Original Paper

An Experimental Investigation of the Air Injection Effect on the Vortex Structure and Pulsation Characteristics in the Francis Turbine

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Abstract

The paper studies the pulsation characteristics of the flow when operating a medium-scale hydrodynamic test bench with a Francis turbine. The pressure fluctuations measurements and flow structure visualization were performed for all operation modes of the hydraulic unit. To control and suppress pulsations in the flow path, a series of experiments on air injection to the hydraulic unit were carried out. Comparison of pressure pulsations for single-phase and two-phase flow experimentation has shown that for modes with maximum loads, the pressure pulsations can be reduced almost to a half by means of air injection. The effect of air injection is also studied with respect to the efficiency of the hydraulic turbine.

Keywords: Francis turbine; pressure pulsations; two-phase flow; experiment; vortex rope; hydroelectric power station.

1. Introduction

The operation of a reaction-type hydraulic turbine is based on the formation of a swirling flow. Passing the spiral chamber and the guide vanes, the flow becomes strongly swirled. It is used then to transmit the turbine torque to the runner. In the optimal operation mode, the turbine runner uses almost all this torque and, as a result, the weakly swirled flow behind the runner does not cause any serious pressure perturbations in the system. In the operation mode with partial loading of the hydraulic turbine, the flow after passing through the runner has a sufficiently large residual swirling, and therefore, a certain portion of the kinetic energy of the flow is not converted into mechanical energy of the turbine shaft rotation, and thus it is wasted in the draft tube. In this case, the flow behind the runner rotates in the same direction as the flow swirled by the spiral chamber and the guide vanes. In high load mode, the flow in the draft tube rotates in the direction opposite to the initial swirling.

The residual swirling of the flow leads to the appearance of the flow recirculation zone, and as a consequence, the formation of a precessing vortex rope [1, 2]. This phenomenon was observed in experimental models of draft tubes [3, 4]. Precession of the vortex rope is one of the mechanisms generating low-frequency flow pulsations in hydraulic turbines [5-20].

The operation of the hydropower plant (HPP) in the power-supply system is associated with the power regulation in the network that inevitably entails the operation of the hydraulic unit at suboptimal operating modes, in which a high level of hydrodynamic pressure pulsations take place in the draft tube. To reduce hydrodynamic pulsations, various methods of the flow stabilization are applied including *air injection* [21-27] into the flow, the use of *stabilizing structures* (*fins* [2, 4, 21, 28, 29], *crosses* [28], *hollow cylinder* [2, 21, 30]), modification of the *runner fairing* [31], and flow stabilization by means of *water jets* [32-34].

It is worth noting that almost all flow stabilization methods have drawbacks. In particular, stabilizing fins show quite a good efficiency in reducing pressure pulsations [28] however their use is advisable only at a partial load of the hydraulic unit. In the optimal mode, on the contrary, fins can lead to an increase in the pressure pulsations [2] acting as additional vortex generators in the flow (*this also applies to the cross, as well as to the cylinder*). The fins, as well as other stabilizing structures, are subject to strong dynamic loads and cavitation wear and can lead to damage of the flow path elements. In addition, the use of structures can reduce the efficiency of the turbine [28].

The use of nozzles and changing the shape of the runner fairing, in turn, can lead to additional dynamic loads on the runner [4].

The use of water jets injected through the runner fairing is apparently impractical, since the required amount of water can reach 10% of the total water flow of the turbine unit [33-35].

From all the above we can assume that the most promising method of dealing with hydrodynamic pressure pulsations is injecting air into the flow path of the hydraulic turbine. A technological solution for air injection into the flow is proposed in [36]. This design provides air injection under the turbine runner; the device is installed on the end of the hollow shaft of the runner. The disadvantages of this method are that the air injection is made spontaneously, the air volume is not controlled, and the injection is carried out after the event when the cavitation rope is already formed. At the same time, the main advantage of air injection, in contrast to the stabilizing structures, is that it can be used selectively within the required ranges of the unit operation.

There is successful practice on forced air injection into the flow path of existing hydropower plants (HPP). For example, Zagorskaya pump-storage plant [37] managed to reduce the pressure pulsations in the area of the guide vanes by 21%, while vibration – by 47%. Turbines of Iovskoe HPP [38] are operated with the air injection into the flow path that reduces the hydrodynamic load by three times.

Conducting experiments on air injection at hydropower plants is not always feasible due to the cost and insecurity of these tests; therefore, experiments on reduced and simplified hydraulic turbine models are an acceptable alternative. Currently, there are a lot of works in this area. Thus, in [21] a series of experiments were carried out using hydraulic units with a 95 MW Francis turbine. The air injection was carried out in front of the guide vanes. As a result, during the turbine unit operation at a partial load, the pressure pulsations amplitude in the draft tube was reduced by 30%, while the pressure pulsations on the wall was decreased more than twice.

In [23-25] the influence of air injection at different points was investigated with respect to turbine operating efficiency. Air was supplied through the central shaft of the turbine runner, the side wall of the inlet diffuser of the draft tube, and the trailing edge of the runner blade. The maximum efficiency drops down to 4% was observed when supplying air through the central shaft, whereas the distributed air injection resulted in a slight decrease of efficiency by 1% at the air fraction of up to 3%.

The study of peripheral air injection into the draft tube, using several hydraulic unit models was carried out in [27]. It was observed that air accumulates in the low-pressure zone in the center of the tube, destroying the vortex rope. However, it was noted that the insufficient amount of air did not stabilize the flow. The central vortex could become more unstable and lead to an increase in the pressure pulsations. When reaching a certain air concentration, the flow was stabilized sharply. It was revealed that the critical air flow rate ranged from 1.5 to 2.5% of the water flow rate for various model installations.

The distributed air injection under the runner is studied experimentally in [26]. The study was conducted for six load control points. Five pressure sensors were distributed along the wall of the draft tube. It is shown that the basic harmonic in the frequency spectrum is associated with the flow instability (vortex precession) and amounts to 15-20% of the runner rotation frequency. For this particular Francis turbine, it is shown that in the partial load mode of 30-60% of the maximum efficiency, the air injection leads to a significant increase in the pressure pulsations. In particular, long-term operation in the mode corresponding to 42% of the maximum efficiency of the turbine with air injection can lead to mechanical problems. These results contradict the data obtained in [22]. Also in the work [26], it is noted that the pulsations of the flow upstream the place of air injection can significantly increase.

Thus, the literature review has shown that there are both works in which a decrease in pressure pulsations was observed when injecting the air, as well as works in which it is shown that injection of the air leads to the opposite effect, namely, an increase in pressure pulsations. In addition, most of the studies on this topic carried out earlier, consider the effect of air injection within very narrow ranges of the turbine operation, usually near the zone with maximum pulsations. In fact, no works are available, in which the effect of air injection is investigated within the entire range of turbine operation. Based on the above, despite a large number of works in this area, the problem of air injection to the hydraulic unit has not yet been fully studied, and additional experimental data are needed.

In this paper, we conducted an experimental study on the impact of air injection on the vortex flow pattern, low-frequency hydrodynamic pressure pulsations, and the efficiency of the turbine within a wide range of operating modes. The experiments were carried out using the medium-scale hydrodynamic test bench with geometrical parameters maximally close to the design of the existing hydroelectric power plants.

2. Experimental test bench and measurements technique

The hydraulic turbine model with a Francis runner is installed in the power test bench of the Hydraulics and Hydraulic Machines of the Sayano-Shushensk Branch of Siberian Federal University (Fig. 1). The head in the test bench varies from 1.5 to 3.5 m, the runner is of Francis type with 14 blades, 0.3 meters in diameter. The guide vanes contains 24 blades with the height of 0.106 m. The servo drive of the guide vanes has 10 opening steps. The inlet diffuser of the draft tube is 0.153 m long with an opening angle of 8.68°.

Fig. 1 Photography of the energy test bench.

The hydraulic unit (Fig. 2) includes the following components: 1 – pressure tank performing the functions of the upper pond; 2 – turbine water pipe 400 mm in diameter with a valve equipped with an electric drive 3. From the water duct 2, water enters the spiral chamber 4, from where through the guide vanes flows to the runner and further, passing through the draft tube 5, runs into the lower pond 6, which is a glass tray 1.52 m wide. After the tray, the water is discharged into the pool 9 through the pipe 8. From pool 9, water is pumped by the pump 10 back to the pressure tank. Thus, continuous water circulation in the closed loop is provided. The test bench is equipped with two pumps with a total capacity of up to 500 m³/h. The parameters of the test bench allow achieving the maximum Reynolds number in the test channel, $Re = 5.4 \cdot 10^5$, and the cavitation number to be far more than 10. The speed coefficient for the runner is $n_s = 140$ rpm.

Fig. 2 Schematic diagram of the model test bench.

The pressure head was determined by the difference between the upper and lower water levels with an error of 0.01 m (about 0.3%). The rotation speed of the runner was controlled by DT-2234C digital tachometer with a measurement error of $\pm (0.05\% + 0.1 \text{ rpm})$. Flow rates were measured by installed Metran-300 PR eddy-acoustic flow meters 7 with a measurement error not exceeding 2%. To register the pressure pulsations, the test bench was equipped with piezoelectric flow sensors of 014MT (014MI) type with the frequency range $\leq 0.1 \text{ Hz}$ for frequencies up to 30 kHz, and the operating pressure range from 0 to 10 MPa with an increment of 10 Pa.

The signal was amplified by an external module LE-41, which was a 4-channel charge amplifier. Analog-to-digital encoder ADC E14-140T was used to input sensor signals to the PC. The sampling frequency of the ADC in the experiment was 1000 Hz. The signal recording time was five minutes. The L-Graph software was used for collecting data from piezoelectric sensors and primary processing.

Two pressure pulsation sensors 014MT were placed in the inlet diffuser of the draft tube opposite to each other 10 cm below the edge of the runner (Fig. 3). The sensors were flush-mounted with the wall and did not make significant changes to the flow. The amplitude and pressure pulsations frequency were measured exactly in these points at a different opening angle of the guide vanes and the pressure head.

Fig. 3 Schematic diagram showing the installation of the sensors and the air injection point.

Air supply to the flow path of the hydraulic turbine was carried out using a Remeza SB4/S-50LB.30A compressor with a capacity of 420 l/min and a pressure of 10 bar. Air was supplied through the fittings installed in the available fabrication holes of the flow path of the hydraulic turbine (Fig. 3).

Table 1 The experimental errors

H, cm	0.3%
ω , rpm	$\pm(0.05\% + 0.1 \text{ rpm})$
N, kW	0.1%
Q_{water} , m ³ /h	2%
Q_{air} , m ³ /h	1%

The air flow rate supplied to the water-conveyance part of the hydraulic turbine was controlled by IRVIS-RS4M-Ultra ultrasonic flow meter with the measurement error not exceeding 1% of the measured volume. Experimental uncertainties are shown in Table 1.

3. Experimental results

During the experimental work, pressure pulsations were measured in the entire range of the hydraulic unit operation modes at different pressure heads and the opening angle of the guide vanes. At that, the rotation speed of the runner, the water flow rate through the hydraulic unit, as well as current and voltage (i.e. load) at the generator were recorded.

The main integral characteristics of the model turbine for the pressure head $H = 310$ cm were measured depending on the opening angle of the guide vanes. The opening of the guide vanes ranged from 1 to 10 (10, 20, ... , 100%). This range allowed covering all operation modes of the hydraulic unit. Turbine efficiency was defined as follows:

$$\eta = \frac{N}{\rho g H Q} \quad (1)$$

where N is the electric power at the generator shaft, Q is the water flow rate through the turbine, ρ is the water density, and g is the acceleration of gravity.

To begin with, data were obtained for the standard operating mode of the turbine (with single-phase flow). The results of this study are given in more detail in [39]. Here we will only describe the major points for a better understanding.

With an increase in the opening angle of the guide vanes, water flow rate increases by about four times, while the efficiency increases from 40 to 60%, reaching a maximum when the guide vanes is opened by 80% [39].

A high-speed video camera was used to observe visually the vortex structure of the flow in the diffuser of the draft tube. High-speed video recording was conducted at a frequency of 1000 frames per second. Analysis of video recording has shown that the flow structure undergoes significant changes with the increase in the opening angle of the guide vanes. At small openings of the guide vanes, no single concentrated vortex is formed in the diffuser of the draft tube. The flow behind the draft tube consists of several barely discernible chaotically moving vortex structures. Besides, in these modes, one can see that blades are streamlined

not in the design modes, vortices are formed in the inter-blade channels of the runner, detaching further from the exit edges of the blade.

With further increase in the opening of the guide vanes, a concentrated precessing vortex rope starts forming behind the runner. When opening at 50%, precessing vortex rope behind the runner reaches its maximum size, stretching to the elbow of the draft tube (Fig. 4). In this mode, the intensity of pressure pulsations in the diffuser of the draft tube reaches the maximum value. In addition to its considerable length, the vortex in Fig. 4 has the largest precession radius, and therefore, maximally approaches the walls of the draft tube, causing significant pressure pulsations at the wall.

With the further opening of the guide vanes, the flow swirling decreases, the concentrated vortex behind the runner loses its intensity, while its precession radius decreases significantly. In the optimal operation mode of the hydroelectric unit, the radius of the vortex precession is reduced to almost zero, and the vortex becomes almost columnar. The pressure pulsations in this mode become minimal.

Next, a series of experiments were conducted on the air injection into the hydraulic turbine. The air injection was carried out by means of the available fabrication orifices (Fig. 3). In this particular case, the orifice is made in the spiral chamber, just below the middle line of the guide vanes. During the experiments, the air flow rate varied from 0 to 11 m³/h.

Figure 4 shows the effect of air injection on the vortex structure. The pictures are obtained by means of high-speed recording in the turbine operation mode with maximum pulsations. Figure 4a shows the standard precessing vortex rope at guide vanes opening $A_0=50\%$. Figure 4b shows the vortex structure at the air injection. It is obvious that the air significantly reduces the intensity of the vortex rope, reducing its precession radius that in turn leads to a decrease in flow pressure pulsations.

Fig. 4 Visualization of the vortex structure at the opening of the guide vanes $A_0=50\%$

(a – without air injection; b – with air injection, $Q_{air} \approx 1\%$).

This fact is confirmed by Fig. 5a. The graph shows the pressure pulsations signal depending on time. The line shows the point in time corresponding to the air injection. It is seen that the pressure pulsations amplitude is significantly reduced after air injection into the flow path of the turbine.

Fig. 5 Pressure pulsations depending on time ($a - A_0 = 50\%$; $b - A_0 = 80\%$) in the draft tube cone ($Q_{air} \approx 1\%$).

Figure 6 shows the pressure pulsations spectra in the cone of the draft tube with and without air injection, respectively. The Fig. 6a shows a comparison of spectra for the mode $A_0 = 50\%$. It is seen that the air injection leads to a significant decrease in the amplitude of the pressure pulsations at the vortex rope frequency (by more than 3 times) and a change in the vortex precession frequency.

Fig. 6 Pressure pulsations spectrum in the draft tube cone (*solid curve – without air; dotted curve – with air injection; a – $A_0 = 50\%$; b – $A_0 = 80\%$*)

The dependence of pressure pulsations at the vortex rope frequency on the quantity of injected air is presented in Fig. 7. The graph shows that the air allows reducing the pulsations at the vortex rope frequency by almost ten times. However, it should be noted that this reduction occurs at a ratio of the air flow rate $\approx 1\%$ of the total flow rate, and does not change significantly with a further increase in the volume of supplied air.

Fig. 7 The pressure pulsations amplitude at the vortex rope frequency depending on the volume of injected air ($A_0 = 50\%$; $H = 350$ cm; $Q = 349.8$ m³/h)

In the modes with the highest level of pulsations, the pressure pulsations reduction when injecting air is observed not only at the vortex rope frequency but across the whole spectrum. The fact of pressure pulsations decrease is confirmed by the dependence of the root mean square (RMS) pressure pulsations on the amount of air injected (Fig. 8a). One can see from the graph that by means of air it is possible to reduce the pressure pulsations almost twice. But it is worth noting that this is achieved by the maximum possible amount of air injected.

Fig. 8 Pressure pulsations into the draft tube cone depending on the amount of air injected
($a - A_0 = 50\%$; $b - A_0 = 80\%$)

The investigation of the air injection within the entire range of the hydraulic unit operation has shown that the air injection can lead not only to a decrease but also to an increase in the flow pressure pulsations. Figure 5b shows the pressure pulsations in the inlet cone of the draft tube depending on the time at the opening of the guide vanes $A_0 = 80\%$, which is close to the optimal mode of hydro turbine operation. The line on the graph corresponds to the beginning of air injection. As can be seen from the graph, the air injection leads to a significant increase in the pressure pulsations amplitude. The dependence of the RMS pressure pulsations in the mode close to the optimal regime is shown in Fig. 8b. It can be seen that with the increase in the volume of injected air, the intensity of the pressure pulsations increases monotonically. At that, the air injection has no significant effect on the range of pressure pulsations (Fig. 6b).

Figure 9 shows the double amplitude of pressure pulsations on the wall, which is nondimensionalized to the full pressure head $H = 310$ cm. One can see the pronounced maximum and minimum in pressure fluctuations. This configuration of the pressure pulsation curve is typical for Francis turbines [40]. On the graph, it is possible to distinguish the zone of high loads with a maximum level of pulsations of the order of 10% of the pressure head, the optimal zone of low pulsations, in which the hydraulic unit is operating most of the time, and the zone of forced turbine load, which again is characterized by an increase in the level of pressure pulsations.

It is apparent that the air injection at the openings of the guide vanes equal to 40 and 50%, which corresponds to the modes with maximum loads, allows reducing the pressure pulsations by 15%, while the air injection at the modes close to optimal ones (70 and 80%) leads to an increase in the pressure pulsations by several times.

Analyzing these data, we can conclude that the air injection into the turbine flow path makes sense for the modes with a partial load in the region where the loads are maximal. In these modes, the air injection can effectively reduce pulsations. However, in the modes close to the optimal, air injection, on the contrary, leads to an increase in the pulsations, although in these modes the pulsations are so close to the minimum so that air supply is impractical.

Fig. 9 The RMS pressure fluctuations in the draft tube cone depending on the opening of the guide vanes (1 – without air injection; 2 – air injection in an amount of 1% of the total flow rate)

In our previous works [41, 42] conducted using this experimental test bench, in the modes close to the optimal, a very interesting phenomenon was revealed, namely, detachment of a vortex ring. Visualization of the flow vortex structure behind the runner of the turbine made it possible to detect the vortex reconnection at the opening of the guide vanes by 70%. As can be seen in Fig. 10a, at an opening of 70%, the concentrated vortex in the turbine is rather extended, and when making precessing motion, it twists forming a loop, followed by detachment of a vortex ring. Such behavior of the precessing vortex in a model installation

with a blade swirler is described in [43, 44] however, in the case of installations close to real hydraulic units this phenomenon was recorded for the first time.

Figure 11a shows the time dependence of static pressure recorded by one of the sensors installed in the diffuser of the draft tube. The graph clearly represents the irregular pressure surges, which are approximately 3-4 times greater in magnitude than the general level of the signal in this mode. Analysis of vortex structures and pressure pulsations has shown that the vortex ring impacts the turbine walls locally since pressure surges are recorded only in the case of passing the ring directly near the pressure sensor. At present, this phenomenon has been studied very poorly with regard to hydraulic turbines and thus is of great interest for both applied and fundamental science.

In this context, it is very interesting to consider how air injection will affect the vortex reconnection and the ring detachment phenomenon. Figure 10b shows the flow pattern for the mode with the ring formation at the air injection. The air flow rate was about 1% of the volumetric water flow rate.

Fig. 10 Visualization of the vortex structure at the opening of the guide vanes $A_0=70\%$

(a – without air injection; b – with air injection, $Q_{air} \approx 1\%$)

Figure 11 shows that air injection does not prevent the formation of vortex rings. However, while looking at the pressure pulsations signal in the diffuser of the draft tube for concerned mode (Fig. 11b) it can be seen that the sensors do not record surges of pressure pulsations (shocks). This can be explained by the fact that the air injected in this mode is distributed along the walls and prevents the ring from hitting the wall of the draft tube.

From the results obtained, it can be concluded that the vortex rings continue to form when the air is injected, but their influence on the diffuser wall of the draft tube is markedly reduced.

Fig. 11 Time dependence of pressure pulsations in the draft tube cone, $A_0=70\%$

(a – without air injection; b – with air injection, $Q_{air} \approx 1\%$)

In many works, it is noted that the main disadvantage of air injection is a significant reduction in the efficiency of the turbine. Figure 12a shows the change in the efficiency (η) of the hydraulic turbine for the mode with maximum pressure pulsations at $A_0 = 50\%$ of the supplied air volume.

Fig. 12 The hydraulic turbine efficiency variations (a – flow mode at $A_0 = 50\%$; b – the hydraulic turbine efficiency depending on the opening (1 – without air injection; 2 – with air injection $Q_{air} \approx 1\%$).

This figure (Fig. 12a) shows that the air injection into the flow path in an amount of up to 1-1.2% of the water flow rate through the turbine does not significantly affect the efficiency of the hydraulic turbine. A further increase in the air flow rate leads to a significant reduction in the efficiency. Figure 12b represents the dependence of the hydraulic turbine efficiency within the entire range of operation for the mode without and with air injection at a flow rate of $\approx 1\%$ of the water flow. The graph shows that in all air injection modes, the efficiency of the hydraulic unit operation is almost independent of the air injection.

Thus, the optimal air flow rate required to effectively reduce the hydrodynamic pressure fluctuations in the draft tube at the operating mode of guide vanes equal to $A_0 = 50\%$ of the optimum value is $\approx 1\%$ of the water flow rate flowing through the turbine. This air flow rate does not affect the efficiency of the hydraulic turbine while results in an effective reduction of the pressure pulsations.

4. Conclusions

A series of studies of the air injection effect on the pressure pulsations in the turbine flow path was carried out using a medium-scale hydrodynamic test bench. Air was injected into the spiral chamber. The volumetric air flow rate varied from 0 to 3% of the water flow rate. The study was performed for various openings of the guide vanes that allowed covering the entire range of hydraulic unit operation modes. In the course of experiments, the amplitudes and frequencies of pressure pulsations in the diffuser of the draft tube were measured.

It is shown that the maximal pressure pulsations, equal to 10% of the water pressure head, were observed in the turbine operation mode corresponding to the load equal to 30-60 % of rated power that is typical for Francis turbines.

In consequence of the study, a significant impact of air injection on the intensity of pressure fluctuations is shown. It is established that the air injection in the modes close to the optimal regimes leads to a significant increase in pressure pulsations, while the air injection in the modes with maximum pulsations can significantly reduce them.

During the experiments, the optimal air flow rate was determined, necessary to reduce effectively the hydrodynamic pressure pulsations in the draft tube of the hydraulic turbine when operating at the guide vanes opening equal to 50% of the optimum value. It was found that the optimal air flow rate is 1.0% of the water flow rate. With this air flow rate, the hydraulic turbine efficiency is not decreasing, while the pressure pulsations in the draft tube are essentially reduced. Thus, in consequence of the research, it was

proved that the use of air injection is advisable only in the modes with maximum pressure pulsations.

Also in the work, the influence of air injection on such an interesting and little-studied phenomenon as the formation and detachment of vortex rings in the flow path of the hydraulic unit is investigated. By means of the high-speed video, it is shown that the vortex rings continue to form when the air is injected, but at that, the pressure pulsation sensors do not record pressure pulsation surges. The rings simply drift down the flow without having a significant impact on the walls of the draft tube.

Acknowledgments

The reported study was funded by RFBR and the government of Krasnoyarsk region according to the research project № 18-48-242007 r_mk.

Nomenclature

A_0	opening guide vane, %	n_s	speed coefficient for the runner, rpm
D	inlet diameter the draft tube, m	Q	volume flow rate the turbine, m ³ /h
g	acceleration of gravity, m/s ²	Re	Reynolds number, $\left(\frac{\rho 4Q}{\pi D \mu} \right)$
H	the pressure head, cm	RMS	root mean square
N	electric power at the generator, W	η	efficiency turbine, %
		ρ	density, kg/m ³

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