ISSN: 2472-3703 DOI: 10.6911/WSRJ.202010_6(10).0023

Research on Optimal Design of Low Hysteresis Brush Seal Structure

Bo Cheng[1, a], Xinyang Wang[1, b, *] and Yifei Ren[1, c]

[1]School of Energy and power, Nanjing University of Aeronautics and Astronautics, Nanjing, China.

[a]1677001939@qq.com, [b]Wangxinyang99@qq.com, [c]1772656340@qq.com

Abstract

The low hysteresis brush seal can effectively reduce the hysteresis effect and the increase in leakage caused by the basic brush seal during the radial deviation of the rotor. However, the structure is relatively more complicated. In order to achieve a low hysteresis brush seal engineering design, we establish the agent-based response surface model gas seals leak coefficient based on ISIGHT, algorithms including MIGA, ASA and POINTER are applied to the optimization design research of the low hysteresis brush seal structure. Research indicates that the established agent-based model based on experiment results can better match the low hysteresis brush seal, and it is concluded that the leakage of the decompression chamber is at its least when the size is 0.2949mm. In addition, the MIGA algorithm has an excellent performance with better optimization efficiency and optimization results.

Keywords

Optimal design, Low hysteresis, Brush seal, Optimization algorithm.

1. INTRODUCTION

The working performance of modern rotating machinery (such as aero engines, gas turbines, etc.) is constantly improving, and the demand for advanced sealing technology is becoming increasingly urgent. In this context, brush seal has a rapid development as an excellent novel seal technique since 1990s, under the same conditions, its leakage rate is only 10~20% of the typical labyrinth seal structure [1], and the brush seal also overcomes the shortcomings that the labyrinth seal is easy to wear, so its engineering application is becoming more and more extensive.

Taking into account that the basic brush seal will have a hysteresis effect in the working process, because the pressure difference between the upstream and downstream leads to the friction between the brush filaments, the brush bundle and the rear baffle plate, which creates a gap between the brush bundle and the rotor is created, thus the leakage increases. In 1996, Short and Basu [2] put forward a low hysteresis brush seal structure, that is, a decompression chamber is added between the brush bundle and the rear baffle, which can reduce the friction between the brush bundle and the baffle, and at the same time, adding another baffle plate between front baffle and the brush bundle can also avoid the blow-down effect and greatly alleviate the hysteresis effect.

Chupp etc. [3] carried out tests on brush seal performance, it was found that at a given pressure ratio, the leakage characteristics depend on the path to reach this pressure ratio, namely the amount of leakage varies with the loading process. Outriba and Hendrick etc. [4] investigated the carbon fiber brush seal used in the bearing cavity of aero-engine, and the

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202010_6(10).0023

change of leakage with pressure ratio was tested at different speeds, it was found that under the same pressure ratio, the leakage rate in the process of pressure ratio decrease is higher than that in the process of pressure ratio increase, meanwhile, its speed has little effect on leakage and hysteresis. Tseing et al. [5] found that the seal performance of the single-stage low hysteresis structure is better than that of the two-stage basic brush seal. Basu and Datta etc. [6] investigated the phenomenon of hardening and hysteresis of the brush filaments in the traditional brush seal structure, and the leakage of the basic and low hysteresis structures at high temperatures was compared as the speed changes.

In China, Cao Guangzhou et al. [7] conducted leakage tests in the process of pressure difference rising and falling under dynamic conditions on basic type and low hysteresis brush type seals. Zhou Kun, Li Ning et al [8] conducted Leakage tests under dynamic and static conditions respectively, and it was concluded that temperature and speed are inversely proportional to the leakage coefficient. As for Huang Yangzi et al [9], numerical simulation comparisons were made between the basic type and the brush seal with a baffle plate. It was found that the axial pressure difference of the low hysteresis structure in the brush zone was much smaller than that of the basic type structure, and the amount of leakage increased relative to the basic model. The numerical analysis by Wang Zhili et al [10] based on anisotropic porous medium model and the properties of basic type and low hysteresis brush seal also showed that low hysteresis structure can effectively reduce hysteresis effect, but also increases the amount of leakage. The optimization of basic, rectangular and airfoil structures is studied by Zhang AiPing et al [11]. It was found that the low hysteresis structure can effectively reduce the hysteresis effect when the axial size of the decompression chamber is 0.1mm, with a good sealing performance at the same time.

At present, most of the research on the hysteresis characteristics of brush seal and low hysteresis brush seal in our country are simplified to two-dimensional calculation models and only pay attention to the influence of a single factor, ignoring the coupling effect of multiple factors, which fails to meet the needs of engineering design. This article based on three-dimension numerical calculation of leakage of low hysteresis brush seal structure, aiming at low leakage and low hysteresis, establish a mathematical model of optimal design coupled with multiple influencing factors, and uses ISIGHT to establish an agent-based model of leakage and conducts research on the optimal design of the seal structure.

2. PHYSICAL MODEL

The low hysteresis brush seal structure in this paper consists of four parts: the front baffle, the brush bundle and the back baffle, as shown in Fig.1.The structure of the baffle is shown in Fig.2, and 45 slits along the radial direction are evenly distributed along the circumferential direction. Several main structural parameters of the seal structure contain brush wire alignment angle (BWA), brush bundle thickness (BBT), axial size of decompression chamber (DCS), the protection height of the rear baffle (RBPH), etc, as shown in Table 1.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202010_6(10).0023

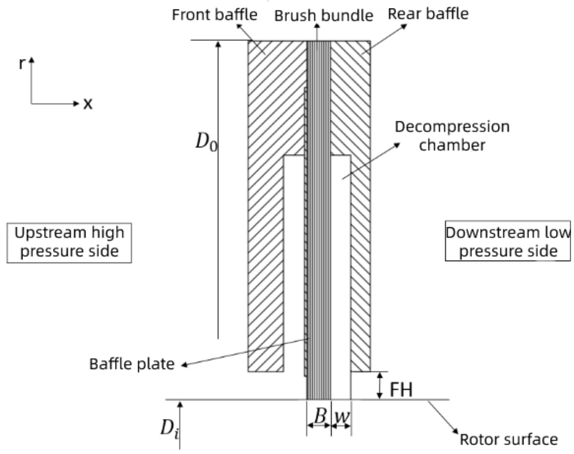

Fig 1. Diagram of low hysteresis brush seal structure

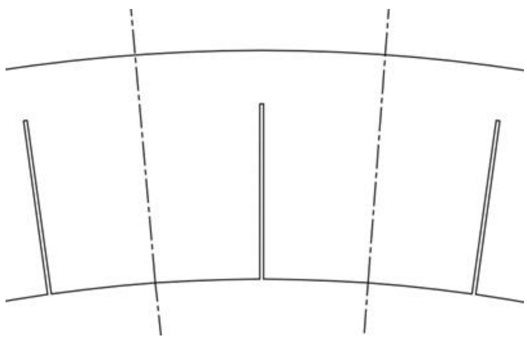

Fig 2. Diagram of shutter plate

Table 1. Geometric parameters of low hysteresis brush seal

Parameters	Value
BWA β/°	45
BBT B/mm	1
DCS w/mm	0.4
RBPH FH/mm	1.2

3. OPTIMIZED DESIGN MODEL OF BRUSH SEAL STRUCTURE WITH LOW LEAKAGE AND LOW HYSTERESIS

The goal of this article is to optimize the design of the structural parameters of the brush seal under the premise of low leakage to obtain a low hysteresis effect. The effect of low hysteresis is manifested that the leakage coefficient [12]f of brush seal has a small difference in the stage of pressure difference rising and pressure falling so the optimization goal is to get the minimum value. Low leakage requires that the leakage coefficient should not be higher than a certain value, combined with engineering practice, the constraints of f1 and f2 in this paper are less than 0.03. The hysteresis of the brush seal is affected by the pressure difference, which is most obvious at 150KPa, so the pressure difference in the optimization variable is taken as a constant at 150KPa.

Low leakage constraints:

$$f1 \leq 0.03 \tag{1}$$

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202010_6(10).0023

$$f2 \leq 0.03 \tag{2}$$

Optimization variables:

$$\Delta p=150Kpa \tag{3}$$

$$0.08 \leq d \leq 0.12mm \tag{4}$$

$$0 \leq w \leq 0.6mm \tag{5}$$

$$0 \leq \beta \leq 0.6mm \tag{6}$$

Optimization goals:

$$\min(f1-f2) \tag{7}$$

Besides, f1 is the leakage coefficient in the rising stage of pressure difference, and f2 is the leakage coefficient in the falling stage of pressure difference, both of them are functions of brush wire diameter(D), brush wire alignment angle(β), decompression chamber size(w) and the differential pressure(Δp),and rotational speed(n). First of all, we put the test pieces in the wind tunnel experiment device to simulate the working characteristic state of the rotor in the engine, and carried out the experiment under different working conditions to obtain the f1 and f2 data under the corresponding working conditions. Table 2 shows part of the data.

Table 2. Experiment data (The value of Δf=f1-f2 is used to indicate hysteresis characteristics, and the following tables are the same)

D/mm	β/°	w/mm	Δp/KPa	f1	f2	Δf
0.8	45	0.4	157.66	0.0233	0.0223	0.0010
	50	0.4	173.21	0.0394	0.0381	0.0013
	40	0.4	177.12	0.0.236	0.0222	0.0014
	45	0.6	175.96	0.0267	0.0243	0.0023

4. OPTIMIZED DESIGN MODEL OF BRUSH SEAL STRUCTURE WITH LOW LEAKAGE AND LOW HYSTERESIS

After determining the constraints, variables and objectives of the optimization model, ISIGHT was used to establish the agent-based model using the experimental data shown in Table 2, and the optimization algorithms were selected for optimization calculation. Finally, the optimization results were analyzed.

4.1. Agent-based Model

The calculation can obtain high-precision results through FLUENT, but it takes a long time. While optimizing the design through the optimization algorithm, it is necessary to calculate the leakage coefficient value corresponding to the current optimization variable, and adjust the optimization variable based on it. It is usually unacceptable in terms of time, so the concept of agent-based model is introduced. The agent-based model is to replace a certain complex process with a certain specific functional relationship, so as to obtain the result quickly under

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202010_6(10).0023

the premise of ensuring the accuracy. In this article, the response surface methodology is adopted.

Response surface methodology is using a polynomial function to fit the design space. Taking into account the randomness of errors in the experiment, the complex unknown function relationship is transformed into a simple polynomial model, and the fitting result is smooth, which is convenient for subsequent calculation and optimization. In this article, by the agent-based model components of ISIGHT, combined with experimental data, the leakage of the brush seal (m) in the rising and falling stages of the pressure difference is obtained. The leakage mass (m) is a quartic polynomial with respect to the brush alignment angle, the brush wire diameter, the pressure difference and the decompression chamber size (As shown in Formulation 8 and Table 3), eventually f1 and f2 are obtained according to the definition of leakage coefficient.

$$\begin{aligned} \mathrm{m} &= k_1 \times \mathrm{d} + k_2 \times \beta + k_3 \times p + k_4 \times \beta^2 + k_5 \times w^2 \\ &+ k_6 \times p^2 + k_7 \times d \times p + k_8 \times \beta \times p + k_9 \times w \times p + k_{10} \times p^3 + k_{11} \times p^4 + k_{12} \end{aligned} \tag{8}$$

Table 3. Polynomial coefficients of differential pressure (DP) rise and fall

Polynomial coefficients	DP Rise	DP Fall
k1	1.00E+03	9.38E+02
k2	2.65E+02	2.47E+02
k3	-4.62E+01	-4.32E+01
k4	-5.43E+01	-4.14E+01
k5	5.24E-01	-2.02E-01
k6	8.79E+01	4.89E-01
k7	-2.07E-03	6.51 4E+01
k8	8.02E-01	-3.56E-04
k9	8.44E-03	8.03E-01
k10	-2.71E-02	9.39E-03
k11	7.39E-06	-2.35E-02
k12	-9.95E-09	4.34E-07

4.2. Optimization

This article uses MIGA (multi-island genetic algorithm), ASA (adaptive simulated annealing algorithm) and POINTER combination algorithm. MIGA algorithm and ASA algorithm are two commonly used global optimization algorithms. They all belong to the guided search method in the approximate algorithm, using some guiding rules to guide the exploration of good solutions in the entire solution space. For the optimization problem of this article, by setting the initial parameters of the algorithm, it will generate a set of initial values for the structural variables of the brush seal and the leakage coefficient, evaluate the solution, and then combine the algorithm parameters to generate a set of new values until the algorithm's stopping conditions are met.

POINTER algorithm is an intelligent automatic optimization algorithm provided by ISIGHT, which consists of four algorithms: linear simplex method, sequential quadratic programming method, steepest descent method and genetic algorithm. POINTER algorithm will automatically capture the information of the design space and automatically combine the four optimization algorithms to form an optimal optimization strategy. It usually takes a long time but the results

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202010_6(10).0023

are relatively accurate, so it can be used as a comparison for the optimization result of the MIGA algorithm and the ASA algorithm, then, to achieve the comparison of the pros and cons of different algorithms in the optimization problem solving in this paper.

4.3. Optimization Results and Analysis

Using the ASA algorithm, the calculation converges about 240 steps by default. Instability of the solution is clear, the results are shown in Table 4:

Table 4. ASA algorithm calculation results

Steps	β/°	w/mm	d/mm	Δp/KPa	f1	f2	Δf
240	45.53	0.2878	0.8001	150	0.02465	0.02386	0.00079
240	45.34	0.2968	0.8001	150	0.02427	0.02347	0.0008
240	45.52	0.3051	0.8001	150	0.02459	0.02379	0.0008
240	45.57	0.2886	0.8001	150	0.02473	0.02393	0.0008
240	45.35	0.3077	0.8010	150	0.02427	0.02347	0.0008

Using the POINTER algorithm, under default conditions, the result converges around 90,000 steps. The solution is basically stable, which are shown in the Table 5:

Table 5. POINTER algorithm calculation results

Steps	β/°	w/mm	d/mm	Δp/KPa	f1	f2	Δf
90000	45.55	0.2949	0.08	150	0.02466	0.02387	0.00079
90000	45.55	0.295	0.08	150	0.02466	0.02386	0.0008
90000	45.55	0.295	0.08	150	0.02466	0.02386	0.0008
90000	45.54	0.2949	0.08	150	0.02464	0.02385	0.00079
90000	45.55	0.2949	0.08	150	0.02465	0.02386	0.00079

Use MIGA algorithm to set different number of islands, subgroup size, evolution algebra at an interval of 5, and calculation steps are from 125 to 15625. Observing through the scatter plot, we can see that the solution is basically stable after 6000 steps. The results are shown in the Table 6:

Table 6. MIGA algorithm calculations results

Steps	β/°	w/mm	d/mm	Δp/KPa	f1	f2	Δ f
125	42.99	0.3898	0.09456	150	0.02615	0.02487	0.00128
125	45.05	0.3536	0. 8014	150	0.02377	0.02291	0.00086
125	43.53	0.347	0.08478	150	0.02346	0.02247	0.00099
125	44.78	0.2778	0.08219	150	0.02407	0.02323	0.00084
125	43.52	0.3197	0.08179	150	0.02265	0.02172	0.00093
1000	44.92	0.2765	0.08184	150	0.02418	0.02335	0.00083
1000	45.2	0.2949	0.08036	150	0.02412	0.02332	0.0008
1000	43.04	0.2995	0.08318	150	0.02295	0.02196	0.00099
1000	45.56	0.2596	0.08008	150	0.02494	0.02413	0.00081
1000	44.86	0.2951	0.08475	150	0.02477	0.02391	0.00086

ISSN: 2472-3703
DOI: 10.6911/WSRJ.202010_6(10).0023

After comprehensive consideration, basically the relatively accurate results are obtained in ten thousand steps. In order to facilitate observation of convergence trend, the scatter diagram of the brush wire alignment angle, the brush wire diameter, and the decompression pressure chamber size were respectively drawn by the MIGA algorithm. As shown in Fig.3,4 and 5, the convergence trend is obvious.

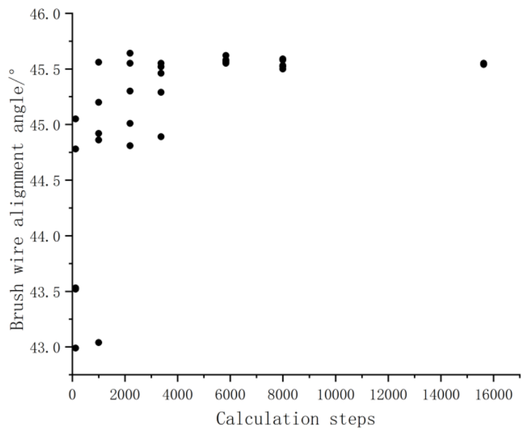

Fig 3. The brush alignment Angle varies with step length

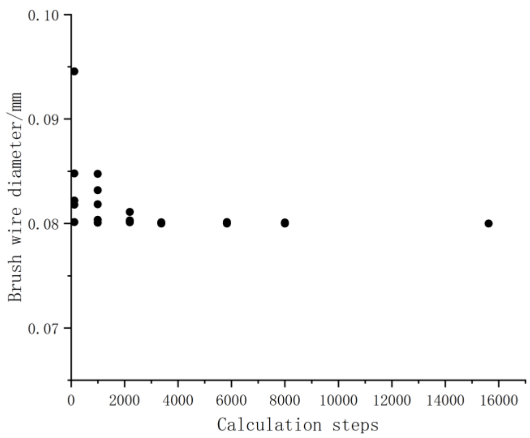

Fig 4. Brush wire diameter varies with the step length

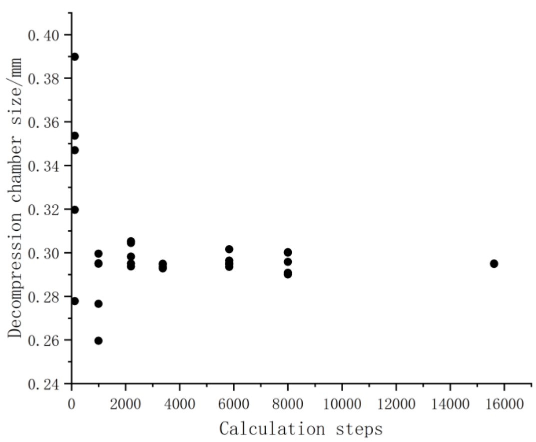

Fig 5. Decompression chamber size varies with the step length

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202010_6(10).0023

It can be seen from the figure that the solution is basically stable after 6000 steps. The optimal structure size of brush seal with low leakage and low hysteresis is obtained, which is shown in Table 7.

Table 7. Optimization Results

Parameters	Value
BWA β/°	45.55
BWD d/mm	0.08
DCS w/mm	0.2929

Compared with the experimental data, we can find that the hysteresis is significantly reduced to the minimum, and meet the constraints.

5. CONCLUSION

In this paper, based on experimental data, ISIGHT software was used to establish a highly reliable fourth power response surface agent-based model, and ASA algorithm, POINTER algorithm and MIGA algorithm were used for the optimization design of low hysteresis brush seal structure. The main conclusions are as follows:

(1) In this paper, an agent-based model was established based on the experimental data. The relative error of the model calculation results was all less than 5%, so the optimization results were closer to the reality. The brush seal structure with low leakage and low hysteresis can effectively reduce the leakage amount and alleviate the hysteresis effect.

(2) From the perspective of optimization results, the multi-island genetic algorithm (MIGA) adopted in this paper can obtain stable optimization results with high efficiency. Combined with the response surface agent-based model, the low hysteresis brush seal structure can be quickly and effectively obtained. This paper provides a quick and effective solution for the design and optimization of low leakage and low hysteresis brush seal structure.

(3) After the optimization results are numerically calculated, Δf of this set of structure is found to be compared with the experimental data, and it is found to have a significant reduction to minimum value, which meets the optimization requirements of low hysteresis in this paper.

ACKNOWLEDGEMENTS

This paper is inseparable from the guidance of my tutor Hu Yaping and senior Li Pengfei. Meanwhile, we acknowledge the support of NUAA (Nanjing University of Aeronautics and Astronautics) for its equipment and research resources.

REFERENCES

[1] Li Jun, Yan Xin, Song Liming, et al: Research progress in turbine mechanical seal technology, Thermal Turbine, Vol.37(2008,) No.3, p.141-148.

[2] Short J, Basu P, Datta A, et al:Advanced brush seal development,Joint Propulsion Conference and Exhibit(Lake Buena Vista, July 1-3, 1996).

[3] Chupp RE, Loewenthal RG:Brush seals can improve power plant efficiency by one-fourth of a percentage point yielding huge annual savings,LubricationEngineering,Vol.53(1997) No.53,p.10-14.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202010_6(10).0023

[4] Outirba B, Hendrick P:Heat Transfer-Experimental Testing of Carbon Brush Seals for AeroEngines Bearing Chambers, Turbine Technical Conference and Exposition-Düsseldorf (Germany, June 16, 2014)

[5] Tseng T, Short J, Steinetz B:Development of a low hysteresis brush seal for modern engine applications,Joint Propul-sion Conference and Exhibit (Los Angeles, CA,June20-24, 1999).

[6] Basu P, Datta A, Loewenthal R, et al:Hysteresis and bristle stiffening effects in brush seals,Journal of Propulsion & Power,Vol.10(1994) No.4,p.569-575.

[7] Cao Guangzhou: Study on the leakage characteristics of brush seal structure (Ph.D,Nanjing University of Aeronautics and Astronautics, China 2006).

[8] Zhou Kun, Lining, Guo Hui, et al:Experimental study on the leakage characteristics of low hysteresis brush seals,Lubrication and Sealing,Vol.42(2017) No.4,p.132-136.

[9] Huang Yangzi, Li Jun:Numerical study on the leakage characteristics of low hysteresis brush seals,Guang dong Electric Power,Vol.25(2012) No.3,p.10-14.

[10] Wang Zhili, Liang Xiaofeng, Song Fei, et al:Numerical analysis of low hysteresis brush seals, Journal of Beijing University of Aeronautics and Astronautics,Vol.34(2008) No.9,p.1080-1083.

[11] Zhang Aiping, Zhang Shuai, Li communication, and the like:Low hysteresis brush seal leakage flow Numerical Simulation and Optimization,Lubrication Engineering, Vol.(2015) No.2,p.67-72.

[12] Du Chunhua, Ji Honghu, Hu Yaping, et.al: Experimental investigation on leakage characteristic of small size brush with low front plate, Journal of Aerospace Power, Vol.32(2017) No.2, p.298-305.