Rational modeling of a wind unit tower taken into account of the features of its dynamic characteristics

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Abstract. Nowadays the level of development of finite element (FE) calculation systems allows us to count on the maximum level of design solutions quality, provided that is created an adequate and at the same time simple design model, which directly determines the level of accuracy of the results obtained when determining the parameters of the stress-strain state, as well as dynamic characteristics of buildings and structures. It is fundamentally necessary for the designer to know the degree of influence of various factors to the creation of a finite element design model on the dynamic response of the design object. There is no doubt the relevance of the problem of identifying the features of modeling tower-type structures, which will simplify the work of an engineer and at the same time reach a qualitatively new level in making design decisions. The purpose of this work is a comprehensive assessment of the influence of the features of creating a design model to the resulting parameter - the frequency behavior of a tubular tower for wind turbines which is the most popular at wind parks in Russia over the past two decades. For numerical research was used the domestic design complex SCAD Office. To create calculation models and perform a comparative analysis of the resulting parameters of tubular towers were used FE types 41, 42, 44, and 50. When determining the influence of the finite element type calculations were made for a cylindrical tower with fixed parameters, taking into account changes in the type and size of the FE. In the calculations the evaluating factors were: changing in the main and equivalent stresses, as well as the change in the frequency of the first form of own oscillations. When comparing the values of the main and equivalent stresses, the plate of the third row from the base was taken as the calculated one.

1 Introduction

Currently the calculation and design of structures is widely performed using the finite element method implemented in various foreign (ANSYS, NASTRAN, RSA, Sap2000,

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Abaqus, Etabs) [1-4] and domestic software systems (Lira SAPR, Lira 10, SCAD, etc.), which require the definition of creating a calculation scheme features (type and size of the finite element, conditions of conjugation of elements in space, etc.) [5-8]. This approach to the solution of numerical problems allows us to expect the highest quality of design solutions, providing the creation of both adequate and easy to execute calculation model, which directly determines the accuracy of the obtained results when calculating the parameters of the stress-strain state (SSS), as well as the dynamic response of the design object. The designer fundamentally needs to know the influence of various factors when creating a finite element calculation model on the dynamic response of the design object. Consequently, the urgency of the identifying the peculiarities of modelling tower-type structures is beyond doubt, inasmuch it allows to simplify the work of an engineer and to reach a qualitatively new level in making a design solution, particularly with regard to wind power engineering, which is currently at the stage of active formation and development and has a significant impact on energy industry of Russia. The issues related to the creation and rationalization of FE-models of tower structures have already been considered in studies [9-14]. Studies [15-21] are devoted directly to modelling of wind power objects in Russia and abroad. Nevertheless their results do not fully reflect the peculiarities of modelling the above-mentioned structures and do not sufficiently give an idea of the dependence between the geometrical dimensions of towers, their stress state and dynamic characteristics. Therefore, the purpose of this work is to comprehensively evaluate the influence of the peculiarities of the calculation scheme on the resulting parameter which is the frequency behaviour of a tubular tower for Turbowind T600-48 and Eviag EV 100 wind turbines, the most popular wind turbines in Russia over the last two decades [22-24]. For numerical studies the domestic design and computing complex SCAD Office was used [5, 14].

The following ***problems*** are solved in order to attain aims:

– rational type of finite element in modelling of tubular cone-shaped tower was determined;

– a sufficient level of discretization of the calculation model was revealed;

– the influence of tower dimensions on its SSS and frequency characteristics has been evaluated taking into account the variations of geometrical parameters (height, diameter at the base, thickness of the tower wall);

– the variation of stresses between a cylindrical tower of annual and polyhedral cross-section was studied comparatively;

– geometrical parameters of towers, the frequency of natural oscillations of wind turbine rotor were determined in order to avoid getting the structure into the resonance state at the stage of object design. определены геометрических параметров башен, частота собственных колебаний которых попадает между диапазонами вынужденных колебаний ротора ВЭУ, для избегания попадания конструкции в резонансное состояние еще на этапе конструирования объекта.

The subject of the study are the SSS parameters and frequency characteristics of a tubular tower for wind turbines.

The structure of a steel tubular tower for wind turbines is taken as the ***object of study***.

2 Materials and methods

SCAD software automatically determines the type of the finite element depending on the specified design scheme. However, the finite element type can be changed manually by the user so the discrepancies in the calculation results may arise if the FE is changed. The universal finite elements described below are used for the calculation of the thin flat shells. Each finite element node has six degrees of freedom [5, 14]:

U, V, W - linear displacements along the X, Y and Z axes;

– rotation angle relatively to the OX axis, the positive direction of which is opposite to the clockwise rotation direction when viewed from the end of the axis;

– rotation angle relatively to the OY axis, the positive direction of which is opposite to the clockwise rotation direction when viewed from the end of the axis;

– rotation angle relatively to the OZ axis.

The degrees of freedom U, V correspond to membrane strains and W, UX, UY to bending strains. The rotation angle UZ in the local coordinate system of the element is always zero. It is introduced to join elements that do not lie in the same plane and is necessary for the spatial operation of the structure.

The introduction of joints in the element nodes is not allowed.

The material of the plate can be isotropic, orthotropic and anisotropic.

It is possible to calculate plate elements using the following types of finite elements:

– rectangular (type 41), Fig. 1, a;

– triangular (type 42), Fig. 1, b;

– quadrangular (type 44), Fig. 1, c.

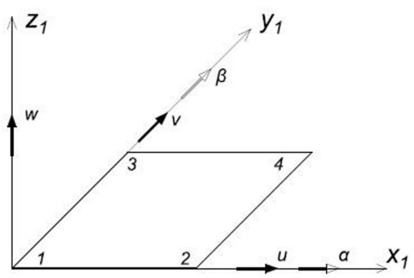
– quadrangular with the number of nodes from four to eight (type 50), Fig. 1, d. In addition vertices of the quadrilateral thee can be one more node on each side. The numbering of nodes from the 5^{th} to 8^{th} is arbitrary.

The order of the first four (three) nodes of the elements is shown in Fig. 1 (a – d).

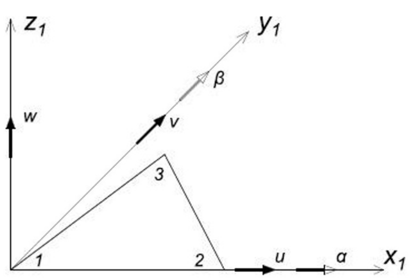
All elements of the shell have a local coordinate system X1 Y1 Z1 in which the X1 axis passes from the first node to the second, the Y1 axis lies in the plane of the element, orthogonal to X1 and directed towards the third node, and the Z1 axis forms the right triple with the X1 and Y1 axes.

In all shell elements the tangential and normal displacements were approximated independently. Element functions of the same shape were used to calculate wall plates and beams.

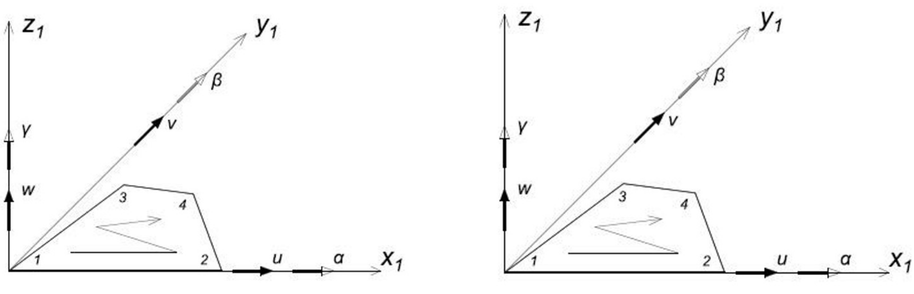
If no force output coordinate system is specified in the corresponding line of the "stiffnesses" document, then by default the forces are calculated in the local coordinate system of the element. At the center of gravity of the element and, as required, at the nodes, the forces NX, NY, τXY, MX, MY, MXY, QX, QY, (if there is an elastic foundation RZ) and nodal reactions Rxi, Ryi, Rzi, RUXi, RUYi, RUZi are calculated.



a)



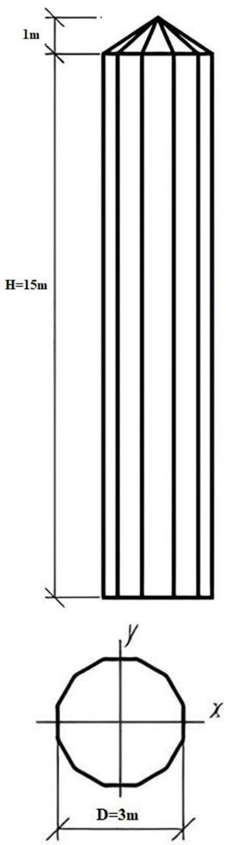
b)



c) d)

Fig. 1. Types of finite elements

In determining the evaluation of the influence of the type of finite element used to calculate the tubular tower of a wind turbine, calculations of a cylindrical tower with fixed parameters were performed (see Fig. 2). The evaluation was performed in terms of the influence of the FE type on the own oscillation frequency.



– height of the cylindrical part of the tower H = 15m;
– height of the cone part of the towers top = 1m;
– diameter D = 3m;
– number of segments along the nR = 12;
– number of segments in height nH = 30;
– thickness of the tower wall t = 20mm;
– loads: own weight of the tower + weight of the wind turbine mB = 10t.

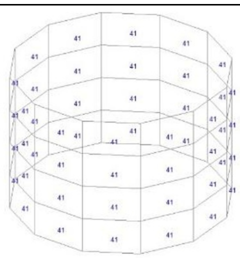
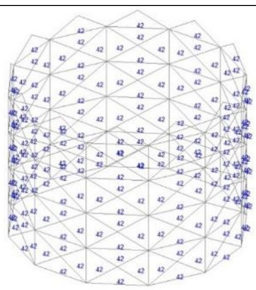
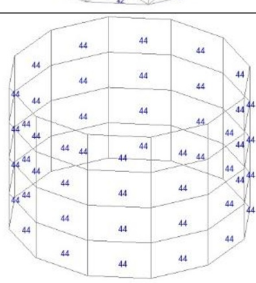
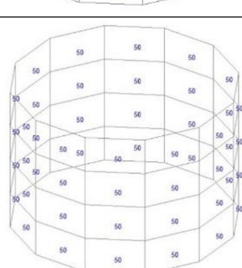
Fig. 2. Calculations of a cylindrical tower with fixed parameters

In the calculations the evaluating factors were: change in the principal (σ_X, σ_Y, τ_{XY}) and equivalent stresses (σ) as well as change in the frequency of the first form of own oscillation. When comparing the values of principal and equivalent stresses, the plate of the third row from the base was taken as the design plate. This was done so that the stress values were not affected by the edge effect phenomenon present in the plates pinched in the base (for FE 41, 44, 50) and the average value of stresses in 4 plates of the third row (for FE 42). The results of the stress calculations are presented in Table 1. The table shows the values of normal and shear stresses, as well as the values of total stresses calculated by the formula:

$$\sigma = \sqrt{N^2_x + N^2_y - N_x \cdot N_y + 3 \cdot \tau^2_{xy}} \le 1{,}15 \cdot R \cdot \gamma_c \quad (1)$$

3 Results and discussion

Table 1. Values of normal and shear stresses when changing the type of FE

FE type	Bottom fragment of the FE model	Stresses, MPa			
		σ_X	σ_Y	τ_{XY}	σ
1	2	3	4	5	6
41		8,93	-0,01	8,93	47,11
42		8,87	-0,01	8,88	46,69
44		8,93	-0,01	8,93	47,11
50		8,98	0,00	8,93	47,12

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The diagram of changes in total stresses is shown in Fig. 3.

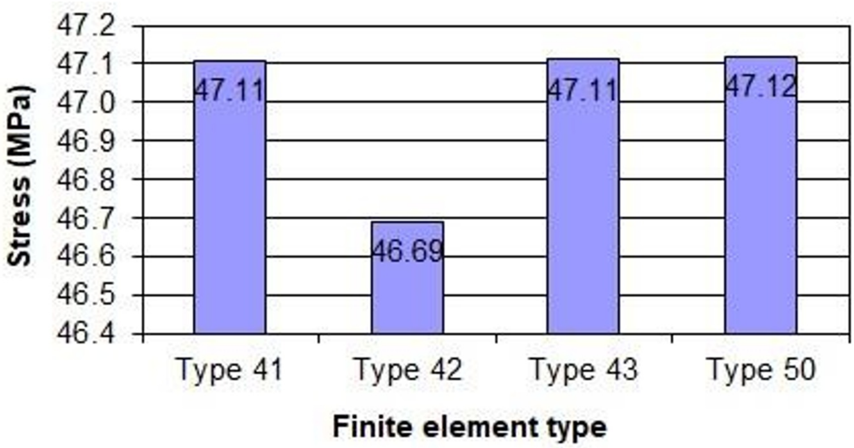

Fig. 3. Change in total stresses when changing the type of FE

In addition to the stress values, the frequency of the «first» tower mode of oscillations was taken into account. The first mode is the bending form of oscillations presented in Fig. 4:

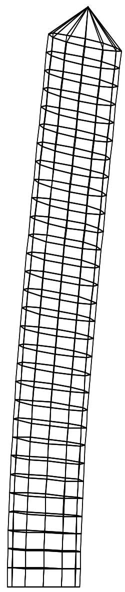

Fig. 4. The first «bending» tower mode of oscillations

The values of own oscillation frequencies are presented in Table 2.

Table. 2. Values of own frequencies

FE type	Own oscillation frequency, Hz
41	11,19
42	11,22
44	11,19
50	18,06

A diagram of the variation of own oscillation frequencies when the type of finite element is changed is provided in Fig. 5.

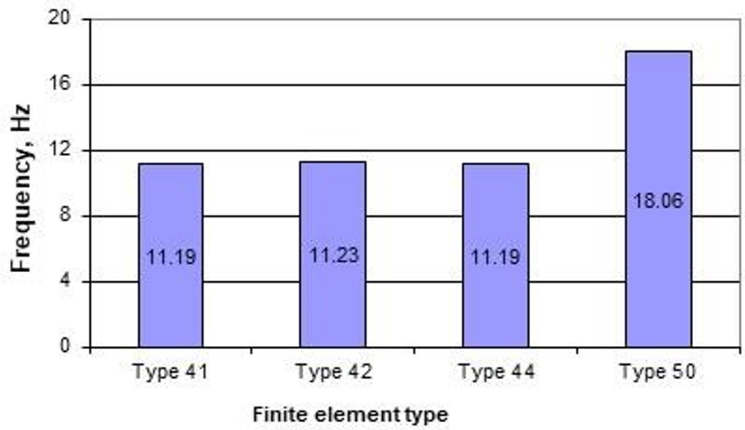

Fig. 5. Own oscillations' frequency changing when changing the type of FE

3.1 Evaluation of the influence of the finite element size on the calculation results

The first step in the design of any structure is the creation of the calculation scheme. It should most accurately characterize the structure being designed and it should be as simple as possible. When calculating cylindrical as well as cone-shaped metal towers in the SCAD program complex it is necessary to set several parameters. In addition to the height, diameters at the base and at the head, and wall thickness of the shell, SCAD requires the number of segments to be entered. The program represents the cylinder as a shell consisting of many segments. *The purpose of the following research is to evaluate the influence of the finite element size on the calculation results.*

The structures of cylindrical shaped towers were taken for calculation. The parameters to be varied were:

– tower diameter *D*;

– height of the structure *H*.

The analyzed dimensions of tower are given in Table 3.

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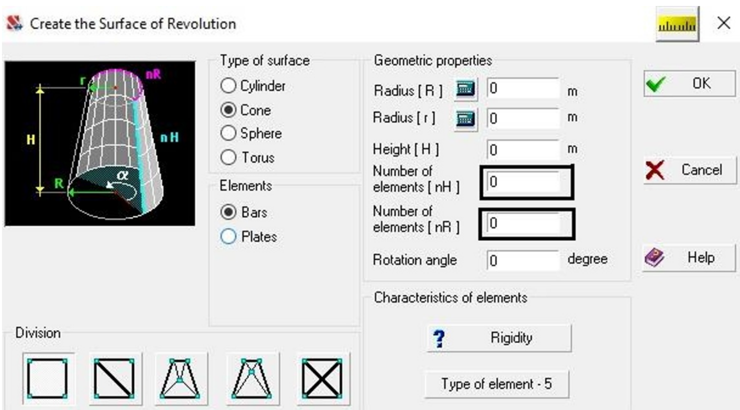
Table. 3. Analyzed of the towers' dimensions

D, m	Tower's height, m when *H/D*:			
	H/D = 5	*H/D* = 7	*H/D* = 10	*H/D* = 13
3	15	21	30	39
5	25	35	50	65
8	40	56	80	104

In addition to changing the geometric characteristics, the construction of each computational scheme was discretized. The discretization parameter was the number of elements at the base of the scheme requested by the software system (see Fig. 6).



$nH - ?$;
$nR - ?$.

Fig. 6. Required parameters of the design model

In Fig. 6 as the required discretization parameters of the rack design model are: *nH* - the number of elements in the height of the scheme and *nR* - the number of elements at the base of the scheme.

Thus each tower structure with fixed height and diameter parameters were calculated with the number of elements in the base *n*. Ratio of width and height of a unit plate $HnR/LnR \approx 1$ (see Fig. 7).

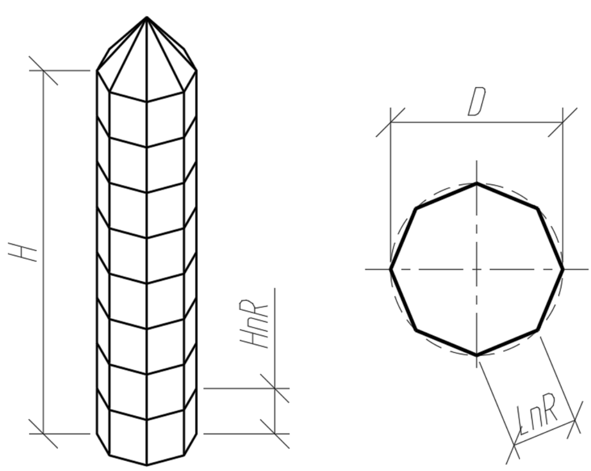


Fig. 7. Finite element's dimensions

The parameter *nH* was determined using formula 3:

$$nH \approx \frac{H \cdot nR}{2\pi \cdot R} \qquad (2).$$

Example 1: A tower with a diameter at the base of 3m and a height of 15m was calculated at *nR* = 6, 8, 10, 12, 14, 16. The initial data for the calculation as well as the result of the calculation – the own oscillation frequency of the tower - is given in Table 4.

Table 4. Frequency changing of the own oscillations with different values of *nR*

H, m	*D*, m	*nR*	*nH*	*ν*, Hz
15	3	6	10	1,507
		8	13	1,177
		10	16	0,942
		12	19	0,785
		14	22	0,671
		16	25	0,588

Similarly, the calculations were made for the towers (Table 3). Having determined the frequency of own oscillations of towers with different geometrical parameters, as well as with different level of discretization of unit plates, the graphs of dependence of the tower frequency on the value of discretization were designed, as well as the relative error between the previous and subsequent level of discretization was determined. For D = 3m see Table 5 and Fig. 8, for D = 5m see Table 6 and Fig. 9, for D = 8m (see Table 7 and Fig. 10).

Table 5. Frequency changing of the tower's own oscillations *D* = 3м

R, м (m)	*nR*	*H/D* = 5		*H/D* = 7		*H/D* = 10		*H/D* = 13	
		ν	%	ν	%	ν	%	ν	%
3	6	5,17	-	3,13	-	2,73	-	1,68	-
	8	5,34	3,4	3,23	3,2	2,81	2,9	1,72	2,4
	10	5,42	1,5	3,28	1,6	2,85	1,4	1,74	1,2
	12	5,47	0,8	3,31	0,8	2,87	0,6	1,76	0,9
	14	5,49	0,5	3,32	0,5	2,88	0,4	1,76	0,4
	16	5,51	0,3	3,33	0,3	2,89	0,3	1,77	0,3

Table 6. Frequency changing of the tower's own oscillations *D* = 5м

R, м (m)	*nR*	*H/D* = 5		*H/D* = 7		*H/D* = 10		*H/D* = 13	
		ν	%	ν	%	ν	%	ν	%
5	6	4,48	-	3,39	-	1,74	-	1,05	-
	8	4,61	3,0	3,47	2,3	1,78	2,5	1,08	2,7
	10	4,68	1,4	3,51	1,2	1,80	1,1	1,09	1,3
	12	4,71	0,7	3,54	0,6	1,82	0,8	1,10	0,7
	14	4,73	0,4	3,55	0,4	1,82	0,4	1,10	0,4
	16	4,75	0,3	3,56	0,2	1,83	0,3	1,11	0,3

Table 7. Frequency changing of the tower's own oscillations *D* = 8м

R, м (m)	*nR*	*H/D* = 5		*H/D* = 7		*H/D* = 10		*H/D* = 13	
		ν	%	ν	%	ν	%	ν	%
8	6	3,45		2,18		1,11		0,67	
	8	3,54	2,7	2,23	2,2	1,14	2,5	0,69	2,6
	10	3,58	1,2	2,26	1,1	1,15	1,1	0,69	1,2
	12	3,61	0,6	2,27	0,6	1,16	0,7	0,70	0,7
	14	3,62	0,4	2,28	0,4	1,16	0,4	0,70	0,4
	16	3,63	0,2	2,28	0,2	1,16	0,3	0,70	0,3

By increasing the value of *nR* when calculating the own frequency of oscillations, the accuracy of the results is slightly improved, but the analysis of the design scheme becomes more complicated. With each subsequent increase in the discretization value, the number of elements increases exponentially. Having analyzed the obtained results we can conclude that a sufficient level of discretization is 12 elements, because further increase in the value of *nR* will lead to a change in the frequency of own oscillations of less than 1%.

Received for further calculations the value of discretization *nR* = 12, is sufficient for dynamic calculations of structures, determination of the frequency of natural vibrations. It is necessary to estimate the relative error in the determination of stresses. The SCAD program complex allows to determine the value of stresses in the midpoint of the unit plate. By changing the discretization value, the geometric dimensions of the FE are also changed.

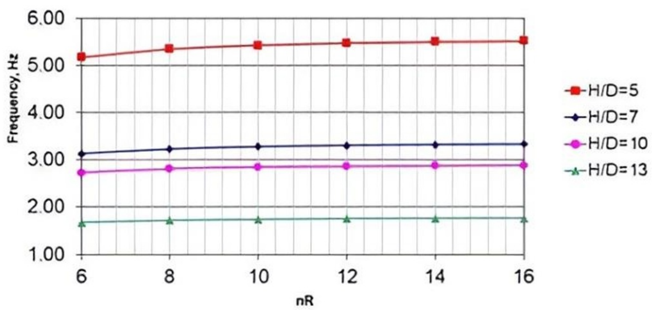


Fig. 8. Frequency changing of the tower's own oscillations (*D* = 3m)

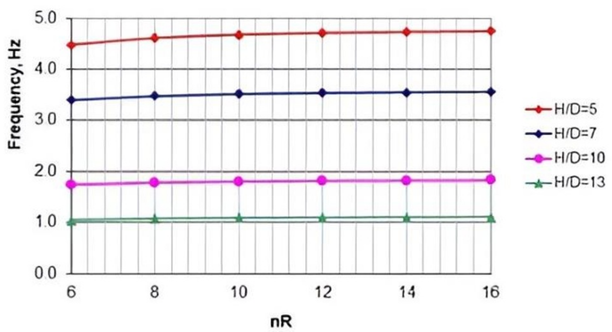


Fig. 9. Frequency changing of the tower's own oscillations (*D* = 5m)

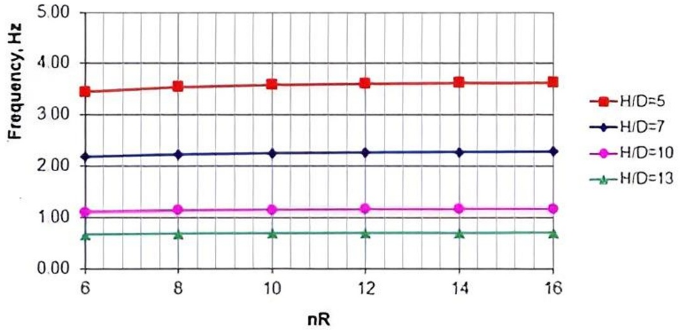


Fig. 10. Frequency changing of the tower's own oscillations (*D* = 8m)

Example 2: Consider the support section of the calculation scheme of a cylindrical tower with height H and base diameter D taking into account different values of the discretization number. The plate of the third row from the base is considered in order to neglect the phenomenon of edge effect (Fig. 11).

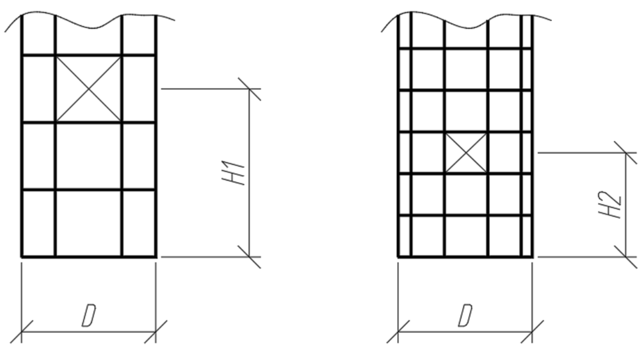


Fig. 11. The absolute height of the calculated FE at different discretization levels

With unchanged geometric parameters of the tower (height, base diameter), different stress values were obtained at points with different absolute heights. Therefore, it is impossible to determine the change in stress values at different degree of discretization due to high error. For this purpose, an alternative approach must be used.

By simplifying the design scheme of the tower to a vertical cantilever rod rigidly clamped at the base, the stresses can be determined as the ratio of the bending moment to the moment of resistance. The change in stresses between a cylindrical tower with a resistance moment of Wcircle = 12 and a tower having a 12-angle cross-section with Wn = 12 does not exceed 5%. Within the framework of calculations for studying the frequency behavior of the tower of the wind turbine, this will not lead to significant errors and is acceptable, since a change in wall thickness by 1...2 mm will lead to a frequency change of 0.5%.

3.2 Evaluation of the influence of the wind turbine tube tower dimensions on SSS and frequency characteristics

Impacts from wind turbines are often a source of strong vibrations. Excitation occurs mainly at two frequencies:
– main frequency *f**, which is defined by the number of rotor rotations per unit time;
– an additional frequency *f***, which is determined by the passage of the blades past the tower (*f*** = *n f**, where n is the number of rotor blades).

Within the 20-year projected lifetime of a wind turbine with annual operation of 2000-3000 hours and rotor speed of 40-70 rates per minute, the tower is resisting more than 10^8 cycles of loading. This requires the use of special methods for endurance calculation based on the theory of damage accumulation effect, which is especially important for welded tubular support under high power wind turbine.

For towers with the first own oscillation frequency $f_{01} < f^{**}$, the phenomenon of starting resonance should be considered when entering the nominal design mode and when stopping.

When designing towers, it is necessary to fulfill the conditions for the ratio of the wind turbine rotation frequency f^{**} to the first own oscillation frequency f_{01} of the system "tower - wind turbine", according to [25]:

According to the Mander's law of concrete deformation, the above-mentioned characteristics are determined by (4):

$$0,3 < \frac{f^{**}}{f_{01}} < 0,95$$
$$1,05 < \frac{f^{**}}{f_{01}} < 1,4 \qquad (3).$$

This can be achieved by increasing the stiffness of the tower structure.

Calculations were made to determine own oscillation frequency of tubular towers with different geometric characteristics. The task of these calculations was to determine the changes in the frequency characteristics of the structure with increasing height, diameter at the base, and wall thickness of the tower. Only the tower diameter at the head d = 2m remained unchanged, which was regulated by the Turbowind T600-48 wind turbine manufacturer.

Determination of frequency characteristics was carried out in the SCAD program complex, with the construction of design models with the main parameters indicated in Fig. 2:

– the discretization value along the circumference $nR = 12$;
– the height of the unit plate is approximately equal to its width $H_{nR} \approx L_{nR}$.

The main geometrical characteristics of the analyzed towers are shown in Figures 12 and 13. The peculiarity of the design model of the towers is the change in the stiffness characteristics of the structure by height. Each tower was conditionally divided into 20-meter sections by height. The wall thickness of the upper section for Turbowind T 600-48 was 16 mm and increased by 1 order (according to the sheet steel grade) for the underlying section, consequently for EV-100 the thickness of the upper section was 18 mm and increased by 1 order of magnitude for the underlying section.

To increase the rigidity of the structure at the boundaries of the sections, diaphragms (10mm thick plates) were introduced into the design scheme.

Masses of internal ladders, fences, communications were not taken into account because of insignificant value.

The mass of the rotor (with blades) and nacelle of Turbowind T600-48 wind turbines was represented as a mass concentrated at a point, found by (4):

$$M = M_P + M_\Gamma \qquad (4),$$

and is 41 tones for Turbowind T600-48 and 81 tones for Eviag EV 100.

Eviag EV 100 is characterized by constant rotor speed, so resonance frequencies have a particular value:

$$f_{cm}{*} = \frac{16,5(rpm)}{60(\sec)} = 0,275(Hz), \qquad f_{cm}{**} = 0,275(Hz) \cdot 3 = 0,825(Hz)$$

The main task was to determine the geometrical parameters of the towers whose own oscillation frequency falls between the forced vibration ranges of the rotor of the wind turbine. Analyzing Fig. 14 and 15 it was concluded that the towers with height from 60 to 80m and base diameters of 4...6m (for Turbowind T600-48) and height from 90 to 100m and base diameters of 8m (for Eviag EV 100) satisfy the requirements of formula 4.

The method of determining the rational height of a wind turbine depends not only on the frequency of own oscillations of the structure, but also on a number of other factors:
– potential output of the wind turbine;
– mass of the structure;
– the cost of installation and further maintenance.

In the following calculations the rational height of wind turbine placement is determined taking into account all the above-mentioned indicators. The graph of changes in the mass of tower structures is shown in Fig. 16, 17.

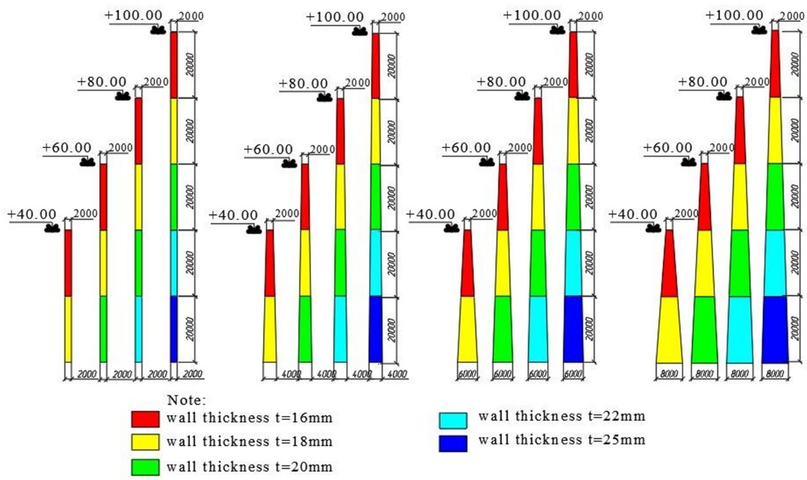


Fig. 12. Design tower's dimensions for Turbowind T 600-48

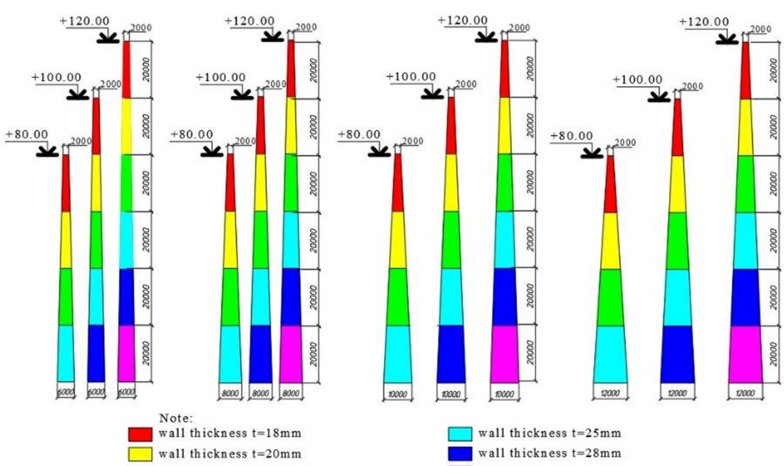


Fig. 13. Design tower's dimensions for Eviag EV 100

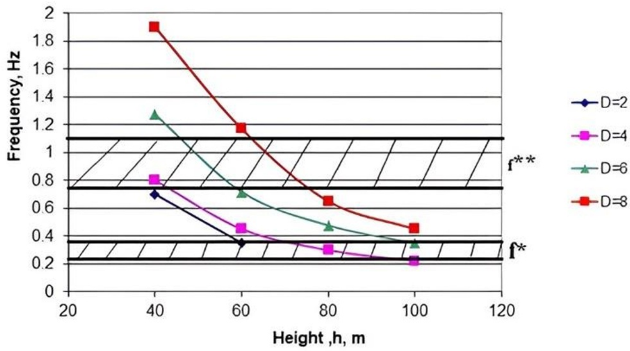


Fig. 14. Frequency changing of the tower's own oscillations with Turbowind T600-48

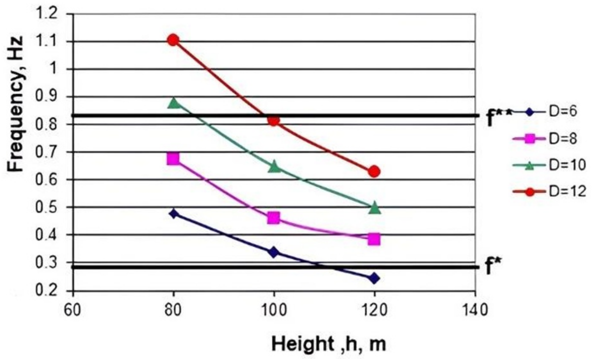


Fig. 15. Frequency changing of the tower's own oscillations with Eviag EV 100

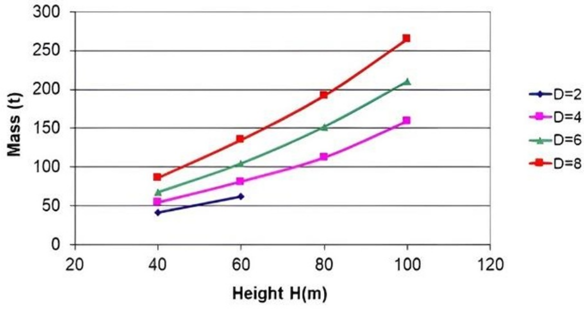


Fig. 16. Tower's mass changing with Turbowind T600-48

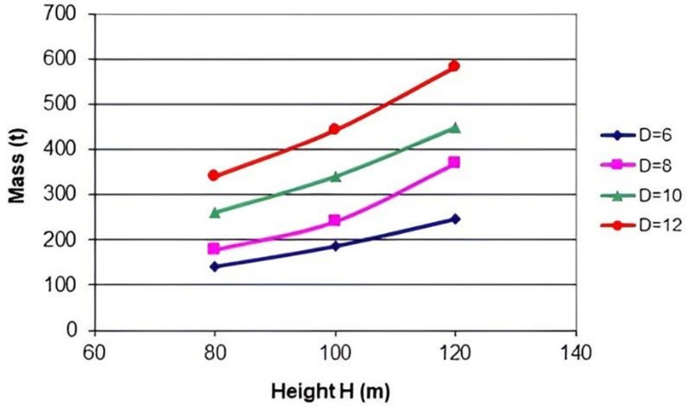


Fig. 17. Tower's mass changing with Eviag EV 100

4 Conclusions

1) In process of forming a design model of cone-shaped tower in SCAD software package it is rational to use the 44th finite element type (4-node plate).

2) The frequency value of own oscillations when using the FE type "50" differs significantly from the frequencies obtained when using other types of FE. The change in frequency when using FE types "41", "42", "44" does not exceed 0.5%. However, in further calculations the FE type "44" will be used as the most universal. The use of the triangular FE type "42" will lead to an increase in the number of elements and will slightly affect the result.

3) Sufficient discretization value of design model to determine the frequency of own oscillations should be taken nR = 12, because further increase in value nR will lead to change in frequency of own oscillations by less than 1%.

4) Fixed frequencies for the Eviag EV 100 wind turbine are determined to be 0.275 and 0.825 Hz. For the Turbowind T600-48, a range of resonant frequencies is defined due to the presence of a variable rotor speed: the starting frequency range is from 0.255 to 0.765 Hz, and the maximum frequency range is from 0.383 to 1.149 Hz.

5) When the tower heights vary in steps of 20 m at D = 2...8 m, the value of the first natural frequency decreases nonlinearly from 1.86 to 0.23 Hz for the Turbowind T600-48 wind turbine and from 1.11 to 0.25 Hz for the Eviag EV 100 wind turbine. At the preliminary stage of analysis the tower it is necessary to compare the own frequencies with the resonant ones and, if there is a threat of the structure falling into a state of resonance, make adjustments to the initially accepted dimensions in order to eliminate the resonant threat.

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