SWIRLING FLOW IN FRANCIS TURBINES DEPENDING ON GUIDE VANES OPENING POSITION

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Abstract. The objective of this paper is to discuss site tests, where the swirling flow and the resulting vortex rope were registered. The vortex rope is a low-frequency phenomenon occurring in the Francis turbine draft tubes. The draft tube surge (instability in the draft tube containing swirling flow) is flow-induced and results in vibration in hydroelectric machinery, which causes instability, restricts the operation of the turbine in specific modes and as a result does not allow to generate as much power as the user would like. The tests also showed that draft tube surge, if severe, could have effect on the generator. The selected data were obtained on the set of the Francis turbine hydropower units (98 MW rated output, 13.8 kV, 50 Hz hydropower units with umbrella-type hydrogenerators) through many years of measurements in the Latvian hydro-electric power plant. The site tests showed that draft tube surge appeared at low generating power, as expected from the literature review, but this phenomenon was detected also quite close to the best efficiency point. The conditions necessary for the swirling flow to appear is not simply small generating power. It rather depends on the water head and the guide vanes opening position, which is adjustable in Francis turbines. For 98 MW unit the swirling flow would appear at 60 MW power, but it could also appear at 80 MW power at specific conditions presented in the paper.

Keywords: Francis, vortex rope, swirling flow.

Introduction

The review paper on the draft tube surge in Francis turbines [1] claims that respective phenomena have been researched for in the last three decades. In a Russian book it was mentioned in 1972 [2], so it has been almost 5 decades till now. The draft tube surge research problem was thoroughly addressed by EPFL, Lausanne, Russian Hydropower Institutes and the China Hydropower Institute, the Brno University of Technology, Kaplan Department of Fluid Engineering, the Czech Republic etc. The specific low frequency phenomena appeared in Latvian hydropower stations as well, but it was never reported before to the research community in details.

The goal of this paper is to summarise and compare the fundamental theoretical techniques of vortex rope prediction with the site tests results. Therefore, this paper aims to provide the summary on cases, when low frequency phenomena were registered in Latvia, as a humble contribution to the knowledge field on the topic.

The authors believe that every hydropower generation unit is unique, and this review of field studies and site investigations would be topical, although so many high-quality researches to examine the draft tube vortex phenomena have been done in the lab on reduced-scale models, stationary swirl generators and complete turbine models with a runner, where radial distribution of velocities are closer to that in an actual turbine [3] and through Computational Fluid Dynamics (CFD) simulations by other scholars. CFD simulations results have been presented since 1999 [3], but for this phenomenon computation simulation and field experiments are both important, because there are always small deviations in the turbine operation on site from that of the model predictions. As stated by Koutnik et.al., the vortex rope shape is hard to predict by CFD analyses [4]. It was fairly noted by Wang et.al. that not many researchers could take a large prototype of the Francis turbine as a research object by using ongoing site tests [5]. Site tests take years, if one would like to experiment with maximally different water head. Meanwhile, model tests do not show the full picture for special operating conditions [5] and “measured pressure pulsations cannot be directly transposed from model to prototype” [4].

In the Francis turbine the draft tube (composed of cone, elbow, and diffuser [6]) is responsible for waste water to flow into the downstream reservoir. There is always a little swirl entering the draft tube [3], because water enters the Francis turbine radially – from the river side, but exits down at some angle (axially), and water keeps some radial momentum. At the best efficiency discharge the swirl is almost zero, therefore called “zero swirl [3]“. In contrary, for some operation modes the swirl gets larger, causes vibration and requires user attention. Since Nishi research in 1980 [7], the research community agrees that “the pulsation consists of a synchronous part, a plane wave, and an

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asynchronous part – the precession movement of the rope" [3]. The authors developed the theoretical equations to describe the phenomena in [8].

Majority of authors agree that swirling flow occurs far from the best efficiency [9] at both high and low load [3;10], and for overload as well [11], and experts point out that swirling flow is characteristic specifically to the low load at 60-65 % from unit optimal power [11].

The hydropower turbines are slow-speed machines. Most of the units have the speed in the range 1-3Hz [11]. The researched units have the rotational speed 1.47 Hz. Meantime, draft tube surge is even more typical for partial load cases, and its frequency is a couple times smaller than the rotational frequency and it is not constant in different modes [11]. A number of vortex rope frequency prediction techniques are available in the literature [1]. The authors mainly try to give one coefficient, which would be useful for the design stage. As noted by Wang: "The characteristic frequency of unsteady hydraulic feature is not clear until now for such a large turbine at different operation conditions" [5]. As early as in 1940 Rheingans quoted in [1] found out the dominant frequency "being close to 1/3.6 times the runner rotational speed at the greatest pressure fluctuations". In a Russian book the coefficient of 4.2-4.6 was proposed for Kaplan turbines [2;11], but for Francis turbines the coefficient 3.6 remains true in the performed site tests.

The fact that swirling flow has low frequency (even as low as 1 Hz) brings some consequences.

As noted by [3], the swirling flow frequency could be close to 1 Hz, and therefore it can produce output power swings [3;10;12;13].

User should use special equipment to register swirling flow vibration, because accelerometers are rarely designed to register such low frequencies, therefore, for the site tests displacement sensors were chosen as described further in the Materials and methods section. Displacement of the shaft shows well the changes in vibration under 1 Hz during slow-speed motion.

Finally, let us discuss the most efficient ways of elimination of the vortex rope. Over two decades users deal with the draft tube surge problem by air injection and installation of fins [8]. However, injection of compressed air into the draft tube requires considerable power [7]. In Latvia the fins (locally called the ribs) were installed on one of the hydropower units, and the researcher, who participated in the design and installation process, claimed that it was a successful solution, which reduced low frequency vibration on part load and reduced vibration in general as well [14], but for this paper we purposely chose the units where no fins were installed. As stated by [3], sometimes neither air injection nor fins installation solve the problem, and the user still needs to adjust operation of the turbine to avoid vibration caused by vortex rope.

Materials and methods

The data presented in this paper were selected from structural vibration measurements. It was specifically radial and vertical displacement of four hydropower turbines of the Francis type, called in the paper F1, F2, F3, F4. The rated speed of the units was 88.2 RPM. Selected units have 98 MW rated power. The units were first put in operation in 1965, two units were modernized ten years ago. Compared to other studies like [5], the investigation was carried for a rather narrow load range of 60 MW-103 MW in the condition of the water head 34 m-39 m, and it still took around five years to complete. Although it is known that vortex rope appears "over a range of the relative turbine discharge between approximately 0.5 and 0.85 of the flow at best efficiency" [3], on site turbine discharge is hard to measure, and we prefer to measure some relative parameters, like the velocity of the flow or the pressure in the water channels. In this paper we would concentrate on the parameters, which are easy to measure and control – water head, guide vanes opening position and generated power.

The directions, in which the user would like to register displacement to get the full picture of the vortex rope effects, are radial and vertical directions.

- Radially. Shaft displacement relative to the thrust bearing case. In radial direction one would register effects of vortex rope, which dissolves at the top of the draft tube [11]. For shaft displacement, two non-contact inductive probes were displaced by 90 degrees on both the generator and turbine bearings to measure the radial relative displacement.
- Vertically. Turbine vertical displacement relative to the turbine casing wall. In vertical direction the user could register greater displacement, when vortex rope dissolves at the

bottom of the draft tube [11]. For some measurements a special rod was added to the turbine wall and an inductive probe attached to this rod to register displacement in vertical direction.

The sensors chosen were inductive displacement sensors of type CMSS68 with sensitivity of 7.8 mV/µm, displacement range 0-2,7 mm. The 3 minutes long signal obtained in each mode was analysed to ensure statistically correct data. The multi-channel FFT analysis of data was made through National Instruments LabVIEW software. For spectrum results FFT was used. In this paper the obtained results were exported to MSC Excel. All presented values are RMS values.

Results and discussion

Vortex rope characteristic frequency amplitude could be greater than nominal rotational speed characteristic frequency amplitude.

As early as in 1972 [2] it was noted that draft tube surge does not depend only on the rotating speed of the turbine, but rather on its load. Both part load and overload instabilities depend on the net head of the machine [12]. In Fig. 1 the spectrum of the shaft displacement relative to the turbine bearing for unit F1 is presented, when the net head was low, and the net load was small.

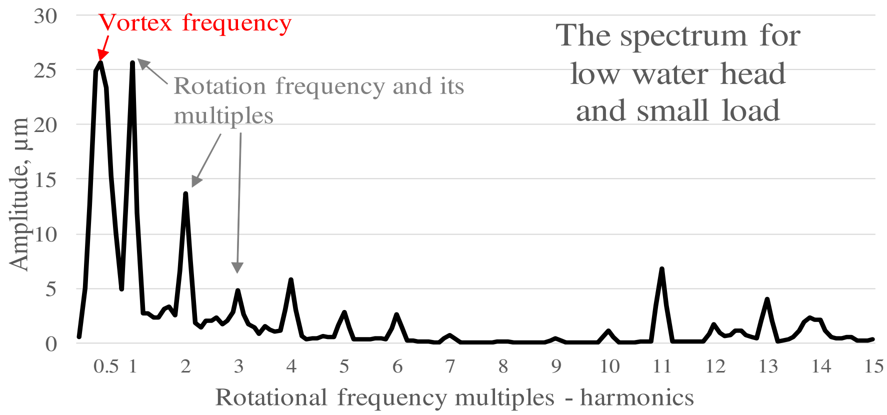

Fig. 1. **Shaft displacement relative to turbine bearing of F1 at 65 MW, 34.03 m head**

In Fig. 1 the harmonic of the draft tube surge is 0.3X-0.5X. It is the vortex rope characteristic frequency [1]. It has greater amplitude than harmonic 1X for nominal rotational speed. The nominal rotational speed frequency 1X is almost always dominant in the vibration spectrum, therefore, this case is of special interest to diagnosticians. The water head was very low, just 34.03 m, and the guide vanes opening position was small 355 mm, so the load was minimal – 65 MW. This example supports the statement that draft tube surge appears on low load, because the turbine was operated at 65-66 MW out of 98 MW, while the maximum load registered at 34.03 m, the head was 88 MW.

The situation, when the vortex frequency was greater than the rotational frequency, was registered for another unit as well. In the year of 2015 the unit F2 was tested for the load from around 58 MW to 98 MW, 0 MVAr, at the water head 37 m, the suction head was 2.84 m. In Table 1 the data, where vortex rope was detected and was greater than the rotational frequency, are presented. For greater power vortex registered, the amplitude was small – 3 µm and 4 µm.

Table 1

Vortex rope amplitude greater than main frequency, unit F2, 37 m head

Power, MW	Guide vanes opening position, mm	Radial shaft displacement, µm				Vertical displacement, µm	
		Sensor 1		Sensor 2			
		Vortex freq.	1X	Vortex freq.	1X	Vortex freq.	1X
58.8	317	71	17	52	16	54	18
62.9	330	46	19	32	21	43	19
66.5	340	21	7	16	6	23	15
69.5	351	19	6	16	4	21	16
73.7	362	11	6	8	5	15	17
75.7	371	7	7	5	4	12	16

Table 1 confirms that vortex rope is indeed the greatest for a small load as 58.8 MW, but it is still present for a medium load 75.7 MW for this unit. The same unit was tested in 2015 for the water head 38 m, the suction head was 4.46 m. Table 2 shows that the draft tube surge was less severe for this head.

Table 2

Vortex rope amplitude greater than main frequency, unit F2, 38 m head

Power, MW	Guide vanes opening position, mm	Radial shaft displacement in µm				Vertical displacement in µm	
		Sensor 1		Sensor 2			
		Vortex freq.	1X	Vortex freq.	1X	Vortex freq.	1X
63.03	317	14	6	10	5	10	5
68.50	335	11	6	7	5	10	5
72.68	349	8	7	5	6	14	5
77.81	361	11	7	6	6	10	6
81.15	370	8	7	4	5	11	5
84.2	379	5	8	3	6	7	5

Comparing Table 1 and Table 2, it may seem that the lower the water head, the greater the vibration caused by vortex rope should be. It is only partly true. In 2015 the unit F2 was tested at the lowest possible water head 34.8 m, the suction head was 1.61 m. For vertical displacement the vortex frequency was noticeable, but not higher than 1X for loads 68 MW, 71 MW, 73.6 MW, meanwhile radial displacement did not show significant effect of the vortex rope, it was not higher than 1X, for 68 MW it was the same – 9 µm and in the rest of the modes it was smaller.

Upgraded units experience vortex caused vibration mainly in vertical direction at low load.

Units F3 and F4 were upgraded one decade ago. Unit F3 was tested in 2015 at the water head of 35.48 m, the suction head was 2.35 m, for the power range from 71.6 MW to 92.8 MW. Vortex caused vibration was detected through vertical displacement in modes under 80 MW, radial displacement showed only values less than 5 µm. Another two tests were performed in 2015 at a similar water head of 34.86 m, the suction head was first 0.54 m, the power range achieved was 66.2-92 MW and then the suction head was 1.72 m, and the power range achieved was 65.3-90.8 MW. Vertical displacement amplitude of vortex rope was greater than 5 µm under 75 MW, reaching 30 µm at 66 MW and 65 MW, while radial displacement amplitude of vortex rope was never greater than 1X, reaching maximum of 20 µm at 66 MW and 15 µm at 65.3 MW, less than 10 µm at under 70 MW, and less than 5 µm at other modes.

Unit F4 was tested in 2015 at the water head 34.36 m, the suction head was 1.59 m, the power range from 66.5 MW to 91.4 MW, and vortex vibration was detected through vertical displacement and radial displacement. It was over 10 µm for small loads under 75 MW only and was never greater than 1X. Specifically, the vertical vortex caused vibration frequency was 18 µm (while 1X was 21 µm) at 66.5 MW, 12 µm (1X was 21 µm) at 69.7 MW, and for the rest of the modes less than 10 µm. Meanwhile, radial displacement showed vortex vibration values greater than 10 µm only in 66.5 MW mode – 19 µm (1X was 63 µm) and 18 µm (1X was 64 µm). However, at the water head 36.85 m (Hs was 2.67) at low load of 64.1 MW vortex effect on vertical vibration was greater – 29 µm (1X was 20 µm). For radial displacement it was 25 µm, although 1X was greater – 62 µm.

Vortex rope caused vibration appears at low load and at medium load of 80 MW.

Another set of tests for unit F4 was run in 2015 at the water head of 37.57 m, the suction head 4.19 m and the water head 38.6 m, the suction head 4.28 m. At the water head 37.57 m vortex rope caused vibration reached maximum at power less than 76 MW, when the guide vanes opening position (GVOP) was less than 351 mm. At the water head of 38.6 m under power of 84 MW it was 10 µm (1X was 21 µm). For unit F4 power as high as 103.7 MW was reached at the water head 38.6 m, and for the power over 100 MW the vortex rope frequency through vertical displacement increased steadily, reaching 9 µm at 103.7 MW and 475 mm GVOP. To sum up, the statement that Francis turbines operate poorly at part loads, which means “low flow rates with small guide vane opening angles” [5] (for our units that was 60-70 MW) remains true even for upgraded units, and it is possible to detect vortex frequency close to 80 MW.

Draft tube surge appears at small guide vanes opening position.

Control over the river head is very limited. Meanwhile, in the Francis turbine the user can change the guide vanes opening position to achieve the desired load at the given head. For example, on unit F1 to obtain 80.64 MW at 38.8 m head, the guide vanes opening should be 349 mm; to obtain 82.48 MW at 37.8 m head, the guide vanes opening should be 365 mm; to obtain 81.87 MW at 37m head, the guide vanes opening should be 376 mm, at 34m head to obtain 80.7 MW the guide vanes opening should be as great as 406 mm. To sum up, the smallest is the water head at the given date, the greater the guide vane opening should be to achieve the same desired power. Fig. 2 hows the data from one displacement sensor, when the load was close to 80 MW, but the water head and the guide opening position were different. In this example 34 m water head is low. GVOP of 406 mm is large. Since the measurements were made on different dates, the data are organised as overlapping spectral lines instead of the waterfall chart.

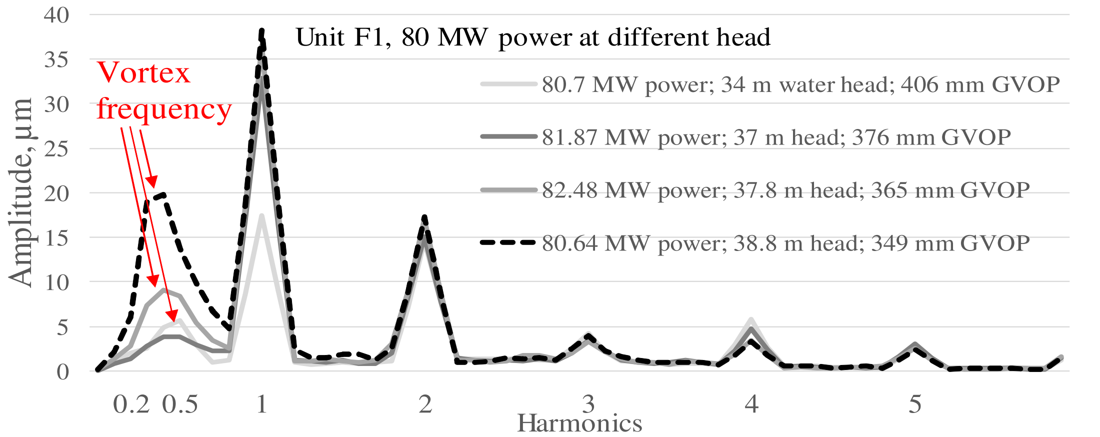

Fig. 2. **Comparison of spectrum lines for unit F1 at load close to 80 MW**

Vortex rope caused vibration was registered in all modes for this unit, but its amplitude was different. Opposite to expectations that amplitude would be the greatest at a low head of 34 m, indicated by the lightest grey line in Fig. 2, it was greater at 38.8 m water head, indicated by the dotted line in Fig. 2. Contrary to the expectation that vortex rope would appear when the guide vane opening position is large and the water head is small, it was greater, when the water head was high and GVOP was small.

Draft tube surge has effect on the generator.

Normally the user would register draft tube surge only at the turbine bearing and only in very severe cases on the generator bearing. Table 3 shows that rarely, but on specifically unfavourable modes, the user would note the vortex typical vibration not only from the turbine bearing shaft displacement sensor, but also from the generator bearing shaft displacement sensors.

Table 3

Different measurement positions – registered vortex rope (< 1X) in μm

GVOP/Sensor	Turbine 1st	Turbine 2nd	Generator 1st	Generator 2nd	Vertical
355	24	26	6	9	24
370	11	10	2	3	13
386	3	3	-	-	5
397	4	3	-	-	-
406	6	6	-	-	-
416-474	5-6	4-5	-	-	1-4

In Table 3 the dash means that vibration was less than 2 μm. The values in the first two rows of Table 3 confirm that draft tube surge, if severe, has effect on the generator vibration.

Conclusions

1. This paper showed appreciation to the fact that every hydropower unit is unique, and site tests are necessary to learn every unit behaviour in different conditions. There are though commonalities in operation. All Francis turbines operated with draft tube surge at part load (in this paper it was 60-70 MW out of maximum 98 MW), far from the best efficiency point.
2. Although all hydropower turbines including upgraded units experienced effects of draft tube surge at low load, there were other specific findings during the tests:
   - For unit F1, F2 and F4 it was possible to detect the vortex rope frequency close to optimum at 80 MW.
   - For unit F1 the vortex rope frequency was greater, when the water head was high and GVOP was small.
3. The site tests confirmed that draft tube surge, if severe, could have effect on the hydropower unit generator vibration.

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