Chapter 8

Multidisciplinary Optimization of Wind Turbine Blades with Respect to Minimize Vibrations

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I. INTRODUCTION

The main objectives of the research related to the development of wind energy are focused on increasing wind turbine power output and decreasing cost of obtained energy. Although wind turbine power output depends on blades shape and their dimensions (i.e., the power output increases three times with respect to the blade length), it is profitable to produce light and long blades, but this requires necessity of proper selection of materials and structures. However, it is important to note that increasing blade length means changing wind turbine dynamic properties. Another reason to design blades that ensure a maximum possible power output and functioning properly and trouble-free for many years, is the fact that they only cost about 10% of the total manufacturing cost of a wind turbine. From a technical point of view, the design of wind turbine consists of looking for solutions that allow the wind turbine to produce as much as possible electrical power per year. On the other hand, the aerodynamic efficiency of the wind turbine depends on the shape of the blade profile. Therefore, the choice of the optimal shape of the wind turbine blade is a primary task in the design process of wind turbine.

The design process of wind turbine blades places strong emphasis on reducing its mass, ensuring adequate load transfer, which often means a reduced stiffness. According to the rules based on experience, the mass of the blade should increase three times depending on its length. Such dependence may be softened by the use of certain techniques, such as modification in blades construction or development of methods for their production. Goeij et al [1] have described some different concepts of production, taking into account the fatigue of composites loaded eccentrically with respect to the fiber orientation. The publication contains also a description of the construction of the blades, manufacturing techniques, materials used. Naturally, modifications in the materials used is another technique - modifications of composite material used as sheathing material may lead to an increase in the thickness and density of balsa layer, or increase of reinforcement layers or changes in the type of fibers and their orientation. The composite materials used in the spars may be modified in a similar manner.

However, while designing wind turbine blades, it is important that the shape of the blade must ensure adequate aerodynamic properties, proper shape and stiffness to avoid collisions with the tower when wind blowing at high speed. Lifetime of wind turbines is at least 20 years. In addition, the wind turbine must provide the possibility of a low noise generation. The outer layer of the sheathing (gel-coat) must be resistant to dirt and temperature variations, which means providing a high aerodynamic efficiency under different weather conditions.

The necessity for consideration of various aspects of design process of wind turbine blades makes the optimization a very complex task, which requires applications supporting multi-criteria optimization methods. The main goal of the optimization process of wind turbine blades, due to the dynamic changes in the operating conditions of wind turbine, is to provide adequate dynamic characteristics for the whole system. The dynamic characteristics of wind turbines depend on the natural frequencies and spectral functions. The model presented in this chapter does not include aerodynamic damping, thus the dynamic properties of wind turbine depends only on the form and values of stiffness matrix and mass matrix. The aim of the research presented in this chapter is to minimize vibration amplitudes of wind turbine blades which are loaded with mass and aerodynamic forces. Loads are determined on the basis of modified BEM method. Calculations are performed for horizontal axis wind turbines (HAWTs). According to IEC classification of turbines, the weather conditions correspond to a wind turbine of Class I.

II. DETERMINATION OF BLADE GEOMETRY

The process of designing wind turbine blades is based on a certain type of optimization process during which the optimal geometry of the blade is determined. This will ensure the production of wind power less than or equal to the rated power of the generator. The determination of optimal shape of wind turbine blades is a compromise between adequate mechanical and aerodynamic properties. Thus, the optimization of geometric properties of wind turbine blade involves the determination of:

- the distribution of the pitch angle along the blade span;
- the distribution of the twist angle along the blade span;
- the distribution of the inflow angle along the blade span;
- the distribution of the chord width along the blade span.

Optimal values of geometric properties of wind turbine blade are developed based on the dependencies described in Blade Element Momentum Theory [2, 3], the values are presented in the graphs shown in Figs. 1-4.

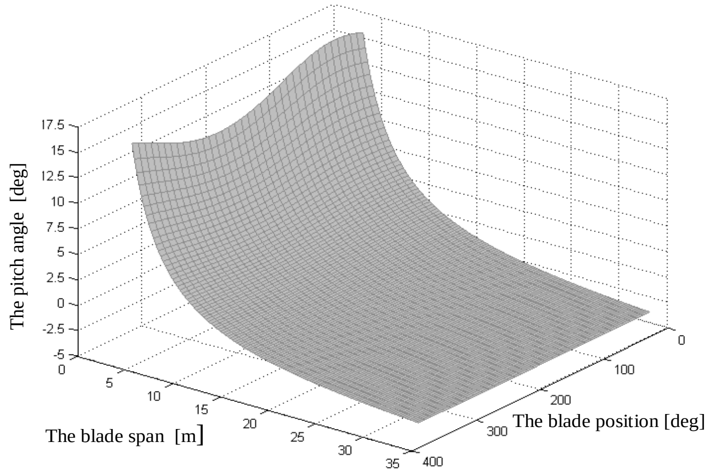


Fig. 1 Distribution of the pitch angle along the blade span depending on the blade position

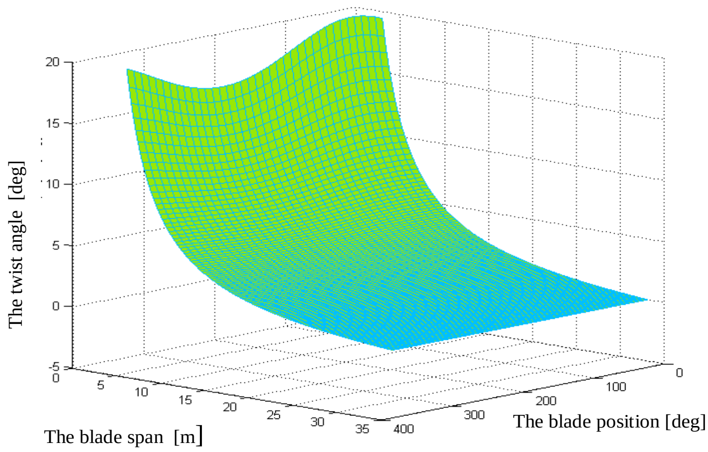


Fig. 2 Distribution of the twist angle along the blade span depending on the blade position

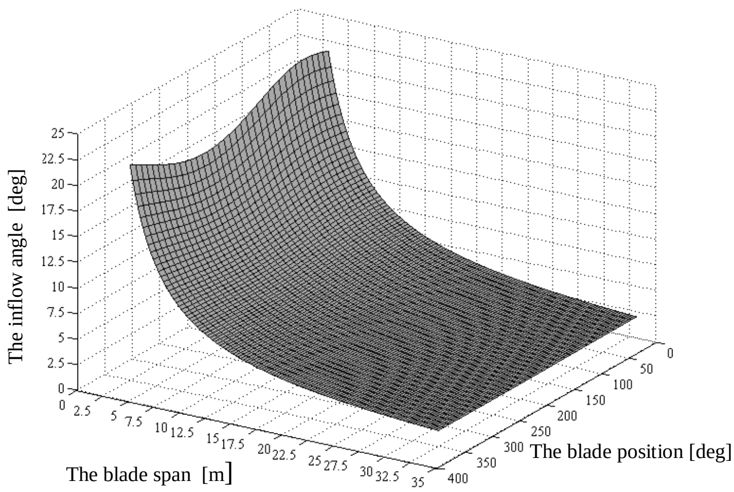


Fig. 3 Distribution of the inflow angle along the blade span depending on the blade position

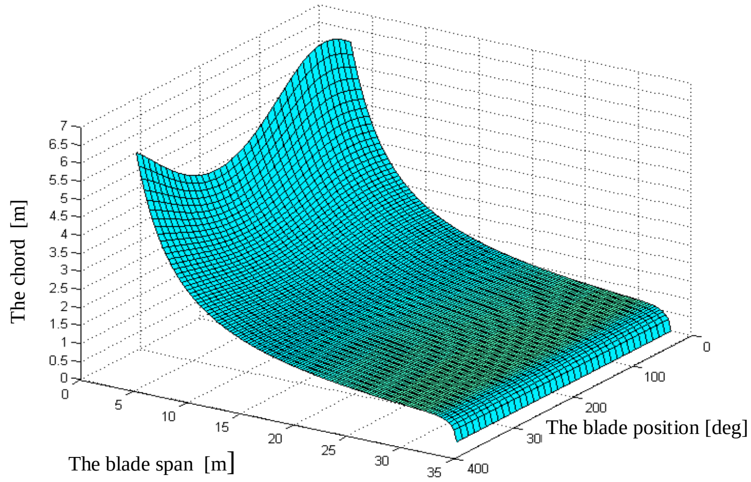


Fig. 4 Distribution of the chord along the blade span depending on the blade position

With the increase of the normal component of induced velocity, which increases proportionally with the distance between rotor axis and aerodynamic cross-section, the value of lift force will also increase. Reducing the width of the blade between the leading edge and trailing edge, namely the reduction of the chord in direction of the blade tip, makes it possible to counteract this phenomenon. But having a significant load at the blade tip makes it necessary to increase the chord at the tip. Aerodynamic cross-sections near hub transfer significant loads and stresses from other parts; therefore the blade profile near the hub has a larger size with respect to the rest of the blade construction. Whereas, along the blade span, it becomes thinner to maintain proper aerodynamic properties. In order to ensure better fit the end of the blade to the hub it has a rim shape [4, 5].

III. NUMERICAL MODEL OF THE WIND TURBINE BLADE

The work presented in this chapter was performed on a three-bladed horizontal axis wind turbine. The turbine under investigation is a turbine rotor which uses asynchronous motor-driven, upwind type with pitch regulation system. The blade was divided into 23 aerodynamic cross-sections, selecting for each one a different airfoil. The numerical model uses airfoil series FFAW3-xxx and RISØ procedures, characterized by further relations between the profile width, the chord length and the aerodynamic properties. The thickness-to-chord ratio depends on the selected aerodynamic profiles. Near the root of the blade, circular profiles are used with a thickness-to-chord ratio equal to 100%, which decreases smoothly to 14% on the tip of the blade.

Additionally, in order to increase the longitudinal stiffness of the blade made of composite, either longitudinal spars or transversal spars are bonded into the half-shells. With this solution the blade internal structure is more stiff and resistant to wind loads [6]. To enable the blade to respond to change in wind velocity vector, which experiences along its span during the rotation, the cross-section of the blade must be twisted along the shear axis along the blade span (Fig. 5) [7]. According to literature data it appears that gravity center of aircraft wing is located between the center of elasticity and the center of aerodynamic forces (center of pressure). In aircraft the position and the order of centers are different than in wind turbine blades. According to [4], the blade is to be twisted around the shear axis. In modern wind turbines, the center of elasticity is placed between the gravity center and the center of aerodynamic forces. The position of the spars can be determined with respect to the position of the shear axis. However, twisting the wind turbine blade along the shear axis must be controlled at the same time as the positioning of the centers of gravity and aerodynamic. These positions and the shear axis can be adjusted by changing the location of the spars and the possible modification of their shape [8].

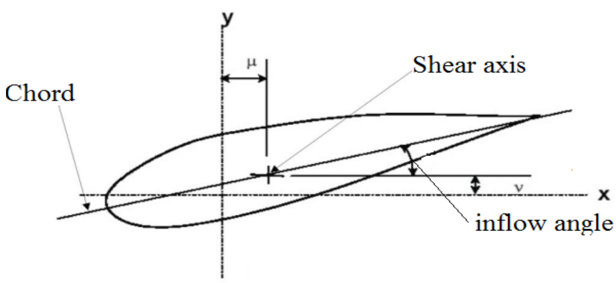


Fig. 5 Location of the shear axis and the main axes of the coordinate system [7]

The longitudinal spars are not twisted in the similar way as airfoils. When twisting the longitudinal spars, the blade would have the form shown in Fig. 6.

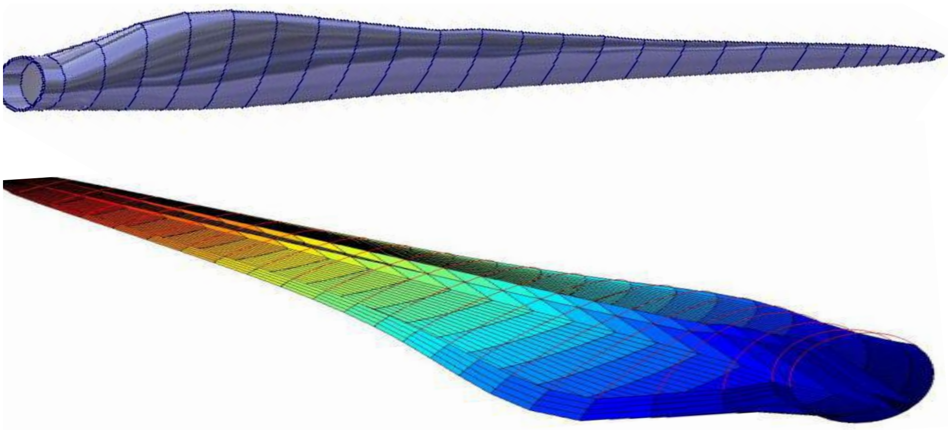


Fig. 6 The model of the blade in CAD software and Ansys

The aerodynamic profiles of wind turbine blade are decided about the aerodynamic characteristic of the blade. In [8] is mentioned that the location of the main longitudinal spars (also called supporting webs) together with the location of the transversal spars (also called stiffening ribs) will have the biggest influence on the bending modes of the blade. Twist of the blade is decided about value of aerodynamic loads, but also the direction in which the blade will vibrates. The twist of the longitudinal spars decides about pitch of principal bending axes. According to [4], the blade has to be twisted around the shear axis.

In addition, it should be pointed out that aerodynamic damping is a very important dynamic aspect. The negative value of aerodynamic damping means that some additional energy is added to the blade during vibration and the amplitude of vibration is increased. Aerodynamic damping has in-plane and out-of-plane components. Damping in in-plane direction will have the negative value if the blade section produces the power. If the damping in out-of-plane direction is positive, by twisting the blade the value of out-of-plane damping will decrease (but must be still positive) and the in-plane damping will receive positive values. Due to the twist of the spar, the blade will vibrate either edgewise or flapwise.

The developed structural model of the blade, which was created with Ansys® in the convention of finite element method, was used to analyse and minimize the amplitude of vibrations. Three groups of components, presented in Fig. 7, were selected for this model; these are: (i) the sheathing, (ii) the longitudinal spars (also called supporting webs) and (iii) the transversal spars (also called stiffening ribs). Selection of these components had enabled specification of various thicknesses, material data and defining various types of components.

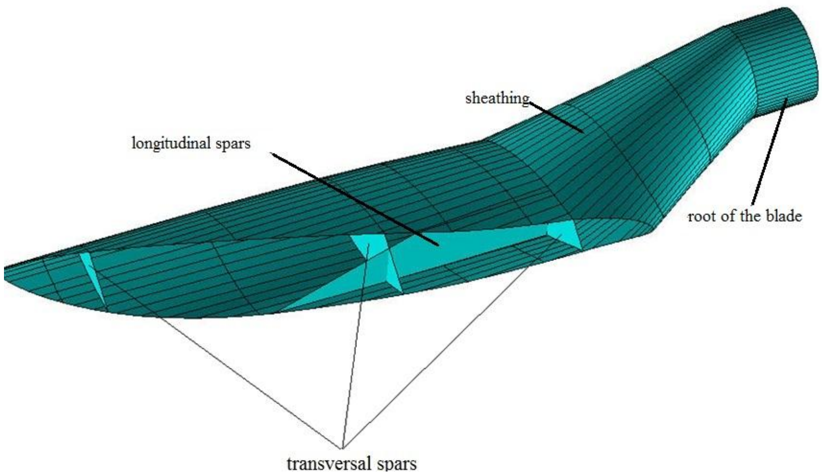


Fig. 7 The numerical model of a wind turbine blade

IV. STATE OF LOAD OF THE BLADE

The analysis of the state of load of wind turbine blade was based on the modified Blade Element Momentum theory [2, 3]. Both mass and aerodynamic loads were investigated. The determined values of mass and aerodynamic forces were used to analyse the blade stresses and strains under defined flow parameters during optimization processes. According to the presented results if only aerodynamic loads are considered the deflection of the blades is happening in the direction of the tower. Consequently, collision and damage of the wind turbine may occur. The rotor of the wind turbine rotates with constant angular velocity and the influence of centrifugal forces is significant. When the gravity and centrifugal forces are included in the load, the deflections of the blades are in opposite direction.

The analysis of the state of load on the wind turbine blade is intended to verify whether the turbine will withstand the action of load within an appropriate range of safety. Various cases of load on the blade, resulting from the action of various external factors on the turbine, have to be considered. The following types of states of load on a wind turbine blade can be defined as:

- Aerodynamic loads;
- Mass loads.

Aerodynamic loads of wind turbine blade are derived from the flow of air across the windwheel. An incoming stream of air with a velocity V_{inf} flows across the wind turbine rotor, parallel to its axis, and creates an aerodynamic force *dR*. The component parallel to the rotation plane of the rotor dF_{τ}^{w} causes the blade to turn, while the perpendicular component dF_{n}^{w} of the force creates an axial pressure which is transferred onto bearings. The aerodynamic force is the resultant of drag force *dD* acting along the velocity vector (but in the opposite sense) and is created due to the pressure of the air stream on the blade, and of lift force *dL*, acting perpendicularly to the direction of the velocity vector. The generation of the lift force can be explained on the basis of Bernoulli's law and theory of circulation. The upper surface of the blade is longer; therefore the air particles have to travel a longer distance above the blade than those under the blade. This phenomenon creates higher pressure above the upper part and lower pressure under the lower part. This pressure difference generates the lift force.

Aerodynamic loads applied on a wind turbine blade are shown in Fig. 8. The symbols used in Figs. 8 and 11 and Eqs. (1), (2), (4) and (6) are defined as follows:

$V_{rel}(r)$: relative velocity over the aerofoil at radius,
V_{inf}: velocity at infinity (see Fig. 11),
ω : angular velocity of rotor,
r : current radius of windwheel, i.e. position of the cross section under consideration in relation to the rotor,
α: : angle of attack,
θ : local twist angle of the blade, i.e. angle between chord line and plane of the rotor.

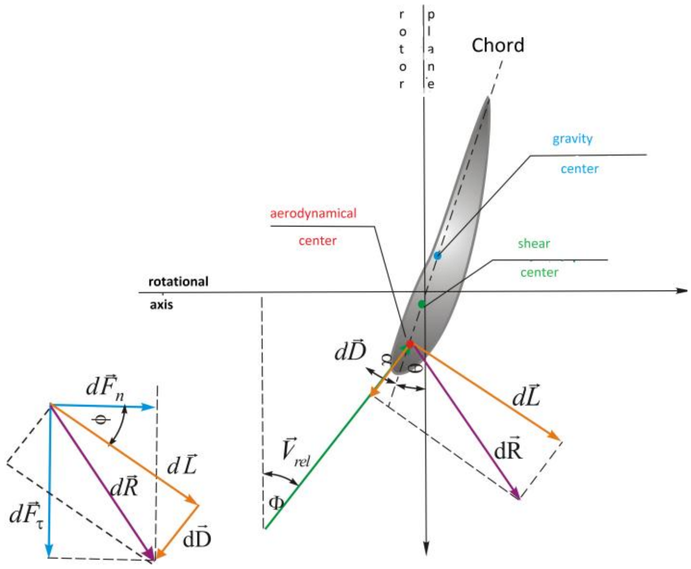


Fig. 8 Aerodynamic loads on aerofoil of a wind turbine blade

The lift and drag expressed per unit length are derived from the following relationships [2, 3]:

$$dL = \frac{1}{2} \cdot \rho \cdot V_{rel}^{2}(r) \cdot C_L(\alpha) \cdot c(r) , \tag{1}$$

$$dD = \frac{1}{2} \cdot \rho \cdot V_{rel}^{2}(r) \cdot C_D(\alpha) \cdot c(r) , \tag{2}$$

where, ρ is the density of air, $C_L(\alpha)$ is the lift coefficient at optimum angle of attack, $C_D(\alpha)$ is the drag coefficient at optimum angle of attack and $C(r)$ is the blade chord length at radius.

The projections of the resultant aerodynamic force on the coordinate axes of the rotor can be expressed in matrix form by the following equation:

$$\begin{Bmatrix} dF_{\tau}^{w} \\ dF_{n}^{w} \end{Bmatrix} = \begin{bmatrix} \sin\phi & -\cos\phi \\ \cos\phi & \sin\phi \end{bmatrix} \begin{Bmatrix} dL \\ dD \end{Bmatrix}, \tag{3}$$

where, pitch angle of the wind flow ϕ is determined from the relation discussed in [5], which takes account of the deviation of the wind turbine rotor both vertically and horizontally, and the inclination of the blade relative to the rotor plane. Thus, the distribution of aerodynamic forces along the blade span will vary depending on the angle position of the blade in a rotor plane. The trigonometric relationships were derived from Fig. 8:

$$\phi = \alpha_{opt} + \Theta;\ \cos\phi = \frac{\omega \cdot r \cdot (1 + a')}{V_{rel}};\ \sin\phi = \frac{V_{\inf} \cdot (1 - a)}{V_{rel}}, \tag{4}$$

where, a is the axial induction factor and a' is the tangential induction factor.

During the analysis of the state of loads of wind turbine blade, the assumption that was made is that the elastic axis is created by shear centers for each cross-section. The grid points are created along the centers of aerodynamic. The aerodynamic forces are applied directly to the grid point and act at the centers of aerodynamic. The force tangential to the rotor plane depends on wind velocity and angular position of the blade. At lowest wind velocities, it is easy to see a visible increase of these forces along the blade span. At higher wind velocities and by adjusting blade angle against wind velocity, the maximal force will move towards the rotor center and the power obtained in rotor will not change. This occurrence is called regulation through axis change against wind velocity.

The designated distributions of axial and tangential components of the aerodynamic forces are presented in the form of graphs as shown in Figs. 9 and 10, respectively.

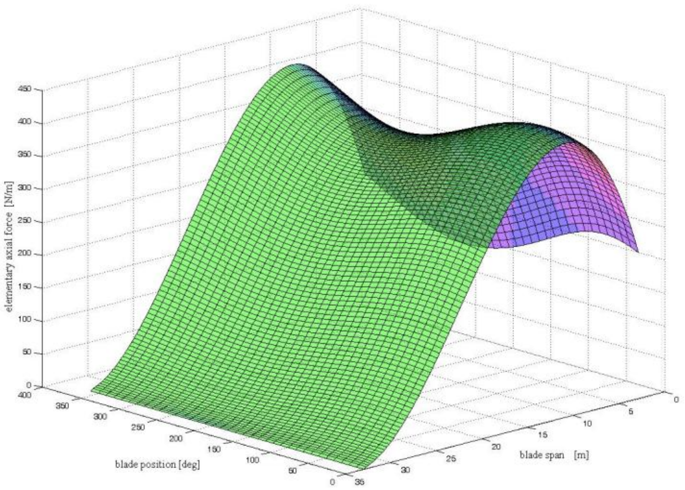


Fig. 9 Distribution of the elementary axial force along the blade span depending on the blade position

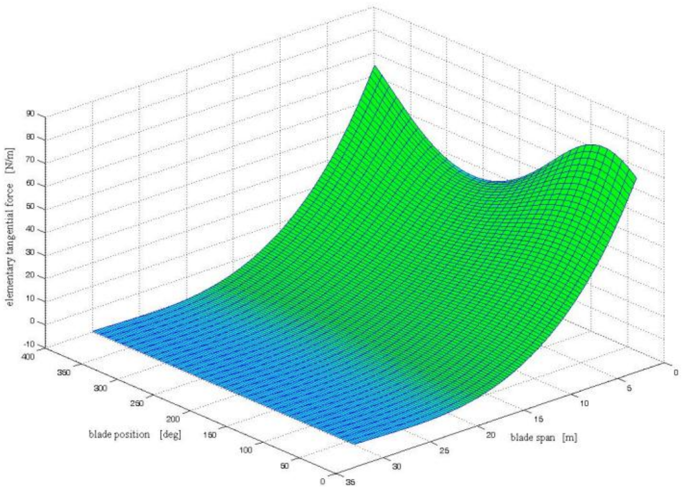


Fig. 10 Distribution of the elementary tangential force along the blade span depending on the blade position

As the wind turbine blade is slender, the loads associated with its inertia are limited to the loads generated by its weight, which causes sinusoidal loads whose frequency corresponds to the rotor rotation. Mass load of the blade is illustrated in Fig. 11.

Gravity forces are applied at the gravity centers. When the wind turbine rotor deflects vertically, then the gyroscopic forces on the blade are generated perpendicular to the rotor plane. Rapid rotor deflection causes an occurrence of large gyroscopic force in the rotor. In real control systems, the deflection of the rotor is programmed to occur slowly, so gyroscopic moments do not play a significant role.

The force of gravity is derived from the following relationship:

$$F_g = m_C \cdot g, \tag{5}$$

where, g is the acceleration of gravity and m_c is the total mass of the blade.

When the wind is blowing on wind turbine blade, this causes its retroversion. To ensure balanced loads that are generated from the wind velocity, the blades are retroversed with an angle β. This causes that tangential and axial components of the centrifugal force will occur along the blade span. The axial component, which acts in the direction opposite to the wind velocity, causes bending moment in the opposite direction of the torque that is created by the wind loads [2]. This effect is called centrifugal relief and its associated force is derived from the following formula:

$$dF_o = \int_r^R dF_o = \int_r^R r \cdot \omega^2 \cdot mdr, \tag{6}$$

where, r is the current radius of windwheel (i.e. position of the cross section under consideration in relation to the rotor); ω is the angular velocity of the rotor and m_i is the mass of the i-th segment of the blade.

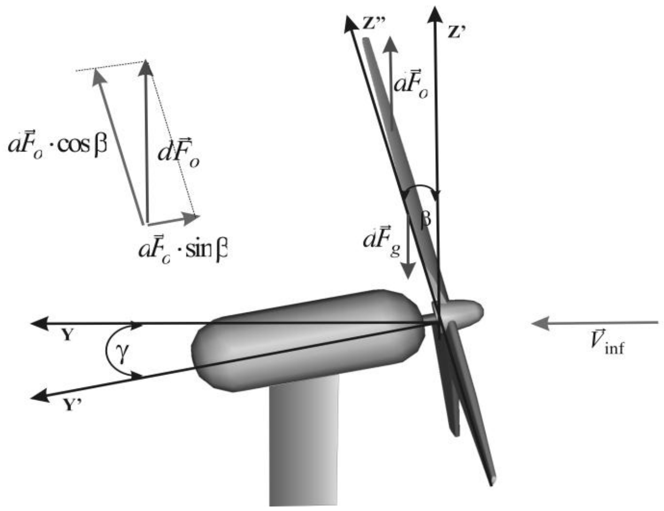


Fig. 11 Gravity and inertial loads on the wind turbine

V. REDUCTION OF THE NUMBER OF DEGREES OF FREEDOM IN THE NUMERICAL MODEL OF THE BLADE

The created simplified model of the real physical system was realized in order to enable the dynamic analysis of the real system to be performed [9].

One of the well-known methods of condensing complex models, which is used in many finite element software packages such as MSC/Nastran and Ansys, is the Guyana condensation method. This method is based on the assumption of energy conservation, kinetic and potential systems under the assumption that the relationship between the master and slave nodes is based on static analysis. To reduce the number of degrees of freedom the Guyana condensation method was applied [10].

According to the Guyana condensation method in the numerical model of complex model of wind turbine blade calculated vector of eigenvalues ϑ with *dofs x 1* dimension (where *dofs* – degrees of freedom) is decomposed as two vectors: subvector ϑ_{mdofs} composed of overrideing degrees of freedom (called master degrees of freedom, i.e., *mdofs*) and subvector ϑ_{sdofs} composed of secondary degrees of freedom (called slave degrees of freedom, i.e., *sdofs*).

By considering the mode condensation technique, only master-type degrees of freedom are saved, therefore self-issue of the structure may be solved using the following equation [11]:

$$\left(\mathbf{K}_K - \mathbf{M}_K \omega^2\right)\vartheta_{mdofs} = 0, \tag{7}$$

where, matrices of mass and stiffness, and eigenvalue vector decrease in sizes to *mdofs x mdofs* and *mdofs x 1*, respectively.

In the reduction of degrees of freedom in the discrete model, very important is appropriate selection of parent nodes called master. Thus decision which nodes becomes master and which will be eliminated is difficult, also very important. Although we can give a hint that says that nodes to eliminate are these which influence on kinetic and potential energy is minimal, it requires a lot of intuition gained earlier, while condensing other models.

In this work the nodes which best reflects the first five mode shapes of wind turbine blade structure were selected as master nodes. The technique of selection of numerical model of master nodes is described in [9].

Comparison of dynamic properties of the numerical models of the blade before and after condensation was based on the criteria specified in the MAC according to the relation expressed by the following equation [12]:

$$MAC(t,k) = \frac{\left| \sum_{i=1}^{n} (\vartheta_t)_i \cdot (\vartheta_k)_i \right|^2}{\left\{ \left(\sum_{i-1}^{n} (\vartheta_t)_i^2 \right) \cdot \left(\sum_{i=1}^{n} (\vartheta_k)_i^2 \right) \right\}} \tag{8}$$

where:

ϑ_t vector of eigenvalues of the complex numerical model,

ϑ_k vector of eigenvalues of the simplified numerical model.

Condensation of model can be considered as correct if the determined values of MAC criterion are in the range of 0.6-1.0. However, it would be better if this value is close to one [10].

The individual error of eigenvalues was determined using the following formula:

$$\delta f_i = \frac{\left| f_c^i - f_k^i \right|}{f_c^i}, \tag{9}$$

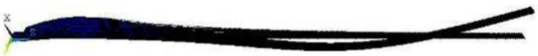
where:

f_c^i – i-th natural frequency of the system without condensation,

f_k^i – i-th natural frequency of the system with condensation.

The determined first five free vibration modes (i.e., natural frequencies and mode shapes) using MAC criterion and the individual error of eigenvalues are shown in Table 1.

TABLE 1 COMPARISON OF DYNAMIC PHENOMENA OF NUMERICAL MODEL OF THE BLADE WITHOUT AND WITH CONDENSATION

No mode shape	Model without condensation [natural frequencies Hz]	Model with condensation [natural frequencies Hz]	MAC criterion	δf [%]
1	 0.27666 Hz	 0.27839 Hz	1	0.6
2	 1.016254 Hz	 1.07095 Hz	0.9972	5
3	 1.1331 Hz	 1.1562 Hz	0.9996	2
4	 2.5354 Hz	 2.58234 Hz	0.9997	1.9
5	 3.7642 Hz	 3.782734 Hz	0.9989	0.5

Analysing obtained values of the MAC criterion (obtained values are close to one) and individual error of eigenvalues, it can be concluded that condensation process has been properly carried out. The simplified numerical model of wind turbine blade was applied to the analysis of the results obtained, i.e. comparison of the dynamic properties of numerical model of the wind turbine blade before and after optimization.

The structure of the numerical model reflecting the real system is described with the available data regarding the stiffness, inertia and damping matrices. The sizes of these matrices depend on the number of finite elements used for the discretization of the numerical model. So, to create a numerical model with large number of degrees of freedom necessities a long time numerical calculations, this can be realized to solve the dynamic problem of such model. The complex numerical model of the blade was applied to optimization calculations. This was ensured by the high accuracy of determining strength and modal properties of the blade model [9].

VI. SELECTION OF COMPOSITE MATERIALS

In the developed numerical model of wind turbine blade, three groups of components were selected; each one with a different material properties. Usually longitudinal spars responsible for the stiffness are made of carbon fibers. Calculations also assume that longitudinal and transversal spars are made of laminate with multiple layers of glass-epoxy, and orthotropic mechanical properties, and adjancted layers are oriented at $\pm 45°$. Calculations are performed using material properties values undertaken from [13]. It is important to note that the number of composite layers used for longitudinal and transversal spars may vary between locations along the blade span. Both longitudinal and transversal spars thickness are design variables. Thus, the number of composite layers is design variable also. Their number may be ranged from 10 to 30, so that the total thickness of the spars corresponds to the value obtained from the optimization.

The main role of the sheathing of wind turbine blade is to achieve best aerodynamically properties, it is usually made of glass fibers and represents a compromise between mechanical parameters and price. Using this criterion the sheathing is finally taken to be a 7-layer composite that contains: gel coat, laminate glass fibers randomly distributed in a matrix epoxy, the triaxial fabric is denoted CDB340 (it has a 25%, 25% and 50% distribution of $+45°$, $-45°$, and $0°$ fibers, respectively), balsa, the uniaxial fabric denoted A260, balsa, the triaxial fabric is denoted CDB340. The mass and stiffness properties for each material for calculations are taken from [14, 15]. Thickness of layers consisting of gel coat, laminate glass fibers randomly distributed in the matrix epoxy are taken from factory data. Balsa thickness is 0,75% and 1,5% of chord in selected aerodynamic part. Thickness of layer made of uniaxial fabric denoted A260 is calculated as 2% quotient of blades length and width. Using this assumptions, sheathing thickness changes proportionally along blade span, it is thick near the base (where the greatest load is applied) and thin at the tip. This construction corresponds well to the real constructions. The triaxial fabric (denoted as CDB340) layer thickness is taken from numerical calculations.

VII. FORMULATION OF OPTIMIZATION PROBLEM

The design of wind turbine blades requires a number of optimization criteria to be taken into account. In general these criteria are mutually uncountable, incomparable and in some cases even contradictory. In such cases the optimization process comes down to finding an optimum compromise by way of implementing preferences among the criteria or using additional information. It is not possible to formulate the problem of optimum design of wind turbine blades as a single-criterion optimization task. The problem of optimum design of the wind turbine blade was formulated as a multicriteria discrete – continuous problem, which enables simultaneous investigation of several criteria. The values of individual criteria depends both on parameters of continuous nature (thickness of chosen elements) and discrete nature (number of transversal spars, their arrangement along blade span). The important aspect of efficiency of scientific researches was to develop suitable way for the exchange of data and cooperation between commercial software Ansys® and author’s proprietary program. The aim of this study was to develop a computer program package that would enable optimization of wind turbine blades with regard to a number of criteria.

Representation of the optimization criterion in the form of an explicit continuous function is difficult in practice; therefore optimization methods inspired by genetics and evolution are often applied. Such algorithms, called genetic algorithms, do not require an explicit objective function, and consequently this does not have to be a continuous and differentiable mathematical function. Another valuable advantage of genetic algorithms is that it readily enables combining the tasks of continuous and discrete optimization. Genetic algorithms were described by [16].

The authors have taken into account the following criteria in the process of wind turbine blades design [17-20]:

- minimization of generated blade vibrations;
- maximization of output generated;
- separation of the natural frequency of the blade from harmonic vibration associated with rotor rotation;
- separation of the natural frequencies of the blade and frequencies that comes from Karman vortices detachment;
- minimization of blade material cost;

- ensuring local and global stability of blade structure;
- ensure the durability and reliability of the blade;
- fulfillment of appropriate strength requirements by the blade structure.

The values of maximal displacements during blade vibration depend on its stiffness, which is a function of material density, thickness of separated structural elements of wind turbine blade, number of transversal spars and their arrangement along blade span. Therefore, when the stability of the blade structure criterion was considered, these parameters should be taken into account. Such a formulation of optimization problem also satisfies the criterion of generated output maximization, as the output of a wind turbine depends also on the optimum shape of blades, i.e. on their optimum geometrical features. These parameters also influence the weight of the blade and the cost of its production [1].

The mass and fabrication cost of a blade depend on the same parameters as the amplitude of blade vibrations. If the cost minimization criterion were considered, then the optimization task would have to be formulated as a weight minimization task. However, in order to ensure stability of the structure, the weight should be maximized. The side effect of such approach is possibility that eigenfrequencies of designed blade will be the same as resonance frequencies.

Furthermore, to meet the strength requirements of the structure, optimization of maximum displacements of the blade in transverse direction would have to be carried out with a limiting condition that permissible stresses be not exceeded. Therefore, it is necessary to optimize the blade maximal displacement, having strain constraints.

Minimization of vibrations is a good way to successfully design the blade structure and at the same time it contributes to other benefits, such as lower cost or high stability. However, when minimizing vibrations of the blade, the natural frequency of the blade must be separated from the harmonic vibration associated with rotor rotation. Such an approach prevents the occurrence of resonance, which under high amplitude of vibration could lead to destruction of the structure. Frequency spacing is one of the methods of isolating frequencies.

The main aim of the optimal – constructional process of wind turbine blade, from the point of dynamic phenomena is to ensure the suitable dynamic characteristics of the system. The dynamic characteristics of the system are defined by eigenfrequencies and frequency response functions, where the eigenfrequencies and frequency response functions were determined respectively from the following formulae:

$$\det\left(\mathbf{K}-\mathbf{M}\omega^2\right)=0\,, \tag{10}$$

$$\mathbf{H}(j\omega)=\left(-\mathbf{M}\omega^2+\mathbf{C}j\omega+\mathbf{K}\right)^{-1}, \tag{11}$$

where:

$\mathbf{M}$ – mass matrix,

$\mathbf{K}$ – stiffness matrix,

$\mathbf{C}$ – damping matrix,

ω – eigenfrequency.

The dynamic characteristics of the system, excluding damping, depend on forms and elements values of stiffness matrix **K** and mass matrix **M**, what follow from Eq.(9) and Eq.(10). In view of the above considerations, the optimization problem should be formulated as objective function, which allowing to the modifications of these matrices.

The stiffness matrix we can modify using, e.g. dependence on deflection:

$$\mathbf{F}=\mathbf{K}\cdot\mathbf{x}\Rightarrow\mathbf{x}=\mathbf{K}^{-1}\cdot\mathbf{F}\,, \tag{12}$$

where:

$\mathbf{F}$ –matrix of generalized forces,

$\mathbf{x}$ –matrix of generalized displacements.

Then the optimization task we can formulate as the minimization of the tip blade displacement task. Modifying the stiffness matrix **K**, the mass matrix **M** also undergoes a modification, for example, reducing the mass of the system causes a simultaneous decrease in the stiffness of this system.

As the next variant of optimization we can chose the criterion of the minimization of the mass of the blade as objective function and formulating other criteria as limitations. The minimization of the mass of the system is classic variant of the optimization problem applied in optimization of design features of the engineering system.

The separate investigation of above – mentioned criteria can lead to conflicting solutions, i.e. improvement of one can result in deterioration the other. So, taking as the optimization criterion the minimization of the tip blade displacement criterion and the minimization of the mass of the blade criterion simultaneous, all above requirements will be satisfied.

In order to indicate of the most effective approach to shown problem of the minimization of the wind turbine blade vibration, three variants of optimization calculations were conducted:

- Variant I—chosen the criterion of the minimization of the mass of the blade as objective function and formulating other criteria as limitations;
- Variant II—chosen the criterion of the minimization of the tip blade displacement as objective function and formulating other criteria as limitations;
- Variant III—formulating objective function as a weighted sum of the most important criteria, i.e. the minimization of the mass of the blade and the minimization of the tip blade displacement and expression other criteria as limitations.

The column matrix of design variables can be represented in the following form:

$$\mathbf{X}^T = [X1, X2, X3, X4] \tag{13}$$

where:

X1 – the transversal spars thickness,

X2 – the longitudinal spars thickness,

X3 – number of transversal spars,

X4 – arrangement of transversal spars.

The other criteria were expressed in the form of inequality limitations $h_j(\mathbf{X})$:

- stresses generated in the blade cannot exceed permissible stresses - compliance with appropriate strength requirements of the structure:

$$\sigma(X) \le \sigma_{dop}, \tag{14}$$

- deformation of the blade must be less than the value of the permissible strain - fulfillment of the relevant conditions for the local stability of the structure:

$$\varepsilon(\mathbf{x}) \le \varepsilon_{dop}, \tag{15}$$

- displacement of individual nodes in the numerical model of the blade cannot exceed the set value - global stability must be ensured:

$$u_i(\mathbf{x}) \le u_{dop}, \tag{16}$$

- displacement of the numerical model of the tip blade cannot exceed the set value - local stability must be ensured. This displacement should not exceed 20% of the radius of the windwheel [14,15]:

$$u_{TIP}(\mathbf{x}) \le 0.2 \cdot R, \tag{17}$$

- separation of natural frequency of the blade f_b from harmonic vibration associated with rotor rotation. It is recommended that the natural frequency of the blade were located outside the scope of the harmonic vibration associated with rotor rotation at $\pm 12\%$ [4]:

$$f_b \notin \langle 0.8 \cdot f_w\ ,\ 1.2 \cdot f_w \rangle, \tag{18}$$

- the natural frequency of the blade must be separated from the frequency of the Karman's vortex:

$$f_b \notin \left\langle 0.1 \cdot \frac{V_{\inf}}{c}\ ,\ 0.3 \cdot \frac{V_{\inf}}{c} \right\rangle, \tag{19}$$

where, $V_{\inf}$ is the velocity at infinity and c is the length of chord.

- wind turbine blade weight must not exceed weight limit. According to [21] mass 1m2 blade should be from 1 kg to 1.5 kg:

$$m_{BLADE} \le m_{DOP}, \tag{20}$$

Further limitations apply to the values of design variables. These can be expressed by means of the following matrix formula:

$$\mathbf{X}_{\min} \le \mathbf{X} \le \mathbf{X}_{\max}, \tag{21}$$

where:

$\mathbf{X}_{\mathbf{min}}$ – column matrix of minimum values of design variables (lower bound variables),

$\mathbf{X}_{\max}$ – column matrix of maximum values of design variables (upper bound variables).

A. Optimization Calculation – Variant III

Multi-criteria optimization problem was solved using the method of weighted sum [22-24]. Formulating objective function $F(\mathbf{X})$ as a weighted sum of most important criteria i.e. mass reduction and minimizing of the tip blade displacement [17]:

$$\begin{aligned} &\min_{\mathbf{X}\in\Omega} F(\mathbf{X}) = w_i \cdot M + w_k \cdot U \\ &h_j(\mathbf{X}) \le 0 \quad \text{dla} \quad j = 1,\ldots,n \end{aligned} \tag{22}$$

where:

Ω – domain of possible solutions within the space of objects,

$\mathbf{X}$ – column matrix of design variables,

$F(\mathbf{X})$ – objective function,

$h_j(\mathbf{X})$ – inequality constraints functions are submitted by dependencies from 14 to 20,

w – column array weights of the respective criterion functions, $w_{i},_{k} \in [0,1]$ and $(w_i + w_k)=1$,

$M = \dfrac{m}{m_{dop}}$ – standardized criterion function representing the weight of the blade,

$U = \dfrac{u}{u_{dop}}$ – standardized criterion function representing the displacement of the blade tip,

m_{dop} – permissible mass of blades,

u_{dop} – permissible displacement of the blade tip.

B. Optimization Calculation – Variant I and Variant II

The next variants of optimization calculations consisted of chosen the one criterion as objective function and formulating other criteria as limitations. Chosen objective function is:

- the minimization of the mass of the blade – variant I:

$$\begin{aligned} &\min_{\mathbf{X}\in\Omega} F(\mathbf{X}) = m(\mathbf{X}) \\ &h_j(\mathbf{X}) \le 0 \quad \text{dla} \quad j = 1,\ldots,n \end{aligned}, \tag{23}$$

where:

Ω –domain of possible solutions within the space of objects,

$\mathbf{X}$ – column matrix of design variables,

$F(\mathbf{X})$ – objective function,

$h_j(\mathbf{X})$ – inequality constraints functions are submitted by dependencies from 14 to 20.

- the minimization of the tip blade displacement – variant II:

$$\begin{aligned} &\min_{X\in\Omega} F(\mathbf{X}) = u_{TIP}(\mathbf{X}) \\ &h_j(\mathbf{X}) \le 0 \quad \text{dla} \quad j = 1,\ldots,n \end{aligned}, \tag{24}$$

where:

Ω – domain of possible solutions within the space of objects,

X – column matrix of design variables,

$F(\mathbf{X})$ – objective function,

$h_j(\mathbf{X})$ – inequality constraints functions are submitted by dependencies from 14 to 20.

VIII. CHOICE OF OPTIMIZATION METHODS

Because the optimization task is solved is a discrete-continuous task, where criterion does not occur in explicit function, the classical methods cannot be used. Simultaneously due to the presence of variables both discrete and continuous, the simple genetic algorithm had to be modified in order to adapt solving the given optimization problem.

Modification mainly applies to one-point crossover operation. Shift is made in this algorithm by 7 bits. Cross point is selected from first to last bit of shorter chromosome (individual with less number of transversal spars). This modification to genetic algorithm is described in detail in [9]. Block diagram presenting the operating of modification genetic algorithm is presented in Fig. 12.

Optimization calculations were done with the use of the authors' proprietary program that implemented a modified genetic algorithm, for which the following assumptions were made:

- number of individuals 20
- number of populations (STOP criterion) 50
- probability of crossing 0.7
- probability of mutation 0.03

In the optimization process design, the variables were: thickness of transversal spars (denoted by tsr), thickness of longitudinal spars (denoted by tsw), number of transversal spars (denoted by nsr) and their arrangement along the blade span (i.e. numbers of assigned transversal spars – denoted by srN).

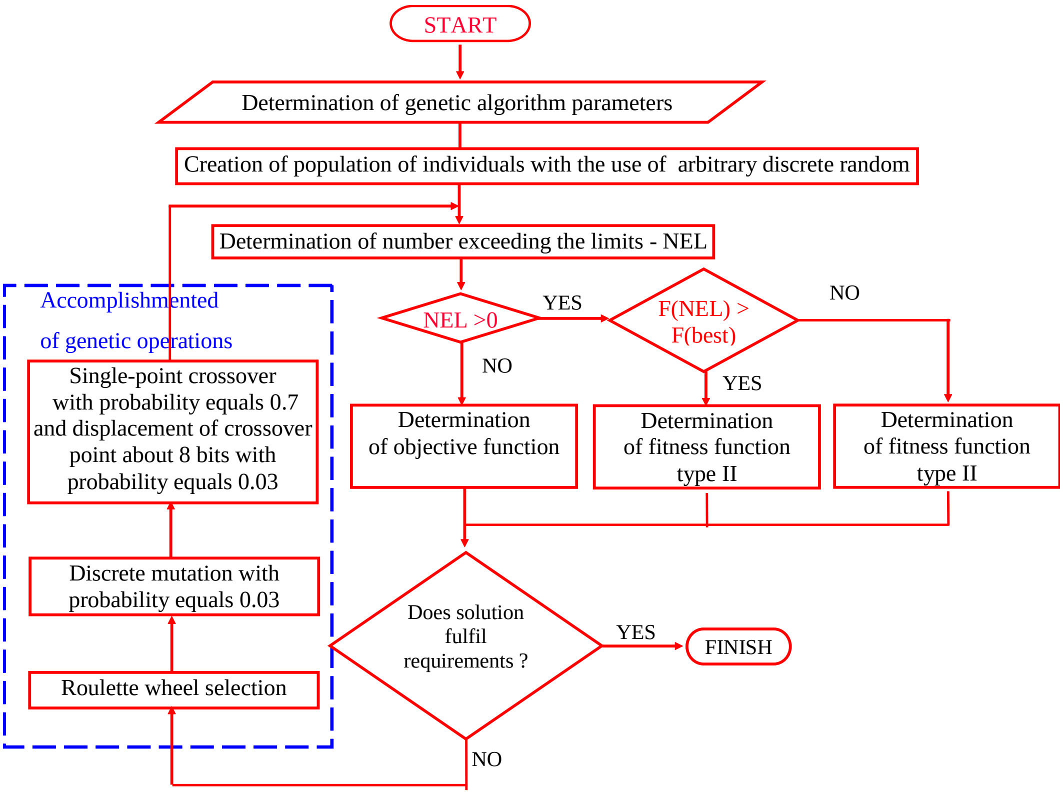


Fig. 12 Block diagram presenting the operating of modification genetic algorithm

IX. ANALYSIS OF OPTIMIZATION PROCESS EFFICIENCY

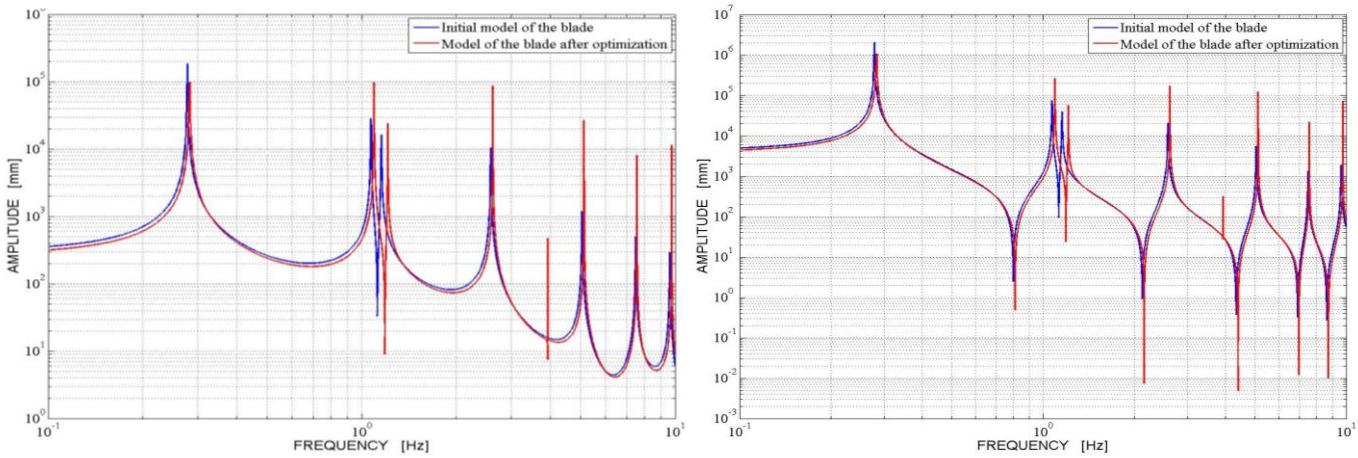
The comparison of mechanical and modal properties of wind turbine blade with constructional features obtained from literature (before optimization) and obtained as a result of optimization process, for conducted variants of optimization calculations, is shown in Table 2.

TABLE 2 COMPARISON OF MECHANICAL AND MODAL PROPERTIES OF THE WIND TURBINE BLADE BEFORE AND AFTER OPTIMIZATION PROCESS

Objective function		Theoretical model		Variant I		Variant II		Variant III	
Design variables	tsr	0.06		0.02		0.0956		0.0960	
	tsw	0.06		0.0331		0.0966		0.0702	
	nsr	27		4		17		14	
	srN	from 4 what 4 to 108		3; 42; 84; 90		2; 14; 21; 32; 35; 36; 58; 60; 75; 76; 84; 94; 101; 103; 106; 108; 109		5; 8; 9; 11; 14; 15; 16; 33; 34; 36; 45; 69; 78; 82	
Mass of the blade [kg]		1119.3		831.786		1487.2		1240.7	
Maximal stress [MPa]		227		322		164		204	
Maximal strain [%]		0.4842		0.5876		0.3376		0.4438	
Displacement of the tip blade [m]		6.244		5.987		4.401		5.493	
Eigenfrequencies values [Hz]		1	0.27666	1	0.25953	1	0.29001	1	0.28109
		2	0.9804	2	0.91616	2	1.1142	2	1.0566
		3	1.1331	3	1.0543	3	1.2687	3	1.1721
		4	2.5354	4	2.3819	4	2.6546	4	2.5736
		5	3.7642	5	3.5295	5	4.1414	5	3.8928

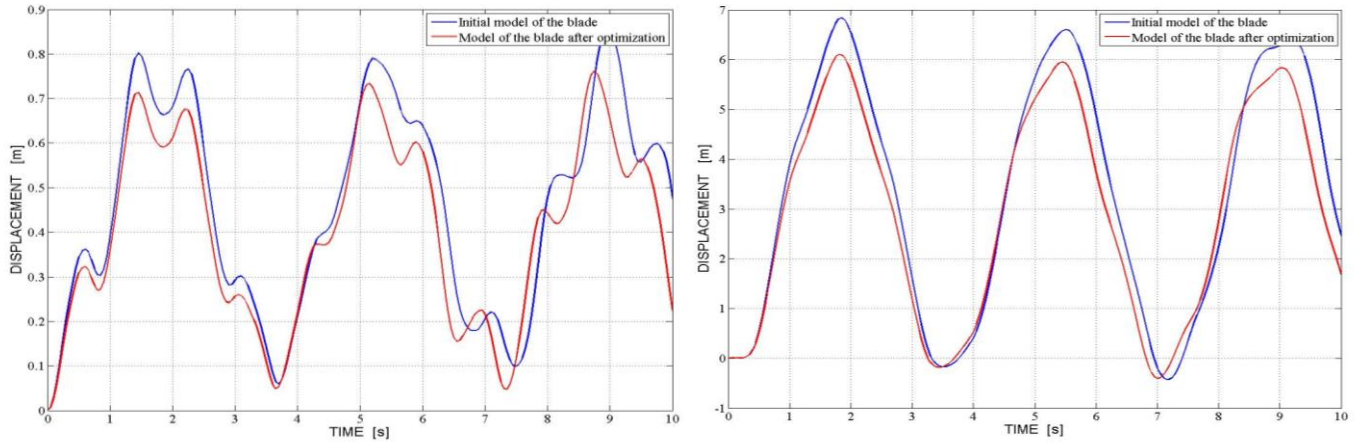
Obtained amplitude-frequency characteristics of displacement signal determined for chosen nodes of the blade model before optimization process and after the minimization of objective function expressed as a weighted sum of the most important criteria, i.e. the minimization of the mass of the blade and the minimization of the tip blade displacement are shown in Fig. 13.

In addition, the results of simulation of displacement vibration signals determined for chosen nodes of the blade model before optimization process and after objective function as a weighted sum expressed of the most important criteria, i.e. the minimization of the mass of the blade and the minimization of the tip blade displacement are shown in Fig. 14. Models of reduced number of degrees of freedom were used. The solution was chosen from Pareto's set.



(a) (b)

Fig. 13 Amplitude-frequency characteristics of displacement signals using the logarithmic amplitude axis determined for: (a) the node in the middle of the blade span, (b) the node at the tip blade

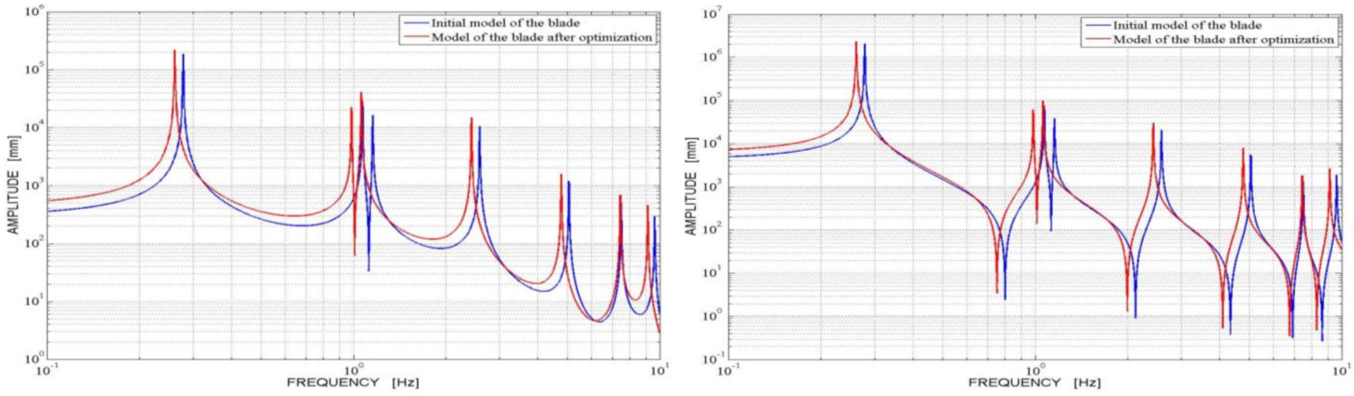


(a) (b)

Fig. 14 Results of simulation of displacement vibration signals determined for: (a) the node in the middle of the blade span, (b) the node at the tip blade

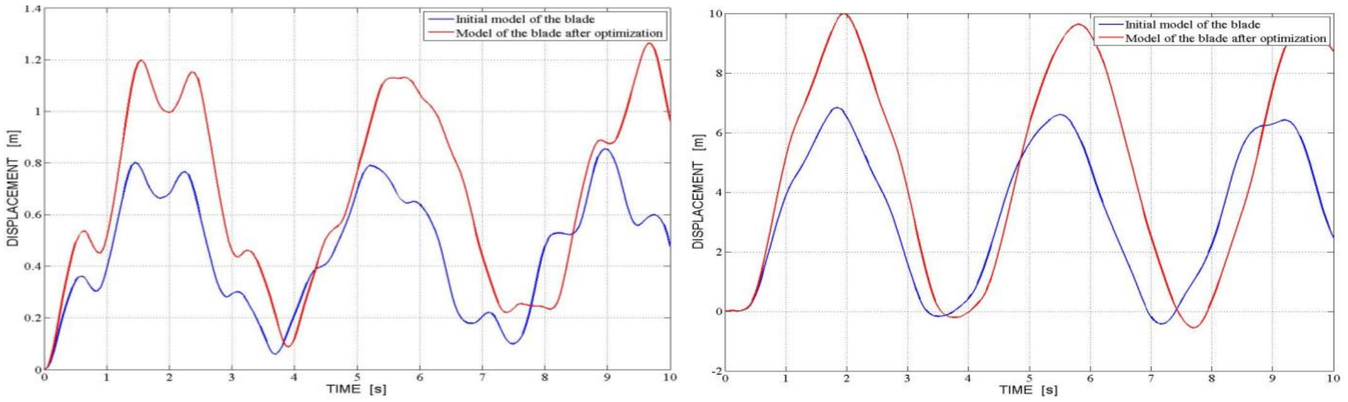
Obtained amplitude-frequency characteristics of displacement signal determined for chosen nodes of the blade model before optimization process and after the minimization of the mass of the blade are shown in Fig. 15.

Furthermore, the results of simulation of displacement vibration signals determined for chosen nodes of the blade model before optimization process and after the minimization of the mass of the blade are shown in Fig. 16. Models of reduced number of degrees of freedom were used.



(a) (b)

Fig. 15 Amplitude-frequency characteristics of displacement signals using the logarithmic amplitude axis determined for: (a) the node in the middle of the blade span, (b) the node at the tip blade

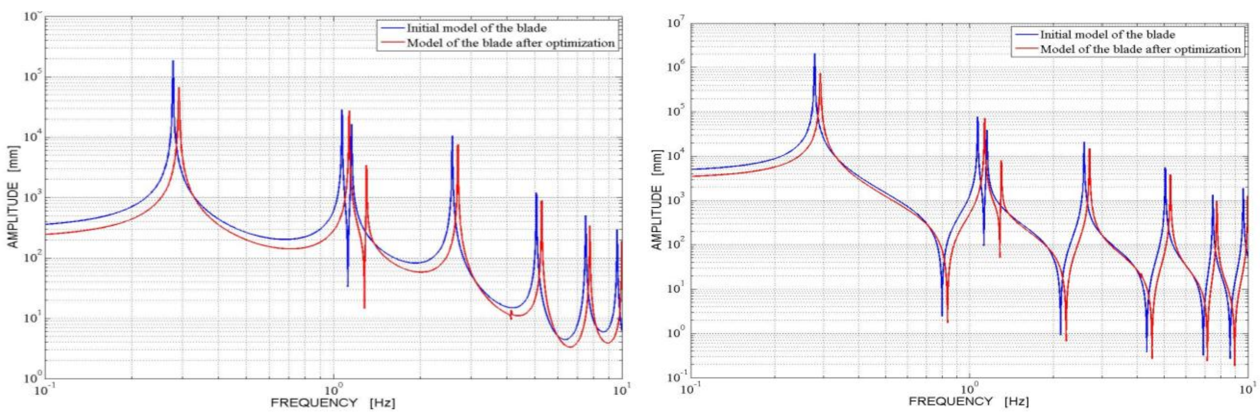


(a) (b)

Fig. 16 Results of simulation of displacement vibration signals determined for: (a) the node in the middle of the blade span, (b) the node at the tip blade

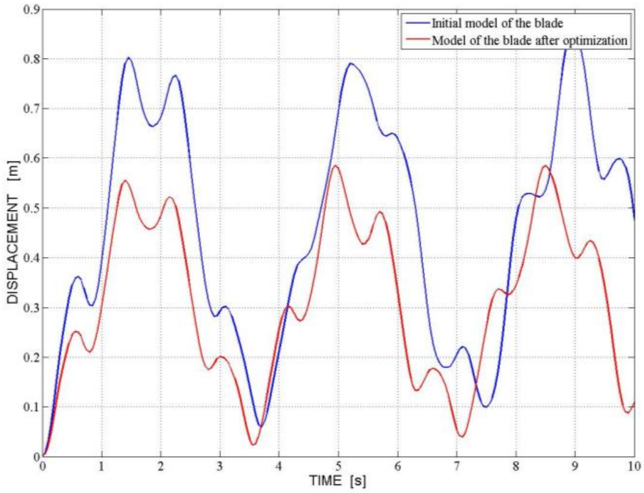
Obtained amplitude-frequency characteristics of displacement signal determined for chosen nodes of the blade model before optimization process and after the minimization of the tip blade displacement are shown in Fig. 17.

In addition, the results of simulation of displacement vibration signals determined for chosen nodes of the blade model before optimization process and after the minimization of the tip blade displacement are shown in Fig. 18. Models of reduced number of degrees of freedom were used.

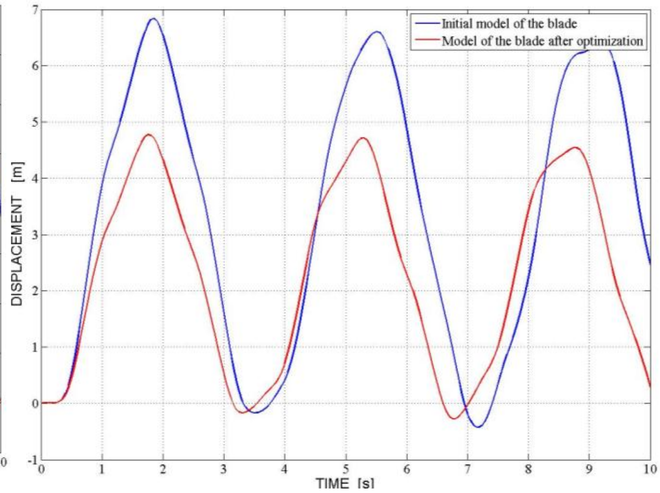


(a) (b)

Fig. 17 Amplitude-frequency characteristics of displacement signals using the logarithmic amplitude axis determined for: (a) the node in the middle of the blade span, (b) the node at the tip blade



(a)



(b)

Fig. 18 Results of simulation of displacement vibration signals determined for: (a) the node in the middle of the blade span, (b) the node at the tip blade

For the three variants of optimization processes, numerical calculations make it possible to conclude that:

- The model of the blade with constructional features obtained as a result of the minimization of the tip blade displacement is characterized by the best stiffness for the sake of the minimization of the blade vibration;
- The model of the blade with constructional features obtained as a result of the minimization of the mass of the blade is characterized by the tip blade displacement with values near the permissible value. This can cause the damage of the wind turbine;
- The considered Pareto's solution is characterized by the value of the tip blade displacement, which is contained in permissible limit;
- The total mass of the blade with constructional features obtained as a result of the minimization of the mass is about 26 % smaller than before the optimization, which reduces the material cost;
- The total mass of the blade with constructional features obtained as a result of the minimization of the tip blade displacement is about 32 % larger than before the optimization, which is the reason for increase in material cost;
- The total mass of the blade with constructional features which are result of the minimization of the weighted function (the considered Pareto's solution) is about 11 % larger than before the optimization, which is the reason for negligible increase in material cost;
- The eigenfrequency range of the blade model for all three variants does not agree with the resonance frequencies range.

The analysis of the results of numerical simulations of displacement vibration signals and the obtained amplitude-frequency characteristics determined for chosen nodes of the blade allow us to put forward the following conclusions:

- the use of minimization of the blade mass as the optimization criterion increased the value of the amplitude vibrations of the numerical model of wind turbine blade comparing to values for the blade model before optimization;
- the use of the minimization of the tip blade displacement as the optimization criterion reduces significantly the value of the amplitude vibrations of the numerical model of wind turbine blade;
- the use in optimization process objective function as a weighted sum of the most important criteria (the considered Pareto's solution) increase values of the amplitude vibrations of the numerical model of wind turbine blade in comparison with values for the blade model before optimization.

Therefore, the use of the minimization of the tip blade displacement as the optimization criterion allowed getting the best solution, which fulfils all guidelines for the wind turbine design. The model of the blade with constructional features acquired in the result of this optimization task is characterized by the best stiffness, the smallest blade tip displacement, the smallest values of the amplitude vibrations of the numerical model of wind turbine blade and a small increase of the blade mass.

In order to fulfill all applied criteria, it is difficult to discern the optimum solution. The best solution in terms of minimizing material cost does not ensure suitable stiffness of the blade and vice versa. The use of the weighted sum as objective function is the best approach to be considered within this task, which allows determining Pareto's set. On this basis, the solution can be determined, which satisfies the required conditions of the task. In the considered case, the chosen solution from obtained Pareto's set [9] provides decrease of blade vibration about of approximately 13 % with a negligible increase of 10 % of the blade mass.

X. CONCLUSIONS

The work presented in this chapter shows that use of the genetic algorithm enables effective forming of dynamic properties of the wind turbine blades, causing considerable reduction of the blade amplitude vibrations. The obtained results of numerical calculations prove the applicability of the developed models and investigation methods used for the determination of dynamic properties of systems.

The choice of a genetic algorithm as an optimization method enables effectively solving problems connected with multidisciplinary discrete-continuous optimization of a complex dynamic system.

The current work demonstrates that the presented computation algorithm is an effective aid in determining optimum structural features at the stage of design and it ensures proper dynamic properties of the system to be designed. This enables considerable time savings in the design process and a reduction in costs of manufacturing of product. However, it should be underlined that the application of the genetic algorithm can provide results with some inaccuracies, which are actually resulting from the stochastic character of calculations.

The main advantage of the approach proposed in this work is to investigate the structural dynamics problem of the complex mechanical systems via the connection of the author's proprietary program that implements multidisciplinary discrete-continuous method with the commercial software Ansys®, which creates a numerical model of the blade using the finite element approach. In the calculations, the use of the algorithm of the optimization method, which was based only on the values of objective function, has expanded the class of systems and problems to which the proposed methodology of investigations can be used to solve these problems. The developed methods for modeling and optimization can be used to solve a large number of problems dealing with structural dynamics.

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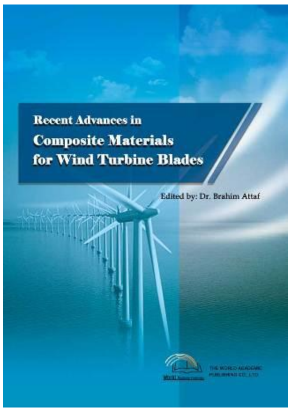

Recent Advances in Composite Materials for Wind Turbine Blades
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This book of science and technology provides an overview of recent research activities on the application of fibre-reinforced composite materials used in wind turbine blades. Great emphasis was given to the work of scientists, researchers and industrialists who are active in the field and to the latest developments achieved in new materials, manufacturing processes, architectures, aerodynamics, optimum design, testing techniques, etc.. These innovative topics will open up great perspectives for the development of large scale blades for on- and off-shore applications. In addition, the variety of the presented chapters will offer readers access to global studies of research & innovation, technology transfer and dissemination of results and will respond effectively to issues related to improving the energy efficiency strategy for 2020 and the longer term.

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