An Improved Design of a Swirl Distortion Generator

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Abstract. In order to study the effect of swirl distortion on the performance and stability of the compressor, this paper optimizes the design of the existing swirl distortion generator, and designs three different structures of pair swirl distortion generator. Using CFD technology, a comparative analysis of the standard pair swirl distortion flow fields and the pair swirl distortion flow fields produced by three newly designed swirl distortion generators and the existing pair swirl distortion generator is performed. The results show that the optimally designed distortion generator reproduces the standard pair swirl distortion flow field to a higher degree than existing distortion generators. On the three measurement rings, the average swirl angle error is reduced by 5.35%, 19.88%, and 8.22%. The total pressure recovery coefficient is increased by 2.2%, which proves that the design method in this paper is more reasonable and achieves the purpose of optimal design.

1. Introduction
The aviation propulsion system must have good reliability indicators and good performance indicators. Besides, due to the interaction between the inlet and the engine, a good aviation propulsion system requires the inlet and the engine to meet certain applicability indicators to ensure that the aviation propulsion system has a good stability margin. With the development of modern warfare, the stealth and mobility of advanced fighters has become the key to improve combat effectiveness. Due to its structural advantages, the S-duct inlet [1] is widely used in the new generation of stealth fighters, and the swirl distortion caused by this inlet [2][3] has gradually become the focus of attention in recent years.

The F-111A development program was forced to suspend due to stall issues that frequently occurred during flight test. In the late 1970s, the Tornado fighter [4] repeatedly encountered problems such as surge and even engine shutdown during the test flight. This caused a serious flight accident. This series of accidents has caused people to gradually pay attention to the problem of swirl distortion and try to
study the mechanism of swirl distortion on the engine by designing the swirl distortion generator. There are three main methods for generating swirl distortion: the guide vane method, the delta wing method, and the chamber-type swirl distortion generator. Govardhan [5] et al deflect the inlet flow through the guide vanes to obtain a specific swirl flow field[6]. This swirl distortion generator is based on the swirl flow field that may occur in actual situations. It can simulate general pair swirl and bulk swirl flow fields. However, it is not accurate enough to make the simulated flow field match the size of the swirl angle of the target flow field at any position. Based on the research of Govardhan, Flitcroft [7] et al used a method of placing a metal net on a load bearing device to generate an bulk swirl. Jiang Jian [8]-[10] of Nanjing University Of Aeronautics And Astronautics and TU Bao-feng [11] et al. also studied the swirl mechanism through a vane-type swirl distortion generator.

Genssler [12] et al used a delta wing method to generate swirl, and adjusted the size of the pair swirl and the position of the swirl core by adjusting the angle of attack and the position of the delta wing. However the delta wing method requires the generator to be placed in front of the engine, which may cause the delta wing to be sucked into the inlet and damage the engine.

Chamber-type swirl distortion generator, by adding an adjustable valve in front of the static pressure chamber, to ensure that only the incoming air from a specific angle can pass through the chamber. This can be adjusted by adjusting the size, position or quantity of the valve to control the direction of airflow to form different swirl pat-terms.

These three types of swirl distortion generators all have a certain degree of limitation, that is, they cannot generate complex pair swirl flow fields, and are not suitable for reproducing the complex pair swirl field patterns generated from real engine / body combinations.

Zhang Lei of Air Force Engineering University has designed a new type of swirl distortion screen, which can design a swirl distortion screen for the target swirl velocity vector field to generate the swirl distortion of the desired structure form. It is possible to reproduce the complex swirl distortion flow field formed by the S-duct inlet and the wing-body fusion aircraft during actual flight. However, the swirl distortion flow field produced by this swirl distortion generator is far from the target flow field. Based on Zhang Lei's research [19], this paper optimizes the pair swirl distortion generator [13] designed by it, and designs three new types of pair swirl distortion generators. Through the simulation calculation method, and then analysis from swirl angle distribution, swirl evaluation index, and total pressure loss coefficient.

2. Design method

In order to simulate the pair swirl distortion flow field, this paper optimizes the existing pair swirl distortion generator and uses a new CDA [14] blade to reduce the flow loss generated when the flow passes through the dis-tortion generator. According to the design method of the swirl distortion screen, three pair swirl distortion gen-erators: constant chord length and forward-swept and backward-swept blades on both sides are designed to compare the recurrence of the three to the standard pair swirl distortion flow field.

The existing pair swirl distortion generators are improved from the following three aspects: (1) The CDA airfoil with better gas flow performance is selected to eliminate or suppress the separation of the surface layer and reduce the pressure loss. (2) Find the best consistency and installation angle, so that
the swirl angle on the aero-dynamic interface (AIP) is closest to the swirl angle of the target flow field. (3) Reduce the interference between the blades by adjusting the blade layout.

2.1 Obtaining the target swirl field

Formula (1)-(3) give the standard pair swirl velocity vector field:

\[
\Omega = \frac{\Gamma}{\pi d^2}
\]

\[
u(x,y) = \frac{1}{2} \left( \frac{d\Omega}{d y} \right) \left( 1 - e^{d x - x_1 i \theta - y_1 j \phi} \right)
\]

\[
v(x,y) = \frac{1}{2} \left( \frac{d\Omega}{d y} \right) \left( 1 - e^{d x - x_1 i \theta - y_1 j \phi} \right)
\]

Table 1 is the relevant parameter values of the pair swirl in this paper:

| name   | value |
|--------|-------|
| \(a_s\) | 0.10  |
| \(\Gamma_0\) | 1     |
| \(x_1\)  | -0.15 |
| \(x_2\)  | 0.15  |
| \(y_1\)  | 0     |
| \(y_2\)  | 0     |
| \(a_s\) | 0.10  |

According to formula (1)-(3), the circumferential velocity at any point in the plane can be calculated. According to the definition of swirl angle formula (4), the axial velocity can be calculated as 6.31 m/s, and the maximum swirl angle is 16°.

\[
\alpha = \tan^{-1} \frac{u_x}{u_y}
\]

When the axial velocity is determined, a VC program can be written according to formula (1)-(4). The VC program can be used to determine the swirl angle at any position in the plane.

As shown in Figure 1, the initial line (red line) is arranged in the standard pair swirl velocity vector field, so that the direction of the red line is consistent with the swirl side, and then the blade line (blue line) is arranged perpendicular to the red line. In this model, each blade is Select 7 feature points on the line, and obtain the target swirl angle at each position according to the program. The 7 feature points are selected randomly with certain intervals between each point, and the left and right sides are symmetric. Then draw the corresponding blade at each feature point according to the obtained swirl angle.
2.2 Blade type selection

After obtaining the layout of the blades, it is necessary to determine the blade parameters at each feature point, mainly including the selection of the blade profile, the appropriate blade consistency, and the adjustment of the installation angle.

2.2.1 Blade type selection

In terms of airfoil, a controllable diffusion airfoil—CDA airfoil[15] with better gas flow performance is used instead of the uniform thickness airfoil which is adopted by existing swirl distortion generator, as shown in Figure 2.

![Image of blade type selection](image1)

Fig.2 CDA blade type

2.2.2 Consistency selection

In order to select the optimal consistency, a bulk swirl model with a constant chord length of 100 mm and a number of blades of 12 was set. Models were drawn using blades with bend angles of 5 °, 10 °, 15 °, and 20 °, and calculated through simulation. The relationship between the output consistency and the swirl angle is shown in Figure 3. When the consistency is greater than 1.45, the consistency has little effect on the swirl angle, and the swirl angle is similar to the expected target at this time, so 1.45 is selected as the blade consistency.

![Image of consistency selection](image2)

Fig.3 Relationship between consistency and swirl angle
2.2.3 Adjustment of installation angle

Set the bulk swirl model with a blade consistency of 1.45 and a number of 12 blades, and determine the relationship between the swirl angle and the blade bend angle through simulation calculations, as shown in Figure 4:

\[ \alpha = \beta + 1.55^\circ \]  \hspace{1cm} (5)

2.3. Drawing of pair swirl distortion generator model

As shown in Figure 5, three new models of pair swirl distortion generators were drawn based on the selected blade shape, consistency, and installation angle. Models with a constant chord length of M1; M2 consistency of 1.45 with blades swept back on both sides; pair swirl distortion generator model with M3 consistency of 1.45 on both sides of the blade swept forward.

3. Calculation method

The calculation domain of this paper is set up according to the single-stage low-speed axial-flow compressor test bench of the Plasma Laboratory of Air Force Engineering University. It is divided into three parts: the front pipe, the distortion section and the rear pipe, as shown in Figure 6. It is 1800mm, 300mm, and 800mm, and the diameter of the pipe is 600mm. Considering the actual situation of the
test bench, the AIP is set at 400mm at the exit of the distortion section.

![Computational domain](image)

In this paper, the ICEM software is used to divide the three-dimensional computing grid. The front and rear pipes and the distortion section use tetrahedral unstructured grids. After grid independence verification, when the number of grids reaches 7.5 million, the number of grids is calculated. The effect of the results can be ignored, the final distortion segment mesh number is 8.4 million. The numerical simulation calculation uses CFD commercial software ANSYS CFX. The inlet boundary conditions set are total pressure 101325pa, total temperature 288K, outlet boundary condition mass flow 6.5Kg / s, wall surface adopt adiabatic non-slip boundary conditions, the convergence criterion is set to reduce the relative change of each quantity to be solved to $10^{-5}$, and monitor the inlet and outlet flow conditions. The total number of grids in the entire calculation domain reaches 11 million. Turbulence model selection k-ω turbulence Model. When studying swirl distortion, the ideal position of AIP is close enough to the cross section of the engine inlet to ensure that the swirl flow field of AIP is the same as the swirl flow field flowing into the engine, and that the gas flowing through AIP can flow into the engine. Therefore, the selection of the AIP surface must meet the requirements of both total pressure distortion and swirl distortion research. Because this article only studies swirl distortion, and the airflow velocity in simulation conditions is very low, the pressure loss is small and the total pressure distortion is negligible, so AIP surface is selected as the compressor inlet. According to the size of the laboratory single-stage low-speed axial flow compressor test bench, AIP is set at the inlet section of the compressor, that is, 400mm away from the distortion section\cite{16}\cite{17}.

4. Results analysis

In order to compare the reproducibility of the standard pair swirl distortion flow field of the pair swirl distortion generator designed in this paper with existing distortion generator, the swirl angle, the swirl evaluation index, and the total pressure loss are used to analyze the recurrence of constant chord length, consistency 1.45 swept back, consistency 1.45 swept forward pair swirl distortion generator and existing pair swirl distortion generator to the standard pair swirl distortion flow field.

4.1 Swirl angle simulation results

The velocity vector diagram and the swirl angle cloud diagram of the target flow field and the flow field obtained from the pair swirl distortion generator are shown in Figure 7. Among them, the swirl flow field obtained by the existing pair swirl distortion generator is M0, the swirl flow field obtained by constant chord length pair swirl distortion generator is M1, and the swirl flow fields obtained by the pair swirl distortion generator of the blades swept back and swept forward on both sides are recorded
as M2 and M3.

(a) Standard pair swirl flow field

(b) M0

(c) M1

(d) M2
It can be seen from the figure that the swirl flow field M1, M2, M3 obtained after the optimization of the swirl distortion generator is closer to the distribution of the velocity vector or the swirl angle than the swirl flow field M0 obtained from the existing swirl distortion generator. It is particularly obvious at the swirl core.

4.2 Flow field analysis

In order to quantitatively compare the reproducibility of M0, M1, M2, and M3 for the standard pair swirl flow fields, and compare the flow fields M1, M2, and M3 formed by three improved models of swirl distortion generator. In this section the swirl flow field will be analyzed from the swirl angle, the swirl distortion evaluation index and the total pressure loss.

4.2.1 Distribution of swirl angle

In order to specifically compare and analyze the similarity of the distortion flow field, three measurement rings were selected on the AIP. The swirl angle distribution of each model on the measurement ring is shown in Figure 8 (b)-(d). On the three measurement rings R1, R2, and R3, the maximum error and average deviation of M1, M2, and M3 from the target swirl angle as shown in table 2.

| Ring position | M0  | M1  | M2  | M3  |
|---------------|-----|-----|-----|-----|
| R1            | 1.114 | 0.910 | 0.912 | 0.918 |
| R2            | 1.647 | 1.122 | 0.798 | 1.003 |
| R3            | 2.565 | 3.012 | 2.558 | 2.968 |
| average error | 1.776 | 1.681 | 1.423 | 1.630 |

According to the table, it is found that the flow field of M1, M2, and M3 is closer to the target flow field than that of M0 on the R1 ring, and the error of M1, M2 and M3 is similar. On the R2 test ring, the errors are relatively large, but it can be seen that the errors of M2 and M3 are small. On the R3 test ring, the four have a large gap with the target flow field, of which M2 is the best. In summary, we can see that in terms of the swirl angle distribution, the optimal design effect of the distortion generator is obvious, especially on the R1 and R2 rings. Besides, from the average errors we can see the swept forward and swept back models are more accurate than the constant chord length model. The
flow field created by the swept forward models is closest to the target flow field.

![Schematic diagram of ring measurement](image)

(a) Schematic diagram of ring measurement

![Graph](image)

(b) R1

(c) R2

(d) R3

Fig.8 Schematic diagram of ring position and swirl angle distribution of different models on the ring

4.2.2 Analysis of simulation results

In order to further compare and analyze the simulation results, based on the relevant standards for the evaluation of swirl distortions air5868 \cite{18} prepared and issued by the S-16 committee, we selected the following four indicators as the evaluation criteria of the swirl distortions we studied this time. They are: Swirl Sector SS, Swirl Intensity SI, Swirl Pair SP, and Swirl Directivity SD.

1) Sector Swirl SS

The Sector Swirl values on the three measurement rings are shown in Figure 9.

Analyze the Sector Swirl of the three measurement rings: On the R1 measurement ring, M1 is closest to the target flow field, and the error is the smallest, but the error of M1 becomes larger as the distance of the selected measurement ring from the center of the circle increases. However, the overall performance is better than M0. For M2 and M3, the blade chord length at R1 is more likely to cause pair swirl mixing, and the error is slightly larger than M1. On R2 and R3, we can see that M2 is related to the target flow field. The reproduction effect is the best, and the error is the smallest. The degree of reproduction of M3 on the R2 measurement ring is similar to M2, but the error increases rapidly with the increase of the radius.

In general, the three improved models have better reproducibility of the target flow field than the existing model M0, and the combination of the three measurement loops shows that M3 is better than M1 and M2 has the best effect.
(2) Swirl Intensity SI

According to Figure 10, it can be found that, on the three measurement rings, the Swirl Intensity of R1 is the largest, R3 is the second, and R2 is the smallest, and the trend of M0 ~ M3 is consistent with the target flow field. The law of the average error of the Swirl Intensity on each measurement ring. It is similar to the Sector Swirl, so won't go into details.

Combining the evaluation indicators SS and SI, it can be found that M2 is closer to the target flow field in the distribution and intensity of the swirl angle, and the recurrence of M1 and M3 are also better than the flow field M0 generated by the existing distortion generator. On the R1 and R3 rings M1 is similar to M3. On the R2 rings M3 is closer to the target flow field than M1 obviously.

(3) Swirl Direction SD

The standard Swirl Direction of the pair swirl flow field is 0. From the figure 11, we can see that the Swirl Direction values of the M0 ~ M3 flow field on the three measurement rings are approximately 0, and M0 ~ M3 on the three measurement rings. There is a small difference in the value of the swirl direction of the flow field. This indicates that there are equivalent reverse swirl on the three measurement rings, and the four distortion generators all have a good reproduction effect on the Swirl Direction. The difference between the four is little.
By analyzing Figure 12: On the R1 and R3 measurement rings, the Swirl Pair in the M0 ~ M3 flow field are close to 1, indicating that there is an equivalent reverse swirl on the measurement ring. On the R2 measurement ring, the target flow field SP is 2.07, because the target flow field has three positive swirl sectors and three negative swirl sectors on the R2 ring, and the intensity of these two sets of positive and negative swirl sectors is larger than the third group, and the intensity of these two groups of positive and negative swirl sectors is similar, so the standard pair swirl flow field at R2 measurement ring has a SP of 2.07. However, M0 ~ M3 only generates two swirl sectors on the R2 measurement ring. The intensity of the two swirl sectors of M3 is similar, with SP of 1.8. M2 is 1.56, M1 is 1.55, M0 is 1.2, and the error of M3 is the smallest, followed by is M2.

It can be seen from the figure that, on the three measurement rings, according to Swirl Pair, M3 is the closest to the target flow field, which proves that the intensity of the swirl sector of M3 is similar on the three measurement rings, and the swirl angle distribution is more uniform; followed by M2, except for R1 measurement ring (the gap between M0 and M2 at R1 measurement ring is small), it is closer to the target flow field in swirl angle distribution, which proves that the swirl angle distribution of M2 flow field is also more uniform; M1 flow under the evaluation index of Swirl Pair, the gap between the target flow field and the target flow field on R1 and R3 is the largest, indicating that the constant-angle distortion generator has a more uneven swirl angle distribution than the constant distortion generator.

4.2.3 Total pressure loss
The M0 model uses a uniform thickness airfoil, which is easy to cause flow separation at the leading and trailing edges of the blade, which will cause a large pressure loss. As can be seen from the figure 13, after using the CDA airfoil (M1 ~ M3 model), the total pressure loss is significantly reduced, of which The total pressure recovery coefficient of the swept back M2 and the swept forward M3 reached 0.999, and the total pressure loss was the smallest. The existing model M0 model had a total pressure recovery coefficient of 0.977, and the total pressure loss was the largest.

![Fig.13 Total pressure recovery factor](image)

**Conclusions**

In this paper, three optimization models for pair swirl distortion generators are designed--constant chord length pair swirl model, two sides of blades swept back and swept forward pair swirl models. The similarity between the pair swirl flow field obtained by the these models and the standard pair swirl flow field was compared and studied in detail using CFD technology, and compared with the pair swirl flow field obtained by the existing pair swirl model. The conclusions are as follows:

1. During the design phase of the swirl distortion generator, by studying the bulk swirl model, it was found that when the blade consistency is 1.45 and the installation angle is 1.55 °, the swirl angle on the AIP is closest to the expected.

2. The CDA airfoil used in this model effectively suppresses air flow separation, improves the accuracy of flow field reproduction, and effectively reduces the total pressure loss, and the total pressure recovery coefficient is increased by 2.2%.

3. The flow field (M1, M2, and M3) generated by the model designed in this paper are more similar to the standard pair swirl flow field than the flow field (M0) generated by the existing swirl distortion generators. On the three measuring rings, the average swirl angle errors are reduced by 5.35%, 19.88%, and 8.22%. The design method in this paper is more reasonable and effective, and achieves the purpose of optimization.

4. The swept forward and swept back models are more accurate than the constant chord length model, and the swirl angle distribution position is more accurate. Combined with the swirl evaluation index, the swept back model has the highest reappearance of the target flow field as a whole which proves that the constant consistency swept back layout is the most reasonable.

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