Study of the optimal reinforcing structure of the compressor wheel from composition material of the transport turbocharged engine

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Abstract. The purpose of the study was to find the optimal configuration of the main parameters of the reinforcing layer of a compressor wheel made of composite material. The optimization problem for an anisotropic system was solved using the Gauss-Seidel method. According to the results of calculations, it was established that under the condition of preserving the strength of the wheel, there is the possibility of transition to reinforcing layers in which the fibers are oriented only in the circumferential direction, which makes it possible to significantly simplify the technology of its manufacture. The use of reinforcement for compressor wheels made of composite material can significantly reduce its mass and polar moment of inertia, which contributes to the improvement of strength and performance of the turbocharger and the engine as a whole.

1. Introduction
At present, there is a tendency to the almost universal application of pressurization systems of transport engines using turbochargers for this purpose. With all the known advantages of turbocharging systems, there are a number of problems associated with the further improvement of their performance. One of these tasks is to increase the strength and operational reliability of structural elements of the turbocharger, reducing the centrifugal load [1,2].

Another important task that requires its solution is the high inertia of the turbocharger rotor, which manifests itself in the period of changing the load mode of the engine. At the moment of increasing the cycle fuel supply to the engine, there is a discrepancy between the fuel supply and the turbocharger performance, which causes such a negative phenomenon as “turbo lag”. Under these conditions, operational fuel consumption and exhaust gas toxicity increase, engine acceleration deteriorates over the whole range of unsteady and transient modes of its operation, which are most characteristic of any engine used for ground transport. It is known that the duration of these modes has a direct dependence on the moment of inertia of the turbocharger rotor.

Thus, it is necessary to search for opportunities to improve the performance of the turbocharger. First of all, it is improving the resource characteristics and reliability, as well as reducing the inertia of the rotor. This is one of the promising directions in the research practice of the transport engine-building industry.

One of the solutions in the direction of achieving the required qualities is the use of composite materials (CM) for the elements of the turbocharger rotor, which have a lower density, and,
consequently, low inertia. Recently, a number of studies on finding such a solution have appeared in foreign and domestic research practice, generally showing its potential opportunities [3-6].

However, despite the large number of proposed design solutions for the development of impellers from CM and a wide range of CM [7, 8], at the moment there are no studies to improve the strength properties of such wheels. The key problem is the search for the optimal reinforcement structure of its matrix, which is one of the factors hindering the practical implementation of these solutions.

Thus, the further development of research to find the optimal reinforcement of impellers from CM is one of the actual directions in the field of creating high-performance turbochargers for transport engines.

2. Object and research methodology

According to the results of a previous study [4], the design of a compressor wheel was proposed. The compressor wheel is made of randomly reinforced composite material with a reinforcing layer in the form of several mono layers of continuous fibers. The search for the optimal configuration of the reinforcement of this wheel in order to identify the maximum indicators of its strength properties was the subject of this study. Taking into account the target orientation of the research, a complex optimization problem was posed, including the selection and description of variable parameters and target optimization functions, localization of intervals of allowable values of variable parameters.

![Figure 1. Scheme of the compressor wheel made of composite material.](image)

The reinforcing layer is formed by alternately stacking monolayers in accordance with the chosen orientation scheme relative to each other. Each monolayer is a unidirectional composite material with continuous fibers with different schemes of laying (orientation). For traditional (metal) wheels of standard size with a diameter of 130 mm, the disk wall usually has a minimum thickness of 3.3 mm. Taking this into account, in the process of optimization, the range of variation within the limits was adopted: \( t_{\text{min}} = 0.2 \text{ mm} \ldots t_{\text{max}} = 1.4 \text{ mm} \). In this case, the thickness of the reinforcing layer should be comparable with the thickness of the outer layer of the base material, which will ensure the possibility of the formation of a blade crown on the disk. In general, for other sizes of turbochargers this range of variation may vary depending on the geometrical configuration of the wheels.

Polyamidoimide is used as the matrix of the composite (base material) in this study. Polyamidoimide, randomly filled with 30% carbon fiber, was used for the blade crown and the inner part of the disk. High-strength carbon fibers, which have high physical and mechanical properties temperature stability and low density, are adopted as reinforcing elements. The properties of the matrix and fiber materials are given in table 1 and 2. The subsequent calculation of the properties of the reinforced composite material, using the material properties of its components given in the tables, was carried out according to [7].
Table 1. Properties of polyamidoimide with randomly arranged carbon fiber (30%).

| Property name                      | Value  |
|------------------------------------|--------|
| Density $\rho$, kg/m$^3$           | 1480   |
| The modulus of elasticity $E$, GPA | 16,5   |
| Ultimate strength $[\sigma_b]$, MPa| 221    |
| Poisson's ratio $\mu$              | 0,39   |
| Coefficient of linear thermal expansion $\alpha$, 10-6 deg$^{-1}$ | 9      |

Table 2. Properties of high strength carbon fiber.

| Property name                      | Value  |
|------------------------------------|--------|
| Density $\rho$, kg/m$^3$           | 1700   |
| The modulus of elasticity $E$, GPA | 240    |
| Ultimate strength $[\sigma_b]$, MPa| 3250   |
| Poisson's ratio $\mu$              | 0,2    |
| Coefficient of linear thermal expansion $\alpha$, 10-6 deg$^{-1}$ | -0,4   |

The study was conducted by the Gauss-Seidel method (coordinate descent method to find the extremum of the objective function). The problem of linear theory of thermoelasticity of anisotropic medium was solved for each combination of variable parameters. The solution to this problem is implemented by the finite element method in the Femap software package. All calculations are made for the maximum possible speed limit of the turbocharger. The nature of the thermal effect on the structure was taken according to the results of the study [2].

According to the results of optimization the comparative analysis of mass-inertial characteristics of turbocharger rotors with compressor wheels made of composite and traditional (metal) material was carried out.

3. The results of the study and their discussion

The solution of optimization problems is associated with the analysis of a large amount of data and results, which leads to the high complexity of their solution. This implies the need to reduce the number of less significant variable parameters and objective functions, localize the intervals of allowable values of the variable parameters.

Below is a description of the adopted variable parameters. The first of these is the share $V_f$ of the fiber of the reinforcing layer in the composition of the composite material. This value for unidirectional composite materials can be from $V_f\min = 0.4$ to $V_f\max = 0.8$.

The second variable parameter is the fraction $m$ of the thickness of the reinforcing layer, in which the fiber is oriented in the circumferential direction. The interval of variation of this parameter was taken from $m\min = 0.5$ to $m\max = 1$.

The third variable parameter is the total thickness $t$ of the reinforcing layer.

In this study, General safety margin of the wheel is adopted as the target function, which for each combination of variable parameters is equal to:

$$ n_0 = \min(n, n_w) $$
where \( n = \frac{[\sigma_b]}{\sigma_{eq}} \) - the safety margin of the blade crown; \([\sigma_b]\) - the ultimate strength of the base material of the matrix (table 1); \( \sigma_{eq} \) - equivalent stresses in the base material, determined in accordance with the Huber-Mises-Hencky energy theory of strength; \( n_w \) – the safety margin of the reinforcing layer with continuous fibers according to the Mises-Hill criterion.

The Mises-Hill criterion was adopted because of its ease of use. The postprocessor Femap automatically determines the minimum value of the safety margin for all monolayers.

During the study, a preliminary assessment of the dependence of the compressor wheel safety factor on the number of splitting the total thickness of the reinforcing layer into monolayers was carried out. For this purpose, calculations were carried out with the following three wheel reinforcement schemes: 0/900, 0/900/0/900, 0/900/0, where 00 coincides with the circumferential direction in the disk.

It was found that the largest relative difference in safety margins between the second and third reinforcement schemes, determined in accordance with the Mises-Hill criterion, was 3%. On the basis of this, it can be concluded that from the point of view of the accuracy of the calculation there is no significant difference from which number of monolayers the reinforcing layer is formed. In the course of optimization in order to simplify the procedure of computational analysis, we can consider the minimum number of monolayers equal to 2.

Thus, the optimization condition will be as follows:

\[
 n_b(V_f, t, m) \to \max ,
\]

\[
 V_{f_{\min}} < V_f < V_{f_{\max}} , \quad m_{\min} < m < m_{\max} , \quad t_{\min} < t < t_{\max} .
\]

Tetrahedral elements and elements of the laminate type were used for the calculation. As the boundary conditions, it was assumed that the compressor wheel was fixed on the surface of the shaft hole in the circumferential direction. In the axial direction - the wheel is stationary along the surfaces of its hub. The finite element model is similar to the model presented in [4].

In the course of the work, separate subprograms were written for performing some operations, such as creating a package of layers, assigning properties of elements, conducting a series of calculations, etc. This significantly reduces the time required for model preparation and calculations.

In parallel with the calculations, the error of their results was estimated. This evaluation was carried out using the Runge rule, based on a comparative analysis of this model, with a finite element model having eight times less nodes. It is established that the stresses arising in the wheel, the error does not exceed 10%.

The analysis of the behavior of the objective function is carried out in the Cartesian coordinate system of variable parameters by alternately “fixing” two of them.

The condition for terminating the optimization process is as follows:

\[
 \max \left( \frac{V_{f_i} - V_{f_{\text{opt}}}}{V_{f_{\text{opt}}}}, \frac{t_{i} - t_{\text{opt}}}{t_{\text{opt}}}, \frac{m_{i} - m_{\text{opt}}}{m_{\text{opt}}} \right) \leq \varepsilon ,
\]

where \( \varepsilon \) - the relative error of determining the variable parameters; \( k \) - the iteration number.

The permissible error of the values of the variable parameters for neighboring iterations in this study was assumed to be 0.05.

At the third iteration of the solution, the condition for terminating the optimization process was fulfilled. As a result, the vector of optimal values of the variable parameters \( V_f = 0.5, m = 0.75, t = 0.8 \text{ mm} \) was obtained.

During the optimization process, it was determined that the maximum general safety margin of the wheel is 1.67. It is limited by the tensile strength of the material of the blade crown. This is due to the
achievement of a reinforcing layer of certain stiffness (more in the circumferential direction), in which the disk material practically ceases to perceive the forces from the centrifugal load. In this case, only the reinforcing layer begins to work. The most stressed zone of the hole is unloaded, and the most vulnerable place is the root part of the blade fig.

The total safety margin of a wheel with a reinforcing layer of continuous fibers exceeds the safety margin of traditional aluminum wheels by 40-50%.

An additional measure aimed at increasing the strength of the wheel may be a decrease in the wall thickness of the disc. Reducing the amount of base material used wheel will reduce the "parasitic" mass and, accordingly, the centrifugal load, which loads the reinforcing layer and the blade crown. This event should be carried out after clarification the minimum required thickness of the outer layer.

![Color graphic diagram of generalized stresses in a compressor wheel made of composite material, with an additional reinforcing layer at optimal variable parameters: Vf = 0.5, m = 0.75, t = 0.8 mm.](image)

**Figure 2.** Color graphic diagram of generalized stresses in a compressor wheel made of composite material, with an additional reinforcing layer at optimal variable parameters: Vf = 0.5, m = 0.75, t = 0.8 mm.

Based on the analysis of the results, we can conclude that there is a possibility of increasing the level of manufacturability of the wheel by reinforcing only in the circumferential direction. In this case, the reduction in the overall safety margin will be less than 5%.

The maximum generalized displacement of a compressor wheel with a reinforcing layer is 30–40% lower than that of the aluminum analogue (Fig. 3). This fact allows us to conclude that the destruction of such a composite wheel with increasing operating speed will occur from exhaustion of the strength of the material, and not from contact with the stationary parts of the compressor housing. The values of the generalized displacements on the radius of the shaft hole are 0.038-0.045 mm, which is also less than the aluminum wheels by 30-40%.

It is also worth noting that the maximum generalized displacements of 0.324 mm are localized on the edges of the blades (Fig. 3). It should be noted that the components of the displacement along the z axis in this zone have negative values, which will not lead to contact of the wheel with the compressor housing. Then the determining movements will be radial ones, which do not exceed 0.277 mm on the edges of the blades, which is also less than the permissible limits (0.7 ... 0.8 mm).
Figure 3. Color graphic diagram of the total displacements of the compressor wheel, made of composite material, with an additional reinforcing layer at optimal values of the variable parameters: $V_f = 0.5$, $m = 0.75$, $t = 0.8$ mm.

At the final stage of the study, a computational analysis was made of the mass-inertia characteristics of the compressor wheel from the composite material with an optimized reinforcing structure. Its mass was 0.266 kg, and the moment of inertia is $360 \cdot 10^{-6}$ kg·m². For comparison: the mass and the moment of inertia of the wheel of similar design made of aluminum alloy are 0.49 kg and $650 \cdot 10^{-6}$ kg·m², respectively. Thus, the use of composite material for compressor wheels allows reducing their mass and moment of inertia by almost two times: by 46% and 45%, respectively. The total mass and the moment of inertia of the entire rotor due to the use of such a wheel can be reduced by 10% and 16%.

4. Conclusion
According to the results of the research carried out on the search for the optimal reinforcing structure for the compressor wheel made from a composite material, the following conclusion can be drawn.

1. For the wheel reinforcement structure, the vector of optimal values of variable parameters was revealed: the fiber share of the reinforcing layer $V_f = 0.5$; the proportion of the thickness of the reinforcing layer $m = 0.75$; the total thickness of the reinforcing layer is $t = 0.8$ mm.

2. The total safety margin of the wheel with optimized reinforcing structure was equal to 1.67, which exceeds the safety margin of traditional aluminum wheels by 40-50%.

3. It has been established that while maintaining the strength of the wheel, it is possible to use reinforcing layers in which the fibers are oriented only in the circumferential direction, which can significantly simplify the technology of its manufacture.

4. The use of reinforcement for compressor wheels from composite material allows reducing its mass and polar moment of inertia almost twice, which helps to reduce the moment of inertia of the rotor by 16%. In general, the results of the study determine the obvious prospect of using composite materials with an optimized reinforcement structure for the compressor wheels of turbochargers, associated with the possibility of a significant reduction in the inertia of their rotors while maintaining the acceptable strength properties. The consequence of this is the improvement of the level of operational qualities of the turbocharger (reduction of inertial loads and increase of the service life, improvement of injectivity during transient modes of operation, etc).
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