Model and prototype investigations of upper partial load unsteady phenomena on the Francis turbine designed for head up to 120 m

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Abstract. The upper partial load unsteady phenomena are often observed at model tests for Francis turbine with high and middle specific speed. It is appears approximately between 70-85% of optima point discharge for constant unit speed value and has accompanied by additional phenomenon with much higher frequency than draft tube vortex precession frequency and also runner rotational frequency. There are some discussions about nature of this phenomena and transposition of unsteady model test results to the prototype. In this paper are presented the results of above mentioned phenomena model investigations and some results of investigation at prototype turbine. Based on the results of model tests the following extensive data have been obtained: pressure fluctuation in the draft tube cone and spiral case, axial force fluctuations, it is demonstrated the significant influence of cavitation on upper partial load unsteady phenomena. The result of measurements of bearing vibrations and pressure pulsations are presented for prototype turbine at corresponded or very close operation points to model. In accordance with obtained data it is demonstrated that at upper partial load operation the unsteady phenomenon is observed as for the model also for the prototype turbine. On the base of model investigation has been demonstrated the influence of air admission and special design solutions to diminish unsteady phenomena at upper partial load range. All investigations were based on the physical experiment. Thus, based on model and prototype experimental investigations it is obtained additional information about upper partial load unsteady phenomenon and confirmed the transposition of model results to prototype turbine.

1. Introduction

The one of the tendency in development of Francis turbines is the increasing of normal operation range where the turbines capable operate without restriction for a long time. The left margin of normal operation is defined by partial load zone where take a place increasing of pressure pulsations in flow passage, vibrations and dynamic load on turbine equipment. This is connected with vortex precession in draft tube cone and cavitation of vortex core. But in the upper partial load range, approximately between 70-85% of optima point discharge Qopt, the corkscrew vortex is often accompanied by unsteady phenomenon with much higher frequency than frequency of vortex precession and runner rotational frequency. In the amplitude-frequency spectra for above mentioned operating points it is appears dominating harmonic at vortex precession frequency (usually 0.3…0.6fn) and a few dominating harmonics with higher than rotation frequency fn – usually in range 1.5…5.0fn. The above
mentioned unsteady phenomenon at upper partial load leads to significant increasing of vibration and to restriction of normal operation range of turbine.

Most observations of this phenomenon are from models with high specific speed. The very interesting research data of this phenomenon and review of corresponded publications are presented in [1]. But for today, there are not complete and adequate understanding of this phenomenon and not enough investigation were collected to predict behavior of prototype turbine when this phenomenon appears at model. Some investigators [2] found a natural mode of the model test rig to be involved in this process and in the result - conclusion: this phenomenon is not typical for the prototype. Other point of view is that the reason of upper partial load unsteady phenomenon is oscillation with elliptical surface of the vortex core [3]. In any way, there is an opinion, that in spite of the significant amplitudes in the model tests at upper partial load zone, at the prototype turbines this phenomenon are very rare [1]. As it was supposed, the lack of Froude similarity prevents from occurring of this phenomenon in large prototype.

The usual practice in model tests to suppress the pulsation in upper partial load zone. This is provided by injection of air under the runner cone or in some case, performing of design modification (shape of runner cone, adjustment of runner blade profile).

Accounting on the importance of the upper partial load unsteady phenomenon investigation in point of view of operation range increasing and the problem of model test results transposition to the prototype conditions it was performed model and prototype investigations at almost the same operating conditions. Another purpose of investigation was to obtain additional information about this phenomenon and various factors influence on it. The model investigations were performed more detailed and thoroughly because of wide possibility to perform measurement and set operating conditions. At model tests were measured pressure pulsation in draft tube cone and spiral case, pulsation of axial thrust. Prototype investigations were performed not so detailed because of tests conditions and restricted possibility to set measuring equipment. At prototype tests were measured pressure pulsation in draft tube cone and spiral case, vertical vibration of turbine bearing. The subject of investigation was Francis turbine for the maximum net head 120 m, rated head 102 m, with runner diameter 6.25 m and rotational speed 125 rpm. Specific speed of turbine in terms of

\[ n_q = nQ^{0.5}/H^{0.75} = 73.6 \]

model turbine has runner diameter 0.46 m (defined from inlet edges of runner). The scope of investigation include: 1) model determination of operating range, where phenomenon appears, and special trait of phenomenon 2) model investigation influence of Thoma number and measure to diminish unsteady phenomenon at upper partial load zone 3) prototype investigation of range where phenomenon appears, and comparing with model data.

2. Model investigations

2.1 Test conditions and measurements

Model investigations of upper partial load unsteady phenomenon were conducted in the hydro turbines laboratory for model of Francis turbine with runner diameter 0.46 m as it was mentioned above. The capacities of the model test rig are: maximum model head 50 m, maximum model discharge 1.2 m³/s, the test rig volume 250 m³, test rig has closed circuit, model head 21 m and Thoma number \( \sigma = 0.14 \ldots 0.22 \), corresponding to the range at plant conditions. Measurements were performed in whole range of guide vane opening for prototype head range. Model tests were performed in accordance with requirements of IEC code 60193[4].

It were used the next measurement equipments for definition of main parameters of model. Water discharge “\( Q \)” passed through the turbine model is determined from the difference between pressures in Venturi flow meter measuring sections. Calibration of flow meter was performed by weighing method. Head “\( H \)” is determined as a difference between the total specific energy values in inlet and outlet measuring sections of the turbine model. For torque measurements was used force transducer and lever arm. The torque is determined by force applied to a lever arm multiplied by the radius at which it is applied. A friction loss as a friction moment in model shaft bearings is taken into account.
by adding it to the torque, which is measured by the basic torque-measuring system. Rotational speed measurement “n” is performed by means of the steel disc with holes fixed on the model shaft and an inductive transducer. Thoma number of model was defined by using differential pressure transducer and electronic barometer for ambient pressure measurements according IEC recommendations. On the results of calibration it was defined relative uncertainties of main measured parameters, which not exceed for: discharge f_\text{Q}<0.15\%, torque f_\text{M}<0.1\%, head f_\text{H}<0.1\%, speed of rotation f_\text{n}<0.1\%. The uncertainty of determination of the Thoma number is determined in the main by the random uncertainty whose absolute value for the turbines of the said specific speed is assessed as \sigma = \pm 0.005.

Pressure pulsations were measured at right bank side (notification of transducer T3, “DTRB”) and down stream side (T4, “DTDS”) of draft tube cone at the distance 0.45D_{\text{runner}}, also in spiral case at inlet section (T2, “SC”), see figure 1. Axial thrust pulsation was determined on the base of measurement of pressure in hydrostatic turbine thrust bearing (transducer T1, “Fax”). An independent data acquisition and processing system is used for pressure fluctuations recording and processing. The system consists of piezoelectric pressure pulsation transducers of membrane type, cables, charge amplifiers 2635 (Bruel & Kjaer), a communicable computer. The frequency range of used transducers is from 0.2 Hz up to 5000 Hz, measurement unseartainty for pressure pulsation value according to certificate ±10%. The values of pressure pulsations are expressed in per cent of the head, the values of axial thrust in terms of axial force factor [4].

**Figure 1.** Pressure pulsation transducer displacement in flow passage

### 2.2 Model determination of upper partial load unsteady phenomenon zone

The peculiarity of upper partial load unsteady phenomenon range is that it has a very narrow range at constant unit speed operation. The results of pressure \Delta H/H and axial force \Delta Fax_{11} pulsation measurement for investigated turbine are presented at figure 2 at constant unit speed value \text{n}_{11}=0.95\text{n}_{11\text{opt}}. On figure are presented peak-to-peak values of parameters as dependence from relative value of guide vane opening Ao. The 100\% of guide vane opening corresponded to the maximum value of opening at power plant and scaled up to the model. The measurements were performed with small steps of Ao to determine range of investigated phenomenon, which is observed between 61...64\% of maximum value.
It is presented dependencies of relative efficiency $\eta$ and output $P$ from relative guide vane opening for the above mentioned unit speed value on figure 3. That was done with respect to compare the results with prototype data hereinafter. As it is seen the optima point for current unit speed value at $A_o=74\%$ and turbine power $P=95\%$. The range of investigated phenomenon in terms of relative power corresponded to 74...80\% of maximum value.

The spectra of pressure and axial force pulsations are presented at figure 4 for operating point $A_o=62.2\%$, $P=76\%$, where especially high level of pulsation observed. It is seen from spectra of pressure pulsation in draft tube (spectrum number 3 and 4), that there are dominating harmonics are at $0.3f_n$ (vortex precession frequency) and $1.9f_n$, $2f_n$ are additional dominating harmonics with almost same amplitude value (upper partial load phenomenon). The spiral case pressure pulsation spectrum (number 2) has dominating frequency at $1.9f_n$ with amplitude twice more then at draft tube cone at the same value of frequency. The similar picture is observed on spectrum of axial force pulsation, dominating frequency is $1.9f_n$ and small increasing of amplitude appears at frequency $0.3f_n$.

This result can be explained based on supposition, that pulsation process with frequency $1.9f_n$ connected with cavity fluctuation of vortex core and has maximum amplitude at center of draft tube.
cone near the source. Pulsations in draft tube cone were measured on wall of cone and vortex precession process has significant influence on measurements and very good seen on the spectra 3, 4. Vortex precession process and corresponding frequencies are almost not seen on the spectra of spiral case and axial force pulsations. This pulsation process was measured at different points of flow passage: it has sin-phase character and transmitted to the spiral case and to the runner (as result – axial force fluctuation) from draft tube cone. The fragment of process is presented on figure 5, where is shown measured signal for process with frequency 1.9fn. Model turbine rotational speed was 725.7 rpm for presented operating point that corresponded to the time period 0.043 second. Measured parameter for axial force determination was pressure in thrust hydrostatic bearing. It is seen from this figure synchronous character of pulsation process, especially accounting on that in draft tube cone was two transducers placed.

Special attention was paid to the repeatability of obtained results at upper partial load operating and investigation of influence of test rig natural frequencies on the investigated phenomenon. It was measured the natural frequencies of tested model. The results of this measurement demonstrate the absence of coinciding with natural frequencies of the exiting in flow passage pressure pulsation dominating frequencies. Also it was investigated the influence of model operating parameters. The measurements of pulsation were performed at same points and same way at various model head. The range of model heads was 9…30 m. The model head 9 m provides the same Froude number for model and prototype. Performed model investigations demonstrate that at the similar operating conditions, especially at the same Thoma number, the observed phenomenon take a place and dominating relative frequencies and amplitude values varieties insignificant. On the base of performed model investigation it is possible to conclude that observed phenomenon at upper partial load range with dominating frequencies highest then rotation frequency is property of investigated flow passage and will be observed at scaled-up turbines.

![Figure 4](image)

**Figure 4.** Spectra of pressure and axial force pulsations, model head 21 m
As it was said before, the upper partial load unsteady phenomenon is observed mainly on Francis turbine designed for the low and middle heads (in accordance with our data at head less than 150 m approximately). The turbines with high specific speed have spacious flow passages and significant irregularity in velocity, pressure, energy distribution. The numerical simulation and theoretical research are not capable for today completely explain and predict this phenomenon appearance. So, it was performed model investigations with purpose to collect information about influenced factors on upper partial load unsteady phenomenon to avoid the negative consequence from it. As it was obtained from model investigation the main factor influenced on arising of pressure pulsation at upper partial zone is cavitation of vortex core. The Thoma number influence on axial force pulsation is shown on figure 6. Axial force pulsation was taken because of it is integral characteristic of unsteady phenomenon and one of more important reason of unit vertical vibration. Figure 7 demonstrates the spectra of axial force pulsation at various Thoma number of investigated operation point.

**Figure 5.** Fragment of unsteady process demonstrating of sin-phase character at frequency 1.9fn

**2.3 Model investigation of influencing factors on upper partial load zone pulsation**

As it was said before, the upper partial load unsteady phenomenon is observed mainly on Francis turbine designed for the low and middle heads (in accordance with our data at head less than 150 m approximately). The turbines with high specific speed have spacious flow passages and significant irregularity in velocity, pressure, energy distribution. The numerical simulation and theoretical research are not capable for today completely explain and predict this phenomenon appearance. So, it was performed model investigations with purpose to collect information about influenced factors on upper partial load unsteady phenomenon to avoid the negative consequence from it. As it was obtained from model investigation the main factor influenced on arising of pressure pulsation at upper partial zone is cavitation of vortex core. The Thoma number influence on axial force pulsation is shown on figure 6. Axial force pulsation was taken because of it is integral characteristic of unsteady phenomenon and one of more important reason of unit vertical vibration. Figure 7 demonstrates the spectra of axial force pulsation at various Thoma number of investigated operation point.

**Figure 6.** Thoma number influence on axial force pulsation at $Ao=62.2\%$, $P=76\%$
The obtained results demonstrate that increasing amplitude at frequency 1.9…2.3fₙ take a place just in range of Thoma number 0.1…0.2. The pulsation process at this frequency is mainly defined the abrupt increasing of unsteady phenomenon at current operation point. And diminishing of amplitude up to neglectful values at frequency 1.9fₙ is observed at highest values of Thoma number. This data demonstrate that unsteady phenomenon is determined by cavitation process and with changing of Thoma number range can be eliminated.

Also it was investigated influence of runner cone on upper partial loads zone pulsation. Various shapes of runner cone (cylindrical, conical, profiled etc.) were used to obtain the more significant influence. All investigated variants had positive influence on pulsation process in upper partial load zone, but not significant it had improved the situation. After that it was performed radical modification – runner cone was dismounted completely and performed measurement at the same conditions and operation points. The result of measurements is shown on figure 8, where presented spectrum of pulsation in spiral case – transducer T2 and in draft tube transducer T4. As it is seen from figure 8 the dismounted runner cone leads to elimination of dominating harmonics on spectra with frequencies higher of rotational frequency. That means that upper partial load unsteady phenomenon appears due to joint influence of cavitating vortex core and shape of runner cone – the place where vortex rope begins.
On the base of performed model investigations it was obtained data about methods of pressure pulsation elimination in flow passage of investigated turbine. That leads to the increasing of normal operating range. Because of the vortex cavitation and shape of runner cone occurs by the source of upper partial load unsteady phenomenon, the diminution of pressure pulsation at this zone can be achieved with air admission under the runner. Optimal volumetric discharge of air for investigated turbine was experimentally determined and approximately corresponded to 0.5% of turbine water discharge at rated operation point. The next way to diminish pressure pulsation at above mentioned operating range is to change runner cone shape and it is necessary to make a changes in runner blade profile at the same time, because this is interdependent things in general. This has to be accounted on at new turbine design but not for improving of the situation at working power station. Performed model investigations with modification just runner cone did not give any significant results for situation improvement with this turbine. And completely dismounted runner cone is not good solution in general, because it leads to the efficiency decreasing and growing up of pulsation at some other operation points. Also very effective solution in respect to pressure pulsation decreasing not only for upper partial load zone but at whole is to install fins [1, 5] in draft tube cone. That gives the positive effect in respect unsteady phenomenon at upper partial load zone almost like air admission. The pressure pulsations were decreased at whole range of partial load after fins mounting.

3. Prototype investigations and comparing with model results

3.1 Test conditions and measurements

One of the wide discussed questions is presence of upper partial load unsteady phenomenon at prototype and transposition of it from model tests to prototype. The mentioned phenomenon investigations presented in this paper were started at prototype turbine. The detailed model investigations of pulsations had been performed after the prototype field and vibration tests, where the operating range of turbine was determined.

The prototype tests were conducted at 5 units and at all of them the upper partial load phenomenon were observed more or less successfully. It was measured at prototype turbine: head, output, guide vane opening, tail water level, pressure difference at Winter-Kennedy section, pressure pulsations at spiral case inlet (at outer radius) and in draft tube cone, vertical vibrations of turbine bearing. The presented in this paper results was obtained at prototype head 115 m, which corresponded to data of model research. It is worth to note that real prototype head was not constant and varied in range 1.5 m. The parameters were recalculated to the constant head after measurements. And there are some remarks concerning the pressure pulsation measurements. The pressure pulsation transducer and measuring complex was used the same like at model tests. But it was not possibility to set the transducers in the flow passage directly. Instead of that, transducers were mounted in piezometric...
blind tubes connecting with flow passage. The length of tube from spiral case flow passage up to the transducer approximately 17 m, and the length of tube from draft tube cone flow passage up to the transducer was 6 m. As the results the pressure pulsation values were understated and the amplitudes values at spectra too. Vertical vibrations were measured by piezo resistive transducers “IVP” which determine the displacement of vibration as output value in the range of frequency 0.8-200 Hz. The measurement of vibration displacement was made very accurate. Vertical vibrations of prototype are compared with axial force pulsation of model because axial trust pulsations are main source of vertical vibrations of unit.

3.2 Results of prototype tests and comparing with model research

The results of measurements vibration displacement at prototype turbine bearing are presented on figure 9. The dependence was prepared as peak-to-peak values of vibro-displacement against power of turbine in percent. At the same time on the figure 9 is shown the dependence of axial force pulsation curve obtained at model tests.

![Figure 9](image_url)  
**Figure 9.** Vertical turbine bearing vibrations of prototype $\delta$ and model axial force pulsations $\Delta F_{ax11}$

![Figure 10](image_url)  
**Figure 10.** Draft tube pressure pulsation at prototype and model
The results of pressure pulsation measurements in prototype draft tube are presented on figure 10. The dependence was prepared as peak-to-peak values of pulsations against power of turbine in percent of head. Also on the figure 10 is shown the dependence of pressure pulsations obtained at model tests.

![Figure 10. Prototype pressure pulsation](image)

Figure 10. Prototype pressure pulsation at operation point with power P=74% in spiral case, draft tube, vertical bearing vibrations. At the same time it is presented axial force pulsation spectrum obtained on the base of model tests.

![Figure 11. Draft tube pressure pulsation at prototype and model](image)

Figure 11. Draft tube pressure pulsation at prototype and model

Figure 11 demonstrate spectra of prototype turbine pressure pulsations at operation point with power P=74% in spiral case, draft tube, vertical bearing vibrations. At the same time it is presented axial force pulsation spectrum obtained on the base of model tests.

The prototype measurements of pressure pulsations and vibrations have the quite satisfactory agreement with model test data. It is well seen from figures 9-11. It is important to note that upper partial load unsteady phenomenon take a place as for prototype so for the model. In term of power the mentioned zone placed in range 73-80% of rated output. The character of model axial thrust pulsation curve is very close corresponded to vertical vibrating displacement of prototype turbine bearing. The character of model draft tube pressure pulsation is also corresponded to prototype data, but the values of prototype pressure pulsation are lower because of long length of piezometric blind tubes. The analysis of prototype pressure pulsation spectra demonstrates the presence of dominating harmonics with high frequency 1.9…2f_n at operation point in range of upper partial load. This is connected with unsteady phenomenon which was observed at model research (compare figure 4 and 11). Also at prototype turbine it was observed sin-phase character of pressure pulsation at frequencies 1.9…2f_n. The lower values of amplitude on prototype pressure pulsation spectra in comparing with model data can be explained in same way as for peak-to-peak model and prototype curves on figure 10.

The performed prototype investigations demonstrate the appearance at prototype turbine the upper partial load unsteady phenomenon, which was observed at reduced model in lab.
5. Conclusion

The upper partial load unsteady phenomenon is observed as abrupt growth of pressure pulsations in narrow operating range close to optima point from left (partial load) side. It is accompanied by presence on amplitude-frequency spectra the dominating harmonics with frequencies higher than rotational frequency \( f_{n} \); usually up to \( 5f_{n} \). Because of closeness to optima point the upper partial load zone restrict of normal operating range.

Model investigations of demonstrate that upper partial load unsteady phenomenon appears due to joint influence of cavitating vortex core and shape of runner cone – the place where vortex rope begins. This phenomenon was observed for investigated turbine just at definite range of Thoma numbers. Pressure pulsations have sin-phase character for al measured points in flow passage.

Model investigations demonstrate that effective ways to diminish the pulsation amplitude at upper partial load zone consist of air admission or fins setting at draft tube cone.

On the base of performed prototype investigations it may be concluded that for investigated large Francis turbine the upper partial load unsteady phenomenon take a place for reduced model and prototype. There is correspondence between model and prototype: at turbine operating range where above mentioned phenomenon appears and at dominating frequencies.

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