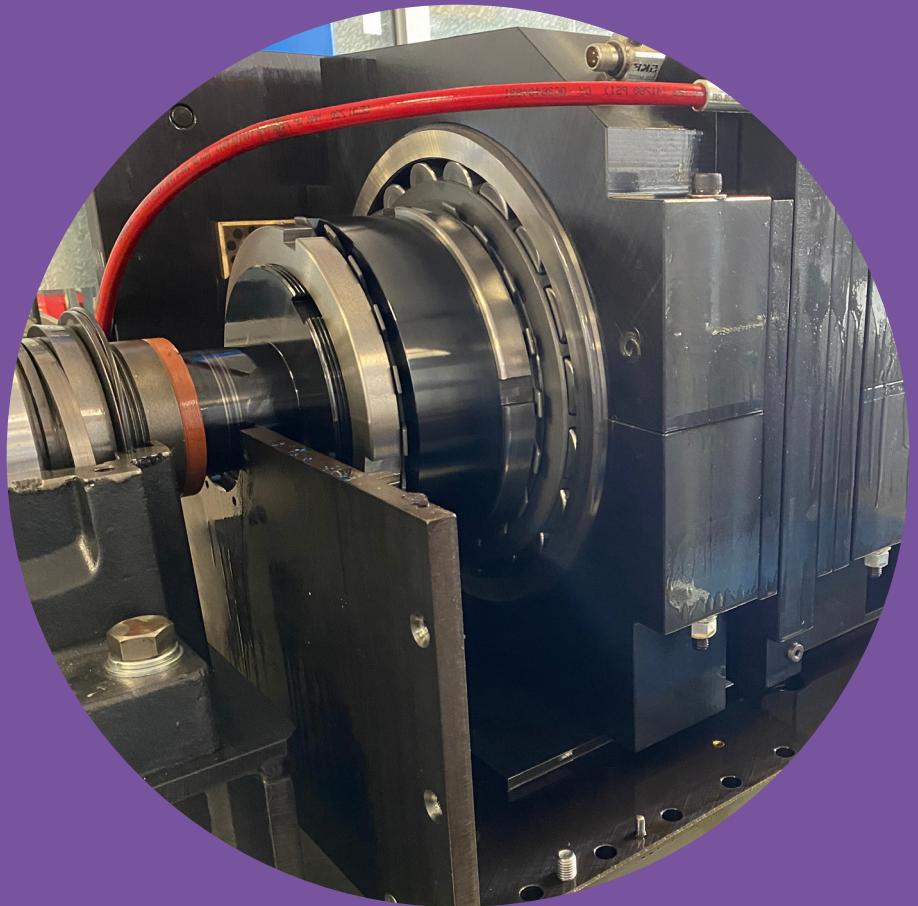


Department of Mechanical Engineering

# Modeling, Design and Testing Techniques for New Generation Industrial Rotors

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Lorenzo Giorio





# Modeling, Design and Testing Techniques for New Generation Industrial Rotors

**Lorenzo Giorio**

A doctoral thesis completed for the degree of Doctor of Philosophy from Italy and Doctor of Science (Technology) from Finland to be defended, with the permission of Politecnico di Torino and the Aalto University School of Engineering, at a public examination held at the Room C. Ferrari of Politecnico di Torino on 05 December 2024 at 12:00. Remote connection via Zoom is available at:  
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**Abstract**

This dissertation explores relevant topics regarding the application of machine fault diagnosis in the design, monitoring, and diagnosing of industrial rotating machinery. Bearings, fundamental components in rotating systems influencing the dynamics of the entire system, are affected by roundness errors developed during production and assembly and may suffer damage during operation, causing unwanted vibration with a detrimental effect on the efficiency and quality of production. In the context of Industry 4.0, sensor-equipped rolling bearings can be used as a sentry for the whole rotor system, providing both internal bearing damage detection and external rotor system anomalies monitoring.

This dissertation focuses upon the installation, sensorization, and experimental activity on a test rig for the monitoring of medium-sized industrial bearings while operating in industrial conditions, available at the Laboratory of Mechanics of Politecnico di Torino. The state-of-the-art of modeling techniques for rolling bearings with localized defects was also examined. An analytical numerical model of the rotor-bearing system was developed, validated through some experimental data acquired on the test rig, able to identify vibrational features from defects and to perform component- and system-level monitoring activities within its vibrational response. A dataset was created for condition monitoring of medium-size spherical roller bearings with various localized defects. Noise reduction in experimental vibration signals, particularly using the Discrete Wavelet Transform (DWT), was also investigated using an experimental literature dataset. A screening of DWT parameters was conducted for the appropriate parameters selection for the identification of localized defects in bearings, enhancing previous literature studies.

Furthermore, the effect of the geometry of the bearing installation seat on the roundness error of bearing inner ring was also analysed. Extensive experimental activity, performed in the ARotor Lab at Aalto University, validated the roundness error stacking methodology to evaluate the roundness error of mounted inner ring raceways considering the roundness error of the tapered shaft and the thickness variation of the inner ring. The existence of an optimal orientation between the components that minimizes the roundness error of the raceways in the assembly was highlighted. The study further explored the application of 3D conical grinding to the tapered installation seats of a large rotor to compensate for roundness error. A significant reduction in the roundness errors of installed inner ring raceways and rotor's subcritical vibration was experimentally demonstrated, also compared to previously published methodologies based on cylindrical grinding and the use of adapter sleeves. Results showed that unmounted bearing inner ring roundness is irrelevant to the final raceway roundness, and that bearing manufacturers should focus on minimizing the thickness variation of the bearing inner ring.

**Keywords** machine design; structural mechatronics; bearing fault diagnosis; bearing test rig; discrete wavelet transform denoising; roundness error stacking.

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Doctoral Dissertation  
Doctoral Program in Mechanical Engineering (36<sup>th</sup> cycle)

# Modeling, Design and Testing Techniques for New Generation Industrial Rotors

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I hereby declare that the content and organization of this dissertation constitute my own original work and do not compromise in any way the rights of third parties, including those relating to the security of personal data.

A handwritten signature in black ink, reading "Lorenzo Giorio". The signature is written in a cursive style with a large initial 'L' and 'G'.

.....  
Lorenzo Giorio  
Turin, October 28, 2024

# Summary

This dissertation explores relevant topics regarding the application of machine fault diagnosis in the design, monitoring, and diagnosing of rotating machinery for industrial applications. Recent scientific literature highlights the benefits of predictive maintenance, reducing cost, enhancing productivity and efficiency, and improving worker safety in industrial rotating systems. The increasing demand for the careful monitoring and control of industrial processes and machinery motivates the research described in this thesis, focusing on the conscious resource consumption and high efficiency of production required to design machines and on the maintenance processes strictly needed to suitably operate systems. Bearings are fundamental components in rotating systems and affect the dynamics of the entire system. They may suffer roundness errors during production and assembly and damage during operation. Such defects give rise to unwanted vibration of the component and the entire system, with a detrimental effect on the efficiency and quality of production. In the context of Industry 4.0, equipping the rolling bearing with sensors makes it suitable to behave as a sentry for the whole rotor system, providing both the so-called “in-monitoring” and “out-monitoring” activities. The “in-monitoring” activity identifies damage and failures occurring with the bearing itself and measures some operational parameters such as rotor speed, temperature, and friction torque, while the “out-monitoring” is an indirect detection of any anomalies exhibited by the rotor system’s dynamics.

This thesis focuses upon the installation, sensorization, and experimental activity carried out on a test rig for medium-sized industrial bearings, available at the Laboratory of Mechanics of Politecnico di Torino, to create a dataset for the diagnosis of localized defects within those bearings, while operating in conditions typical of industrial applications. It also examines the state-of-the-art of modeling techniques applied to rolling bearings with localized defects and develops an analytical numerical model of the rotor-bearing system, validated through some experimental data acquired on the test rig. This activity appears to be fundamental for recognizing the vibrational features arising from defects and for separating the in- and out-monitoring activities performed by the smart bearing within its vibrational response. The results from the preliminary test of bearings’ frictional torque

in the test rig show good correspondence with analytical model data. A dataset was created for Condition Monitoring on medium-size spherical roller bearings exploring different localized defects in the bearing under test, in terms of load cases and machine rotational speed, extending the experimental data available from literature datasets. The comparison of the analytical numerical model with experimental data from the test rig validates the ability of the model to accurately predict the characteristic frequencies of various localized defects configurations, as well as performing both “in-monitoring” and “out-monitoring” activities, by also measuring the characteristic frequencies in the frequency spectra from the signal of healthy bearings, identifying a localized defect affecting another component of the system.

Attention is also given to noise reduction techniques in experimental vibration signals, particularly those based on the Discrete Wavelet Transform, using an experimental literature dataset to conduct a comprehensive screening activity of the parameters involved in this methodology for the appropriate selection of such parameters for the identification of localized defects in bearings. This activity demonstrates the existence of some specific metrics for performing the optimal selection of the DWT method parameters aimed at reducing signal noise in experiments to better identify the localized damage within bearings. This screening activity extends already available studies in the literature, in which a complete analysis of all the parameters affecting the Discrete Wavelet Transform denoising of damaged bearing was not yet available.

The dissertation also investigates the effects of roundness error in the bearing installation seat of the shaft on the raceways, through an extensive experimental activity performed in the ARotor laboratory of the Department of Mechanical Engineering at Aalto University. Those tests consider the roundness error of the tapered shaft and the thickness variation of the inner ring of a spherical roller bearing. The investigated roundness error stacking mechanism is studied experimentally for several relative orientations between the components during assembly and for two bearings’ mounting conditions, highlighting the existence of an optimal orientation between the components that minimizes the roundness error of the raceways in the assembled component. The study further explores the application of the compensative 3D conical grinding methodology to the tapered installation seats of a large rotor for paper production to compensate for roundness error, experimentally demonstrating a significant reduction in the rotor’s subharmonic vibration. The results showed that the roundness of the bearing inner ring in unmounted condition is irrelevant to the final roundness profile of the raceways, and that bearing manufacturers should focus on minimizing of the thickness variation of the bearing inner ring. The 3D conical grinding methodology was proven to accurately reduce the roundness error of the installed inner ring raceways, with a direct reduction effect on the subcritical vibration of the rotor, also when compared to previously published methodologies based on cylindrical grinding and the use of adapter sleeves.