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Dynamic behavior of power transmission line supports under wind influence

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Abstract. In this article, we give experimental research on the dynamic behavior of steel supports of overhead power lines (OHPL) under the action of wind loads. The methodology and scheme of the experiment were created in two stages on the corner dead-end and intermediate supports of OHPL 220 kV “TPP Zmiev – Zalyutino”. In the first stage, excitation of the support’s oscillations was achieved using wind exposure; in the second stage, there were recorded free oscillations of the system “support – current wires”, which were created by means of handmade resonance. There are presented graphs of stress variations in the structural elements of tower lattice supports under wind action along and across the OHPL. There were experimentally determined basic natural frequencies of steel supports, which are shown on the damping graphs of free oscillations. Analysis of the obtained spectra of longitudinal velocity wind pulsations allowed conclusions about the stationary nature of wind flow. There is a determination of the necessity of the frequency detuning of OHPL support from the natural frequency of 2.2 Hz because external action with the given frequency is possible at the current wire breakage in one of the phases. The first three natural frequencies of oscillations for overhead line support were determined experimentally. Frequencies below 0.75 Hz are associated with the effect of wind on current wires. Analysis of the results made it possible to clarify that the wind at angle of 90° to the overhead line route not only exerts maximum static pressure but is also almost twice as susceptible to the considered “support – wires” system in dynamics. The presented methodology makes it possible to study the dynamic properties and study the response of structures to wind influences not only of overhead line supports but also of wind power installations and antenna supports of radio relays and cellular communications.

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1. *Introduction*

Overhead power lines (OHPL) are characterized by a significant variation not only in structural forms but also in geometric parameters, such as the length of the spans, the difference in the marks of the foundations, various sag arrows, etc. [1–3]. Moreover, as a rule, even on the same line, it is almost impossible to find building structures with overhead line supports with exactly the same static design loads. The spectrum of dynamic impacts is much wider, and the latter not only have a significant impact on the stress-strain state of metal structures, such as towers and masts, but also lead to fatigue damage, which is currently quite difficult to predict due to a significant number of variable factors [4–6].

That is why it is necessary not only to improve the principles of monitoring and observing the behaviour of structures in the wind flow but also to develop simple ways to take into account the dynamic component under the action of climatic and emergency loads, which by their nature are dynamic phenomena.

Improving OHPL supports by increasing their reliability and durability through design using numerical methods, including taking into account the dynamic nature of wind loads on the structure of supports and current-carrying wires is an urgent task today.

The research object is a single-column free-standing lattice support of OHPL.

OHPL is a complex engineering structure, in which flexible elements (wires and cables) work together with rigid supports, and at the same time, the entire network is prestressed and exposed to dynamic phenomena [7].

In [8] is noted that when determining the maximum response of support structures to impulsive impacts attenuation is not as important as for harmonic loads. In this case, the maximum value of the ground reaction is achieved in a very short period of time [9]. The highest values of dynamic coefficients are observed under the action of a "rectangular" pulse [10].

Work [11] sets out the basic principles of dynamic analysis of transition tower supports for OHPL. In this work is noted that is possible to take into account resistance forces when using method of decomposing solutions of oscillatory motion into their own modes of vibration by introducing them into decayed solution. This technique allows one to significantly simplify the solution of equations, however, the presence of dampers and dissimilar materials in design leads to errors in solutions obtained in this way.

Works [12–15] also noted the effectiveness of using numerical integration of the system "support – wires" motion equations under complex form of disturbance.

Solving dynamic problems is usually much more difficult than solving similar problems of static analysis. There is a widely used rule of thumb states that for system with n dynamic degrees of freedom approximately $n/2$ of the first own frequencies and their corresponding own mode shapes can be reliably obtained [16].

The simplest calculation algorithm aimed at using a one-dimensional oscillatory system, such as a cantilever rod, as a construction model is given in [17].

Thus, based on of literary sources analysis, there is a lack of information on the nature of propagation of disturbances from wind loads in time and along the span and have not been studied the shape of pulse and its characteristics in support sections of wires and cables.

Therefore, is necessary not only to revise the existing principles of monitoring and observing the behavior of structures in wind flow but also to develop simple ways to take into account the dynamic component under wind action, ice and emergency loads, which by their nature are dynamic phenomena.

The research purpose is to study the magnitudes and shapes of pulses on anchor and intermediate supports of overhead lines under wind load action taking into account the supporting influence of current-carrying wires and lightning protection cables.

The goal is achieved by solving the following tasks:

1. Experimentally to determine the own vibration frequencies for OHPL supports to further clarify the influence of dynamic characteristics on the supports design models together with current-carrying wires and cables.
2. To determine the main modes of vibration for support structures that describe mechanical properties of "support – wires" system under action of dynamic wind loads.
3. To analyze stresses in structural elements of supports under dynamic influence depending on wind gusts at different speeds.
4. To analyze the influence of wind gust duration on the periods of own vibration frequencies for support structures.

2. Materials and Methods

2.1. Experimental Research Methodology

The purpose of these experimental studies was to study the dynamic properties of tower-type supports in the "support – wires" system and to determine the reaction of these systems to wind impacts.

The anchor-angular support No. 57 (Fig. 1) and intermediate support No. 72 (Fig. 2) belong to the 220 kV OHPL “TPP Zmiev – Zalyutino”. The brand of the anchor-angle support is U-38; the brand of the intermediate support is PBG-4 of the “barrel” type with blind clips.

Figure 1. General view of the anchor-corner support of a 220 kV OHPL.

Figure 2. General view of the intermediate support of a 220 kV OHPL.

The supports are located in rural areas and on arable land in the Donetsk region. In accordance with paragraph 2.5.45 [7, 8], terrain type II. The orientation of the line at this location north-northwest – south-southeast (NNW–SSE). To the south of the experimental site, there was a forest belt at a distance of 0.7 km; from the other sides, at a distance of more than 3 km, there were no significant obstacles causing changes in the wind flow. The terrain of the site has a slight slope of 0.50 in the direction of north-northeast (NNE).

During a full-scale inspection, corrosion wear of the steel structures of the supports was revealed, which for belts and inclined braces was 0.6–0.8 mm, and for horizontal struts located up to the level of the lower traverse, 0.6–1 mm. Corrosion damage to bolted connection packages was also recorded. There was no development of crevice corrosion.

In preparation for the experimental studies, calibration tests of primary converters, in particular strain gauges and thermo-anemometric converters (TAPT), were carried out. After calibration and selection of the experiment location, the sensors were installed on the support structure. Load cells were attached to the belts and braces of the support zone on the belts of the lower traverse. In the cross section, three strain gauges were installed (on the corner feathers and on the rim) parallel to the axis of the corner with an indentation of 10 mm in order to avoid the influence of the edge effect. When the load cells were glued together, the wind speed was recorded. When the wind speed was exceeded by a gust of 2 m/s during the process of load cell labelling and glue polymerization, the load cells were discarded and the process was repeated. The response of the structure was also measured using vibration velocity meters of the VEGIK type installed at the level of the upper traverse in mutually perpendicular directions.

To monitor the incoming air flow at the top of the support so as to exclude shading of the sensors by structural elements, a wind speed meter (thermo-anemometer) and a wind direction meter (rumbometer) were installed. The second thermo-anemometer was installed at a height of 10 m on a horizontal bar made of a corner profile with a length of 750 mm, located at an angle of 45° to the face of the support.

During the experiment, when the wind direction changed in such a way that the angle between the bar of the thermo-anemometer and the incoming flow became less than 90°, the thermo-anemometer was moved to the opposite belt.

As an autonomous power source, a gasoline alternator was used, generated by a voltage of 220 V and a power of 1 kW/h. To reduce the level of noise and interference from the voltage transmitted by the OHPL, the monitoring system, the personal computer, and the generator were grounded.

During the experiment, the system was located in a passenger car. The scheme of the experiment is shown in Fig. 3.

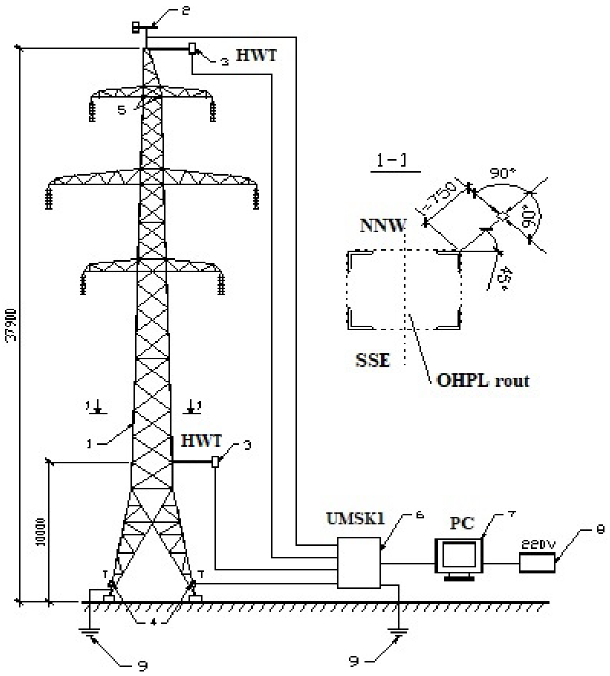

Figure 3. The experimental research scheme: 1 – support PBG-4 type; 2 – rumbometer; 3 – hot-wire transducer (HWT); 4 – strain gauges; 5 – vibration sensor VEGIK; 6 – monitoring system "USMK-1"; 7 – personal computer; 8 – gasoline generator; 9 – ground loop.

The experiment was conducted in two stages. At the first stage, the excitation of vibrations of the structure was achieved with the help of wind; at the second stage, free vibrations of the system were recorded, which were created using manual resonance.

When conducting such studies, it is necessary to control not only the internal parameters of the structure (response) but also external influences, and measurements must be carried out synchronously with a sufficiently high frequency of polling of primary converters and the ability to collect a significant amount of statistical information [8, 9].

3. Results and Discussion

3.1. Experimental Research Results of Support Dynamic Behavior in Wind Flow

The first stage of the experiment was carried out for five days. In total, 57 hours of implementations of the output signals of the primary converters were recorded, of which 16 hours were selected for analysis. The survey of all primary converters was conducted at a frequency of 64 Hz.

In the course of the experiment, two wind directions: north-west (NW) and east-northeast (ENE) – were recorded. According to the results of wind speed measurements at altitudes of 10 m and 37.9 m, the following ratios of average wind flow velocities with an averaging interval of 1 hour were obtained: for the ENE direction, 1.52, and for the NW direction, 1.67. Norms [7] recommend a coefficient of 1.5 in this case. Thus, it can be concluded that the actual measured wind profile corresponds to the normative value.

Fig. 4 shows the characteristic realization of the wind speed in the NW direction. The average velocity with an averaging interval of 1 hour was 2.56 m/s, standard deviation (SD) – 0.788, and turbulence intensity I(t) – 0.307. For the wind in the NNE direction, the average speed was 3.42 m/s, SD – 0.584, I(t) – 0.171.

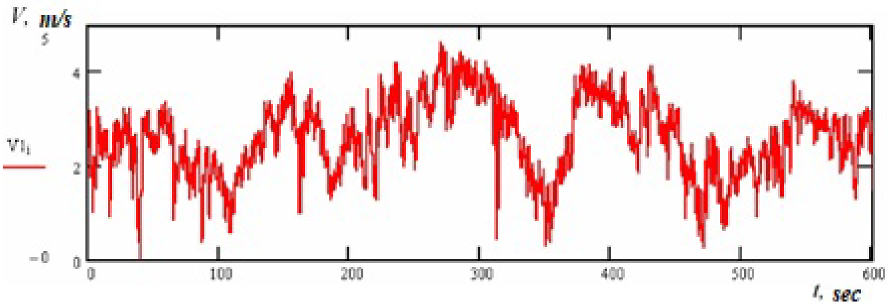

Figure 4. Typical realization of wind speed in the NW direction.

To determine the natural oscillation frequencies of the PBG-4 support, the obtained implementations of the random process were transformed using the fast Fourier transform [10, 11].

The obtained spectra of longitudinal wind velocity pulsations in the NW and ENE directions are shown in Fig. 5. The analysis of spectral densities allows us to conclude that the wind process is stationary, since these spectra correspond to classical representations [12, 13].

a b

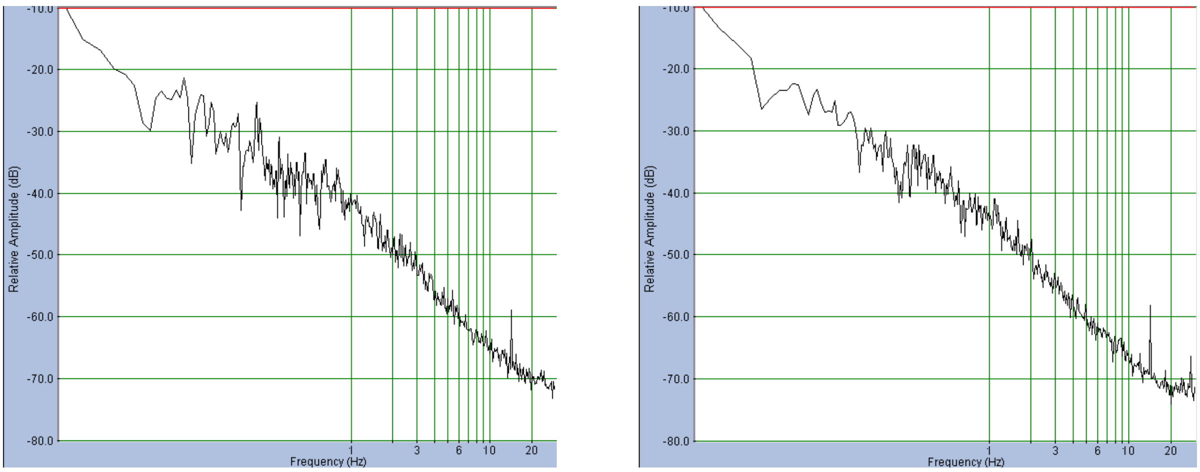

Figure 5. Spectral wind densities: a – NW; b – ENE.

Fig. 6 shows the characteristic implementations of the received signals. Fig. 6a shows graphs of stress changes in windward belts with wind perpendicular to the overhead line; Fig. 6b shows graphs of stress changes in diagonal belts with wind along the overhead line.

a b

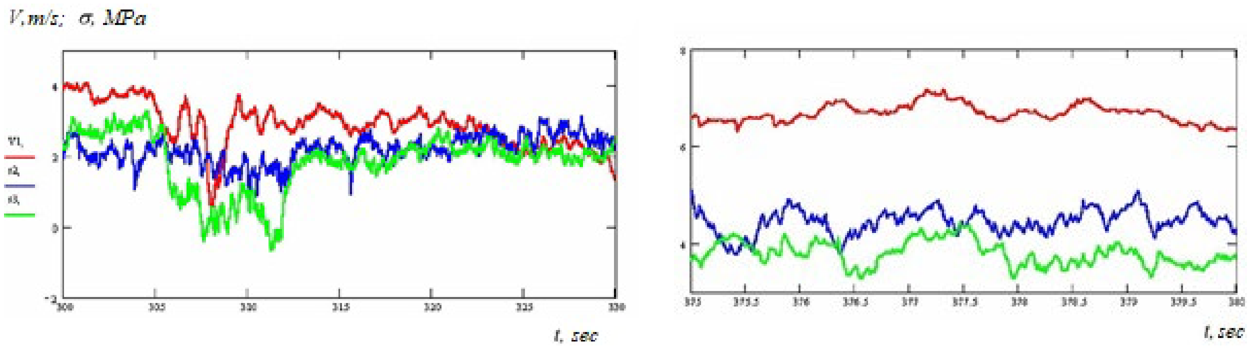

Figure 6. Typical implementations of received signals.

In Fig. 6, the graph ‘Vl’ characterizes the wind speed at an altitude of 10 m above the earth surface; graphs ‘s2’ and ‘s3’ characterize tensions in the belts, MPa.

To remove various noises, a simple coherence function was used [14, 15], showing the coincidence of the signal spectra at different frequencies. A similar function constructed for the windward face belts (Fig. 7) shows almost complete coincidence of the signal spectra. At the frequency bands of 0.85 to 7.5 Hz, the mutual coherence of the two processes exceeds 0.9. This indicates that the main frequencies of natural oscillations are located exactly in this interval. Coherence at lower frequencies also exceeds 0.9; however, this fact is due to the fact that at frequencies less than 0.1 Hz, systems whose first eigenvalues are in the range f ∈ [0,5; 8] Hz perceive the wind load as quasi-static [16].

a b

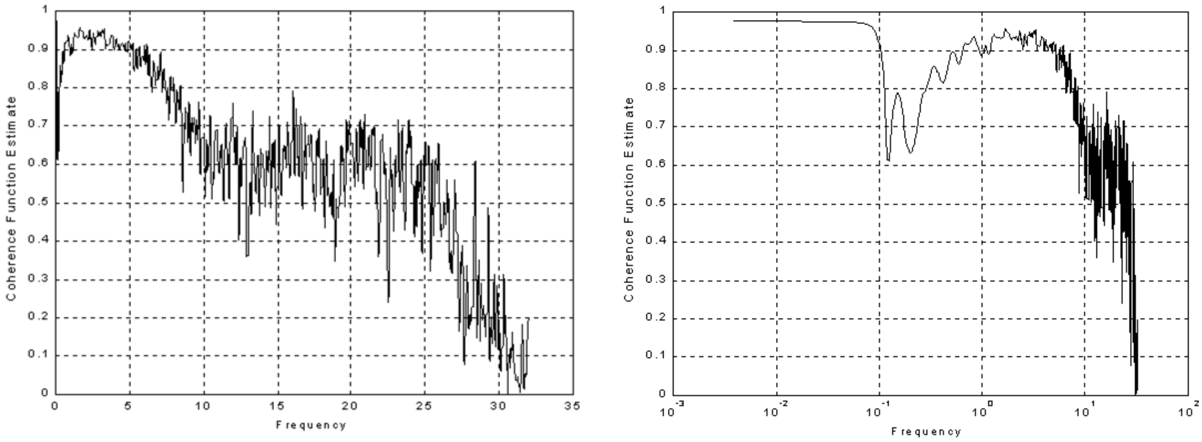

Figure 7. Coherence function of stress realizations in the belts of the windward face: a – linear scale; b – logarithmic scale.

A completely different picture can be obtained for the realizations of stresses in diagonally arranged belts, on which all the natural frequencies of oscillations manifest themselves, and the noise disappears due to some time delay in the reaction of opposite belts to wind action (Fig. 8).

a b

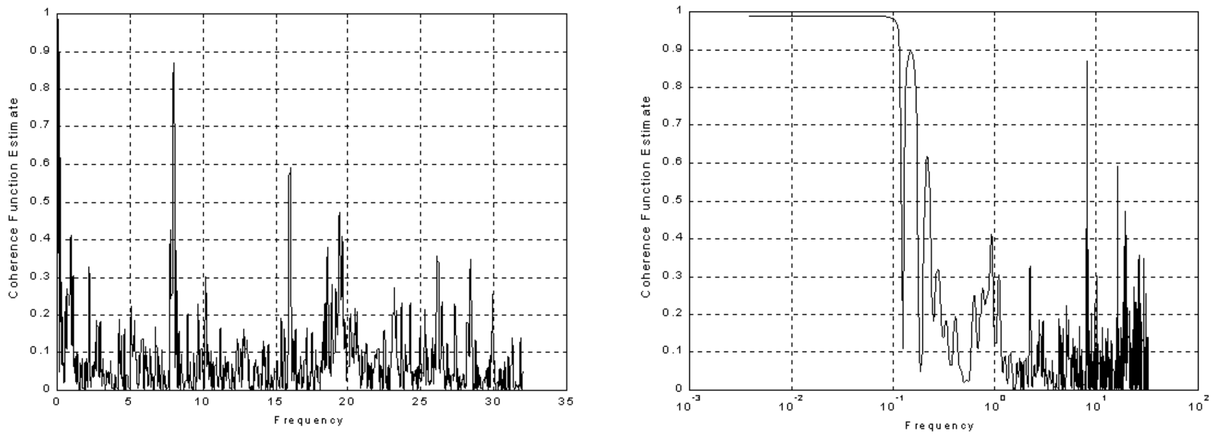

Figure 8. Coherence function of stress realizations in diagonal belts: a – linear scale; b – logarithmic scale.

The analysis of Figs. 5–8 allowed us to establish the natural frequencies of vibrations in the support. The first natural frequency is 1.09 GHz, the second is 2.04 Hz, and the third is 7.98 Hz. Oscillation frequencies below 0.75 Hz on different spectra (Fig. 5) manifest themselves in different ways and are associated with the effect of wind on current-carrying wires.

To compare the spectra of wind speed signals and the response of the structure, graphs of the coherence function for the direction of the wind across the line were constructed (Fig. 9).

In general, the coherence of this process can be characterized as weak [14, 15]. Some peaks have been obtained in the eigen frequency region of the structure, but their magnitude is not significant.

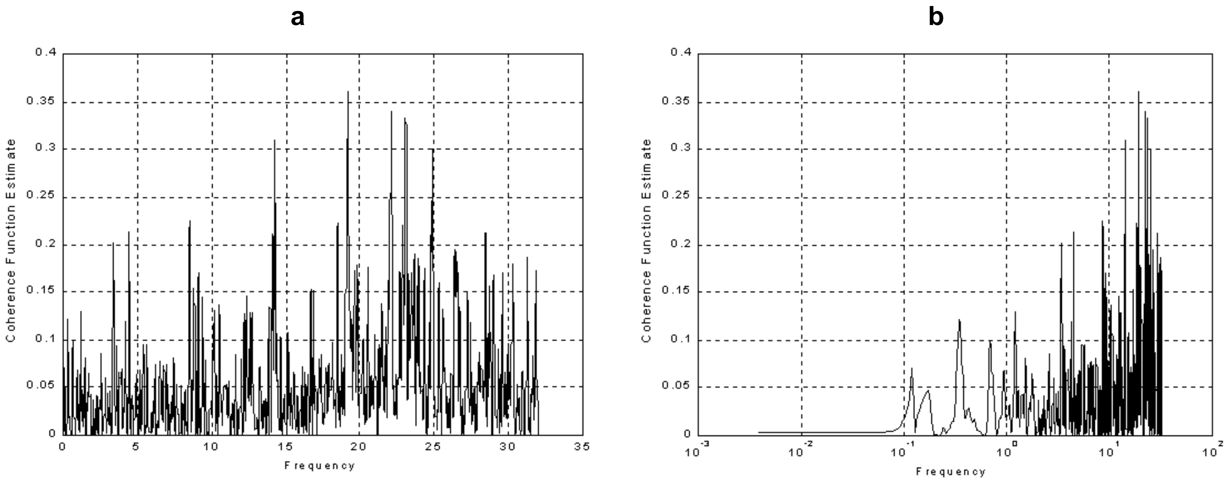

Figure 9. Coherence function of wind speed and structure response when the wind direction is across the line: a – linear scale; b – logarithmic scale.

3.2. Experimental Research Results of Free Oscillations for the "Support – Wire" System

The second stage of the experiment consisted of the study of free oscillations in the "support – wires" system. The excitation of vibrations was carried out by the method of manual resonance. The driving force was applied at the level of attachment of the cable-resistant to the trunk of the anchor-angular support U-38 m No. 57 perpendicular to the line.

A characteristic graph of the damped oscillations of the system for an anchor-angular support is shown in Fig. 10. The type of graph allows us to conclude that there are several frequencies, and in the first third, the vibrations of the support structure with a frequency of about 1 Hz are dominant, and in the rest of the implementation period, the vibrations of the wires with a frequency of 0.2 Hz are predominant. Moreover, the damping of vibrations occurs under the action of dry (Coulomb) friction [15, 18, 19].

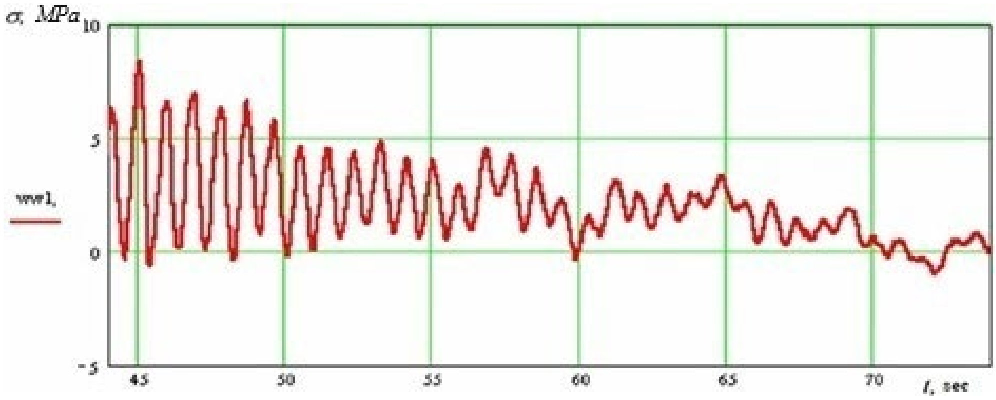

Figure 10. Graph of free damped vibrations for an "anchor support – wires" system.

To determine the average value of the logarithmic decrement of oscillations, the formula [20, 21] is used:

$$\delta = \frac{\ln\left(\frac{A_0}{A_n}\right)}{n}, \quad (1)$$

where A_0 and A_n are the initial and final amplitudes separated by n periods of free, damped oscillations.

For this system, the logarithmic decrement of oscillations obtained in this way is 0/191, with a variance of $4*10^{-4}$.

The coefficient of internal friction of the overhead line support structure is equal to (2) [20, 22, 24]:

$$\xi = \frac{\delta}{\pi} = 0.04. \quad (2)$$

The transformation of signal implementations using fast Fourier transform (FFT) allowed us to construct spectral dependences of the oscillatory process (Fig. 11). The natural frequencies obtained as a result of the first and second stages agree quite well.

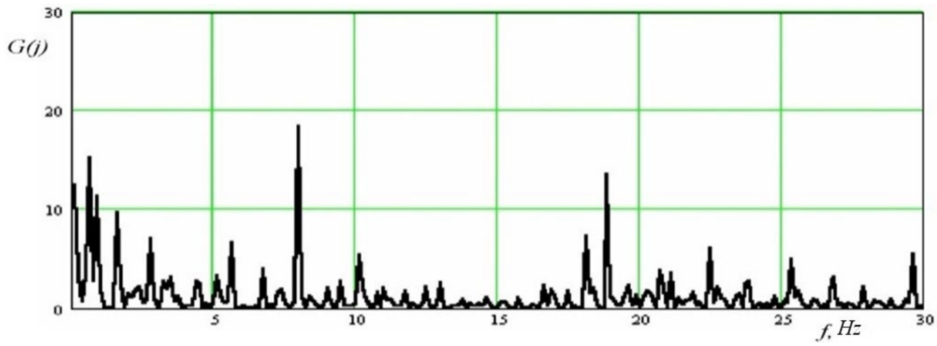

Figure 11. Spectral density of vibrations for an "anchor support – wires" system with freely damped oscillations.

Approbation of this technique was also carried out on the intermediate support PBG-4 No. 72 with blind clamps belonging to the 220 kV OHPL "TPP Zmiev – Zalyutino".

A characteristic graph of the attenuation of free oscillations is shown in Fig. 12, and the spectral density constructed according to this implementation is shown in Fig. 13, in which the dominant first natural frequency equal to 2.37 Hz is clearly visible. Moreover, this frequency was maintained when the direction of the driving force changed along and perpendicular to the overhead line axis. The logarithmic decrement of vibration damping in this case is 0.049, and the coefficient of internal friction of the structure is 0.016.

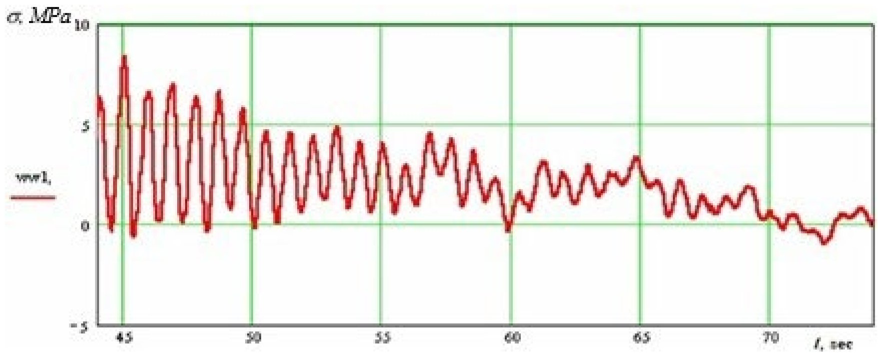

Figure 12. Graph of free damped oscillations for an "intermediate support – wires" system.

The amplitude-frequency characteristics of the system were obtained using the expressions (3) [21–23, 25]:

$$A = \frac{1}{\sqrt{\left(\left(1 - \left(\frac{F_p}{F_c}\right)^2\right) + \left(2 \cdot \delta \cdot \left(\frac{F_p}{F_c}\right)^2\right)\right)}}, \quad (3)$$

where F_p is the frequency of forced oscillations and F_c is the frequency of natural oscillations.

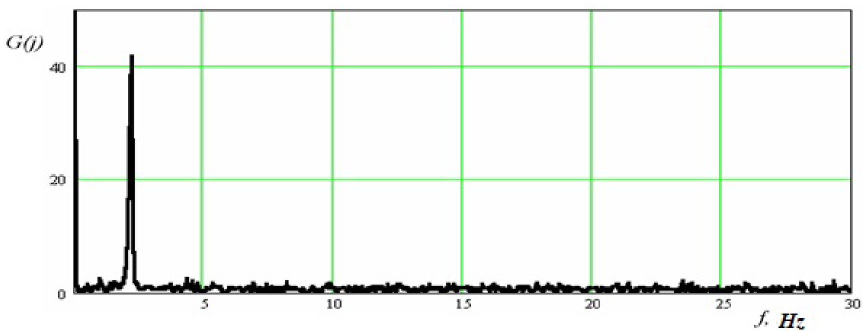

Figure 13. Spectral density of oscillations of an "intermediate support – wires" system with freely damped oscillations.

Thus, if the frequencies of external influence and the natural frequencies of the structure coincide, the dynamic coefficient can be 2.61 for the anchor-angular support U-38 m and 3.99 for the immediate support PBG-4 (Fig. 14).

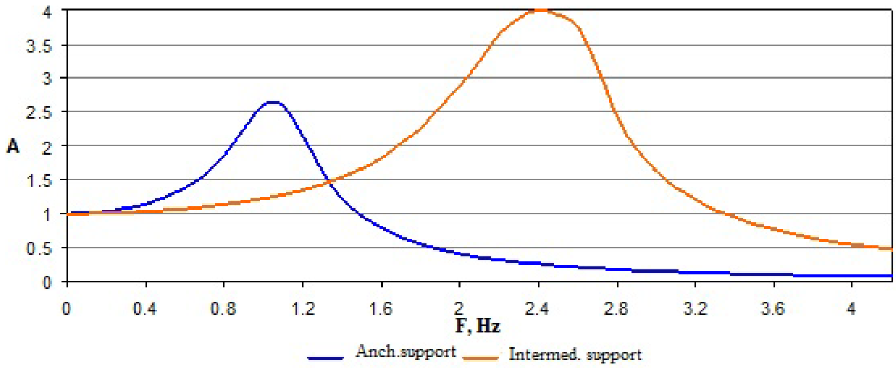

Figure 14. Amplitude-frequency characteristics of supports.

4. Conclusions

1. The first three natural oscillation frequencies of the OHPL support have been experimentally determined. Frequencies below 0.75 Hz are associated with the effect of wind on the current-carrying wires.
2. The analysis of the results made it possible to clarify that the wind at an angle of 90° to the overhead line route exerts not only the maximum static pressure but is also almost twice as susceptible to the considered "support – wires" system in dynamics.
3. As a result of experimental studies, the need for frequency detuning of the support structure from the natural frequency of 2.2 Hz has been established, since an external effect with this frequency is possible when a current-carrying wire breaks in one of the phases.
4. The presented technique makes it possible to study the dynamic properties and investigate the reactions of structures to wind impacts, not only of overhead line poles but also of wind power poles and antenna poles of radio relays and cellular communication.

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