A comprehensive multi-objective, multi-parameter and multi-condition optimization of a spiral groove in dry gas seals

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Abstract
Dry gas seals are widely used in rotating equipment for fluid leakage control and operating efficiency enhancement, while the geometric parameters of the spiral groove affect its sealing performance significantly. Groove width ratio $\delta$, groove length ratio $\alpha$, and spiral angle $\beta$ are the selected optimization geometric parameters for different objectives, including opening force $F_o$, film stiffness $k_z$, and stiffness–leakage ratio $\Gamma$. The genetic algorithm and loop iteration optimization method are used to solve the multi-dimensional optimization problems under different working conditions, which are reflected in a new dimensionless number $\lambda$ in the range 1 to 1000. Moreover, a concept of optimum spectrum is developed to obtain the global optimal geometric parameters. The performance comparison of two dry gas seals with different geometric parameters is conducted experimentally to verify the effectiveness of numerical results. Results show that both genetic algorithm and loop iteration optimization method can provide optimal geometric parameters for better sealing performance than single factor optimization, and the global optimal results were significantly influenced by working conditions and objectives. The multi-dimensional optimization methods and results presented in this paper provide a theoretical and experimental reference for designing dry gas seals in different working conditions to meet various sealing performance requirements.

Keywords Dry gas seal · Geometric parameters · Multi-dimensional optimization · Genetic algorithm

1 Introduction

In terms of less friction and wear, lower power consumption, lower leakage, and longer service life, non-contacting dry gas seals (DGSs) are extensively used in high and middle speed rotating equipment, among others in centrifugal compressors [1], turbochargers, and expanders [2], replacing the traditional oil film mechanical seals and labyrinth seals. There are a growing number of applications of spiral groove DGS for its extremely strong hydrodynamic effect and uniform pressure distribution generated by its asymmetric groove pattern [3]. The search for lower leakage rate, larger load-carrying capacity (LCC), and higher film stability through proper design of structural shape and geometric parameters of surface groove has been the main motivation for the development of new techniques of DGSs.

The introduction of different shapes and structures of surface grooves onto the mating seal plates has been performed to enhance film stability and LCC of DGSs and gas bearings. It is common to optimize one parameter for a specific sealing performance while keeping other parameters and conditions constant. Jiang [4, 5] proposed a series of typical types of bionic grooves based on bird wings, the influence of geometric parameters of bionic grooves on film stiffness was studied, and then optimal values of the main geometric parameters were obtained. Subsequently, several universal geometrical models to characterize different surface textures were proposed [6, 7], and the optimal geometric parameters for the maximum film stiffness and low leakage rate were obtained. Liu [8] presented the optimization design of the geometries under the assumption of fixed film thickness or fixed closing force to achieve maximum film stiffness. Zhao [9] discussed the relation between LCC and surface groove texture parameters and pointed out that there is a strong interaction between groove depth and groove width.
Feldman [10, 11] proposed two trade-off sealing performances, $E$ as the ratio of average pressure difference to leakage rate and $E_1$ as the ratio of film stiffness to leakage rate, to come up with an optimum design that minimized the risk from face contact but also provided good sealing properties. However, the single factor optimization method adopted in these studies ignores the interaction between the given geometric parameter and the other parameters. The optimum performance obtained is always the local optimal values rather than the global ones.

Naturally, the interaction of different geometric parameters drives the employment of multi-parameter optimization methods. Hashimoto [12] presented an entirely new optimum design methodology, in which the groove shape is determined by combinations of micro-segment spline functions. By optimizing the geometric parameters of each micro-segment, the optimized bearing presented more superior film stiffness and LCC than spiral groove bearing. Shen [13] divided the texture geometry into several imaginary lines with undetermined lengths and corresponding center locations, and the optimum textures for LCC are found always have chevron shapes with flat fronts. Scaraggi [14] developed an efficient multigrid optimization procedure based on the sequential genetic and conjugate gradient optimization, allowing to determine optimal solutions based on a two-scale hierarchy of structures, and the existence of particularly effective optimal geometries is presented and discussed. Based on the full factorial design, Peng [15] performed a geometric optimization of spiral groove DGS at low and medium pressure, which took the interaction effect of multiple geometric parameters on sealing performance into consideration. Response surface methodology (RSM) explores the relationships between several explanatory variables and one or more response variables, which is always used to study the influence of multiple geometric parameters on performance [16]. Utilizing the RSM, Jin [17] established the second-order relational model among the equilibrium film thickness, stiffness–leakage ratio, and their main hydrostatic geometric parameters of a regulatable DGS, and the optimal values of hydrostatic structures were obtained. RSM was also employed by Hirayama [18] to present the influence of two geometric parameters of surface groove changed together on the run-out characteristics of journal bearings. Based on particle swarm intelligence algorithm, a multi-dimensional optimization of groove geometries in gas film seal was presented [19], indicating that the effect of each geometry dimension on steady performance of cylindrical gas film seal was not independent, and the multi-dimensional optimization method effectively improved the seal performance compared to single factor optimization. However, the main objectives in DGSs are still to provide a minimal leakage rate to prevent environmental pollution, maximum film stiffness to keep film stable when subjected to disturbances, or enough opening force to balance closing force for forming an appropriate sealing gap during operation.

In general, it is more practical to make a trade-off of multiple objective functions rather than to maximize a single one. Several superior algorithms, such as the artificial bee colony algorithm [20] and genetic algorithm [21], are for multi-objective optimization and a high probability of achieving the global optimum in a complex problem. In the optimal design of gas thrust bearings, Hashimoto [22] introduced the ratio of dynamic stiffness $K$ and friction torque $T_f$, as the trade-off objective functions for optimization. To prevent premature convergence in the early stage of evolution for multi-objective optimization, the Pareto optimality was used by Wang [23] as an effective criterion in offspring selections. Optimum configuration of bearings ensures the best load and stability are obtained by using the GA method for multi-objective function [24]. A new multi-objective algorithm based on particle swarm optimization (PSO) and Pareto methods that could greatly reduce the number of the objective function was introduced by Chan [25] to improve the multi-objective optimization design of hybrid journal bearings.

Despite the numerous researches focused on multi-objective and multi-parameter optimization of surface structures of thrust bearings and mechanical seals, there are few studies concentrated on the global optimal geometric parameters of surface grooves of dry gas seals by taking into account working condition, objective functions, and several geometric parameters simultaneously. Hence, the optimal geometric parameters are always the local ones, not global ones. The main purpose of this paper is to optimize the geometric parameters of the spiral groove by taking into account the comprehensive effect of multiple factors, including objective functions, working conditions, and the other geometric parameters for maximum steady performance. The global optimal values of key geometric parameters of a spiral groove, including groove width ratio, groove length ratio, and spiral angle, are obtained under various working conditions. The newly proposed optimization method can be used for the multi-parameter and multi-objective optimal design of groove geometry in both gas-lubricated and liquid-lubricated mechanical seals and thrust bearings.

2 Numerical models of dry gas seals

2.1 Geometrical model

Dry gas seal with a logarithmic spiral groove, the most widely used DGS patterns in rotating equipment, as shown in Fig. 1 is selected as the typical example investigated in this paper. To illustrate the basic geometric configuration of the spiral groove DGS, Fig. 2 shows schematics drawings
of the seal plate. The grooved region adjacent to the outer radius extends from \( r_g \) to \( r_o \), while leaving the other regions adjacent to the inner radius \( r_i \) ungrooved. The film thickness at the sealing dam and groove depth is expressed by \( h_0 \) and \( h_g \), respectively. The main dimensionless geometric parameters affecting the steady performance are spiral angle \( \beta \), groove length ratio \( \alpha \) representing the length ratio of the grooved area that extends from \( r_g \) to \( r_o \) to the whole width of seal face in the radial extent, groove width ratio \( \delta \) representing the width ratio of groove area in the circumferential direction with an angle of \( \theta_g \) to the whole angle of one period \( (\theta_g + \theta_l) \), and the dimensionless groove depth ratio \( H_g \) (\( H_g = h_g/h_0 \)).

### 2.2 Mathematical model

The sealed gas is assumed to be compressible and viscous with constant viscosity. The pressure distribution over a single period of grooves for Newtonian gas in laminar flow is obtained from the following two-dimensional, steady-state dimensionless Reynolds equation:

\[
\frac{1}{R^2} \frac{\partial}{\partial \theta} \left( PH^3 \frac{\partial P}{\partial \theta} \right) + \frac{1}{R} \frac{\partial}{\partial R} \left( RPH^3 \frac{\partial P}{\partial R} \right) = \Lambda \frac{\partial}{\partial \theta} (PH) \tag{1}
\]

where the dimensionless parameters can be expressed as:

\[
R = \frac{r}{r_i}, \quad H = \frac{h}{h_0}, \quad P = \frac{p}{p_i}, \quad \Lambda = \frac{6 \mu \omega r_i^2}{(p_i h_0^2)} \tag{2}
\]

where \( p \) and \( h \) describe the local pressure and film thickness over the whole seal face, respectively. \( p_i \) is the inner pressure, \( \Lambda \) is the compressibility number, \( \mu \) is the gas viscosity, and \( \omega \) is the angular speed.

The pressure boundary condition in the radial direction for Eq. (1) is:

\[
P = \begin{cases} 
1 & r = r_i \\
\frac{p_o}{p_i} & r = r_o 
\end{cases} \tag{3}
\]

The periodic pressure boundary condition in the circumferential direction is:

\[
P(\theta + 2\pi/N_g, R) = P(\theta, R) \tag{4}
\]

where \( N_g \) represents groove number, \( p_o \) is the outer pressure.

Once Eq. (1) is solved by using the finite difference method (FDM) based on the given film thickness and boundary conditions, the pressure distribution is determined. The steady-state analytical solution for the dimensionless opening force is computed by integrating film pressure. The opening force \( F_0 \) can be expressed as:

\[
F_o = p_i r_i^2 \overline{F}_o \tag{5}
\]

where \( \overline{F}_o \) is the dimensionless opening force, and its expression is as follows:

\[
\overline{F}_o = N_g \int_0^{2\pi/N_g} \int_1^{R_o} P R dR d\theta \tag{6}
\]

The film stiffness \( k_z \) is the derivative of the opening force \( F_o \) for the film thickness \( h \), representing the resistant ability when subjected to disturbances, which can be expressed as:

\[
k_z = \left. \frac{\partial F_o}{\partial h} \right|_{h=h_0} \tag{7}
\]

According to the steady flow continuity principle, the leakage rate should not vary with radius, and its expression is as follows:

\[
q_r = \frac{h^3 r}{12 \mu p_i} \int_0^{2\pi} \frac{\partial p}{\partial r} p d\theta \tag{8}
\]

The stiffness–leakage ratio \( \Gamma \) is defined as the ratio of film stiffness \( k_z \) to leakage rate \( q_r \) in the following:
\[ \Gamma = \frac{k_r}{q_r} \]  

(9)

### 3 Optimization method

Figure 3 shows a schematic drawing of the S-DGS and the influencing factors should be taken into consideration in the optimal design of geometric parameters of surface grooves. The steady performance of the S-DGS is affected by working and geometric parameters of spiral grooves during operation. Working parameters consist of film thickness, working conditions (such as medium pressure, rotating speed, and medium temperature), and fluid property parameters (such as gas viscosity and density). The geometrical parameters for a typical spiral groove consist of groove length ratio, groove width ratio, groove depth ratio, spiral angle, and groove number.

Enhancing the opening force to separate the two sealing rings during start-up, maximizing film stiffness to improve the resistant ability when subjected to external disturbances, maintaining a low leakage rate to avoid excessive leakage, and making a good trade-off between film stability and sealing performance are the several objectives should be concerned in the design of DGSs. The optimal values of geometric parameters of surface grooves differ from one another in terms of different objective functions, including opening force, film stiffness, and stiffness–leakage ratio. Moreover, the optimal values of geometric parameters obtained in the single factor optimization are always local ones rather than global ones, for the reason of interaction among different geometric parameters. Moreover, it's more acceptable in the optimal design to make two or three steady-state performances reach a relatively large value simultaneously rather than to maximize a single objective function.

The optimal value of a geometric parameter of surface groove obtained by a single factor optimization method is only applicable to the given working parameter and objective function under the fixed geometric parameters. It is an effective way to obtain universal optimal values of geometric parameters by multi-parameter and multi-objective optimization of a spiral groove under different working conditions, that is, taking the interaction of other geometric parameters on a given geometric parameter into consideration, making a trade-off among different objective functions, and introducing a comprehensive parameter to characterize the working parameters synthetically.

#### 3.1 Optimization method with considering multi-working conditions

The working parameters, including medium pressure and temperature, rotating speed, film thickness, and physical properties of sealing gas, have a modest effect on the optimal values of geometric parameters of surface grooves. However, it's impractical to provide all of the optimal values of geometric parameters under each working condition point. It's essential to define a new feature parameter to characterize the working conditions synthetically. As is known, the larger

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Fig. 3 Influencing factors in a given geometric parameter optimization

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value of compressibility number $\Lambda$ [26] means the stronger hydrodynamic effect, while the higher sealing pressure $P_o$ means the stronger hydrostatic effect. Both the increases of compressibility number and decreases of sealing pressure tend to result in increases in the ratio of hydrodynamic load support. Compressibility number to pressure ratio $\lambda$ is defined as the ratio of compressibility number to dimensionless medium pressure:

$$\lambda = \frac{\Lambda}{P_o} = \frac{6\mu \omega r_i^2}{P_o p_i h_0^2}$$

(10)

3.2 Optimization method with considering multiple objective functions

No doubt that it’s not the best optimization strategy to maximize a single-sealing performance at the expense of a substantial reduction of other sealing performance. However, all of the objective functions reduce with a small amplitude compared to the corresponding optimal values obtained by geometric parameter optimization are much more fit the engineering reality. It seems more practical to obtain the preferred values of geometric parameters by a trade-off of multiple objective functions rather than to obtain a certain optimal value of the geometric parameter in terms of a certain objective function.

As is known to all, the high-efficiency operation range of the centrifugal pump can be widened significantly at the expense of a slight reduction in working efficiency with less than 5% to 10% by changing the rotating speed or cutting impeller of pumps, which can be charted to form a type spectrum. Enlightened by this, the preferred values of geometric parameters of surface grooves can be widened at the expense of a small reduction in sealing performance, which can be charted to a type spectrum of preferred values of groove geometric parameters.

Figure 4 shows schematic drawings of a spectrum of a surface groove for the dry gas seal. Region I and region II represent the sealing performance $P$ and compressibility number to pressure ratio $\lambda$ as a function of the geometric parameter of surface grooves $S$, respectively. $S_B$ represents the optimal value of geometric parameters for maximum sealing performance $P_{\text{max}}$ at a given $\lambda_1$, which can be connected to curve 2 (dashed line) under different values of $\lambda$. Curve 1 and curve 3 (solid lines) represent the equal performance curves of maximum preferred geometric parameter $S_{\text{max}}$ and minimum preferred geometric parameters $S_{\text{min}}$ for acceptable decreasing amplitude $\Delta P$, respectively. The shadow region between curve 1 and curve 3 is the preferred values of geometric parameters by selecting sealing performance $P$ as the objective function under different values of $\lambda$.

The upper and lower boundary values of geometric parameters $S$ corresponding to the sealing performance of $(P_{\text{max}} - \Delta P)$ can be expressed as:

$$SC = SB + \Delta S_u, \quad SA = SB + \Delta S_l$$

(11)

where $\Delta S_u$ and $\Delta S_l$ are the upper and lower offsets of optimal values of geometric parameters, respectively.

3.3 Optimization with considering the interaction of multi geometric parameters

Many geometric parameters can be used to describe the geometric features of a spiral groove, while a big limitation exists in the single factor optimization. It is noticeable that the analytic solution of the relationship between sealing performance and geometric parameters of surface groove always does not exist, especially for the DGSs with complex surface structure, which makes it hard to get the global optimal value of sealing performance. To obtain the global optimal value of sealing performance $P$ under given working conditions, two multi-parameter optimization methods, including loop iteration optimization and genetic algorithm optimization, are employed in this paper.

Figure 5 presents the flow chart of the loop iteration method and the genetic algorithm method employed in solving multi-parameter optimization problems. In terms of loop iteration optimization method as shown in Fig. 5a, based on the given operation parameters and objective function, the golden section method is adopted to obtain the local or global
optimal value of given geometric parameters when keeping the other geometric parameters constant, and the new calculated optimal values will cover the old ones in the loop iteration procedure. The golden section method, inspired by the bisection method, adopts a new constant reduction factor to determine the search interval in each step. For $x_1$ and $x_2$ somewhere in $[a, b]$, when $f(x_1) < f(x_2)$, then search internal $[a, b]$ transfers into $[a, x_2]$, where $x_2 = 0.382*a + 0.618*b$, and when $f(x_1) > f(x_2)$, then search internal $[a, b]$ transfers into $[x_1, b]$, where $x_1 = 0.618*a + 0.382*b$. The procedure would not stop until the iterative number $k$ equals the given required iterative number $k_{re}$. In terms of the genetic algorithm optimization method as shown in Fig. 5b, based on the given operation parameters and objective function, the evolution starts from a population of randomly generated individuals, and it is an iterative process, with the population in each iteration called a generation. In each generation, the fitness, the value of the objective function of every individual in the population, is evaluated. The more individuals are randomly selected from the current population, and a new generation is formed by the selection, crossover and mutation operation. The procedure would not stop until a maximum number of generations has been produced.

4 Results discussion and analysis

To obtain the preferred values of geometric parameters of spiral groove under various working conditions, the globally optimal values of groove width ratio $\delta$, groove length ratio $\alpha$, and spiral angle $\beta$ are obtained numerically for the maximum film stiffness and opening force under different values of $\lambda$ with a combination of sealing pressure, average velocity, and film thickness. The medium pressure ranges from...
0.2 to 1.5 MPa. Considering that the thermal–mechanical deformation of the sealing ring is small under the condition of low pressure and low temperature, the thermal–mechanical deformation of the sealing ring can be ignored [27]. The average linear velocity of sealing face ranges from 2.5 to 140 m/s and covers the low, medium and high-speed conditions of DGSs. The film thickness ranges from 2 μm to 5 μm, which is the typical sealing gap of DGSs [28]. The corresponding λ ranges from 1 to 10³ and covers the working conditions of most current centrifugal compressors, centrifugal pumps, and agitators employed in the oil, petrochemical, and general process industries. Table 1 presents the initial geometric parameters of the spiral groove and sealing ring adopted in the optimization design, and the sealing medium is nitrogen, the viscosity of which is 0.0178 mPa.s, and the sealing gas temperature is 293 K. In the optimization, both groove width ratio δ and groove length ratio range α from 0.05 to 0.95, and the spiral angle β ranges from 5° to 45°.

4.1 Dependence of optimal groove geometric parameters

The optimal value for a given geometric parameter of the spiral groove is strongly dependent upon working conditions, objective function and other geometric parameters. Figure 6 presents the contour map of the sealing performance (opening force $F_o$ and film stiffness $k_z$) under different groove length ratio, groove width ratio, and linear velocity. It is obviously that the sealing performance at different geometric parameters and working conditions differ from each other. Thus, the maximum opening force $F_{o\text{max}}$ and maximum film stiffness $k_{z\text{max}}$ can be obtained at different locations on the contour map. Both the optimal groove length ratio $α_{\text{opt}}$ and optimal groove width ratio $δ_{\text{opt}}$ for maximum sealing performance decrease with the increase of the velocity. This means that the optimal geometric parameters obtained by single factor optimization, which only considering the variation

| Items                   | Symbols and units | Values   |
|-------------------------|-------------------|----------|
| Outer radius            | $r/o$ mm          | 77.78    |
| Groove number           | $N_g$             | 12       |
| Groove width ratio      | $δ$               | 0.5      |
| Spiral angle            | $β/°$             | 15       |
| Inner radius            | $r/i$ mm          | 58.42    |
| Groove length ratio     | $α$               | 0.6      |
| Groove depth ratio      | $H_g$             | 2.0      |

![Fig. 6](image) The effect of the objective function and working parameters on optimal geometric parameters
of a single geometric parameter while maintaining all other parameters unchanged, could not fit for other cases when the other parameters changed. The global optimal values for a given geometric parameter remain consideration of working condition, objective function and other geometric parameters.

4.2 Parameter selection in the multi-parameter optimization method

The generation number $G$ in the genetic algorithm optimization method and iterative number $k$ in the loop iteration optimization method have significant effects on the steady performance of spiral groove DGS. It is obvious that the larger values of generation number and iterative number make the optimal geometric parameters closer to global optimal values, and the larger steady performance could be obtained. Figure 7 presents the effect of the optimization parameter on film stiffness and stiffness–leakage ratio when $v = 140$ m/s, $p_o = 0.2$ MPa, and $h_0 = 2$ μm. In genetic algorithm optimization when the population size is 100, film stiffness and stiffness–leakage ratio increase rapidly as generation number increases when $G < 40$ and $G < 75$, respectively. The generation number has little effect on steady performance at a large value of $G$. The generation number can be selected as 100 by taking both optimization results and computing time into consideration. In loop iteration optimization, film stiffness and stiffness–leakage ratio increase rapidly as the iterative number increases when $k < 3$. The maximum film stiffness and stiffness–leakage ratio obtained in the third iteration are up to 13% and 41% compared to that obtained in the first iteration. Although the iterative number has little effect on steady performance when $k > 3$, the required iterative number $k_e$ is selected as 5 for a better consideration of optimization results and computing time.

4.3 The influence of multi-parameter optimization method

To create further insight for the advantages of multi-parameter optimization compared with the single factor optimization, this section presents the quantitative analysis of the maximum film stiffness and stiffness–leakage ratio based on the genetic algorithm method and loop iteration optimization method with different iterative number $k$, as shown in Fig. 8. Increment ratio of film stiffness $R_k$ and stiffness–leakage ratio $R_{\Gamma}$ are defined as the increment ratio of maximum film stiffness and stiffness–leakage ratio obtained by genetic algorithm and loop iteration optimization when $k \geq 2$ compared to those obtained by the single factor optimization.

As can be seen from Fig. 8, both the increment ratio of film stiffness and opening force depict initially a decreasing trend and then turn to an increasing trend with increasing $\lambda$. Besides, the maximum $k_z$ values of S-DGS obtained in the fifth iteration optimization for $\lambda = 1.1$ are up to 30% larger than that of the corresponding $k_z$ values obtained in the single factor optimization. On the contrary, the optimum $k_z$ and $\Gamma$ values in the multi-parameter optimization only show a slight enhancement of lower than 2% and 5% compared to those of the corresponding $k_z$ and $\Gamma$ values obtained from the single-parameter optimization when $10^1 < \lambda < 10^2$. This can be explained by the fact that the initial values of geometric parameters are very close to the globally optimal values.

4.4 Optimal geometric parameters of the spiral groove

The circumferential width of the spiral groove has a modest influence on the pump-in gas quantity and hydrodynamic effect. It is hard for the pressurized gas to enter into the spiral groove with too narrow circumferential width, further
leading to a weak hydrodynamic effect and unstable gas film. The too large value of groove width ratio means narrow sealing land between two adjacent spiral grooves in the circumferential direction and will narrow the high-pressure region and reduce the high-pressure peak produced by the hydrodynamic effect.

Groove extent in the radial direction has a significant influence on film stability and sealing performance. The too-short radial extent of the spiral groove corresponds to a weak hydrodynamic effect, which is detrimental to generate sufficient opening force to balance the closing force and to create a stable gas film. On the contrary, the radial width of the sealing dam shortened remarkably by a surface groove with too long radial extent leads to excessive leakage of sealing gas along with the reduction of opening force caused by a smaller area of the high-pressure region.

The spiral angle of the spiral groove has a remarkable influence on the leading effect of gas flow direction in the sealing gap, further influencing the pressure and fluid distribution on the entire face. Spiral groove with a small spiral angle just closes to an annular groove and generates insufficient opening force for the weak hydrodynamic and hydrostatic effect, induced by the flow resistance of the long groove channel. On the contrary, it’s difficult for a spiral groove with too large spiral angle, closes to a radial groove, to create a stable gas film for the real short groove channel.

Figure 9 presents the optimal groove width ratio $\delta_{\text{opt}}$, optimal groove length ratio $\alpha_{\text{opt}}$, and optimal spiral angle $\beta_{\text{opt}}$ obtained by the first loop iteration optimization (solid square), the fifth loop iteration optimization (hollow square) and the corresponding polynomial fitting curve (dashed line), genetic algorithm optimization (solid line) for the maximum opening force $F_{\text{omax}}$ (black), maximum film stiffness $k_{\text{zmax}}$ (red), and maximum stiffness–leakage ratio $\Gamma_{\text{max}}$ (blue), respectively. As can be seen from Fig. 9, the optimal geometric parameters of the spiral groove obtained in genetic algorithm optimization at different values of $\lambda$ fit well with that in the fifth loop iteration optimization, while different from that in the first loop.
iteration optimization. In consideration of the excellent global search ability of the genetic algorithm, the optimal geometric parameters obtained in the first loop iteration optimization, the so-called single factor optimization, are always the local optimal values, not the global ones.

In Fig. 9a, it is noticeable that the optimal groove width ratio $\delta_{\text{opt}}$ for $F_{\text{omax}}$ and $k_{\text{zmax}}$ depicts initially a decreasing trend and then turns to an increasing trend or trend to be a constant value at large $\lambda$ with the increase of $\lambda$. The optimal groove width ratio for $\Gamma_{\text{max}}$ keeps 0.15 ~ 0.3 at different values of $\lambda$, which is not strongly affected by $\lambda$. In Fig. 9b, the optimal groove length ratio $\alpha_{\text{opt}}$ for different objective functions presents a linearly decreasing trend with the increases of $\log(\lambda)$. In Fig. 9c, the optimal spiral angle $\beta_{\text{opt}}$ for different objective functions decreases gradually with the increase of $\lambda$.

Furthermore, the optimal geometric parameters are obtained by genetic algorithm optimization for $F_{\text{omax}}$ which is the largest, followed by which for $k_{\text{zmax}}$ and $\Gamma_{\text{max}}$. The relationship between the optimal geometric parameters and $\lambda$ can be expressed by quartic polynomial forms:

$$S_{\text{opt}}|_{\lambda_i} = \sum_{j=1}^{4} A_j (\log \lambda_i)^j + A_0$$

where $S_{\text{opt}}$ is a geometric parameter which can be $\alpha$, $\beta$, or $\delta$. $\lambda_i$ is the compressibility number to pressure ratio in the $i^{th}$ working condition point. $A_j (j = 0 \sim 4)$ is the coefficient of the quartic fitting polynomial. Thus, the global optimal geometric parameters of spiral groove, including groove width ratio, groove length ratio, and spiral angle, at any working parameters when $\lambda = 1 \sim 1000$ based on a given objective function can be obtained utilizing Eq. (12) and the corresponding coefficient shown in Table 2.

Figure 10 presents the variation amplitude of preferred groove width ratio $\delta_{\text{pre}}$, preferred groove length ratio $\alpha_{\text{pre}}$ and preferred spiral angle $\beta_{\text{pre}}$ obtained by maximum film stiffness or with given decreasing amplitude versus $\lambda$. It can be seen that the optimal zone of preferred geometric parameters is only a point for the maximum film stiffness at a given $\lambda$. However, the acceptable width between the upper and lower boundary of preferred geometric parameters broadens as $\Delta P$ increases from 0 to 0.2$P$, indicating a more possible intersection area with the preferred geometric parameters obtained by the other objective functions.

### 4.5 The influence of multi-objective functions

As mentioned above, the optimal geometric parameters of the spiral groove obtained by different objective functions
differ from each other. The preferred zone of different geometric parameters could be obtained by the intersection of preferred values for large $F_{omax}$, $k_{zmax}$, and $\Gamma_{max}$, and the preferred geometric parameters obtained by integrative performance parameter by taking $F_{omax}$, $k_{z}$, and $\Gamma$ into consideration at a given $\lambda$ can be defined as the average value of the upper and lower boundary.

Figure 11 presents preferred values of groove width ratio, groove length ratio, and spiral angle obtained by $0.9F_{omax}$, $0.8k_{zmax}$, and $0.8\Gamma_{max}$ at different values of $\lambda$. In terms of groove width ratio and groove length ratio, the upper and lower boundary of the optimal zone depends on the stiffness–leakage ratio and film stiffness, respectively. The upper and lower boundary of the optimal zone of the spiral angle also depends on stiffness–leakage ratio and film stiffness when $\lambda < 40$, while the upper and lower boundary of which depends on film stiffness and opening force when $\lambda > 40$. The relationship between preferred geometric parameters and $\log(\lambda)$ could also be characterized as the quartic polynomial just as Eq. (12) shows.

Figure 12 presents the optimal shape and pressure distribution of S-DGS at different working conditions and objective functions, including $F_{omax}$, $k_{zmax}$, $\Gamma_{max}$, and multi-objective parameter (M–O for short). The optimal groove width ratio $\delta_{opt}$, optimal groove length ratio $\alpha_{opt}$, and optimal spiral angle $\beta_{opt}$ all decrease as the increase of $\lambda$ from 4.4 to 440 at the same objective function, making the optimal shape of the spiral groove turn to be slender. All of $\delta_{opt}$, $\alpha_{opt}$, and $\beta_{opt}$ of spiral groove for $F_{omax}$ are largest at a given value of $\lambda$, followed by which for $k_{zmax}$. It is quite obvious that the optimal shape of the spiral groove for the multi-objective parameter is between those for $F_{omax}$ and $k_{zmax}$.

### 5 Experimental verification

Figures 13 and 14 show a photograph and schematic diagram of the test rig used to measure the steady performance of dry gas seals at static pressure. The main parts of the test rig include a gas supply and regulation system, a computerized data acquisition system, and two external pressurized seals. The test smooth rotating ring made of carbon is fixed on the shaft, while the grooved stationary ring made of silicon carbon is supported by an auxiliary ring and can move freely in the axial direction. The closing force of the stationary ring can be adjusted by the adjustable gas pressure and measured by three uniformly distributed force transducers in
the second seal chamber. The film thickness and seal leakage rate can be measured by eddy current sensor and gas flowmeter, respectively. Film thickness, opening force, leakage rate, and seal pressure are measured and recorded by the data acquisition system. Hence, the film stiffness and stiffness–leakage ratio at different values of the film thickness of DGSs can be obtained.

For the rotation function of the test rig has not yet been realized, the performance comparison of DGSs with different geometric parameters is conducted at static pressure $p_o = 0.35 \text{ MPa}$ and $v = 0 \text{ m.s}^{-1}$. In terms of results in Fig. 8, the predicted preferred geometric parameters of the spiral groove for the maximum steady performance when $\lambda = 0$ are shown in Table 3. The optimal geometric parameters for the maximum film stiffness and maximum stiffness–leakage ratio can be adopted as $\delta_{\text{opt}} = 0.7$, $\alpha_{\text{opt}} = 0.9$, and $\beta_{\text{opt}} = 45^\circ$ and $\delta_{\text{opt}} = 0.4$, $\alpha_{\text{opt}} = 0.7$, and $\beta_{\text{opt}} = 25^\circ$, respectively. The photographs of the stationary ring with different values of geometric parameters are shown in Fig. 15. The spiral groove with $\delta = 0.7$, $\alpha = 0.9$ and $\beta = 45^\circ$ can be called a wide groove, while the spiral groove with $\delta = 0.4$, $\alpha = 0.7$ and $\beta = 25^\circ$ can be called a narrow groove. The geometric parameters of the sealing ring and surface groove are inner

| Performance | $\delta_{\text{opt}}$ | $\alpha_{\text{opt}}$ | $\beta_{\text{opt}}^\circ$ |
|-------------|------------------|------------------|------------------|
| $F_{\text{omax}}$ | 1.0 | 0.85 | 45 |
| $k_{\text{max}}$ | $0.7 \sim 1.0$ | 0.95 | 45 |
| $\Gamma_{\text{max}}$ | $0.2 \sim 0.4$ | $0.7 \sim 0.75$ | $20 \sim 25$ |
radius \( r_i = 29.5 \text{ mm} \), outer radius \( r_o = 37.5 \text{ mm} \), groove number \( N_g = 12 \), and groove depth \( h_g = 9 \mu \text{m} \).

Figure 16 presents the measured opening force and leakage rate of the two DGSs at different film thicknesses. The relationship between the fitted values of the opening force, leakage rate, and film thickness of wide groove and narrow groove DGS can be expressed by Eqs. (13) and (14), respectively.

\[
F_o = 235.83h_0^{-0.114}, \quad F_o = 222.18h_0^{-0.065} \tag{13}
\]

\[
q = 0.114h_0^2 + 0.179h_0 + 0.554, \quad q = 0.09h_0^2 - 0.021h_0 + 0.192 \tag{14}
\]

Based on Eqs. (7) and (9), the fitted film stiffness and the stiffness–leakage ratio of wide groove DGS and narrow groove DGS at different film thicknesses are shown in Fig. 17. The film stiffness of wide groove DGS is up to 70% larger than that of narrow groove over the entire film thickness range, while the stiffness–leakage ratio of narrow groove DGS is larger than that of wide groove DGS. The correctness and effectiveness of the recommended geometric parameters of the spiral groove for different objective functions are confirmed.

6 Conclusions

Multi-dimensional optimization of the geometric parameters of the spiral groove dry gas seal with considering the influence of working conditions, objective function, and other geometric parameters has been performed to obtain the globally optimal values of geometric parameters. The following conclusions can be obtained from the above analysis.

1. The two multiple parameters optimization methods, genetic algorithm and loop iteration optimization method, are available to provide global optimal geometric parameters of the dry gas seal. When the iterative number is greater than 3, the sealing performance obtained by loop iteration optimization is close to the result of the genetic algorithm and never changes significantly. The maximum film stiffness and stiffness–leakage ratio of spiral groove dry gas seal obtained by the two multiple parameters optimization method increased significantly compared to that obtained by the single factor optimization.

2. The global optimal geometric parameters for the maximum steady performance strongly depend on the working conditions and objective functions. The optimal values of geometric parameters of the spiral groove, including groove width ratio, groove length ratio, and spiral angle, decrease with the increases of compressibility.
number to pressure ratio. The optimal values of geometric parameters for the maximum opening force are the largest, followed by those for the maximum film stiffness, and those for the maximum stiffness–leakage ratio are the smallest.

(3) The multiple objectives optimization method developed with the intersection area of optimum spectrums is theoretically and experimentally proven to obtain the global optimal geometric parameters effectively. The optimization results can be further expanded or refined by changing the acceptable variation amplitude for different objectives.

**Author contributions** CZ and JJ carried out numerical simulation and manuscript writing. WZ, JJ, and XP assisted with sampling preparation, experimental results analysis, and revision of the manuscript. All authors read and approved the final manuscript.

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**Declarations**

**Conflict of interest** The authors declare that they have no competing interests.

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**Fig. 17** Fitted film stiffness and stiffness–leakage ratio of two DGSs at different film thicknesses
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