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REVERSIBLE PUMP-TURBINES – A STUDY OF PUMPING MODE OFF-DESIGN CONDITIONS

REVERZIBILNE TURBINE-ČRPALKE – ANALIZA NESTACIONARNIH POJAVOV V ČRPALNEM REŽIMU OBRATOVANJA

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Abstract

The role of pumped storage power plants (PSP) in electrical grid systems has been changing in recent years. Demands for switching from pumping to generating mode are becoming increasingly frequent. Moreover, the operating ranges of the reversible pump-turbines used in PSP systems are becoming wider in order to use the PSP as a regulator and a stabilizer of the electrical grid. The primary challenges in the development of pump-turbines are the hydraulic instabilities that occur in pumping and generating modes. The present paper focuses on partial load pumping mode instabilities, such as cavitation and rotating stall. Modern tools, such as CFD, are used for the analysis of the phenomena along with conventional experimental approaches. Rotating stall has been investigated in hydraulic laboratory experimentally and reproduced numerically using commercial CFD code. Three rotating stall cells with a rotational frequency of 2.5% of nominal pump-turbine frequency have been identified. Cavitating vortices related to rotating stall were found in the guide vanes region. Both phenomena indicate highly unstable and potentially dangerous operating conditions that need to be investigated in detail. Understanding the causes for the instabilities will lead to an improved pump-turbine design that will enable safer, more flexible and more reliable operating with fewer unwanted instabilities.

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Povzetek

Vloga črpalnih hidroelektrarn v električnih omrežjih se v zadnjih letih spreminja. Zahteve po prehodu s črpalnega v turbinski režim in nazaj postajajo vse pogostejše. Območja obratovanja reverzibilnih črpalk-turbin se ob tem širijo, saj se črpalne hidroelektrarne uporabljajo kot regulator in stabilizator električnega omrežja. Glavni izzivi pri razvoju reverzibilnih črpalk-turbin so hidravlične nestabilnosti, ki se pojavijo v črpalnem in turbinskem režimu. Članek se osredotoča na nestabilnosti v črpanem režimu pri delnih obremenitvah, kot sta kavitacija in vrteče zastojne celice. Sodobna orodja, kot računska dinamika tekočin (CFD), se uporabljajo za analizo pojavov kot dodatek klasičnim eksperimentalnim pristopom. Vrteče zastojne celice so bile eksperimentalno raziskane v hidravličnem laboratoriju ter numerično reproducirane s komercialnim CFD programom. Odkrite so bile tri zastojne celice s frekvenco vrtenja 2.5 % nazivne frekvence črpalke-turbine. V območju vodilnih lopat so bili opaženi kavitacijski vrtinci povezani z zastojnimi celicami. Oba pojava kažeta na zelo nestabilno in potencialno nevarno obratovanje, ki ga je potrebno podrobno raziskati. Razumevanje vzrokov za nestabilnosti bo pripeljalo do izboljšane zasnove črpalke-turbine, ki bo omogočila varnejše, prožnejše in zanesljivejše obratovanje z manj neželenimi nestabilnostmi.

1 INTRODUCTION

The market for pumped storage power plants (PSP) is growing every year. The main reason is the increasing number of weather-conditioned sources of energy, such as wind and solar power plants. To provide a reliable electrical grid, power plants that can balance the differences between demand and supply of electricity must be included. A PSP with reversible Francis runner that has a wide operating range and enables a fast transition from the generating to the pumping mode is highly suitable for this task. Besides new PSP projects, refurbishments of the pump-turbine runners represent an important part of the market.

The development process of a new pump-turbine runner is related to several major challenges. The customer demands and final goals of the development process are the operation of the pump-turbine from zero to maximum output in the generating mode and non-restricted operation in the pumping mode. To achieve that, the whole operating range should be free of hydraulic instabilities. An additional reason for the refurbishment is frequently the improvement of the total efficiency of the cycle. The development of the new runner with the expected reliability and performance must be supported by effective cooperation among hydraulic and mechanical designers and by the application of precise manufacturing technology.

Both generating and pumping mode instabilities have been analysed during this study in order to prepare the new runner design for a 2×325 MW pump storage powerplant in Dlouhe Strane in the Czech Republic, which will be able to operate from 0–100% output power, *[1].*

The main instability in the generating mode is considered the S-shaped curve close to the runaway operating point. It has been studied numerically and experimentally by various researchers, *[2, 3, 4, 5, 6].* In contrast, cavitation and rotating stall are considered to be the main hydraulic instabilities in the pumping mode operation. Cavitation in the pumping mode regime mostly occurs at the impeller leading edge, where local pressure drops to vaporization pressure. However, in combination with the phenomenon called rotating stall, it is possible that the cavitation also occurs in the high-pressure distributor region.

Rotating stall is a phenomenon present at partial load operation and was first investigated for the compressor applications, *[7].* In recent years, the problem became highly relevant in the field of pump-turbines, which lead to several studies, [8, 9, 10]. The rotating stall is sometimes related to the positive slope of the performance curve also called hump zone, *[11]*, which is an unstable and potentially dangerous operating region. Fig. 1 shows typical pump-turbine characteristics for pumping regime in a non-dimensional form (Φ – flow rate coefficient, Ψ – specific energy coefficient, ω – rotational speed, ω_s – rotating stall rotational speed). If present, it can lead to uncontrollable changing of the discharge through the machine and consequently strong vibrations. The intensity of the rotating stall in pump-turbines can vary. As shown several times, experimentally and numerically, *[8, 11, 12]*, changing discharge and guide vane opening angle can lead into a different number of the stalled cells and a different rotating stall frequency. Various shapes of rotating stall influence pressure fluctuations, radial forces acting on the impeller as well as guide vanes vibrations related to the torque fluctuations. If the rotating stall is very intense, the appearance of the cavitating vortex is possible in the distributor region. Operating under the described conditions should be completely avoided. However, rotating stall can be present even if the slope on the performance curve is negative.

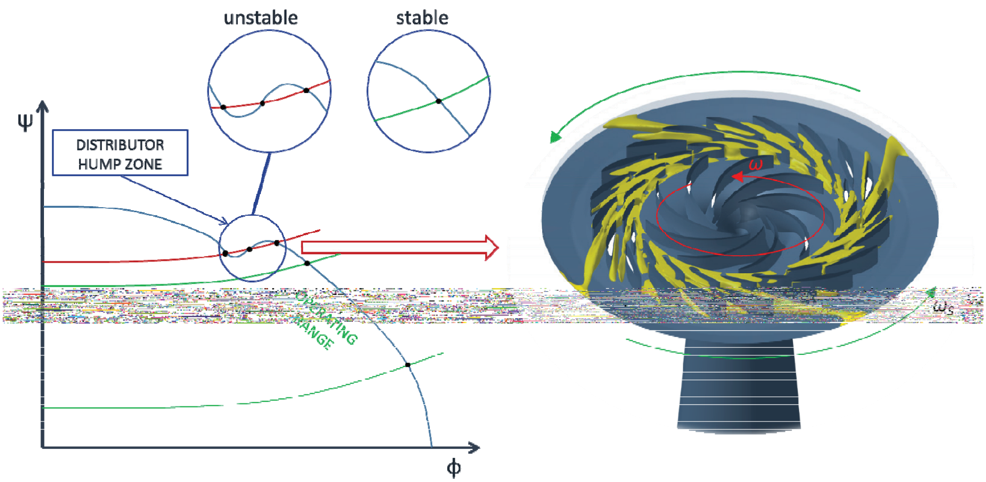

Figure 1: *Pumping mode operating range with distributor hump and related rotating stall*

Rotating stall has been investigated experimentally and numerically in order to propose a hydraulic design that would be free of instabilities and would satisfy very demanding criteria of non-restricting operation.

2 EXPERIMENT

Experimental measurements took place in Litostroj Engineering hydraulic laboratory, *[12].* Additional to the standard performance measurement, eight (8) pressure sensors have been distributed around vaneless space between the impeller and the guide vanes. The rotational speed of the model pump-turbine has been set to n = 1400 min^{-1}. Even though the whole range of guide vane openings has been measured, one constant guide vane opening a_0 = 20 mm is presented and analysed in the paper. The guide vane channel and vaneless space have been observed during the measurements by installing Plexiglas window in the distributor region. The goal of the experimental setup was to measure low-frequency pressure pulsations in pumping and generating mode. Measurements have been done for the entire part load regime, however, for the analysis, operating points at the best efficiency point (BEP) $Q = Q_{BEP}$ and at $Q = 0.65\ Q_{BEP}$ have been chosen and will be presented.

Fig. 2 shows pressure fields around the distributor at $Q = 0.65\ Q_{BEP}$. Three pressure cells are formed and are rotating around the distributor with governing frequency $f = 0.59$ Hz, which corresponds to around 2.5 % of the pump-turbine rotation frequency. The relationship between pressure fields and velocity contours obtained by CFD and presented on Fig. 4 have been discussed in detail by *[10]* together with governing mechanisms of rotating stall on different pump-turbine geometry and indicate the presence of the rotating stall. In contrast, the flow has been stable with no pressure pulsations at the $Q = Q_{BEP}$. The level of low-frequency pressure oscillations has been presented in *[13]* and reached ±15 % of the average pressure level around the distributor.

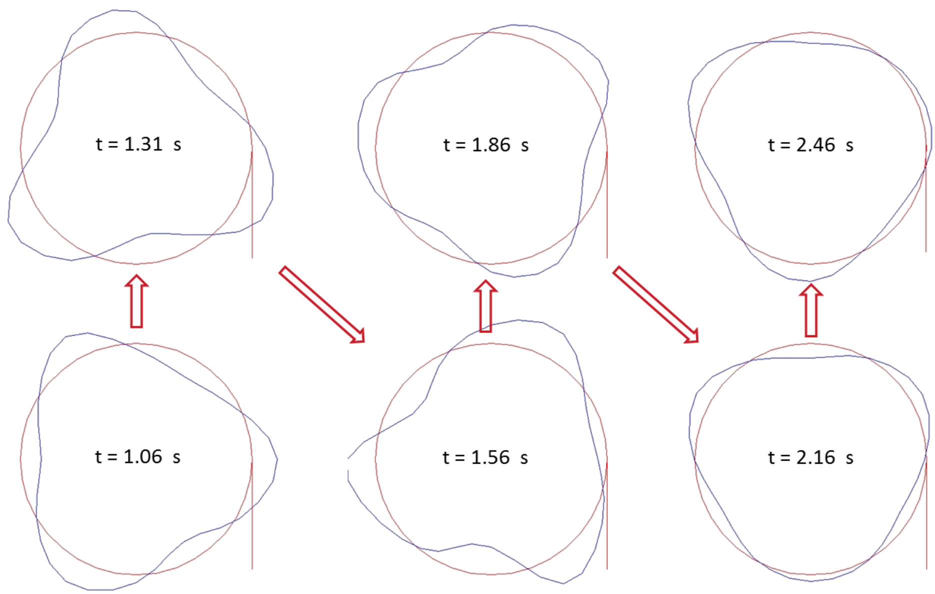

Figure 2: *Pressure fields around the distributor at $Q = 0.65Q_{BEP}$ at different time steps*

Occasionally, during the pressure measurements at $Q = 0.65\ Q_{BEP}$, cavitating vortexes have been observed in the distributor between the guide vanes, as seen in Fig. 3. Sometimes, there was one vortex, attached to the suction side of the guide vane (Fig 3, left). At some other instances, the phenomenon has been observed as several separated, smaller cavitating vortices, as seen in Fig. 3, right. In both cases, the vortices occur only for a short time. It should be pointed out that the cavitation in the distributor region is highly unusual due to very high pressure in the surrounding.

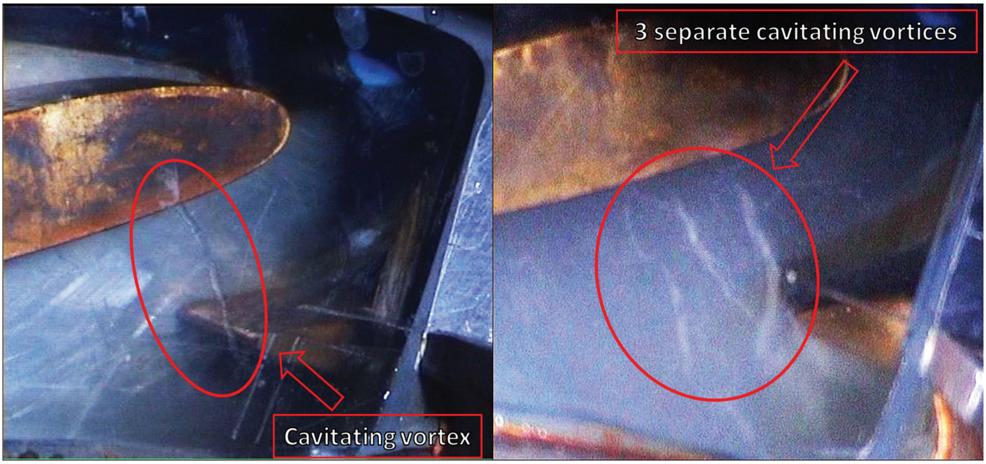

Figure 3: *Cavitating vortices in the distributor region*

3 NUMERICAL ANALYSIS

For the flow analysis, numerical flow simulation (Computational Fluid Dynamics) software is nowadays the most common tool. It uses a set of Navier-Stokes equations to compute the transport of mass and momentum in all parts of the computational domain. Commercial software has been used for the simulation. Transient simulations were performed in the premises of Litostroj Engineering a.s. by using URANS equations and turbulence model based on the k-ε model. Choosing the appropriate turbulence model is essential for the successful reproduction of complex phenomena, such as rotating stall. It should be a robust model to enable convergence with wall functions that enable exact prediction of first flow separation on the guide vanes. The time step corresponds to 2° of the impeller revolution, which has been proved by *[8]* and *[10]* to be a good compromise between quality of results and computational cost. Around 20 revolutions of the impeller have been simulated. Boundary conditions are very important for the stability of the simulations.

Moreover, in some cases, they also have a significant influence on the obtained results, especially at non-optimal flow conditions, such as part load. In our case, constant mass flow rate Q has always been set at the inlet of the domain and at the outlet of the domain, static pressure p_s has been imposed. A no-slip condition has been applied on the solid walls.

The meshing of the domains has been done using commercial software, using structured and unstructured mesh. The total mesh contains around 10 million cells; special attention has been put into meshing the distributor region, since this would be the place where the rotating stall occurs. Dimensionless criteria $y+$ that indicates mesh quality close to the walls has reached mean values around $y+ = 10$ in all parts of the domain.

Unsteady CFD analysis has been focused on the rotating stall parameters and related phenomena. Operating points at $Q = 0.65\ Q_{BEP}$ have been chosen for the comparison to the experiment. Three regions with high velocity have been found (Fig. 4 - right) in between three cells of blocked discharge, which corresponds to the experimental findings. Separation zone regions periodically appeared and disappeared at the guide vanes surfaces (Fig. 4 - left) and caused backflow from stay vanes and even spiral case region. A detailed description of the complex rotating stall origins is given in *[11].* Numerical rotating stall frequencies have been estimated to 0.5 Hz. Since the frequencies of the rotating stall are very low, more impeller revolutions should be simulated for more accurate frequency prediction. However, we can say that the phenomenon has been accurately described by using CFD and simple k-ε based *turbulence model.*

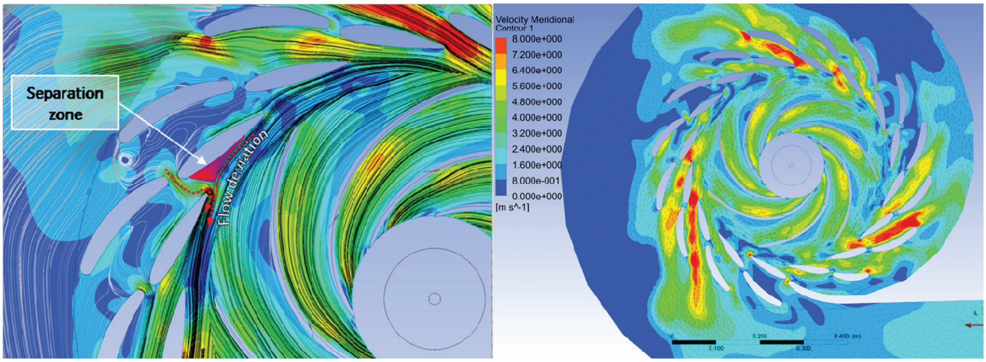

Figure 4: *Left - Separation zone during rotating stall occurrence; Right - Meridional velocity contour during rotating stall*

Cavitating vortices in the distributor channel have been occasionally observed under rotating stall. The vortex is attached to the guide vanes and reaches the next upstream channel, as seen on Fig. 5. Constant *Q*-criterion has been used for the vortices representation. The estimated time of the cavitating vortex appearance is around 0.011 s, which corresponds to around one quarter of the impeller revolution. The vortex appears and disappears several times at different positions around the distributor during the impeller revolution. The appearance time is very short, which means that the phenomenon is visually demanding to observe. The vortex appears when the discharge through the guide vane channel is partially blocked (Fig. 5). First, the blockage appears at the hub side and later also at the shroud side. The moment when the flow is still strong at the shroud side and blocked at the hub side is favourable for the occurrence of the cavitating vortex in the guide vane channel. A comparison of the experimental and numerical appearance of the cavitating vortex (Figs. 3 and 5) show very good agreement. More post-processing images of the cavitating vortex can be found in *[13].*

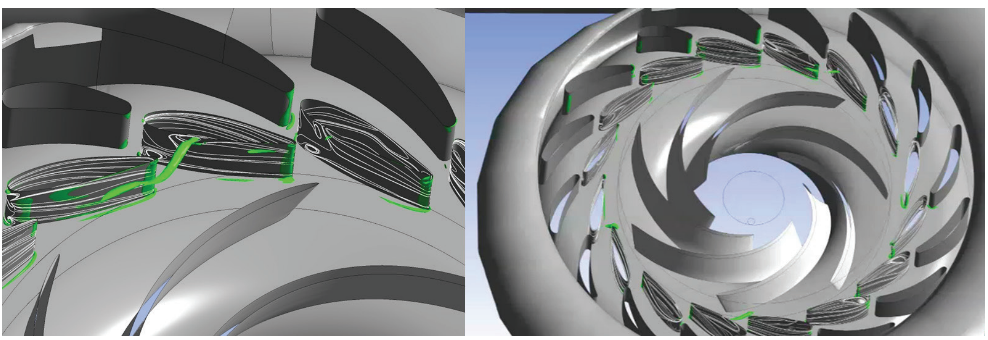

Figure 5: *Numerically simulated cavitating vortex*

4 CONCLUSIONS

The main goal of the study has been to improve the understanding of the instabilities that occur at the off-design operation of the reversible pump-turbine in order to enable a wide operating range at the pumping and generating modes. The present paper has been focused on the partial load pumping mode instabilities, such as rotating stall and cavitation. CFD analysis has been used to successfully reproduce the rotating stall and related cavitating vortex that has been observed during the experiment in the hydraulic laboratory. The numerical governing frequency of the rotating stall is f = 0.5 Hz, and it is a reasonable approximation of experimental value f = 0.59 Hz. A cavitating vortex has been visualized and compared to the experimental one. The analysis explains the governing mechanisms of the cavitating vortex. The methodology can be used for pump-turbine impeller and guide vanes geometry optimization. The ongoing study has been used in the scope of the development project of pump-turbines with reversible Francis runner and non-restricted operating ranges in pumping and generating mode. The first rehabilitation project that includes the findings of the study and enables a wide operating range is Dlouhe Strane PSP in the Czech Republic.

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Nomenclature

(Symbols)	(Symbol meaning)
a_0	Guide vane opening
f	Frequency
k	turbulent kinetic energy
CFD	Computational fluid dynamics
PSP	Pump storage power plant
Q	Discharge
$y+$	Wall spacing
ε	Dissipation
Φ	Flow rate coefficient
Υ	Specific energy coefficient
ω	Rotational frequency
(Subscripts)	(Subscripts meaning)
s	Stall, static
BEP	best efficiency point
max	maximum

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