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Analysis and control of the part load vortex rope in the draft tube of a pumpturbine

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ABSTRACT

Because of the strong increase of fluctuating renewable energies for the electricity generation there is an enormous demand of regulating power. This is an increasing task of pump storage power plants. As a consequence, pump turbines often have to run under extreme off-design conditions. This can result in extremely complicate flow situations and in unstable vortex behavior causing severe oscillations. Especially in part load a vortex rope is forming in the draft tube. This vortex rope rotates and generates a rotating oscillatory pressure field. These pressure oscillations can lead to severe vibrations and can lead to restrictions of the operating range of the machines. By injecting an axial water jet in the center of draft tube through the hub of the runner this vortex rope can be positively influenced or even prevented. This was experimentally shown e.g. by Kirschner et al. [1] and [2] and will be here investigated numerically.

Analysing and predicting this vortex rope by computational fluid dynamics (CFD) methods is still a challenging task. Since the vortex rope phenomenon contains flow instabilities its prediction requires a sophisticated turbulence model, otherwise the dynamic vortex behavior can not be treated accurately. As a consequence, the classical pure RANS models do not lead to an accurate prediction [3] and [4]. Therefore, in this paper a Very Large Eddy Simulation (VLES) approach [4], [5] and [6], which is a hybrid RANS/LES Model, is used. Similar to the LES approach a filtering procedure in space and time of the turbulence is adopted. Only very large eddies are solved directly in the simulation and smaller eddies which still can show anisotropic behavior are treated by an adequate turbulence model.

In this paper the unsteady flows in two different draft tubes of a pump turbine in part load are simulated by both VLES and SST RANS models. In one draft tube, the flow is computed with and without jet injection in order to show the damping of the oscillation by the water jet. The simulations are carried out using the CFD code OpenFOAM. The results show that the vortex rope as well as the vortex control can be predicted sufficiently accurately by the VLES approach and it allows carrying out parametric studies by simulation.

KEYWORDS

VLES, vortex rope, water injection

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1. INTRODUCTION

There is a complex flow instability phenomenon named vortex rope in the draft tube of a hydraulic machine operating at part load which means lower flow rate than the designed one. Working at part load of hydraulic machines can not be avoided because nowadays hydro power plants are increasingly operating at off-design conditions in order to take the task of power-frequency control in the electrical grid. Although currently hydraulic machine can be designed, which can works very well at the optimum working condition the hydraulic machines may suffer from heavy vibration or severe noises resulting from the vortex rope when it runs at part load. It is possible that these heavy vibrations result in the damage of hydraulic machine components due to resonance. In this context, the ability of hydropower plants to handle the operation in a wide range of off-design conditions has become more important. And the research for the flow instabilities phenomenon and the mitigation of vortex rope in draft tube is very meaningful.

Many experimental investigations were done to mitigate or prevent the vortex rope phenomenon. However the most measures lead to a loss of efficiency or unfavorable behavior in other operating points. In 2006 Susan-Resiga et al. [7] presented a new approach in mitigation of the vortex rope phenomenon by injecting water axially in the center of the draft tube. The injected water can change the profile of the axial velocity at the inlet of the draft tube in such a way that the development of the vortex rope can be avoided. One big advantage of this method is that the injection can be switched on in operating points with appearance of a vortex rope and switched off otherwise. That means the operating points without the vortex rope are not affected by this method. Experimental investigation of this mitigation strategy in simplified test rig was presented by Ruprecht et al. [2]. In their test rig measurements in a simplified straight draft tube downstream of a swirl generator were done. Recently by experiment, in which a pump-turbine model with an elbow draft tube are adopted, Kirschner et al. [1] has already verified that by means of water jet injection through turbine hub the amplitude of the pressure fluctuation in the draft tube can be significantly reduced if the pressure fluctuation is caused by the rotation of vortex rope. At this situation, it is shown that injection of water even can reduce the amplitudes of the pressure fluctuations a little more than the injection of air or both water and air. They also show the diameter of the used nozzle has an influence in the quantity of the reduction of the amplitude.

In parallel to the experimental and analytical studies, a considerable number of numerical investigations were attempted and results were compared to experimental data. In general, having available the computational resources, development costs can be decreased by means of more CFD analysis and less experiment in lab. Therefore, the prediction of vortex rope in draft tube by CFD method is a significant research field. Because both large and small turbulent scales are important and synchronously exist in the flow in the draft tube and conventional turbulent models can not solve the small turbulent scales, CFD analysis with traditional turbulent model, e.g., SST model, can not predict the vortex rope properly. Therefore, in order to predict the vortex rope correctly, high sophisticated numerical simulation, such as hybrid RANS/LES simulation, is necessary. Ruprecht et al. [4] developed a very large eddy simulation (VLES) approach which is a hybrid RANS/LES approach based on an extended k-ε model and applied it to the unsteady simulation of flow in a draft tube. They showed that unsteady features of the flow, e.g., pressure amplitudes and vortex rope size, are better predicted by this model than the standard k-ε model by which the flow becomes stationary due to too much damping. The frequency of pressure fluctuations is well predicted in their simulations but amplitudes are underestimated. Krappel et al. [10] used a IDDES model for the whole machine and got better results of both velocity and pressure fluctuation in draft tube than SST model. In present paper the performance improvement of VLES comparing with pure SST model for the flow in draft tube is furtherly investigated.

As mentioned above, mitigating or preventing the vortex rope phenomenon by a water jet injection through runner hub was confirmed by experimental investigations. But there is still a limit of current knowledge. At the moment no mature knowledge database of the various parameters, e.g., jet velocity and discharge, is available to support the design of a hydraulic turbine with water jet injection component. Hence, how to design vortex rope control components for water jet injection with acceptable design cost is a challenging subject. Apparently, VLES is a possible good methodology. But before widely applying VLES for this new flow regime resulting from new technology of mitigating or preventing the vortex rope phenomenon, the performance of VLES for this new flow regime must be investigated and confirmed. Therefore, another aim of the present paper is developing a mature and reliable methodology, i.e., VLES, to predict the influence of the water jet injection components on the vortex rope in the turbine draft tube. The reason adopting VLES is that, on the one hand, the capability of VLES for complex flow phenomenon is preliminarily verified by some flows, on the other hand, not so huge computer resources are needed compared with the computer resources for LES and DNS which are nearly impossible today because of extremely high Reynolds number ($\sim 10^7$) in the turbine draft tube.

In the present paper the unsteady flows in two different draft tubes of a pump turbine in part load are simulated. One draft tube is a straight draft tube, the other one is an elbow draft tube. For the elbow draft tube the flows with and without water jet injection are investigated. The flow in the straight draft tube and the flow without water jet injection in elbow draft tube are simulated by both VLES and SST models in order to confirm that VLES is better than the SST model. The flow with water jet injection in elbow draft tube is simulated only by VLES because the purpose is to investigate the difference of flows with and without water injection. The predicted pressure fluctuations at two points on the wall of draft tubes are compared with the measured results.

The adopted software is OpenFOAM, version 1.6-ext. Preliminary investigation showed that the simulation can be carried out at least on 1024-2048 cores with a rather good performance.

2. EQUATIONS

In order to predict the flow instabilities in draft tube currently both RANS turbulence models and LES are not acceptable due to wrong results or large computational resource. Then the method of VLES is brought forward for the prediction of flow instabilities in draft tube. By means of VLES the less fine meshes can be used compared to LES, which do not require enormous computational resource. Ruprecht [4] developed one version of VLES and applied VLES model firstly for simulation of flow instabilities in draft tube. In this paper, the VLES methology developed by Ruprecht [4] and [5] is adopted and is applied for Menter’s 2003 SST model [8]. The whole SST-VLES turbulence model is defined as follows.

$$\frac{\partial k}{\partial t}+U_j\frac{\partial k}{\partial x_j}=\tilde{P}_k-\beta^* k\omega+\frac{\partial}{\partial x_j}\left[\left(\nu+\sigma_k\nu_t\right)\frac{\partial k}{\partial x_j}\right] \tag{1}$$

$$\frac{\partial \omega}{\partial t}+U_j\frac{\partial \omega}{\partial x_j}=\gamma S^2-\beta\omega^2+2\left(1-F_1\right)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial \omega}{\partial x_j}\frac{\partial k}{\partial x_j}+\frac{\partial}{\partial x_j}\left[\left(\nu+\sigma_\omega\nu_t\right)\frac{\partial \omega}{\partial x_j}\right] \tag{2}$$

$$\nu_t = \min\left[1, \left(\frac{\Delta_f}{L_t}\right)^{4/3}\right] * \frac{a_1 k}{\max(a_1\omega, SF_2)} \tag{3}$$

Where,

$$\Delta_f = \alpha * \max\left(|U|\delta t, \Delta^{1/3}\right) \tag{4}$$

$$L_t = \frac{\sqrt{k}}{\beta^* \omega} \tag{5}$$

$$\tilde{P}_k = \min\left(2\nu_t S_{ij} S_{ij}, 10\beta^* k\omega\right) \tag{6}$$

$$S = \sqrt{2 S_{ij} S_{ij}} \tag{7}$$

$$\alpha = 3 \tag{8}$$

The Δ in Eq.(4) is the volume of local cell of mesh. The blending functions F_1 and F_2 are the same as those of SST model. Except α, the other constant coefficients are the same as those of SST model. Therefore, the difference between SST-VLES turbulence model and SST turbulence model is at the Eq.(3).

3. RESULTS

3.1 Results of straight draft tube

The boundary conditions used for the computation are as following Tab.1.

Flow rate (m^3/s)	Rotational speed of runner (RPM)
0.0861	1404.3

Tab.1 Boundary conditions for the case with straight draft tube

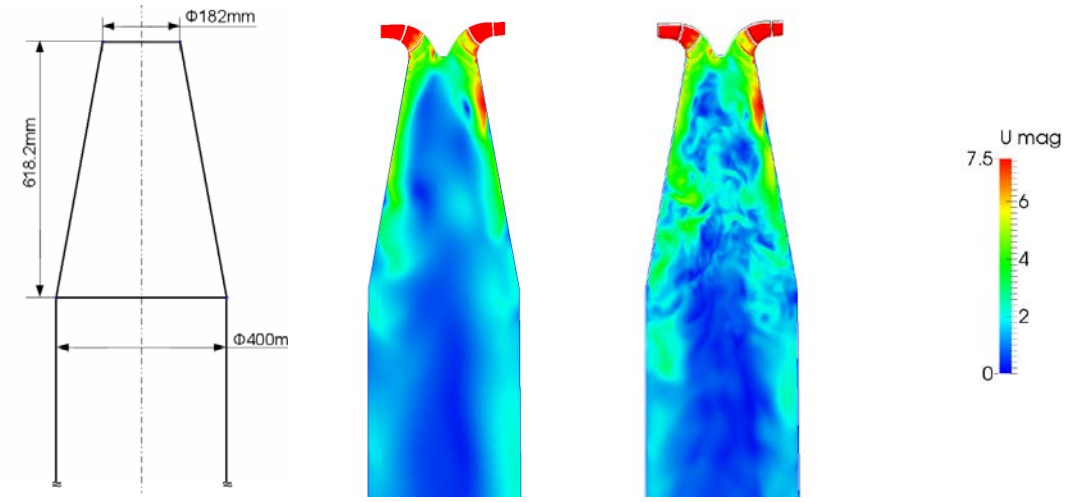

Fig.1 Geometry and velocity results of the straight draft tube. The right contour is predicted by VLES and the other one is predicted by SST model.

The geometrical model of the straight draft tube and the velocity results at the cutting plane which is through the axis of draft tube are shown in Fig.1. The runner is also modeled for the computation in order to avoid assigning the inlet boundary condition of draft tube directly because Göde et al. [9] have shown the influence of inlet boundary condition of draft tube on the shape of vortex rope in the draft tube, frequency and amplitude of pressure fluctuation which results from vortex rope is remarkable. The mesh used for computation is made up of approximately 31 mio cells. The solver transientSimpleDyMFoam of software OpenFOAM is adopted for the computation. Time step is 0.00024s with which the runner rotates about 2.02 degree per time step. It was found that this time step is fine enough to activate the VLES model. It was also found that the results from this time step are almost the same as those from very fine time step, e.g., 0.000008s. Therefore, adopting 0.00024s as the computational time step is suitable.

The predicted pressure results varying with time at 2 locations which are on the wall of the straight draft tube are written out in order to compare them with the measured results. The measurement points P2 and P1 are located at 99.02mm and 148.3mm under the draft tube inlet respectively. After the fast Fourier transform (FFT), the pressure amplitudes in frequency domain of pressure fluctuation at points P2 and P1 are shown in Fig.2.

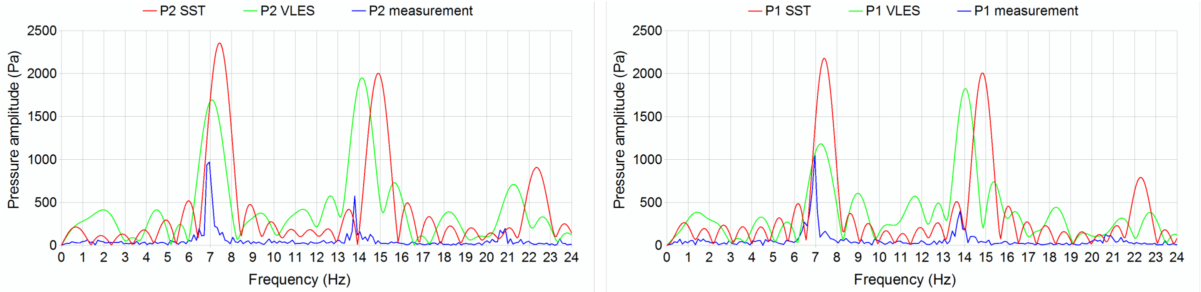

Fig.2 Pressure amplitudes in frequency domain for points P2(left) and P1(right)

The first 2 dominating frequencies of the pressure fluctuation at points P2 and P1 are listed in Tab.2 and Tab. 3 respectively. According to the FFT results in these tables, VLES predicts good the frequencies of the pressure fluctuations at point P2. At point P1 VLES also predicts good 2nd order frequency but predicts a little high (4.17%) 1st order frequency. However, for all the frequencies at both points P2 and P1, VLES predicts better results than k-ω SST model. Therefore, VLES is superior to SST model according to this case.

Unit (columns 2, 3 and 4): Hz

Order	Measurement	SST	VLES	SST relative error	VLES relative error
1st	6.96	7.44	7.06	6.91%	1.43%
2nd	13.79	14.88	14.11	7.85%	2.32%

Tab.2 Measured and predicted frequencies of pressure fluctuation at point P2.

Unit (columns 2, 3 and 4): Hz

Order	Measurement	SST	VLES	SST relative error	VLES relative error
1st	6.958	7.375	7.248	5.99%	4.17%
2nd	13.794	14.814	14.051	7.39%	1.86%

Tab.3 Measured and predicted frequencies of pressure fluctuation at point P1.

3.2 Results of elbow draft tube with flow without water injection

The total number of cells in the mesh, the boundary conditions and time step used for this case are similar to those of the previous case for straight draft tube. The predicted pressure results varying with time at one location are compared with the measured results. For this case, both VLES and SST model predict very high and almost same frequency of pressure fluctuation. However, VLES predicts better amplitude than SST. The difference between measured amplitude and that predicted by VLES is less than 10%. Therefore, in this case

VLES still has advantage over SST model according to the FFT results. The predicted vortex ropes at a time are compared with the vortex rope observed in lab as shown in Fig. 3. It shows that the vortex rope predicted by VLES is longer than that predicted by SST model and meets the phenomenon observed in lab better than that predicted by SST model.

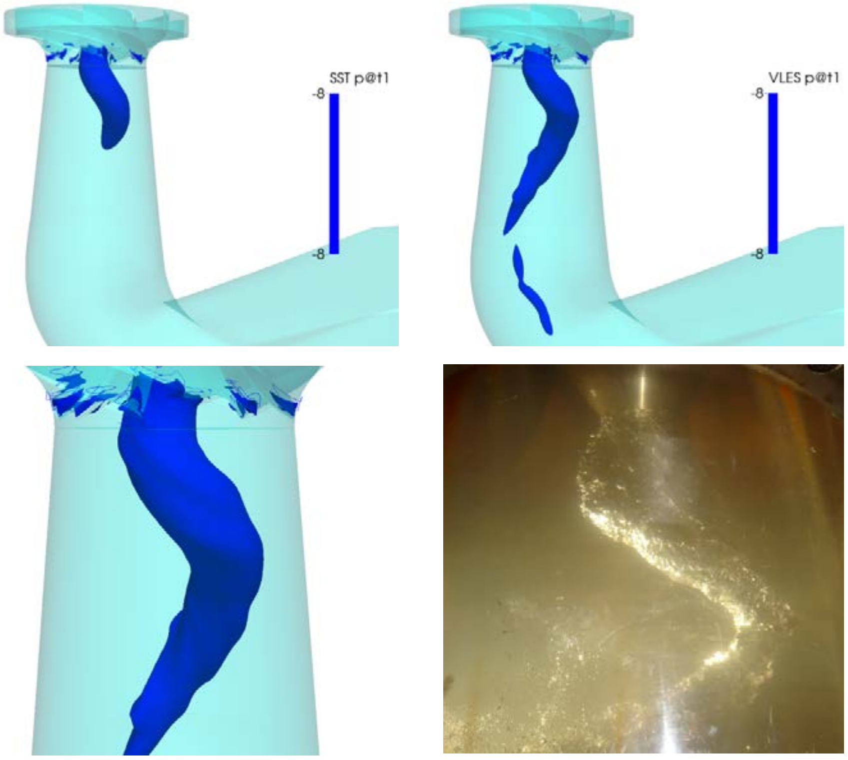

Fig.3 Pressure iso-surface predicted by SST model(top left) and VLES(top right and bottom left) at a time and the vortex rope observed in lab (bottom right)

3.3 Results of elbow draft tube with flow with water jet injection

In this case, water jet is injected into the draft tube through the runner hub. Only VLES is executed. The total number of cells in the mesh, the boundary conditions and time step used for this case are similar to those of the previous cases. The pressures variation with and without water jet injection at one location on the wall of draft tube are shown in Fig. 4 and Fig. 5. The predicted pressure iso-surfaces at a time are shown in Fig. 6. These figures show that the vortex rope is completely suppressed by the water jet injection.

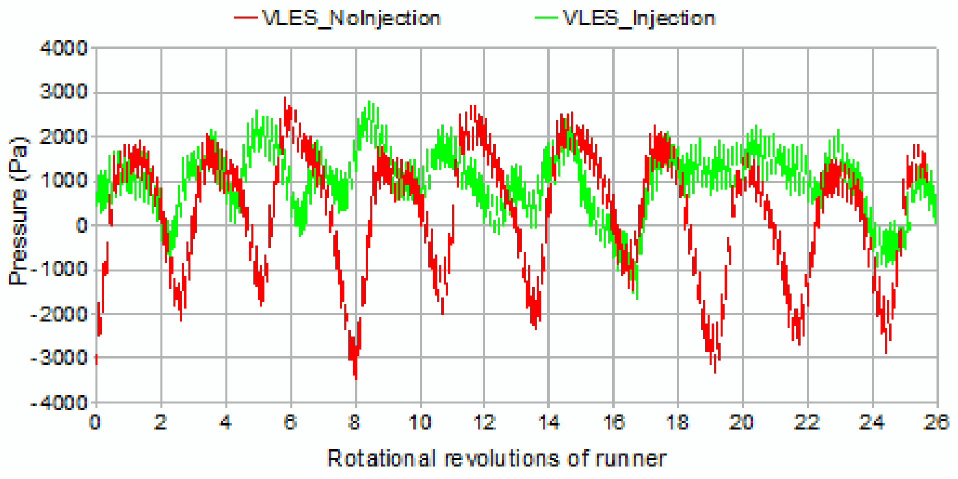

Fig.4 The pressures of flow with and without water jet injection with time

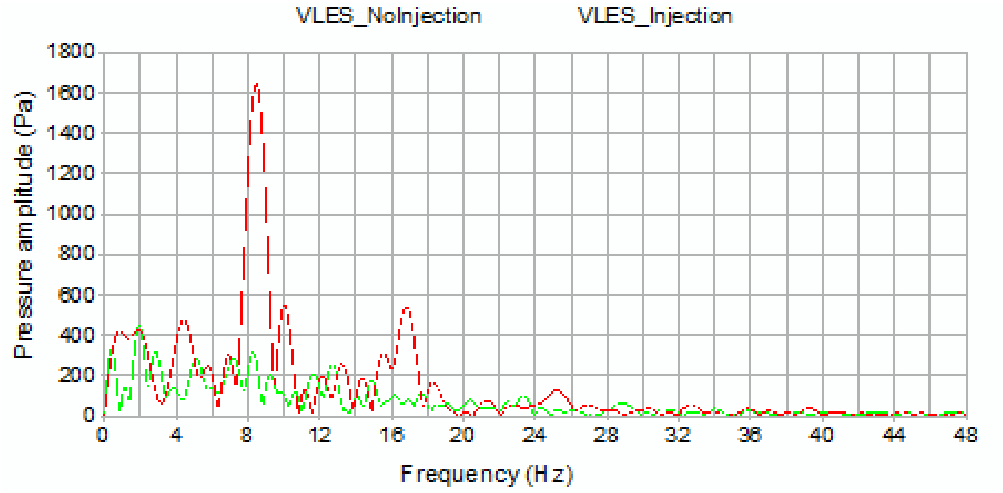

Fig.5 The pressures of flow with and without water jet injection at frequency domain

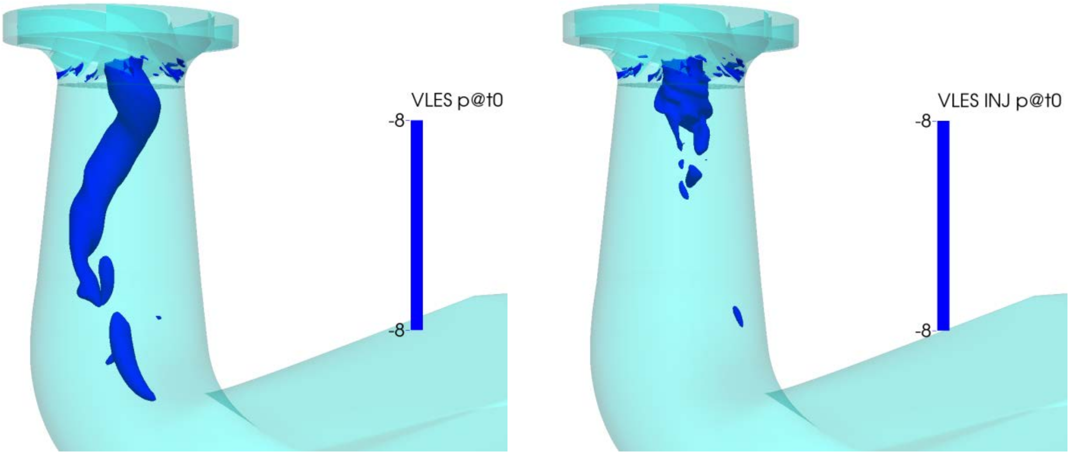

Fig.6 Pressure iso-surfaces of flow without(left) and with(right) water jet injection at a time

4. CONCLUSION

According to the results of straight draft tube and elbow draft tube, it is found that in general VLES predicts better the amplitudes and the frequencies of pressure fluctuations in draft tube than SST model or at least VLES predicts the same results as those predicted by SST model. In addition, VLES predicts a better shape of vortex rope than SST model according to the vortex rope observed in lab. Because the vortex rope can completely be suppressed by the water jet injection and the influence of water jet injection on the turbine performance, i.e., the water head and the runner torque, is very small and can be ignored, the water jet injection through the runner hub is a good method to suppress or at least to mitigate the pressure fluctuations resulted from the vortex rope in the draft tube.

5. ACKNOWLEDGEMENTS

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