DOI: 10.63550/ICEIP.2025.74.91.021

Structural Shapes and Loads for Steel Wind Turbine Towers

Igor Garanzha[a], Alexander Golikov[b], Milena Pisareva[c]
Moscow State University of Civil Engineering (National Research University), 129337 Moscow, Russia

Keywords: wind turbine, steel tower, natural frequencies, structural shape, operating mode, wind speed.

Abstract: The article deals with the issue of analyzing the structural design of towers for wind power plants (WPP), as well as the loads acting on them. When it is necessary to locate wind turbines at a height of up to 40 m, towers are usually designed as lattice towers (trihedral or tetrahedral). Tubular design of towers is used when their height exceeds 40 m. Russian wind farms mainly use tetrahedral lattice towers with a crossed variant of lattice organization, firstly, because of the relative complexity of manufacturing trihedral supports, and secondly, because of the possibility of the effect of wind shading of the wind turbine unit by a tower of tubular design. The height of the tower is based on the diameter of the wind wheel and the required height of the wind turbine to ensure its performance. The optimum base width of wind turbine towers is usually small and the D/H ratio is shifted to 1:20. Tubular towers are designed most often with a simple weakly conical shape or have a stepped-cylindrical outline. Currently, the most promising are wind turbines with variable rotor speed and direct power transmission. The frequency parameters of towers, as well as the loads on the wind turbine tower, are primarily determined by the characteristics of the wind turbines used. The main loads absorbed by the tower are the result of the operation or aerodynamic resistance of the wind turbine generator or its parts. Loads on the tower, especially in dynamic formulation, should be determined only taking into account the joint operation of the system “support - wind turbine”. A special problem in determining the loads on wind turbine towers is the determination of loads from a particular type of wind turbine. In addition to the rotor pulling force, foreign standards regulate the determination of loads associated with the friction of parts of mechanisms during tower rotation, eccentric application of the rotor pulling force and other similar aspects. In operating mode, wind turbines are a source of rather strong vibrations, which are composed of a main frequency, determined by the number of rotor revolutions per unit time, and an additional frequency, determined by the number of blades passing by the tower. Necessary conditions for dynamic behavior of the tower can be achieved by adopting new design solutions, increasing its stiffness, as well as by using frequency tuning techniques.

1 ITRODUCTION

In the practice of wind turbine construction, lattice (fig. 1) and tubular (fig. 2) towers are mainly used; there are known designs of tubular towers supported on the system of “spaced legs”, however, this solution has not been widely used (Kudelin, Kucherov, 2021; Lu, McElroy, 2017).

a) b)

Figure 1: Lattice towers of wind turbines: three-sided (a) and four-sided (b).

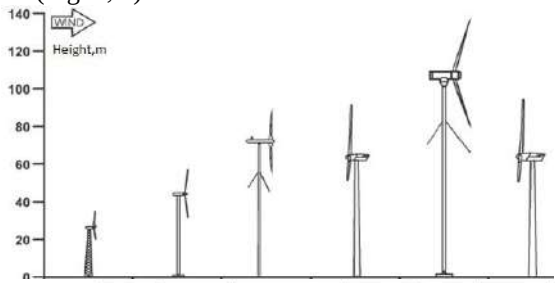
[a] https://orcid.org/0000-0001-6588-6031
[b] https://orcid.org/0000-0002-6687-7249
[c] https://orcid.org/0009-0006-3012-2852

DOI: 10.63550/ICEIP.2025.74.91.021

a) b)

Figure 2: Tubular tower of wind turbine: a - with a constant wall slope; b - with one fracture in height.

Lattice towers are designed triangular (Fig. 2, a) using tubular profile elements for the belts, but more often tetrahedral (Fig. 2, b) from angle profile elements. The scheme of lattice is diverse: triangular, slanted, half-slanted, crossed (with combined and not combined nodes in two adjacent faces). Sometimes prestressing of struts is used to increase the rigidity of structure (Kudelin, Kucherov, 2021; Lu, McElroy, 2017). In order to reduce the loads on foundation when they are separated, as well as to increase the stability of the tower structure, a single fracture along the length of the shaft can be used to widen its lower part (Fig. 2, b).



	AOC 15-50	AWT 27	Cannon/Wind Eagle	ZOND Z-50	WTC-1000	ZOND Z-56
Nominal power kWh	50	275	300	750	1000	1000
Rotor's diameter m	15	27	29	50	54	56
Number of blades	3	2	2	3	2	3
First prototype year	1993	1996	1997	1996	1999	1999

Figure 3: Variants of constructive solution for wind turbine towers.

Analysis of foreign sources has shown that tubular design of towers is used when its height exceeds 40 m (Fig. 3) (Eurek, Sullivan, Gleason, Hettinger, Heimiller, Lopez, 2017).

Research goal: to analyze the peculiarities of determining the shape and geometric dimensions of wind turbine towers taking into account the current loads for the subsequent development of recommendations on the choice of a rational structural form taking into account the requirements of current standards.

The list of problems has been solved within the framework of the conducted work:

– determination of design forms of wind turbine towers currently used at wind farms in Russia;

– analysis of peculiarities of determining the shape and geometric dimensions of wind turbine towers;

– analysis of loads on wind turbine tower structures;

Research object: structures of lattice and tubular steel towers of wind turbines.

Research subject: structural shape and acting loads on the wind turbine tower.

2 MATERIALS AND METHODS

Russian wind farms mainly use tetrahedral lattice towers with a crossed variant of lattice organization. This design of towers is explained by a number of reasons (Denisov, Elistratov, Gzenger, 2017; Nikolaev, Ganaga, Kudryashov, 2008):

- The complexity of manufacturing (multi-division) of trihedral towers;

- availability of a developed production base for manufacturing tower lattice structures from angle profile elements (these are plants for manufacturing overhead transmission line supports);

- the type of wind turbine USW 56-100 used at Russian wind power plants has a windy solution, a tubular tower would create a significant shading, and in case of setting of tensions it would require constant strict control of their tension; for heights of 20...40 m the lattice solution of the tower is less material-intensive than the tubular one.

For wind turbines of the Turbowinds T600-48 type, which are popular at wind farms in Russia, tubular towers with a height of 60 m are used (Denisov, Elistratov, Gzenger, 2017; Nikolaev, Ganaga, Kudryashov, 2008).

The reliability of metal wind turbine towers is largely determined by the operating conditions. Moreover, the main loads, which are perceived by the tower, are the result of the operation or aerodynamic resistance of the wind turbine generator or its parts. The loads on a wind turbine tower are most fully presented in (Fil'kin, 2022; Miroshnik, Podberezkin, Kopejkin, Sokolov, Artamonova, 2016; Butuzov,

DOI: 10.63550/ICEIP.2025.74.91.021

Bezrukih, Gribkov, 2021). However, it should be noted that this paper considers the loads associated with wind effects, i.e., maximum wind head, wind flow turbulence, extreme wind gusts, zonal effects and abrupt changes in wind direction.

A modern wind turbine is usually controlled by an automatic system that starts the machine at some wind speed V1, and turns it off at speed V_0, preventing unacceptable overloading of all systems. In the speed range (V_1, V_0) this system controls the rotational motion of the rotor by changing the angle of attack of the blades, and brings the system to the rated power mode at a certain wind speed V_R. Provided $V>V_0$, The blades are rotated to the "vane position" and the load on the system is reduced, allowing it to absorb the maximum design wind at a speed of V_{max}, which is not exceeded more than once every 50 years (Bezrukih, Bezrukih, Gribkov, 2014; Zhavoronok, Harchenko, 2015; Afanas'ev, Baranov, 2021).

2.1 Analysis the Peculiarities of Determining the Shape and Geometric Dimensions of Power Plant Towers

The analysis of data on the applied wind turbine heights (Fig. 4) reveals a general tendency of its increase with increasing wind wheel diameter. However, the large scatter relative to the approximating line indicates the diversity of heights of the applied towers, which is dictated by the desire to increase the wind turbine performance with increasing the height of its location (Fomenko, Udovikov, Manaenko, Fomenko, 2020; Karamysheva, Arakelyan, Konyahin, Ivanov, 2018).

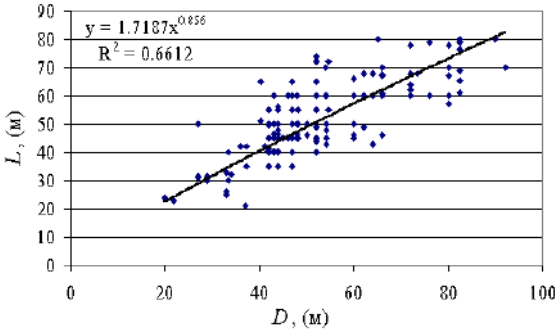


Figure 4: Dependence of tower height on wind wheel diameter.

The height of the tower (L) is taken based on the diameter of the wind wheel, as well as the required height of the wind turbine location to ensure its performance. Approximately the height of the wind turbine location can be determined by dependence (1) (Karamysheva, Arakelyan, Konyahin, Ivanov, 2018):

$$L = D + 1000 / D^2 \qquad (1).$$

Values of optimal width of the base of towers of wind turbines, usually obtained small and the ratio D / N moves to the boundary of 1:20, but practically used values can increase due to the consideration of two factors:

– the desire to increase the stiffness of the support and avoid resonance;

– the need to reduce the forces transmitted to the foundations if they are designed as separate foundations.

Tubular towers are most often designed with a simple weakly conical shape or have a stepped-cylindrical outline. In the latter case, the cylindrical sections are mated by conical inserts with the slope of the cone formation of the order of 1:3 - 1:4 (Karamysheva, Arakelyan, Konyahin, Ivanov, 2018). For tubular towers, the diameter of the tower at the base is usually much smaller than the width of a through support of similar purpose, which is caused both by the desire to reduce the wind pressure on the tower structure and by the fact that in this case a common foundation is often used. Tubular towers supported by spaced legs with separate foundations are known, although they have not been widely adopted.

The design of the upper part of the support is determined by the conditions of adjoining the wind turbine to the tower (Bezhan, 2021). In the topmost part of the tower (headband) holes for mounting bolts are placed, and the headband is subjected to machining to ensure the necessary accuracy and tightness of adhesion of the HEI housing. The headband directly perceives intensive dynamic impacts, for some types of wind turbines there are data on the appearance of fatigue cracks here. For this reason, higher quality requirements must be placed on the welded seams of the headband, which are often subjected to 100 percent physical weld inspection.

In the same upper part there is often a platform from which the operating personnel performs inspection and current repair of the responsible unit of blade attachment to the hub and mechanisms of windward rotation of the wind turbine. In order to reduce the aerodynamic shadow of the tower, its external platform is sometimes designed without railings, and to ensure the safety of personnel are provided with brackets for fixing the carabiner of the climbing belt.

For sheathing supports, there is often no external platform, which simplifies the safety problem. If there

is an external platform, a manhole is required to access it. In places where the manholes are located in the shell, it is necessary to provide reinforcement of the hole contour to compensate the cross-section, for which the manhole openings are framed with spigots, serving simultaneously for the location of door fastening parts, and sometimes reinforced with additional sleeves or insertion of a thicker sheet shell section. The contours of holes, inserts and collars are oval-shaped to reduce the concentration of stresses at the cutout. This is especially important for the upper manhole, where the cross-section is weakened to a greater extent (due to the smaller overall dimensions of the shell with the same dimensions of manholes) and, in addition, in this zone the influence of vibrations is more intense (Karamysheva, Arakelyan, Konyahin, Ivanov, 2018; Bezhan, 2021; Elistratov, 2016).

There are tower designs where, in addition to the upper platform, an additional intermediate platform is provided at a level that allows inspection of the blade ends, since this part of the blade, which has the highest linear velocity, is the most damaged.

The dynamic and frequency parameters of towers, as well as the loads on the tower of wind turbines, are primarily determined by the characteristics of the applied wind turbines (Elistratov, 2016).

Wind turbines can be subdivided into wind turbines with constant rotational speed and variable blade aerodynamic resistance and wind turbines with variable rotational speed and constant blade aerodynamic resistance, depending on the loads transferred and the constancy of the rotational speed. The main characteristic of a wind turbine is the power curve, i.e. the dependence of the generated power on the speed of the incoming air flow.

Currently, the most promising are wind turbines with variable rotor speed and direct power transmission. In areas with an average wind speed of 4.5 - 5 m/s, the performance of wind turbines of this class increases the efficiency of wind turbines with constant rotational speed by 5 - 10 % on average. Along with the advantages, these wind turbines are characterized by the fact that the frequency of the forcing force is constantly changing within a wide enough range. This means that for this type of wind turbine the requirements for changing the natural frequency are decisive. The next aspect of this problem is that studies of loads, in particular the rotor pulling force, for variable speed wind turbines are significantly complicated by the aerodynamic resistance of the system “blades - generator”, and it is possible to determine these loads only on the basis of a large number of bench tests (Perel'muter, Mikitarenko, 2001).

2.2 Analysis of Loads on Wind Turbine Tower Structures

As noted earlier, the loads on the tower, especially in the dynamic formulation, should be determined only taking into account the joint operation of the system “support - wind turbine”. However, following the results given in (Gorohov, Turbin, Bakaev, Bus'ko, 2016; Gorohov, Turbin, Nekrasov, Bus'ko, Zhabskij, 2017), the calculation of the wind turbine support for the ultimate loads caused by extreme wind impact, due to the aerodynamic resistance of the wind turbine blades, can be carried out as a quasi-static one. Nevertheless, the calculation of the natural frequencies of the system under the action of operational values of wind loads should be carried out only in the dynamic formulation (Pichugin, Mahin'ko, 2015).

The concept of determining the ultimate loads caused by critical values of wind speed is close to the traditional approach adopted in foreign standards to account for the effects of wind on structures. In normative documents, e.g. Germanisher Lloid, special attention is paid to the specification of meteorological and orographic conditions at the installation site. For wind turbines that are installed as part of a wind farm, their mutual influence must be taken into account. This can be manifested in an increase in turbulence and uneven distribution of the surging flow. In this case, the rotational gating effect associated with the repeated impact of partial gusts is manifested. It can have a significant effect on fatigue resistance. The increased level of transverse velocity pulsations in the downstream jet of neighboring wind turbines also causes yaw system errors, which lead to a 180 degree turn of the wind turbine and its stopping. This also contributes to fatigue of the structural elements of the tower and blades (Perel'muter, Mikitarenko, 2001; Gorohov, Turbin, Bakaev, Bus'ko, 2016; Gorohov, Turbin, Nekrasov, Bus'ko, Zhabskij, 2017). Wave effects are also significant problems leading to fatigue damage occurrence.

A special problem in determining the loads on wind turbine towers is the determination of loads from a particular type of wind turbine generator. In addition to the rotor pulling force, the standards (Lu, McElroy, 2017) regulate the determination of loads associated with the friction of parts of mechanisms during tower rotation, eccentric application of the rotor pulling force and other similar aspects.

DOI: 10.63550/ICEIP.2025.74.91.021

Thus, the main load on the support is a group of forces and moments transmitted from the operating wind turbine to the tower top (Fig. 5) and caused by the following reasons:

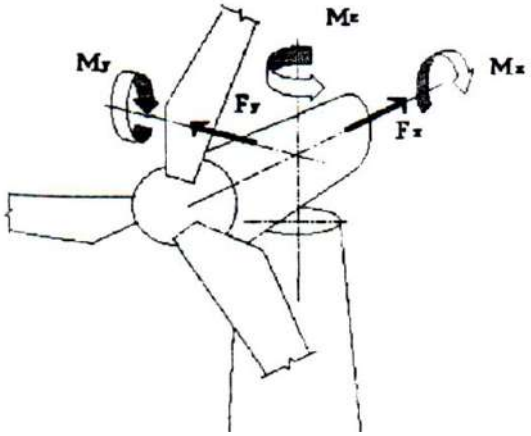


Figure 5: Impacts of the wind turbine on the tower.

– aerodynamic loads on the blades of the wind turbine;

– inertial and gyroscopic forces arising from changes in the operating mode or turbine orientation;

– unbalance of blades and other moving elements;

– wind flow variability in speed and direction, including - - turbulent wind pulsations;

– icing of the tower structure.

From the number of aerodynamic loads, the main one is the rotor pulling force, which, following (Lu, McElroy, 2017), can be defined as follows (2):

$$F_x = \pi(DV)^2 / 7200 \qquad (2),$$

where V is the nominal wind speed in m/s, and force F_x is defined in kN. This load determines the dimensions of the main elements of the tower, the other loads only affect the design of individual parts and assemblies.

In (Gorohov, Turbin, Bakaev, Bus'ko, 2016), a methodology for determining the pulling force of a wind turbine by conducting experimental studies of the stress-strain state of the wind turbine tower at the level of the foundation cutoff is proposed. In this case, it is rightly noted that the "tower-PPP" system works as a certain low-pass filter, hence, there is a certain functional dependence "wind load - rotor pulling force - stresses in the belts of the pylon zone", which was determined on the basis of the conducted monitoring. The results showed that expression (2) significantly overestimates the value of the pulling force, however, it should be noted that only one tower was investigated in (Gorohov, Turbin, Bakaev, Bus'ko, 2016), and a rather small statistical material was processed, in which there were no measurements at wind speeds close to the stopping wind speeds, i.e. in the area in which the tower design is analyzed.

During design, various combinations of operating modes (normal - *N*, critical - *E*, special - *S* and maintenance mode - *M*) with possible environmental conditions are used in the calculations. The wind turbine tower should be designed for the following possible loads (Table 1).

Table 1: Possible design combinations of acting loads on the wind turbine tower.

Environmental influences (what parameter can be expressed in tower analysis)	Wind turbine operating mode		Transportation, assembly (M1); repair, installation (M2)
	Reserve $V = V_{max}$	Electric power generation $V_R \le V \le V_0$	
Normal average conditions V = $V_{ср.год}$ / V = 10 m/s	-	-	M1.1 / M2.1
Normal operating gust	-	N1.1	M1.2 / M2.2
Wind turbulence (e_w, M_z)	-	N1.2	-
Ice deposits on the wind turbine and tower	E2	E3	-
Zonal wind action (M_y)	-	E1.1	-
Extreme operating gust	-	E1.2	-
Seismic shaking	-	S1	-

3 RESUTS AND DISCUSSION

The standby mode, which corresponds to the critical wind speed with a 50-year period of repeatability (*Vmax*), is considered when the wind turbine is switched off, when the blades are turned to the "vane position". The starting and stopping modes are not considered, as they will be decisive in the calculation of the blades, although in the case of start and stop resonances they must be taken into account in the endurance calculation of the structure. In the case of a tubular tower solution, the temperature variation should be additionally taken into account. The seismic load calculation should be performed in accordance with the requirements of the current domestic standard SP.14.13330.2018.

DOI: 10.63550/ICEIP.2025.74.91.021

In the operating mode wind turbines are a source of rather strong vibrations, which are composed of the main frequency (f^*), determined by the number of rotor revolutions per unit time, and additional (f^{**}), determined by the number of times the blades pass the tower ($f^{**} = n \cdot f^*$, where n – number of wind turbine blades) (Gorohov, Turbin, Nekrasov, Bus'ko, Zhabskij, 2017; Pichugin, Mahin'ko, 2015). In this regard *the designed tower should be checked for the possibility of resonance phenomena at different operating modes* (start, power generation mode, stop).

When designing towers according to Germanisher Lloid standards, the conditions for the forced speed ratio must be met f_R to the natural frequencies of tower vibrations f_0:

$$0,3 < \frac{f_R}{f_0} < 0.95 \text{ or } 1,05 < \frac{f_R}{f_0} < 1,4 \qquad (3).$$

In this case, it is necessary to take into account the dynamic nature of the load application by introducing a dynamicity coefficient.

According to (Lu, McElroy, 2017;Gorohov, Turbin, Bakaev, Bus'ko, 2016; Pichugin, Mahin'ko, 2015), the value of the dynamicity coefficient can be determined by the formula (4):

$$\xi = \frac{1}{\sqrt{\left(1 - \frac{f^2}{f_0^2}\right)^2 + \left(2 \cdot \delta \cdot \frac{f}{f_0}\right)^2}} \qquad (4),$$

where δ – logarithmic decrement of oscillations.

The necessary conditions for the dynamic behavior of the tower can be achieved by adopting new structural solutions, increasing its stiffness, as well as by using frequency tuning techniques.

In addition to the considered loads and impacts, the wind turbine supports are characterized by an emergency condition associated with blade breakage. Unfortunately, at present in Russia there are no standards that normalize these situations. Nevertheless, when operating a large number of wind turbines, in case of control system malfunction, a situation may occur when the structure will operate in the resonance mode for some time. In particular, when one of the blades breaks, the forced frequency from the USW 56-100 wind turbine will be 2.4 Hz, which may cause resonance of the used 18 m high tower structure, the first natural frequency of which is 2.2 Hz. Therefore, there is a need to develop and apply a safety system that will prevent such phenomena or react in a timely manner when they occur.

4 CONCLUSIONS

1. Regulatory literature devoted to the analysis, construction and operation of wind turbine towers is currently absent in the Russian Federation.

2. The issues related to the design and operation of building structures need more detailed consideration, including the need to develop measures for technical diagnostics and assessment of the technical condition of building structures of wind power plants.

3. Taking into account the actual loads on the wind turbine tower allows not only to increase its reliability and durability, but also to perform the design of the structure with a given level of stresses and dynamic characteristics.

4. The designed tower should be tested for the possibility of resonance phenomena at different modes of operation.

5. The necessary conditions for the dynamic behavior of the tower can be achieved by adopting new structural solutions, increasing its stiffness, as well as by using frequency tuning techniques.

6. Identified the need to develop and implement a safety system that will prevent such phenomena or respond in a timely manner when they occur.

REFERENCES

Kudelin, A., Kucherov, V. J., 2021. En. Strat. Rev. **V.34(2)**, 100627.

Lu, X., McElroy, M.B., 2017. J. Wind En. Onsh. Offs. Wind Turb. **V.11(4)**, 51-73.

Renewable Capacity Statistics 2019, IRENA, 123 (2019). https://www.irena.org/publications/2019/Mar/Renewable-Capacity-Statistics-2019.

Gis renewable energy sources Of Russia. http://gisre.ru/.

Eurek, K., Sullivan, P., Gleason, M., Hettinger, D., Heimiller, D., Lopez, A., 2017. J. Ener. Econ. **V.64(4)**, 552-567.

Denisov, R.P., Elistratov, V.V., Gzenger, S.H., 2017. J. Sc. Tech. Bul of SPbSTU, **V.2(4)**, 17-27.

Nikolaev, V.G., Ganaga, P.V., Kudryashov, Yu.I., 2008. Nauka, **584**.

Fil'kin, M.E., 2022. J. Reg. Econ and Dev, **V.3 (71)**, 14-24.

Miroshnik, V.V., Podberezkin, D.A., Kopejkin, D.A., Sokolov, P.P., Artamonova, E.Yu., 2016. Int. Sc. J. **V.12(54)**, 13-26.

Butuzov, V.A., Bezrukih, P.P., Gribkov, P.V., 2021. S.O.K. J. **V.5**, 62-76.

Bezrukih, P.P., Bezrukih, P.P., Gribkov, P.V., 2014. Teploenergetik, **304**.

Zhavoronok, A.V., Harchenko, U.A., 2015. Mod. Sc. Res. And Inn. J. **V.7**, 106-110.

Afanas'ev, A.A., Baranov, N.N., 2021. J. Ener.: Econ.,

DOI: 10.63550/ICEIP.2025.74.91.021

Tech., Ecol. **V.4**, 34-48.
Fomenko, N.E., Udovikov, A.K., Manaenko, I.N., Fomenko, L.N., 2020. J. Eng. Bul. of Don. **V.1**.
Karamysheva, A.A, Arakelyan, A.A., Konyahin, V.O., Ivanov, N.V., 2018. J. Eng. Bul. of Don. **V.3**.
Bezhan, A.V., 2021. J. of Arc.: Ecol. and Econ. **V.3(11)**, 449-457.
Elistratov, V.V., 2016. Politekh, **424**.
Perel'muter, A.V., Mikitarenko, M.A., 2001. Bul. of DonNACEA. **V.5(30)**, 8-13.
Gorohov, E.V., Turbin, P.V., Bakaev, S.N., Bus'ko, M.V., 2016. Bul. of DonNACEA. **V.4(29)**, 13-18.
Gorohov, E.V., Turbin, P.V., Nekrasov, Yu.P., Bus'ko, M.V., Zhabskij, Yu.V., 2017. Bul. of DonNACEA. **V.2(39)**, 7-13.
Pichugin, S.F., Mahin'ko, A.V., 2015. PSTU, **324**.