3D optimization of the hollow fan blade internal structure

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Abstract. Design optimization to reduce fan impeller mass is an important and urgent task. One way to solve the problem is to design a hollow blade. In addition to lightening the blade this also reduces the fan disk load, that in turn makes it possible to minimize the weight of the disk and the weight of the impeller as a whole. The hollow blade has a complex shape, and this significantly increases development time because modification of the structure in order to define its optimal shape is a very time-consuming and costly task. Therefore, automating this process and transforming it into an optimization task is very important and relevant. In this paper, an approach to optimal hollow fan blade design in the form of an optimization problem in 3D formulation is developed. To do this, a parameterized 3D model of the hollow blade was created in the ANSYS APDL environment. Using the developed model, a comparative optimization of a typical hollow blade was carried out.

1. Introduction
Designing the internal structure of a hollow three-layer fan blade is a complex and time-consuming task [1]. This is due to the difficulty of simulating hollow blade manufacturing processes and the complexity of the internal structure of the corrugation part and its points of connection to the blade back and pressure side. This paper is dedicated to solving the problems of reducing labor intensity related to this latter aspect. Technological and design requirements (including those related to manufacturing) are taken into account in the form of dimensional restrictions.

When manually modifying the design, there is a need to repeatedly create a large number of geometric objects forming the blade and to rebuild the finite element mesh. On the other hand, internal design of the three-layer hollow blade is determined by a large number of sizes. This leads to significant difficulties in intuitively searching for the optimal configuration that causes design quality degradation.

Labor intensity was reduced by automating the processes of creating a computed 3D finite element model and its analysis [2]. To do this, a parameterized 3D model of a typical hollow blade was created in the ANSYS APDL environment. The design task was formalized, automated and converted to an optimization problem in which minimizing the weight of the blade was used as a criterion, requirements for strength, frequency detuning, technological requirements – as constrains, and characteristic dimensions of the corrugations and thickness of the back and pressure side – as parameters. The optimization problem was solved in the multicriterial optimization package IOSO NM.
2. Optimization object
To demonstrate the developed approach to automated 3D strength design, a hollow fan blade of a typical fan with a high bypass ratio was used. This blade was designed using the iterative "gas dynamics - strength" approach with a large number of clarifying and verification computations. The design of the corrugation, and the back and pressure side walls was obtained as a result of laborious manual refinement work. The original blade meets all the requirements for gas dynamic characteristics.

A general view of the original hollow blade and its dimensions is shown in Figure 1. The same figure schematically shows internal structure and the general appearance of the corrugation. The blade material is titanium alloy.

Strength calculations of the original design and those in the process of optimization were carried out for the high stress area in the frame of elastic formulation, taking into account geometry nonlinearity. Uneven gas pressure distributions were applied for the surface of the back and pressure side. The blade rotation speed was 3500 rpm. The thermal state was assumed to be unvarying, temperature - 70°C.

3. Original design characteristics analysis
Analysis of the strength and natural frequencies was carried out for the original design of a typical fan hollow blade. The finite element model of the original blade is shown in Figure 2. Figure 3 shows distribution of equivalent Mises stresses on the walls of the blade back and pressure side and in the corrugation. An excitation diagram for the original blade is shown in Figure 4.

Figure 3 shows that the maximum stress value is achieved in the middle part of the blade. The maximum stress level is 578 MPa which is less than the material yield stress. Therefore, the original blade meets maximum stress requirements. However, the excitation diagram shows the blade dangerously approaching:
- 1st natural frequency and 2 harmonic;
- 2nd natural frequency and 4 harmonic;
- 3rd natural frequency and 4 harmonic;
- 2 and 3 natural frequencies.

Weight of the original structure is 6.66 kg.
Figure 2. Finite element model of the original blade A) blade; B) corrugation; C) section A-A

Figure 3. Distribution of equivalent Mises stresses (MPa) on the walls of the back and pressure side (A) and the corrugation of the original blade (B)

Figure 4. Campbell diagram of the original fan hollow blade design
The purpose of the optimization task is to minimize mass of the original hollow blade, taking into account its frequency detuning and maximum stress requirements (no more than the original design). At the same time, since the original blade meets gas dynamic requirements, it was concluded that the optimization will be carried out by changing the shape of only the internal part of the blade (thickness of the back and pressure side walls and corrugation design). The outer profile of the blade will remain unchanged. Such an approach to "strength" optimization makes it possible to avoid subsequent gas-dynamic refinement and refining gas-dynamic calculations of the optimized design.

4. Formulation of the optimization problem
The process of the hollow blade design optimization in order to minimize its mass was unified and formalized. Optimization was carried out using a specially designed parameterized 3D model of a hollow three-layer fan blade.

Optimization criterion was to minimize mass of the hollow blade. The following requirements were used as restrictions:
- maximum equivalent Mises stresses should be no more than the original design, < 570 MPa;
- frequency detuning of the first five natural frequencies should be present;
- interval between 2nd and 3rd natural frequencies should be not less than 50 Hz.

5. Description of the optimization process
A general block diagram of the optimization process is shown in Figure 5. The IOSO NM software package was used as an optimization module. All optimization iterations included several steps:

1) Vector of variable parameters was formed in IOSO software and transferred to the used parameterized finite element model;
2) The parameterized finite element model was ran: solid and finite element models of the blade were created sequentially, stress-strain state analysis and modal analysis were performed, criteria and constraints were calculated;
3) A list of output parameters was generated and transferred to IOSO;
4) The obtained data was analyzed in IOSO and checked for convergence:
   4.1) if there is no convergence, the procedure transferred to step # 1, that is, a new list of variable parameters was formed in IOSO and transferred to the model;
   4.2) if there is convergence, the optimization process was stopped.

A PC with the following characteristics was used for the optimization process: 34 GB RAM, 12 cores 3.6 GHz.

6. Description of the optimization process
The design optimization can be conducted using various numerical optimization methods. The choice of a numerical method depends on the number of variable parameters, the nature of the estimated relationships between the variable parameters, criteria and constraints, as well as the number of set criteria and restrictions.

In this paper the optimal structure search was carried out using the modern multi-criteria optimization package IOSO (Indirect Optimization on the base of Self-Organization) [3] developed for solving constrained and unconstrained optimization complex one-criterion and multicriteria problems for objective functions of different categories.

IOSO uses a method of indirect statistical optimization based on self-organization. This method is based on the application of response surface creation technology for approximation of objective function and restrictions. IOSO algorithms have good invariant properties and a high level of stability; they allow structural parameterization outside the domain when there are noncomputability domains during optimization of compound objects.
7. Structure parameterization scheme

To automate and unify the process of strength design of the internal structure of the hollow fan blade, a unified scheme for parameterization of the corrugation and the blade walls was developed. This parameterization scheme does not fully describe the entire design of the hollow blade, but relies on some already existing original blade for which profiles were obtained as a result of preliminary gas dynamic design (or iterative "gas dynamics-strength" design). Therefore, before starting optimization, it was necessary to present the original blade as a set of external profiles located at characteristic radii. Profile data was obtained using coordinates of the back and pressure side points from which they are formed [4, 5].

The profile arrangement used for the original blade is shown in Figure 6. In this Figure, green boxes highlight sections in which internal design was not varied. Red boxes show cross-sections in which typical dimensions of the inner part were varied. Black boxes show cross-sections which changed but were not varied during the optimization process. They were defined by approximating the values of corresponding parameters for varied and non-varied sections. This approach can significantly reduce the number of variable parameters (by 2-3 times) which significantly reduces the time required to solve the optimization problem.

The blade cross-section parameterization scheme is shown in Figure 7. Parameters varied in the course of the optimization process are highlighted with red boxes, non-variable parameters - with black boxes. The following parameters were varied in the process of optimization:

- $h_{g1}$ – the corrugation thickness (constant for entire corrugation over all blade sections);
- $v_g$ – the width of the corrugation connection with the back and pressure side (same for all connection areas in one section, but different for different sections);
- $h_2, h_4, h_5, h_6, h_7, h_8$ – the characteristic wall thickness of the blade near the back and pressure side (different for different sections);
- $s_{in2}, s_{out2}$ – the distance from the back and pressure side connection to the first corrugation bend at input and output sides (different for different sections).

The following parameters were not varied in the course of optimization:

- $s_{in1}, s_{out1}$ – the width of the back and pressure side connection at input and output sides (different for different sections);
• $h_1, h_3$ – the wall thickness near the back, at the back and pressure side connection (different for different sections);
• $h_{g2}$ – the thickness of the corrugation near connection with the back and pressure side (constant for entire corrugation over all blade sections).

![Figure 6. Used original blade profile arrangement](image)

![Figure 7. The blade section parameterization scheme](image)

The corrugation topology (the number of bends, the relative distance between the connection with the back and pressure side walls, etc.) was not changed in the optimization process, but the corrugation dimensions themselves change proportionally in accordance with changes in varied parameters of changing sections. As a basic design, corrugation of the original blade was used.

Thus, 50 parameters were varied in the course of the optimization process:
• 2 corrugation parameters ($h_{g1}, v_g$);
• 48 section parameters: 8 parameters per section, 6 varied sections.

The external profile of the blade was not changed in the optimization process and remained the same as in the original design.
The developed parameterization scheme was unified and allows describing design for other types of hollow three-layer fan blades. This means that this parameterization scheme and a parameterized 3D model developed using this scheme can be used not only for the blade strength optimization under consideration, but also for other types of hollow blades.

8. Description of a parameterized FE 3D model
A parameterized 3D model is developed on the basis of the parameterization scheme described above. In the course of each optimization iteration, the model is automatically modified taking into account current values of variable parameters, and stress-strain state analysis and modal analysis of the hollow blade are carried out according to the following scheme:

1) definition of internal structure parameters for "non-varied" sections (highlighted with a black box);
2) creation of internal structure for each section;
3) creation of a hollow blade solid model based on the created sections;
4) carrying out stress-strain state analysis for elastic problem taking into account geometric nonlinearity;
5) modal analysis considering geometric nonlinearity.

Figure 8 shows the progress of creating a computational 3D FE model by iterations of the optimization process.

Figure 8. Progress in creating a computational 3D FE model by iterations of the optimization process

9. Optimization Results
Mass reduction (criterion) in the course of the optimization process is shown in Figure 9. As can be seen from this Figure, the process converges (the mass stops decreasing) after 431 iterations. The computation time of one iteration is 5-7 minutes. Thus, the total time to reach the optimal project is about two days.

Comparative optimization parameters are given in Table 1. The distribution of equivalent Mises stresses throughout the optimized blade is shown in Figure 10. The optimized blade excitation diagram is shown in Figure 11. Figure 12 shows the cross-sectional variation of the varied cross-sectional
parameters for the original and optimized blades. Based on the results, it can be concluded that, during optimization, it is possible to reduce weight of an already well-designed blade by 13.8% (0.79 kg). In this case, the stress level in the optimized blade is the same as in the original one. However, in the course of optimization, it is possible to detune the 1st, 2nd and 3rd natural frequencies and to move the 3rd and 2nd natural frequencies away from each other.

![Graph showing mass change in the course of optimization process](image)

**Figure 9.** Mass change in the course of optimization process

| Table 1. Comparison of optimization parameters. |
|-----------------------------------------------|
|                                      | Original | Optimal | %     |
| Mass, kg                              | 5.72     | 4.94    | ↓13.8 |
| $\sigma_{eqv}$, MPa                  | 578      | 577     | ---   |
| $f_1$, Hz                             | 107      | 93      | ↓13   |
| $f_2$, Hz                             | 221      | 207     | ↓6    |
| $f_3$, Hz                             | 251      | 262     | ↑4.3  |
| $f_4$, Hz                             | 433      | 431     | ---   |
| $f_5$, Hz                             | 560      | 545     | ↓2.7  |

It can be seen from Figure 12 that the blade weight decreases due to a decrease in the thickness of the corrugation and walls of the back and pressure side. This should lead to increased stress, however in the optimized blade the maximum stress is the same as in the original one. Maintaining the same stress level is achieved by optimally selecting parameters $s_{in2}$ and $s_{out2}$ at each section which affect "elongation/reduction" of the corrugation inside the blade. In this case, the stiffness of the blade changes in such a way that the stress, despite decrease in thickness, does not increase.
Figure 10. Distribution of equivalent Mises stresses on: walls of back and pressure side (A) and corrugation of the optimized blade (B)

Figure 11. Campbell diagram of the optimal fan hollow blade design

Figure 12. Changing varied cross-section parameters
10. Conclusion
This paper demonstrates a design optimization of the internal part of a hollow three-layer fan blade. The purpose of the optimization process is to minimize blade weight taking into account requirements for static strength characteristics, frequency detuning, and structural limitations. In the process of optimization external contours of the profiles remained unchanged and only internal structure (corrugation, wall thickness of the back and pressure side, etc.) was changed.

A parameterized 3D model of the hollow blade was created in the ANSYS APDL environment to automate the processes of hollow blade design modification and analysis. Optimization was carried out using the IOSO NM multicriterial optimization package.

The developed optimization technology was tested on a typical design hollow blade. As a result of the optimization the weight of the blade was reduced by 13.8% (0.79 kg). In this case, the stress level in the optimized blade was the same as in the original one. Frequency detuning requirements were also met.

The results show the high efficiency of the proposed approach in terms of improving the quality and reducing the complexity of strength design of hollow blades internal structure.

Further work will be aimed at expanding the scheme of blade internals parameterization, increasing the number of varied parameters, and adding additional analysis disciplines to the optimization process.

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