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Development of a Novel Test Apparatus for the Evaluation of an Active Geometry Tilting-Pad Thrust Bearing

D. Macmillan, E. H. Smith, I. Sherrington, P. M. Johns-Rahnejat

Jost Institute for Tribotechnology, University of Central Lancashire, Preston PR1 2HE, UK

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Corresponding author: David Macmillan (dwmacmillan@uclan.ac.uk)

ABSTRACT

The paper outlines the design of a novel test apparatus for the evaluation of an active geometry tilting-pad thrust bearing (AGTPTB). The primary objective of the AGTPTB is to minimise viscous shearing losses of the thin lubricant film whilst maintaining reliable operation.

Conventional hydrodynamic thrust bearing test rigs usually lack provisions for active systems due to the space required for actuation mechanisms and data acquisition from various sensors. The proposed equipment employs a horizontally loaded bearing, enabling the inclusion of actuation mechanisms at the rear of the bearing. Data acquisition includes monitoring power loss, speed, bearing load, lubricating film thickness and temperature. A test cycle is discussed, which includes variations in speed, applied load, oil supply temperature and lubricant flow rate. It is planned to compare performance data collected from an active bearing and its conventional counterpart.

1. INTRODUCTION

Tilting-pad thrust bearings (TPTBs) utilise a low friction hydrodynamic lubricating film to separate moving surfaces subjected to direct thrust. However, despite their low friction characteristics, conventional designs still consume some energy through viscous shearing of the thin lubricant film. The shearing of the oil film leads to heat generation, which is conveyed to surrounding bearing components. In large bearings, such as those employed in hydroelectric generators, the amount of heat generated can reach 1 MW [1].

Frictional losses of TPTBs are affected by numerous design parameters and operating conditions, including pad geometry and pivot configuration, liner material, lubrication parameters, shaft speed, and bearing load. Like many tribological components, the design of tilting-pad systems is passive but self-adaptive. In other words, these devices are designed to operate at an equilibrium condition, which depends on their fixed design parameters and operating conditions. The main drawback of any passive design is the inability to change performance outside the passive design limits, meaning that any additional form of objective optimisation is impossible following installation.

The current emphasis on reducing environmental impact necessitates tribological designs that are affine to environmental protection. Ideally, bearings should operate optimally to conserve energy using advanced technologies, including active control. This paper introduces an innovative tribotronic bearing concept known as an Active Geometry Tilting-Pad Thrust Bearing (AGTPTB), which involves controlling the oil film thickness ratio during operation. The AGTPTB incorporates capacitive measurement of lubricant film thickness and linear actuators to measure and adjust pad inclination. A tribotronic control strategy is proposed to improve efficiency, employing geometric control to minimise viscous shearing losses while ensuring a sufficient minimum film thickness to prevent direct boundary interactions and subsequent wear.

A novel test apparatus has been developed to evaluate and compare the performance of the AGTPTB. This test apparatus enables power loss measurement through a torque arm and an energy balance method. Additionally, the arrangement of the test apparatus allows for convenient interchangeability between the tribotronic bearing and a conventional one, facilitating direct performance comparisons between the two.

1.1. Tribotronic Tilting-Pad Thrust Bearing Design Concept

The term "tribotronics", coined by Glavatskih and Hoglund [2], describes a novel field in which electronics are combined with tribological components and control systems to adjust and optimise performance. A tribotronic system consists of four interacting elements: the sensors, control unit, actuators, and tribological interface (in this case, the tilting-pad and runner), as shown in Figure 1.

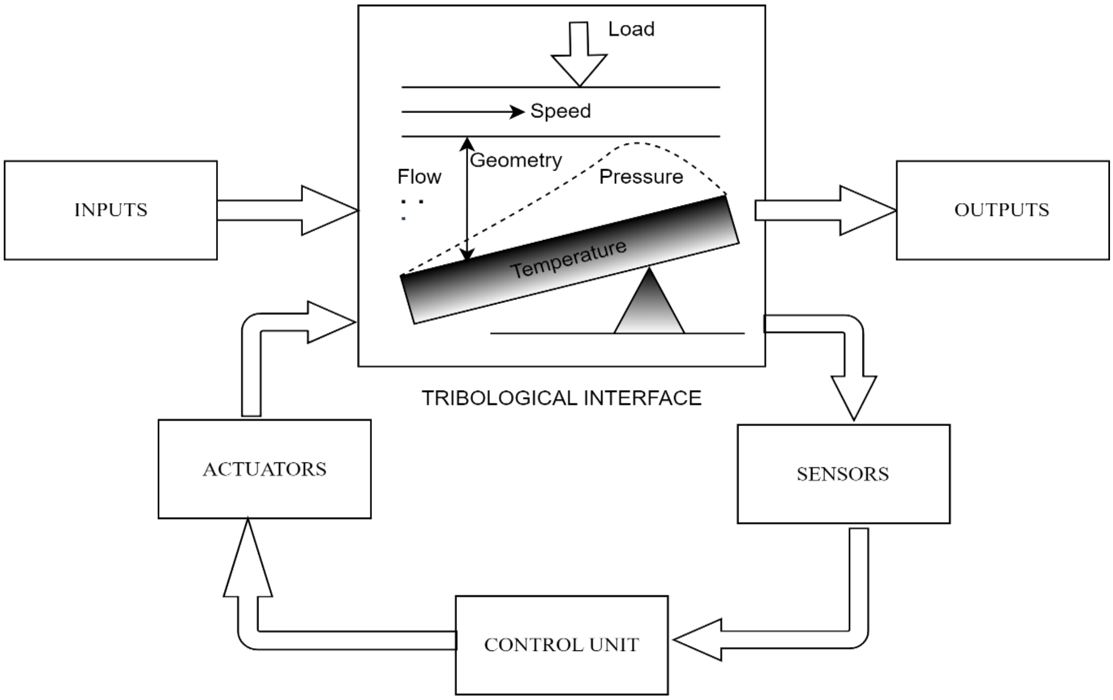

Figure 1: Elements of a Tribotronic TPTB

The concept of tribotronics integrates sensors into the tribological interface to provide feedback on various performance characteristics, including power loss, film geometry, flow rate, pressure, and temperature. The control unit, equipped with a tribological algorithm, collects measurements from these sensors and determines the appropriate control action to be carried out by a dedicated actuator. One or more actuators can be designed to control geometric and lubrication parameters, which largely influence system performance.

The main advantage of a tribotronic system lies in its ability to measure loss outputs to provide system feedback. This data can be used to monitor the system's state and establish corrective action based on the current optimisation goal. Moreover, state measurements can be used in machine learning and model training data sets.

2. REVIEW OF LITERATURE

2.1. Development of Tilting-Pad Thrust Bearings

Michell and Kingsbury independently developed the TPTB design in the early 1900s to improve performance over previously fixed geometry pads [3,4]. Each design incorporated a fixed pivot that enabled the pads to tilt freely during operation. Following the invention of the TPTB, the design has undergone some notable changes in pursuit of enhanced performance, reliability, and efficiency. These include the development of directed lubrication supply systems for reduced power consumption [5,6] and the introduction of the leading-edge-groove supply [7]. Other modifications involved the use of different pad-facing/liner materials like PTFE [8–11], the implementation of hydrostatic systems for increased load-carrying capacity at transient conditions [12], and the addition and optimisation of surface features and treatments [13], such as artificial texturing [14,15], and hydrophobic pads [16].

More recently, attention has shifted towards implementing active technologies that offer higher levels of multi-functionality and adaptability compared to passive alternatives [17]. These designs incorporate a control variable, often referred to as lubrication control or geometric control. Controllable/active lubrication involves controlled variations in lubricant viscosity, flow velocity, or pressure, usually achieved through modifications to the lubrication system, such as employing control valves. Controllable hydrostatic/hybrid bearing systems have been developed using this approach [18,19]. Babin et al. [20] developed an active thrust hybrid bearing with a controllable oil-feeding orifice. The control system was designed to maintain the most energy-efficient oil film thickness and improve rotor stability. Results showed a possible 20% decrease in mean frictional power loss and a significant reduction of unwanted rotor oscillations.

On the other hand, controllable geometry bearings typically require a more invasive approach. The strategy typically involves modifying the lubricant film geometry by controlling the bearing clearance or pad inclination through hydraulic, mechanical, piezoelectric, or electromagnetic actuators. For example, Aguirre et al. [21] developed a controllable aerostatic thrust bearing test equipment utilising piezoelectric actuators to modify the curvature of the air gap profile. Pai et al. [22–24] developed a novel journal bearing with externally adjustable tilting pads to modify the radial clearance and circumferential tilt. Under identical operating conditions, this configuration exhibited lower power absorption than the conventional bearing [23].

2.2. Configurations of Thrust Bearing Test Apparatus

A typical test apparatus for a Tilting-Pad Thrust Bearing (TPTB) consists of a single housing, single collar, and dual thrust bearing system. These arrangements typically load the collar and test bearing using an auxiliary hydrostatic bearing [25–28]. This design is compact and straightforward as it avoids complex housing designs and additional bearings to distribute the load away from the drive. However, a drawback is the need for an external hydraulic power pack to operate the hydrostatic loading system.

The presence of loaded auxiliary thrust bearings adds to the challenge of isolating friction losses specific to the tested TPTB. To isolate the frictional losses of a single thrust bearing, previous test equipment [29,30] used hydrostatic bearings to support the test bearing, allowing free rotation and torque measurements, but these arrangements do not represent typical industrial applications.

In some cases, the test apparatus utilises an energy balance method to measure power loss to overcome the difficulties of obtaining direct torque measurements. This method involves calculating energy losses by monitoring the oil temperature rise within the bearing housing, measuring the oil supply flow rate, and considering the lubricant's specific heat capacity and density [31]. However, this approach overlooks additional energy losses from thermal conduction and radiation. Furthermore, the accuracy of this method of measuring instantaneous power loss can be affected by transient variations in oil flow rate and temperature [32]. An additional challenge is separating churning and shearing losses. To address these concerns, Dabrowski and Wasilczuk developed a complex torque-meter spring [33]. The torque meter was utilised in an experimental study to evaluate the friction torque of a centre-pivoted pad operating against a collar coated with a carbon-based coating [34].

Omitting hydrostatic systems for loading and friction measurements substantially reduces the cost and complexity of the test apparatus. For example, Dadouche et al. [35] employed a vertical arrangement for a lightly loaded fixed geometry thrust bearing and loaded it axially with a simple threaded rod, but frictional losses were not measured. Xiang et al. [36] utilised a hydraulic cylinder to load a water-lubricated fixed geometry bearing. The system provided torque measurements through a rotary inline torque meter. However, the shaft was supported by additional radial bearings, which influenced frictional measurements.

3. DEVELOPMENT OF THE EXPERIMENTAL TEST APPARATUS

3.1. Tribotronic Control Strategy

In the following, a control strategy has been developed that involves controlling the inlet-to-outlet film thickness ratio using a dedicated actuator. This control action was chosen for its ability to regulate minimum film thickness and power loss without directly modifying lubricant properties, such as by additional heating. Furthermore, the proposed strategy offers potential benefits such as optimising the wedge geometry in applications that commonly utilise centre pivot pads and enable implementation in thrust bearing systems that do not rely on an external circulating oil supply.

A block diagram representing the feedback control system is presented in Figure 2.

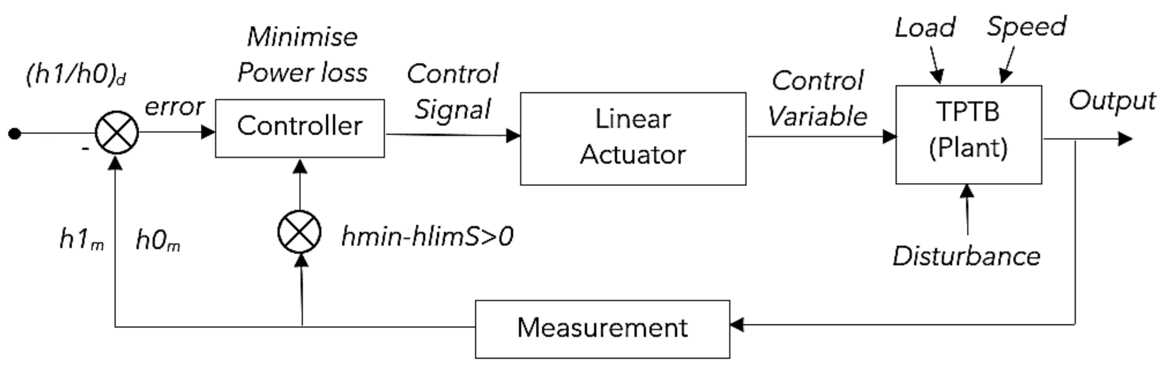

Figure 2: Feedback control loop for AGTPTB

The objective of this approach is to minimise power loss while ensuring an adequate minimum film thickness (*hmin*). The method entails setting a desired inlet-to-outlet film thickness ratio $(h_1/h_0)_d$, based initially on theoretical analysis, to achieve power loss reduction. A controller is employed to adjust the tilt angle of the pad using a linear actuator, with a constraint to maintain the minimum film thickness above a safe threshold (*hlimS*).

3.2. General Arrangement of Test Apparatus

Various design iterations of the test apparatus were considered based on the proposed control strategy and the ease of interchangeability between the tribotronic and conventional bearing. The arrangement was developed without using an external hydrostatic system to facilitate friction measurement to reduce cost and complexity. Instead, a horizontal, dual shaft, single collar configuration was employed. The general arrangement is shown in Figure 3.

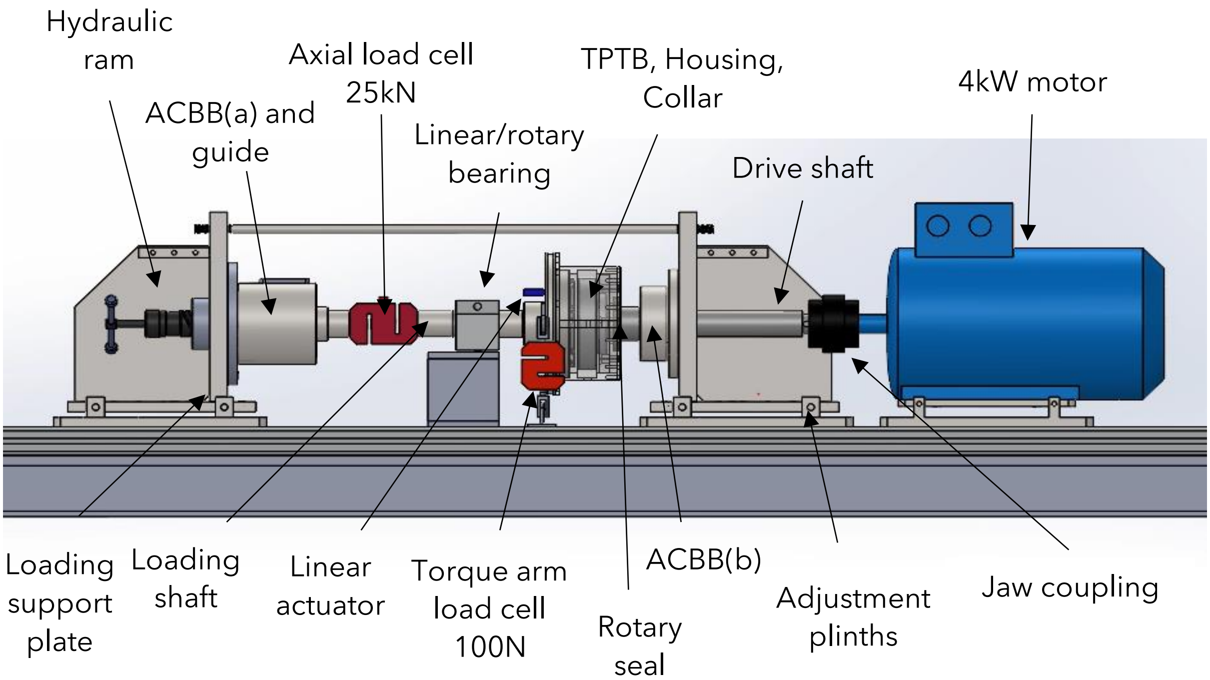

Figure 3: General arrangement of test apparatus

This setup uses a hydraulic ram to load the TPTB against the rotating collar. The main parameters of the TPTB and collar are given in Table 1.

Table 1: Main bearing parameters

Parameters	Values
Outer bearing diameter (mm)	130
Inner bearing diameter (mm)	53
Number of pads	6
Pivot type	Offset line pivot
Liner material	White metal faced (1mm thickness)
Circumferential pivot offset (%)	60
Bearing thrust surface area (mm^2)	8436
Pad thickness (mm)	16.5
Pad angle (deg)	53
Mean pressure diameter (mm)	99.3
Collar diameter (mm)	134
Collar thickness (mm)	25

The axial bearing load is measured through the loading shaft using an S-Type load cell with a maximum rating of 25kN. The loading shaft is designed to slide within the linear bearing to facilitate access to the test bearing,

A 4kW motor and inverter drive controls the shaft speed, ranging from 0 to 3000rpm. Since the current design lacks an encoder, the inverter estimates the shaft speed based on the frequency and voltage supplied to the motor. The drive shaft is supported by an Angular Contact Ball Bearing (ACBB(b)) and connected to the motor via a jaw coupling. Loading support plates are utilised for load transfer to prevent axial forces from affecting the motor. Each loading plate is positioned on adjustment plinths, which facilitate shaft alignment.

A series of linear mechanical actuators are connected to the rear of each tilting pad to control the inlet-to-outlet film thickness ratio during operation. Simple and cost-effective fine-thread adjustment actuators have been selected for the initial testing phase to evaluate the feasibility of the proposed method.

The test apparatus also incorporates a circulating oil supply system (not depicted in Figure 3). This system comprises a 30L tank, a 0.4kW motor and 3.7Lmin^{-1} pump, an air blast cooler, and a 15μm filter. The bearing lubrication system also includes a needle valve to regulate the oil flow rate, an immersion heater and a three-way oil mixer valve to control supply temperature and a pressure gauge and relief valve to maintain supply pressure.

3.3. Test Measurements

In this design, the housing, TPTB, and loading shaft can rotate freely with the support of the Angular Contact Ball Bearing (ACBB(a)) and rotary bearings, allowing for torque measurements. A torque arm is connected to an S-Type load cell rated up to 100N to prevent the housing from rotating. The direct friction torque of the TPTB can be calculated using the equation:

$$\tau_{total} = rFsin\theta$$

where r is the radius from the axis of rotation to the point of application of force, F is the magnitude of applied force on the torque arm load cell, and θ is the torque arm angle with respect to the line of action of force.

As noted above, isolating friction torque measurements in simple design configurations that lack hydrostatic elements can be challenging. In this case, the ACBB(a) breakaway torque needs to be overcome before a measurable force can be observed at the torque arm load cell. The breakaway friction torque of ACBBs is influenced by the sliding moment and the frictional moment of the seal. To mitigate this torque, seal-less ACBBs are utilised, aiming to reduce resistance during initial rotation. Experimental determination of the contribution of breakaway friction torque is performed by measuring the applied torque required to initiate rotation at various loads.

The energy balance method will also be employed to measure the power loss of the TPTB as determined from the following equation:

$$P_{bear} = Qin\ \rho\ Cp\ (T_{drain} - T_{supply})$$

where Qin is the volumetric oil flow rate, ρ is the lubricant density, Cp is the specific heat capacity of the lubricant, and T_{drain} and T_{supply} are the oil drain and oil supply temperatures, respectively.

The volumetric flow rate is measured using a viscosity-compensated variable area flow meter. Inline oil temperature sensors are positioned near the bearing housing inlet and outlet orifices to measure the oil drain and supply temperatures. It is recognised that the lubricant density and specific heat capacity are a function of mean temperature rise.

Three equidistant pads are equipped with two capacitance-type film thickness transducers, which measure the inlet and outlet film thickness at the mean pressure diameter slightly offset from the leading and trailing edges. The transducers have been calibrated in a purpose-built test stand using the ISO VG 46 lubricant, which serves as the dielectric and lubricating oil in the test.

In addition to the film thickness transducers, several thermocouples are employed to measure the sub-surface pad temperature. These thermocouple probes are positioned slightly below the liner surface, with a 75% offset from both the leading edge and the inner radius of the pad. This position is commonly used in industrial applications to measure maximum pad temperature. Moreover, additional temperature sensors are positioned close to the film thickness transducers. These sensors enable the estimation of both the mean temperature rise across the pad and the localised film temperature at the film thickness measurement location.

3.4. Test Procedure Proposal

A draft experimental procedure has been developed to study and compare the performance of the passive and active bearings.

During the initial tests, the oil flow rate and feed temperature will be kept constant at 1.75Lmin^{-1} and 50°C. During a 300-minute test cycle, each bearing will be subjected to a selection of speeds (500-3000rpm) and mean bearing pressures (0.5-2MPa). The transition between different operating conditions will be carried out over a period of 2 minutes. The proposed test cycle is shown in Figure 4.

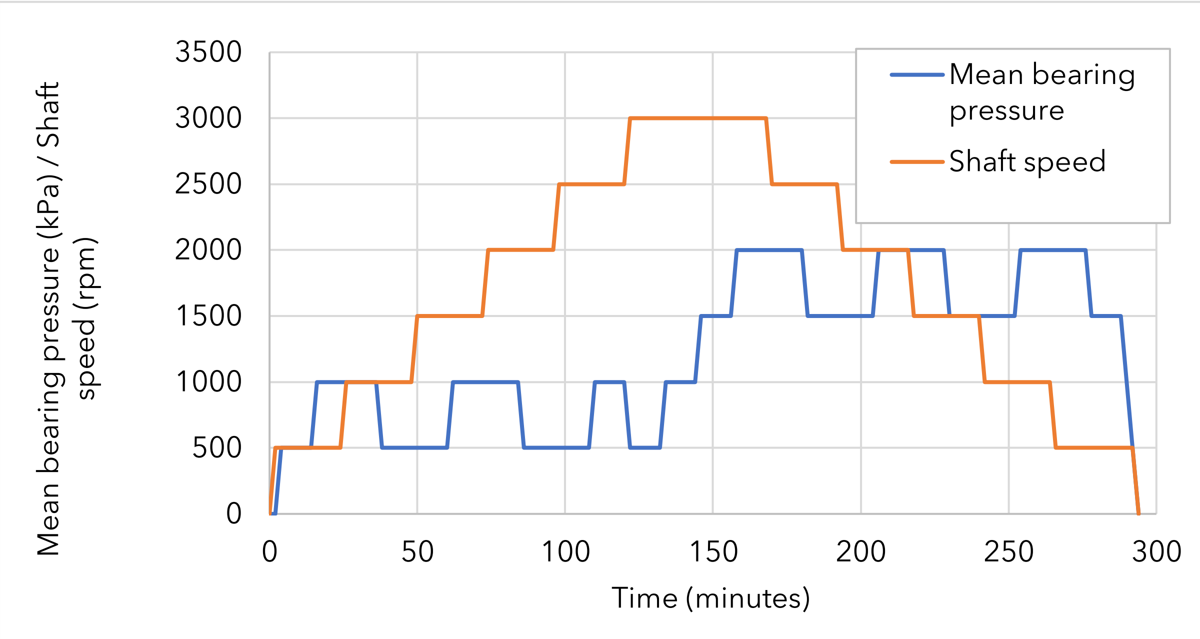

Figure 4: Test cycle

The test cycle will be repeated for changes in lubrication parameters, including oil flow rate and supply temperature. These variations or disturbances about the ideal operating conditions are intended to replicate practical circumstances, such as a reduction of oil flow due to a loss of circulating system pressure or an increase/decrease in supply temperature based on a failure of the oil heating/cooling system. The tribotronic bearing will be evaluated on its ability to optimally control the film thickness geometry in the event of such disturbances.

A comprehensive investigation is proposed to assess the effectiveness of the control strategy in mitigating power loss under different operating conditions involving speed, load, and lubrication parameter variations. It is hypothesised that operating conditions leading to a larger minimum film thickness, specifically the combination of low load, high speed, and increased viscosity, will exhibit a greater reduction in power loss for the active bearing configuration compared with the passive arrangement. This is based on the premise that an increased safety threshold allows for more substantial trade-offs between reducing power loss by minimising minimum film thickness, resulting in greater potential for power loss reduction.

4. CONCLUSIONS AND FURTHER WORK

This paper presents the development of an AGTPTB test apparatus and a tribotronic control strategy. The focus is on regulating the inlet-to-outlet film thickness ratio to minimise power loss. The proposed low-cost solution uses mechanical actuators and capacitive film thickness measurements for pad inclination control.

The test apparatus features a horizontal, dual shaft, single collar configuration, enabling easy interchangeability between the tribotronic and conventional bearing. Integration of various measurement devices facilitates comprehensive performance measurements and valuable feedback for the control system, including load cells, flow meters, temperature sensors, and film thickness transducers.

Future research aims to validate the proposed control strategy across diverse operating conditions through experimental studies on both the active and conventional thrust bearings. Further enhancements to the tribotronic system's optimisation capabilities could involve integrating additional actuators to regulate lubrication parameters. Moreover, the investigation of dynamic characteristic improvements, such as controlled film forces for vibration attenuation, holds potential within the concept of the active geometry tilting-pad thrust bearing.

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