329. Vibrodiagnostics and Dynamic Behaviour of Machinery in Small Hydroelectric Power Plants*

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Abstract. The presentation introduces the solution for the vibroactivity problems in small hydroelectric power plants, based on original stationary vibromonitoring and diagnostic systems as well as their application to solve various problems. Dynamic behaviour of hydromachinery and causes of increased vibrations are analysed taking into account structural, design- and construction-related issues. It is demonstrated that condition monitoring and analysis of vibrations enable identification of causes of large vibrations in hydromachinery.

Keywords: hydroelectric power plant, machinery, vibrations, dynamic behaviour, monitoring and diagnostic systems

Introduction

Machine vibrations have been used as primary information about the technical condition of a machine for a long time. Therefore vibration monitoring, which originated as a subjective evaluation of vibratory condition of the machine, has become a necessary procedure based on the objective analysis. Vibration measurements, analysis and studies performed in the last decades allowed to gain a lot of experience, which is generalized by various standards [1-8] and reviews [9,10]. The standards for evaluation of machinery vibrations and the peculiarities of their application in vibroacoustic diagnostics depend on the type of machine and its application in different plants [1,7]. Rigorous evaluation of vibroacoustic processes of machines is the constituent part of security assurance, while the standard procedures allow treatment of actual information, which is collected and scrutinized by the professionals in the field, and it is especially important in the globalisation process of economics. Machinery condition monitoring by means of vibration measurements and application of diagnostic procedures is a field that is increasingly regulated by the standards, where a number of practically tested methods are transformed into standard procedures and their correct selection determines the reliability and effectiveness of diagnostics and monitoring.

The normative documents [3-8] encompass the measurement methods of absolute and relative vibrations of hydromachinery, its operating regimes during the measurement procedure, and assessment of vibration levels of hydromachinery of various types.

Accredited Laboratory of Vibratory Monitoring and Diagnostics at Kaunas University of Technology (KTU) is the first in Lithuania who has developed (in the period of 1994-2002) a series of certified automated monitoring and diagnostic system VIMOS: VIMOS-T for turbomachinery, VIMOS-H – for hydromachinery, VIMOS-P for periodical vibromonitoring of rotary systems. All the VIMOS systems are based on the above-mentioned standards, original software and technical solutions.

In 2001 Kaunas hydroelectric power (HEP) station initiated the development of general monitoring system. Testing and research of building vibrations were carried out, which served as a basis to create the subsystem of vibration monitoring of hydromachinery (25 MW) in 2002 (now its VIMOS-HM version is used [9]). The long-term experience and the system of periodical vibromonitoring VIMOS-P, as well as databases of Kaunas HE in this field were used in the complex research work performed on small (1,4 MW) hydromachinery and HE building. It enabled evaluation of the dynamics-related problems of one of Lithuanian small hydroelectric power stations, which is a representative of other similar objects. This paper presents the methodology for testing the vibroactivity of small HE buildings and hydromachinery, and the results of its application, considering the problem of safe operation.

During investigation, technical documentation on the issues of condition of buildings was analyzed as well as vibration measurements and evaluation of hydromachinery was performed leading to the development of the methodology for measurements and analysis.

The developed methodology was applied at Balskai hydroelectric power station, where the analysis of vibrations and the condition of the hydromachinery was evaluated. It was determined that the radial vibrations of upper bearing of both generators at Balskai hydroelectric power station exceed the permissible levels. Furthermore, the causes for high vibrations were subsequently revealed. The results of the research are presented below.

1. Measurements of vibrations and methodology of analysis

Small HEP stations usually have two averagely similar pieces of hydromachinery. The measurements of the vibrations of building at Balskai HEP station and hydromachinery were carried out when the level of water was the following: headwaters – 45,6 m ... 45,7 m, afterbay

– 41,0 m ... 41,3 m. The vibrations of the building of the station were measured on the ground surface above the gallery of water supply of a hydromachine in the distance of 3,5 m and 7 m from the building of the station and on the wall of the building in the height of 0,7 m and 2 m. The vibrations of hydromachinery were measured in the following points:

- relative vibrations of turbine shaft by the turbine bearing;
- absolute vibration of turbine bearing in the radial direction;
- absolute vibration of turbine cover in the vertical direction;
- absolute vibration of reducer in the radial and vertical directions;
- absolute vibration of generator bearings in the radial direction.

Fig. 1. Measurement of vibrations of the machinery at Balskai hydroelectric power station

Directions of vibration measurements:

- X direction – horizontally along the dam from the left bank to the right one;
- Y direction – horizontally square to the dam from the afterbay to the headwaters;
- Z direction – vertically along the shaft of hydromachine.

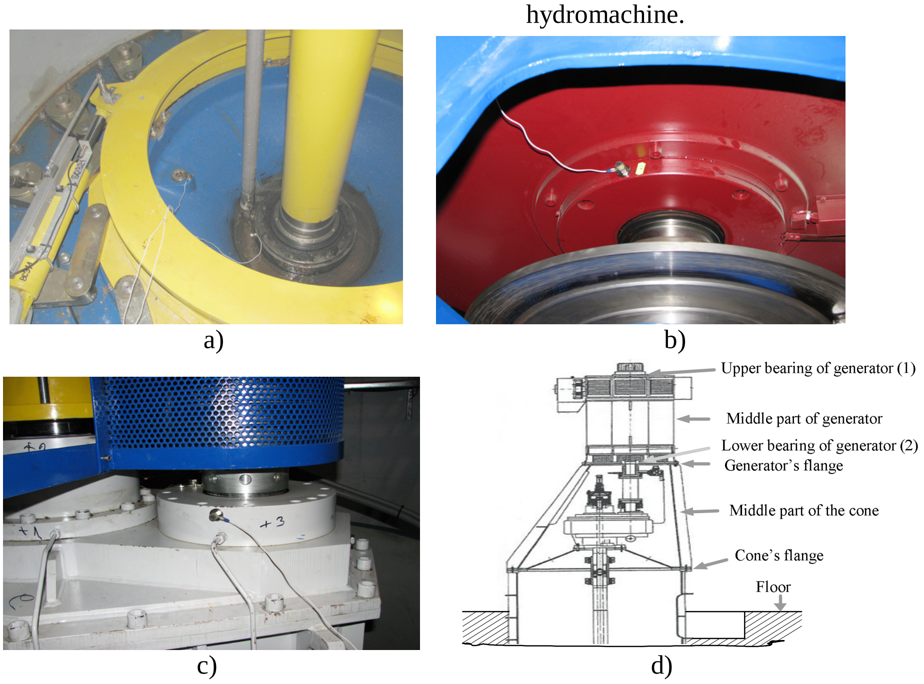

Fig. 2. Mounting points of transducers while measuring the vibrations of hydromachinery bearings: a) vibrations of turbine bearing in the radial direction (1) and vibrations of turbine cover in the vertical (2) direction; b) vibrations of generator bearing in the X direction; c) reducer vibrations in the radial (1) direction; d) measurement points of vibrations along the hydromachine

The following tools were used to measure vibrations: modular precision noise level analyser Pulse 3560 and universal vibration analyser VIBROTEST 60. The measurements were carried out in the following frequency ranges: acceleration of vibrations – 1 Hz ... 10 kHz; velocity of vibrations – 1 Hz ... 1 kHz; displacement of vibrations – 1 Hz ... 200 Hz, relative vibrations of turbine shaft (displacement) – 0 Hz ... 200 Hz. The measurements and analysis of the vibrations were carried out according to the normative documents: absolute vibrations - according to ISO 10816-5:2000, while relative vibrations of a shaft were measured according to ISO 7919-5:2005.

In order to measure vibrations of ground surface above the gallery of water supply and walls of the building at HEP station, the seismic accelerometers were used. They measure acceleration of vibrations in the range from 1 Hz. The velocity and displacement of vibrations are calculated once or twice by digitally integrating signal of acceleration. When low frequency signals are integrated, large errors are introduced. Therefore the measurement results are characterized by fairly high indeterminacy. There were found no normative values in the analysed technical documentation to evaluate the vibratory values of the building at hydroelectric power station.

3. Vibroactivity of the HEP station building and hydromachinery

The level of vibration velocity of the ground surface above the gallery of water supply and walls of the building at hydroelectric power station is 0,1 mm/s ... 0,3 mm/s. When the change of vibrations in time was monitored, the non-periodical impulses (displacement) of big amplitude were determined. They repeat every 3 s ... 30 s. The velocity amplitude of the vibrations of these impulses is up to 2 mm/s ... 3 mm/s, while the vibration displacement peak-to-peak value in separate cases reaches 0,8 mm ... 1,0 mm. These impulses may be caused by hydraulic forces, which operate in the gallery of water supply, and which need individual research. The characteristic spectrums of vibrations of ground (Fig. 3) and building wall at HEP station (Fig. 4) are presented below.

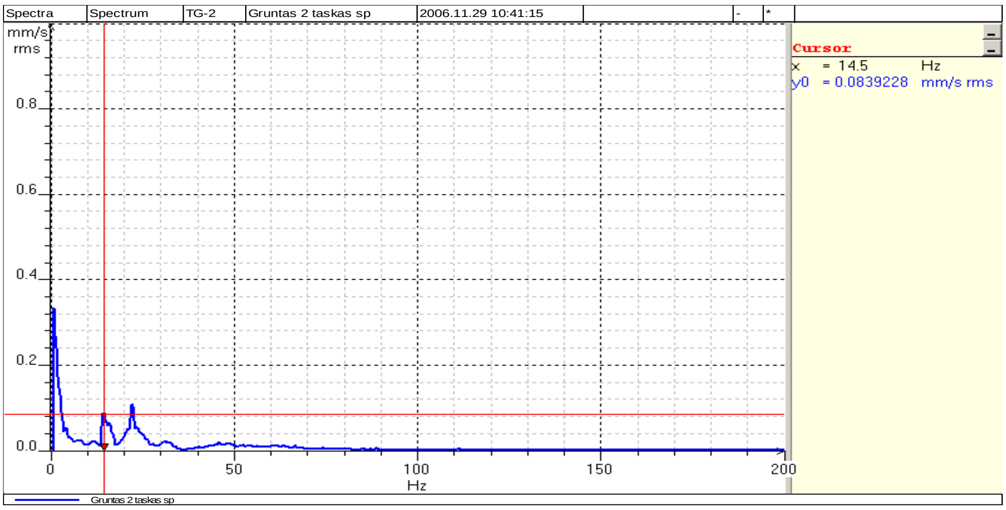

Fig. 3. Vibration spectrum of the ground by the building of the hydroelectric power station

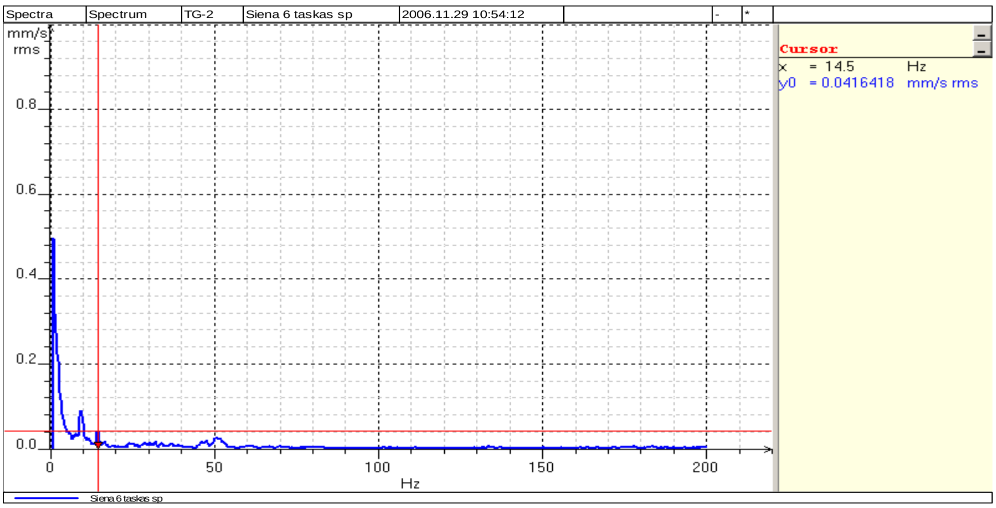

Fig. 4. Vibration spectrum of the wall of the building of the hydroelectric power station

The spectrum shows the influence of very large impulse forces of low frequency on the vibroactivity. They are caused by the pulsation of water flow in the gallery of water supply and it is necessary to measure water pressure and speed for further analysis. In order to determine the impact of these forces on the vibration of hydromachinery, the correlative characteristics of indirect means were used. For this purpose the sudden changes of the amplitude in the vibratory characteristics of the hydromachinery were analysed, especially in the oscillograms. The orbits of shaft displacement illustrate it partly, but it is impossible to confirm that it is the consequence of the ground vibrations, because the monitoring time of the orbit was not sufficient (1 s). This investigation could not demonstrate any clear dependence between ground vibrations and vibroactivity of hydromachinery.

The measurements and analysis of vibrations of hydromachinery bearings show that the vibratory levels do not exceed the permissible level, except for generator bearings (see Table 1).

Table 1. Vibrations of generator bearings

Generator load	Bearing	Direction of measurement*	Displacement	Velocity	Acceleration
			μm	mm/s	m/s^2
No. 1 460 kW	Upper	X1	**108****	**10.5****	2.7
		Y1	**117****	**11.6****	1.8
	Lower	X2	32	1.9	2.0
		Y2	38	2.1	1.8
No. 1 1460 kW	Upper	X1	**108****	**10.6****	3.3
		Y1	**127****	**12.5****	2.4
	Lower	X2	31	2.0	3.6
		Y2	37	2.1	4.0
No. 2 460 kW	Upper	X1	**84****	**8.2****	1.7
		Y1	**138****	**13.7****	1.8
	Lower	X2	38	2.2	2.0
		Y2	47	3.2	1.8
No. 2 1460kW	Upper	X1	**87****	**8.3****	2.4
		Y1	**138****	**13.4****	2.9
	Lower	X2	42	2.3	4.1
		Y2	**63****	3.1	4.0
B/C limit, according to ISO 10816-3:1998			**57**	**4,5**	-
C/D limit, according to ISO 10816-3:1998			**90**	**7,1**	-

* Directions of vibratory measurements: X1, X2 – horizontally along dam; Y1, Y2 – horizontally square to dam.

** Level of vibrations exceeds permissible limits.

In order to explain this fact we have carried out the research on vibrations of natural frequencies of bearing constructions of hydromachinery generators and supporting cones of generators as well as concrete supporting cylinders. The vibration of the machinery was measured along its axis (see Fig. 2 d) in response to the impact of the impulse force on the top point of the generator.

The measurement results of the vibrations during the operation of the machinery and the reaction of the non-operating machinery allow evaluating more accurately the ratio of vibratory level in various parts of the hydromachinery, as the vibratory level is constantly undergoes a slight change during the operation.

According to the analysis of vibrations, the largest vibrations of hydromachinery are in the zone of upper bearing of the generator. The vibrations of the lower bearing and generator fastening flange are within the permissible limits. The vibrations of the lower part of the supporting cone of the generator and floor of the machine room by the hydromachinery are small.

The phases of the hydromachinery vibrations in the characteristic points may be compared on the basis of the vibratory time histories presented in Figs. 5-6. It is noted that the phase of the vibrations of generator rotating frequency in the Y direction coincides in all the measurement points from the upper part of the machinery until the middle part of the cone. It proves that the upper part of the hydromachinery vibrates in the first resonant frequency (16 Hz) as the cantilever beam fixed by the one end (in this case – bottom).

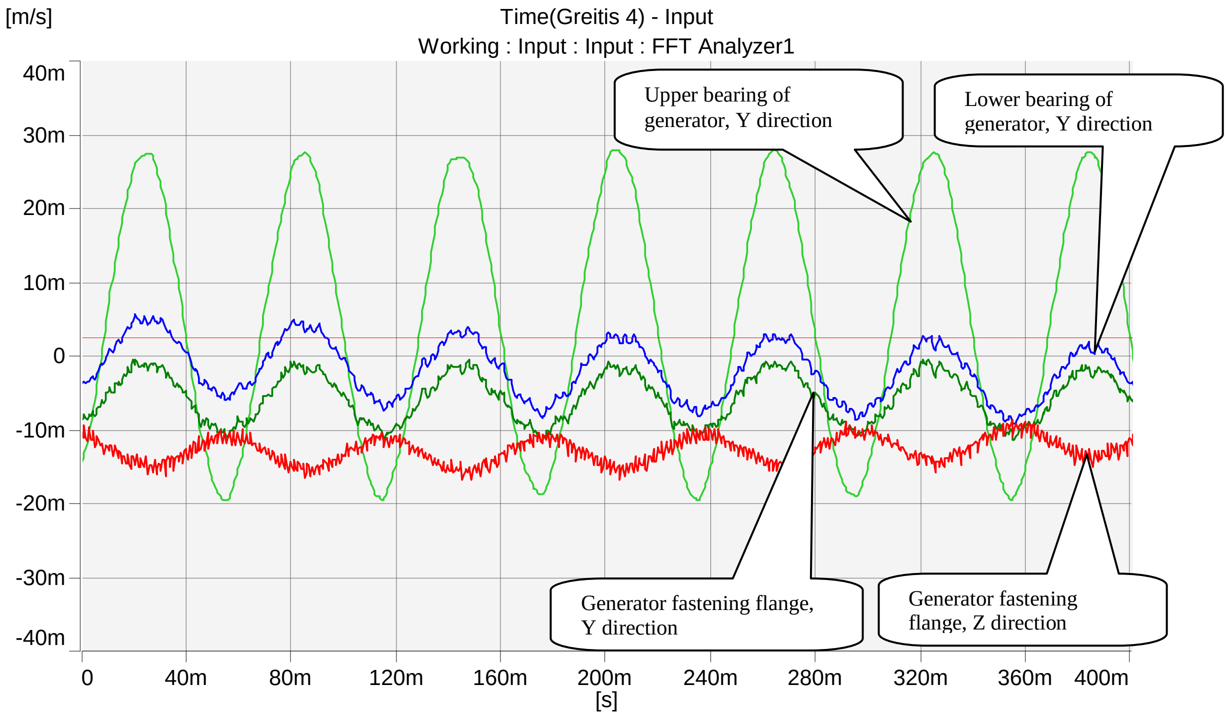

Fig. 5. Oscillograms of the vibrations of generator bearings and fastening flanges of the hydromachinery TG 2

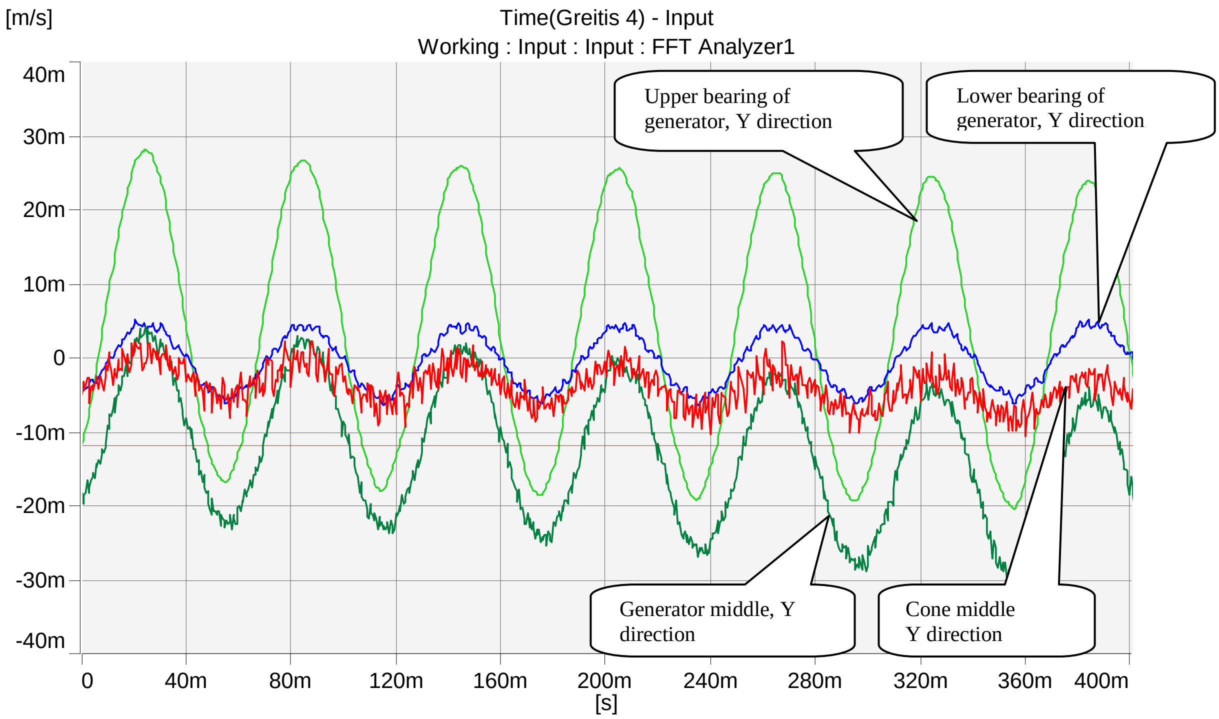

Fig. 6. Oscillograms of the vibrations of generator bearings, its middle part and cone middle part of the hydromachinery TG 2

The upper part of the hydromachinery is the mechanical system like cantilever beam with mass. The mass is generator mass, and the rigidity of beam consists of the rigidity of the generator supporting cone, concrete cylinder and lower concrete constructions.

3. Investigation of the natural frequencies of the hydromachinery

The performed investigation allows analysing the dynamic behaviour of the machinery as the simplified mechanical system, which consists of the vertical cantilever beam with tightly fixed bottom, and the mass fastened to the top of the beam (generator mass). In such a way the beam is loaded in the axis' direction with load force *N*, which can be considered constant and formulated in the following way:

$$N = Mg\left(1 - \frac{1}{g}\cdot\frac{\partial^2 u}{dt^2}\right), \quad (1)$$

here:
M – generator mass; *u* – displacement of the beam end along the axis.
This force will affect the dynamics of the system due to the Euler critical force P_{kr} [11,12]:

$$P_{kr} = \frac{\pi^2 EJ}{4l^2}, \quad (2)$$

here:
EJ – rigidity of beam; *l* – length of beam.
Then the proportion of the generator gravity and Euler critical force P_{kr} will determine the frequencies of the mechanical system, and the first frequency may be formulated in the following way:

$$\omega = \Omega_o\left(1 - \frac{Mg}{P_{kr}}\right), \quad (3)$$

here:
Ω_o – first natural frequency, which could be determined from the characteristic equation of the mechanic system $\Delta(\gamma) = 0$:

$$\begin{aligned}&\frac{1}{\alpha}(1 + ch\gamma\cos\gamma) - \gamma(\sin\gamma ch\gamma - \cos\gamma sh\gamma) -\\ &- 2\varepsilon\gamma^2\sin\gamma sh\gamma - (\delta + \varepsilon^2)(\sin\gamma ch\gamma + \\ &+ \cos\gamma sh\gamma)\gamma^3 + d\delta\gamma^4(1 - \cos\gamma ch\gamma) = 0\end{aligned}, \quad (4)$$

and equation:

$$\Omega = \frac{\gamma^2}{l^2}\sqrt{\frac{EJ}{F\rho}} \quad (5)$$

here:

$$\alpha = \frac{M^2}{\rho F l}; \quad \delta = \frac{\rho_1^2}{l^2}; \quad \varepsilon = \frac{d}{l};$$

F – beam cross-section; ρ – its density; ρ_1 – radius of generator inertia; *d* – distance from the upper end of the beam to the centre of generator masses.

Thereby it becomes evident that the proportion of the generator gravity and Euler critical force P_{kr} will determine the dynamic behaviour of the machinery, i.e. incorrectly chosen generator mass and total rigidity of bearing constructive elements may produce such frequency that would be close to the rotating frequency of the generator.

The additional research of the natural frequencies was performed. The characteristics of the hydromachinery frequencies when the machine vibrations are excited in the Y direction and at approximately 45° angle with the Y axis are presented in Figs. 7-10. According to the research, the natural frequencies of the vibrations in the X and Y directions are different. This explains the difference in the amplitude of the hydromachinery TG 2 vibrations in the X and Y directions. The resonant frequencies of the hydromachinery TG 2 construction are 15,9 Hz and 16,6 Hz, while average vibrations are 9,5 mm/s and 15,2 mm/s in the X and Y directions respectively.

The resonant frequencies of the hydromachinery TG 1 construction are 16,8 Hz and 16,3 Hz (see Figs. 7-10).

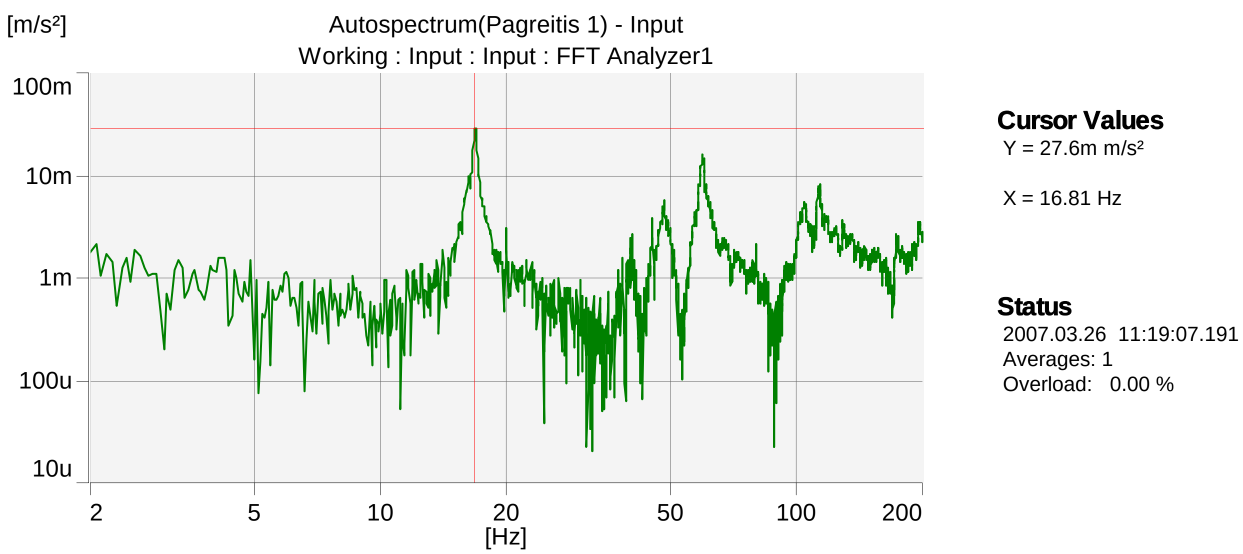

Fig. 7. Frequency characteristics of the hydromachinery TG 1. The excitation in the upper point of the generator in the Y direction. The measurement point is the upper bearing of the generator, Y direction.

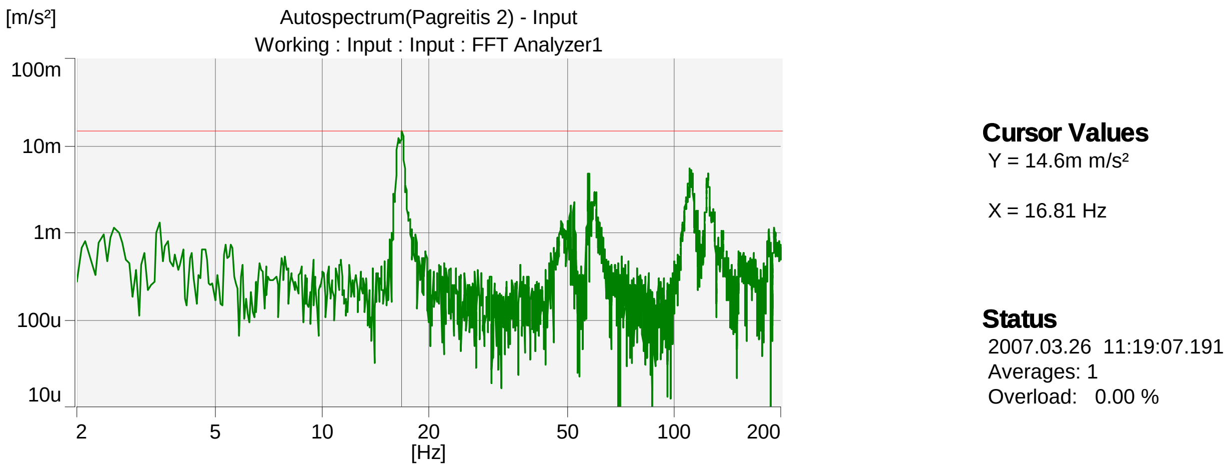

Fig. 8. Frequency characteristics of the hydromachinery TG 1. The excitation in the upper point of the generator in the Y direction. The measurement point is the upper bearing of the generator, X direction.

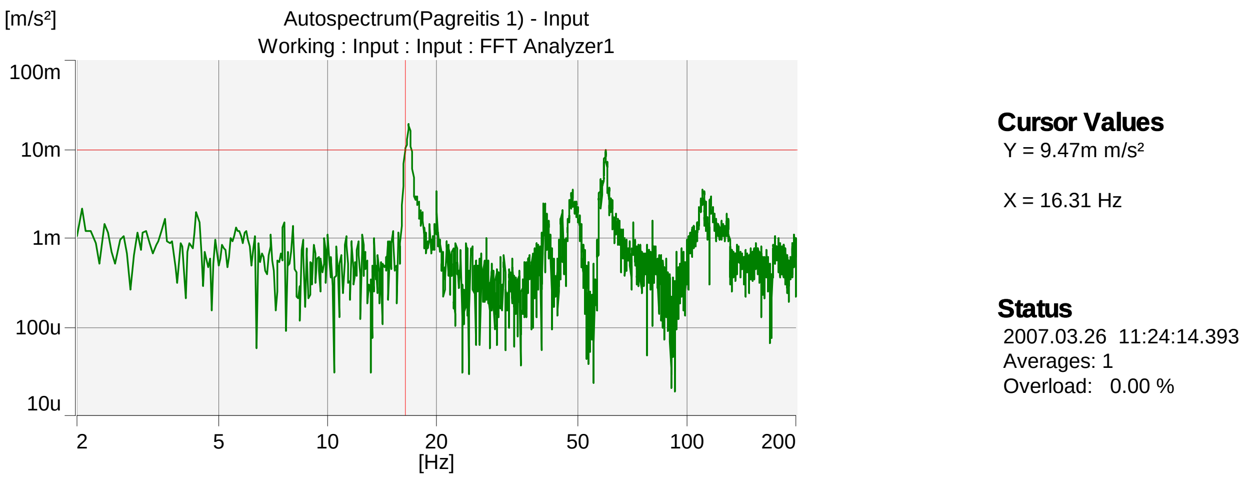

Fig. 9. Frequency characteristics of the hydromachinery TG 1. The excitation in the upper point of the generator at approximately 45° angle with the Y direction. The measurement point is the upper bearing of the generator, Y direction.

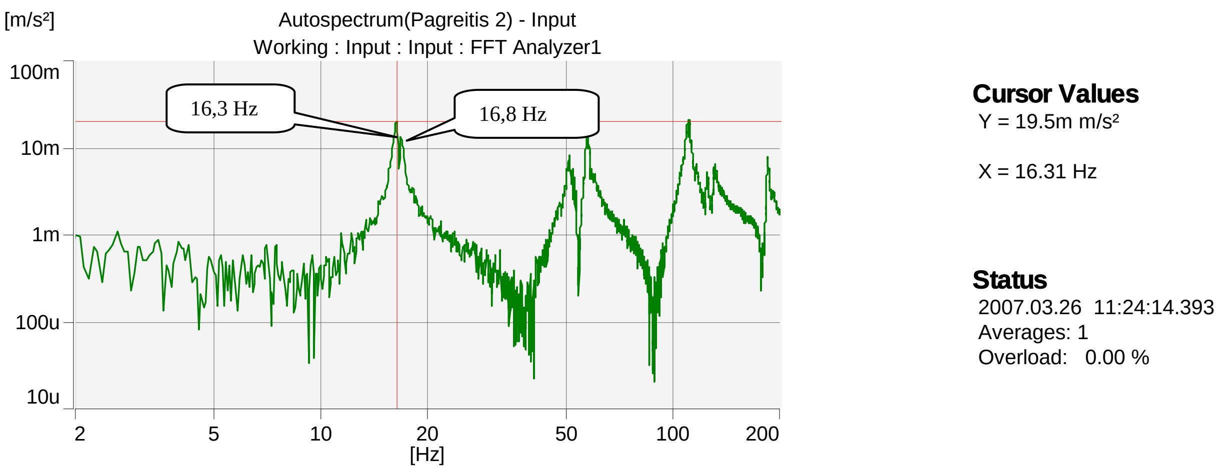

Fig. 10. Frequency characteristics of the hydromachinery TG 1. The excitation in the upper point of the generator at approximately 45° angle with the Y direction. The measurement point is the upper bearing of the generator, X direction.

The rigidity of the generator supporting cone is significantly smaller than the rigidity of other constructions and it varies in different directions. It determines the first resonant frequency of the aforementioned mentioned vibratory system, because the rotating frequency of generator is 16 Hz.

Conclusions

1. The radial vibrations of the upper bearing of the generators of both hydromachines significantly exceed the permissible level of vibrations. The cause of the increased vibrations is the coincidence of the generator rotating frequency with the first resonant frequency (critical frequency) of the bearing constructions. As the result of pronounced vibrations of bearing constructions, the metal fatigue may occur therefore the possibility of severe troubles and accidents increases. The additional tests of the vibrations of bearing constructions demonstrated that the first resonant frequency of the hydromachinery constructions corresponds to the generator rotating frequency due to the incorrectly selected relation of the rigidity of generator supporting cone with generator mass.

2. The analysed normative documents do not indicate the limited values of vibrations in order to evaluate the condition of the HEP station building. In order to determine the causes of vibrations of the building and their correlation with the vibration levels of hydromachinery, it is necessary to analyse separately and thoroughly the dynamics of the building.

3. It is possible to reduce the vibrations of hydromachinery generators by changing the rigidity of the bearing constructions so that the first critical frequency differed from the generator rotating frequency by at least 30%. The analogous effect will be achieved if the generator with different nominal rotating speed is used, e.g. 1500 rot/min or 750 rot/min.

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