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Optimized Design of Centrifugal Compressor splitter Blades in Marine turbocharger

Turbochargers & Air/Exhaust Management

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ABSTRACT

With the increasing emphasis on the economic performance of marine low-speed engines in the shipping industry, high-flow, high-pressure-ratio centrifugal compressors have been extensively applied in turbochargers for marine low-speed engine turbocharger. And the high flow rate and elevated pressure ratio lead to more complex internal flows in the compressor and a significant increase in flow-induced noise. The International Maritime Organization (IMO) currently stipulates that the noise level in ship engine rooms must not exceed 105 dB(A). As the aerodynamic noise generated by centrifugal compressors in turbochargers is a primary source of noise for marine low-speed engines, investigating methods to control this aerodynamic noise is of great significance.

As a critical component of the centrifugal compressor, the aerodynamic noise of the impeller is a prominent issue in marine turbochargers, which has received limited attention. Therefore, this research first focuses on a high-flow centrifugal compressor designed for marine low-speed engines, exploring its aerodynamic performance under various operating conditions through numerical calculations and experimental validation. Subsequently, using a hybrid Computational Aeroacoustics (CAA) method based on the acoustic boundary element approach, the pressure fluctuation at the inlet plane of the centrifugal compressor were extracted as the noise source to study its aerodynamic radiation noise, and the findings were validated experimentally.

Finally, by investigating the effects of different structural parameters of splitter blades on the aerodynamic performance of the compressor, it was found that the leading-edge blade tip inlet angle, leading-edge sweep angle, and splitter blade position significantly impact the aerodynamic performance of the centrifugal compressor. Subsequently, using the Kriging surrogate model, the optimization design of splitter blades for low-noise and high-performance marine centrifugal compressors was carried out, targeting isentropic efficiency and aerodynamic noise. The optimization process was aimed at achieving a low-noise, high-performance design for marine centrifugal compressors. The results indicate that for different objective functions, the Kriging surrogate model and genetic algorithm can rapidly yield global optimal solutions, with numerical validation confirming their accuracy. The optimization of the splitter blades under different objective functions effectively improved the compressor's aerodynamic performance and reduced aerodynamic noise. Among these, using SPLave-0.75EFF (mean overall sound pressure level minus 0.75 times the compressor isentropic efficiency) as the optimization objective achieved the best results. In this case, the splitter blade’s leading-edge tip shifted toward the pressure surface of the main blade, the leading-edge tip was swept forward, and the splitter blade was offset toward the pressure surface of the main blade. Consequently, the maximum isentropic efficiency of the compressor increased by 0.49%, and the average sound pressure level of inlet noise was reduced by 2 dB(A).

0 ABSTRACT

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1 INTRODUCTION

Turbocharging technology has been widely adopted in marine low-speed engines due to its unparalleled advantages in energy saving, improving engine power and economy, and reducing exhaust emissions and noise. It has already become one of the most effective measures to enhance the power of marine low-speed engines [1-2]. To better balance the power and economy of ship engines, ultra-high boost, high-efficiency, and large-flow turbochargers have been widely applied in low-speed engines [3]. Operating at high speeds and high pressure ratio can improve the economy and emission levels of low-speed engines, but the noise of turbochargers increases as well. Excessive turbocharger noise not only pollutes the environment and affects the health of engine room personnel but also increases the overall noise level of low-speed engines. Therefore, as the primary noise source of turbochargers, the study of centrifugal compressor noise is of great significance.

At present, the design and optimization of centrifugal compressors based on the configuration of impeller main blades have been extensively discussed in the literature, but there has been relatively little research on splitter blades. As a core component of centrifugal compressors, the primary function of splitter blades is to divert and guide airflow, making the flow field distribution more uniform and reducing turbulence and losses. Krain [4] proposed in splitter blade design that appropriate blade thickness and leading/trailing edge shapes can improve airflow uniformity and effectively reduce the adverse effects of flow separation and secondary flows on efficiency. In recent years, research based on computational fluid dynamics (CFD) and experimental testing has made significant progress in the optimization of splitter blades in marine centrifugal compressors. For example, A. Malik [5] validated the unsteady flow characteristics of centrifugal compressors with splitter blades for small gas turbines through numerical simulations and experiments, while exploring methods to increase the pressure ratio and improve efficiency by using multiple splitter blades. Khalil [6-7] and others optimized the main and splitter blades in parameterized micro gas turbine impellers using genetic algorithms and CFD solvers. The optimized impeller effectively reduced blade tip leakage flow and increased the maximum isentropic efficiency of the compressor impeller. Ou [8] and others used CFD to study the impact of load distribution between main and splitter blades on the aerodynamic performance, flow field, and internal vortices of high-load centrifugal compressors. By applying blade load distribution techniques, appropriately reducing the load ratio between splitter and main blades helps suppress splitter blade leakage vortices and effectively improve aerodynamic performance.

Over the past decades, research on turbocharger noise, particularly centrifugal compressor noise, has gradually increased. Li [9] and others investigated automotive turbocharger noise using acoustic array identification, finding that centrifugal compressor noise is higher than turbine noise and confirming that the impeller of the centrifugal compressor is the primary source of aerodynamic noise. Raitor and others conducted detailed experimental analyses of the noise characteristics of two types of centrifugal compressor impellers. The results showed that the aerodynamic noise of centrifugal compressors primarily includes discrete tonal noise, blade tip clearance noise, and multiple tonal noises. Among these, discrete tonal noise is prominent under various operating conditions, manifesting as a series of peaks at the blade passing frequency (BPF) and its harmonics [10-11]. Wang conducted systematic experimental research on the radiated noise of automotive turbochargers and found that discrete tonal noise is the most prominent noise component of turbochargers. However, research on the aerodynamic noise of marine turbocharger centrifugal compressors is relatively scarce [12]. Bao tested the aerodynamic noise at the compressor inlet of a certain type of marine turbocharger, revealing that discrete tonal noise is the dominant noise component of the compressor [13]. Wen conducted experimental tests on the noise of marine turbochargers, which similarly showed that the aerodynamic noise at the compressor inlet is mainly composed of blade tip clearance noise and discrete tonal noise, with the radiated acoustic power of the aerodynamic noise proportional to the compressor speed [14]. Liu studied the aerodynamic noise characteristics of centrifugal compressors under different operating conditions using a hybrid CAA numerical method and validated the results through experiments.

It can be observed that current research on centrifugal compressor splitter blades mainly focuses on the aerodynamic performance of the centrifugal compressor, and most of these studies optimize the design based on the aerodynamic performance of the main blades. Few studies, however, have addressed the optimization design of low-noise splitter blades. To fill this gap, this study focuses on marine centrifugal compressors and takes high aerodynamic efficiency and low aerodynamic noise as optimization objectives. Using a genetic algorithm with the Kriging surrogate model, key parameters of the centrifugal compressor are optimized to ensure that the marine centrifugal compressor operates efficiently while effectively reducing aerodynamic noise.

2 RESEARCH METHODOLOGY

2.1 Numerical simulation and validation of aerodynamic performance

This study is based on the centrifugal compressor of a marine turbocharger, featuring 9 main blades, 9 splitter blades and 17 diffuser blades. The design speed is 12,878 rpm, and the design pressure ratio is 5.1. The compressor numerical model is shown in Figure 1, which also zooms in to show the rotor and stator mesh. Previous research has shown that in performance calculations, the results using single-channel and full-channel numerical simulations are basically consistent. In noise calculations, using the noise source information obtained from single-channel simulations can also effectively capture the dominant aerodynamic noise, such as discrete tonal noise [15]. Therefore, this study adopts a single-channel numerical model. The impeller and diffuser meshes are divided using ANSYS Turbo Grid with the "HI" topology structure, resulting in hexahedral meshes. The inlet pipe and volute meshes are divided using Hyper Mesh into a combination of hexahedral and tetrahedral meshes.

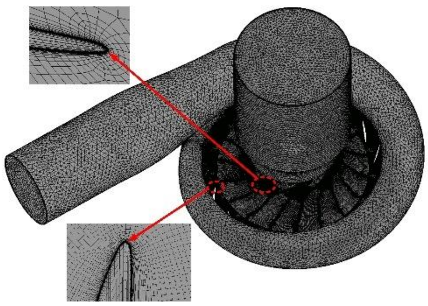
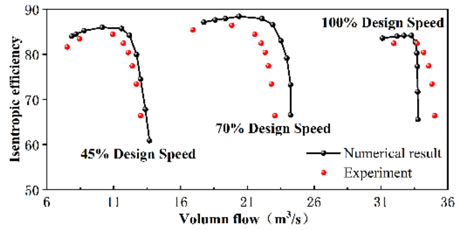
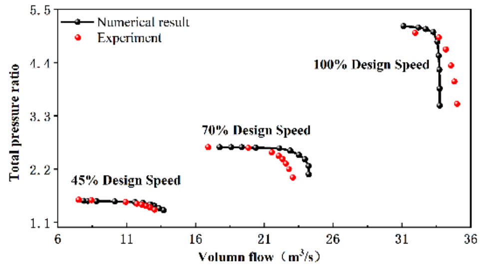


Figure 1 Compressor numerical model

The compressor aerodynamic performance are numerical predicted using steady CFD simulations, to validate the accuracy of the numerical results, experimental data were utilized, as shown in Figure 2. During the experiments, speed variations were achieved by adjusting the fuel control valve and the number of combustion chambers in use, while different operating conditions at the same speed were achieved by adjusting the compressor outlet control valve. The numerical results at different speeds were validated against the experimental data. It is found that the discrepancies between the numerical and experimental results for the total pressure ratio and isentropic efficiency are within 5%. Therefore, it can be concluded that the numerical simulation can accurately predict the compressor aerodynamic performance.



（a）Isentropic efficiency



（b）Total pressure ratio

Figure 2 Validation of compressor performance

2.2 Numerical simulation and validation of aerodynamic noise

Previous studies have shown that setting the optimal operating point of a centrifugal compressor at 88% of the design speed's peak efficiency point is beneficial for optimizing the entire map of the compressor [16]. Therefore, this study selects 88% of the design speed, equivalent to 11,333 rpm, to conduct the optimization design of high-performance, low-noise splitter blades for the centrifugal compressor.

The experimental measurements of compressor aerodynamic noise was conducted on a marine turbocharger performance test bench, with noise measurement points arranged as shown in Figure 3. The testing equipment included the MPA471S microphone and the BK3560D noise signal analyzer. The compressor aerodynamic noise was measured at several operating points in the high-efficiency operating region of the compressor.

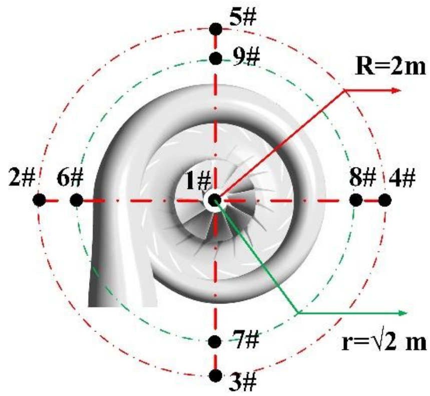


Figure 3 Top view of microphone arrangement

The hybrid CAA method was used to calculate the radiated aerodynamic noise at the compressor inlet. The sound source information was obtained from unsteady CFD calculations. The transient rotor-stator method was used to simulate the real transient interactions of fluid within the rotor and stator passages. The noise prediction was conducted at study speed 11,333 rpm, the corresponding time step was set to 2.94e-5 s, equivalent to a 2° rotation of the impeller. This ensured that the unsteady flow results met the requirements for noise calculations. The total calculation time was set to 0.043 s, equivalent to eight impeller rotations. Pressure fluctuation data from approximately six stable rotations of the impeller were selected as the aerodynamic noise source. The time-domain pressure fluctuations were transformed into the frequency domain using discrete Fourier transformation. These were then interpolated and transferred onto the acoustic source surface mesh. Finally, the frequency-domain BEM (Boundary Element Method) was used to simulate the propagation of aerodynamic noise in space.

Actually, single-passage computations neglect variations between different blades, assuming uniform flow conditions across all passages. As a result, they fail to accurately capture the effects of blade-to-blade differences, leading to relatively poor numerical simulation accuracy for flow details such as rotor-stator interactions and the influence of the volute tongue. Consequently, the predictive capability for multiple tonal noise components and broadband noise is limited. Existing literature [15] indicates that discrete tonal noise is the dominant component of aerodynamic noise in centrifugal compressors under various operating conditions. The single-passage model can effectively simulate discrete tonal noise and provide a reasonable prediction of the overall sound pressure level of the centrifugal compressor. Additionally, the aerodynamic noise source of the compressor is simplified as a dipole source, while the influence of quadrupole sources is neglected, leading to weaker predictive capability for broadband noise caused by flow-induced turbulence. Therefore, if future research aims to further investigate the aerodynamic noise characteristics of centrifugal compressors and improve broadband noise prediction, it will be necessary to incorporate the modeling of quadrupole noise sources. Moreover, if computational resources permit, full-annulus numerical simulations should be conducted.

Overall, the single-passage model can effectively simulate the aerodynamic performance of the compressor, capture its main flow characteristics, and accurately predict the discrete tonal noise of the centrifugal compressor. Therefore, its prediction of the overall sound pressure level of aerodynamic noise meets the research requirements.

A comparison of the numerical results with experimental data is shown in Figure 4. It is found that the hybrid CAA method used in this study effectively simulated the first three orders of blade-passing frequency (BPF) noise, the discrepancies of numerical overall sound pressure level (OASPL) were within 2 dB(A) compared to experimental data. The average OASPL of numerical and experimental results at various measurement points differed by less than 1 dB(A). It should be noted that this study simplified the compressor numerical model to a single-passage model and the aerodynamic sound source to a dipole sound source, it lacked the ability to capture broadband noise accurately. But in general, it can be concluded that the numerical method used effectively simulates the compressor aerodynamic noise.

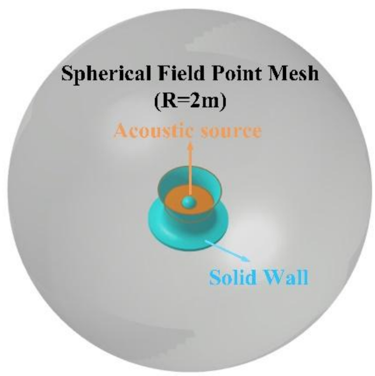


Figure 4 Acoustic numerical Model

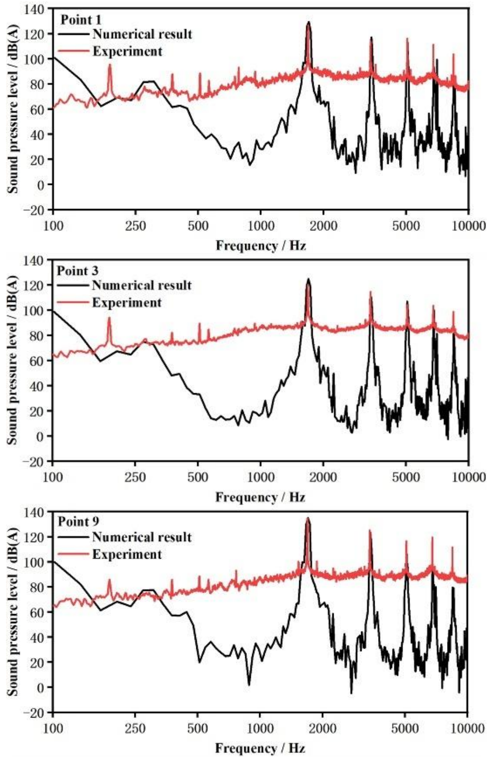


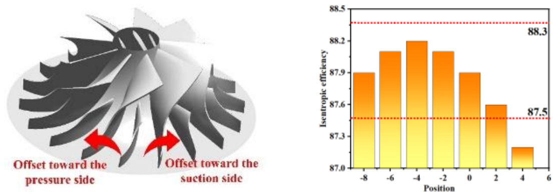
Figure 5 Comparison of noise spectra at different monitoring points

3 PARAMETER ANALYSIS

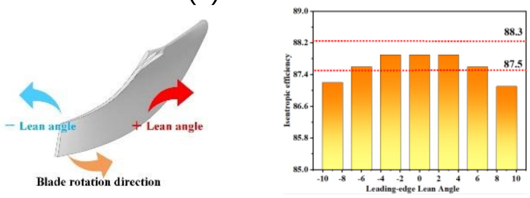
This study first investigated the effects of splitter blade position, leading-edge lean, trailing-edge lean, and leading-edge sweep angle on the compressor's aerodynamic performance. By analyzing the impact of these splitter blade parameters on aerodynamic performance, as shown in Figure 3, key parameters for optimizing the splitter blade design were identified.

To ensure that the compressor maintains high efficiency during the low-noise optimization design process, this study imposes a constraint on the parameter ranges to ensure that the compressor's maximum isentropic efficiency remains between 87.5% and 88.3%, since the original compressor efficiency at optimization point is 87.9%.

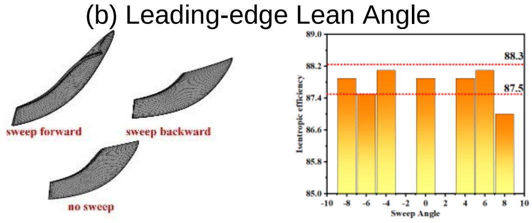
The results indicated that the trailing-edge lean of the splitter blade has a minimal impact on the compressor's aerodynamic performance. Thus, the optimization design for a high-performance, low-noise compressor was focused on adjusting the leading-edge lean angle, leading-edge sweep angle, and splitter blade position. The splitter blade position was varied between -8° and 2°, where positive angles represent alignment with the rotor's rotation direction, and negative angles are in the opposite direction. The leading-edge sweep angle was adjusted by modifying the position of the leading-edge rim, with a range of -5° to 5°, where a negative value represents forward sweep and a positive value represents backward sweep. The range of the leading-edge rim bending angle was also set from -5° to 5°, where positive angles align with the rotor's rotation direction and negative angles are opposite to it.



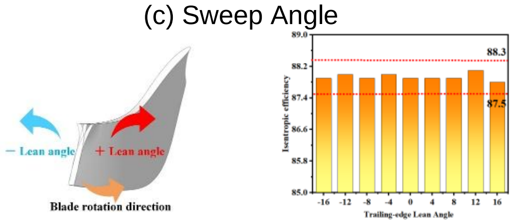
(a)Position



(b) Leading-edge Lean Angle



(c) Sweep Angle



(d) Trailing-edge Lean Angle

Figure 6 Influence of different parameters on compressor aerodynamic performance

4 OPTIMIZATION DESIGN

This research introduces the Kriging surrogate model to construct a fast analysis model, where the genetic algorithm repeatedly invokes the surrogate model during the optimization process to reduce computational effort [16]. Sampling points are randomly selected within the range of design parameter optimization, and their objective values are calculated to construct the Kriging surrogate model. The surrogate model is then used to quickly obtain approximate objective values for any new points in the design space [17]. The optimization process is shown in Figure 7. First, Latin hypercube sampling (LHS), a method for approximately random sampling from a multivariate parameter distribution, is used to randomly select initial sampling points. These points are then subjected to mesh generation and simulation calculations to establish the Kriging surrogate model. The surrogate model is evaluated using the mean square error (MSE). If the requirements are not met, the point with maximum error is added to the sampling points, and the surrogate model is reconstructed. If the requirements are met, the next step is to perform optimization and solution using the genetic algorithm. The computed solution is validated through simulation. If the error between the simulation result and the computed solution does not meet the requirements, the simulation point is added to the sampling points, and the surrogate model is reconstructed. If the error between the two satisfies the requirements, the solution is considered the global optimal solution.

In this study, Latin Hypercube Sampling (LHS) is used to randomly sample 40 initial points within the range of parameters for the leading edge tip lean angle, leading edge sweep angle, and the position of the splitter blades, as shown in Figure 8. The goal of this study is to optimize the compressor to achieve high efficiency and low sound pressure level, with a relatively stronger emphasis on noise optimization. Therefore, 3D simulations are performed for these 40 sampling points. The maximum isentropic efficiency value (EFF), the average sound pressure level (SPL_{ave}), and their linear combination (SPL_{ave}-0.75EFF) are calculated, and each is used as an objective function for subsequent optimization solving. The results are shown in Appendix 1.

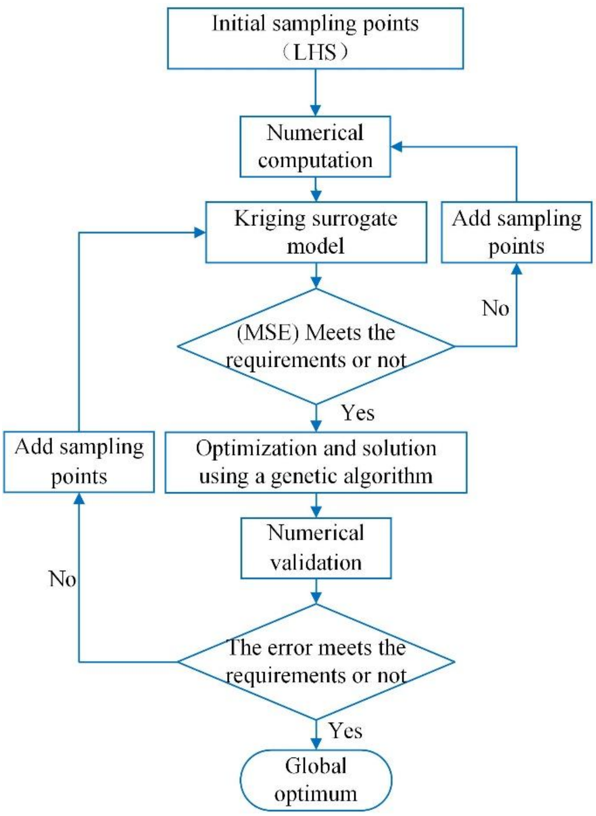


Figure 7 Optimization Process

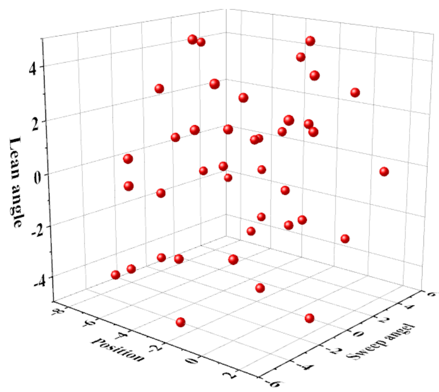


Figure 8 Results of Latin Hypercube Sampling

5 OPTIMIZATION RESULTS AND VALIDATION

5.1 Objective function EFF

The genetic algorithm is applied to the splitter blade optimization design, with the maximum isentropic efficiency as the optimization objective. The mesh is divided, and a 3D simulation is performed to solve the problem. The mesh is divided, and a 3D simulation is performed, with the results shown in Table 1. It can be observed that, in the first optimization, the error between the genetic algorithm's computed solution and the simulation result is 0.034%, meeting the accuracy requirement. The baseline compressor has a maximum isentropic efficiency of 87.9%, and the average overall sound pressure level at nine noise measurement points is 134.7 dB(A). Therefore, when the objective function is EFF, the maximum efficiency value, which is the global optimum, is 88.46%, representing an improvement of 0.56%. At this point, the leading-edge tip lean angle is -2.029°, the leading-edge sweep angle is -4.379°, and the splitter blade is shifted by 2.796° toward the pressure side of the main blade. Under these conditions, the average sound pressure level at nine points near the compressor inlet is 133.2 dB, reduced by 1.5 dB(A), effectively reducing the aerodynamic radiation noise of the compressor while improving aerodynamic performance.

Table1 Results for Optimization with EFF as the Objective Function

EFF /% (GA)	EFF /% (Simulation)	error/%
88.46	88.43	0.034

5.2 The objective function is SPL_{ave}

When the minimum average sound pressure level is used as the optimization objective, the mesh is divided, and a 3D simulation is performed, with the results shown in Table 2. It can be observed that the error between the computed solution from the genetic algorithm and the simulation result is 0.076%, meeting the accuracy requirement. Therefore, when the objective function is SPL_{ave}, the average sound pressure level at nine measurement points near the compressor inlet is 132.4 dB(A), which is reduced by 2.3 dB(A) compared to the prototype. At this point, the leading-edge tip lean angle is -0.18°, the leading-edge sweep angle is 1.967°, and the splitter blade is shifted by 1.539° relative to the pressure side of the main blade. Under these conditions, the isentropic efficiency of the compressor increases to 88.25%, effectively reducing the aerodynamic radiation noise while slightly improving the overall aerodynamic performance of the compressor.

Table2 Results for Optimization with SPL_{ave} as the Objective Function

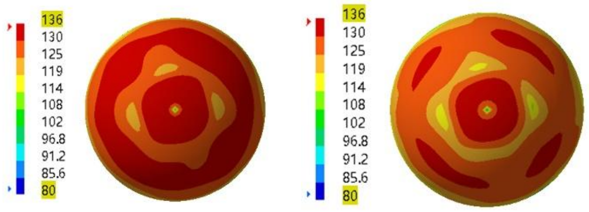
SPL_{ave} / dB(A) (GA)	SPL_{ave} / dB(A) (Simulation)	error/%
132.5	132.4	0.076%

5.3 The objective function is SPL_{ave}-0.75EFF

When the minimum value of SPL_{ave} -0.75EFF is used as the optimization objective, the results shown in Table 3. It can be observed that the error between the computed solution from the genetic algorithm and the simulation result is 0.093%, meeting the accuracy requirement. At this point, the maximum isentropic efficiency of the compressor increases to 88.39%, and the average total sound pressure level at the nine measurement points is 132.7 dB(A), reduced by 2 dB(A) compared to the prototype. The leading-edge tip lean angle is -3.805°, the leading-edge sweep angle is -4.987°, and the splitter blade is shifted by 2.874° relative to the pressure side of the main blade. The maximum isentropic efficiency of the compressor at this point is only 0.08% lower than when the maximum isentropic efficiency is used as the optimization objective alone, and the average total sound pressure level at the nine measurement points is only 0.23% higher than when the minimum aerodynamic noise is used as the optimization objective alone. Therefore, it can be concluded that when the minimum value of SPL_{ave}-0.75EFF is used as the optimization objective, the aerodynamic performance of the compressor is in the optimal state. The aerodynamic noise distribution at the compressor airflow inlet in BPF can be observed in the top view shown in Figure 9. It is evident that using SPL_{ave}-0.75EFF as the optimization objective significantly improves the aerodynamic noise radiating outward from the compressor airflow inlet.

Table3 Results for Optimization with SPL_{ave}-0.75EFF as the Objective Function

SPL_{avg} -0.75EFF (GA)	SPL_{avg} -0.75EFF (Simulation)	error/%
66.47	66.41	0.09%



(a) prototype machine

(b) objective function SPL_{ave}-0.75EFF

Figure 9 Aerodynamic noise contour of the compressor in BPF

6 CONCLUSION

This study introduced the influence of different parameters of diffuser blade on compressor performance, and a low-noise optimization of centrifugal compressor was performed. The conclusions are presented below:

(1) The CFD method and hybrid CAA calculation method can accurately simulate the discrete tonal noise of the centrifugal compressor's aerodynamic noise, with the error between each measurement point and the total sound pressure level within 1 dB(A).

(2) By modifying different structural parameters of the splitter blades and establishing multiple compressor models for numerical calculations, the study found that the front edge rim angle, leading edge sweep angle, and splitter blade position can significantly improve the aerodynamic performance of the centrifugal compressor and establish the reasonable optimization range for each parameter.

(3) Based on different objective functions, the Kriging surrogate model and genetic algorithm can quickly obtain the global optimal solution. Furthermore, under optimized conditions, the improvement in compressor performance due to each optimized impeller is very significant. Among them, when SPL_{ave}-0.75EFF is used as the optimization objective, the best optimization effect is achieved. At this point, the leading edge of the splitter blade shifts toward the pressure side of the main blade, and the leading edge of the splitter blade is swept forward and offset towards the pressure

side of the main blade. The maximum isentropic efficiency of the compressor increases by 0.56%, and the average sound pressure level of the inlet noise decreases by 2 dB(A).

(4) This study employs CFD method and hybrid CAA method, which has been widely validated. And the optimization process leverages a Kriging surrogate model-based genetic algorithm, which has been extensively validated across various fields, ensuring theoretical generalizability. While the methodology is fully applicable to large turbochargers, optimization outcomes may not universally extend to all compressors due to inherent impeller design variations, particularly in cases with significant differences in blade geometry or flow capacity. But optimization outcomes may not universally extend to all compressors due to inherent impeller design variations, particularly in cases with significant differences in blade geometry or flow capacity.

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Appendix 1

Table 1 Simulation results of initial sampling points

Sample	Position	Lean Angle	Sweep Angle	EFF	SPL_{ave}	SPL_{ave}-0.75 EFF
1	-5	-5	1	87.6	135.8	70.10
2	-8	5	-2	87.8	134.1	68.25
3	-3	1	1	87.9	134	68.08
4	-1	-1	-4	88.4	134.1	67.80
5	-4	0	0	88.3	133.8	67.58
6	-3	3	1	88.2	134.4	68.25
7	-5	-5	0	87.7	135.5	69.73
8	-4	2	-3	88.3	134.2	67.98
9	-1	2	-2	88.2	134.8	68.65
10	1	0	-5	87.9	134.3	68.38
11	0	1	2	88	133.1	67.10
12	-6	-2	-1	88.1	134.4	68.33
13	-4	-3	-3	88.4	135.8	69.50
14	1	0	2	87.9	134	68.08
15	-5	4	-3	88.1	134.7	68.63
16	2	-3	3	87.2	133.2	67.80
17	-2	-1	3	88	134.7	68.70
18	-6	-2	3	87.7	135.4	69.63
19	0	-4	-2	88.2	134.5	68.35
20	-1	1	-2	88.3	134.4	68.18
21	-2	3	4	88	134.9	68.90
22	-5	4	1	88	134.6	68.60
23	-7	2	-1	88	134.8	68.80
24	-6	-1	1	88.1	134.6	68.53
25	-4	-2	5	87.5	134.2	68.58
26	-2	2	1	88.3	134.3	68.08
27	2	4	0	87.2	135	69.60
28	-6	5	0	88	134.8	68.80
29	-1	-4	4	87.1	133.8	68.48
30	1	0	4	87.7	134.3	68.53
31	-3	-4	-5	88.4	133.4	67.10
32	-7	-3	-4	88.1	134.8	68.73
33	0	4	-3	87.8	134.3	68.45
34	-3	-3	2	87.7	133.5	67.73
35	-7	-4	-4	88.1	134.9	68.83
36	0	1	5	87.9	133.7	67.78
37	-2	-2	2	87.9	132.8	66.88
38	-7	-1	-4	88.1	134.8	68.73
39	1	3	3	87.7	134.8	69.03
40	-8	3	4	87.8	136.2	70.10