Topology optimization parameters of blades of wind turbines

Krzysztof Pytel ORCID ID: 0000-0002-1924-8351

AGH University of Science and Technology
Faculty of Mechanical Engineering and Robotics
Department of Power Systems and Environmental Protection Facilities, Krakow
email: kpytel@agh.edu.pl

Andriy Zdobytskyi ORCID ID: 0000-0001-8044-9593

Lviv Polytechnic National University
Institute of Computer Science and Information Technologies
Department of Computer-Aided Design Systems, Lviv
email: andrii.y.zdobytskyi@lpnu.ua

Mykhaylo Lobur ORCID ID: 0000-0001-7516-1093

Lviv Polytechnic National University
Institute of Computer Science and Information Technologies
Department of Computer-Aided Design Systems, Lviv
email: mykhaylo.v.lobur@lpnu.ua

Roman Panchak ORCID ID: 0000-0002-6422-7656

Lviv Polytechnic National University
Institute of Computer Science and Information Technologies
Department of Computer-Aided Design Systems, Lviv
email: roman.t.panchak@lpnu.ua

Anna Hnatiuk ORCID ID: 0000-0002-0623-5041

Lviv Polytechnic National University
Institute of Computer Science and Information Technologies
Department of Computer-Aided Design Systems, Lviv
email: anna.hnatiuk.knm.2019@lpnu.ua

ABSTRACT

This work provides peculiarities of the production of various elements of complex geometric shapes by the newest technologies of additive production. It considers the possibility of modernizing and improving the design of wind turbine blades by the classical method of topological optimization while taking the wind load vector into account and preserving their functional properties. Using the topological optimization algorithm of the Inventor Nastran software environment, the design of a wind turbine blade was automatically generated in accordance with the geometric constraints on the shape and minimization in terms of its weight and maximum rigidity. It also shows the peculiarities of generating a wind turbine blade design with changes in the parameters of topological optimization ([COMPVF], [TOPTMANCONSTR], [TOPGEN], and [TOPTMANCORD]) and the maximum and minimum airflow forces.

Keywords: topological optimization, blade, wind turbine, stiffness, material minimization, wind load

1. Introduction and research objective

The development of alternative energy sources (namely, wind energy) is undoubtedly an important area for implementing energy systems. Modern wind turbines are bulky structures that can only work properly in a narrow area of wind load; under the influence of variable wind loads, however, the blades of wind turbines become deformed, which leads to a decrease in their efficiency (Ma et al. 2016). Therefore, the main criteria for designing wind turbine blades are optimization by the weight and maximum rigidity of a structure while taking the spectrum of the natural frequencies of oscillations, geometric, and production constraints into account (along with their contact interaction).

The gradual development of composite materials has opened up new ways of using them in fundamentally new industries and aspects. Due to the expansion of such functional properties as their increased strength, corrosion resistance, and lightweight construction, composite materials are gradually gaining popularity in the wind energy industry. However, ensuring the proper functionality of materials is virtually impossible without the use of modern technologies of engineering calculation and design. The rapid development of new technologies and models of additive production (namely, the introduction of new design techniques) contributes to the production of various elements of complex geometric shapes. As a result, the requirements for the quality of manufacture of both individual parts/components and units as a whole increase.

Generative design, generated design, topological optimization, structural optimization, and bionic design are the most common ways of developing, optimizing, and creating lightweight structures.

In the environments of computer aided design and engineering analysis, the following optimization methods are have been implemented at:

- topological – which provides the optimal distribution of the material in a calculation area based on the boundary conditions, objective function, and constraints;
- topographic – which determines the optimal direction of stiffening ribs of stamped sheet metal parts based on the boundary conditions, target function, and constraints;
- thickness optimization – determines the optimal thickness of sheet metal parts in a structure based on the boundary conditions, target function, and constraints;
- optimization of mesh structures – the optimal area of the intersection of the elements of mesh structures based on the boundary conditions, target function, and constraints (Altair Inspire 2021; Bendsøe, Kikuchi 1988).

Generating structures by using methods of topological optimization and generative design significantly expands their functionality (Meng et al. 2020). Due to the creation of lightweight matrix structures of blades, their proper geometric parameters are provided, taking fatigue and impact resistance into account as well as durability in accordance with the action of wind load.

2. Methodology of research

Topological design optimization provides the optimization of the structure of a design object at the initial stage within a given three-dimensional spatial location with a set of rules that are set by the user. Accordingly, the maximum performance of the system is ensured by the mathematical modeling and optimization for external forces, boundary conditions, and existing constraints.

However, the topology optimization of the part is the first step in the design process; this is usually too difficult to implement, as it is also necessary to take the issue of the manufacturability of a structure into account. Nonetheless, the use of topology optimization at the initial stage of design provides the appropriate functionality and necessary characteristics of the structural elements to perform their functions. As a result, the basis of the final design is programmatically implemented.

Conventional topology optimization uses the finite element method for evaluating the effectiveness of a design according to certain criteria.

The classical method of topological optimization is based on the method of density distribution (Ma et al. 2016); within this, the material distribution parameter is set by using controlled parameters through the interpolation function. Interpolation functions for solid and non-solid materials are built into the functionality of Autodesk

Nastran In-CAD software, so the density of isotropic material is taken into account for optimization (ranging from 0 to 1). Other methods consider local material orientation (for non-isotropic materials) and even other characteristics (Bendsøe 1989; Bendsøe, Sigmund 2003).

Each element is filled with material for those areas in which it is needed or its absence for those areas where it can be removed (representation of voids). The distribution of the material density within design domain ρ is discrete; therefore, each element is assigned a binary value (Fig. 1) (Razvan 2014).

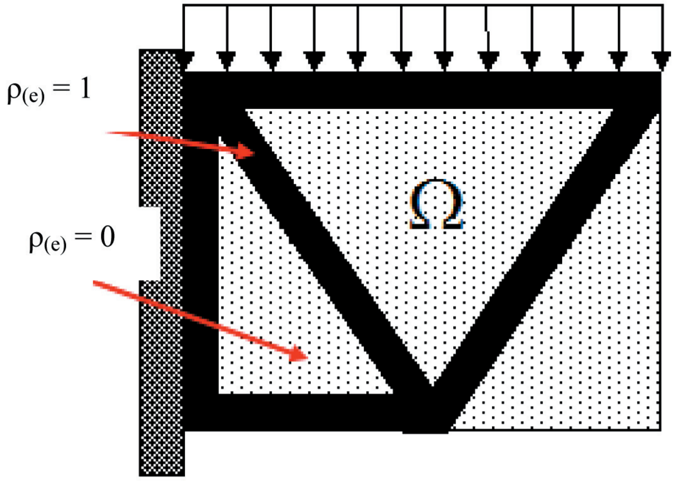

Fig. 1. Optimized structure of material distribution according to set conditions: $\rho_{(e)} = 1$ – material required (black); $\rho_{(e)} = 0$ – material removed (white)

Since the relative density of a material can change continuously, the material's Young's modulus can also be constantly changing on each element. For each element "e", there are correlations between the coefficient of relative density of the material ρ_e and Young's modulus for elasticity of the isotropic model of the material E_0 (as calculated by the power function) (Fig. 2):

$$E(\rho_e) = \rho_e^p E_0 \tag{1}$$

The loss-correction parameter reduces the proportion of the elements with intermediate densities (gray elements) to total stiffness and controls the optimization solution for those elements that are represented by total black ($\rho_e = 1$) or removed – white ($\rho_e = \rho_{min}$). The loss adjustment parameter is usually $p = 3$.

In the process of performing each iteration, optimization algorithms analyze the sensitivity to estimate the types of material density on the target indicators in order to maximize the stiffness.

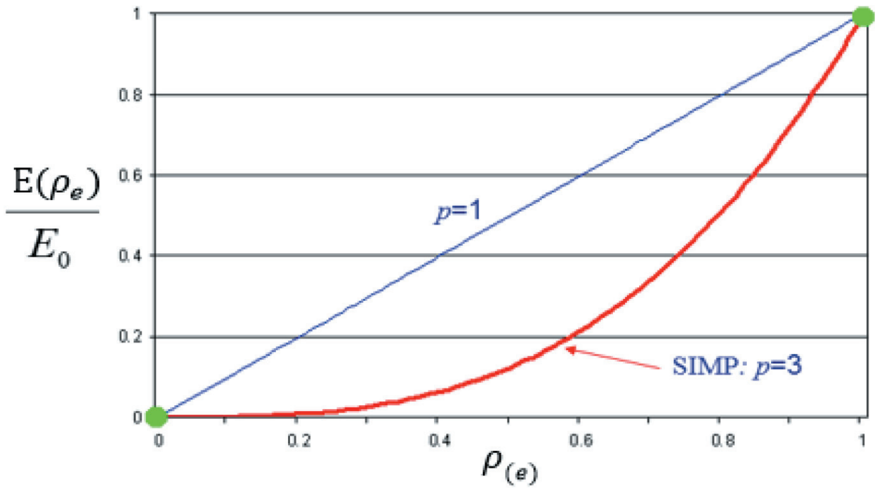

Fig. 2. Optimized structure of material distribution according to set conditions

The optimization algorithm is based on finding the local minimum, starting with different initial volume particles and different grids – the densities of which will lead to different construction designs. Topology optimization is determined based on isogeometric analysis with a global stress limitation. The iterations of the optimization continue until the convergence of different target functions and the achievement of iterations of their matching criteria:

$$\sigma_{\text{global}} = \sigma_{\max} \left\{ \frac{1}{N} \sum_{e=1}^{N} \left(\frac{\sqrt{\rho_e}\,\sigma_{\text{vM}}^{e}}{\sigma_{\max}} \right)^{p} \right\}^{\frac{1}{p}} \leq \sigma_{\max} \tag{2}$$

where:

σ_{max} – allowable stress [MPa],

σ_{vM} – von Mises stress [MPa],

N – number of topology optimization elements,

$p \sim 10$ – approximation exponent.

3. Main results and their discussions

To verify the adequacy of the described assumptions about increasing the strength of wind turbine blades by topological optimization methods, we will use computer-aided CAD modeling and CAE engineering analysis with the appropriate modules of topological optimization and design (Rozvany et al. 1992; Zdobytskyi et al. 2021).

A wind turbine blade is made of polymeric material with high mechanical strength and impact resistance, abrasion resistance, and multiple deformations during the stretching and bending; it retains its high impact resistance and strength characteristics in an operating temperature range of –40° to +60°C. Therefore, we will use the classic method of topological optimization solid isotropic material penalization (SIMP) (for isotropic materials). In the Autodesk Inventor Nastran environment, we will create constraints to remove unwanted material and generate a more optimal wind turbine blade design (Fig. 3), making its structure hollow (Pedersen, Allinger 2006).

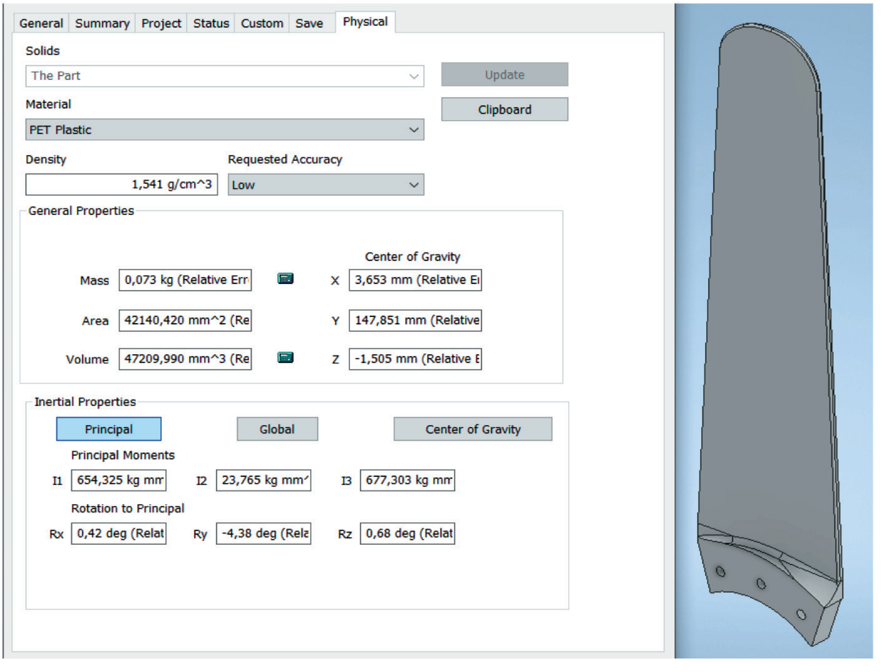

Fig. 3. Automatically generated wind turbine blade structure

At the initial stage of the design, we will create a three-dimensional model of a wind turbine blade and investigate it for tensions and deformations that arise under the action of a wind load of 380 Pa (Fig. 4).

Since the classical method of topological optimization is based on the finite element method, the density of the material varies from 0 to 1 at each given optimization point. For the automatic generation of topology optimization (TOPGEN) that is in accordance with a linear static analysis of the stress-strain state of the structure, we set design constraints on volume particle minimization (COMPVF) and additive layer fabrication (TOPTMANCONSTR). We also indicate the planes of symmetry of the constraints and the direction of the extrusion of the material (TOPTMANCORD) in Figure 5.

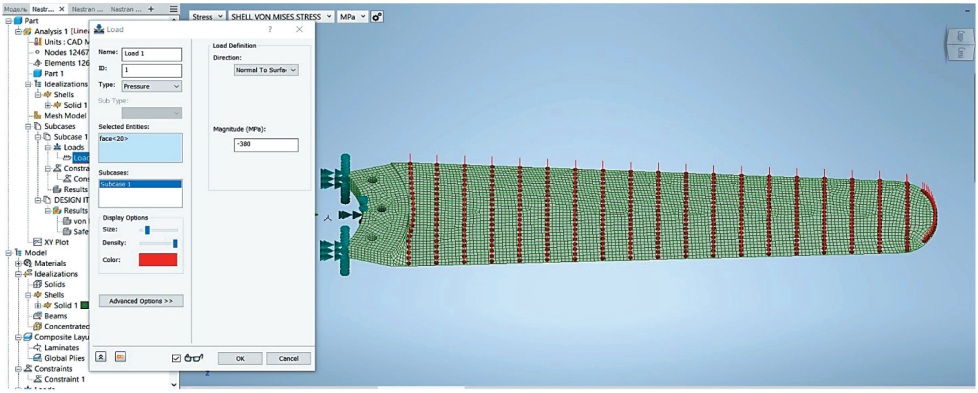

Fig. 4. Automatically generated wind turbine blade structure

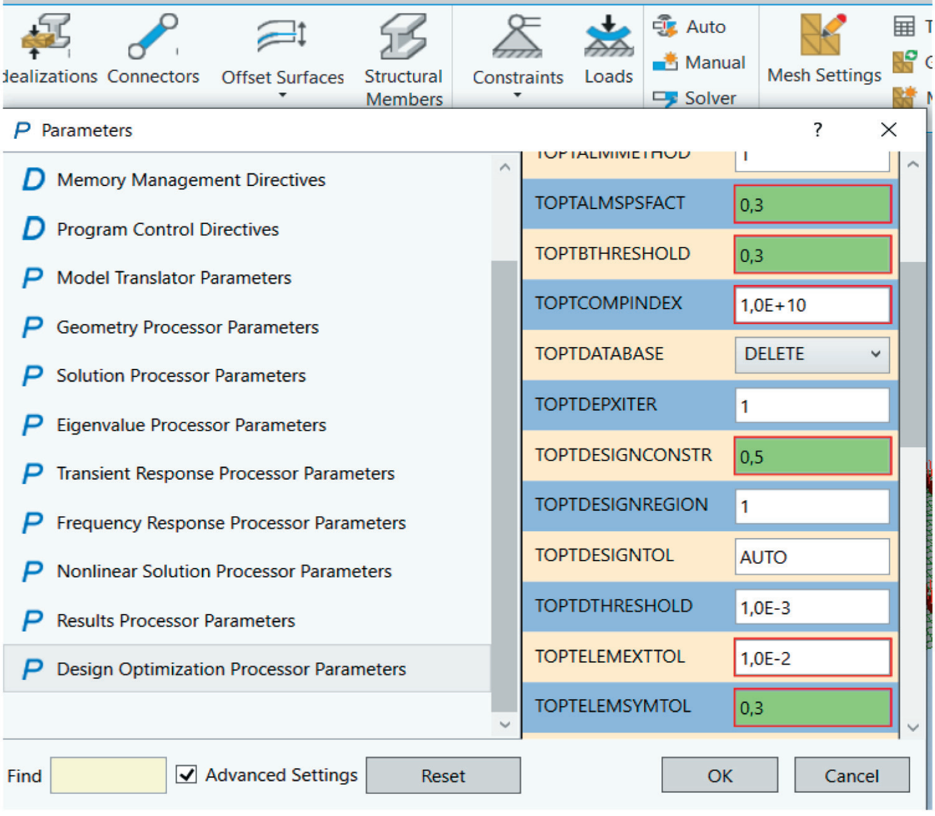

Fig. 5. Topology optimization processor parameters

The material constraints were determined by the volume fraction, where the maximum material that is allowed in the final design is described as the fraction of the material that is available at the beginning of the optimization. The values of the topology optimization design constraint based on the TOPTGEN parameters were 0.3, 0.5, and 0.7, respectively (Fig. 6).

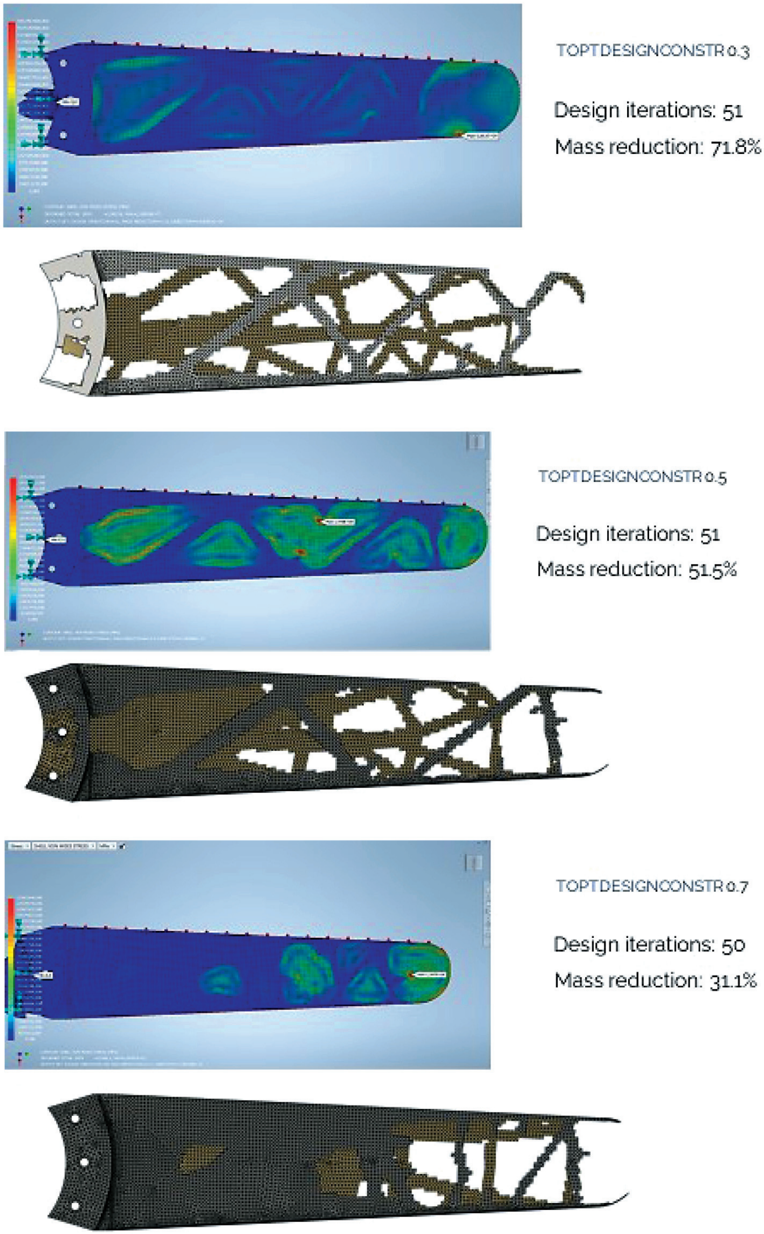

Fig. 6. Automatically generated structure of wind turbine blades by limiting density of grid and volume fractions of 0.3, 0.5, and 0.7

4. Conclusion

The topological optimization of a structure optimizes the structure of a design object at the initial stage within a given three-dimensional spatial location with a set of rules that are set by the user. Accordingly, the software implements the maximum performance of the system through the mathematical modeling and optimization for external forces, boundary conditions, and existing constraints.

The implementation of the topological optimization algorithm by Autodesk Inventor Nastran enables solutions to multi-purpose design problems that are intuitively difficult to predict. The structure of a wind turbine blade is automatically generated and provides the maximum possible rigidity and minimization of the material in accordance with the action of the wind load vector. By changing the TOPTDESIGNCONSTR parameter to within a range of 0 to 1, the method gives us a wide range of improved forms of the model for its further reproduction while employing additive production.

REFERENCES

Altair Inspire. Available: https://infcs.ru/catalog/promyshlennyy-dizayn/altair-inspire/ [18.10.2021].

Bendsøe M.P., 1989, *Optimal shape design as a material distribution problem*, Structural Optimization, 1, 193–202.

Bendsøe M.P., Kikuchi N., 1988, *Generating optimal topologies in structural design using a homogenization method*, Computer Methods in Applied Mechanics and Engineering, 71(2), 197–224.

Bendsøe M.P., Sigmund O., 2003, *Topology Optimization: Theory, Methods, and Applications*, Springer-Verlag, Berlin – Heidelberg – New York.

Ma Y., Xu S., Liu H., Wang X., 2016, *Optimization of reinforcing ribs of a hollow fan blade using metamodel-based optimization algorithm conference*, Proceedings of ASME Turbo Expo 2016: Turbine Technical Conference and Exposition June 2016. DOI: https://doi.org/10.1115/GT2016-57226.

Meng L., Zhang W., Quan D., Shi G., Tang L., Hou Y., Breitkopf P., Zhu J., Gao T., 2020, *From topology optimization design to additive manufacturing: today's success and tomorrow's roadmap*, Archives of Computational Methods in Engineering, 27, 805–830. DOI: https://doi.org/10.1007/s11831-019-09331-1.

Pedersen C.B.W., Allinger P., 2006, *Industrial implementation and applications of topology optimization and future needs*. In: Bendsøe M.P., Olhoff N., Sigmund O. (Eds.), *IUTAM Symposium on Topological Design Optimization of Structures, Machines, and Materials: Status and Perspectives*, Springer, 147–156.

Razvan C., 2014, *Overview of structural topology optimization methods for plane and solid structures*, Annals of the Oradea University, Fascicle of Management and Technological Engineering, 3(3). DOI: https://doi.org/10.15660/AUOFMTE.2014-3.3043.

Rozvany G.I.N, Zhou M., Birker T., 1992, *Generalized shape optimization without homogenization*, Structural Optimization, 4(3–4), 250–252.

Zdobytskyi A., Lobur M., Panchak R., Sika R., Kalinowski K., 2021, *Increasing the strength of materials by topological optimization methods*, 16th International Conference on the Experience of Designing and Application of CAD Systems (CADSM), 6–9. DOI: https://doi.org/10.1109/CADSM52681.2021.9385222.