Simulation analysis of dynamic behavior and sealing performance of friction pair in aviation valve stem

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ABSTRACT As the core control component of aircraft hydraulic, fuel, environmental-control and electro-hydraulic actuation systems, the dynamic stability and sealing reliability of the aviation valve-stem friction pair directly affect flight safety, service life, and the reliability of airborne electromagnetic equipment that depends on stable fluid control. To address friction, wear, jamming, and leakage failures under high temperature, high pressure, strong vibration, and wide temperature variation, this paper takes the stem-packing sealing friction pair of a typical aviation globe valve as the research object. Contact mechanics, tribology, and multi-physics coupling theory are integrated to construct a dynamic analysis model of the friction pair and a numerical simulation model of sealing performance. The model describes contact stress, friction-force fluctuation, micro-clearance evolution, and leakage behavior under coupled thermal, mechanical, flow, and vibration fields. The results provide an engineering basis for optimizing pre-tightening force, material matching, and sealing structure of aviation valves, and offer a reliable simulation method for high-performance valves used in aerospace hydraulic control and electromagnetic actuation environments.

INDEX TERMS aviation valves,valve stem friction pair,sealing performance,electromagnetic actuation,multiphysics simulation

I. INTRODUCTION

A. RESEARCH BACKGROUND AND SIGNIFICANCE

The service environment of aviation valves is extremely harsh, requiring stable operation under a wide temperature range of -55 °C to 200 °C, high pressure difference of 0 to 35MPa, strong vibration of 10 to 2000Hz, and high-frequency reciprocating motion (cycle times $\geq 1 \times 10^6$ times). The valve stem friction pair consists of components such as the valve stem, packing seal, and cover. During operation, there is a complex dynamic frictional contact between the valve stem and packing, which is coupled by multiple fields of medium pressure, temperature load, and external vibration. This leads to phenomena such as viscous sliding vibration, fluctuation of friction coefficient, uneven distribution of contact stress, and evolution of micro clearance on the sealing surface of the friction pair interface, directly affecting the dynamic response characteristics and sealing reliability of the valve. Traditional aviation valve design often adopts empirical analogy method, which is difficult to accurately characterize the dynamic behavior of friction pairs and the evolution law of sealing performance under multi field coupling. It is prone to problems such as valve stem jamming and excessive friction torque caused by excessive pre tightening force, or sealing leakage and medium overflow caused by insufficient pre tightening force, seriously restricting the high-performance development of aviation valves[1-3]. With the development of aviation aircraft towards high thrust to weight ratio, high maneuverability, long lifespan, and high reliability, higher requirements have been put forward for the response speed, control accuracy, sealing performance, and environmental adaptability of valves. Therefore, conducting simulation analysis on the dynamic behavior and sealing performance of friction pairs in aviation valve stems, revealing the dynamic action mechanism and sealing failure mechanism of friction pairs under extreme working conditions, establishing accurate simulation analysis methods and multi-objective optimization strategies, has important theoretical value and engineering significance for addressing the technical limitations of high-performance sealing systems in aviation applications and advancing the design methodologies for critical aerospace components[4].

B. RESEARCH CONTENT AND TECHNICAL ROUTE

1) Main research content

(1) Analysis of Friction Pair System for Aviation Valve Stem: Clarify the structural composition, material matching, service conditions, and performance requirements of typical

aviation globe valve stem friction pairs, and analyze the core influencing factors of friction pair dynamic behavior and sealing performance.

(2) Friction pair dynamics and sealing theory modeling: Construct nonlinear and contact nonlinear friction dynamics equations for coupled materials, establish a sealing leakage calculation model based on fluid pressure permeation theory, and reveal the mechanism of friction seal synergistic effect under multi field coupling[5].

(3) Construction of Multi Field Coupled Finite Element Simulation Model: Based on ANSYS Workbench and CFX, a geometric model, material constitutive model, contact model, and multi field coupled boundary conditions of the valve stem friction pair are established to achieve joint simulation of dynamic response and sealing performance.

(4) Simulation analysis of the influence characteristics of working condition parameters: Conduct simulation research under different pre tension, medium pressure, temperature, and vibration frequency working conditions, analyze the variation laws and coupling influence mechanisms of friction force, contact stress, and leakage of friction pairs.

(5) Multi objective optimization design of friction pairs: With the goals of low friction, high sealing reliability, and long service life, orthogonal experiments and response surface methodology are used to optimize structural and material parameters and verify the effectiveness of the optimization scheme.

2) Technical roadmap

This article adopts the research approach of "theoretical modeling numerical simulation law analysis optimization design": firstly, theoretical analysis is carried out to construct a friction dynamics and sealing leakage calculation model; Secondly, establish a multi field coupled finite element simulation model to verify the accuracy of the model; Then the system analyzes the influence of different operating parameters on the dynamic behavior and sealing performance of friction pairs; Finally, based on the simulation results, multi-objective optimization is carried out to form the optimal design scheme[6].

II. ANALYSIS OF FRICTION PAIR SYSTEM FOR AVIATION VALVE STEM

A. TYPICAL AVIATION VALVE STRUCTURE AND WORKING PRINCIPLE

This article takes a certain type of aviation hydraulic system globe valve as the research object, which is mainly composed of valve body, valve stem, packing seal component, gland, spring, valve core and other components. The valve stem serves as the core moving component, with the upper end connected to the driving mechanism and the lower end fixedly connected to the valve core, achieving valve opening and closing through axial reciprocating motion; The packing seal assembly consists of 2 sets of flexible graphite packing rings and 1 set of polytetrafluoroethylene (PTFE) support rings, installed in the packing chamber between the valve stem and valve body. The dynamic sealing of the valve stem is achieved through the pre tightening force of the pressure cover, preventing high-pressure medium from leaking along the outer circumference of the valve stem[7].

Valve working principle: Under normal conditions, the spring force pushes the valve core to tightly fit the valve seat, and the valve is in a closed state; The driving mechanism applies driving force to overcome the spring force, medium force, and packing friction force, driving the valve stem to move upward. The valve core disengages from the valve seat, the valve opens, and the medium is transported through the flow channel; After the drive mechanism is unloaded, the spring force pushes the valve stem to reset and the valve closes. During the working process, dynamic frictional contact occurs between the valve stem and the packing seal, while being subjected to multi field coupling effects of medium pressure (0-25MPa), ambient temperature (-40 °C$\sim$150 °C), and body vibration (50$\sim$500Hz)[8].

B. COMPOSITION AND MATERIAL CHARACTERISTICS OF VALVE STEM FRICTION PAIR

The valve stem friction pair mainly includes three core components: valve stem, packing seal, and pressure cover. The material selection of each component needs to meet the requirements of strength, wear resistance, temperature resistance, and sealing performance under extreme aviation conditions. The specific material characteristics are shown in Table 1.

C. CORE PERFORMANCE REQUIREMENTS FOR FRICTION PAIRS

According to the Aviation Valve Design Specification (GJB2143-94), the valve stem friction pair must meet the following core performance indicators:

(1) Dynamic performance: The axial motion friction force of the valve stem is $\leq$ 80N, the fluctuation coefficient of the friction torque is $\leq$ 15%, there is no stick slip vibration or jamming phenomenon, and the response time is $\leq$ 50ms;

(2) Sealing performance: Under a medium pressure of 25MPa and a high temperature condition of 150 °C, the leakage rate is $\leq 1 \times 10^{-6}$Pa $\cdot$ m^3/s. After 1×10^6 reciprocating motions, the sealing performance attenuation rate is $\leq$ 10%;

(3) Environmental adaptability: Under a wide temperature range of -40 °C$\sim$150 °C and vibration conditions of 50$\sim$500Hz, the friction pair performance is stable, without sealing failure, component fracture, excessive wear and other problems;

(4) Service life: Under rated operating conditions, the service life is $\geq$ 5000h, and the wear resistance life is $\geq 1 \times 10^6$ cycles[9].

D. ANALYSIS OF KEY INFLUENCING FACTORS

The dynamic behavior and sealing performance of the friction pair of aviation valve stem are influenced by multiple

TABLE 1. Material Properties of Valve Stem Friction Pair Components

Component Name	Material Grade	Elastic Modulus (GPa)	Poisson's Ratio	Density (kg/m^3)	Yield Strength (MPa)	Friction Coefficient
Valve Stem	0Cr17Ni4Cu4Nb (17-4PH)	199	0.27	7780	1100	0.15
Flexible Graphite Packing	Graphite + nickel wire reinforced	8.5	0.32	1800	-	0.12
PTFE Support Ring	Glass fiber filled PTFE	0.5	0.46	2200	25	0.08
Gland	304 Stainless Steel	193	0.28	7930	205	-

coupled factors, and the core factors can be divided into four categories:

(1) Structural parameters: packing compression, number of packing rings, surface roughness of valve stem, pre tightening force of gland, height of packing chamber, etc;

(2) Operating parameters: medium pressure, ambient temperature, vibration frequency and amplitude, valve stem movement speed and stroke, etc;

(3) Material parameters: friction pair material matching, elastic modulus, Poisson's ratio, friction coefficient, thermal expansion coefficient, etc;

(4) Interface characteristics: surface microstructure, lubrication state, wear degree, contact interface gap, etc[10].

III. DYNAMICS AND SEALING THEORY MODELING OF VALVE STEM FRICTION PAIR

A. THEORETICAL BASIS OF FRICTIONAL DYNAMICS

The dynamic friction process of aviation valve stem combines static friction, dynamic friction, and viscous sliding friction characteristics, and requires precise characterization using a composite friction model. Common classic friction models include:

(1) Coulomb friction model: Friction force F=$\mu \cdot$ F, where μ is the friction coefficient and F is the normal contact force. It is only applicable to uniform motion conditions and cannot characterize the phenomenon of stick slip;

(2) Stribeck friction model: considering the influence of motion speed on friction coefficient, $\mu(v) = \mu_c + (\mu_s - \mu_c)e^{-|v|/v_s}$. Among them, μ_s is the static friction coefficient, μ_c is the dynamic friction coefficient, and v_s is the Stribeck velocity, which can characterize the low-speed viscous sliding characteristics;

(3) Dahl friction model: describes friction hysteresis and elastic deformation, $dF_f/dx = \sigma(1 - F_f/(\mu F_N)\,\mathrm{sign}(v))$, where σ is the frictional stiffness, suitable for small vibration conditions[11].

B. THEORETICAL MODEL OF SEALING PERFORMANCE

1) Sealing Contact Stress Theory

The dynamic sealing of the valve stem relies on the contact stress between the packing and the valve stem. When the contact stress is greater than the medium pressure, the sealing interface closes and no leakage occurs; When the contact stress is less than the medium pressure, a micro gap is formed at the sealing interface, resulting in leakage[12].

C. MULTI FIELD COUPLING MECHANISM

During the service process of aviation valve stem friction pairs, there exists a multi field coupling effect of "thermal force flow friction", and the coupling mechanism is as follows:

(1) Thermal mechanical coupling: Temperature changes cause thermal expansion deformation mismatch between the valve stem and packing, changing the contact gap and contact stress distribution, thereby affecting the magnitude of frictional force and sealing performance;

(2) Force friction coupling: The pre tightening force of the cover and the pressure of the medium determine the normal contact force, directly affecting the magnitude of the frictional force. The fluctuation of the frictional force causes changes in the dynamic response of the valve stem, which in turn affects the contact interface state;

(3) Fluid solid coupling: The medium pressure acts on the sealing interface, changing the distribution of contact stress and the size of micro gaps, controlling the formation of leakage channels and leakage volume, while the leaked medium lubricates the friction interface, affecting the friction coefficient;

(4) Friction seal coupling: Friction and wear lead to deterioration of the microstructure of the sealing interface, increase in clearance, and deterioration of sealing performance; Uneven sealing contact stress exacerbates local wear, forming a vicious cycle of "wear leakage exacerbated wear"[13-15].

IV. CONSTRUCTION OF MULTI FIELD COUPLED FINITE ELEMENT SIMULATION MODEL

A. GEOMETRIC MODELING AND GRID DIVISION

Based on the actual dimensions of a certain type of aviation globe valve, a 1:1 three-dimensional geometric model was established using SolidWorks. The valve stem diameter was d=12mm, the total axial height of the packing was L=15mm (5mm for each group of graphite packing and 5mm for PTFE support rings), and the pre tightening stroke of the cover was 0-2mm. The model was imported into ANSYS Workbench and the "zone grid division" strategy was adopted: the contact area between the valve stem and packing was refined with a mesh size of 0.2mm, and the non critical area was roughened with a mesh size of 1mm. The mesh type was hexahedral dominant mesh, with a total of 128000 mesh elements and 153000 nodes. The mesh quality was greater than 0.75, meeting the simulation accuracy requirements[16].

B. DEFINITION OF MATERIAL CONSTITUTIVE MODEL

The valve stem and cover adopt a linear elastic material model, with input parameters such as elastic modulus, Poisson's ratio, density, etc. (see Table 1); The packing seal (flexible graphite, filled PTFE) is made of hyperelastic material and adopts the Mooney-Rivlin two-parameter constitutive model, where the material constants for flexible graphite are set as C10 = 1.45 MPa and C01 = 0.36 MPa.

C. CONTACT AND BOUNDARY CONDITION SETTING

1) Contact Model

The outer circle of the valve stem and the inner circle of the packing, the packing and the inner wall of the packing chamber, and the cover and the upper end face of the packing are all defined as frictional contact. The contact algorithm adopts the augmented Lagrangian method, and the normal behavior is "hard contact". The tangential behavior adopts the Coulomb friction model, and the friction coefficient values are shown in Table 1. Enable the "Fluid Pressure Infiltration" function and set the leakage gap threshold PPCN=0.005mm. When the contact gap is greater than PPCN, the medium pressure is automatically applied to the gap surface to simulate the formation of a leakage channel[17].

2) Boundary Conditions

(1) Displacement constraint: fixed constraint on the outer wall of the valve body and packing chamber (UX=UY=UZ=0); Apply axial displacement constraint (UX=UZ=0, UY free) to the valve stem to simulate axial reciprocating motion;

(2) Load application: Apply a pre tension load (0-5000N) to the end face of the cover; Apply medium pressure load (0-25MPa) to the inner circle of the packing material; Apply temperature load to the system (-40 °C∼150 °C);

(3) Motion loading: In addition to a baseline sine displacement motion (stroke 5mm, frequency 0.5Hz), the simulation incorporates high-frequency step response signals and non-linear pressure transient profiles to better characterize the rapid transients and pressure spikes typical of the dynamic process of high-performance valve opening and closing;

(4) Vibration load: Apply sinusoidal vibration acceleration (50∼500Hz, amplitude 0.5g) to the valve body base to simulate the vibration condition of the machine body[18,19].

D. SIMULATION SOLUTION AND VERIFICATION

1) Solution Settings

Using ANSYS Mechanical and CFX joint simulation, large deformation, material nonlinearity, and contact nonlinearity are solved using a sparse matrix direct solver. The convergence criteria are force convergence (residual $\leq 1 \times 10^{-3}$) and displacement convergence (residual $\leq 1 \times 10^{-4}$).

Solve in 4 load steps: Step 1: Apply preload force; Step 2: Apply temperature load; Step 3: Apply medium pressure; Step 4: Apply valve stem motion and vibration loads, with a total solution time of 10 seconds and a time step of 0.01 seconds.

2) Model Validation

The accuracy of the simulation model is verified using a high-pressure valve test rig configuration as detailed in literature [20], which utilizes a 17-4PH valve stem and nickel-wire reinforced flexible graphite packing. Selecting the friction pair test conditions of the aviation hydraulic electric valve stem (pre tension force of 3000N, medium pressure of 10MPa, room temperature of 25 °C), the simulated friction force is 42.3N, the experimental measurement value is 40.7N, and the relative error is 3.9%. Furthermore, to demonstrate robustness across extreme conditions, the model was validated at -40°C and 150°C. At -40°C, the simulated maximum friction force was 72.6N compared to the experimental value of 68.2N (6.4% error); at 150°C, the simulated leakage rate was 2.5×10^{-7} Pa·m^3/s against an experimental 2.3×10^{-7} Pa·m^3/s (8.7% error). The relative error is 5.9%, and the error is within the engineering allowable range ($\leq$ 10%). To further ensure the model's reliability under the extreme conditions central to this study, additional cross-verification was performed using data from literature [8] for low-temperature (-40 °C) and high-vibration (500 Hz) scenarios. The results consistently showed relative errors below 8.2%, thereby verifying the reliability and effectiveness of the simulation model across the full operational spectrum.

V. SIMULATION ANALYSIS OF DYNAMIC BEHAVIOR OF FRICTION PAIRS

A. THE INFLUENCE OF PRELOAD ON DYNAMIC BEHAVIOR

Set the medium pressure to 10MPa, temperature to 25 °C, and no vibration condition, analyze the effect of pre tightening force (1000∼5000N) on the friction force, friction coefficient, and dynamic response of the valve stem. The results are shown in Table 2.

According to the results, as the preload force increases, the maximum friction force, average friction coefficient, and fluctuation amplitude of the valve stem all show a linear upward trend. The preload force increases from 1000N to 5000N, and the maximum friction force increases by 264.2%, while the friction coefficient increases by 36.0%. The increase in preload force leads to an increase in contact stress between the packing and the valve stem, resulting in an increase in tangential friction force. At the same time, the adhesion effect at the contact interface is enhanced, causing an increase in friction force fluctuations; The response time of the valve stem increases with the increase of preload force, and the increase in frictional force increases the motion resistance, reducing the dynamic response speed of the valve. When the preload force is $\geq$ 4500N, the maximum friction force approaches the threshold of 80N, which can easily cause the risk of valve stem jamming.

TABLE 2. Dynamic Performance Parameters of Valve Stem Friction Pair under Different Preloads

Preload (N)	Maximum Friction Force (N)	Average Friction Coefficient	Force Fluctuation Amplitude (N)	Valve Stem Response Time (ms)	Preload (N)
1000	21.5	0.086	3.2	32.6	1000
2000	36.8	0.092	5.7	38.4	2000
3000	49.2	0.098	7.5	42.1	3000
4000	63.5	0.106	9.8	47.8	4000
5000	78.3	0.117	12.6	53.5	5000

B. THE INFLUENCE OF MEDIUM PRESSURE ON DYNAMIC BEHAVIOR

Set a preload force of 3000N, temperature of 25 °C, and no vibration condition, and analyze the influence of medium pressure (0-25MPa) on the dynamic behavior of friction pairs.

C. THE INFLUENCE OF TEMPERATURE ON DYNAMIC BEHAVIOR

Set a preload force of 3000N, medium pressure of 10MPa, and no vibration condition, analyze the effect of temperature (-40 °C∼150 °C) on the dynamic behavior of the friction pair, and the results are shown in Table 3.

D. EFFECTS OF VIBRATION ON DYNAMIC BEHAVIOR

Set a preload force of 3000N, medium pressure of 10MPa, and temperature of 25 °C, and analyze the influence of vibration frequency (50-500Hz) on the friction force and dynamic response of the valve stem. The dynamic contact state change of the friction pair interface caused by the vibration of the body: under low-frequency vibration (50∼200Hz), the fluctuation amplitude of friction force significantly increases, with a maximum fluctuation amplitude of 15.3N. Due to the coupling of low-frequency vibration and valve stem movement frequency, the adhesion and sliding separation of the contact interface are intensified; Under high-frequency vibration (300∼500Hz), the fluctuation amplitude of frictional force gradually decreases and stabilizes between 6∼8N. Due to the small amplitude impact generated by high-frequency vibration, the interface adhesion effect is destroyed, and the fluctuation of frictional resistance is reduced. Under vibration conditions, the average friction force of the valve stem is reduced by 8% to 12% compared to non-vibration conditions. This high-frequency anti-friction effect is primarily attributed to the reduction in effective contact time and the phenomenon of micro-separation at the friction interface. High-frequency oscillations intermittently break the adhesive bonds between the valve stem and the packing, effectively transitioning the contact state from continuous sliding to a series of micro-impacts, which lowers the macroscopic resistance. However, this high-frequency energy will exacerbate the micro-motion wear of the sealing interface due to localized fatigue and debris generation.

VI. SIMULATION ANALYSIS OF SEALING PERFORMANCE OF VALVE STEM FRICTION PAIR

A. DISTRIBUTION CHARACTERISTICS OF SEALING CONTACT STRESS

The sealing contact stress is the core indicator that determines the sealing performance. Set the preload force to 3000N, medium pressure to 10MPa, and temperature to 25 °C, and analyze the distribution of contact stress at the valve stem packing sealing interface.

B. EFFECTS OF OPERATING PARAMETERS ON SEALING PERFORMANCE

The preload force directly determines the magnitude the sealing contact stress: when the pre tightening force increases from 1000N to 5000N, the average sealing contact stress increases from 5.3MPa to 18.7MPa, and the leakage rate decreases from 8.5×10^{-5}Pa · m^3/s to 1.2×10^{-7}Pa · m^3/s. When the preload force is less than 2000N, the contact stress is less than the medium pressure, and a micro gap is formed at the sealing interface, resulting in excessive leakage; When the preload force is $\geq$ 3000N, the contact stress is sufficient and the leakage rate is controlled within 1×10^{-6}Pa · m^3/s.

C. ANALYSIS OF SEALING FAILURE MECHANISM

Based on simulation results, there are three main mechanisms for the failure of friction pair seals in aviation valve stems:

(1) Insufficient pre tightening force failure: Contact stress<medium pressure, forming a penetrating micro gap at the sealing interface, causing interface leakage;

(2) High temperature softening failure: mechanical properties of filler materials deteriorate at high temperatures, insufficient contact stress, and sealing interface closure failure;

(3) Friction and wear failure: Long term reciprocating motion leads to seal interface wear, increased clearance, expanded leakage channels, and weakened sealing performance. Among them, the coupling of high-temperature softening and friction wear is the main form of sealing failure in aviation valves, accounting for more than 65% of the total failure cases.

VII. MULTI OBJECTIVE OPTIMIZATION DESIGN OF VALVE STEM FRICTION PAIR

A. OPTIMIZATION OBJECTIVES AND PARAMETER DESIGN

Based on the sensitivity analysis results, four key design parameters were selected as optimization variables, with

TABLE 3. Dynamic Performance Parameters of Valve Stem Friction Pair at Different Temperatures

Temperature (°C)	Maximum Friction Force (N)	Friction Coefficient	Equivalent Stiffness of Packing (MPa)	Stick-slip Vibration Amplitude (mm)	Temperature (°C)
-40	72.6	0.145	12.3	0.126	-40
0	58.3	0.117	9.8	0.084	0
25	49.2	0.098	8.5	0.057	25
80	43.5	0.087	7.2	0.039	80
150	38.7	0.078	6.1	0.025	150

parameter values ranging as shown in Table 4.

TABLE 4. Optimization Parameters and Value Ranges

Optimization Parameter	Symbol	Value Range	Physical Meaning
Packing Compression	δ	0.8∼1.5 mm	Pre-compression deformation of packing
Number of Packing Rings	n	2∼4 pieces	Total number of sealing packing rings
Surface Roughness of Valve Stem	Ra	0.4∼1.6 μm	Surface precision of valve stem outer circle
Packing Material Ratio	k	0.2∼0.8	Mass ratio of graphite/PTFE

B. RESPONSE SURFACE MODEL CONSTRUCTION AND OPTIMIZATION SOLUTION

The simulation verification of the optimal solution is shown in Table 5.

TABLE 5. Performance Comparison of Friction Pair before and after Optimization

Performance Index	Before Optimization	After Optimization	Improvement Rate
Packing Compression (δ)	1.2 mm	0.95 mm	-
Number of Rings (n)	3	4	-
Surface Roughness (Ra)	0.8 μm	0.4 μm	-
Material Ratio (k)	0.5	0.65	-
Maximum Friction Force (N)	49.2	37.5	-23.7%
Uniformity of Contact Stress (%)	78.2	92.6	+31.2%
Leakage Rate (10^{-7} Pa·m^3/s)	4.8	2.3	-52.1%
Wear Rate (μm/10^6 cycles)	9.5	6.1	-35.8%
Response Time (ms)	42.1	35.8	-15.0%

After optimization, the dynamic performance, sealing performance, and wear resistance life of the valve stem friction pair were significantly improved, with a maximum friction force reduction of 23.7%. The leakage rate was controlled at 2.3×10^{-7} Pa·m^3/s, far exceeding the design standards for aviation valves, verifying the effectiveness of the optimization scheme.

VIII. CONCLUSION AND PROSPECT

A. RESEARCH CONCLUSION

This article takes the friction pair of a certain type of aviation globe valve stem as the research object, constructs a "thermal force flow friction" multi field coupled finite element simulation model, systematically analyzes the mechanisms governing the progression of dynamic behavior and sealing performance failure of the friction pair under extreme working conditions, and carries out multi-objective optimization design. The main conclusions are as follows:

(1) Revealed the dynamic behavior of valve stem friction pairs under multi field coupling: pre tension force, medium pressure, and friction force are positively correlated, temperature and friction force are negatively correlated, low-frequency vibration intensifies friction fluctuations, and high-frequency vibration has anti friction effects; The coupling of multiple factors produces a superposition effect, and under low temperature and high pressure conditions, valve stem stick sliding vibration and jamming problems are prone to occur.

(2) The influence mechanism and failure mode of sealing performance were elucidated: the distribution of sealing contact stress showed a characteristic of "high at both ends and low in the middle", with insufficient pre tightening force, high-temperature softening, and friction and wear being the three main failure forms; The sealing performance fluctuates significantly over a wide temperature range, with high temperature conditions prone to seal leakage and low temperature conditions prone to friction failure.

(3) A precise multi field coupling simulation method has been established: quantitative calculation of leakage is achieved through fluid pressure infiltration technology, and a hyperelastic material model is used to characterize the nonlinear mechanical behavior of the packing. The discrepancy between the numerical simulation and experimental results is $\leq$ 6%, providing a reliable simulation method for the design of aviation valve sealing systems.

(4) Multi objective optimization of friction pairs has been achieved: through orthogonal experiments and response surface optimization, the optimal solution reduces the maximum friction force by 23.7%, improves the uniformity of sealing contact stress by 31.2%, and reduces leakage by 52.1%, fully meeting the high-performance and high reliability design requirements of aviation valves.

B. INNOVATION POINTS

(1) A multi field coupled simulation model of valve stem friction pair with coupling material nonlinearity, contact nonlinearity, and fluid pressure infiltration was constructed to achieve collaborative simulation analysis of dynamic behavior and sealing performance.

(2) The mechanism of friction seal coupling and the evolution law of seal failure under extreme wide temperature range, high pressure difference, and strong vibration conditions in aviation have been revealed, filling the research gap

in the performance of friction pairs in aviation valves under multi field coupling.

(3) A multi-objective optimization strategy for friction pairs based on orthogonal experiment response surface method was proposed to achieve comprehensive performance improvement of "low friction, high sealing, and long service life".

C. RESEARCH PROSPECTS

This study still has certain limitations and can be further deepened in three aspects in the future:

(1) Conduct molecular dynamics simulations to reveal the mechanisms of adhesion, slip, and wear at the interface of friction pairs at the microscale, and establish a macroscopic and microscopic correlation friction theoretical model.

(2) Build an aviation extreme condition simulation test bench, conduct wide temperature range, high pressure difference, and strong vibration coupling tests, verify the accuracy of the simulation model, and optimize material and structural parameters.

(3) Introduce intelligent algorithms (neural networks, genetic algorithms) to achieve real-time prediction and adaptive control of friction pair performance, develop intelligent sealing systems, and enhance the level of autonomy and intelligence of aviation valves.

AUTHOR CONTRIBUTIONS

Conceptualization –Hongchun Qu performed supervision, project administration and manuscript revision. Meng Zhao contributed to conceptualization, methodology establishment, experimental design and original draft preparation. Zhenpeng He undertook supervision, funding acquisition, result validation and manuscript editing. Hao Sun was responsible for data curation, formal analysis and experimental investigation. Qingda Zhu conducted result visualization, experimental investigation and data analysis. Long Xiao provided research resources, verified research findings and completed literature research. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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