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Research article

Analysis of the effects of dust particle flow motion on the geometrical parameters of compressor blades in a gas turbine engine

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ABSTRACT

The axial compressor of a gas turbine engine is the main part that determines the characteristics of the engine (aerodynamic characteristics, geometry, weight, efficiency, reliability, etc.). The technological features of blades in axial compressors have a fundamental influence on the aerodynamic-dynamic characteristics of engines and their reliability during operation. The strength characteristics of the compressor blade and rotor also have a basic effect on the reliability performance; then, the breakage of the compressor blade can lead to local destruction of the engine and cause disaster for the plant. Considering the operating conditions of compressor blades and their role in gas turbine engines, it is found that compressor blades are a decisive factor in the reliability and quality of engines. When the compressor blade is damaged, it is understood as a change in geometrical characteristics, weight, physical and chemical properties of the substrate and coating, etc., due to the influence during engine operation. For the outside of the blade, the leading edge of the blade is often eroded (changing the radius of the leading edge, reducing the length of the pitch); damage by foreign bodies (significant deformation of the profile); change the shape of the tips of the blades; excessive roughness of the surface of the blades. It is mainly caused by foreign objects such as dust particles in the air, contamination of the blades, and significantly increased surface roughness of the blades. Therefore, it is necessary to pay attention to the exploitation of the engine and to solve the problem of causes and rules of erosion, pitting, and roughness. The article presents the results of studying the movement rules of dust particles in the clearance of the flow path of the axial compressor and the general characteristics of erosion, the change in shape of the compressor blade and other parameters and the characteristics of the gas turbine engine. This article presents a model to calculate the basic parameters of air flow and dust particles moving in the flow path of the compressor. Simulation can be performed using the ANSYS Fluent application, thereby comparing the assessment of the actual results with those of surveys. The results presented in the envelope are the basis for studying the negative effects of operating conditions on the engine, as well as proposing effective measures to protect the compressor blade from erosion and the methods of diagnostics of gas turbine engine.

Key words: dust particle, erosion, air flow, flow path, axial compressor blade

INTRODUCTION

From reality through analysis a varies of the reasons cause the erosion and destruction of compressor blades of gas turbine engines. Today, technicians are more concerned about protecting gas turbine engines from the effects of dust particles in the air. The density of dust in the air due to the pollution of the environment and its humidity differs according to the weather. Dust particles in the air suck the flow path of the compressor with different velocities and angles of incidence; they collide with the blades and deform the geometry of the blades and the radial clearance of the blades. The data acquired from reality showed that the compressor of the engine is the most eroded part[1,2]. The degree of erosion occurs along the inlet edge and the pressure surface; moreover, the rotor blade is eroded to a greater extent than the stator blade. The typical geometrical parameter of a blade is the curvature of the S-shaped profile, which affects the radial clearance.

Although the changes in the geometrical parameters of the blade stages have been studied for many years, the quantification of the extent of these changes is not clear. Published studies have identified the erosion process and the degree of change in the shape of the blades as the main factors causing the failure of gas turbine engines[2,3]. In particular, the compressor is the most affected component by corrosion, so it is central in the development of new methods to diagnose, study the measures and erosion protection de-

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vices as well as standardizing the recovery process and deal with the defects of compressor blades when repairing gas turbine engines.

Determining the change in the geometrical parameters of the blade stages during the erosion process, the presence of dust particles in the flow path, and the nature of the erosion along the flow path of the blades are issues that need to be studied.

This article will present a mathematical model to determine the influence of dust levels in the air on the geometrical parameters of blade stages of the compressor in a gas turbine engine, setting up the movement trajectory of dust particles in the flow path of the compressor.

METHOD AND CALCULATION MODEL

In operation, there are many measures to prevent and limit the intrusion of dust particles, such as cleaning the inlet case and using filters at the intake. However, the erosion of the compressor blade still occurs and exhibits an increasing trend from the inlet to the outlet of the compressor, as shown in Figure 1.

This first causes the slippage of the air flow, and then this makes a sharp change affect the working parameters of the engine (taking place at each specific time). Engine operation will have to stop when there is a sudden change in working parameters or a surging phenomenon occurs in the compressor.

Figure 1: Erosion of compressor blade in gas turbine engine.

It is essential to properly assess the movement trajectory of dust particles in the air flow when studying the erosion phenomenon of compressor blades. Due to the higher density of dust particles, their orbits have less curvature than the orbits of air particles. The first thing is concerned that the meridian section and range of the air flow surfaces (in the air flow of the blades and the blade cascades) must be calculated; the radial and rotational accelerations cause the air flow and dust particles to have similar static pressure gradients (the gradients in the radial and cross-sectional sections in the air flow between the blades). The radial and rotational accelerations of the dust particles can be calculated through the equivalent accelerations of a portion of the air flow of corresponding density.

From this, it is possible to calculate the rotational velocity components of a portion of the air flow in terms of relative and absolute motion. It is assumed that the axial velocities of the air flow and the dust particles are the same, which allows us to determine the particle velocity vectors at any point of the flow path section of the blade, as well as at any angle in terms of any frequency with which impulse they attack the different parts of the blade (mainly the leading edge and pressure surface to determine the degree of blade erosion). Then, it will also allow us to determine the trajectory of dust particles in the meridian section, i.e., to redistribute dust areas along the height of the air flow of the blade.

Determine the velocity of the dust particle

Theoretically, the velocity components in the composite motion of a particle are analyzed, as shown in Figure 2. where c is the absolute velocity, w is the relative velocity, and u is the rotational velocity of the blade.

Consider the motion of the particles in the radial direction. The centripetal acceleration will be determined:

$$\frac{dc_r}{dt} = \frac{c_{u1}^2}{r} \qquad (1)$$

where c_{u1} is the rotational velocity of the dust particle; c_r is the radial velocity; and r is the radius of curvature of the blade.

Centripetal acceleration produces a pressure gradient:

$$\frac{dP}{dr} = \rho\frac{dc_u}{dt} \qquad (2)$$

This expression holds true for particles with circular motion. However, the motion of the dust particles is not circular; they move with acceleration toward the tip of the blade.

$$\left(1-\frac{\rho}{\rho_1}\right)\frac{c_{u1}^2}{r} = \frac{d^2r_1}{d^2t} = \frac{d^2r_1}{dS^2}c_a^2 \qquad (3)$$

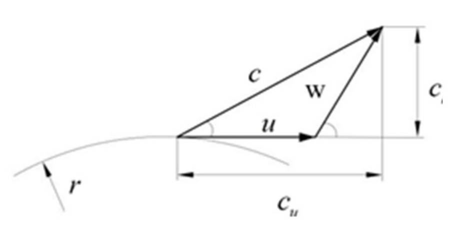

Figure 2: Diagram of air flow velocity in the clearance of the flow path of blade.

where: ρ - air density; ρ_1 - dust density in the air; r_1 - the radius of curvature determined at the dust particle location; c_a - the axial velocity of the gas stream; c_u - rotational velocity of the gas stream; S - arc length in each S-shaped section $dt = \frac{dS}{c_a}$.

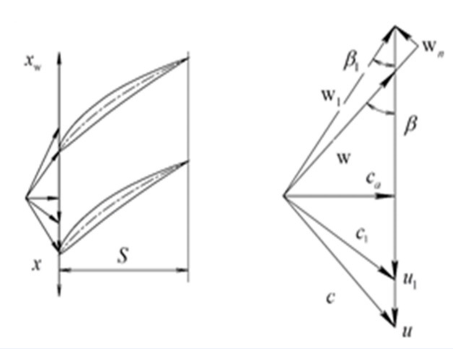

Figure 3: Diagram of movement velocity of dust and gas particles in the flow path between the blades.

In formula (3), the axial velocity of the dust particle is considered to be equal to the axial velocity of the air flow $c_{al} \approx c_a$. Figure 3 shows the diagram of the movement velocity of dust and gas particles in the flow path between the blades. Figure 4 shows the distribution of the dust area in the flow path.

The radial velocity at the inlet of the first stage is considered to be $c_{r0} \approx 0$. The radial velocity of the dust particles at any point of the S-shaped blade section is expressed by formula (4):

$$\begin{aligned} c_{r1} &= c_{r0} + \int_0^S \left(\frac{d^2 r_1}{dS} c_a^2\right) dS \\ &= c_{r0} + \int_0^S \left[\left(1-\frac{\rho}{\rho_0}\right)\frac{c_{u1}^2}{r}.c_a^2\right] dS \end{aligned} \quad (4)$$

When dust particles move in a multistage axial compressor, it is necessary to consider the movement of dust particles at the first inlet blade and then to the next working blade stages and guide vanes along the blade pressure surface. The radius of curvature of the blade can be described by the following expression:

$$\begin{aligned} &r(S) = r_{ol} + \int_0^S c_{r0} dS + \\ &\int_0^S \left[\int_0^S \left(1-\frac{\rho}{\rho_1}\right)\frac{c_{u1}^2}{r}.c_a^2\right] dS \end{aligned} \quad (5)$$

r_{ol} - radius of coaxial bushing;

This means that the particle velocity in the direction of blade rotation is:

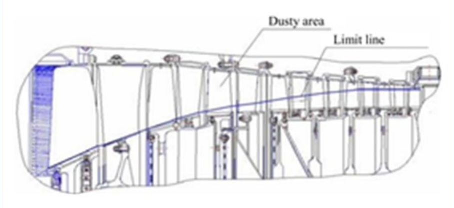

Figure 4: Distribution of dust area in the flow path.

$$c_{u1} = \left(1-\frac{\rho}{\rho_1}\right) c_a = u\left(1-\frac{\rho}{\rho_1}\right)(1-tg\beta_1.\overline{c_a}) \quad (6)$$

($\overline{c_a} = \frac{c_a}{u}$: air flow coefficient)

and the velocity of the air flow in the direction of rotation is:

$$c_u = \frac{dx}{dS}c_a = u - \frac{dx}{dS}v_a = u(1-tg\beta_1.\overline{c_a}) \quad (7)$$

Substituting (5) into:

$$\begin{aligned} &r(S) = r_{ol} + \int_0^S c_{r0} dS \\ &+ \int_0^S \left[\int_0^S u^4 \left(1-\frac{\rho}{\rho_1}\right)^2 \frac{1-tg\beta_1\overline{c_a}}{r} c_a^2 dS\right] dS \end{aligned} \quad (8)$$

From equation (8), it can be seen that the wear of the blades depends on the degree of separation of dust particles from the air flow in the clearance of the flow path. The value of the rotational velocity u is the main factor, and the wear increases gradually from the inlet to the tip of the blade, as shown in Figure 4. This occurs due to the influence of centrifugal force in the compressor stage. The density of dust particles increases gradually from the root to the tip of the blade. Therefore, the erosion f the first stage and the root of the last stage is practically nonexistent. This argument is confirmed by the actual data obtained during disassembly and the ultrasound method on the blade of the axial compressor in a gas turbine engine, as shown in Figure 2.

The distribution of dust particles according to their size and density are the most important parameters characterizing the degree of dust contamination of the air. The determination of density is measured through the amount of dust in 1 cubic meter of air. The air density basically depends on geographical and time factors.

The density of dust in the clearance of the flow path of the axial compressor is determined according to the inlet factor of the air flow, and then the mass flow of the dust is calculated by:

$$\frac{\pi d_1^2}{4} c_x \rho \frac{v_y}{2} = (\rho_1 - \rho) \frac{\pi d_1^3}{8} g \qquad (9)$$

where d_1 is the diameter of the dust particle; c_x is the dust density in the clearance of the flow path of the compressor; and v_y is the air speed at the inlet.

Therefore:

$$\frac{\rho_1}{\rho} = \frac{c_x v_y^2}{d_1 g} + 1 \qquad (10)$$

When the rotational velocity of the air flow c_u is known, the rotational velocity of the dust particles can be determined:

$$c_{u1} = c_u \left(1 - \frac{\rho}{\rho_1}\right) \qquad (11)$$

The relative velocity of the dust particle is determined as follows:

$$w_{u1} = w_u + c_u \left(1 - \frac{\rho}{\rho_1}\right) = w_u + c_{u1} \qquad (12)$$

Movement trajectory of dust particles in the clearance of the flow path between the blades

Diagram of the establishment of the movement trajectory of dust particles through the clearance of the flow path between the blades in the stages, as shown in Figure 3 and Figure 5.

The angle at which the dust particles attacked the blade surface is determined by the expression:

$$ctg\beta_1.\overline{c_a} = \left(1 - \frac{\rho}{\rho_1}\right) + \left(1 - \frac{\rho}{\rho_1}\right).ctg\beta.\overline{c_a} \qquad (13)$$

which means that:

$$ctg\beta_1 = \frac{\left(1 - \frac{\rho}{\rho_1}\right) + \left(1 - \frac{\rho}{\rho_1}\right).ctg\beta.\overline{c_a}}{\overline{c_a}} \qquad (14)$$

In design, the rotor blades (working blades) are larger than stator blades (guide vanes). This can be explained by the fact that the particle velocities upon impact on the rotor blade are significantly larger than the impact velocities on the stator blade.

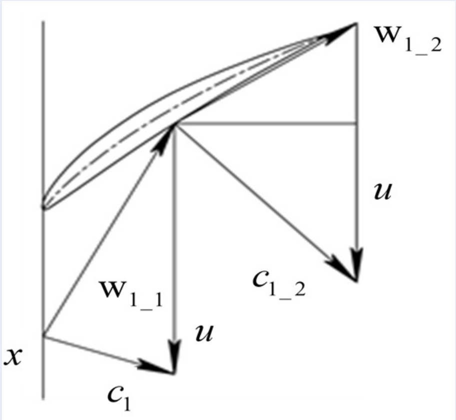

Figure 5: Diagram of the movement trajectory of the dust particle.

When the velocity distribution is known $\overline{c_a}\,(c_a)$ it is possible to determine the relative displacement of the air flow $\frac{dx_w}{dS}$, allowing the relative displacement of dust particles to be determined $\frac{dx_{w1}}{dS}$ according to the formula:

$$\frac{dx_{w1}}{dS} c_a = \left(1 - \frac{\rho}{\rho_1}\right) + \frac{\rho}{\rho_1} \frac{dx_w}{dS} c_a \qquad (15)$$

Division into (13) by the rotational velocity u yields the following:

$$\frac{dx_{w1}}{dS} \overline{c_a} = \left(1 - \frac{\rho}{\rho_1}\right) + \frac{\rho}{\rho_1} \frac{dx_w}{dS} \overline{c_a} \qquad (16)$$

Along any trajectory, the energy of the air flow in the compressor is:

$$dL = \frac{F}{m} dx = F_{mu}.dx \qquad (17)$$

where F_{mu} is the impact force of the air flow in the direction of rotation and m is the mass flow of air.

$$\begin{aligned} &\frac{dL}{dS} = F_{mu} \frac{dx}{dS}; \\ &F_{mu} = \frac{dL/dS}{dx/dS} = u^2 \overline{c_a} \frac{d^2x/dS^2}{dx/dS}; \\ &\frac{F_{mu}}{u^2 \overline{c_a}}.x = \frac{dx}{dS} \end{aligned} \qquad (18)$$

Then, $x = e^{\frac{F_{mu}(S)}{u^2 \overline{c_a}}} - 1$, value $F_{mu}(S)$ is solved by the request e - the law of the blade profile, where x_w - the coordinates of the profile of the rotor blade.

Various factors affect the degree of erosion, including dust particle size, velocity, material and working time. Operating time also affects the movement trajectory of the dust particle, as it is related to the level of exploitation, increased erosion, and the change in geometrical parameters in the flow path. The change

Table 1: **Input Parameters**

Parameter	Value
Absolute velocity of the air flow at the blade inlet	$c_u = 97\ m/s$
Rotational velocity of the air flow	$u = 342\ m/s$
Relative velocity of the air flow at the blade inlet	$w_u = 247\ m/s$
Axial velocity of the air flow	$c_a = 189\ m/s$
The angle of attack of the air flow	$\beta = 37^o$
Density of dust particles in the clearance of flow path of the compressor blade	$c_x = 500\ mg/m^3$
Diameter of dust particle	$d_1 = 1\ \mu m$
Average velocity of air	$v_y = 0.5\ m/s$

in the absolute rotational velocity of the dust particle can be determined as follows:

$$\frac{dc_{u1}}{dt} = \frac{\rho}{\rho_1}\frac{dc_u}{dt} = -\frac{\rho}{\rho_1}c_a^2\frac{dx_w^2}{dS} \tag{19}$$

where the acceleration of the dust particle depends on the density, axial velocity and slip of the gas flow along the blade (affected by the erosion of the blade surface). Then,

$$\begin{aligned} c_{u1} &= c_{u1}|_{t=0} + \int_0^t \frac{\rho}{\rho_1}\frac{dc_u}{dt}.dt \\ &= c_{u1}|_{t=0} + \left(-c_a^2\right)\frac{\rho}{\rho_1}\int_0^S \frac{d^2x_w}{dS^2}.dS \end{aligned} \tag{20}$$

However:

$$c_u = c_u|_0 + \left(-c_a^2\right)\int_0^S \frac{d^2x_w}{dS^2}.dS$$

Therefore:

$$\begin{aligned} c_{u1} &= c_u|_0 + \frac{\rho}{\rho_b}\int_0^t \frac{dc_u}{dt}dt \\ &= c_u|_0 + \frac{\rho}{\rho_1}\int_0^S \frac{dc_u}{dS}dS \end{aligned} \tag{21}$$

SIMULATION CALCULATION IN ANSYS PROGRAM

The argument cited above is verified by 3D modeling and CAD/CAE simulation. Calculations are performed in the ANSYS program. To carry out the simulation in the ANSYS program, it is necessary to enter intermediate parameters that are calculated according to the thermodynamic cycle for gas turbine engine ДР76 (with reference to the technical documentary of the engine). The input parameters of the calculation program are as follows, as shown in Table 1.

Boundary conditions of blade in ansys (Tables 2 and 3)

According to (10), it can be remarked that the higher the density of dust at the inlet is, the higher the velocity of the dust particle, leading to the impact of dust particles on the surface of the blade. According to[2], the erosion rate is proportional to the velocity of the dust particle, which means that the higher the dust density is, the faster the blade is eroded.

The velocity components calculated above are relative to the pressure surface. The particle velocity and trajectory relative to the pressure surface, suction surface, and camber line are different. The relative velocity component w_n (perpendicular to the blade) affects the material distribution (degraded surface of the material layer); then, it has a value corresponding to w_u^2. The erosion of material along the suction surface will gradually approach zero, and in the middle part of the pressure surface of the blade, it will be the smallest. Particles have a velocity component in the direction of impact with the blade surface, the other in the direction of bounce.

As shown in[2], when hitting normally, the velocity quantity loses approximately 0.81-0.85 of its value at the inlet before the impact.

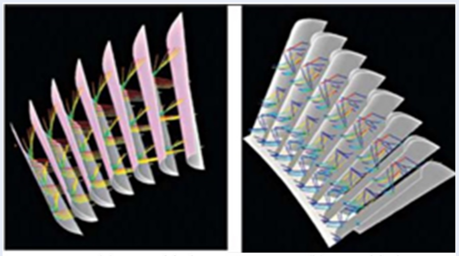
(a) stator blades (b) rotor blades

Figure 6: Motion trajectories of particles size 31μm

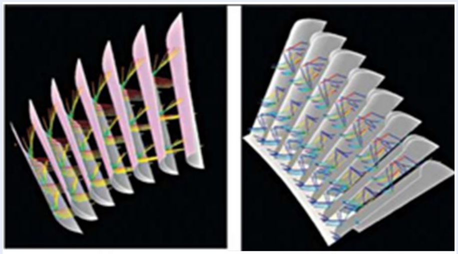
(a) 31 µm (b) 98 µm

Figure 7: Movement trajectory of particles in the clearance of the flow path when changing its size.

Table 2: Information of Total Elements

Total Elements	Total Nodes	TRI_3	TETRA_4	LINE_2	NODE	QUAD_4	PENTA_6
958380	212309	56430	757532	1546	24	1516	141332

Table 3: Information of Individual Part

Part Name	Number of Elements	Number of Nodes
BODY	898864	212309
CANH1	17531	8859
CANH2	17802	8997
CURVES	1546	1534
IN	3230	1703
MAT_DUOI	4055	2586
MAT_TREN	4699	2931
OUT	3737	1951
PERIOD1	3446	1801
PERIOD2	3446	1801
POINTS	24	24

RESULTS AND DISCUSSION

Calculation results performed in the ANSYS program are given as follows. The particle trajectory in the clearance of the flow path between the axial compressor blades is shown in Figures 6 and 7.

From the data of the ДР76 engine collected during the actual survey and calculation, the lower limit of the dust area can be established according to the height of the flow path of the blade. It is clear that according to the degree of separation of dust particles at the inlet of the blades, the lower limit of the dust area is gradually pushed away from the axis of rotation, as shown in Figure 4. In this region, the level of dust accumulation is not uniform, increasing from the lower limit to the edge of the blade.

Comparing the obtained results shown in Figure 8 with the erosion and scratches obtained when surveying the ДР76 engine and measuring the cavitation after working time in high dust conditions, as shown in Figure 1, it has been shown that there is good agreement between the simulated calculation and reality.

The rule of velocity distribution of the dusty air flow when simulated gives the rule of the erosion that is appropriate to reality of the blade stages.

CONCLUSION

The problems raised in the article allow the analysis of the movement trajectory of dust particles in the flow path between the blades of the axial compressor, predicting the erosion level of the blades of any shape. At the same time, it is possible to determine the most eroded area for a pair of blades with a specific profile. This paper shows that the rotor blades and stator blades of the first compression stage are eroded over the entire height of the blade (the greatest extent is concentrated on the pressure surface near the front and rear edges of the blade), while the rotor blades of the final compression levels have gradually increased erosion toward the trailing edge of the blade tip due to the centrifugation of the particles in the stages. Therefore, the dust density also increases toward the trailing edge away from the center of the last stage, which are the thinnest, most worn parts of the engine. The measurements for the actual eroded blades and the calculations show that the erosion images have proven the appropriateness of the arguments made about the motion of the dust particles.

This article presents the research results of the rule of the movement of dust particles in the flow path of an axial compressor in a gas turbine engine, the nature and characteristics of the erosion phenomenon, the change in the geometrical parameters of the blade, the change in the shape of the blade and the characteristics of the engine. This allows us to calculate the operating conditions in designing the engine, as well as to study the measures to protect the blades from erosion and to diagnose the parameters of the gas turbine engine.

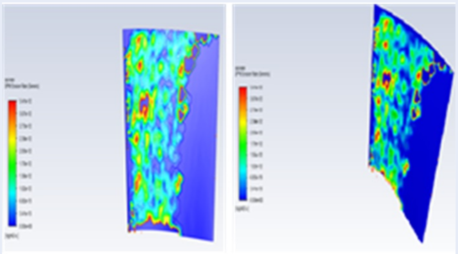

Figure 8: Distribution of erosion level on the airfoil of rotor blade according to simulation results.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of whatsoever involved in publishing this research.

AUTHORS' CONTRIBUTIONS

Quoc Toan Tran is the supervisor, contributes ideas for the proposed method and participates in the work of gathering data and checking the numberical results. Huu Binh Le works as the developer of the method and runs the Ansys program.

Ngoc Thanh Huynh works as the manuscript editor and contributes to the work of gathering data.

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