Influence of dry run speed on the cleaning of compressor blade

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Abstract
To optimize the on-line cleaning process parameters of aero-engines, the influence of the engine’s dry run speed on the cleaning flow field was analysed. Through the reverse modelling and numerical simulation of the CFM56-7B compressor, the changes of static pressure, velocity and vorticity of the cleaning flow field under different dry run speeds were analysed. The results showed that the static pressure and speed of the cleaning flow field increased linearly with the increase of the dry run speed; the vortex of the cleaning flow field decreases with the increase of the speed, but the increase of the speed was beneficial to the cleaning of the compressor. Through the aero-engines online cleaning test, comparing the recovery of EGTM at different speeds, when the engine dry run speed was 323 r/min, a better cleaning effect and higher economic benefits can be obtained. The research can provide a theory for engine online cleaning.

1 | INTRODUCTION

During the working process of aero engine, suspended particles such as dust and salt are inhaled and deposited on the surface of the compressor blade and casing wall, which increases the surface roughness and airfoil thickness of the blade, resulting in a decrease in inlet air flow and an increase in the thickness of the boundary layer on the blade surface. The performance of the compressor is reduced [1, 2], and the exhaust gas temperature margin (EGTM) is reduced. In severe cases, it will cause engine surge and affect the reliability of aircraft operation [3–5]. To obtain the same thrust, more fuel will be consumed, which will increase fuel consumption and increase airplane operating costs. When the pollution is serious, the engine will be replaced in advance to reduce the time of the aircraft engine on the wing, and increase the frequency of engine disassembly and repair, leading to higher maintenance costs for airlines.

The online cleaning of aero-engines can effectively slow down the performance degradation of gas path components, prolong the service time of the engine on the wing, and save maintenance costs. Through online cleaning, the surface roughness can be reduced, the effective surface between the blades can be increased, and the air flow can be increased, which is an economic and effective means to restore the aerodynamic performance of the compressor [6]. On-line cleaning is to install a cleaning device at the air intake lip of the aircraft. The engine is powered by the starter of the aircraft engine and rotating at a low speed. The cleaning fluid enters the engine after being atomized through the nozzle to achieve cleaning [7, 8]. The cleaning process parameters are the key to the cleaning effect. Zhang [9] studied the cleaning process of shipborne aircraft engine and the running state of washing equipment in cold and analysed the concentrations of cleaning solution on cleaning effect. Chiariotti [10] used the unidirectional coupling method to analyse the motion of multiphase flow, ignoring the effect of droplets on the airflow, and the Lagrange method is used to track the droplets. The erosion simulations of 25- and 100-micron droplets were carried out respectively, and it was found that the erosion was proportional to the droplet size, and the erosion at the leading edge of the blade was serious. Keyi et al. [11] used the flow field simulation method to determine the cleaning method and cleaning jet parameters of a certain type of turbofan engine, and concluded that the mass flow parameters of cleaning fluid, but the influence of nozzle back pressure and cleaning fluid flow on cleaning effect cannot be determined by compressor flow field simulation for lack of online cleaning test.

The research on the mechanism of aero-engine cleaning flow field mainly focuses on the research of engine droplet parameters on the cleaning flow field, and the lack of comparison of online experimental results leads to the fact that the research results cannot be applied to the actual engine cleaning. In this paper, numerical simulation and experimental analysis are used...
to analyse the cleaning flow field at different speeds by combining numerical simulation and experimental analysis. The variation law of static pressure, velocity and vorticity of the cleaning flow field is explored, which provides an important theoretical basis for the optimization of online cleaning process parameters. The simulation results are applied to online cleaning, and the cleaning speed is optimized, which provides important theoretical support for the optimization of online cleaning process parameters of aero-engine.

2 CONSTRUCTION OF DESCALING MODEL FOR COMPRESSOR BLADES

2.1 The establishment of erosion and descaling mechanical model

Figure 1 is a schematic diagram of online engine cleaning. The droplets atomized by the nozzle enter the engine and interact with the fouling on the surface of the blade. To obtain the effect of dry run speed on the cleaning result, the first step is to establish a descaling kinetic model.

In the boundary layer of the blade surface, the micro-element on the blade surface is regarded as a plane area, the airflow direction is the $x$ axis, and the direction perpendicular to the blade surface is the $y$ direction. The particle dynamics model is shown in Figure 2. The fouling particles are subjected to adhesion force $F_A$ on the blade surface, and when the fluid in the boundary layer flows through the fouling particles adhered to the blade surface, the drag force $F_D$, lift force $F_L$ and rolling moment $M_D$ exerted by the particles by the fluid are expressed as [12]:

$$F_D = 1.7009 \cdot 3\pi \mu dv$$  \hspace{1cm} (1)

$$F_L = 1.615\mu d\left(\frac{\rho \mu dv}{\mu dv_0} \right)^{\frac{1}{2}} v$$  \hspace{1cm} (2)

$$M_D = 0.943993 \cdot 2\pi \mu d^2 v$$  \hspace{1cm} (3)

where the constant 1.7009 accounts for the effect of the surface on the drag force, the constant 0.943993 accounts for the effect of the surface on the external moment, $\mu$ is the fluid viscosity, $d$ is the diameter of the fouling particles, $v$ is the fluid velocity at the center of the particle, and $\rho$ is the fluid density.

Previous research results show that, relative to lifting removal and sliding removal, rolling removal is the main mechanism of scale removal [13]. From the moment balance theorem, the rolling removal mechanism can be expressed as:

$$M_D + F_D \cdot l + F_L \cdot a \geq F_A \cdot a$$  \hspace{1cm} (5)

In addition, as shown in [14], the effect of lift on particle removal is negligible. Therefore, the above formula can be simplified as:

$$M_D + F_D \cdot l \geq F_A \cdot a$$  \hspace{1cm} (6)

The size of the scouring force depends on the flow state of the fluid around the particles. The above formula can rewrite the critical fluid velocity of the fluid in the centre of the fouling particles:

$$V \geq \frac{F_A \cdot a}{1.7009 \cdot 3\pi \mu dv + 0.943993 \cdot 2\pi \mu d^2}$$  \hspace{1cm} (7)

The fluid in the boundary layer flows over the surface of the fouling particles, and the viscous bottom layer of the fluid generates a scour torque on the particles. When the scour torque is greater than the adhesion torque of the fouling particles, the fouling particles are successfully removed. Based on this mechanism, the critical fluid velocity model is used to define the criteria for particle removal from the blade surface. The lowest critical fluid velocity for fouling particles to be removed from the blade surface is the particle starting velocity. When the critical fluid velocity of the fouling particles is greater than the particle starting speed, the fouling particles can be successfully removed. For the particle adhesion force is known, the removal of
FIGURE 3  Compressor blade model

particles can be predicted based on the drag and lift forces acting on the particles. It can be seen from the above formula that the critical fluid velocity of particles mainly depends on particle adhesion, fluid flow rate, viscosity and particle diameter. The online water washing of aero-engines reduces the adhesion of the particles through the wetting effect of droplets on the particles, reduces the starting speed of the particles, and completes the online cleaning of the aero-engine.

2.2 Descaling geometric model construction

The 1.5-stage compressor blades of the CFM56-7B turbofan engine are selected, and the computational physical model is composed of inlet guide vanes, a first-stage rotor, a stator and the wall of the inner duct. The inlet guide vane, stator and rotor of the engine are rotationally symmetrical. The number of inlet guide vanes, rotor and stator blades is 80. In order to save computing resources and speed up the calculation convergence, the circle 1/80 is selected to establish a single blade flow channel model, and the rotation period is set the boundary conditions can meet the simulation calculation of the entire cleaning flow field. The computational physical model of the compressor is shown in Figure 3.

2.3 Turbulence model

The Reynolds time-averaged Navier–Stokes equation is used in the numerical simulation of turbulence. Compared with the direct numerical simulation method, it has a relatively small amount of calculation and moderate calculation accuracy. The compressor flow field is a flow field with a pressure gradient, and the shear stress transport k-model is adopted, which is more accurate for the calculation of the viscous sublayer and the negative pressure gradient [15]. The transport equations of turbulent kinetic energy and turbulent large eddy frequency are:

\[
\frac{\partial (\rho k \omega)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \frac{\partial k}{\partial x_j} \right] - \rho \beta^* k \omega \tag{8}
\]

\[
+ \min \left( \mu_t S^2, 10 \rho \beta^* k \omega \right) + S_k
\]

\[
\frac{\partial (\rho \omega \omega_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \frac{\partial \omega}{\partial x_j} \right] - \rho \beta^* \omega^2 + S_\omega
\]

\[
+ \frac{\alpha \mu}{\mu_t} \min \left( \mu_t S^2, 10 \rho \beta^* k \omega \right) \tag{9}
\]

\[
+ 2(1 - f_1) \rho \sigma_{\omega,2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}
\]

The turbulent viscosity \( \mu_t \) is:

\[
\mu_t = \frac{\rho k}{\omega} \frac{1}{\max \left( \frac{1}{\alpha^2}, \frac{\sqrt{c_f}}{\omega} \right)} \tag{10}
\]

In the near-wall area, the fluid flow is greatly affected by the fixed wall, and the accuracy of the numerical simulation results is closely related to the near-wall simulation effect. Using the \( k-\omega \) model, the near-wall surface is a low Reynolds number model. The height of the first layer of grid directly determines the authenticity of the near-wall surface simulation. The low Reynolds number model should meet \( y^+ \leq 1 \), and the best approach is 1.

2.4 Meshing

In order to better capture the boundary layer flow, this paper performs mesh refinement on the blade surface, and adds hexagonal triangular prism grids to the near-wall boundary layer. According to the different wall treatment methods selected, there are also different requirements for the height of the first layer of grid. The grid height of the first layer of the low Reynolds number model chosen in this paper satisfies \( y^+ \leq 1 \), the calculation formula is as follows:

\[
y^+ = \frac{\Delta y \mu_t}{v} \tag{12}
\]

where \( \Delta y \) is the distance from the centre of mass of the first layer of mesh to the wall, \( \mu_t \) is the friction speed, and \( v \) is the kinematic viscosity.

The calculation formula of the grid height \( \Delta y \) of the first layer is as follows [16]:

\[
\Re_{L} = \frac{\rho U_{\infty} L}{\mu} \tag{13}
\]

\[
\mu_t = U_{\infty} \sqrt{\frac{\epsilon_f}{2}} \tag{14}
\]

\[
\epsilon_f = 0.027 \Re_{L}^{-1/7} \tag{15}
\]
Reₜ = CReₜ, C is the score, C⁻¹/₇ ≈ 1. Then bring the above formula into the available Δy:

\[ Δy = L \sqrt{\sqrt{\frac{74}{l}} Re_{\text{L}}^{-13/14}} \] (16)

In the formula, L is the characteristic length, Reₜ is the Reynolds number, cₜ is the wall shear stress coefficient, Uₜ is the characteristic velocity, and µ is the dynamic viscosity.

According to the above formula, the height of the first layer of prism grid is 0.0025 mm under the conditions \( y^+ \leq 1 \) that are satisfied.

During the meshing process, the local boundary grid size setting determines the number of grids. In the numerical simulation, the numerical calculation results of different grid numbers may be different. In order to ensure the accuracy of the calculation results, the grid independence verification is also required. While ensuring the accuracy of the calculation results, it is necessary to save computer resources and select the appropriate number of grids. Under the condition that the height of the first layer of prism grid is the same and the geometric topology of the grid is the same, the grid size is modified and the average exit velocity is monitored. The result is shown in Figure 4. It can be seen from the figure that after the number of grids exceeds 4 million, the average exit velocity no longer changes drastically with the change of the number of grids. The number of grids in the calculation model in this paper is not less than 4.857 million, which has nothing to do with grids.

### 2.5 Boundary condition parameters

According to the airline manual, the mass flow rate of the cleaning fluid is 21 L/min, and the cleaning fluid is pure water at 80 °C. The rated speed of the low-pressure rotor speed N1 of the CFM56-7B engine is 5380r/min, and the low-speed dry run speed is 3%, 4%, 5%, 6%, and 7% of the N1 speed to compare and analyse the effect of dry run speed on the cleaning flow field. During engine operation, the fan boost ratio is between 1.5 and 1.8, and the average pressure ratio of the unipolar compressor blades is 1.5–1.6 [17]. The inlet pres-

### Table 1: Boundary condition

| Dry run speed (r/min) | 161 | 215 | 269 | 323 | 377 |
|-----------------------|-----|-----|-----|-----|-----|
| Inlet pressure /atm   | 1.024 | 1.032 | 1.04 | 1.048 | 1.056 |
| Outlet pressure /atm  | 1.044 | 1.057 | 1.071 | 1.086 | 1.098 |
| Cleaning droplet size /μm | 300 |
| Jet pressure /bar     | 3   |
| Fluid temperature /°C | 80  |
| Flow / L/min          | 21  |

### Figure 5: Static pressure cloud diagram at different leaf heights at 323 r/min

3 | RESULTS AND ANALYSIS

#### 3.1 The effect of dry run speed on static pressure of cleaning flow field

Through numerical simulation, the influence of dry run speed on pressure change of cleaning flow field is obtained. Figure 5 shows the static pressure distribution of a single blade at different blade heights at a speed 323 r/min. From the figure, it can be concluded that at the same speed, the pressure change along the blade height direction is small, and the pressure field distribution law is consistent. This is mainly because in the calculation domain, after the compressor blade speed is determined, the inlet and outlet pressures maintain a certain value, leading to the increase of static pressure in the compressor basin. The speed has a certain influence on the pressure distribution of the cleaning flow field.
3.2 The influence of dry run speed on cleaning flow field speed

Analyse the boundary layer velocity of the cross-section at 50% of the leaf height under the three rotation speeds, and the velocity cloud diagram is shown in Figure 7. It can be seen from the figure that with the increase of the dry run speed, the air velocity near the wall of the suction surface of the blade decreases significantly, the thickness of the boundary layer at the tip of the blade decreases greatly, and the air velocity on the pressure surface increases greatly, so the boundary layer thickness also decreases a lot. Compared with the leading edge of the suction surface of the blade, the speed increase at the trailing edge is not obvious, and the increase of the dry run speed has a greater impact on the speed of the leading edge of the blade. It can be predicted from the velocity cloud graph that the wall shear force at the leading edge of the blade changes significantly.

Figure 8 shows the changing trend of the section velocity of the compressor blade under different speed conditions and different blade heights. It can be seen from the figure that under the same speed conditions, the average speed of the cylindrical section first increases with the increase of the blade height. It tends to decrease after large and reaches the maximum near the 60% blade height area. This is because the cleaning flow field has viscous friction and velocity gradients on the compressor hub wall and casing wall, which hinders the average velocity value. Effect: Under the same leaf height condition, in the 15–80% leaf height area, the average speed of the cleaning flow field increases with the increase of the compressor blade dry run speed. In the 80–90% leaf height area, the average speed value of the cleaning flow field decreases with the increase of the compressor blade dry run speed. This is mainly because as the compressor blade speed increases, the more work it does on the cleaning flow field, the more kinetic energy of the cleaning flow field is larger, the larger the average velocity value of the cylindrical section, and as the height of the blade increases, in the region close to the casing wall, the higher the speed of the compressor blade, the stronger the effect of centrifugal force and viscous forces, resulting in more speed attenuation fast.

3.3 The influence of dry run speed on the vorticity of cleaning flow field

Analyse the change of the vortex field at different blade heights for a single blade. As shown in Figure 9, when the engine speed is 323 r/min, the vorticity of the cleaning flow field is distributed along the blade height. The vortex field changes more drastically towards the top of the blade, which is mainly affected by the airflow in the clearance at the top of the blade, which accelerates the instability of the flow field.

Figure 10 shows the change trend of the vorticity of the compressor blades at different blade heights under different speed conditions. It can be seen from the figure that under different speed conditions, as the blade height increases, the average vorticity value of the cylindrical section is the trend of first decreasing and then increasing, the vorticity value is the smallest in the 30–75% cross-sectional area. This is because in the main flow area, the effect of the flow field velocity and the wall surface is weak, and more of it passes through the compressor blades along the airflow direction. So the cross-sectional vorticity value is the smallest; under different blade height conditions, within the range of 15–80% blade height, as the speed
increases, the cylindrical cross-section vorticity value decreases instead, because the cleaning at lower speed. The effect of the flow field and the compressor wall is stronger than the cleaning of the flow field and the compressor wall when the speed is higher. In the range of 80–90% blade height, the higher the speed, the larger the average vorticity of the cross section. In this case the centrifugal force generated by the rotation plays a great role in cleaning the flow field.

3.4 | Dry run speed optimization

When the jet parameters are fixed, the speed of the compressor blades is changed, and the static pressure, speed and vortex changes of the cleaning flow field under different speed conditions are obtained. From the perspective of static pressure, increasing the speed to increase the static pressure of the cleaning flow field is not a necessary condition for parameter optimization; from the perspective of speed analysis, along the direction of the leaf height, the average cross-sectional velocity value increases first with the increase in speed. The higher the speed of the compressor blades, the faster the average speed value decays close to the casing wall, and the better the speed increase effect on the flow field close to the hub wall. According to the changing trend of the flow field speed, the compressor is dry run speed is 323 r/min. It is more appropriate. From the perspective of vorticity, the increase in compressor speed can significantly improve the transport characteristics of the cleaning flow field, which has a greater impact on the vorticity of the single-stage compressor flow field, but Multi-stage compressor cleaning is still advantageous. The increase in speed can improve the online cleaning effect of the engine. However, it will cause the starter to generate heat and reduce the working time with the speed increases. Set the dry run speed to 6% of the N1, the 323 r/min is the best choice.

4 | EXPERIMENTAL TESTING AND ANALYSIS

Exhaust gas temperature targin (EGTM) refers to the difference between the exhaust gas temperature limit specified by the engine manufacturer and the engine exhaust temperature at the inflection point temperature. The inflection point temperature is the maximum atmospheric temperature at which the engine manufacturer can guarantee maximum thrust (or power) during takeoff. EGTM is the core parameter for airlines and engine manufacturers and maintenance companies to monitor engine performance. Using EGTM data can diagnose engine faults, infer engine life, develop maintenance and cleaning plans, monitor the running-in status of new engines, and check the quality of overhauls. Generally, EGTM will recover to varying degrees after online engine cleaning, so EGTM is also regarded as an important indicator for evaluating the effect of engine online cleaning.

The CFM56-7B engine of the National Bank Boeing aircraft was used to carry out an online cleaning test. As shown in Figure 11, the cleaning fluid enters the engine through the injection system and is squirted from the tail nozzle. According to the simulation analysis results, the effect is better when the speed is higher. Therefore, the test only selects the speeds of 269, 323 and 377 r/min for testing. During the test, the cleaning pressure is 3 bar and the cleaning fluid temperature is 80 °C, the flow rate is 21 L/min, and the size of the cleaning liquid after atomization is 300μm. The cleaning parameters are shown in Table 2.

The left and right engines of the two aircraft were cleaned and compared and analysed to obtain the cleaned engine EGTM data, and the obtained EGTM data was preprocessed to eliminate noise points and gross errors and smooth the data to eliminate interference. The recovery of EGTM as shown in Figure 12 is obtained.

In the Figure 12, compare and analyse the cleaning effect of two engines of the same aircraft, EGTM has the best recovery effect when the engine’s dry run speed is 323 r/min, which is
5 CONCLUSION

In this paper, the first-stage rotor flow field model of CFM56-7B engine was established. Through numerical simulation method, k-turbulence model was used to simulate the changes of static pressure, velocity and vorticity of compressor cleaning flow field under different dry run speeds. The influence of dry run speed on cleaning flow field characteristics was analysed. On this basis, the optimization selection of engine water washing dry run speed was carried out, and the engine online cleaning test was compared and analysed. The following conclusions can be obtained:

1. The static pressure in the cleaning flow field increased with the increase of the dry run speed. When the rotating speed increases within a certain range, the static pressure in the flow field was evenly distributed, which was conducive to cleaning. When the rotational speed increases, the velocity of cleaning flow field attenuates faster near the casing wall. When the rotational speed increased, the average cross-sectional vorticity of the cleaning flow field in the range of 80–90 % blade height increases, and the centrifugal force can better improve the cleaning effect.

2. According to the simulation results of the cleaning flow field, the improvement of the compressor dry run speed can effectively improve the flow field transportation characteristics, and then improve the cleaning effect on the line. Based on the simulation results and the cleaning requirements on the line, the optimized cleaning dry run speed is 323 r/min. The results were applied to the on-line cleaning of the engine. The results showed that the recovery effect of the EGTM after cleaning meets the requirements of the route operation, and the engine loss was small.

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