Defining the Field of Existence of Shrouded Blades in High-Speed Gas Turbines

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Abstract: This work provides a method for determining the region of existence of banded blades of gas turbines for aircraft engines based on the analytical evaluation of tensile stresses in specific characteristic sections of the blade. This region is determined by the set of values of the parameter, which forms the law of distribution of the cross-sectional area of the cross-sections along the height of the airfoil. When seven independent parameters (gas-dynamic, structural and strength) are changed, the choice of the best option is proposed at the early design stage. As an example, the influence of the dimension of a turbine on the domain of the existence of banded blades is shown.

1. Introduction

The tendency to reduce the number of stages of the turbine determines the need to increase the gas dynamic load on the blade rims. To achieve a high efficiency of the stage, an increase in peripheral rotation speeds is required, which leads to a quadratic increase in the centrifugal load on the rotor parts.

The circumferential speeds of rotation of 500–600 m / s, achieved in existing turbines, predetermine the difficulties in the strength design of blades and disks. This problem is especially important for banded working blades, since the shroud platform additionally loads the pen, the locking connection and the disk. In high-speed turbines, the effect of centrifugal force on the shroud can become critical, which will lead to the impossibility or inexpediency of creating a bandage blade [1–3]. Also the modernization of gas turbine units for ground application requires the using of turbine rotor with hard centrifugal force constrain, and the reducing blade weight is an important problem [4, 5].

2. The influence of the bandage volume on the impeller mass

We determine the influence of the volume of the shroud on the mass of the impeller of the turbine on the following example: a peripheral speed of 480 m / s, a radius of the center of the weight of the shroud of 309.5 mm, a blade height of 45 mm. We take the material of the blade and the shroud platform - ZhS32 (density 8.8 g / cm³).

Let's consider three variants of blades with volumes of shrouds:
- 0 mm³ (unshrouded blade);  
- 320 mm³ (corresponds to a lightweight shroud platform);  
- 500 mm³ (corresponds to an unweighted shroud platform).
The chosen parameters of the shroud platform correspond to the design parameter so the high-pressure turbine blades of NK-110 and NK-93 prop fan engines developed in the ND Kuznetsov construction bureau.

For the given volumes of the shroud platform, the distribution of the cross-sectional areas along the blade's height was selected and the load-carrying sections of the disks ‘figure 1’ were determined with practically the same strength.

‘Table 1’ shows the weights of the blades and disks. The weight of the impeller of a high-speed turbine can double when the blades are shrouded, and the volume of the shroud can have a decisive influence on the structural shape of the unit.

For this reason, in the early stages of turbine design, it is important to predict the possibility of bandage blades and to estimate the weight of the working wheel.

![Figure 1](image-url) The contours of discs for different blade options

| № Variant | Mass of the blade, g | Mass of the disc, kg | Mass of the rotor, kg |
|------------|---------------------|---------------------|----------------------|
| Bap. 1     | 46                  | 42,1                | 50                   |
| Bap. 2     | 69                  | 58,3                | 71                   |
| Bap. 3     | 99                  | 91,8                | 110                  |

### 3. The precision of the field of existence of shrouded blades

For impure blades, an evaluation is made of the strength of the tension stresses in the characteristic sections of the feather [6]. Let us take the power law of distribution of areas over the blade height in the following form:

\[ F_i = F_{om} \left( \frac{R_{om}}{R_i} \right)^m, \]

Where \( F_i \) – Area of the i-th cross section on the radius \( R_i \);

\( m \) – The exponent characterizing the distribution of the cross-sectional areas along the blade height.
For blades with shrouds, the tensile stresses from centrifugal forces in the bushing cross section \( \sigma_{p,em} \) can be written in the form:

\[
\sigma_{p,em} = 2 \rho \frac{U}{c_p} \frac{h}{d} \Phi + 4 \rho V \frac{U}{c_p} \frac{d}{F_{em}} \frac{2}{d} + h + \delta
\]

Where, \( \rho \) – density of the blade material; \( U \) – circumferential velocity on the average radius of the blades.; \( h \) – blade height; \( d \) – average diameter of the turbine stator; \( V \) – volume of the blade shroud platform; \( \delta \) – The difference between the position of the center of gravity of the shroud platform and the peripheral sub-sectional section of the airfoil, which is 2-4mm in size for different sized blades; \( \Phi \) – coefficient of the airfoil shaping of the blade (is a function of \( m \)).

Having integrated the centrifugal force from the lower sections by the height of the blade, it is possible to determine the tensile force and tensile stresses in any section of the blade.

Possible configurations of the blade with a shroud are realized in the range of values of \( m \) under the following two conditions:

1) the stresses in the bushing and peripheral sections of the pen do not exceed the permissible level;
2) the ratio of the areas of the hub and peripheral sections of the blade, which determines, in the first approximation, the vibrational state of the blade, is in the required range.

Thus, it is possible to introduce the concept of "the domain of existence of shrouded blades". Under the definition we mean the set of values of the parameter \( m \) for which the two conditions indicated above are satisfied.

Let us analyze the first condition. In the bushing cross section, the stress level can be taken from the expected material temperature and the required blade life:

\[
\sigma_{p,em} = \frac{\sigma_{b,t}}{k}
\]

Where, \( \sigma_{b,t} \) – long-time strength of the blade under temperature \( t \) and operation time \( \tau \);

\( k \) – structural load factor.

In the peripheral section, the tensile stresses should not exceed the value \( \mu \sigma_{em} \), where \( \mu = 0.3 \) – 0.7. The physical meaning of the coefficient \( \mu \) lies in the fact that it determines the law of variation of stresses along the blade’s height. The stresses are determined only by the centrifugal load from the shroud, expressed by the second term of formula (2).

The second condition is based on the fact that the parameter \( \chi \) can vary in the range 1.2 – 7.0 depending on the height of the blade.

Then the domain of existence of shrouded blades can be described by the following system of equations and inequalities:

\[
\frac{F_{em}}{F_{nep}} = \left( \frac{R_n}{R_{em}} \right)^m 
\]
\[
\sigma_{p,\text{em}} = \frac{\rho \omega^2}{F_{\text{em}}} \left( \frac{V_n \cdot (R_n + \delta)}{2 - m} \cdot R_n^m - R_{\text{em}}^2 \right) \frac{V_n \cdot (R_n + \delta)}{2 - m} \cdot R_n^m - R_{\text{em}}^2 \right); \tag{5}
\]

\[
\sigma_{p,n} = \frac{\rho \omega^2 V_n (R_n + \delta)}{F_{\text{em}} \cdot \left( \frac{R_{\text{em}}}{R_n} \right)^m}; \tag{6}
\]

\[
\sigma_{p,n} < \mu^* \sigma_{p,\text{em}} < \frac{\sigma_{p,\tau}}{k}; \tag{7}
\]

\[
\chi_{\text{min}} < \left( \frac{R_n}{R_{\text{em}}} \right)^m < \chi_{\text{max}} \tag{7}
\]

The limiting case of the existence of blades is reached when the stresses in the bushing and peripheral sections are equal to the maximum. Linking the second and third expressions in \((7)\), we obtain:

\[
\frac{V_n \cdot (R_n + \delta)}{F_{\text{em}}} \cdot \frac{R_n^2 - m \cdot R_n^m - R_{\text{em}}^2}{2 - m} = \frac{V_n (R_n + \delta)}{F_{\text{em}} \cdot \left( \frac{R_{\text{em}}}{R_n} \right)^m} \cdot \mu F_{\text{em}} \cdot \left( \frac{R_{\text{em}}}{R_n} \right)^m \tag{8}
\]

From where we get,

\[
V_n = F_{\text{em}} \cdot \frac{(R_n^2 - m \cdot R_n^m - R_{\text{em}}^2) \mu}{(m - 2) |R_n + \delta| \left( \mu - \left( \frac{R_n}{R_{\text{em}}} \right) \right)^m} \tag{9}
\]

Volume of the blade shroud platform

\[
V_n = F_{\text{em}} \cdot \frac{\mu \sigma_{p,\text{em}}}{(R_n + \delta) \rho \omega^2} \left( \frac{R_n}{R_{\text{em}}} \right)^m \tag{10}
\]

Equating expressions \((9)\) and \((10)\), we obtain an equation for determining

\[
\frac{\sigma_{p,\text{em}}}{R_{\text{em}}^2 \cdot \rho \omega^2} = \frac{\left( \frac{R_n}{R_{\text{em}}} \right)^2 - \left( \frac{R_n}{R_{\text{em}}} \right)^m}{(m - 2) \left( \mu - \left( \frac{R_n}{R_{\text{em}}} \right) \right)^m} \tag{11}
\]
Equation (11) establishes a relationship between the geometric characteristics of the blade and its stressed state through the parameter $m$ at the limiting stress values. The domain of existence of shrouded blades lies in the range of numbers $m$, determined by the following conditions:

$m > m_{\text{пред}}$, where, $m_{\text{пред}}$ is a solution of equation (11) – The condition for ensuring the strength of the blade to tensile stresses;

$$\chi_{\min} < \left( \frac{R_n}{R_m} \right)^m < \chi_{\max}$$

The condition of the correspondence of a given ratio of cross-sectional areas to ensure a favorable vibration state.

4. **Graphical interpretation of the field of existence**

The graphical interpretation of the domain of existence is shown in Fig. 2. The left-hand side of equation (7) is graphically represented by a straight line parallel to the horizontal axis. The right-hand side corresponds to the curve of a monotonically decreasing function.

In Figure 2 shows the results for a turbine with a blade height of 50 mm, an average radius of 0.4 m and a peripheral speed of 440 m/s (the first stage of a turbine turbojet thrust 300-350 kN). For comparison, the area of existence of a blade without a shroud for the same specified conditions is also shown.

We draw lines corresponding to different values of the peripheral section strength $\mu$ (Fig. 3). It is convenient to reconstruct the illustration of the field of existence for practical application in terms of the ratio of the areas $\chi$ (Fig. 4).

![Figure 2. Graphical interpretation of the area of existence of the blades: 1- the line of ultimate stretching stresses of non-shrouded blades; 2–line of limiting spreading stretches of shrouded blades; 3- area of the existence of the blade; 4- area of existence of blades with a shroud](image)

Reducing the volume of the shroud, leading to a decrease in the strength of the peripheral section of the blade, expands the area of possible existence of blades. In the extreme case, when $\mu = 0$, the existence region of the shelving and non-platformed blades coincide.

In practice, the blades with numbers $\mu < 0.2 – 0.3$ Do not apply because of low loading of the peripheral part and increased in connection with this mass of the blade.

For a given dimension, shrouded turbine blades may be in the range of area ratio $\chi$ from 3 to 7 depending on the specified strength of the peripheral section.
Figure 3. Areas of existence of shrouded and non-shrouded blades with different levels of tension in the peripheral section.

Figure 4. Borders of the areas of existence of the blades for a turbine of smaller dimensions.

For comparison, we will construct similar graphs for a turbine of smaller dimensions: an average radius of 220 mm and a blade height of 40 mm (corresponding to the first stage of a turbine of a turbojet with thrust of 140-160 kN), for the same circumferential velocity of 440 m/s (see Fig. 4).

For this dimension of the turbine at permissible tensile stresses in the bushing section of 160 MPa, the permissible ratio of the areas is in the range 4.8-6.

5. Conclusion

With an increase in the dimension of the turbine, the banded blades are realized in a wider range of the area ratio. This is due to a quadratic increase in the centrifugal load due to an increase in the rotational speed with a decrease in the average diameter of the turbine.

So, the gas dynamic parameters of the turbine, the specific strength of the material and the design features of the blade itself determine the domain of existence of the blades with the shrouds. Its definition will allow choosing the parameters of the bearing sections and the configuration of the shroud platform that are most suitable for the purpose of the engine being designed.

References

[1] Belousov A.I., Nazdrachev S.V. (2015) Dialectics of relief of the shrouds of turbine blades. Pumps. Turbines. Systems. 2015. № 3 (16). P. 7-14.
[2] Belousov A.I., Nazdrachev S.V. (2016) Principles of facilitating the shroud of the turbine blade. Izvestiya Vuzov. Aviation equipment, 2016. № 1. P. 48 - 53.
[3] Belousov A.I., Nazdrachev S.V. (2016) Weight optimization principles for turbine blade shroud platform. Russian Aeronautics (Iz. VUZ), 2016. Vol. 59. No 1. P. 378–382. DOI 10.3103/S1068799816010086 Print ISSN 1068- 7998; online ISSN 1934-7901.
[4] Belousov A.I., Nazdrachev S.V. (2014) Methodology of modernizing the serial converted gas turbine unit. Russian Aeronautics, 2014. Vol.57. № 4. P. 378–382. DOI 10.3103/S1068799814010102.
[5] Belousov A.I., Nazdrachev S.V. (2014) Methodology of modernizing the serial converted gas turbine unit. Izvestiya Vuzov. Aviation equipment, 2014. № 4. P. 36 – 38.
[6] Kholschhevnikov K.V. (1970) Theory and calculation of aircraft scapular machines / Moscow: Mechanical Engineering. 356 p.