ME- PhD Thesis Colloquium

EXPERIMENTAL AND NUMERICAL INVESTIGATIONS OF AEROSTATIC THRUST BEARINGS FOR HIGH-SPEED APPLICATIONS

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ABSTRACT

Supercritical carbon dioxide (sCO_2) turbomachinery's typically operate at notably higher rotational speeds compared to conventional steam or gas turbines, thus enabling them to provide higher power densities in a small footprint. However, higher operating temperatures, and pressures in sCO_2 turbomachines induce large axial thrust loads that pose significant challenges to rotor integrity, bearing reliability, and dynamic stability. An effective way to mitigate some of these issues is by coupling the motor/generator pair directly to the turbomachinery. Magnet-less and winding-free rotor construction makes switched reluctance machines (SRMs) an ideal choice for direct-drive sCO_2 applications. However, conventional laminated SRM rotors are vulnerable to delamination under high centrifugal and thermal loads. While monolithic solid rotors improve mechanical strength, but suffer from high eddy-current losses. On the other hand, though, slitted rotors with axial slits significantly alleviate eddy current related losses, but compromise stiffness, stress, deformation, and vibrational performance. The concern of large thrust force in a sCO_2 turbomachinery is overcome by incorporating aerostatic thrust bearings. These bearing systems are designed to handle large axial loads with a few microns of clearance and provide near-frictionless support. The performance of an aerostatic thrust bearing is greatly influenced by clearance, restrictor geometry, supply air/gas pressure, and manufacturing-induced nonuniformities. Typically, full scale 3d CFD simulations are used to design and predict the performance of aerostatic thrust bearings in such critical applications. Although, these simulations provide high-fidelity reliable data but are computationally expensive and time consuming. In contrast, gas-film based traditional modelling methods relying on oversimplified assumptions such as uniform orifice geometry and constant discharge coefficients, yield poor accuracies and unreliable bearing performance predictions. Further adding to the complexity, influence of clearance gap variations and bearing nonuniformities on coupled rotor–bearing rotordynamic behaviour remains insufficiently understood field, thus, motivating the need for developing an integrated, robust and computationally efficient modelling framework.

This research focuses on comprehensive experimental and numerical investigations to gain insights into the design and analysis of gas-film thrust bearings and high-speed switched reluctance machine (SRM) rotors exclusively being explored for high-speed sCO_2 turbomachinery applications. The influence of axial slits in SRM rotors on stresses, deformations, natural frequencies, and mode shapes is systematically analysed and quantified, revealing stiffness reduction effects and providing design guidelines to prevent resonance and mechanical failures in high-speed rotor–bearing systems. A semi-analytical modelling framework for aerostatic thrust bearings is developed by deriving the Reynolds equation from thin-film lubrication theory and coupling it with a detailed orifice flow model. The model is used to predict pressure distribution, load capacity, and gas-film stiffness as functions of clearance gap, orifice geometry, and supply pressure. Subsequently, with the intent to reduce computational time and effort without significantly compromising accuracy, a unified computational framework combining an ANN-based surrogate model with the 2d Reynolds solver is developed. The efficacy of the surrogate model is tested by analyzing the performance of bearings featuring both uniform and non-uniform orifice geometries. The robustness of the model is exhibited in its ability to provide CFD level accuracy for discharge coefficient prediction, thus enabling rapid evaluation across a wide range of operating conditions geometric and flow parameters. Additionally, a dedicated thrust experimental test facility is developed and designed inhouse to measure load capacity, stiffness, mass flow rate, and dynamic behaviour of aerostatic thrust bearings under realistic static and transient conditions. The test setup incorporates precision sensors and safety controls ensuring accurate measurements while testing at micron-scale clearances and high rotational speeds. Finally, an integrated rotor–bearing model is established to capture the coupled effects of bearing stiffness and load capacity on rotor natural frequencies, critical speeds, and mode-veering behaviour. The integrated model in validated using industry standard, 3d finite-element analysis tool- ANSYS. A key contribution of this research is the development of a unified modelling framework for thrust bearings that has rigorously tested and validated both computationally and experimentally to provide a robust platform for the design of high-speed sCO_2 turbomachines equipped with gas-lubricated rotor-bearing systems.

ABOUT THE SPEAKER

Ashutosh Patel is a Ph.D. student in the Department of Mechanical Engineering at the Indian Institute of Science (IISc), Bangalore. He received his B.E. degree in Mechanical Engineering from OP Jindal Institute of Technology in 2014 and his M.S. degree in Mechanical Engineering from the Indian Institute of Technology (IIT) Mandi in 2017. His research interests include the design, modelling, and experimental validation of gas-film thrust bearings and rotor systems for high-speed, high-temperature applications.