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VIBRATIONAL STRESSES IN THE LAST-STAGE BLADES OF A POWERFUL STEAM TURBINE UNDER KINEMATIC EXCITATION OF OSCILLATIONS. PART 2. INVESTIGATION OF SYSTEM WITH CYCLIC SYMMETRY VIOLATIONS

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The influence of kinematic excitation of vibrations on vibration stress in a disk–blade system with a violation of cyclic symmetry when one blade is damaged is evaluated. To assess the trouble-free operation, it is relevant to determine their stress state when the blade shape changes due to erosion damage. The results of calculations of the maximum stresses in the blades under power and kinematic excitation of oscillations are presented. The three-dimensional finite element models of the disk–blade system and the corresponding mathematical software are used to determine the parameters of stationary vibrations and blade stresses. The force effect of a steam flow with a frequency of 2100 Hz (the number of guide blades is 42) and kinematic excitation when the center of the disk moves along an elliptical trajectory in its plane with a frequency of 50 Hz, which is caused by rotor vibration in sliding bearings in stationary operating conditions, is taken into account. The load from the steam flow on each blade was set to be linearly variable from zero at the root of the blades to 1 and 5 kPa at the periphery and for a uniformly distributed 2.5 kPa along their length, acting normally at the points of the blade working surfaces. It is assumed that the physical and mechanical properties of the damaged blade material are preserved after repair and surface treatment. The change in the maximum equivalent stresses in the impeller blades for different loading conditions is determined. The amplitude-frequency characteristics for the maximum stresses in the region of rotational speeds and the action of the load on the blades are given. The results are compared for the system with and without kinematic excitation of oscillations. The studies confirmed the practicality of considering the influence of kinematic excitation when assessing the stress state of the last stage blades of a powerful steam turbine.

Keywords: cyclic symmetry violation, forced oscillations, vibration stress, three-dimensional finite element model, amplitude-frequency characteristics, restorative repair.

Introduction. Blade systems of powerful steam turbines are designed to be cyclically symmetrical. During their manufacture, technological deviations are possible that lead to a violation of the cyclic symmetry of the system, although appropriate control methods are used in practice. One of the possible ways to assess the cyclic symmetry violation is to compare the natural vibration frequencies of the blades on the disk with the nominal value.

According to the practice of operating powerful steam turbines [1], the blades of the last stages operate under the influence of a low-potential wet steam environment (at the inlet edges in the upper parts of the blades and the outlet edges in the lower parts) often show damage that significantly affects the reliability of their operation. This leads to a violation of the system's cyclic symmetry. If it is possible to perform repair work, it is advisable to process all blades similarly so that the cyclic symmetry of the disk–blade system is not disturbed or to replace damaged blades. The peculiarities of the formation of free and forced oscillations of flaked steam turbine disks with a disorder of the vibration

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frequencies of the blades of the last stages of steam turbines have been considered in many works, particularly in [2–6]. For example, the influence of the blades' technological/geometric (directional) frequency difference on their aerodynamic stability was studied in [7–9]. In [10], the influence of the dispersion of energy dissipation characteristics on the formation of vibrations of flaked disks was studied.

The effect of damage and uniform machining of the lower parts of the blades at the outlet edges on the amplitude-frequency characteristics of a cyclic-symmetric disk–blade system of a powerful steam turbine was considered in [11]. It was found that restorative machining in these parts of the blades can be performed so that the chord in the machining area is not less than 150 mm. At smaller values of the chord in the blades, a significant increase in the maximum equivalent stresses is observed during their oscillations [12, 13]. The nature of the change and distribution of the maximum equivalent stresses in a system with a violation of cyclic symmetry during the processing of one damaged blade was considered earlier [14]. It was shown that in such a system, a significant increase in the maximum equivalent stresses in individual blades is possible compared to the stresses in the blades of a cyclicly symmetric system.

Paper [11] considered the influence of kinematic excitation on the maximum equivalent stresses of the blades of a cyclicly symmetrical disk–blade system of the last stage of a powerful steam turbine. This work aims to determine the change in the maximum stresses in the system with a violation of cyclic symmetry under different forms of blade loading from the steam flow, which correspond to the reduced and rated capacities of the unit with linearly variable and evenly distributed blade loading. The influence of kinematic excitation on blade stresses under violations of the cyclic symmetry of the system with the presence of one damaged blade in the lower third is determined.

1. Blade Stresses of a Cyclic Asymmetric System at the Rotor Rotation Frequency. Calculated studies of the maximum equivalent stresses in the blades of the disk–blade system were performed in the frequency range of 20–60 Hz. In this range, two frequency regions were recorded – without and with kinematic excitation – in which a sharp increase in the maximum stresses in all blades was observed (respectively, within 32–58.5 Hz and 27–51.5 Hz), including the damaged blade (Fig. 1).

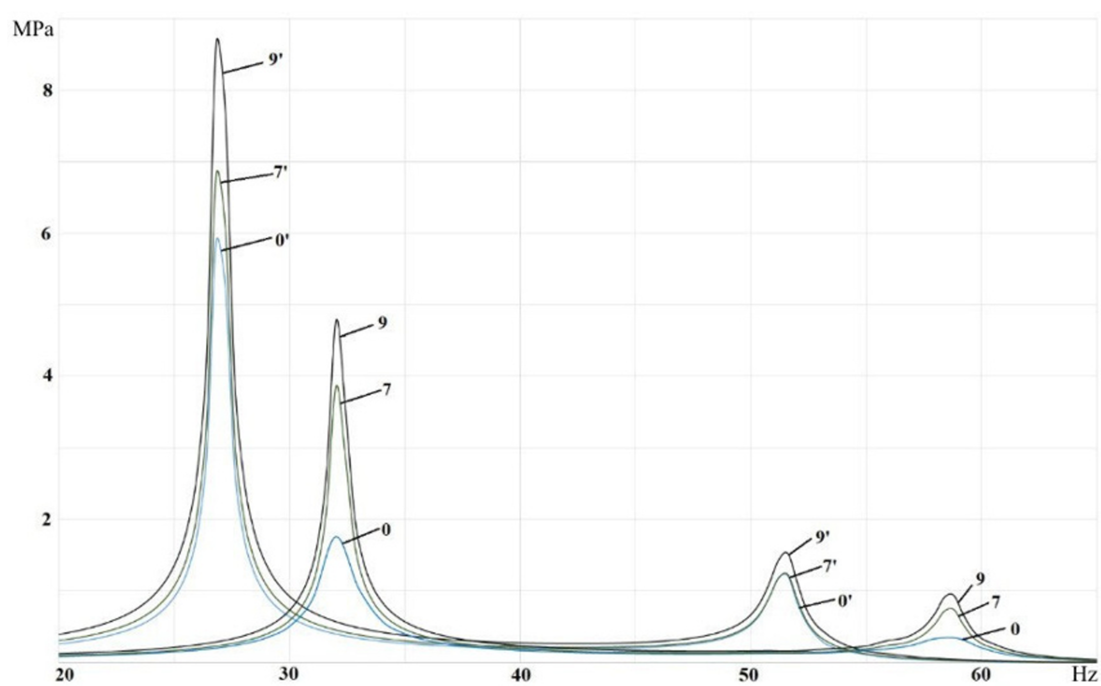


Fig. 1. Amplitude-frequency characteristics of the maximum blade stresses without kinematic excitation (*0*, *7*, and *9*) and with kinematic excitation (*0′*, *7′*, and *9′*): *0* and *0′* – damaged blade, *7*, *7′* and *9*, *9′* – blades to the left of the damaged blade.

In the following, we will consider frequency regions around 50 and 2100 Hz, since the first is the rotor speed during turbine unit operation, and the second corresponds to the excitation frequency of vibrations from 42 guide vanes.

From comparing the results of calculations of the maximum equivalent stresses taking into account the kinematic excitation of the oscillations of the disk–blade system when the blades are loaded from 0 to 1 kPa in the frequency range of 48–55 Hz, the following can be noted [15]. According to the general similarity of the curves characterizing the maximum stresses in the blades (to the left and right of the damaged one), there are some differences in the results obtained. There are unequal values of stresses in terms of magnitude and, accordingly, the shape of the amplitude-frequency curves for maximum stresses. On average, the stresses in the blades to the right of the damaged blade are higher than those to the left. At the same time, this difference in the curves characterizing the dependence of the maximum stresses in the blades on frequency can be considered insignificant. The relative proximity of the blade to the damaged blade has a much greater influence on the maximum stresses in the blades. In some blades, these stresses are higher than those in the damaged blade; in others, they are much lower. These changes can be considered significant given the geometric similarity of all blades (except for the damaged one). The main reason for such changes in the maximum equivalent stresses in the blades can be considered a violation of the cyclic symmetry of the system in the presence of one damaged blade.

Considering that the kinematic excitation of the disk–blade system has a different effect on the dynamic properties of the blades compared to all damaged and equally treated blades [14], except for one located to the left of the damaged one, where the stresses decrease. The maximum stresses in most blades increase significantly several times when the system is excited at an operating frequency of 50 Hz.

Note that the increase in maximum stresses in most blades is also because, under the influence of kinematic excitation, the disk–blade system is more pliable in the frequency range of 48–55 Hz. In this case, the maxima of the frequency characteristics are shifted to the region of lower frequencies (Fig. 1), and the peaks of maximum stresses increase. Thus, in particular, the second peak of the maximum stress increase approaches the kinematic excitation frequency of 50 Hz. Thus, the resonance properties of the disk–blade system with kinematic excitation are manifested under a conditional load from a steam flow with a frequency of 2100 Hz on the blades.

The change in the maximum equivalent stresses in the blades located to the left and right of the damaged blade in the region of the second resonant stress increase, the frequency for which is close to the system rotation frequency, was considered in [15]. According to the maximum stresses in the results obtained, several groups of blades can be distinguished with similar characteristics for some adjacent blades and those located one or two apart. Among the blades located to the left and right of the damaged one, a group of blades that have significantly higher peak stresses can be conditionally distinguished, which is associated with the resonant properties of the elastic system.

Comparing the results of the calculation of the maximum equivalent stresses in the blades at a frequency of 50 Hz with and without the influence of kinematic excitation under a conditional load distribution from 0 to 1 kPa on all blades at a frequency of 2100 Hz, the following can be noted.

At a rotor speed of 50 Hz, with the specified load of all blades without considering kinematic excitation, two areas of stress increase are observed – in the lower thirds of the blades and above them. Significant stresses occur in the lower thirds of 34 blades on the left and 36 on the right of the damaged blade (and in the damaged blade). In the remaining 21 blades, the higher stresses occur in the upper thirds (compared to those in the lower thirds). Still, they are significantly lower than the average value of the maximum stresses in all blades. For example, the maximum stresses in the lower thirds of the blades are 106 times higher than the corresponding stresses in the upper parts, and they are observed in the 16th blade on the left and 74 times in the 32nd blade to the right of the damaged one.

When taking into account the kinematic excitation with a frequency of 50 Hz, the maximum equivalent stresses in the lower thirds of the blades are greater than in the upper ones in all blades except for the 31st, on the left, and the 14th, on the right of the damaged one. At the same time, the maximum increase in stresses in the lower thirds compared to the upper thirds is more than ten times higher in the 30th blade on the left and 34 times higher in the 24th blade on the right of the damaged blade.

The highest maximum equivalent stresses under this loading are observed in the ninth blade on the left and in the 36th blade on the right of the damaged one, without and with consideration of kinematic excitation. When kinematic excitation is considered, the maximum equivalent stresses in the blade to the left of the damaged one increase 4.16 times, and in the 36th blade to the right, 3.84 times. The 15–20 blades located next to them (on the left and right) have smaller but significant maximum equivalent stresses in the lower thirds compared to other blades. On average, when kinematic excitation is considered, the maximum equivalent stresses in the blades increase several times. The largest increase due to the influence of kinematic excitation (41 times) is observed in the eighth blade, which is to the right of the damaged one. This is because, without kinematic excitation, this blade has the lowest values of maximum stresses (293 times lower than the maximum values in the ninth blade). This may be due to the proximity of the nodal line to this blade without kinematic excitation.

The above results show the results of estimating the maximum equivalent stresses in blades with a distributed load from zero at their roots to 1 kPa in the periphery, the equivalent of which corresponds to the operating mode with a several times reduced power of the unit. Next, we will consider the blade stress with a linearly varying load from 0 at the blade root to 5 kPa in their periphery. The equivalent of this load on the blades is close to the equivalent of the steam component at the rated power of the unit.

As with lower loads, the areas of maximum equivalent stresses at the specified blade loading occur in the lower thirds of the blades and above them. In this case, the maximum stress values without taking into account kinematic excitation are observed to the left of the damaged (zero) blade in the lower thirds – from the zero to the 28th, from the 35th to the 41st, and in the 45th and 46th. The maximum stresses occur in the upper thirds in the other blades to the left of the damaged blade.

The highest stresses in the lower thirds of the blades to the right of the damaged blade were obtained in blades from the damaged blade to the sixth blade, from the 20th blade to the 46th blade, and in blades 10 and 11. The maximum stresses were found in their upper thirds in the other blades to the right of the damaged blade.

It should be noted that, without considering kinematic excitation, the maximum stresses in the lower thirds of these blades are, on average, several times higher than those in the upper thirds. When assessing the service life of blades, the stresses in the lower thirds are crucial. As with blade loading from 0 to 1 kPa, the highest maximum equivalent stresses occur in the ninth blade, which is to the left of the damaged blade, and in the 36th blade, which is to the right.

Taking into account the kinematic excitation at a frequency of 50 Hz, the maximum equivalent stresses are observed in the lower thirds of all blades to the left and right of the damaged one, except for the 31st blade to the left of the damaged one, where they are located above the lower third of the blade. A significant increase in maximum stresses is observed in the group of blades from the fifth to the 19th blade to the left of the damaged blade (Fig. 2), from the 30th to the 39th blade to the right of the damaged blade, and in the damaged blade. Without kinematic excitation, the highest stresses with its consideration are observed in the ninth blade on the left and the 36th blade on the right of the damaged blade. When kinematic excitation is taken into account, the maximum equivalent stresses increase in the ninth blade by 3.96 times and in the 36th blade, to the right of the damaged one, by 3.65 times (Fig. 3). The largest increase in maximum stresses due to kinematic excitation among all the blades is observed in the ninth blade.

The calculated estimate of the maximum equivalent stresses at a frequency of 50 Hz with a uniformly distributed blade load of 2.5 kPa, which corresponds to the equivalent load at the rated power of the unit, shows the following. Without kinematic excitation, the maximum stresses in the upper thirds of the blades are higher than in the lower thirds, in 30 blades on the left and 14 blades on the right of the damaged one. Considering the kinematic excitation, the maximum stresses in the upper thirds are higher than in the lower thirds in 10 blades on the left and eight blades on the right of the damaged blade. However, these stresses are generally much lower than those in the lower thirds of the other blades, so they are not decisive in assessing the service life of blades of this degree.

The highest equivalent stresses are observed without and with kinematic excitation, as in the previous variants of blade loading, in the ninth blade on the left and the 36th blade on the right of the damaged one.

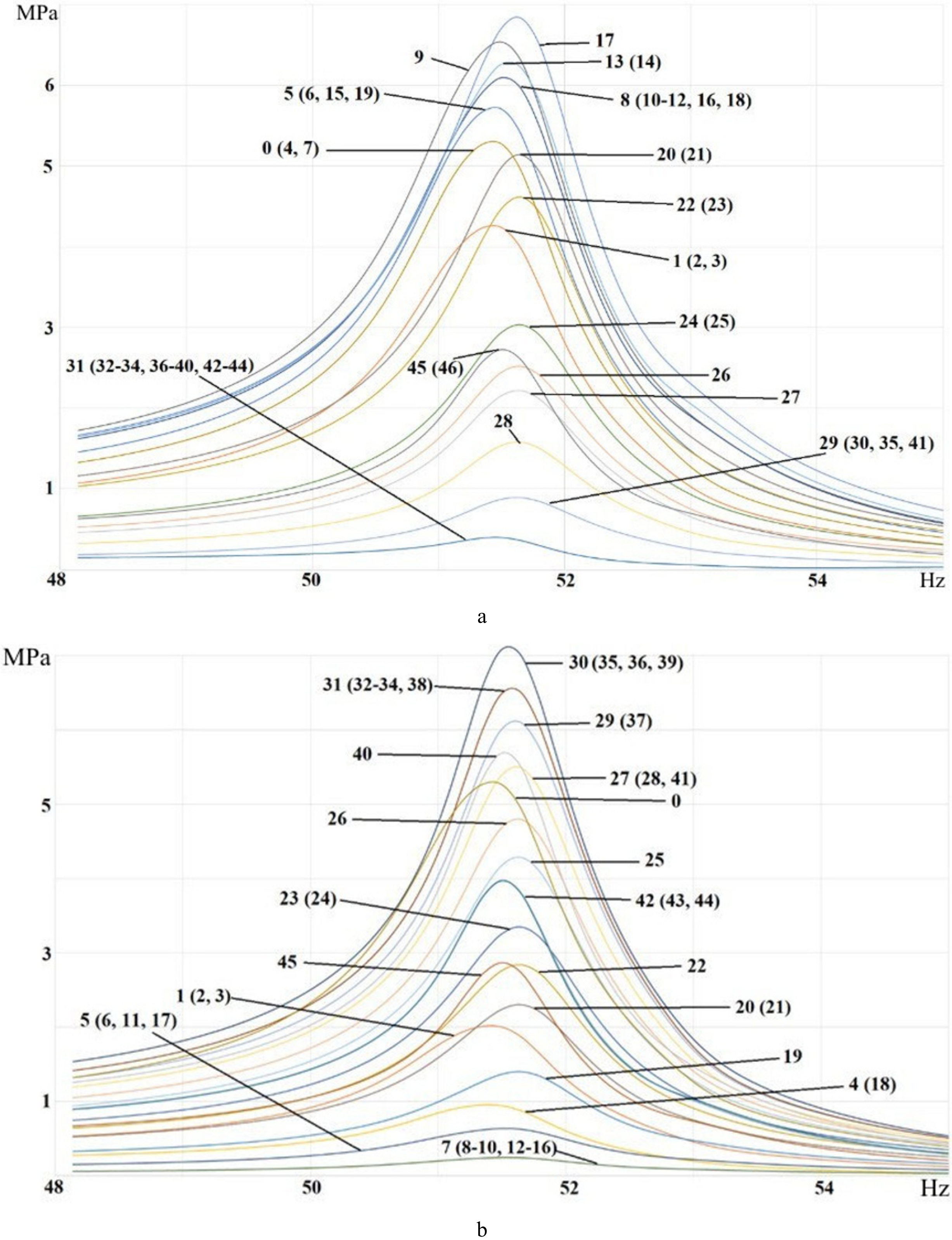
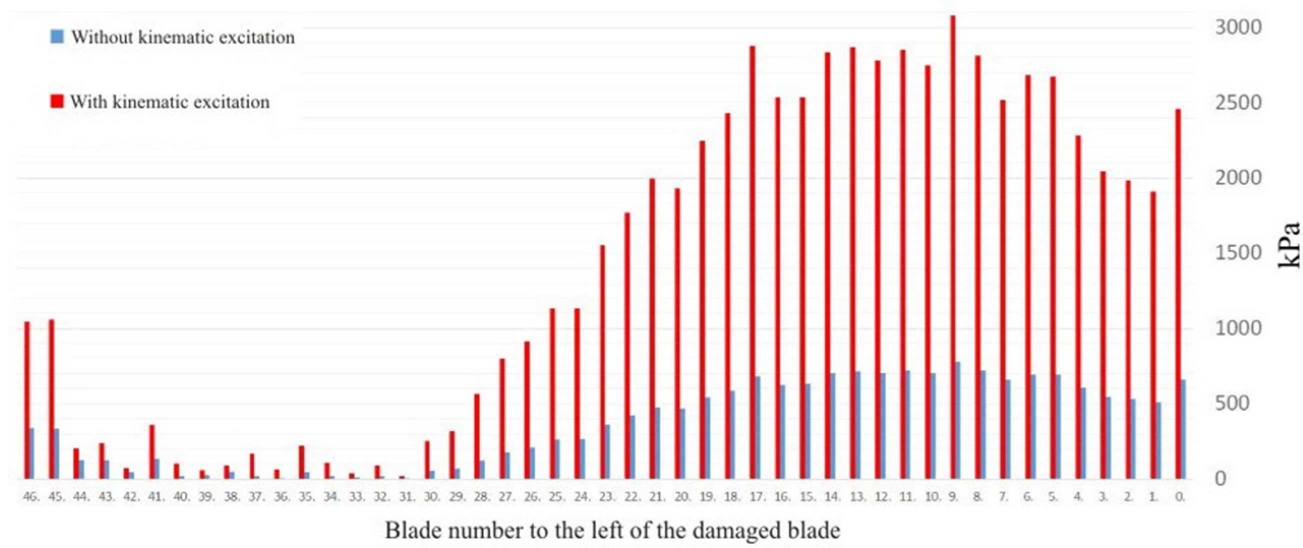


Fig. 2. Amplitude-frequency characteristics of the maximum blade stresses to the left (a) and right (b) of the damaged blade (the numbers on the curves correspond to the blade numbers) with kinematic excitation at a load from 0 at the root of the blades to 5 kPa at their periphery, in the range of 48–55 Hz.



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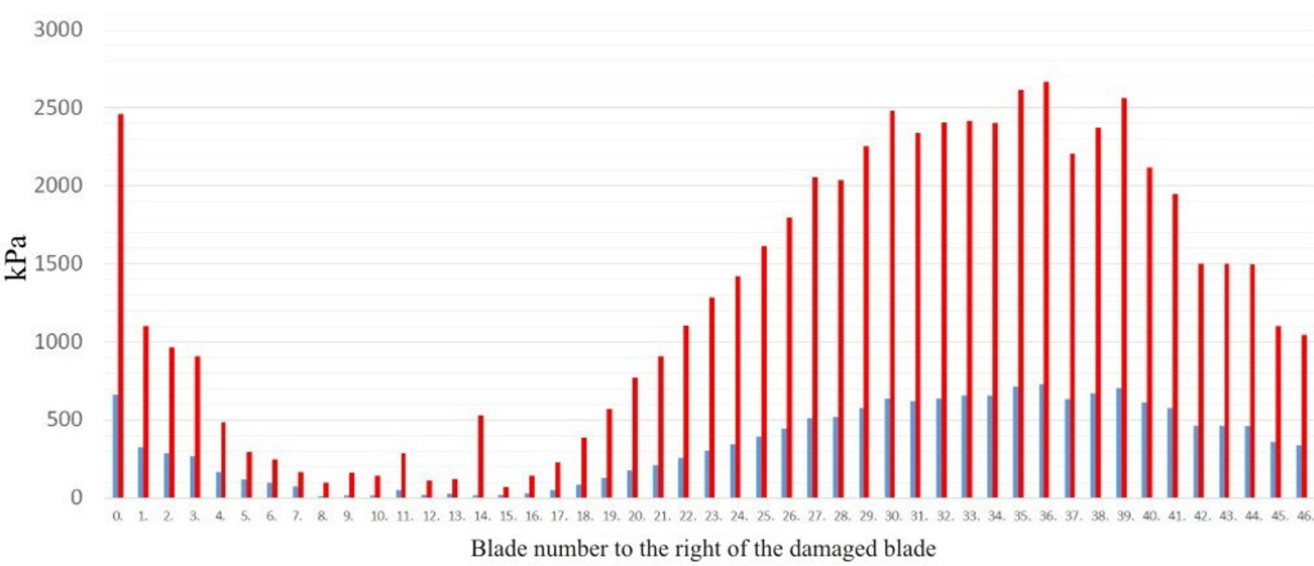

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Fig. 3. Stresses in the lower thirds of the blades on the left (a) and right (b) relative to the damaged one at a frequency of 50 Hz when loaded from 0 at the root to 5 kPa in the periphery.

When considering the kinematic excitation, the maximum stress values increase by 1.73 times in the ninth blade, which is to the left of the damaged one, and by 1.62 times in the 36th blade, which is to the right of the damaged one. In most of the other blades with lower stresses, the effect of kinematic excitation increases, but the maximum equivalent stresses are significantly lower than the stresses in the ninth and 36th blades, where the stresses are comparable when taking into account kinematic excitation (the difference is about 3%).

It should be noted that with the same value of the resulting force on the blades from the applied load, the maximum equivalent stresses under kinematic excitation increase with a linearly variable load from 0 to 5 kPa by 3.96 times and with a uniformly distributed 2.5 kPa over the blade trough by 1.73 times. The ratio of the maximum stresses in the ninth (36th) blade from a linearly variable load of up to 5 kPa and from a uniform 2.5 kPa is 4.9 times with kinematic excitation and 2.1 times without it. A change in the area of action of the equivalent for these variants can explain this. Therefore, to assess the stressed state of the blades when determining their service life, it is advisable to use the results for the variant of blade loading from 0 to 5 kPa, as possible during the unit's operation.

2. Blade Strain at the Frequency of Vibration Excitation by Steam Flow. The last stage's steam turbine's blades are oscillated by the steam flow entering through the lattice formed by 42 guide blades. This leads to periodic loading of the blades with a frequency of 2100 Hz and the kinematic excitation from the rotor with a frequency of 50 Hz. Therefore, assessing blade stresses near 2100 Hz and the stress data at 50 Hz is important.

Computational studies show that at a frequency of 2100 Hz, three areas of stress increase are observed in the blades, located in the lower, middle, and upper thirds of the blades. At the same time, in the middle third of the blades, the maximum equivalent stresses are less than the stresses in the lower and upper thirds. The stresses in the upper third of all blades are higher than those in the lower third, both with and without kinematic excitation. Therefore, in the following, the blade stresses will be considered mainly in the upper thirds. When the blades are loaded from zero to 1 kPa, the maximum stresses in the upper thirds of all blades are 21.5 times higher than those in the lower thirds. At the same time, in several adjacent blades (for example, from 12 to 28, which is to the left of the damaged one), the stress increase varies from 9 to 76 times, and on the right of the damaged one – from 10 to 510 times (from 17 to 35 blades) without kinematic excitation. When considering the kinematic excitation, the maximum equivalent stresses in the upper thirds of the blades are, on average, 13.6 times higher than those in the lower thirds. The maximum difference between the stresses in the upper and lower thirds occurs in the 24th scapula (more than 94 times), which is on the left, and in the 23rd scapula (55 times), which is on the right of the damaged one.

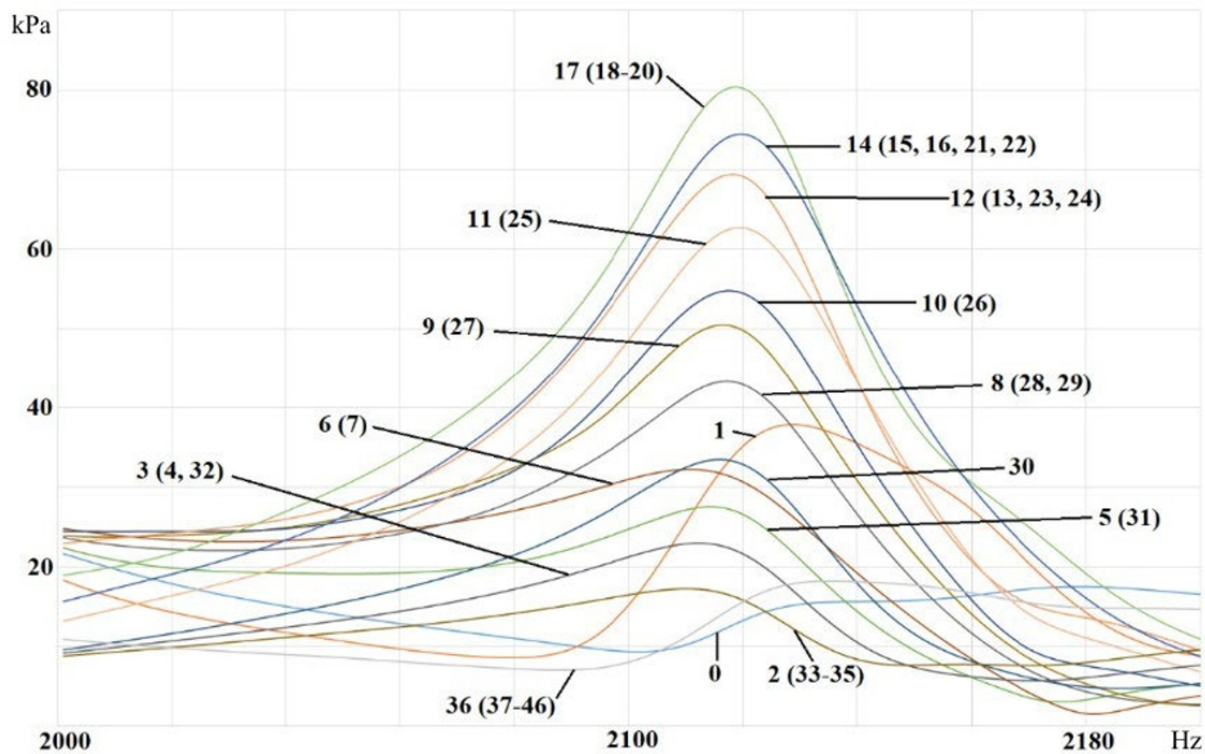
It should be noted that the highest maximum equivalent stresses in the upper thirds are observed in the 17th blade on the left and the 28th blade on the right of the damaged one, both without and with consideration of kinematic excitation. At the same time, the maximum stresses in these blades differ by 2–3%, and the increase in stresses with kinematic excitation is 13%.

Considering the kinematic excitation, the largest increase in the maximum equivalent stresses is 1.3 times in the damaged (zero) blade and 1.5 times in the 43rd blade, which is to the right of the damaged one. In general, an increase in vibration stress due to the influence of kinematic excitation (to the left and right of the damaged one) in 80 blades. In comparison, it decreased in the remaining twelve blades (in seven blades – by less than 5%, in five – by less than 12%).

It should be noted that the equivalent of the above load on the blades corresponds to a several-fold reduction in the unit's power from the nominal value.

Calculations at a linearly variable blade load from 0 at the root to 5 kPa at the periphery, the equivalent of which corresponds to the blade load at the rated power of the unit, showed that there are three areas of stress increase in the blades (as well as at a load several times lower). They are located in the blades' lower, middle, and upper thirds. As in the previous loading scenario, the highest stresses occur in the upper and the lowest in the middle thirds of all the blades.

Figure 4 shows the results of determining the maximum equivalent stresses in the blades in the 2000–2200 Hz frequency range, considering kinematic excitation. Note that for a significant number of blades (about 67%), these characteristics are similar to those shown in Fig. 2 (considering different scales along the coordinate axes). At the same time, there are significant differences like the change in the curves for other blades: the damaged one and the one next to it on the left, and the 14th blade to its right. For these blades, there is practically no resonant stress increase in the vicinity of 2120 Hz in this frequency region, as is the case for most other blades. By the nature of the curve change, one can judge the shift of the resonant stress increase to the frequency region below 2000 Hz. Such changes in stress are also observed in blades located near the opposite edge of the wheel diameter that passes through the damaged blade. To the left of the opposite edge of the nominal diameter, these changes occur in 11 blades, and to the right – in four blades. It should be noted that the above features of stresses changing with frequency occur in the same number of blades located near the opposite edges of the wheel diameter. The change in the maximum stresses with frequency in these blades is somewhat similar to that in a cyclic-symmetric system when considering kinematic excitation (these results were given earlier [11]).



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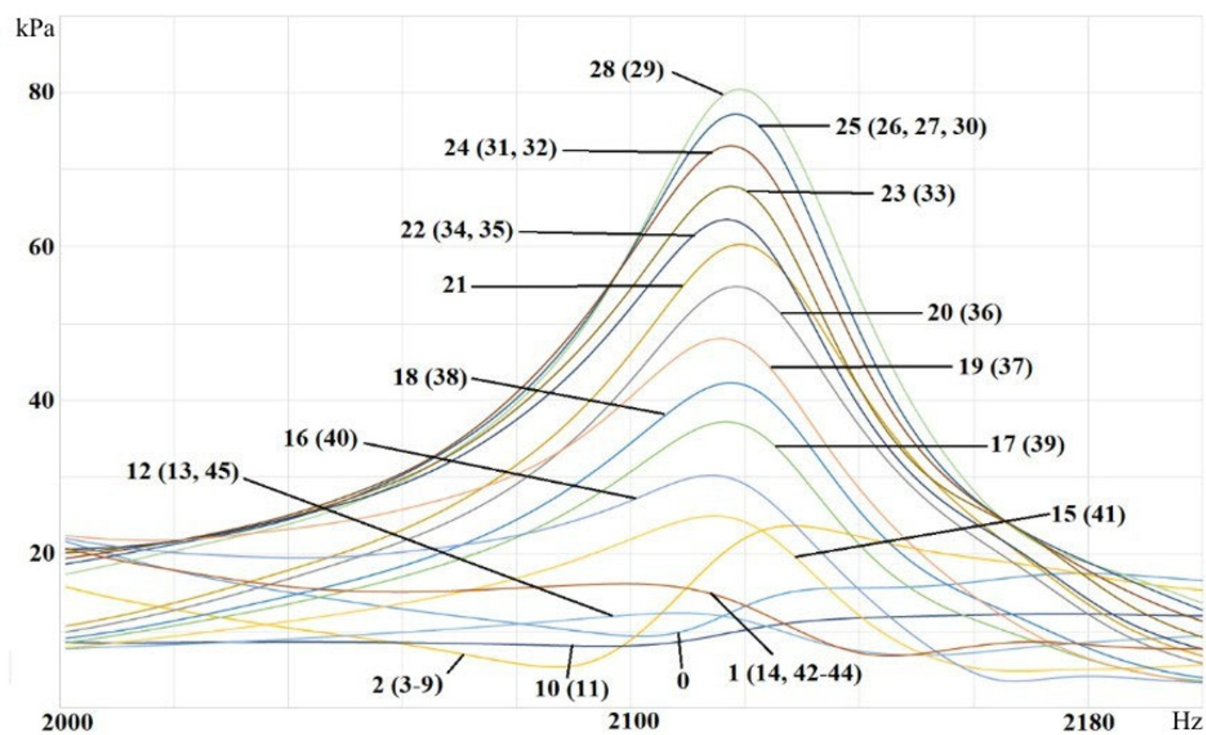

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Fig. 4. Amplitude-frequency characteristics of the maximum equivalent stresses of the blades to the left (a) and right (b) of the damaged one (the numbers on the curves correspond to the blade numbers) with kinematic excitation under a load from 0 at the root to 5 kPa at their periphery in the range of 2000–2200 Hz.

It should also be noted that the above-described pattern of changes in the amplitude-frequency characteristics of the maximum blade stresses under kinematic excitation was also obtained when the blades were loaded from 0 to 1 kPa. In 31 blades, no resonant stress increases in this frequency region were observed. There are 16 such blades on different sides of the diameter near the damaged blade and 15 on the opposite edge.

Without considering the kinematic excitation, the highest maximum stresses in the upper thirds of the blades, when loaded from 0 to 5 kPa, are observed in the 17th blade on the left and in the 28th blade on the right of the damaged one. In the 17th blade, these stresses are 2.3% higher than in the 28th (Fig. 5). Considering the kinematic excitation, the maximum stresses are also observed in the same blades. In the 17th blade, the maximum stresses are 2.5% higher than in the 28th, considering kinematic excitation.

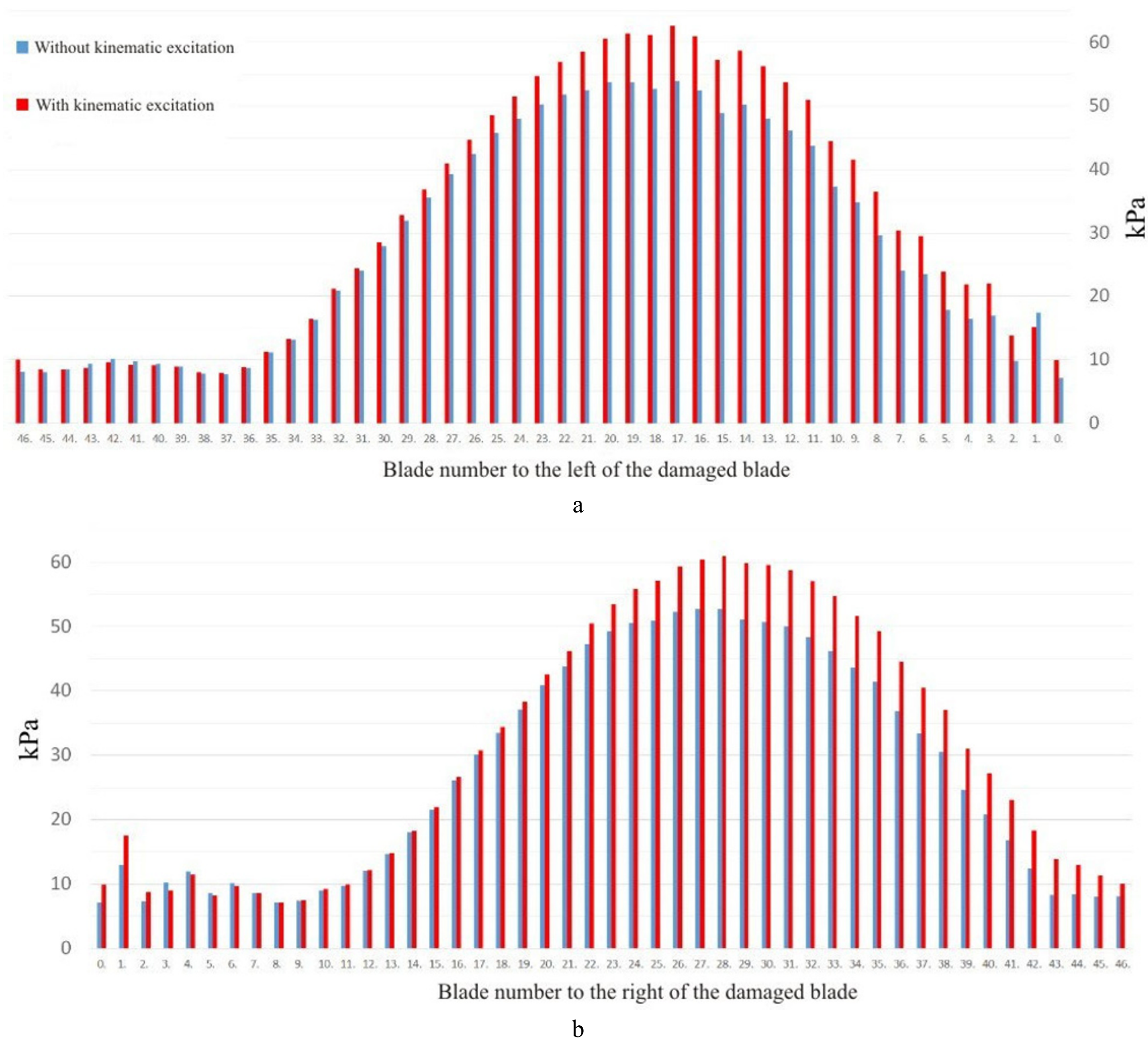

Fig. 5. Stresses in the upper thirds of the blades on the left (a) and right (b) relative to the damaged one at a frequency of 2100 Hz under a load from 0 at the root to 5 kPa in their periphery.

It should be noted that the maximum stresses in the lower third of the blades are observed under this loading variant in the third blade on the left and the 39th blade on the right of the damaged one. However, they are less than the highest values of the maximum equivalent stresses of the blades in their upper thirds to the left of the damaged blade by 4.8 times and to the right by 4.6 times without kinematic excitation and by 4.9 and 4.8 times with it.

The effect of kinematic excitation on the maximum equivalent stresses in the blades manifests itself in different ways: in some blades, the stresses increase, and in others, they decrease. The stresses decrease to the left of the damaged blade: in the first one – by 13%, and from the 39th to the 44th – from 1 to 6%, and to the right of the damaged blade: from the fourth to the seventh - from 1 to 3%, and in the third – by 12%.

In other blades, there is an increase in maximum stresses when kinematic excitation is taken into account. The largest increase is observed in the damaged blade – 1.4 times, to the left of it in the second – 1.4 times, in the fourth and fifth – 1.34 times. To the right of the damaged blade, the greatest increase in stresses was found in the following blades: in the first blade – 1.36 times, in the 40th blade – 1.3 times, in the 41st blade – 1.37 times, in the 42nd blade – 1.48 times, in the 43rd blade – 1.66 times, in the 44th blade – 1.54 times, in the 45th blade – 1.42 times. In most other blades, the stress increase varies from 1.1 to 1.3 times (Fig. 5).

The distribution of displacements at a frequency of 2100 Hz in a disk–blade system with a violation of cyclic symmetry is shown in Fig. 6. The results indicate the presence of circular nodal lines and three zones of stress increase, which are unevenly distributed between the blades of the considered system.

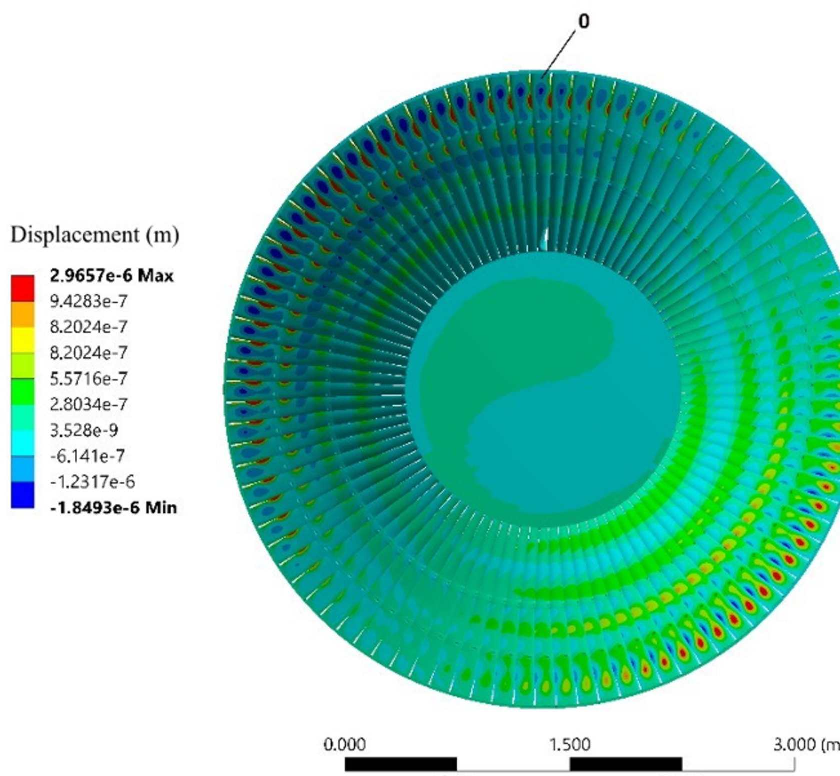

Fig. 6. Distribution of displacements along the rotational axis in a disk–blade system with one damaged blade at a frequency of 2100 Hz under a load from 0 at the root to 5 kPa in the periphery (zero corresponds to the damaged blade).

The above results were obtained when the blades were loaded from 0 at the root to 5 kPa at their periphery. This load equals the unit's rated power. Next, we consider the blade stress on their working surfaces at a uniformly distributed load of 2.5 kPa. With an almost identical equivalent to the linearly variable load, the moments of the distributed load differ in this case, which leads to a change in the blade stress.

Three areas of stress increase are observed under this load at a frequency of 2100 Hz. As in the previous two cases, they are localized along the blades' lower, middle, and upper parts along their length. The highest values of the maximum equivalent stresses occur in the upper thirds of the blades and the lowest in the middle ones. For example, the maximum values of stresses without taking into account kinematic excitation in the upper thirds are higher than in the lower ones in 11 blades (from 16 to 26) to the left of the damaged one by 10...43 times and in 15 blades to the right of the damaged one (from 18 to 32) by 10...76 times. The average values of the stresses in the upper thirds of the blades relative to the stresses in the lower thirds to the left of the damaged blade are close to 8.4 times, and to the right of it - up to 11.6 times. Without considering kinematic excitation, the highest maximum stresses are observed, as in the previous variants, in the 17th blade on the left and in the 28th blade on the right of the damaged one. These values differ by 3.4%.

Considering the kinematic excitation, the highest stresses occur in the 17th blade on the left and the 28th blade on the right of the damaged one. The stress in these blades increases by 1.25 and 1.22 times, respectively. In the damaged blade (zero), they increase by 1.62 times. At the same time, their greatest increase of 2.05, 1.79, and 1.78 times occurs in the 43rd, 44th, and 42nd blades, respectively. An increase of 1.5...1.62 times is observed in six more blades to the left and right of the zero blade. On average, the increase in stresses in all blades (except for four, where they decrease), taking into account kinematic excitation, is 10%. In the first and 41st blades on the left and in the third and sixth blades on the right of the damaged blade, the maximum stresses decrease by 11, 8, 2, and 0.15%, respectively. In the other blades, no stress decrease due to kinematic excitation was observed.

The analysis of the obtained amplitude-frequency characteristics by the maximum equivalent stresses in the upper third of the blades under a distributed load of 2.5 kPa shows the following. The number of blades without a resonant increase in the vicinity of the frequency of 2120 Hz is 18 near the damaged blade, and at the opposite edge of the wheel, the diameter of such blades is 19. Near the damaged blade, there are five blades on the left and 13 on the right. On the other edge of the wheel diameter that passes through the damaged blade, there are 13 blades on the left and six on the right.

Conclusions. Given the results obtained from the study of the oscillations of the disk–blade system with the violation of cyclic symmetry, taking into account the kinematic excitation of the disk center, the following can be noted.

In the region of rotational frequency, considering the kinematic excitation, the resonant peak of the maximum equivalent blade stresses is shifted to the region of lower frequencies, leading to an increase in stresses at the operating frequency. The maximum stresses in the blades at the excitation frequency from the steam flow of 2100 Hz increase with consideration of kinematic excitation, but no shift of the resonant peak in this region is observed.

At the rotor speed, considering the kinematic excitation, there are two areas (along their length) of stress increase in the blades: in the lower thirds and above them. Stresses in the lower thirds of most blades are much higher than in the upper thirds. In the frequency range of 2100 Hz, three areas of stress increase are observed in the blades: in the lower, middle, and upper thirds. The maximum stresses in the upper thirds of the blades are higher than those in the middle and lower thirds. At the same time, in the lower thirds of the blades at a frequency of 50 Hz, they are significantly higher (by 1–1.5 orders of magnitude), taking into account the kinematic excitation and by 11–15 times without it, than the stresses observed at a frequency of 2100 Hz in the upper thirds of the blades.

Under the studied forms of blade loading at a frequency of 50 Hz, the maximum equivalent stresses occur in the ninth blade on the left and in the 36th blade on the right of the damaged one, both with and without kinematic excitation. At a frequency of 2100 Hz, the highest stresses are observed in the 17th blade on the left and the 28th blade on the right of the damaged one, with and without kinematic excitation.

Based on the results obtained for cyclic asymmetric systems with damage to one blade, it is advisable to consider the disk–blade system's kinematic excitation when assessing the service life and reliability of the last stage of a powerful steam turbine. In case of violations of cyclic symmetry caused by damage to several adjacent or scattered blades on the disk, it is advisable to determine their effect on the stress of all blades of the stage when assessing the reliability of the blade apparatus.

Conflict of Interests. All authors declare that they have no conflicts of interest.

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