

Research Progress on the Dynamic Stability of Dry Gas Seals

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Abstract: Concerning the application of high-precision, enormous rotating equipment under harsh working conditions, the advantages of dry gas sealing technology are increasingly obvious. Herein, research on the dynamic stability of dry gas seals is reviewed based upon their operating mechanisms. The influence of the dry gas seal structure, vibration response, and dynamic followability on the reliability of the shaft end sealing system of rotating machinery is the focus of current dry gas sealing technology. This work reviews the research history; analyzes the key coefficient of the instability of the sealing system under external disturbances, and the existing research on stability models; discusses the influence of starting and stopping characteristics, working conditions, and groove parameters on the stability of dry gas seals; and points out the shortcomings in the existing research. In addition, potential developments in dynamic stability are proposed, including improving model accuracy, improving experimental techniques, or applying intelligent control and optimization methods to enhance the dynamic stability of the sealing system. Finally, the development prospects for dry gas sealing technology in intelligent monitoring and wide temperature range adaptations are discussed, and theoretical guidance for improving a dry gas seal system is provided.

Keywords: dry gas seals; dynamic characteristic coefficient; vibration response; followability



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1. Introduction

With the rapid advancement of industrial technology, rotating machinery is progressively transitioning towards extreme, intelligent, green, and interdisciplinary development. However, ensuring long-term stable operation of the unit poses a challenge for high-quality equipment [1–3]. The current dry gas sealing technology has revealed various latent risks in practical applications, such as airflow excitation, thermal deformation, and grinding. Factors like severe vibration of the rotating shaft and installation deviations between seal pairs can lead to instability in the gas film. This instability results in friction-induced failures, vibrations, and sudden leakages leading to energy loss and environmental pollution [4]. Research indicates that equipment reliability is directly determined by sealing performance; hence, advanced and efficient sealing technology plays a pivotal role in guaranteeing the stable operation of rotating machinery [5]. Enhancing the shaft end sealing systems of rotating machinery can effectively improve overall machine efficiency by 4.2% [6]. Analyzing and optimizing frictional losses, vibrations encountered during dry gas seal operations can enhance performance and reliability while reducing maintenance requirements and failure rates, as well as production costs. Therefore, it is crucial to investigate the dynamic stability aspects related to dry gas seals to ensure unit safety. Figure 1 illustrates several types of shaft end seals used in rotating machinery.

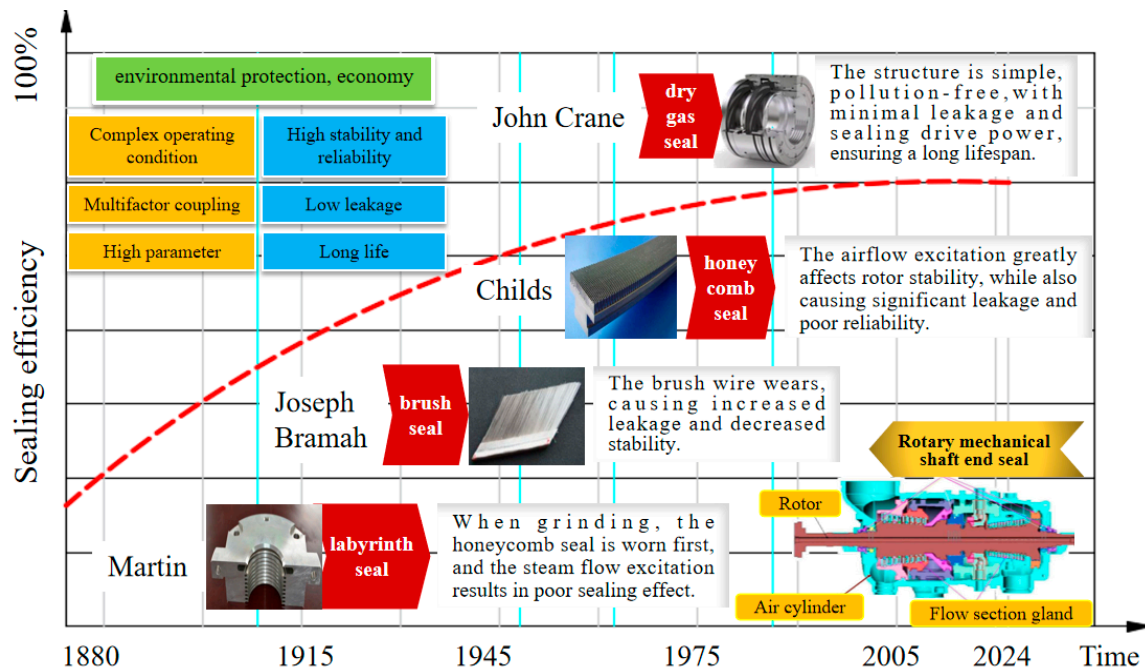


Figure 1. Rotary mechanical shaft end seal forms [7–10].

Figure 1 compares the sealing efficiency of these various shaft end seals for rotating machines. In increasing order of efficiency, the labyrinth seal generates airflow excitation, the brush seal's wires wear easily, and the honeycomb seal has problems with friction and sparks. The dry gas seal has gradually become the standard shaft end seal for rotating machinery because of its good sealing performance and adaptability to high-pressure and high-speed conditions. The characteristics of dry gas seals save energy, protect the environment, and improve production efficiency. High-precision and enormous rotating equipment operating in harsh working conditions has made the superiority of dry gas sealing technology increasingly valuable [11]. From the perspectives of environmental protection, economy, energy conservation, and production efficiency, intelligent control units for extremely complex conditions are the trend in green development of rotary power plants. The sealing system is an important part of rotary equipment and the key to research. At present, although the dry gas seal has obvious advantages over the traditional shaft end seal, its stability under extreme working conditions is still poor. Therefore, further research to improve the long-term stability of the dry gas sealing system is important for the development of large-scale rotating equipment.

2. Dry Gas Seals

2.1. Structure and Working Principle of Dry Gas Seals

The structure of the dry gas seal is shown in Figure 2, which primarily comprises the static ring seat, spring, sealing ring, pressing sleeve, shaft sleeve, rotating shaft, static ring, moving ring, and other parts. As can be seen from Figure 2a, the static ring installed in the static ring seat is sealed by a sealing ring. The static ring moves freely along the axis under the guiding action of the static ring seat and the spring load. The moving ring is fixed on the rotating axis and rotates with the axis by the interference fit. To improve the dynamic pressure effect of the seal, microgrooves are usually added to the surface of the moving ring. When the shaft rotates at a high speed, a gas film with high stiffness is formed between the sealing pairs, thus producing the sealing effect [12]. The structure of the sealing pairs is shown in Figure 2b, and the spiral-groove structure of the end face of the moving ring is shown in Figure 2c.

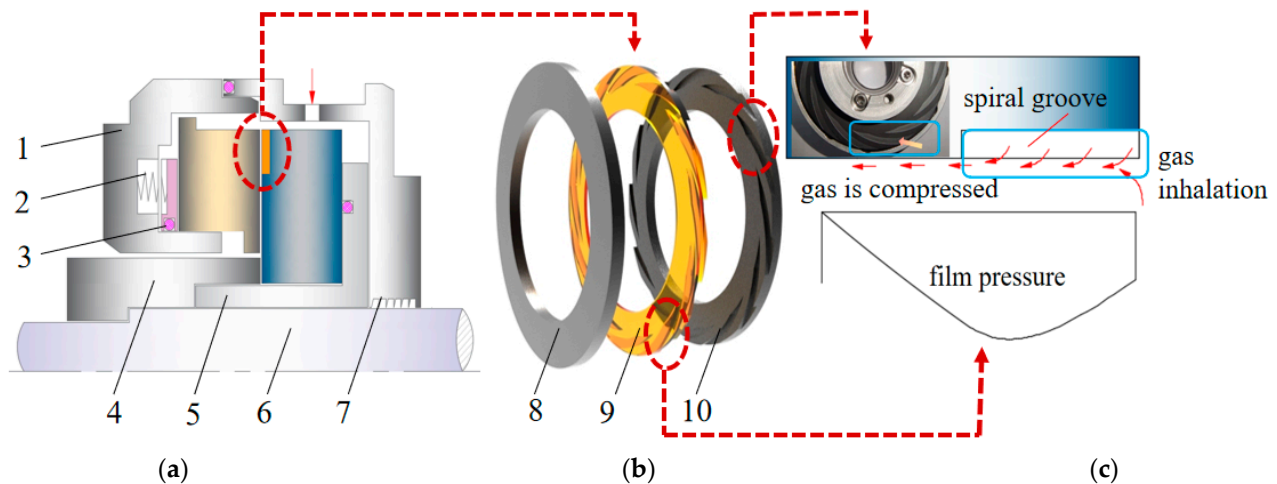


Figure 2. Structure and working principle of dry gas seals [13–15]: (a) dry gas seal structure; (b) seal pairs; (c) working principle of hydrodynamic pressure. 1—Spring seat; 2—spring; 3—o-ring; 4—clamping ring; 5—shaft sleeve; 6—rotating shaft; 7—secondary seal; 8—stationary ring; 9—gas film; 10—rotary ring.

2.2. Dry Gas Seal Force Analysis

The dynamic balance of forces in the sealing system is essential to the stable operation of dry gas seals [16]. Figure 3 shows a force analysis of the dry gas seal structure, in which the opening force F_o is caused by the hydrodynamic pressure and hydrostatic pressure acting on the seal end face, while the closing force F_c comprises the spring force p_{sp} , medium pressure p_1 , and back pressure p_2 . The pressure distribution of the gas film when the seal is working normally is shown in Figure 3a. Under normal operation, $F_o \approx F_c$ and a stable gas film with high rigidity forms between the sealing pairs. A change in seal clearance will change the dynamic balance. If the seal clearance decreases, so that $F_o > F_c$, it develops in the direction of equilibrium due to the unbalanced force of the seal pair, and the thickness of the gas film increases until the seal gap equilibrates. The pressure distribution of the gas film when clearance decreases is shown in Figure 3b. When the gas film gap increases, the compression of the sealing gas decreases, and the dynamic pressure effect weakens, leading to $F_o < F_c$. The gas film pressure distribution when clearance increases is shown in Figure 3c. Therefore, in a certain range, the dry gas seal has an adaptive ability, which reduces the probability of friction between the sealing pairs.

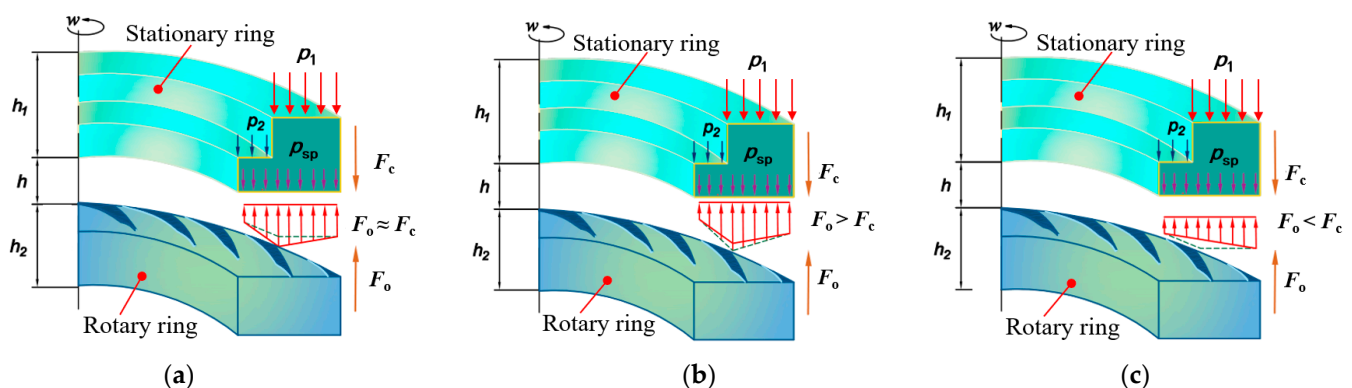


Figure 3. Dry gas seal force analysis: (a) gas film pressure distribution during normal operation; (b) gas film pressure distribution when clearance decreases; (c) gas film pressure distribution when clearance increases.

3. Research on Dynamic Characteristics of the Dry Gas Seal

3.1. Dynamic Characteristic Coefficients

The dynamic characteristic coefficients of the dry gas seal are numerical values obtained by theoretical calculation or experimental measurement. The coefficients are used to evaluate the dynamic response and stability of the seal system when the rotor changes rapidly. In dry gas sealing technology, the commonly used dynamic characteristic coefficients include the stiffness coefficient, damping coefficient, and inertia coefficient. The stiffness coefficient is a measure of the stiffness response of the dry gas seal to the numerical direction, indicating the elastic characteristics of the gas film. The higher the stiffness coefficient, the higher the seal stiffness, which means that the deformation or vibration of the seal has less influence on the thickness of the gas film. The damping coefficient is a measure of the damping response of the dry gas seal to the relative velocity, indicating the energy dissipation characteristics of the gas film. The larger the damping coefficient, the better the seal damping effect, which can effectively reduce vibration and shock. The inertia coefficient is a measure of the inertial response to acceleration, indicating the degree of reaction of the gas film to acceleration. The greater the inertia coefficient, the more obvious the inertial effect, which may lead to deformation and vibration. Therefore, research on the dynamic characteristic coefficients of the gas film in dry gas seals is the key to evaluating the advantages and disadvantages of dry gas seal system designs [17]. Usually, researchers obtain the stiffness coefficient and damping coefficient of the gas film based on different theoretical calculation methods. Relevant motion equations are established to discuss the dynamic behavior of the gas film on the seal end face and to determine whether the sealing system will be unstable due to external interference. The dynamic performance of the lubricating gas film of the dry gas seal structure can then be analyzed [18].

Badykov et al. [19] analyzed the axial vibration of a sealing system under different working conditions, obtained the influences of the elasticity of the gas film dynamic response and of the damping component on the dynamic characteristics of the dry gas seal, and calculated the relevant dynamic characteristic coefficients. Ding et al. [20] established a calculation model for dynamic characteristic coefficients by using the PH linearization method, solved the relevant calculation using the numerical software, analyzed its dynamic stability, obtained the optimal stable spiral angle range, and verified the correctness of their model through experiments. Liu et al. [21] used the perturbation method to numerically solve for the damping coefficient and stiffness coefficient of the gas film on the end face of the seal and believed that the interaction between axial vibration and angular oscillation was small and could be ignored. Xu et al. [22] established a mathematical model under multiple effects and analyzed the influence of different parameters on the stiffness coefficient and damping coefficient through numerical examples. These research examples solve for the characteristic coefficients of each degree of freedom of the dry gas seal, by analyzing the structural parameters and external excitation, and then evaluate the dynamic stability and reliability of the dry gas seal. In addition, the influence of inertia effects on the dynamic characteristic coefficients cannot be ignored. Yang et al. analyzed the dynamic characteristic coefficients of a supercritical carbon dioxide dry gas seal under inertia effects and considered the changes in the dynamic characteristic coefficients. Figure 4 shows the influence of speed on the axial dynamic characteristic coefficient. Compared with ignoring the inertia effect, the axial dynamic characteristic coefficient is lower when the inertia effect is considered. With an increase in speed, the calculated differences of the axial damping coefficient and axial stiffness coefficient can reach 5.27% and 12.2%, respectively.

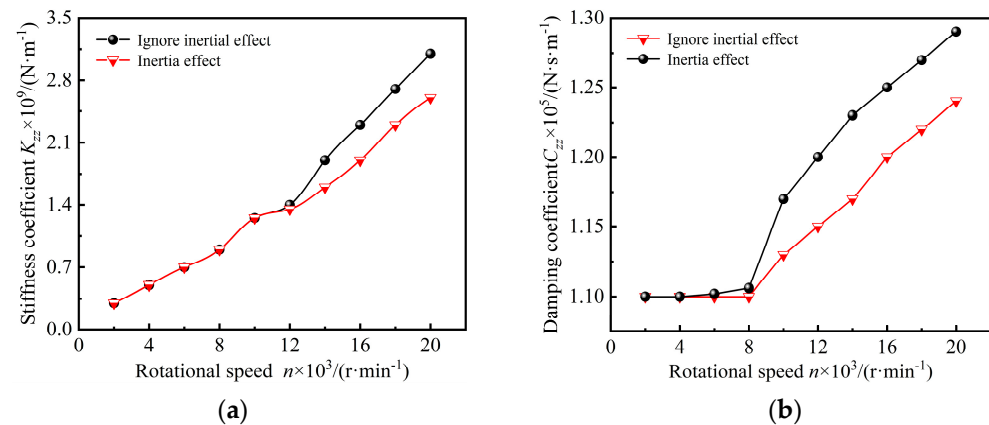


Figure 4. Effect of rotational speed on axial dynamic characteristic coefficient [23]: (a) influence of axial dynamic stiffness coefficient; (b) influence of axial dynamic damping coefficient.

The application range of the dynamic characteristic coefficients of the dry gas seal depends on the structure and working condition of the seal. For high-speed rotating equipment such as shaft seals or turbines, the axial (or radial) dynamic characteristic coefficient is suitable for evaluating the stiffness and damping response of the dry gas seal in the axial (or radial) direction. The application range of the dynamic characteristic coefficients needs to be quantitatively evaluated and analyzed according to specific working conditions, medium properties, sealing structures, and other factors. Calculation errors in the dynamic characteristic coefficients are affected by many factors, including the accuracy of the calculation model, the calculated instability accuracy, and the choice of parameters. To accurately evaluate the dynamic characteristic coefficients of the dry gas seal, finite element analysis, experimental analysis, and numerical simulation are often used to obtain calculation results. To improve the calculation accuracy, experiments can be repeated several times to minimize errors. In the process of numerical calculation, it is necessary to consider certain model assumptions and accuracy verifications. These methods can provide a reference for the optimization of dry gas seal structures and further improve the performance and stability of dry gas seals under complex working conditions.

3.2. Research Methods of Dynamic Characteristics

Both the dry gas seal and the gas dynamic pressure bearing produce dynamic pressure effects through gas compression, and there is a close relation between these parts. Many research methods for dry gas seals have been introduced and further developed from the field of gas dynamic pressure bearings. Through the in-depth study of the dynamic characteristics of dry gas seals, scholars use different research methods to solve for and analyze dry gas seal stability.

Faria et al. [24] analyzed the influence of rotational speed on the dynamic characteristics of the dry gas seal. By calculating the characteristic parameters of the end-face gas film, the change behaviors of the dynamic characteristic coefficients of the gas film at high excitation frequency were analyzed. Sato et al. [25] used a visual method to study the performance of the end grooves of a bidirectional rotary seal structure and, compared with unidirectional grooves, its lubrication characteristics were reduced. Zirkelback et al. [26] used the finite element method to solve the static and dynamic performance equations of the dry gas seal, compared the influence of the isothermal compressible fluid model the seal performance, and obtained the axial stiffness coefficient and damping coefficient under the disturbance frequency. As the frequency increased, the axial stiffness coefficient and damping coefficient tended to be asymptotic values. Ruan et al. [27] studied the dynamic characteristics of the dry gas seal with a semi analytical method. They analyzed the axial and angular modes by using dynamic coefficients related to frequency and found that the coupling forces and moment coefficients were zero and decoupled. Ding et al. [28] used the iterative method and PH linearization method to solve the approximate equation of

gas film stiffness. They concluded that under different working conditions, the gas film stiffness increased with increased groove depth, and the maximum value appeared near the bottom of the groove. Liu et al. [29] analyzed the influence of geometric parameters on the dynamic coefficients of dry gas seals based on a semi analytical method, obtained reasonable value ranges for the seal end parameters by optimizing the structural parameters, and then proposed effective measures to improve the dynamic performance of the seal. Liu et al. [30] studied the influences of end-face structure parameters on the dynamic characteristics of dry gas seals through the particle swarm optimization (PSO) algorithm and projection tracking analysis method in the global optimization algorithm. Table 1 summarizes the existing commonly used research methods for stability models.

Table 1. Analysis method of dynamic characteristics of dry gas seals.

Stability Model Methods	Advantage	Shortcoming	Scope of Application	
Perturbation method [31]	The calculation speed is fast, and the complex physical systems can be solved more accurately.	The uncertainty is limited by the small perturbation hypothesis.	Suitable for systems with sufficiently small perturbations.	A computational method for characterizing gas film characteristics.
Step-by-step method [32]	Parallelizes the iterative process to speed up calculations.	The convergence is unstable, and there may be cases of nonconvergence for some problems.	It is especially effective for solving nonlinear problems and optimization problems.	
PH linearization method [33]	It has good convergence when the initial solution is close to the real solution.	The choice of initial solution is closely related to convergence.	Suitable for local analysis of the system.	
Runge–Kutta method [34]	It has high numerical stability and accuracy.	When solving large-scale problems, it consumes more computing resources.	Reliable and accurate numerical solutions are provided in cases where high numerical accuracy is required.	A method for solving equations of motion.
Fault tree analysis method [35]	It provides a means to evaluate the reliability of the system and helps to identify the main factors leading to system failure.	As a static analysis method, the influence of dynamic behavior and interaction of the system cannot be considered.	It can be used to identify system weaknesses, optimize design, develop security policies, and control risks.	Methods for evaluating the reliability of sealing systems.
Analytical method [36]	Relatively simple problems and specific types of equations can be solved quickly, saving calculation time.	For complex problems and nonlinear problems, analytical solutions may not be obtained.	It is widely used to solve wave equations, heat conduction equations, and electrostatics or electromagnetism problems.	The sealing linear motion differential equation is established by using the characteristics of the gas film.
Particle swarm optimization (PSO) and projection tracking analysis [37]	Simple and easy to understand and implement, without complex mathematical derivation and optimization skills.	In some cases, PSO may be trapped in the local optimal solution, and it cannot find the global optimal solution.	In the case of large a problem space and high complexity, it performs well and can find good approximate solutions.	Multi-objective optimization algorithm.

To summarize, the key aspects of research methods for dry gas seal stability models involve enhancing experimental accuracy, refining numerical calculation models, introducing precise analysis methods, and considering real-world application conditions. The conventional dry gas seal stability model assumes linearity in system behavior, however, improved models should incorporate factors such as contact stiffness and vibration characteristics. Experimental validation is necessary to ensure model accuracy and enhance applicability. The study of dry gas seal stability models encompasses various disciplines, allowing for the selection of appropriate research methods based on specific problems and conditions or a comprehensive integration of multiple approaches. Regression analysis and statistical simulation can be employed to assess uncertainties in sealing systems or measure uncertainties through experimental verification.

3.3. Experimental Studies on the Dynamic Stability of Dry Gas Seals

The analysis of dry gas seals typically encompasses sealing performance, friction characteristics, thermal characteristics, and other aspects to determine their feasibility under actual operating conditions. Evaluating the dynamic characteristics of dry gas seals is a crucial research area that assesses their dynamic performance and design effectiveness. By simulating real-world operating conditions, parameters such as leakage rate, vibration behavior, temperature rise, and others can be evaluated to optimize seal performance and refine seal design based on specific characteristics. The stability of dry gas seals measures their ability to operate continuously and reliably under certain conditions, ensuring the safety and stability of shaft end seals in rotating equipment. Establishing an experimental test device is often necessary to analyze the performance of dry gas seals by controlling pressure, temperature, speed, and other working conditions. Such analyses enable researchers to comprehensively evaluate the stability of dry gas seals accurately while optimizing and enhancing their structure.

Rozova et al. [38] developed a dry gas seal modeling program, based on experimental research, to evaluate its stability under fluctuating working conditions. Kolomoets et al. [39] conducted experiments to evaluate the dynamic stability of a dry gas seal system under a certain pressure and rotational speed and verified the correctness of the design parameters. Green [40] conducted real-time monitoring and control of the seal's dynamic behavior through experiments, and further explored the root cause of poor seal dynamic stability. Based on the Reynolds equation model, Lu et al. [41] tested the stiffness of the gas film in a dry gas seal under the sliding effect using a new technology and found that the optimal spiral angle of the stiffness of the air-enhanced film was 76.8° , the groove depth was 1×10^{-5} m, and the average error of the experimental and theoretical calculations was $<20\%$. He et al. [42] conducted experimental research and verification on the gas film flow field at the end face of the dry gas seal under different working conditions and analyzed the influence of working condition fluctuations on the balance state of the gas film gap. Zou et al. [43] numerically calculated the angular motion response of the moving ring under a certain angular deviation and monitored the angular displacement and angular motion trajectory of the sealing ring through experiments. Ding et al. [44] conducted experimental research and comparative analyses on the performance parameters and stability of dry gas seals and obtained their dynamic characteristic coefficients under different speeds and pressures. Rozova et al. and Kolomoets et al. verified the rationality of structural parameter design under different working conditions through experimental research. Based on their work, He et al. and Ding et al. obtained the stability parameters through experimental research. However, due to the limitations of experimental methods and testing techniques, the parameters obtained are not ideal. The new technology employed by Lu et al. determined the gas film stiffness and corresponding slot parameters. Both theoretical and experimental errors were confined within a specific range, thereby elucidating design parameters and reducing error margins, which is conducive to future optimization.

In practical engineering applications, the dynamic operation of dry gas seals is complex due to various random factors such as external excitation disturbances, installation deviations, machining errors, and fluctuations in working conditions. Currently, there exists a disparity between simplified theoretical calculation models of dry gas seal stability based on assumptions and actual operating conditions. This disparity leads to discrepancies between test data and numerical simulation results. Although existing experimental studies provide references for theoretical modeling and computational optimization coordination, further enhancements are necessary to achieve precise measurements. Moreover, the working principle of dry gas seals involves intricate fluid thermodynamics and dynamics. To ensure the feasibility of theoretical analysis modeling and its application in experimental design and data analysis, it is imperative to continue exploring its operational mechanism under different working conditions.

Experimental studies not only validate theoretical calculations but can also provide the basis for monitoring and control of the high-parameter sealing system. Experimentation

is the most effective way to solve practical engineering and technological problems, and to evaluate parameters related to the dynamic characteristics of a dry gas seal within a certain range. The dry gas seal experimental device is shown in Figure 5. It comprises the seal system, gas path system, power system, and test system. However, with the development of science and technology, and the increased demands of extremely complex working conditions, the current experimental research is still insufficient. The three main problems are as follows: (1) poor accuracy due to uncertainty; parts machining accuracy and installation deviations affect the measurement accuracy. (2) The experimental method needs to be improved; the accuracy and authenticity of monitoring data are difficult to verify due to the complex and changeable influencing factors in practical engineering applications and the measurement of the instability region needs to be further improved. (3) Monitoring system improvements; the influences of external excitations on experimental measurements and of the disturbances in experimental equipment signals on experimental accuracy need to be better understood.

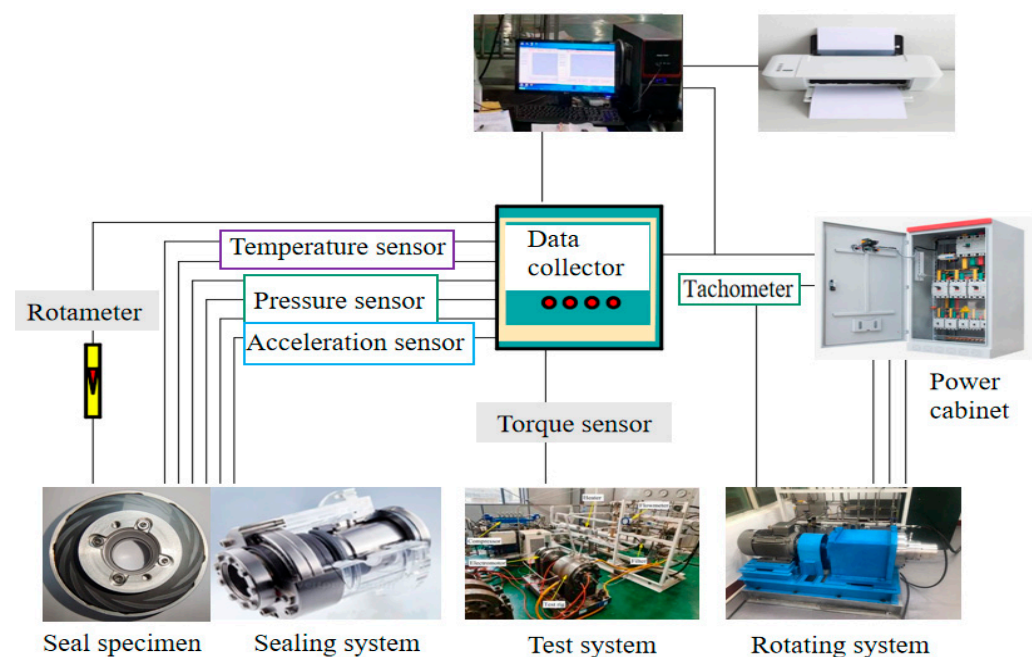


Figure 5. Dry gas seal test device.

3.4. Factors Affecting the Stability of Dry Gas Seals

3.4.1. Starting and Stopping Phases

The starting and stopping processes of dry gas seals are quick, but the sealing mechanism is complicated. During operation, the sealing system inevitably experiences a low-speed stage before the opening of the seal face when transitioning from the stopped state to the operating condition or from the operating rotation to shut down. At this time, the dynamic contact friction caused by external excitation affects the reliability and stability of the sealing system to a certain extent [45,46]. Industrial practice [47] demonstrates that wear failures in dry gas sealing devices occur during the startup and trial operation stages of sealing. Therefore, increasing the stiffness of the gas film improves the stability of dry gas seal operations.

The influence of starting and stopping conditions on the stability of the dry gas seal system has been analyzed. To improve the starting stability of the seal system, Wang et al. [48] analyzed changes in the opening force of the seal face by exploring the starting and stopping conditions of the dry gas seal. They designed a new seal face structure that reduces the seal face contact frequency during the starting process. Gao et al. [49] established a three-dimensional contact model based on the channel structure of the dry gas seal in the starting and stopping stages to study the friction characteristics and the friction thermodynamics

of the end-face micro-texture under dry friction conditions. Peng et al. [50] established a dynamic pressure opening performance analysis model for dry gas seal structures of three typical channels, compared and analyzed the influence of critical dynamic pressure on the opening performance of the seal, and numerically calculated the gas film pressure distribution behavior of the seal end face under different working conditions. Fan et al. [51] used acoustic emission technology to analyze the stability of the actual startup process and divided the state evolution into the grinding contact stage, normal operation stage, transition stage, and failure stage according to changes in the test parameters. This method provides a comparative reference for exploring the starting and stopping characteristics of dry gas seals in the field of high parameters. Ding et al. [52] used numerical calculations to analyze the friction characteristics in an unsteady state. They quantified the influences of friction heat caused by elastic deformation stress and temperature rise on sealing performance, which provided a theoretical basis for the later optimization of structural parameter design. Sun et al. [53] revealed the contact friction mechanical characteristics of the end face of the dry gas seal by analyzing the surface topography of the seal pair experimentally, determining the initial parameters of the contact model, and obtaining the change behavior of the starting parameters of the dry gas seal. Deng et al. [54] analyzed the influences of the gas effect and the gap inlet gas film temperature on the startup conditions under different groove parameters. They studied the variations of viscous shear heat during startup, providing certain theoretical references for the engineering design of dry gas seals under high-pressure conditions. Li et al. put forward the criterion of opening critical speed for analyzing the opening performance of the dry gas seal and analyzed the influence of starting conditions on the seal performance. The performance parameter changes during startup are shown in Figure 6. Figure 6a shows the curves for friction power consumption, and frictional torque as the rotational speed increases before and after the critical speed. Figure 6b indicates that when the operating speed is lower than the critical speed, the seal end face is in contact, $F_o < F_c$. As speed increases, the dynamic pressure effect increases sharply. The gas film thickness and opening force increase, and when the critical speed is reached, $F_o \approx F_c$. Figure 6c demonstrates that the gas film stiffness increases sharply with the increase in the dynamic pressure effect, and then the curve stabilizes with increasing gas film thickness. When the working speed is lower than the critical speed, the gas film thickness is unchanged and the leakage amount changes slightly, and the leakage amount increases with the increase of the speed.

In the described research, the various scholars analyzed the friction characteristics of the dry gas seal in the starting and stopping stages by numerical calculation, acoustic emission testing, and critical condition parameter discrimination. Friction and vibration in the starting and stopping stage have profound influences on the operating stability of the dry gas seal system and are the main causes of early seal failure. Considering the instantaneity and complexity of the dry gas sealing system during starting and stopping, it is necessary to explore more accurate and advanced analysis methods to develop efficient sealing technology.

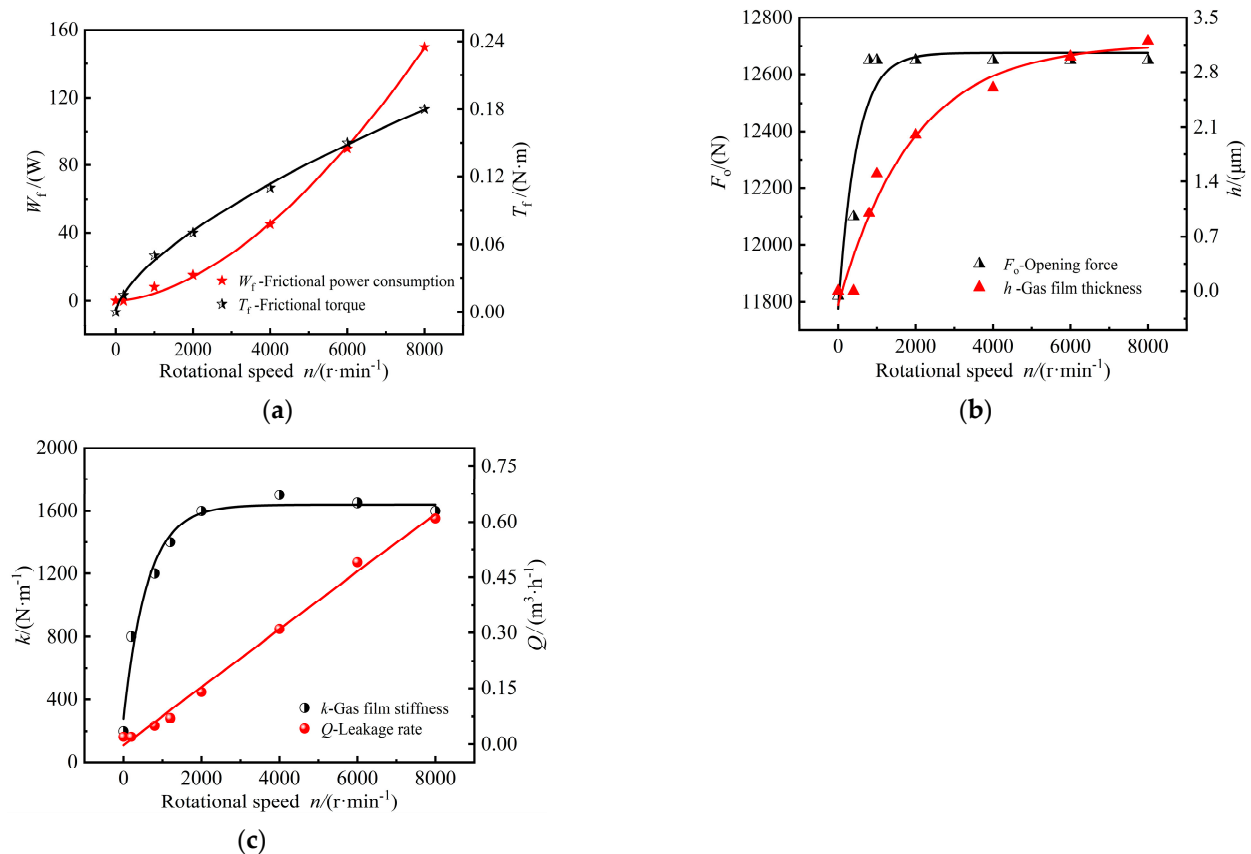


Figure 6. Changes in performance parameters during startup [55]: (a) friction power consumption and frictional torque during starting process; (b) opening force and gas film thickness during starting process; (c) gas film stiffness and leakage rate during start-up.

3.4.2. Effects of Operating Parameters

Frequent friction failures of the dry gas seal end face in practical engineering applications have affected the normal operation of the dry gas seal [56]. Exploring the operating mechanism of the dry gas seal under fluctuating conditions is the basis for the development of efficient sealing technology.

Based on the Navier–Stokes equation, Wang et al. [57] analyzed the characteristics of the flow field under different speeds and inlet pressures and concluded that increasing the positive pressure zone and decreasing the negative pressure zone increased the opening force of the seal end face and the stiffness of the film, thereby improving its stability. Dotsenko et al. [58] experimentally determined the stability parameters of the dry gas seal under different working conditions, which provided a reference for the coordinated optimization of the seal face structure under fluctuating working conditions in the later stage. Hu et al. [59] analyzed the influence of different speeds, pressures, and temperatures on the steady-state performance of the dry gas seal and on the leakage and friction power consumption. Chen et al. [60] obtained the flow–field distribution behavior of the dry gas seal under different operating conditions using the finite difference method and calculated the steady-state performance parameters, such as opening force and leakage rate. Ran studied the effect of operating parameters on the dynamic characteristics of supercritical carbon dioxide dry gas seals. When the frequency ratio is one, the changes in the calculated gas film stiffness coefficient and damping coefficient under different working conditions are shown in Figure 7. Figure 7a,b show that with the increase of rotational speed, the dynamic stiffness coefficient and damping coefficient of the gas film tend to increase, which is caused by the enhancement of the dynamic pressure effect. Figure 7c shows that the gas film stiffness coefficient increases linearly under different pressures and substantially

changes near the critical point. Figure 7d shows that the higher the pressure, the greater the medium viscosity and the increase in the gas film resistance. Figure 7e shows that the gas film stiffness coefficient decreases at different temperatures, while the damping coefficient increases with the increase in temperature in Figure 7f. As the temperature increases, the density of the medium decreases and it is easily compressed, which decreases the stiffness coefficient. Similarly, the medium viscosity increases with temperature, and the damping of the dissipation mechanism increases. The research described here shows that the working condition parameters are some of the main factors that affect the dynamic characteristics. Increasing the inlet pressure and the rotational speed will promote the stable operation of the dry gas seal system. Simultaneously, increasing the inlet temperature reduces the ability of the gas film to resist external disturbances, but the mechanism of stabilizing against external disturbances is improved. With increases of medium pressure and rotational speed, both gas film stiffness and gas film damping increase, and the stability is improved to a certain extent.

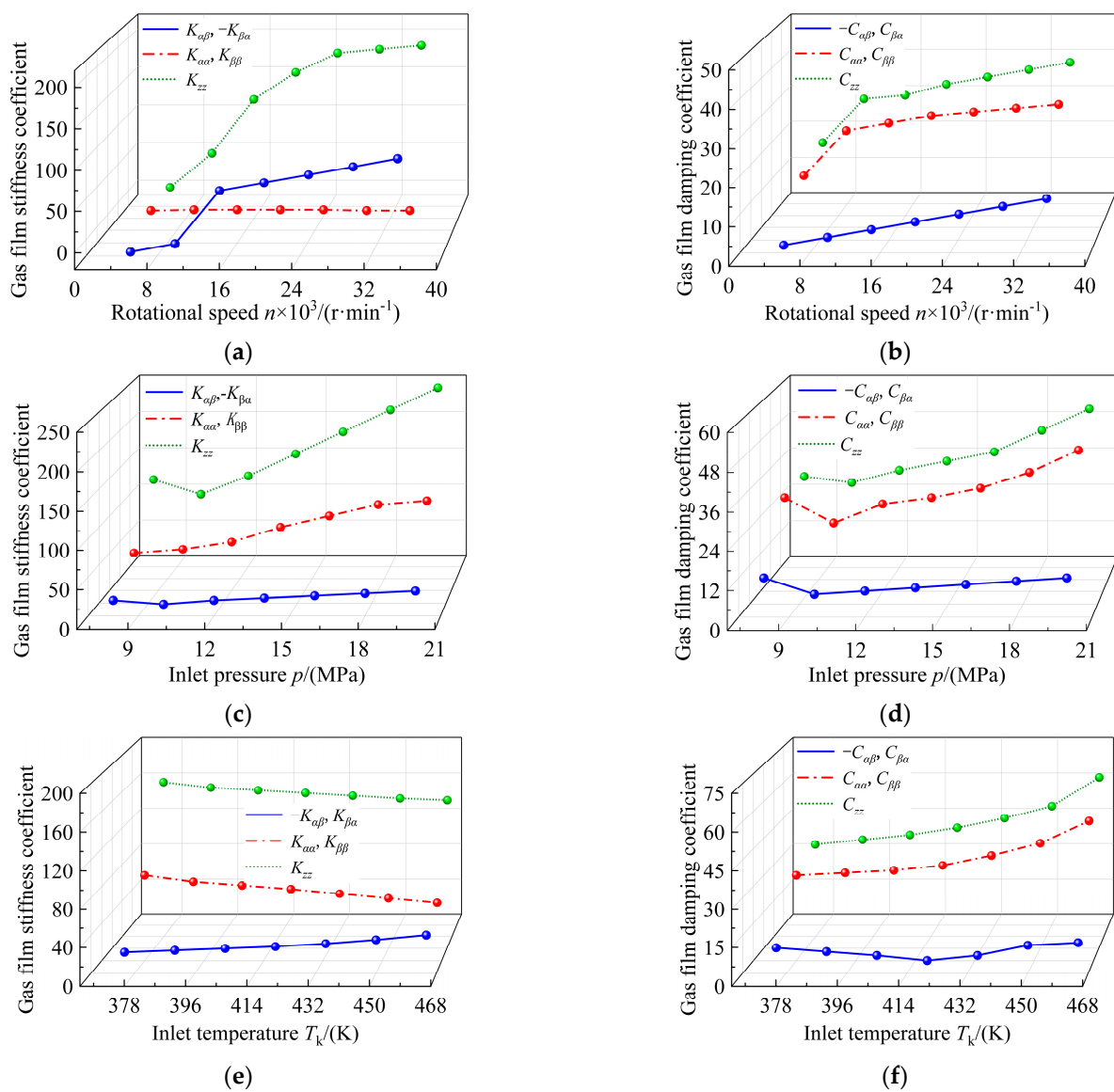


Figure 7. Dynamic characteristic coefficients of the gas film under different working conditions [61]: (a) stiffness coefficients at different speeds; (b) damping coefficients at different speeds; (c) stiffness coefficients at different inlet pressures; (d) damping coefficients at different inlet pressures; (e) stiffness coefficients at different inlet temperatures; (f) damping coefficients at different inlet temperatures.

3.4.3. Influence of the Groove Structure

In the design of dry gas seals, changes in gas film thickness stability are considered. However, in actual production applications, changes in gas film thickness are often ignored to simplify design and reduce costs. In some application scenarios, the stability of the gas film thickness may not be a key issue, so the designer can decide whether to consider the changes of gas film thickness stability according to their actual needs. However, for some key applications, such as high-speed rotating equipment, changes in the stability of the gas film thickness may have a serious impact on the safety and performance of the equipment. It is necessary to seriously consider the stability of the gas film thickness and act appropriately to solve the issue. The dynamic pressure effect of the end surface fluid of the dry gas seal is closely related to the groove parameters. If the groove parameters are not designed properly, the gas pressure is easily destabilized or vibrated, which will affect the operation and service life of the sealing system. To improve the problem of poor stability caused by the weak dynamic pressure effect of dry gas seals in actual operation, scholars optimized the structural parameters of the dry gas seal end face to meet the demand for gas film stiffness [62].

Zirkelback et al. [63] studied the influence of the structural parameters of a spiral-groove dry gas seal on dynamic performance, calculated the optimization range of the structural parameters of the end face, and obtained a method to improve the stability of the dry gas seal system. Based on the narrow groove theory, Li et al. [64] compared and analyzed dry gas seal structures with an inner-ring groove and with a traditional dry gas seal structure and found that under low-speed and high-pressure conditions, the gas film stiffness of the dry gas seal structure with an inner-ring groove increases, and the difference is <5%. Kou et al. [65] obtained the maximum steady-state stiffness coefficient of 1.3 and maximum dynamic stiffness coefficient of 1.4 by improving the stability dynamic analysis of the dry gas seal groove structure. These values can provide references for the optimal design of the dry gas seal structure with low leakage and high stiffness under high-speed working conditions. Yu et al. [66] designed and analyzed the channel structure of the dry gas seal under different working conditions and believed that a reasonably designed channel structure under high pressures and low speeds could improve the rigid-leakage ratio of the dry gas seal and the gas film stiffness of the seal end face. The stability performance parameters of the traditional spiral groove, spiral groove with inner-ring groove, and goose-shaped spiral-groove dry gas seal were compared and analyzed by Huang Li et al. [67]. It was concluded that the goose-shaped spiral-groove dry gas seal exhibits higher stability and superior sealing performance compared to the traditional seal, making it more widely utilized. Zirkelback et al. developed a method to improve stability based on the spiral-groove sealing structure. By comparing and analyzing the dynamic characteristics of the optimized seal structure, Kou et al. found that the stability was improved. In summary, the structural parameters of the end face have considerable influence on the stability of the dry gas seal. Reasonable structural design can improve the sealing stability and reduce the possibility of leakage. Specific structural parameter designs should be coordinated and optimized according to the actual engineering requirements, working conditions, and relevant experimental verifications.

Additionally, the multiple coupling effect significantly influences the dynamic characteristics of dry gas seals. This effect encompasses the mutual influence of temperature, pressure, speed, material characteristics, seal structure, and other factors. These effects directly impact the dynamic response and sealing performance of dry gas seals under combined action. For example, changes in temperature affect the material characteristics of dry gas seals by altering their elastic modulus, thermal expansion, and cold shrinkage, subsequently affecting the dynamic stiffness and damping properties of seals. Variations in pressure result in increased or decreased seal leakage, which affects the dynamic stability of seals. Moreover, higher speeds intensify friction and wear, leading to alterations in the dynamic friction and wear conditions of seals. Therefore, when designing and implementing dry gas seals it is crucial to fully consider these multiple coupling effects

while improving their performance under dynamic conditions through theoretical analysis, simulation studies, and experimental verification.

4. Research Hotspots and Improvement Measures for Dry Gas Seal Stability

4.1. Vibration Response of the Dry Gas Seal System

With the development of rotating machinery for use in extreme conditions, the anti-interference ability of the dry gas sealing device is relatively poor. Most of the existing research is based on steady-state conditions. However, under extreme working conditions, the gas film stability of the sealing end face is easily damaged due to the intensification of shaft vibration. The sealing performance under steady working conditions does not represent the actual situation well. To further improve the reliability of the dry gas sealing device in actual operation, its dynamic behavior is beginning to attract notice. The dry gas seal is commonly believed to exhibit slight fluctuations in end clearance and leakage, maintaining a constant average value with minimal changes over time. Consequently, when these conditions are met, the seal can be considered to be in a stable state [68]. The vibration response of the dry gas seal refers to a vibration phenomenon caused by an external disturbance or internal instability of the sealing system during operation. Specifically, when the dry gas sealing system is affected by an external disturbance or by internal instability factors, some parts of the system will have unstable vibrations, which are manifested in different forms, such as axial vibration and angular swing. Figure 8 shows a kinematic model of the dry gas seal. When the system is in normal operation, the moving ring and the static ring are not in contact, and there is an extremely thin gas film between the sealing pair. The gas film with certain damping and stiffness characteristics is regarded as a damper and spring structure. Under the synergistic action of the spring-damping structure of the dynamic ring, the dynamic ring responds to the angular and axial excitation, and the sealing ring response follows [69,70]. The vibration model of the gas film sealing ring is shown in Figure 8a, and the dynamic analysis model of the gas film is shown in Figure 8b.

- A. According to the axial vibration model of the gas film seal auxiliary system, the axial vibration equation is established:

$$mx'' + C_g x' + (K_s + K_g)x = K_g x_d + C_g x_d' = K_g b \cos \omega t - C_g b \omega \sin \omega t \quad (1)$$

- B. For the two degrees of freedom angular disturbance of the static ring, the motion equation is established as:

$$\begin{cases} J_x \ddot{\alpha}^* + [d^* + d_{se}^*] \dot{\alpha}^* + d^* \beta^* + [k^* + k_{sp}^*] \alpha^* + k^* \beta^* = 0 \\ J_y \ddot{\beta}^* + d^* \dot{\alpha}^* + [d^* + d_{se}^*] \dot{\beta}^* + k^* \alpha^* + [k^* + k_{sp}^*] \alpha^* = 0 \end{cases} \quad (2)$$

- C. The stability conditions of angular oscillation are set as follows. Angular vibration instability condition:

$$J \geq J_{cr} \quad (3)$$

Static ring vibration inertia:

$$J = \frac{1}{4m(r_o^2 - r_i^2)} \quad (4)$$

Angular vibration stability condition:

$$J < J_{cr} \quad (5)$$

- D. Judgment and analysis of angular instability.

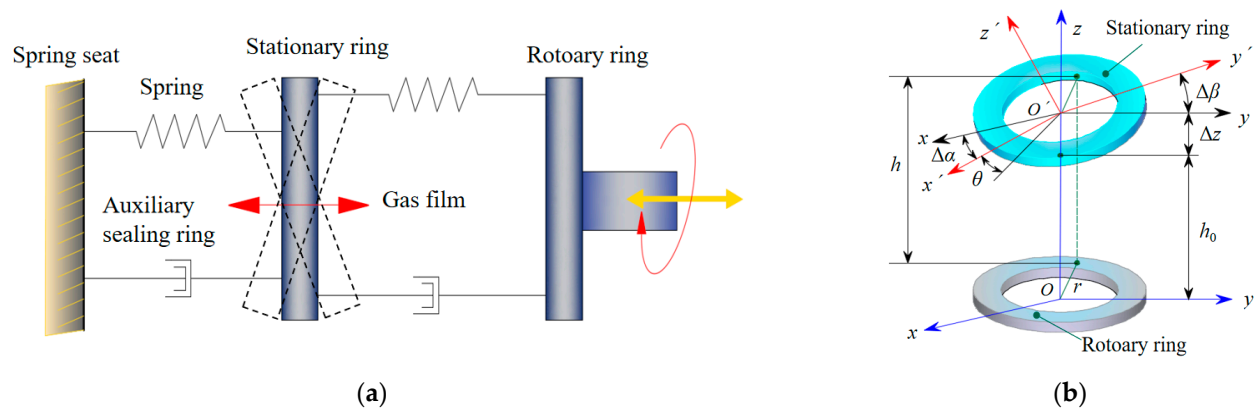


Figure 8. Kinematic model of the dry gas seal: (a) sealing ring vibration model; (b) gas film dynamic analysis model.

The micro-clearance of the dry gas seal is affected by angular swing, which can easily increase the leakage or dry friction of the seal pair. Therefore, it is necessary to ensure the dynamic stability of the gas film between the seal pair. By solving the dynamic motion equation of the gas film and analyzing the relation between the critical moment of inertia (J_{cr}) and the helix angle (β), the instability range of the helix corner can be obtained, and the stability behavior of the angular swing of the sealing pair can be further analyzed. From the angular vibration instability condition (Equation (3)), it is known that the swing inertia of the static ring J is greater than J_{cr} . Because J is small, the instability region is very narrow and only in the point region at $J_{cr} = 0$. Figure 9 shows the relation between J_{cr} and β . β has 16 instability point domains within the range of $60^\circ \sim 80^\circ$, and the specific instability region parameters are shown in Table 2. Figure 10 shows the relations between J_{cr} , β , and slot depth ratio (η). The surficial changes in Figure 10 indicate that β has a major influence on J_{cr} , and the steady-state optimized β has a discontinuous stable region in the range of $60^\circ \sim 80^\circ$ [71].

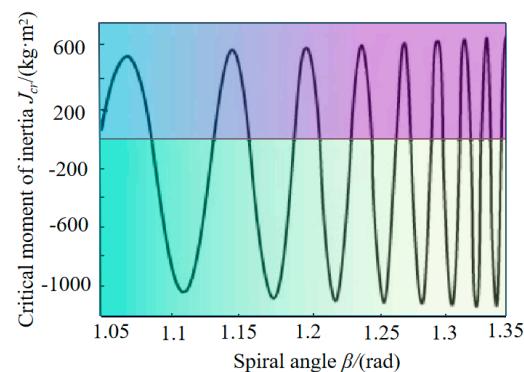


Figure 9. J_{cr} – β relationship diagram.

Table 2. Spiral angle instability point ranges.

Spiral Angle Range		Instability Point Range		
$60^\circ \sim 70^\circ$	$62.47^\circ \sim 62.49^\circ$	$65.51^\circ \sim 65.53^\circ$	$67.28^\circ \sim 67.30^\circ$	$69.34^\circ \sim 69.36^\circ$
	$70.72^\circ \sim 70.74^\circ$	$72.27^\circ \sim 72.29^\circ$	$73.24^\circ \sim 73.26^\circ$	$74.39^\circ \sim 74.41^\circ$
	$75.25^\circ \sim 75.27^\circ$	$76.16^\circ \sim 76.18^\circ$	$76.85^\circ \sim 76.87^\circ$	$77.60^\circ \sim 77.62^\circ$
	$78.05^\circ \sim 78.07^\circ$	$78.69^\circ \sim 78.71^\circ$	$79.14^\circ \sim 79.16^\circ$	$79.60^\circ \sim 79.62^\circ$

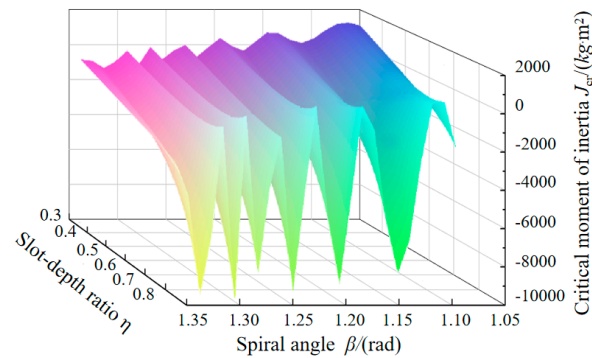


Figure 10. J_{cr} – β – η relationship diagram.

The instability region parameter ranges of the dry gas seal are judged by the angular swing stability condition. Based on the above research, Han et al. [72] analyzed the dynamic stability of the dry gas seal system with the Floquet theory as the criterion for the stability of the angular swing and obtained the influences of the spiral angle range and damping size of the system on the chaotic motion during stable operation. The effect of the axial vibration response on the stability of the dry gas seal was also analyzed. Based on the Laplace transform, Teng et al. [73] obtained the axial vibration and forced vibration displacement responses of dry gas seals under different conditions and analyzed the influence of external factors and dynamic characteristic parameters on the axial vibration. Liu et al. [74] studied the dynamic characteristics of gas film thickness stability in a dry gas sealing system based on numerical calculations. They analyzed the factors affecting the vibration response and stability under different working conditions by establishing axial vibration models of the dynamic and static rings. Ding et al. [75] analyzed the dynamic stability of the dry gas seal based on the nonlinear vibration theory and microscale thermal dissipation deformation and obtained stable operation ranges for the structural parameters of the end face of the seal pair. The bifurcation problem of the system is studied by solving the Floquet index method without external excitation. Zhang et al. [76] analyzed the axial vibration and angular oscillation stability of the dry gas seal system in an impeller rotor system and obtained the influences of gas film stiffness and excitation force on axial vibration and angular oscillation.

Based on the analysis method of dynamic characteristics of dry gas seals in Table 1 and the research described in this section, it is considered that the perturbation method and the Runge–Kutta method have high calculation accuracy and strong reliability and are the first choices for research algorithms to analyze the axial vibration and angular oscillation responses of the dry gas seal system. The effect of the dry gas seal vibration response on the normal operation and service life of rotating equipment is analyzed. When the equipment vibrates, the dry gas seal may leak or generate additional friction, which will affect the service performance of the equipment. In addition, the power consumption or torque of the dry gas seal increases with the rotating speed during operation, and the rotation speed and impact load response also have certain effects on the dynamic characteristics of the dry gas seal. Therefore, the vibration response of the sealing system should be minimized to ensure the normal operation.

4.2. Improving Dynamic Followability and Reducing Film Thickness Disturbances

The thickness disturbance amplitude of the dry gas sealing film reflects the dynamic followability of sealing system. Most scholars calculate the dynamic stiffness coefficient and damping coefficient to determine whether the sealing system is unstable due to self-induced vibration, and then evaluate the dynamic characteristics of the gas film. However, in addition to the influence of the gas film dynamic coefficients on the stability, the flexible installation form of the seal ring and the stiffness or damping characteristics of the elastic element or the auxiliary seal ring greatly affect the dynamic tracking of the seal device.

To further reduce the film thickness disturbance and improve the dynamic stability of the dry gas seal, Blasiak et al. [77] compared and analyzed the dynamic followability of sealing devices with various groove types and learned that operating speed, groove structure, and elastic components would all affect the axial vibration and angular swing responses of the sealing system. Based on the above research, a test device was designed to compensate for the dislocation of the flexible mounting ring and automatically control the height of radial clearance. Hu et al. [78] calculated the dynamic characteristics of the gas film on the end face of the bidirectional dry gas seal, and then analyzed the influence of the gas film thickness on its stability. By improving the dynamic followability, the film thickness disturbance is reduced, and the operating stability is further improved. Green et al. [79] coupled the Reynolds equation and motion equation to study the transient motion behavior of film thickness disturbance and static ring flexible installation. They conducted a structural coordination optimization, and finally obtained a reasonable clearance structure that was conducive to the dynamic followability of the seal ring. Hu et al. [80] analyzed the dynamic performance of dry gas seals under different disturbance conditions and the influence of auxiliary sealing rings. They concluded that the gas film force between the dynamic and static sealing rings indirectly alleviates the interaction between axial vibration and angular oscillation, and effectively weakens the transient vibration caused by disturbance. Shang et al. [81] studied three typical dry gas seal structures under different film thickness disturbances and believed that when the gap film thickness amplitude of the seal pair was severe, the average values of the sealing performance parameters were slightly higher than the steady-state values, and the calculation errors were large. The typical spiral-groove dry gas seal is less affected by nonlinear factors and is in good agreement with the actual changes. Figure 11 shows the transient disturbance distribution of dry gas seal film pressure. Figure 11a–c show the film pressure distribution cloud maps on the seal end face at various times during the rotation period, when the film pressure disturbance $\Delta p(r, \theta)$ is generated at the angular excitation amplitudes of $A_r = 0 \mu\text{rad}$, $A_r = 100 \mu\text{rad}$, and $A_r = 300 \mu\text{rad}$, respectively. The cloud images show that the membrane pressure disturbance is obvious when the excitation amplitude is greater than 0. The main reason for this is that the wedge gap formed between the sealing pairs after the angular excitation affects the dynamic and static pressures. The greater the excitation, the greater the nonuniform membrane pressure disturbance. By comparing the film pressure disturbance $\Delta p(r, \theta)$ at different times with the same amplitude, it is found that the wedge-shaped gap at a certain angle severely disturbs the gas film, and the amplitude is also affected by the axial film thickness disturbance, which indicates that the film pressure of the dry gas seal is affected by the interaction between the wedge-shaped gap and the axial disturbance.

The stability of a dry gas seal is improved by increasing the dynamic stiffness of the dry gas seal system or considering compensation measures to offset disturbance of the film thickness. To solve the problem of frequent failure caused by the insufficient disturbance capacity of the dry gas sealing system under extreme operating conditions, two actions can be taken: (1) coordinate and optimize the structural design parameters. Reasonable structural design and layout result in a small, low-frequency disturbance amplitude, which is conducive to maintaining the stability of the seal end face. (2) Improve dynamic followability and use active control technology, such as a vibration suppression device or adaptive adjustment, to adjust the sealing system in real time. By improving the sealing environment, reducing external excitation interference, or using dynamic balancing technology to balance the rotating parts of the equipment, the problem of film thickness disturbance can be alleviated, and the dynamic stability of the dry gas sealing system can be improved.

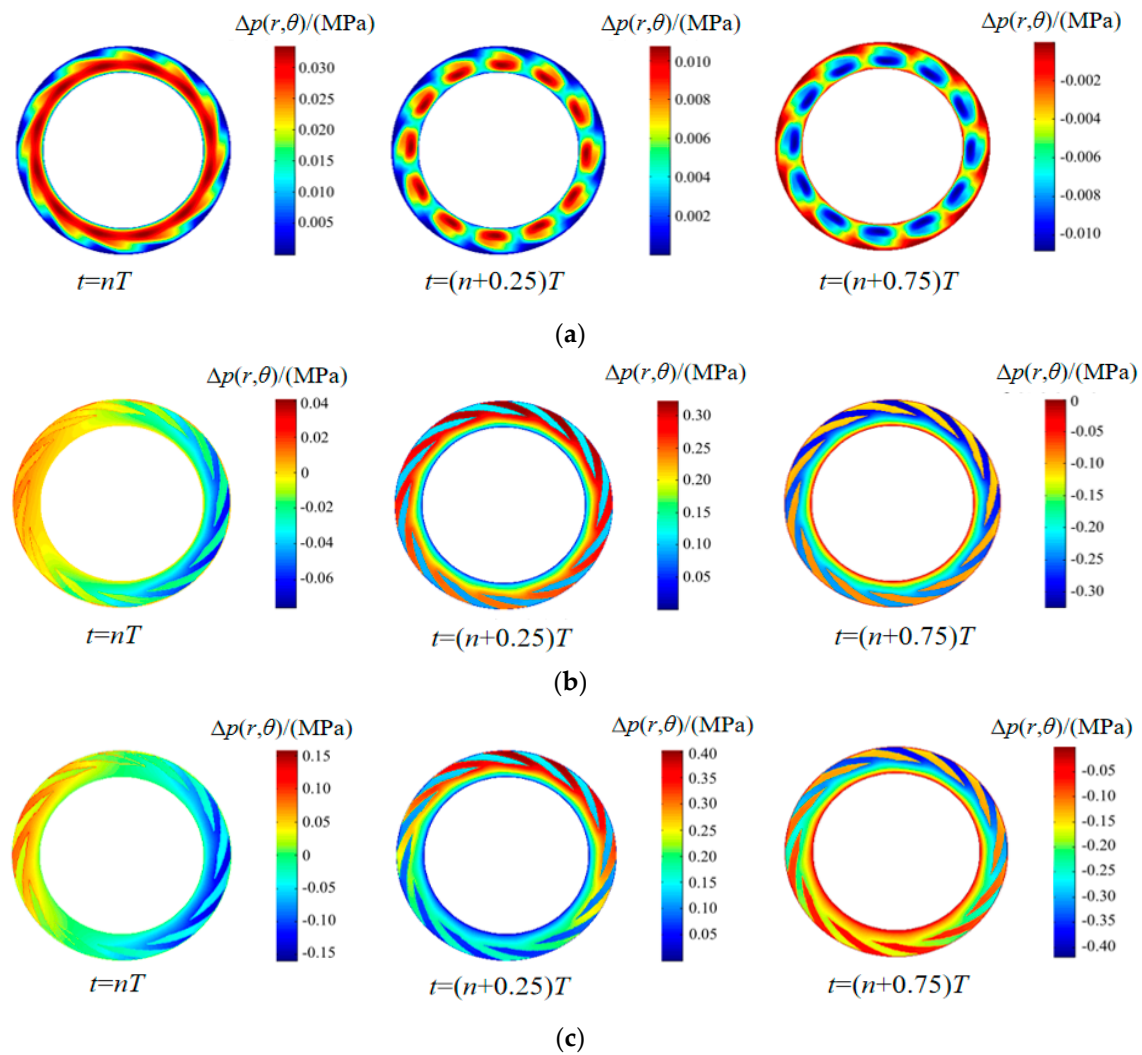


Figure 11. Transient disturbance distribution of membrane pressure [82]: (a) $A_r = 0 \mu\text{rad}$ membrane pressure cloud image; (b) $A_r = 100 \mu\text{rad}$ membrane pressure cloud image; (c) $A_r = 300 \mu\text{rad}$ membrane pressure cloud image.

5. Development Trend

Dry gas sealing technology has a wide range of applications in industrial and manufacturing fields, especially in high-speed rotating equipment and equipment with high sealing requirements. With the progress and innovation of science and technology, additional developments are expected in terms of improving efficiency, expanding applications, increasing reliability, and reducing costs [83–86].

- (1) A remote intelligent control system can be used to monitor and adjust the working status of the sealing system in real time, and regular predictive maintenance can be conducted to describe the stable operating status of the dry gas sealing system in a more timely and accurate manner and improve its operational reliability.
- (2) Exploration can be conducted on the application of new materials and coating technologies to adapt to extreme working environments. The coordinated optimization can be strengthened to further reduce the gap leakage, reduce energy consumption and environmental pollution, and improve the service cycle of the dry gas sealing system. Further study of the advanced sealing technology for stable operation within a wide temperature and pressure range can be conducted.
- (3) There are corrosion and wear challenges in some industrial environments, which can easily lead to the deterioration of the dry gas seal performance. Future development

can focus on more wear-resistant and corrosion-resistant materials to expand the application range of dry gas seals.

- (4) Lubrication plays a key role in sealing performance and friction loss. The use of advanced lubrication technology, such as nanoscale lubricants or frictionless lubrication technology, can effectively reduce energy consumption and leakage.

The research on dry gas seals encompasses various interdisciplinary fields, including dynamic rotating machinery, material science, and fluid dynamics. Future advancements necessitate interdisciplinary collaboration. Advanced digital technology is employed to conduct dynamic optimization methods, while simulation technology and experimental integration are utilized to further enhance research efficiency. Only through continuous expansion of the field and adoption of advanced lubrication technology can we drive progress and enhancement in dry gas seal technology to better cater to industrial demands.

6. Conclusions

The dynamic characteristics and stability of dry gas seals are reviewed and summarized in this work. To ensure the excellent dynamic characteristics of the dry gas sealing system, structural design and performance analyses have been conducted to determine the best structural design parameters by considering the influencing factors under multiple effects. The stability of the dry gas seal is crucial for the reliability and safety of the rotating equipment: if not optimized and controlled, it will easily lead to friction and wear, leakage, and even failure of the seal end face. This review highlights the importance of the stiffness and damping coefficients of the gas film for evaluating dynamic stability, as well as the effectiveness of experimental research in model verification. The research methods for stability models provide a theoretical basis for comprehensively characterizing the non-linear dynamic behavior of dry gas seals. In addition, the effects of starting and stopping characteristics, working parameters, and groove parameters on the flow characteristics of the dry gas seal have been analyzed. Finally, the influence of vibration responses on dynamic stability and reliability is discussed. Although the dry gas sealing system has been studied from the perspectives of the operating mechanism, research methods, dynamic characteristics, vibration response, etc., the following problems remain to be solved in terms of dynamic stability:

- (1) The coupling effect between multiple factors has been ignored, and the sealing performance in the actual environment is comprehensively affected by various factors such as gas dynamics, heat conduction, and fluid mechanics. The current theoretical models tend to treat these factors independently, ignoring the interactions and coupling effects among them, resulting in incomplete descriptions and predictions of dry gas sealing behavior.
- (2) The experimental data are affected by calculation errors, working conditions, and external interference, which can easily lead to inaccuracies. Concurrently, there are differences in experimental methods and complex conditions, resulting in some errors in experimental results.
- (3) The dynamic vibration response relies on numerical simulation and theoretical derivation and lacks unified standard mathematical models and evaluation methods to predict the dynamic behavior and nonlinear effects of dry gas seals, resulting in limitations in research results.
- (4) Application in high-temperature and high-speed environments. Dry gas seals encounter challenges such as thermal expansion, friction, and wear, necessitating the development of high-performance materials that can adapt to complex operating conditions. Additionally, there is a need for environmentally friendly and energy-efficient seal structure designs.
- (5) Vibration and noise control. The presence of vibration and noise issues in high-speed rotary mechanical seal systems has always been apparent. Therefore, research on vibration and noise control is required to enhance equipment stability.

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Nomenclature

A_r	angular excitation amplitude, μrad
c_{xx}, c_{yx}	angular principal dynamic damping and angular cross damping, N·s/rad
c_{zz}	axial dynamic damping, N·s/m
$C_{\alpha\alpha}, C_{\alpha\beta}, C_{\beta\beta}$	dimensionless damping coefficient
F_c, F_o	closing force, opening force, N
h, h_o	transient gas film thickness, equilibrium gas film thickness, μm
J, J_{cr}	static-ring swing inertia, critical moment of inertia, $kg \cdot m^2$
k_{xx}, k_{yx}	angular principal dynamic stiffness and angular cross stiffness, N·m/rad
k_{zz}	axial dynamic stiffness, N/m
$K_{\alpha\alpha}, K_{\alpha\beta}, K_{\beta\beta}$	dimensionless stiffness coefficient
n	rotational speed, r/min
p, p_1, p_2, p_{sp}	inlet pressure, medium pressure, back pressure, and spring pressure, MPa
Q	leakage, m^3/h
r, r_i, r_o	the radius of any point on the moving ring, inner radius, and outer radius, mm
t	time, s
T_f	frictional torque, N·m
T_k	inlet temperature, K
W_f	frictional power consumption, W
x, y, z	x axis, y axis, and z axis
α, β	helix angle and helix angle, rad
η	slot-depth ratio
ω	moving ring angular velocity, rad/s
Δp	film pressure disturbance, MPa
$\Delta\alpha, \Delta\beta, \Delta z$	perturbation displacement in the x, y, z direction

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