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Research Progress of Bearing Test Machines for Special Conditions

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ABSTRACT

Bearings are essential components in mechanical systems, with their performance being a key factor influencing the reliability and service life of machinery. Bearing test rigs, as critical equipment for evaluating bearing performance, simulate diverse operating conditions to investigate failure mechanisms and performance characteristics under practical applications. These evaluations offer crucial insights for optimizing bearing design and operational parameters. Specialized working environments, such as heavy-load conditions, deep-sea operations, space applications, and extreme high/low temperatures, impose stringent demands on bearing performance. Consequently, performance assessment and lifespan evaluation of bearings in these conditions have become focal points in the development of advanced bearing test rigs. This paper reviews the research progress of bearing test rigs under heavy load conditions, deep-sea environments, space environments, and high/low-temperature environments. It analyzes the characteristics of bearing test rigs under different environmental simulation technologies and provides an outlook on the research trends in this field, offering a solid foundation for technological advancements in related areas.

KEYWORDS

Bearing Test Machine; Heavy-load Operating Environment; Marine Environment; Space Environment; High/Low Temperature Environments.

1. INTRODUCTION

Bearings are one of the essential fundamental components in various mechanical equipment. Based on their operating principles and structural characteristics, they can be classified into two main categories: sliding bearings and rolling bearings. Bearings are primarily used to reduce the friction coefficient between shafts and bearing housings, ensure the rotational capability of shafts, and minimize energy consumption. They are widely applied in fields such as rail transit, aerospace, and high-end equipment. In recent years, with China's groundbreaking advancements in aerospace, rail transit, and other sectors, the industry's demands for the comprehensive performance of bearings have significantly increased. Key performance parameters such as long service life and high reliability are becoming increasingly critical. Enhancing these parameters requires bearings to maintain excellent operational performance even under special working conditions, including extreme temperatures, high pressures, strong radiation, and corrosive environments. Consequently, it is essential to develop bearing test equipment designed to meet the requirements of various environments and to conduct reliability testing and service life evaluations for bearings and related components under diverse conditions.

Taking the space environment as an example, in the 1960s, the United States conducted a series of studies on the effects of phenomena such as the deformation of space motion mechanisms and the "cold welding" of material surfaces on the reliability of these mechanisms. However, this research only enabled partial on-orbit performance testing for certain components. Between 1960 and 1990, NASA launched two Ranger-series satellites, four ERS-series satellites, and seven OV-1-13 satellites, establishing an on-orbit testing platform for space motion mechanisms. This platform, equipped with essential measurement devices and data acquisition systems, was specifically designed to study the "cold welding" issue of motion mechanisms, resulting in a wealth of experimental data. It is evident that on-orbit testing in space involves prolonged launch durations, significant environmental variations across different orbits, and factors such as orbit adjustment delays. These challenges lead to lengthy testing cycles, slow overall progress, and high costs [1-2] -0. In contrast, conducting targeted environmental validation for components such as bearings can significantly reduce research and development expenses. Environmental validation is a crucial method for assessing the adaptability of equipment to its environment and verifying its performance parameters [3-4]. The environmental reliability of equipment refers to its ability to operate continuously and normally under specific environmental conditions(e. g. temperature, humidity, high pressure, vacuum, and corrosion). This reliability reflects the equipment's capability to withstand various environmental stresses over extended periods without failure or performance degradation in real-world working conditions. Given the technical sophistication, high cost, and lengthy development cycles of equipment used in aerospace, deep-sea, and extreme exploration environments, stringent assessments of environmental adaptability are essential during testing and validation. Conducting extensive environmental tests on test rigs during early stages allows for the identification of performance characteristics and vulnerable components under different conditions, enabling targeted improvements and optimizations. Through comprehensive environmental testing and validation, bearings and similar components can be ensured to function reliably under various extreme conditions, enhancing their applicability and reliability while reducing failure rates and extending service life. These tests provide critical information for improv the necessity ing bearing performance parameters and verifying the effectiveness of modifications, ultimately reducing maintenance and replacement costs. The above analysis highlights of using test devices capable of simulating environmental conditions to conduct operational environment simulations for various types of bearings. The primary challenge lies in accurately defining the actual operating environments of bearings within different motion mechanisms.

Due to the broad range of applications for bearings, they frequently face challenging operating conditions such as extreme temperatures, high-impact loads, and chemical corrosion, which significantly affect their performance. For instance, in aerospace engines and metallurgical equipment, bearings must withstand extreme temperatures reaching several hundred degrees Celsius. This places higher demands on bearing materials and lubricants, oftenNecessitating the use of high-temperature alloys or ceramic materials and lubricants with superior thermal stability and oxidation resistance to ensure optimal performance under such extreme conditions. Similarly, high loads and impacts are common in mining equipment and heavy machinery. The size, material properties, and structural design of bearings all influence their load-bearing capacity and fatigue life. Using more robust materials and optimizing structural designs can effectively enhance the operational stability of bearings under high-impact loads. Additionally, in marine environments or chemical plants, bearings must resist corrosive media, requiring the use of corrosion-resistant materials such as stainless steel or specialized coatings. Regular monitoring and lubricant replacement are also essential to prevent corrosion-induced failures.

Given the diverse operating conditions that bearings encounter in real-world applications, the use of bearing test rigs equipped with environmental simulation capabilities becomes particularly important. These test rigs can simulate complex working conditions such as high temperatures, heavy loads, and chemical corrosion, enabling the evaluation of bearing performance in practical applications. For certain types of bearings, such as self-lubricating spherical bearings, the research on service life is stillNot fully standardized, and existing life prediction formulas remain immature. Relying solely on theoretical research is insufficient to accurately determine the service life of these bearings. Therefore, it isNecessary to develop specialized bearing test rigs for experimental evaluation. Equipped with environmental simulation functions and advanced monitoring systems, these test rigs can record real-time data on bearing performance under different working conditions, including temperature, friction, and vibration frequency. Such data not only helps assess the performance of existing bearings but also provides critical experimental evidence for the design ofNew bearing types. This underscores theNeed for bearing test rigs capable of replicating actual operating conditions and characteristics [5-6].

This paper provides a brief overview of the research progress on environmental simulation systems for bearing test rigs at home and abroad, with a particular focus on the recent advancements in environmental simulation devices for bearing test rigs.

2. PRINCIPLES & CLASSIFICATION OF EXISTING BEARING TEST MACHINES

The basic working principle of a bearing test machine involves setting parameters such as load, oscillating frequency, and operating environment, and then subjecting the test bearing to reciprocating or continuous rotational oscillation. This process allows for real-time monitoring of its tribological properties[7] . Typically, when collecting performance parameters of the bearing, the test machine employs various sensors, including displacement sensors, torque sensors, temperature sensors, and vibration sensors, to monitor performance data under different lubrication mechanisms in real-time. These sensors assess key performance indicators such as wear degree, friction force variation, temperature response, and vibration status, thereby meeting the diverseNeeds of bearing testing[8] .

Bearing test machines are commonly used to evaluate the long-term rotation of rolling bearings and reciprocating rotating joint bearings, In terms of structural composition, bearing test machines are composed of loading system, oscillation system, detection and control system, environment simulation system and so on. According to the bearing in the test machine on the number of dimensions, the bearing test machine can be divided into one-dimensional, two-dimensional and multi-dimensional three types, one-dimensional test machine is used to simulate the bearing around the core axis of the slewing or oscillation, is currently on the market bearing test common equipment. Two-dimensional testing machine can realize the bearing around the x, y, z three axes in any two dimensions of the movement, such as Li Zhengguo et al[9] . developed a composite swing type joint bearing life testing machine, can be clamped four joint bearings, but also can realize the rotation, tilt, and composite swing of the joint bearing. The two-dimensional testing machine increases the complexity and comprehensiveness of the test, and the multidimensional testing machine is used to realize the motion test of the bearing in three dimensions and more than three dimensions. Sun Bo et al[10] . carried out the test for the tail rotor articulating bearings, and used the crank pendulum mechanism to realize the bearing's high-frequency swing, and realized the variable pitch movement of 0-10mm through the servo cylinder with the rolling spline, the pitch fork holder, and the adjusting rod to drive the pitch drawbar up and down to realize the pitch movement of 0-10mm. This kind of testing machine can provide the testing platform closest to the actual working conditions, but the design of the testing machine is difficult.

Effectively improving the environmental adaptability of bearings is one of the critical challenges that must be addressed to advance China's equipment manufacturing industry. Internationally, companies such as SKF began testing various technical parameters of bearings as early as the 20th century. SKF's R2, R4, and R5 bearing test rigs, for instance, are capable of simulating working conditions such as high and low-temperature environments and varying loads [11-12]. However, due to technical protection measures and limited availability of relevant information, publicly accessible data on foreign bearing friction and wear test rigs remain scarce, making reference materials for New product development exceedingly limited. Therefore, based on the existing bearing bench testing devices and evaluation systems, it is of great importance to establish a more comprehensive, environmentally accurate, precise, and reasonable testing device and evaluation system. Such advancements would play a crucial role in driving technological innovation within China's bearing industry.

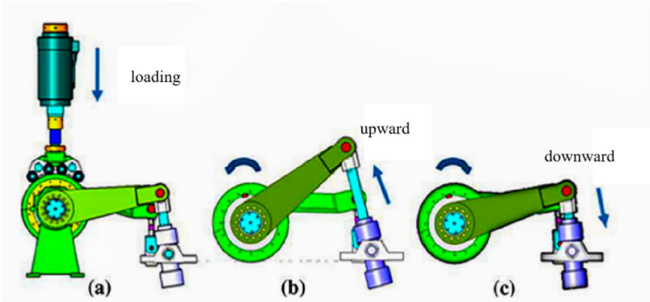
3. BEARING TEST DEVICES FOR SIMULATING VARIOUS ENVIRONMENTS

Bearings are indispensable core components in various mechanical systems and are critical to the performance of special equipment. The reliability of bearings directly affects the overall stability of equipment operation. Therefore, bearings must withstand the challenges posed by a wide range of complex environmental factors, such as heavy load conditions in atmospheric environments, extreme high and low temperatures, high pressure and corrosion in marine environments, oxygen atom erosion in space, and continuous collisions with interstellar media (including gases and dust). These dynamic and varied external conditions impose unprecedented high standards on the environmental adaptability of bearings [13]. Consequently, it is essential to conduct performance parameter testing of bearings under different environmental conditions.

3.1. Heavy Load Operating Conditions

With the rapid development of China's technological innovation capabilities, advancements in fields such as transportation, aerospace, and deep-sea exploration are occurring at an unprecedented pace. The heavy-load operation of machinery and equipment is Now commonplace in daily life. Bearings, which are subjected to heavy loads and extreme operating environments, often face lubrication failures such as excessively thin oil films and localized dry friction, which severely impact the stability of equipment [14]. In response to the practical challenges of heavy-load bearings under high load and harsh working conditions, both domestic and international research has focused on conducting load tests on heavy-load test bearings. The goal is to investigate the failure modes and performance parameters of heavy-load bearings under actual operating conditions, providing valuable data support and experimental evidence for improving bearing performance.

The loading system of existing bearing test rigs can achieve axial, radial, or combined loading of bearings, with adjustable loading ranges. Some loading methods support stepless adjustment. Currently, the loading systems of bearing test rigs primarily include servo-electric cylinder loading, hydraulic loading, pneumatic loading, gravity loading, lever loading, electromagnetic loading, and eccentric mechanism loading. Kim et al[15] from the Korea Institute of Science and Technology employed pneumatic loading to apply radial force to joint bearings, achieving a maximum radial load of 30kN. Hu Hongwei et al[16] designed a movable crossbeam that indirectly applies energy from a hydraulic cylinder to the bearing fixture, enabling constant force loading. This design can achieve a maximum radial load of 115kN, improving the integration of the testing equipment and enabling heavy-load simulation, making a significant contribution to bearing test rigs for loads exceeding 100kN in China. Sheng Jin et al. [17] used hydraulic proportional loading to apply axial and radial loads to test bearings, achieving a maximum axial force of 500kN and a maximum radial load of 1500kN. This method provides a broader loading range and enhances the authority of the tests. Chen Hongzhan et al. [18] combined an electric cylinder with an electromagnet, using the electric cylinder to adjust the gap between the electromagnet and armature or adjusting the current during energization to achieve stepless loading. However, this loading method may be influenced by the current's thermal effects on test results, and its control is more challenging. Therefore, optimizing the control technology of this loading method is an important direction for future research. Lei Yaguo et al. [19] conducted radial load tests of 12kN, 11kN, and 10 kN on the XJTU-SY bearing using hydraulic proportional loading, obtaining full lifecycle signals of the bearing and, for the first time, globally publishing rolling bearing accelerated lifetime test data. Rezaei A et al. [20] used hydraulic loading to apply a maximum load of 1500kN to bearings. This device drives a piston to alter the bearing's rotational direction and measures the force on the lever arm connected to the bearing bush to determine the frictional torque, aiming to identify the tribological behavior of large journal bearings subjected to reciprocating angular motion, as shown in Figure 1.



(a)Loading;(b)counterclockwise rotation of the shaft;(c)clockwise rotation of the shaft[20]

Figure 1. Test setup

The characteristics of bearing test rigs under heavy load operating conditions are summarized in Table1. In the future, with the continuous optimization of loading methods for bearing test rigs, the performance parameters of bearings under heavy load conditions will be significantly improved. This willNot only support the reliable operation of bearings in extreme heavy-load environments but also provide higher stability and efficiency for the development of various industries. By integrating more intelligent and precise loading systems, the adaptability and loading capacity of bearing test equipment will be further expanded, enabling the acquisition of test data more representative of actual working conditions and meeting the higher demands of modern industrial development.

Table 1. Features of Bearing Test Rigs for Heavy-Load Conditions

Test Rig Name	Bearing Type	Simulated Special Working Conditions	Key Features
Pneumatic Oscillating Spherical Plain Bearing Life Tester[15]	Spherical plain bearing	Heavy-load condition(30kN)	Hydraulic loading;simple structure;only suitable for bearings within a certain size range.
Spherical Plain Bearing Life Tester[16]	Spherical plain bearing	Heavy-load condition;temperature control(-60℃to 300°C)	Hydraulic loading;compact structure;movable crossbeam design;easy adjustment.
Wind Turbine Main Bearing Test Platform[17]	Double-row spherical roller bearing	Heavy-load condition(max axial 500kN;max radial 1500kN)	Cantilever beam structure to facilitate installation and removal of test bearings.
Ultra-Low-Temperature Vacuum Bearing Tester[18]	Solid self-lubricating spherical plain bearing	Vacuum;wide-range temperature cycling(-150℃ to 150°C)	Measures friction torque;inner/outer ring cooling or heating modules;electromagnetic loading;loading module includes adjustable bellows to maximize vacuum retention.
Accelerated Bearing Life Test Platform[19]	Rolling bearings	Heavy-load conditions	Three conditions;proportional hydraulic loading;radial load tests at 12kN, 11kN, and 10kN.
Large-Scale Journal Bearing Tribology Test Equipment[20]	Polymer composite journal bearings	Heavy load(1500kN)	Friction torque determined via lever force measurement;online measurement of normal force, friction force, temperature, and wear rate.

3.2. Marine Environment

The ocean is the largest aquatic ecosystem on Earth, rich in resources, and plays a crucial role in supporting the sustainable development of humanity. With the limited exploitation of land resources and the growing demand for resources due to human activities, deep-sea exploration and development have become key National strategic priorities[21]. The average global ocean depth is approximately 3, 897meters, with about 90% of the ocean depths exceeding 1, 000meters, and the deepest regions reaching over 10, 000 meters, where the water pressure can reach up to 10, 500kPa. Compared to land environments, the high humidity, low temperatures, high salinity, alkalinity, and erosion from solid particles in the marine environment contribute to more severe corrosion of metals and harsher working conditions for tribological components[22-23]. Frictional components operating in the ocean are inevitably affected by the high water pressure, raising doubts about whether the research results obtained in atmospheric environments are applicable to high-pressure deep-sea conditions[24-25]. Therefore, developing bearing test rigs that can simulate full-depth marine environments and investigating the failure mechanisms of bearing materials in marine and other liquid environments is of great significance for advancing China's independent research and development of deep-sea equipment.

The tribological characteristics of material interfaces are crucial factors influencing the tribological performance of key components such as bearings. In studies focused on the tribological properties and failure mechanisms of metal materials, Han Gaofeng, Ding Hongyan, and others[26-27] utilized an independently developed friction-wear test machine that simulates marine environments. This machine fixes the tribological pair inside a high-pressure container, using magnetic force drive while isolating external factors that could interfere with loading. Before testing, approximately 150mL of seawater is added to the container to ensure the tribological pair is fully submerged. Nitrogen gas is then introduced to simulate the seawater pressure, and gas pressure is adjusted to replicate different seawater depths. Yuan Zuhao and others[28] employed acid-and alkali-resistant, corrosion-resistant materials to construct a sealed environmental chamber, which is filled with seawater and heated using a temperature control device with an electric heating rod to simulate marine environments. This test rig can also fill the sealed chamber with other liquids and gases, enabling the simulation of various bearing operating environments, facilitating the analysis of bearing performance in specific conditions. Dong Conglin and others[29] combined a water medium temperature control system with a vertical pin-disk friction-wear test machine, immersing the pin sample in a lubricating medium to maintain a stationary state, while the stainless steel disk sample is driven to frictional motion against the pin. By adjusting the immersion medium, this device can simulate various seawater temperatures, salinities, and other marine conditions, accurately reflecting the tribological performance of tail shaft materials in the ocean environment. Wang Di and others[30] cleverly employed a hydraulic vibration excitation device to simulate the fluctuating environment of sea waves. By adjusting the output pressure of hydraulic oil, the vertical reciprocating motion of the hydraulic cylinder is controlled, generating impact vibrations on the bearing test rig to simulate the wave fluctuation and impact environment, thus filling the gap in marine equipment bearing test rigs. In marine environments, backpressure simulation is also an important aspect of bearing test rigs. Wang Jianzhang and others [31] injected Nitrogen and argon gas above the simulated seawater surface and used a hydraulic pump to pressurize artificial seawater, recreating the high-pressure conditions of deep-sea environments. This device can simulate underwater static pressure at a maximum depth of 3, 000 meters(30MPa); however, it currently lacks the capability for corrosion electrochemical testing. Yang Cong and others [32-33] installed a hydraulic loading system on the outer side of the hub to simulate centrifugal force load, rotational resistance load, and rotational torque load on the blades. This system can achieve a maximum pressure of 35MPa and provides a variable flow rate of 0-180L/min, simulating loading conditions of the hub in a marine environment, as shown in Figure 2. Shimizu T and others[34] added a sewage environment simulation system to the bearing test rig, but due to the earlier development of the test rig, the wear of the pad had to be manually measured, and the detection system was Not fully developed.

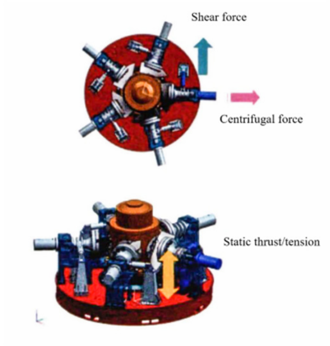


Figure 2. Schematic of applied load types[32] .

Table 2. Features of Bearing Test Rigs for Marine Environments

Test Rig Name	Specimen/Component Type	Simulated Special Conditions	Key Features
Simulated Deep-Sea Environment Friction Tester[26–27]	Pin-on-disk	Marine/deep-sea environment	Simulates seawater depth by adjusting gas pressure.
Marine Environment Friction and Wear Tester[28]	Ball-on-disk, pin-on-disk, ring-on-block, ball, etc.	Marine/salt-spray environment	Uses corrosion-resistant materials to avoid salt-spray corrosion; supports performance testing of multiple tribo-pairs.
CBZ-1 Marine Shafting Friction and Wear Tester[29]	Pin-on-disk	Marine environment	By adjusting the immersion medium, simulates different seawater temperatures and salinity.
Marine Power Transmission Bearing Life Simulation Test Rig[30]	Rolling bearings	Marine and high-temperature environments	Simulates wave fluctuation conditions while achieving high-temperature conditions.
MRH-03 Ring-on-Block Friction and Wear Tester[31]	Ring-on-block specimens	Marine environment	Injects nitrogen and argon above the liquid surface to simulate a marine environment.
High-Power Pitch-Control Propeller Hub Assembly Test Bench[32–33] .	Propeller hub assembly	Marine environment	Adjustable centrifugal, thrust, and shear forces; comprehensively simulates actual working conditions.
Unidirectional Sliding Tester[34] .	Self-aligning sliding bearing	Marine/wastewater environment	Adjustable liquid composition to simulate complex liquid environments.

The characteristics of bearing test machines for simulating marine environments are summarized in Table 2. Although existing bearing test devices vary in functionality, they all aim to replicate more realistic marine conditions, providing crucial data support for the performance analysis of bearings and related materials. Through continuous optimization of test conditions and environmental simulation apparatus, these devices are Now capable of effectively reproducing extreme conditions such as high pressure, corrosion, and temperature fluctuations in the deep sea, thereby offering deeper insights into the failure mechanisms of bearings in marine environments. In the future, as the exploration of deep-sea resources progresses and technologies continue to evolve, bearing test machines will develop towards higher precision and broader applicability, establishing a more solid technological foundation for the independent research and development of deep-sea equipment in China. This will play a key role in advancing technological innovation in marine engineering, deep-sea exploration, and other related fields, with significant strategic importance.

3.3. Space Environment

Spacecraft typically operate at altitudes between 200 km and 900 km, where the vacuum level generally ranges from 10^{-4} to 10^{-7} Pa, and atomic oxygen concentration can reach up to 80%. In this environment, spacecraft are subject to severe impacts from high-speed atomic oxygen, microgravity, and high-temperature oxidation during their service life[35-36]. Numerous space and ground simulation test results have shown that high-speed impacts from atomic oxygen and high-temperature oxidation cause significant erosion of aerospace materials, particularly organic materials. This leads to degradation of bearing mechanical parameters, such as changes in the material properties of self-lubricating composite materials like fabric liners in joint bearings, which shortens the equipment's service life[37-39] . Hoang et al. [40] predicted and quantified the potential effects of interstellar gas and dust collisions through theoretical research. The results indicated that atomic oxygen impact at 0. 2 times the speed of light would cause surface damage to quartz materials. As a result, the performance of bearings in low Earth orbit environments is significantly reduced. With the groundbreaking progress of projects such as the BeiDou satellite and the manned space station, stricter requirements for the service life of aerospace equipment have been proposed. For example, the in-orbit operational lifetime requirement for geostationary satellites has increased from 8 years to over 15 years, the design in-orbit flight time for the Chinese space station is over 10 years with a service life of 15 years, and deep space exploration spacecraft are required to maintain reliable service for over 20 years[41] .

As a crucial component of space exploration equipment, studying the performance of bearings under space conditions is particularly important. Wang Jun et al. [42] designed a high-speed motor system combined with a frequency converter to achieve speeds of up to 20, 000 rpm. This system, along with a manual hydraulic loading system and load sensors, can apply loads up to 10, 000N with contact pressures reaching 3 GPa. Additionally, an environmental chamber with both high-temperature and room-temperature lubrication systems simulates temperatures ranging from -197°Cto 300°C, fulfilling the stringent test requirements for aerospace environments. However, this system lacks the ability to simulate vacuum conditions. Wang Jian et al. [43] developed a dual-station vacuum chamber equipped with magnetic fluid seals, achieving a vacuum level of 1×10^{-6}Pa. This system can simultaneously test 8 sets of bearings and simulate a vacuum state. Zhang Zhinan et al. [44] conducted friction torque tests on space momentum wheel bearings in a vacuum environment. Their test setup, placed in a vacuum chamber to simulate space conditions, featured a design that eliminated measurement errors using bolted rollers and torque transmission blocks. Mu You et al. [45] developed a test machine for MoS2 solid lubrication bearings under thermal vacuum conditions. This system used heating plates placed on the inner and outer rings of the shaft and was placed in a vacuum chamber to simulate a vacuum environment with temperatures ranging from -40°Cto 60°C. The friction torque was measured using a back-to-back angular contact bearing with a balance torque method. Zhou et al. [46] employed magnetic transmission technology, integrating a relative humidity control device inside the environmental chamber, to assess the bearing's moisture resistance while maintaining the vacuum level in the chamber. Existing lubricants, known for their low evaporation rate, excellent corrosion resistance, radiation resistance, and temperature stability, are widely used in space environment equipment. However, atomic oxygen irradiation is one of the key factors that affect the lifespan of bearing lubrication films in the complex space environment [47] . Ma Guozheng et al. [48] installed radiation equipment and an atomic oxygen device at the top of the vacuum chamber to simulate a real low Earth orbit space environment. This system uses air pressure loading, with a limited range of loading force, as shown in Figure 3. Zhu et al. [49] used a ball-on-disk friction and wear device, generating oxygen ion plasma using an electron cyclotron resonance (ECR) microwave source (MY-1000AD)to perform multiple impact tests on prepared samples in a vacuum environment with a pressure of less than 6×10^{-3} Pa, successfully recreating the atomic oxygen conditions in space.

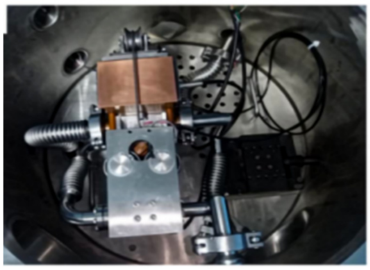


Figure 3. Spherical plain bearing test rig simulating a space environment [48] .

The characteristics of bearing test machines for simulating space environments are summarized in Table 3. These testing systems not only assist researchers in better understanding the wear and aging mechanisms of bearings under high vacuum and high radiation environments but also provide crucial experimental data for the design and optimization of aerospace equipment. These technological advancements lay a solid foundation for ensuring the long lifespan and high reliability of aerospace equipment, while also offering essential technical support for the ongoing breakthroughs in China’s space programs. In the future, with further advancements in simulation technology and materials science, bearing test machines will focus on simulating a wider range of space environments, including microfluidics, microgravity, and various types of radiation. These developments will enable more precise experimental validation, providing comprehensive solutions for the design of critical components in space exploration and further enhancing China’s autonomous innovation and international competitiveness in the aerospace sector.

3.4. High/Low Temperature Environments

Bearings operating in high and low temperature environments must possess excellent environmental temperature adaptability to prevent embrittlement in extreme cold conditions, ensure long-term stable operation, and prevent issues such as seizing and crack propagation. As a result, the lubrication performance of bearings in such environments also faces higher demands. Numerous studies have shown that friction is one of the main causes of temperature rise during bearing operation, and lubrication is crucial in reducing the friction coefficient between mechanical parts and maintaining the normal operation of bearings [50]. Huang et al. [51] found that when the temperature exceeds 80℃, the frictional heating in water intensifies the friction and wear of polymer resin materials. Lubricants play a key role in ensuring the reliable operation of bearings within an appropriate temperature range. However, traditional oil or grease lubrication struggles to provide effective lubrication in extreme high and low temperatures. As a result, new forms of lubrication, such as oil-free lubrication or solid self-lubrication, have gradually become dominant and exhibit excellent stability, wear resistance, and durability in extreme temperature and heavy load environments.

In summary, studying the adaptability of bearings in extreme environments such as high and low temperatures and heavy loads is of significant importance for driving industrial development. Lou et al. [50] conducted design experiments on bearings used in New energy vehicles under rapid acceleration-deceleration conditions and high-low temperature environments. They utilized a high-speed electric spindle controlled by a frequency converter, achieving an emergency response capability of 18, 000 r/min. A compressor cooling system and high-quality nickel-chromium alloy electric heaters enabled a tunable temperature range of -55°Cto 150°C. Wang et al. [52] adopted temperature-controlled lubrication, integrating the lubrication and heating systems. This approach uses heated and circulated lubricant to control the bearing's temperature, differing from traditional hot-air heating methods, thereby achieving rapid heating and improved efficiency.

Table 3. Features of Bearing Test Rigs for Space Environments

Test Rig Name	Specimen/Component Type	Simulated Special Conditions	Key Features
High-Speed Sliding–Rolling Contact Friction Tester[42]	Disk-shaped roller	Space environment	Supports temperature-controlled lubrication and changes of lubricant media.
Bearing Life Tester for Meteorological Satellite Scanning Mechanism[43]	Angular contact ball bearings	Vacuum(up to 1×10^{-6}Pa)	Dual-station vacuum chamber with ferrofluidic seal valves; supports simultaneous testing of 8 groups of bearings.
Space Momentum Wheel Bearing Friction Torque Tester[44]	Momentum wheel bearings	Space environment	Bolt roller and torque transfer block design eliminates torque error.
Dedicated Test Apparatus for Solid-Lubricated Bearings[45]	Solid-lubricated bearings	Thermo-vacuum environment	Uses the balanced torque method to measure friction torque, enabling high-precision data acquisition.
Vacuum Bearing Performance Test Device[46]	Rolling bearings	Vacuum(10^{-4}Pa);high-temperature/high-humidity(30°C, 85%RH)	Magnetic drive and 1: 1 gears enable continuous rotation of bearings.
Spherical Plain Bearing Life Tester Using Pneumatic Loading[48]	Spherical plain bearings	Vacuum, atomic oxygen, UV irradiation, proton irradiation, and other space environments	Uses the pressure differential during vacuum testing for pneumatic loading.
Ball-on-Disk Tribometer[49]	Ball-on-disk pair	Vacuum(6×10^{-3}Pa), atomic oxygen, etc.	Equipped with an optical microscope and Raman spectrometer for convenient observation.

Li et al. [53] developed a test rig suitable for a wide temperature range and high-speed, heavy-load conditions. They combined a liquid nitrogen cooling system with electric heating wires for low-temperature control. liquid nitrogen was pre-heated to the desired low-temperature Nitrogen gas using heating wires, which was then injected into the test chamber for precise temperature control. The chamber's gaps were filled with cold-resistant and low-thermal-conductivity polytetrafluoroethylene materials. Tests confirmed a stable minimum temperature of -175°C or lower, meeting experimental requirements. Additionally, a heating system for lubricant oil utilized electric wires wound around spiraling supply pipelines for heating, achieving temperatures up to 150°Cwith a ±3°Cerror margin. Wu et al. [54] employed liquid nitrogen delivery to maintain a vacuum chamber at -190°C. While the low-temperature requirement was met, continuous liquid nitrogen flow significantly affected the vacuum level. Xia et al. [55] developed a horizontal liquid nitrogen-cooled bearing test rig for ceramic bearings, achieving extreme low-temperature conditions(-196°C) with a radial load of 4750N. Yu et al. [56] innovatively controlled the temperature by regulating the amount of liquid nitrogen within an insulated chamber, achieving precise temperature adjustment(±5K)across a range of 93K to 323K, facilitating continuous temperature variation for bearing testing. Cai et al. [57] considered factors like heating rate, temperature adjustment, and precise temperature control. They selected a two-stage cascade air-cycle refrigeration compressor with centrifugal fans for mixing and heating, combined with BTR balanced temperature regulation, achieving precise temperature control, As shown in Figure 4. Sikorski et al. [58] placed bearings in a low-temperature chamber and introduced liquid nitrogen dried by a desiccator, creating a low-temperature test environment while minimizing the impact of moisture on test data. Liu et al. [59] employed a ring-ring(disc-disc)and pin-disc self-balancing configuration to ensure full contact under pneumatic loading, applying loads up to 2000N and simulating contact pressures from 0. 01 to 4. 00MPa. The test rig's water temperature could be adjusted up to 300℃, with a maximum water pressure of 10 MPa, provided by an electric heater.

Figure 4. Wide-temperature-range low-temperature bearing test rig [56].

The characteristics of bearing test rigs for high and low-temperature environments are summarized in Table4. These studies demonstrate that bearing test rigs designed for high and low-temperature environments have become critical platforms for investigating the performance limits of bearings and developing new bearing lubrication materials. Research on the temperature adaptability of bearings Not only addresses the limitations of traditional lubricants and materials but also ensures effective friction and wear control during operation in extreme temperature conditions, laying a solid foundation for long-life performance under harsh conditions. With the ongoing development of advanced lubrication materials and temperature control technologies, the performance and lifespan of bearings in extreme environments will be further enhanced, providing forward-looking technical support for industries such as aerospace, marine engineering, and new energy vehicles.

4. CONCLUSION

Due to China's relatively late start in bearing test rig development and the technical blockade from foreign countries, there are still shortcomings in China's bearing test rigs, such as incomplete environmental simulation systems and inconsistent evaluation standards. To address the operational environment requirements across various industries, China is actively designing bearing test rigs with efficient environmental simulation capabilities and developing standardized testing and evaluation methodologies. These studies are Not only crucial for enhancing bearing performance under extreme conditions but also play a significant role in driving innovation in bearing base materials, lubricants, and design principles. Environmental simulation has become a key approach to ensuring that the tested lifespan of joint bearings aligns with their actual operational lifespan. Therefore, improving the simulation of extreme conditions, including high/low temperatures, high salinity, sand and dust, strong radiation, and deep-sea environments, as well as complex multi-factor scenarios, can significantly enhance the accuracy of bearing performance testing. Future research should continue to focus on simulating diverse and complex environments to meet the stringent performance requirements of bearings in various industries and to provide robust support for the efficient and stable operation of machinery. Based on these considerations, this paper provides the following outlook on bearing test rigs under special environmental conditions:

Table 4. Features of Bearing Test Rigs for High/Low-Temperature Environments

Test Rig Name	Specimen/Component Type	Simulated Special Conditions	Key Features
High/Low-Temperature Tester for Bearings of High-Speed Automotive Drive Motors[50]	Deep groove ball bearings	High/low temperature(−55°C to 150°C)	Allows simultaneous testing of two sets of bearings.
Comprehensive Performance Tester for High-Speed, High-Temperature Bearings[52]	Rolling bearings	High temperature	Hydraulic loading; capable of axial and radial loading.
Ball-on-Disk Tester[53]	Ball-on-disk specimens	High/low temperature environment	Designed for lubricant drag characteristics of aerospace bearings; meets specialized needs for lubricant performance studies; narrow application scope.
Multifunctional Low-Temperature Vacuum Bearing Test Bench[54]	Various bearings	Ultra-low temperature(−190°C)	Can maintain −190°C for extended periods.
Low-Temperature Bearing Test Rig[55]	Full ceramic ball bearings	Low temperature; heavy load	Low-temperature friction sensor minimally affected by temperature changes; simultaneous monitoring of vibration parameters of the outer ring.
Wide-Temperature-Range Low-Temperature Bearing Test Rig[56]	Self-lubricating radial spherical plain bearings	Low temperature(93–323K)	Supports GE90 and GE40 bearing sizes; can simultaneously test four sets of the same size bearings.
Oscillating Bearing Tester for High/Low-Temperature Environments[57]	Rolling bearings	Integrated high/low temperature environment(−60°C to +250°C)	Simultaneous comparative testing of four sets of bearings(same or different sizes), saving time.
Liquid-Nitrogen-Cooled Ball Bearing Friction Test Apparatus[58]	Ball bearings	Low temperature(liquid nitrogen)	Introduces desiccated liquid nitrogen into the chamber, reducing moisture effects on test data and corrosion of the apparatus.
High-Temperature, High-Pressure Water Friction and Wear Tester[59]	Ring-on-ring and pin-on-disk	High temperature(300°C)	Ensures full contact when the pneumatic loading device applies a maximum load of 2000 N.

(1) More Complex Load Simulation Systems: Future developments in bearing test rigs will focus increasingly on accurately simulating complex multi-dimensional load environments. In real-world applications, bearings are often subjected to dynamic, transient, and multi-directional combined loads. Consequently, testing equipment must achieve higher precision and responsiveness, enabling the simultaneous simulation of radial, axial, and torque forces while dynamically adjusting loading conditions in real time.

(2) Enhanced Adaptability to Multi-Environments: As the demand for bearings in extreme environments such as deep-sea exploration, polar expeditions, and outer space increases, test rigs will progressively overcome current limitations in environmental simulation. They will enable testing across broader temperature ranges (e. g., from ultra-low to ultra-high temperatures) while simulating unique conditions such as space microfluidics, microgravity, radiation, and sand-dust environments.

(3) Integration of Intelligence, Digitalization, and Autonomous Learning Systems: Leveraging emerging technologies like sensor technology, artificial intelligence (AI), and big data analytics,

future bearing test rigs will evolve toward greater intelligence. By integrating multi-dimensional sensors, they will facilitate real-time data collection on mechanical, thermal, and vibration parameters during tests. AI will be utilized for data analysis and pattern recognition, enabling self-adjustment of testing parameters, automated fault detection, and fatigue life prediction for bearings. Additionally, through machine learning, test equipment will continuously optimize the testing process, improving efficiency and accuracy.

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