

INVESTIGATION OF WATER LIFT STATION WIND WHEEL BLADES

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Abstract. The article is devoted to improving the efficiency of water supply and watering animals in pastures and walking areas by optimizing the design and technological parameters of wind water stations. In the main studies of technologies and technical means the wind water stations are analyzed and it is revealed that wind energy in mechanical installations (mills, water pumps) has been used for several centuries. It has been established that the actual direction of increasing the efficiency of water wind stations is to protect the blades from destruction by very strong gusts of wind. A vibration stand was used to test fatigue and crack resistance of turbine elements with a horizontal axis of rotation of the water station. The operating frequency range of the shaker was within 5-5000 Hz, and the temperature values were -60...60 °C (213...333 K). The influence of operational defects on fatigue was studied on materials of different classes: DIT aluminum alloy and VT6S titanium alloy. The characteristics of crack resistance and endurance of the material of the blades is determined at different temperatures and asymmetry load cycle. It has been established that lowering the temperature increases the resistance to the tedious destruction of experimental materials, so that these phenomena manifest themselves in different ways. The DIT alloy is more sensitive to the effects sub-zero temperatures, according to the characteristics of crack resistance, than VT6S. For VT6S alloys, a decrease in temperature from 60 °C to -60 °C leads to minor changes in the threshold stress intensity factors and crack growth rate, while for FIT the thresholds increase by 3...4 times, and the crack growth rate decreases by 1...2 orders. For VT6S alloys, there is a slight decrease in fracture toughness with decreasing the temperature, however, at high temperatures, the crack resistance values are at a high level and are several times higher than those of DIT.

Keywords: water supply, wind wheel, endurance, cracks, blade.

Introduction

The future development of wind energy presents significant opportunities in terms of electricity supply. It must be cost-competitive with electricity from fossil fuels and other competitive renewable energy sources. The total rate of wind power production in the world is 4.5%. In Ukraine, this figure is 2.2%. In some European countries, this percentage is much higher: Denmark – 48%, Ireland – 38%, Germany and the United Kingdom – 27%, Portugal – 24%, Spain – 22%.

Analyzing the turbines of wind turbines, we found that traditionally wind power plants have three blades, but can have 2, 4, 6 etc., for any diameter of the wind wheel, with an increase in the number of blades, the wind utilization coefficient increases. The increase in this coefficient in the transition from 1 to 2 blades is 10%, and in the transition from 2 to 3 blades – 5%. With an increase in the number of blades, the cost increases and the arrangement of the wind wheel hub becomes more complicated. Options with many blades are disks and so called “monolithic” installations. Such installations are primarily used as water pumps. For the most efficient operation of a windmill, its blades must interact as much as possible with the wind flow passing through the area of rotation of the rotor. Windmills with many blades usually operate at low rotational speeds. The main characteristics of the design of the blades are the cut profile and shape, material, and the manufacturing method. Typically, blade sections with a wing profile are used to achieve a high lift-to-drag ratio, and hence a high wind energy utilization factor. The materials from which the blades are made are different – wood, aluminum, steel, fiberglass, etc. In this case, one of the main types of destruction of the blades, leading to serious consequences, is the breakdown of fatigue life. Such destruction can occur unexpectedly. Under conditions of variable voltages, this can occur at loads much lower than under the action of stable static forces. The development of trappable fracture usually starts from the surface of the structural element in places of high stress concentration.

Papers [1; 2] present an expert view from Europe and Asia on future new technologies in the wind energy sector giving their potential, challenges, applications, and technology readiness, and how they may evolve in the coming years. In [3], it is indicated that during operation, the blades of wind turbines are exposed to rain, hail, insects, or solid particles (for example, sand) carried by the wind. This can lead to blade erosion, resulting in reduced electrical efficiency and blade weight balancing, and consequently costly repairs. Article [4] provides an overview of the advanced materials used to manufacture wind

turbine blades. The advantages and disadvantages of these materials are explained when comparing the properties. In [5; 6], an analysis of the design and weight of the installation blade was carried out. It is indicated that the optimization of the design and design variant resulted in a weight savings of 23%. Using the optimal blade resulted in savings of approximately 15.5% on the total cost of manufacturing blades.

The study [7; 8] theoretically calculated the design and testing of a small windmill. Three different models with different numbers of blades were chosen for different analysis and experimental verification. In [9; 10], the characteristics of a composite material of four different types are studied. Composite materials were examined for total strain, maximum shear stress and strain energy, and the values of the results are given. The works [11; 12] present a brief overview of composite materials for use in wind turbines. A power increase of 7.5% is also indicated. The results of the work [13] show that under different wind speeds the blade torque of the bionic blade of total improved airfoil increases by 10.2%, the bionic blade of partially improved airfoil increases by 14%, and the configuration improved blade increases by 7%.

Materials and methods

Based on the analysis of previous studies, we have performed theoretical and experimental studies. Light alloys of aluminium D1T and titanium VT6S were used as the materials under study for the rotor blades of the wind wheel, which they can be made of. The tests were carried out on a vibrodynamic stand, which is an electromagnetic coil with a core that performs vertical oscillations. There is a clamp on the coil that allows to fix the console sample. An incision was made at the base of the sample - a stress concentrator. The research methodology was as follows. The resonant frequency of natural vibrations was found, at which the sample performs bending vibrations. Crack growth and load control were carried out visually with a metallographic microscope with a scale separation value of 0.014 mm. In this case, the range of the oscillation amplitude F , mm of the free end of the sample and the change in the crack length Δl , mm was monitored. As a result of the load, a crack formed in the stress concentrator, which was also observed with a different microscope. As the crack grew, the stress gradually decreased until the crack no propagation conditions were reached. Thus, we reached the threshold value. The asymmetry was created due to the addition of an additional tensile force of the free end of the sample to the bending loads with the control of its value by a dynamometer. For tests at temperatures other than 20 °C (293 K), a heat chamber with a system for supplying liquid nitrogen of a certain concentration or heated air was used. The temperature was controlled by thermoelements installed in the working area of the chamber. Experimental studies were carried out after preliminary calibration of the bending load with strain gauges of the 2PKB-5-100GV type in the working zone of the crack development. Calibration was carried out by gluing strain gauges on the opposite surface of the samples from the applied stress concentrator.

Between the swing of the free end of the sample and the normal bending stresses in the cross section of the working area the sample is subject to a directly proportional relationship:

$$\sigma = \xi_{l=0} \cdot F, \quad (1)$$

where σ – maximum normal stress in the working cross section of the sample, MPa;
 F – amplitude ranges of the free end of the sample, mm;
 $\xi_{l=0}$ – sample calibration factor in the absence of a crack (zero crack length).

The relationship between the natural frequency and the size of the sample will be as follows:

$$f = \frac{(k_{bn}L)^2}{2\pi L^2} \cdot \sqrt{\frac{EI}{\rho S_0}}, \quad (2)$$

where I – moment of inertia of the cross section of the sample, Nm;
 S_0 – cross-sectional area, m²;
 E – modulus of elasticity, MPa;
 ρ – material density, kg·m⁻³.

In the first form of bending oscillations, the maximum stresses of the console rectangular rod are in accordance with the expression:

$$\sigma = 10.87 \frac{F}{2} f \sqrt{\rho E} [1 - 0.734 \cdot k_{bn}(L - l_{lr})], \quad (3)$$

where l_{lr} – length of the dangerous section relative to the free end of the rod, mm.

The relationship of deflection with the stress intensity factor $K_{I_{bn}}$ under the action of the transverse concentrated force P on the console prismatic sample can be established by:

$$K_{I_{bn}}^2 = \frac{E}{1-\nu^2} \cdot \frac{P^2}{2t'} \quad (4)$$

where G – intensity of elastic energy release, MNm^{-1} ;
 l – crack length, mm;
 ν – Poisson's ratio.

On the other hand, at a console bend of a prismatic core:

$$K_{I_{bn}} = Y(l) \frac{6M}{tb^2} \cdot \sqrt{l}, \quad (5)$$

$$Y_{bn}(l) = 1.99 - 2.47\lambda + 12.97\lambda^2 - 23.17\lambda^3 - 24.8, \quad (6)$$

where $M = P \cdot l$ – bending moment, Nm;

$\lambda = \frac{l}{b}$ – ratio of the crack length to the sample width.

As a result, we obtain the ratio:

$$\frac{F}{P} = D \cdot \Sigma + C, \quad (7)$$

where C – sample yield without crack:

$$C = \frac{L^3}{3EI}, \quad (8)$$

The other two factors will be equal respectively:

$$D = \frac{72L^2(1-\nu^2)}{tb^4E}, \quad (9)$$

$$\Sigma = \int_0^l Y^2(l) \cdot l dl, \quad (10)$$

As the crack grows, the stiffness of the sample in the direction of the crack opening will decrease, and when it closes, it will not change practically up to the value of the parameter $\lambda < 0.7$. In this case, the maximum stress in the working section in the direction of opening σ'' and closing σ' of the crack will also be different:

$$\sigma' = r \cdot \sigma'', \quad (11)$$

where r – coefficient directly proportional dependence will be defined as:

$$r = \frac{D \cdot \Sigma + C}{C}, \quad (12)$$

As a result, in a sample with a crack, the relationship between the range of the free end of the sample and normal bending stresses in the cross section of its working zone will be subject to the following dependence:

$$\sigma''_{l \neq 0} = \xi_{a \neq 0} (f'_{l \neq 0} + f''_{l \neq 0}), \quad (13)$$

where $f'_{l \neq 0}$, $f''_{l \neq 0}$ – deflection of the sample, respectively, in the extreme upper and lower positions.

Of course, when closing the crack $\sigma'_{l \neq 0} = \sigma'_{l=0}$, therefore it is possible to obtain the theoretical value of the calibration factor $\xi_{a \neq 0}$ for a sample with a crack:

$$\xi_{a \neq 0} = \xi_{a=0} \cdot \frac{2}{r + r^2}, \quad (14)$$

Finally, the stress intensity factors for the sample with a crack from the bending load under vibration load will be determined by the expression:

$$K_{I_{bn}} = (\xi_{a \neq 0} \cdot Y_{bn}(l) \cdot \sqrt{l}) \cdot F = S \cdot F, \quad (15)$$

Therefore, considering the elastic constants of the previous equation in the process of the experiment, you can calculate the value of the parameter S , which depends on the size of the crack in the sample:

$$S = \xi_{a \neq 0} \cdot Y_{bn}(l) \cdot \sqrt{l}, \quad (16)$$

The tensile strength coefficient was determined similarly:

$$K_{Ip} = Y_p(l) \cdot \sigma_p \cdot \sqrt{l}, \quad (17)$$

$$Y_p(l) = 1.99 - 0.41\lambda + 18.7\lambda^2 - 38.48\lambda^3 - 53.85\lambda^4, \quad (18)$$

where $\sigma_p = \frac{P_p}{bh}$ – tension from tensile force, MPa;

b, h – dimensions of the working cross section of the sample, mm.

The magnitude of the stress intensity factor ΔK_I and the load cycle asymmetry factor R is defined as:

$$\Delta K_I = K_{I_{bn}} + K_{Ip} \text{ with } R < 0;$$

$$\Delta K_I = 2K_{I_{bn}} \text{ with } R \geq 0;$$

$$R = \frac{K_{Ip} - K_{I_{bn}}}{K_{Ip} + K_{I_{bn}}}. \quad (19)$$

During the tests with an asymmetric load cycle to maintain a given asymmetry in the development of the crack, the amplitude F of the oscillations of the free end the sample was corrected by the dependence:

$$F = \frac{1}{\xi_{l \neq 0}} \cdot \frac{Y_p(1-R)}{Y_{bn}(1+R)} \cdot \sigma_p, \quad (20)$$

where σ_p – tension from tensile force, MPa.

At temperatures other than $T = 293$ K, the values of the calibration factor $\xi_{l=0}$ and the oscillation range F of the free end the sample were determined in proportion to the change in the modulus of elasticity E of the material according to the change in temperature.

The range of values of the threshold coefficient of stress intensity ΔK_{th} was obtained provided that the crack did not spread for $4 \cdot 10^6$ cycles and did not exceed its growth rate $1 \cdot 10^9$ mm cycle⁻¹. At the same time, the transition zones in the upper part of the crack were eliminated and the load was reduced step by step by no more than 5%.

Results and discussion

The results of the study of the cyclic crack resistance of the blade material with asymmetry of the load cycle are presented $R = -1.0, 0.5$. The average values of the threshold coefficients of the stress intensity obtained ΔK_{th} with symmetric and asymmetric load cycles in the temperature range of the experiment are presented in Table 1.

The analysis of the given data shows that in the D1T alloy with asymmetry of the load cycle $R = 0$ and $R = 0.5$ crack resistance indicators in the temperature range $T = 293 \dots 333$ K change little, but increase significantly as the temperature drops to a negative value $T = 213$ K. A similar picture is observed with a decrease in temperature and with a symmetrical load cycle $R = -1$. In this case, the threshold stress intensity factors ΔK_{th} increase by 3-4 times, and the crack growth rate slows down by 1-2 orders of magnitude. As for the influence of the asymmetry of the load cycle, it reduces the threshold stress intensity factors ΔK_{th} by 1.5-2.5 times compared to a symmetrical load cycle at the same values of the studied temperatures over the entire range.

Consequently, a decrease in temperature leads to an increase in the crack resistance, and the D1T alloy has its minimum characteristics at a temperature of $T = 333$ K with an asymmetric load $R = 0.5$.

In the VT6S alloy over the entire range of temperatures under study with an asymmetry of the load cycle $R = -1.0; 0.5$ the crack resistance indices differ little. Here, the threshold stress intensity

factors ΔK_{th} are reduced by 10-20% compared to a symmetrical load cycle. The VT6S alloy also has the lowest crack resistance at a temperature $T = 333$ K with asymmetric load $R = 0.5$. Lowering the temperature to $T = 213$ K increases ΔK_{th} by 10%.

Table 1

Average values of threshold stress intensity factors ΔK_{th} of materials studied

Blade material	Loading cycle asymmetry R	Temperature T, K	$\Delta K_{th}, \text{MPa}\sqrt{\text{m}}$
Alloy D1T	-1	213	8.11
		293	2.77
		333	2.08
	0	213	5.68
		293	1.49
		333	1.39
	0,5	213	4.71
		293	1.12
		333	1.09
Alloy VT6S	-1	213	3.88
		293	3.84
		333	3.83
	0	213	3.52
		293	3.46
		333	3.43
	0,5	213	3.48
		293	3.11
		333	3.11

Compared to the D1T alloy, the VT6S titanium alloy has lower crack resistance at negative temperatures. $T = 213$ K for all values of asymmetry $R = -1, 0; 0.5$, but several times higher in the range of positive temperatures $T = 293 \dots 333$ K.

Thus, the studies of D1T and VT6S alloys at the design stage make it possible to establish certain criteria for the temperature conditions of operation of wind wheel blades. Thus, the blades made of aluminum alloy D1T should be used in cold climates with low temperatures, and the blades made of titanium alloy VT6S - in climates with medium and high temperatures.

Conclusions

According to the above method, the characteristics of cyclic crack resistance of D1T and VT6S alloys for wind wheel rotor blades were studied with the loading cycle asymmetry $R = -1.0; 0.5$ and the corresponding temperature indicators $T = 213$ K, 293 K, 333 K. As a result of the research, it was found that the VT6S titanium alloy is no longer sensitive to the range of temperatures under study and the asymmetry of the load cycle. Despite the lower values of the threshold stress intensity factors of the VT6S alloy at a negative temperature $T = 213$ K, these indicators are several times higher than the similar indicators of the D1T alloy at positive temperatures. These studies allow us to give preliminary recommendations on the choice of material for rotor blades of the wind wheel at the design stage, depending on the temperature conditions of operation. Other performance criteria for design selection of wind wheel blade materials require further research.

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