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An experimental study of aperiodic pressure pulses in Francis turbine

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An experimental study of aperiodic pressure pulses in Francis turbine

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Abstract. The paper presents the results of experimental studies of the vortex rope reconnection in the flow of a Francis turbine. The studies were carried out on a mid-scale hydrodynamic set-up, with a model similar to the actual hydroelectric units. With the help of high-speed camera in a mode with a load of 82% a reconnection of the precessing vortex rope with detachment of the vortex rings was observed in the diffuser of the draft tube. Aperiodic pressure pulses associated with the vortex rope reconnection in diffuser in the draft tube.

1. Introduction

One of the reasons for the increased level of pressure and vibrations in water turbines of high-head hydro power plants is the phenomenon of a precessing vortex core. Precession of the vortex rope, which formed downstream the runner in the modes of partial or forced load of the hydraulic unit, is one of the main sources of the generation of low-frequency pulsations of the high-swirling flow [1-6].

Analysis of the experimental and numerical data shows [2-4] that the maximum pressure pulsations are observed in the mode of partial load on the hydraulic unit (40-50% of the nominal power of the turbine). However, in some works [1, 7, 8] the presence of aperiodic pressure pulses due to irregular and unstable forms of the vortex rope was observed in modes close to the optimum (70-80% of the nominal power). In [9], a phenomenon of reconnection of a precessing vortex rope with subsequent formation and detachment of the vortex ring was found on a set-up with a model simulating the conical diffuser of draft tube of water turbine. The process of reconnection is random, that gave grounds for formulating the scenario of the onset of aperiodic pulses caused by the passage of vortex rings near the wall [9].

Systematic experimental studies of the vortex reconnection phenomenon in real water turbines are currently unknown. This fact was the main motivation to perform current study on a hydrodynamic set-up with mid-scale model of a real Francis turbine.

2. Experimental methods

The set-up with a model water turbine is shown in Figure 1. The hydraulic unit consists of: 1 - a pressure tank performing the functions of the overflow, 2 - turbine flow path with a diameter of 400 mm with the electric valve 3. Water from the flow path 2 enters the spiral case 4, than goes through the guide vanes to the runner, draft tube 5, lower tank 6, drain tank 7, then through pipe 8 water goes to storage tank 9. From storage tank water is pumped back to the pressure tank by the pump 10. Thus, continuous circulation of water is ensured in the set-up. The maximum head of water at the set-up is

3.5 m, the diameter of the runner is D = 0.3 m. The diffuser of the draft tube is made of plexiglass for possibility of optical flow diagnostics and flow structure observing.

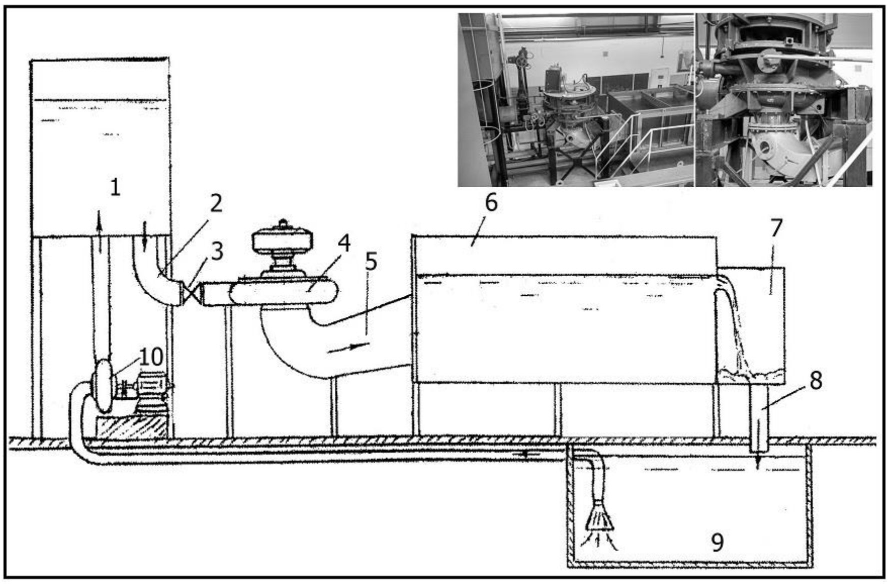

Figure 1. Scheme of the set-up

Recording of pressure pulsations was made by calibrated piezoelectric pressure sensors 014MT, which convert the rapid changes of pressure to electrical signal. Two sensors were mounted in the opposite walls of conical diffuser of draft tube. An external 4-channel charge amplifier LE-41 module was used to amplify the signal. The ADC E14-140 was used to record signals on the PC. In addition to the pressure pulsations, the water head, water flow, runner rotation frequency and the power produced by the turbine were measured.

Variation of operating modes is carried out by changing of the water head and the wideness of opening of the guide vanes. Pressure pulsations were measured and the flow structure was visualized in a wide range of operating modes of the hydraulic unit. The paper shows three successive operating modes of the hydraulic unit corresponding to 73%, 82% and 91% of the nominal power approximately.

3. Results

The 73% mode is characterized by the presence of a large vortex rope with occasional instability of the spiral structure. The vortex structure and the pressure sensor signal are shown in Figure 2. A uniform signal with constant amplitude can be observed.

Figure 2. Visualization of mode with 73% loads and a pressure sensor signal

Due to the rather stable structure of the vortex the fast Fourier transform (FFT) of the signal makes it possible to accurately determine the precession frequency. In this case, the precession frequency is f_{pvc} = 2.9 Hz and the frequency of the runner rotation is f_{rot} = 8 Hz (Fig. 3)

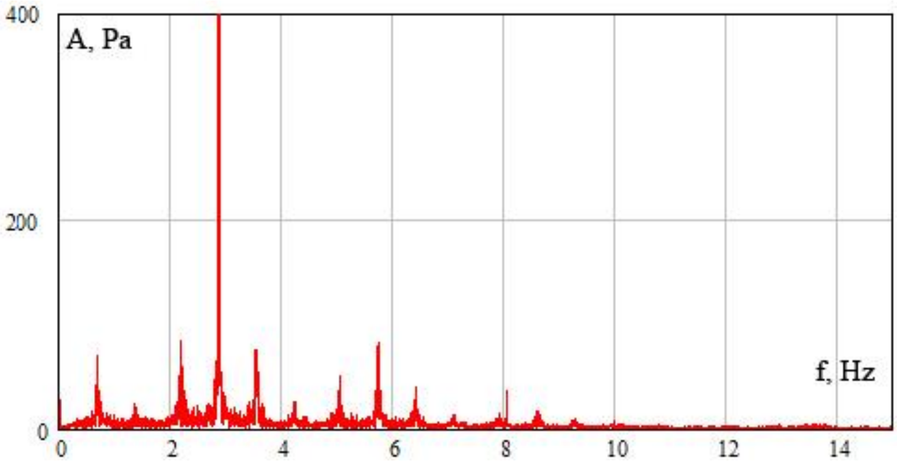

Figure 3. Spectrum of pressure pulsations (73% loads)

At 82% mode, a thin "wriggling" vortex with the reconnection effect and a subsequent formation and detachment of the vortex ring are observed. The vortex structure and synchronous signals from two pressure sensors (red line and blue line) are shown in Figure 4.

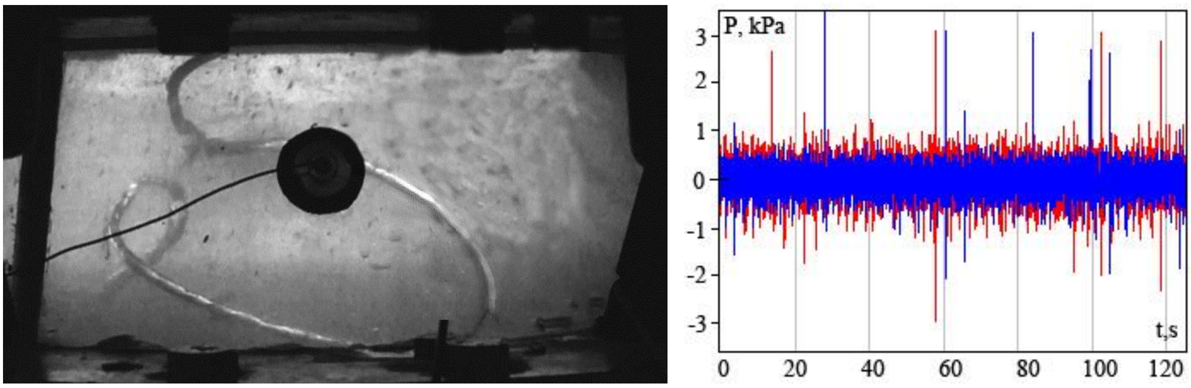

Figure 4. Visualization of mode with 82% loads and two pressure sensors signals

It can be seen that the overall level of pulsation decreases, but the signals have aperiodic pressure pulses with amplitude of 2-5 above the mean. It is clearly seen that the pressure pulses are random in time and different for both sensors.

Visual observations made it possible to determine that the formation of vortex rings occurs fairly regularly with frequency of about 0.45 Hz, it corresponds to 0.18 of the vortex precession frequency and 0.05 of the runner rotation frequency. However, from pressure sensor signals it can be seen that pressure pulses are irregular and occur much less frequently. The synchronization of high-speed video recording and the signal from the pressure sensor showed that pulses of pressure fluctuations are observed only when the vortex ring either hits directly to the sensor or passes very close to it.

The result of FFT is shown in Figure 5. In this case the frequency of precession is not so single-valued; nevertheless, a range of 2.4 Hz to 2.7 Hz can be distinguished. Also on the plot is clearly visible $f_{rot} = 8.3$Hz.

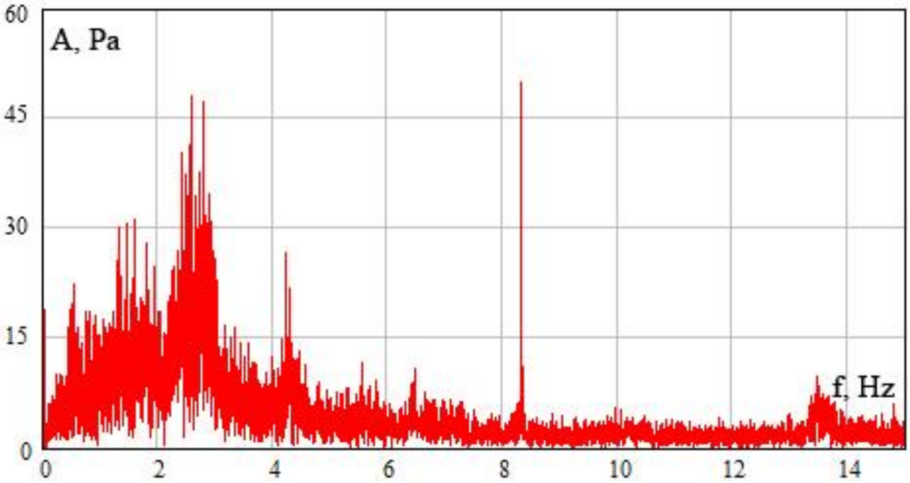

Figure 5. Spectrum of pressure pulsations (82% loads)

For a more detailed study of the operation mode with a reconnection of a vortex (83% load), signals with length of one hour for two pressure sensors were recorded and analyzed. The time between two neighboring pulses was determined to plot a histogram of the probability that a vortex ring hits a sensor or passes close to it. Probability of pressure pulses appearance in each time period T divided to the period of runner rotation T_{rot} shown in figure 6.

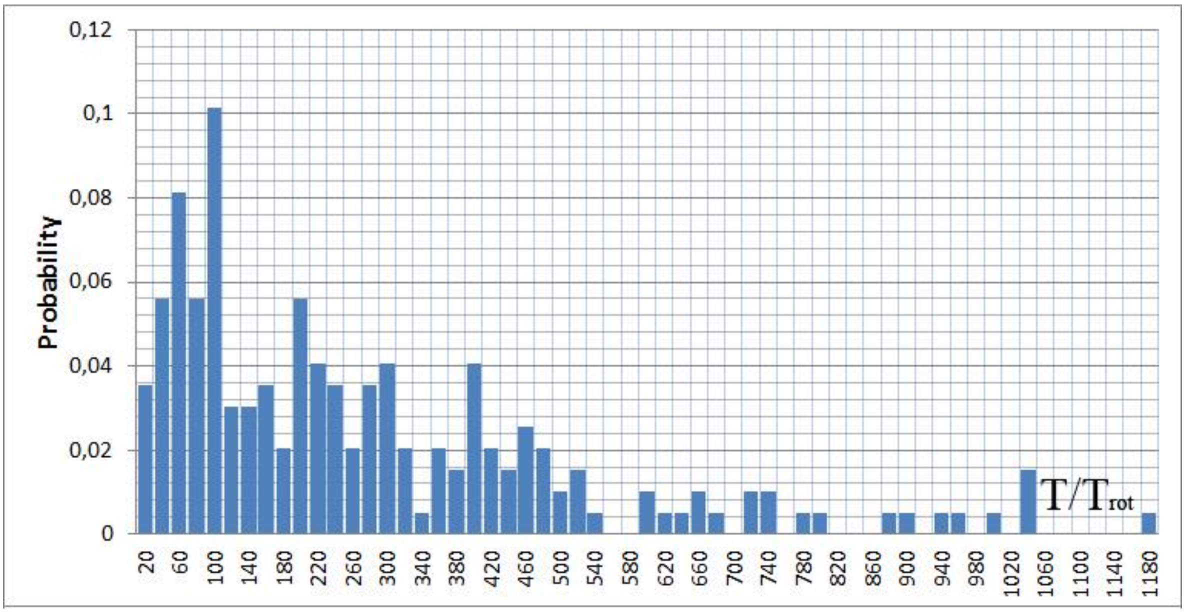

Figure 6. Probability of pressure pulses to $\mathbf{T/T_{rot}}$

As can be seen from the distribution, the maximum probability of the pressure pulses occurs at 60-100 T_{rot}, although, the average period of pulses appearance is 303 T_{rot} (defined by the total time and number of pressure pulses). Table 1 summarizes the periods of main phenomena of flow with vortex reconnection with dependence to runner turn period.

Table 1.

Phenomena	Average period
Precession	**3.33 T_{rot}**
Ring separation	**18.5 T_{rot}**
Pressure pulse	**303 T_{rot}**

At 91% mode, vortex structures are not observed visually, the sensor signal also does not have sharp pressure pulses (Fig. 7).

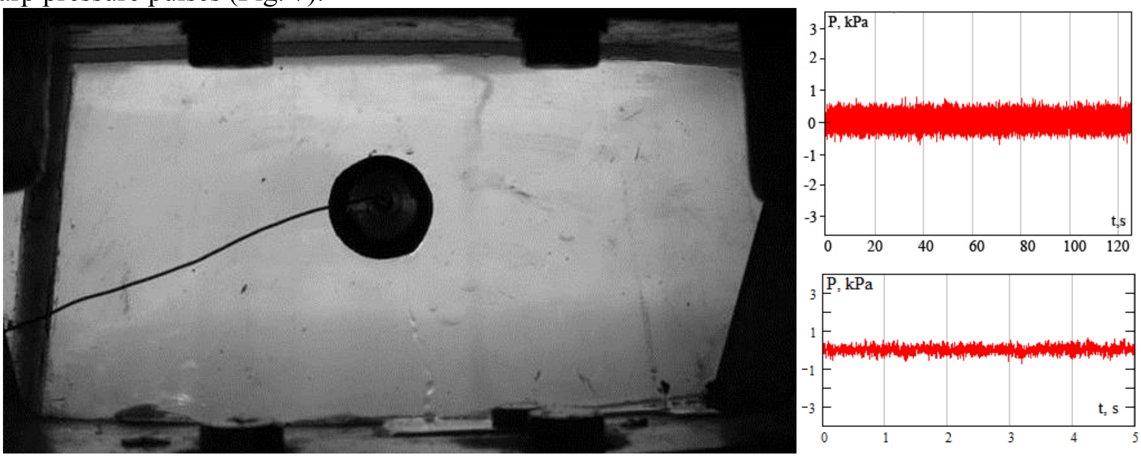

Figure 7. Visualization of mode 91% and a pressure sensor signal

The FFT also does not detect the presence of vortex structures with a constant frequency. Only the f_{rot} = 8.5 Hz is visible (Fig.8).

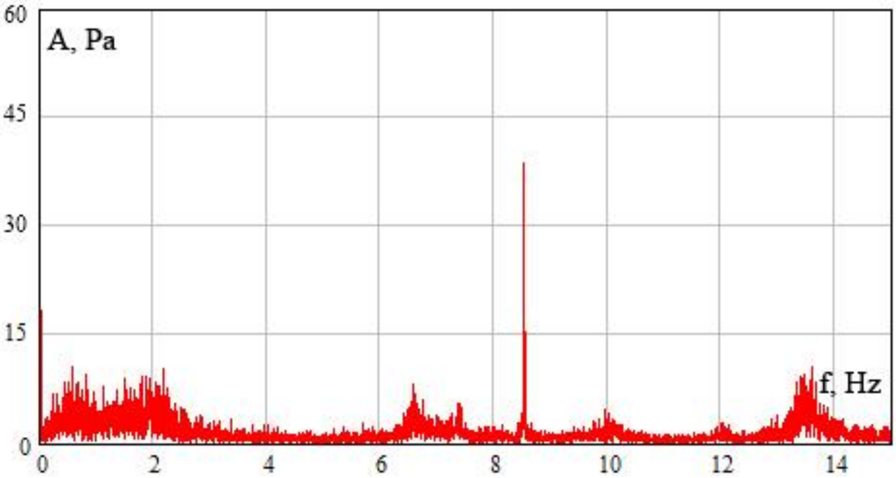

Figure 8. Spectrum of pressure pulsations (91% loads)

4. Conclusions

Thus, in this paper, on a hydraulic set-up with a Francis turbine constructed similar to real hydraulic units the operation mode with phenomenon of vortex rope reconnection was studied. Aperiodic pressure pulses connected with separation of vortex rings and their passage near the wall were observed experimentally. The following parameters of the flow with phenomenon of the vortex rope reconnection and separation of vortex rings were defined in first time and divided to period of runner rotation: Average periods of vortex rope precession, vortex rings separation, pressure pulses on the pressure sensor and most probable period of pressure pulses appearance.

Such phenomena can take place in the flow path of full-scale water turbines. Therefore, reconnection of the vortex and formation of vortex rings in water turbines is of great interest for fundamental and applied science and requires further study.

Acknowledgments

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