Results of the study of vibrations of concrete structures of the hydropower plant building

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Abstract. The paper considers the results of studying vibrations of certain components of the hydropower plant building and their influence on the structure of the building as a whole. Vibration loads on various elements of the hydropower plant building which can cause damage to the building, thereby reducing the operational reliability of the whole structure and doing potential harm to the environment and human life support, is analyzed. The necessity for vibration monitoring of structures which should be conducted constantly or periodically to determine the present condition of structures is reasoned. Vibrations of the section concrete parts and vibrations of hydroelectric power plant units are considered. To detect the vibrational movements of the section as a solid body on an elastic base Section № 2 of the hydropower plant building has been chosen. The recording of vibrations has been conducted for all three components: Z (vertical), H II (horizontal, parallel to the flow) and H ⊥ (horizontal, perpendicular to the flow) and the obtained data are given in this paper. The intervals of observed and dominant periods of vibrations are estimated. The research provides the data on amplitudes and accelerations of vibrations, as well as on the maximum recorded peak-to-peak swing. Based on the analysis of the received vibrograms, it is stated that the recorded vibrations are non-periodic and have a relatively narrow range of periods. In conclusion it is underlined that in order to determine the maximum possible amplitudes of section vibrations as well as to calculate the corresponding dynamic stresses in ceiling trusses it is necessary to observe vibrations when hydraulic units are operated simultaneously and the flow passes through the fully open bottom spillways of the inspected section.

1. Introduction
The most important challenge when operating hydraulic structures is to ensure their safe performance. This area of the research is of high priority for scientists of the Samara State Technical University [1-5]. In this regard, the detailed study of the condition of objects that have been in direct contact with the pressure waterfront for a long period and (or) subject to constant dynamic impacts is particularly relevant and important [6-10].

A typical example of such structures is the building of a hydropower plant (HPP), structural elements of which are dynamically affected by the rotating masses of hydraulic units and the water flow. The building of the Zhigulevskaya HPP has been in operation for a long time and is subject to various vibration loads, both natural and man-caused. Moreover, vibration loads on various elements of the hydropower plant building can cause damage to the building structure, thereby reducing the operational reliability of the HPP building itself and doing potential harm to the environment and human life support. Loss in operational reliability can appear in the form of cracks, damaged elements,
and other structural changes. Vibration monitoring of structure condition should be conducted constantly or periodically to estimate the present state of structures [11].

Recent investigations lack sufficient data that allow determining a correspondence between the vibration severity grade and the damage caused by it.

2. Materials and methods

To study the vibrations of the Zhigulevskaya HPP building, it is proposed to estimate the influence of certain parts of the hydropower plant building on the structure of the building as a whole. Let us consider the vibrations of concrete parts of the Zhigulevskaya HPP section. To detect the vibrational movements of the section acting as a solid body on an elastic base, section № 2 of the Zhigulevskaya HPP building has been chosen. The devices were installed in the following point locations of the section:

1- power house, at level 41.30, the middle of the section;
2- at level 37.25, the middle of the section;
3- at level 37.25, the left bank face of the section;
4- at level 37.25, the right bank face of the section;
5- crane beam over the ground gate, at level 41.50 m, the middle of the section.

Vibrations of the first (counting from the right bank) support of the high-voltage line tower of this section have been also recorded (point location 6). Vibrations have been recorded in all three components: Z (vertical), H II (horizontal, parallel to the flow) and H ⊥ (horizontal, perpendicular to the flow). Sample recording of section vibrations is shown in figure 1.

Based on the analysis of vibrograms obtained for point locations 1-5 the following facts can be stated: recorded vibrations are non-periodic, but they have a relatively narrow range of periods. Based on the research results, histograms of vibration periods for all three components discussed above have been constructed. The intervals of observed periods have been put on the X-axis, and the probability of the period occurrence of the corresponding interval - on the Y-axis. The time intervals between two adjacent humps or depressions have been assumed to be the periods of vibrations when processing oscillograms. Histograms allowed determining the intervals of observed and dominant periods (table 1).

Due to the fact that the recorded vibrations are not periodic, and the rotation period of hydraulic units (0.88 s) lies outside the dominant periods of section vibrations, the observed vibration of the HPP section cannot be explained by the unbalance of the units’ rotors.

![Figure 1. Vibrations of massive parts of section № 2.](image-url)
Table 1. Intervals of the observed and dominant periods of vibrations.

| Location of devices | Component | Dominant periods of vibrations, (s) | Range of observed periods of vibrations, (s) |
|---------------------|-----------|-------------------------------------|---------------------------------------------|
| Section №2, point locations 1-5; levels 37.25-41.50 | Z | 0.6±0.8 | 0.3±1.0 |
| | H II | 0.6±0.8 | 0.3±1.1 |
| | H ⊥ | 0.6±0.8 | 0.3±1.1 |

At the same time the vibration records, obtained at closed spillways, show that in this case the sections of the HPP experience periodic vibrations with the period that lasts 0.88 seconds and coincides with the period of hydraulic units rotation and with an amplitude of no more than 3-4 µm.

3. Results and discussions

Having compared the results of observations at operating and non-operating bottom spillways, it can be concluded that the vibration of HPP sections during the operation of hydroelectric units alone is rather insignificant, and the main vibration source is the pressure pulsation that occurs when flow passes through the bottom water outlets.

Data on amplitudes and accelerations of vibrations are given in table 2. The third column of the table shows the maximum observed peak-to-peak swings (double amplitudes) of vibrations $2A_{\text{max}}$, the fourth column shows the average quadratic amplitude $A_\delta$ which has been calculated in the standard way based on the records, the fifth one shows the amplitudes maximum for this hydraulic mode $A_3\delta$, which have been calculated using the "three-sigma rule". The last column gives the values of conditional accelerations which have been calculated using the formula of the sinusoidal vibration law and correspond to the maximum amplitudes $A_3\delta$ and dominant periods. Thus, vertical vibrations in amplitude are the largest, and vibrations in direction H ⊥ are the smallest.

The records of tower support' vibration (point location 6) indicate the following:
- vibrations in directions Z and H ⊥ are identical in periods and amplitudes to vibrations measured at point locations 1-5;
- for vibrations H II, the interval of dominant periods is 0.4÷0.6 s, and amplitudes also increase.

Table 2. Data on amplitudes and accelerations of vibrations.

| Location of devices | Component | Maximum observed peak-to-peak swing $2A_{\text{max}}$ (µm) | Average square amplitude $A_\delta$ (µm) | Maximum amplitude $A_3\delta$ (µm) | Maximum acceleration $Y_3\delta$ (cm/s²) |
|---------------------|-----------|------------------------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Section №2, point locations 1-5; levels 37.25-41.50 | Z | 87 | 20 | 60 | 0.66 |
| | H II | 54 | 14 | 14.8 | 0.50 |
| | H ⊥ | 26.6 | - | ≥ 20 | ≥ 0.50 |

Data on dominant periods, amplitudes and accelerations are shown in table 3.
Table 3. Data on dominant periods, amplitudes and accelerations.

| Location of devices | Component | Dominant periods | Maximum observed peak-to-peak swing | Average square amplitude | Maximum amplitude | Maximum acceleration |
|---------------------|-----------|------------------|-------------------------------------|--------------------------|-------------------|---------------------|
|                     |           |                  | $T$ (s) | $2A_{max}$ ($\mu$m) | $A_\delta$ ($\mu$m) | $A_{3\delta}$ ($\mu$m) | $Y_{3\delta}$ (cm/s$^2$) |
| Section № 2         | Z         | 0.6÷0.8          | 47     | -             | ≈60            | ≈0.66              |
| point location 6    | H II      | 0.6÷0.8          | 122    | 34.2          | 103            | 2.54                |
| tower support       | H ⊥       | 0.6÷0.8          | 37     | -             | ≈20            | ≈0.50              |

In some recording areas H II angular points can be observed that indicate abrupt changes in the velocity of vibration motion at certain time intervals. For the component H II (tower support) higher accelerations can be expected than it is indicated in table №3. The increase in vibrational amplitudes of the tower support under the component H II can hardly account completely for the movement of the section as a solid body (the increase of the horizontal component with height). It is most likely due to bending vibrations of the powerhouse wall in the direction H II.

Taking into account that at some areas of recording vibrations of the section and the power support there can be observed vibration groups with approximately the same period, it is recommended to make a verification calculation of periods of the high-voltage line tower’s free vibrations. Their occurrence within the range of 0.3-1.0 seconds is undesirable due to the possible coincidence of forced and natural frequencies and the related large dynamic effect.

To measure vibrations of hydraulic units the vibrographs have been installed with the approval of the maintenance service at the following point locations:

1. on generator bearings №№ 1, 2, 3- respectively point locations 12, 22, 32;
2. on covers of hydraulic unit turbines №№ 1, 2, 3- respectively point locations 13, 23, 33;
3. on upper generator brackets №№ 1, 3, 4- respectively point locations 14, 34, 44;
4. at the remote end of the stiffener plate of upper generator bracket № 3- point location 35.

Besides the devices located on the parts of hydraulic units in indicated places, the sensors have been also installed on the concrete floor of the power and turbine houses (at levels 41.3m and 37.25m). All sensors have been installed from the upstream side respect to the axis of the unit. Vibrations have been recorded for all three elements: vertical $Z$, horizontal in the direction of the flow $H \parallel$, and horizontal across the flow $H \perp$.

Analysis of the obtained vibrograms shows the following:

1. Vertical vibrographs mounted on the turbine cover record steady almost periodic vibrations (Fig. 2), which maximum recorded swings (double amplitudes) and periods are shown in table. № 4;
2. As may be supposed, it is possible to correlate the vibration occurrence either with free vibrations of individual elements of the units, or with the turbine rotation, as the period of the turbine blades move coincides with recorded values;
3. All devices record non-periodic vibrations with a peak-to-peak swing of about several tens of microns and dominant “periods” of 0.6÷0.8 seconds. These vibrations are nothing more than vibrations of the hydropower plant building, which are transmitted to the hydraulic units installed in the section.
4. Vibrations of hydroelectric units related to the unbalance of the rotors in most cases turned out to be less in amplitudes than the HPP building vibrations, and therefore it is impossible to distinguish them from the vibration of the building.

In some cases, when the level of hydroturbine vibration of the units exceeded the level of vibrations of the HPP building, vibrations with a constant period coinciding with the rotation period of the unit (0.88 s) have been recorded on the vibrograms. Their average and largest observed double amplitudes are shown in table 4.
Figure 2. Vibrations of unit № 2.

Table 4. Data on the maximum recorded swings.

| Measurable value                  | Unit №1 | Unit №2 | Unit №3                |
|----------------------------------|---------|---------|------------------------|
| Vibration period (s)             | 0.146   | 0.147   | 0.143–0.145            |
| The largest recorded swing (µm) | 118     | 196     | 100                    |
| Acceleration (cm/s²)             | 10.9    | 18.0    | 9.5                    |

In all other cases of measuring it was impossible to distinguish vibrations of hydraulic units with a period of 0.88 seconds from the hydropower plant vibration, therefore it can be assumed that the swing of vibrations with a period of 0.88 seconds in these other cases of measuring was less than 90-100µm. Vibrations with a period of 0.88 seconds are caused by the unbalance of the rotor or insufficient shaft alignment. The average amplitude of these vibrations reaches 67.5µm (180µm is acceptable).

Besides vibrations with a period of 0.88 seconds and swinging related to the movement of the section, devices H II and H ⊥, mounted on bearings of units and upper brackets, have recorded unsteady horizontal vibrations with the dominant period of 0.14–0.15 seconds and average peak-to-peak swing of about 30–40µm, which are likely to be free vibrations of the upper brackets.

Due to the presence of a relatively large background noise, which, in that case, meant vibrations of the building, it turned out to be impossible to monitor the nature of transmitting vibrations with periods of 0.88 seconds and 0.14 seconds from units to concrete parts of the hydropower plant.

As indicated above, vibrations of the building caused by the pulsation of hydrodynamic pressure in the flow are also transmitted to the hydraulic units installed in the sections.
4. Conclusions
Based on the results of studying vibrations of concrete structures in section № 2 of the Zhigulevskaya HPP building the following conclusions can be drawn:
1) according to the results of study, the observed vibration of section 2 of the HPP building cannot be explained by the unbalance of the rotors of hydraulic units. A number of factors suggest that this vibration is caused by a pulsation of hydrodynamic pressure in the water flow passing through the bottom spillways;
2) the maximum amplitudes of vertical vibrations of section № 2 have been observed under hydraulic conditions - up to 60µm, the maximum amplitudes of horizontal vibrations of the section - up to 45µm.
3) to establish the maximum possible amplitudes of section vibrations, as well as to calculate the corresponding dynamic stresses in the ceiling trusses, it is necessary to conduct vibration observations while simultaneously operating hydraulic units and passing the flow through the fully open bottom spillways of the section being studied;
4) vibrations of the power house' roof, caused by vibrations of section № 2 at the Zhigulevskaya HPP, have been recorded. But it needs more scope of study.

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