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On the flow-induced pulsating forces during load reduction of a Kaplan turbine model

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Abstract. Intermittent renewable energy sources have become a significant part of the electric grid in the last few decades. With their implementation into the energy system and varying electricity demands from the market, certain challenges in maintaining a stable electric grid have arisen. Hydropower here finds an important role in the stabilisation of the grid with its possibilities to regulate frequency and power. However, this causes hydropower to operate in transient modes more frequently. Consequentially, more studies are necessary in order to safely operate the turbines during transients, to plan maintenance, and to predict the lifetime of the hydropower plants and the costs associated with new operating circumstances. There has been an extensive series of studies on transient operation of Francis turbines and pump turbines in recent years. However, transient operation of Kaplan turbines needs more in-depth studies. Therefore, the present work is focusing on the formation of oscillating flow structures and the evolution of the resulting flow-induced forces during load reduction of the U9-400 Kaplan turbine model. The study of the flow field is performed using the OpenFOAM open-source CFD code. The flow-induced horizontal and axial forces, and consequential bending moments and torque acting on the runner are analysed together with the flow structures forming in the draft tube at the best efficiency point (BEP) and at part load (PL).

1. Introduction

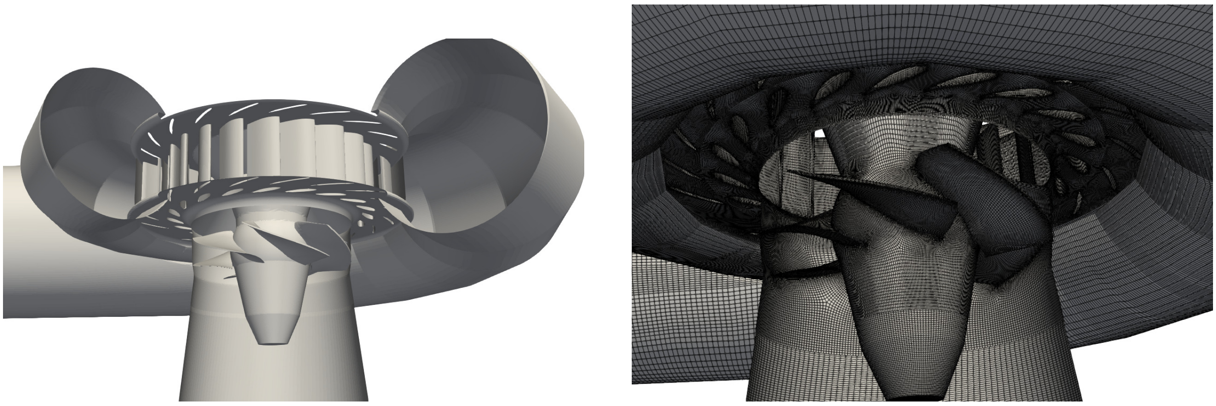
The world's energy demand has been growing continuously in the last years, which combined with the recent energy crisis [1] results in the extensive installation of new power plants that use intermittent sources of energy like solar and wind. This causes instabilities in the electric grid, which is why controllable energy sources need to be used in order to stabilise the grid. Since hydropower is a renewable and controllable source of energy, it will be used more often to maintain the stability of the grid. This means that hydro turbines have to be more flexible [2] and work with variable loads, while they were designed to continuously operate at their best efficiency point (BEP). This can negatively affect the lifetime of the machines. Consequentially, more studies are necessary to predict the effects on the machines during transient operation. Computational Fluid Dynamics (CFD) provides a possibility to simulate the flow in the turbines during transients. Extensive research studies have in recent years been reported on CFD simulations during transient operation of Francis turbines [3, 4, 5, 6, 7, 8, 9, 10, 11, 12] and pump-turbines [13, 14, 15]. However, there is still a need for in-depth studies of transients in Kaplan turbines. For this purpose, we have recently developed an open-source framework for performing numerical studies of transient operation of Kaplan turbines [16, 17].

The purpose of the present paper is to investigate the flow-induced forces acting on the

U9-400 Kaplan turbine model during load reduction, using the OpenFOAM open-source CFD code.

2. Geometry and operating conditions

Simulations are performed on the U9-400 Kaplan turbine model shown in figure 1a. It is a 1:3.875 scale model of the U9 prototype located at the hydropower plant Porjus in the north of Sweden. The model includes a spiral casing, 18 stay vanes, 20 guide vanes, 6 runner blades and a draft tube. The runner has a diameter of $D = 400\,\mathrm{mm}$ and a rotational speed of $\omega = 870\,\mathrm{rpm}$. The head is $H = 6.97\,\mathrm{m}$. The flow rate is $Q_{\mathrm{BEP}} = 0.451\,\mathrm{m}^3/\mathrm{s}$ at the best efficiency point (BEP) and $Q_{\mathrm{PL}} = 0.398\,\mathrm{m}^3/\mathrm{s}$ at part load (PL), which means that the PL flow rate is 88.44% of the BEP flow rate. In Kaplan turbines [18], the guide vane and runner blade angles are adjusted at the same time as the runner is rotating. This enables more control of the load on the turbine. However, in the present work a load reduction from BEP to PL along the propeller curve is studied, changing only the guide vane angles. The opening angle of the guide vanes is 26.5° at BEP and it is reduced by 6.5° during 4 seconds to achieve the PL condition.



(a) Geometry (b) Computational mesh

Figure 1: The U9-400 Kaplan turbine model

3. Numerical framework

OpenFOAM-v2112 was used to carry out the computations. The discretisation of the temporal derivatives is conducted using the implicit second-order backward scheme. The convective terms in the momentum equations are discretised using the Linear-Upwind Stabilised Transport (LUST) scheme. The PIMPLE algorithm is adopted for pressure-velocity coupling. For the turbulence modelling, the $k - \omega$ SST SAS model is used. For more details about the numerical aspects, please see our previous works as the same schemes and methods are adopted here [5].

The computational mesh contains 15×10^6 cells and is shown in figure 1b. The complex mesh motion is enabled through the open-source semi-implicit slip mesh deformation algorithm developed by Salehi and Nilsson [17]. A fixed total pressure boundary condition is utilised at the inlet and a static pressure is prescribed at the outlet, meaning that the flow rate is automatically adjusted through the pressure drop increase caused by the guide vane closure.

4. Results and discussion

The predicted decrease of the flow rate as the guide vane angle is reduced can be seen in figure 2. The first two seconds represent the BEP condition, followed by four seconds of transient operation. The turbine reaches the stationary PL condition from $t = 6\,\mathrm{s}$ until the end of the simulation. The similarity between the two curves is visible with a small deviation in the slope of the flow rate curve due to the inertia of the system. After the start of moving the guide vanes, some time is necessary for the system to adapt to the change in conditions. When the guide vanes reach the final position of 20°, the flow rate oscillates around a value of 0.39 m^3/s. This is attributed to the strong oscillations in the draft tube caused by the Rotating Vortex Rope (RVR) forming at PL.

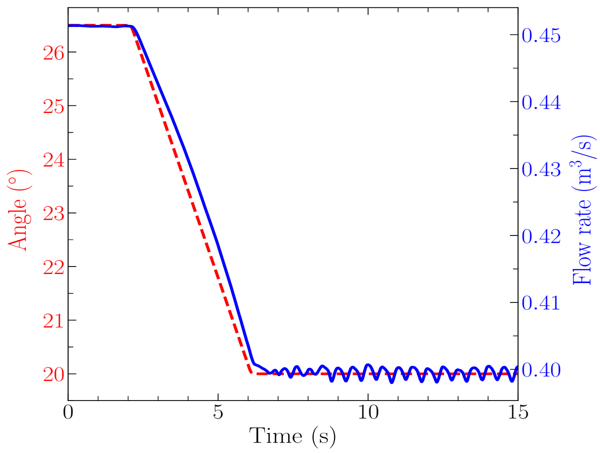
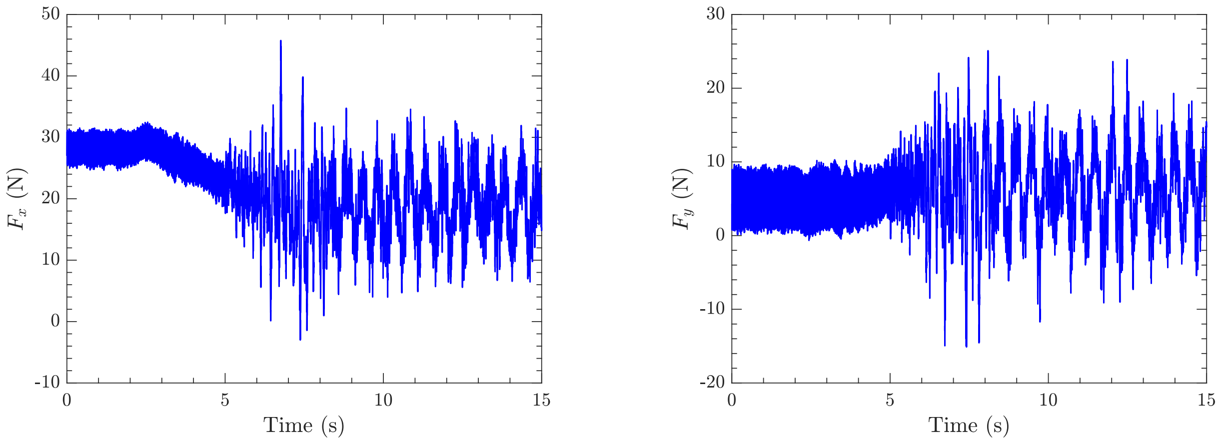


Figure 2: Predicted flow rate reduction with the guide vanes closure

For further explanations of the results, the definition of the axes orientation has to be given. The positive z-direction is defined as downwards, the origin for the torque and bending moments calculation is at the axis of rotation at mid-height of the guide vanes, and the x-axis is pointing in the main flow direction at the inlet. Figure 3 shows the horizontal forces acting on the runner (hub and blades) during the load reduction sequence. The horizontal forces at BEP are fluctuating around a stable mean value. The fluctuations are attributed to the rotor-stator interaction. As a result of the start of closing the guide vanes, shown in figure 2, at $t = 2$ s a slight increase in the value of the force in the x-direction is seen. It can also be seen that both the horizontal force components have a positive mean value at BEP, while they should be zero in ideally axisymmetric flow. This is attributed to the imperfect distribution of the flow through the spiral casing and also the direction of the downstream flow field inside the draft tube. From $t = 2$ s to $t = 6$ s, when the closing of the guide vanes happens, the force in the x-direction reduces due to the decreasing flow rate, while the mean value of the force in the y-direction stays almost constant. From $t = 6$ s to $t = 9$ s, when the turbine operates at a part load condition, some large fluctuations in the horizontal forces can be seen. They originate from the formation of the well-known Rotating Vortex Rope (RVR). The process of formation of the RVR instability starts at $t = 6$ s. At around $t = 9$ s, a well-developed stable RVR seems to be created, and the turbine reaches a quasi-stationary PL operating condition that is kept until the end of the simulation. A visually observed rotational frequency of RVR matches the value of $f/f_n = 0.138$, where f_n is the runner's rotational frequency. The oscillations of horizontal forces during PL operating condition have an average peak-to-peak amplitude of 30 N.

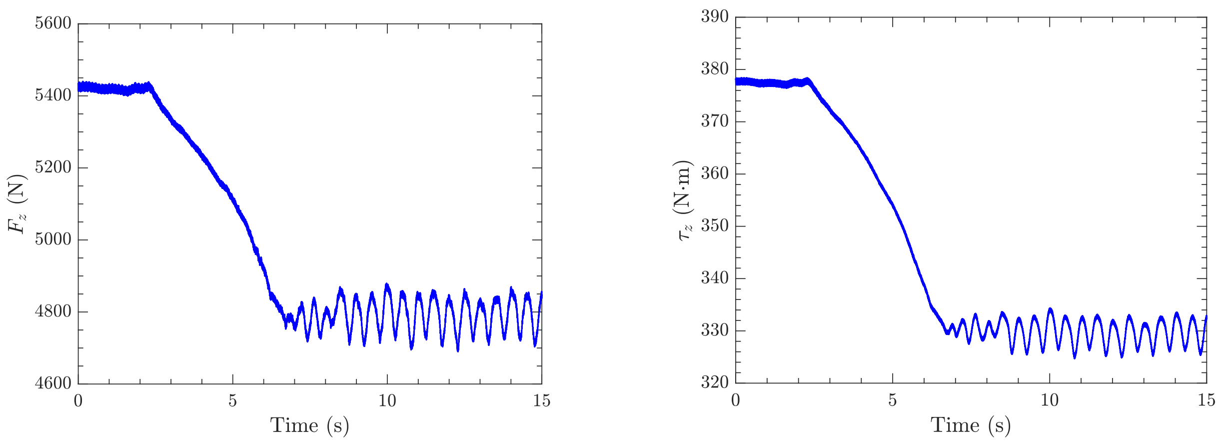
The axial force and torque about the z-axis acting upon the runner are shown in figure 4. It can be seen that the axial force oscillates around a steady mean value at BEP, it decreases with closing the guide vanes as a result of flow rate reduction, and then it oscillates until the end of the simulation as a consequence of the RVR. It is interesting to observe that the higher amplitude fluctuations during the formation period of the RVR, visible in both horizontal directions in figure 3, are absent in the axial force. This shows that the pressure pulsations produced by the



(a) Force in x-direction (b) Force in y-direction

Figure 3: Horizontal forces on the runner

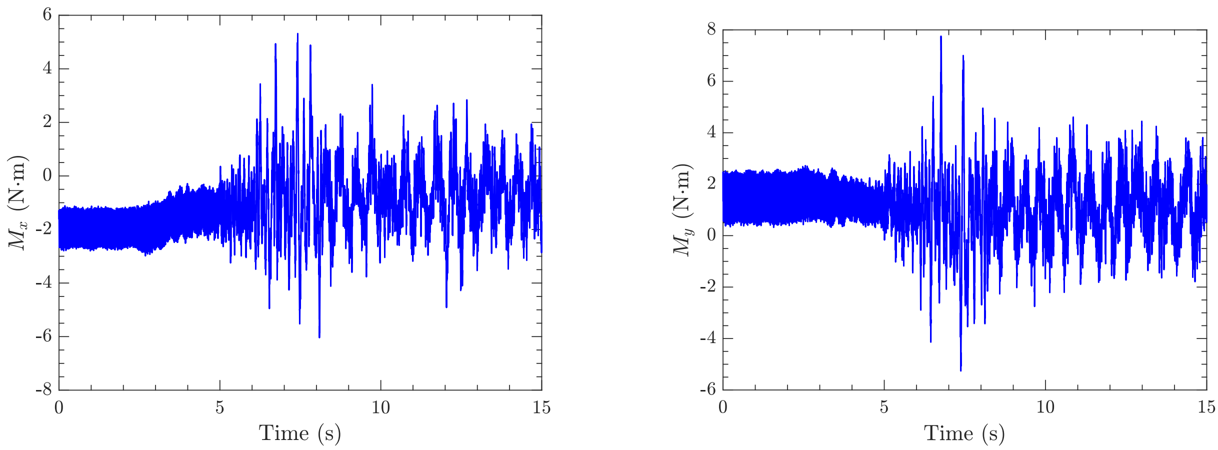
RVR during its formation have more effect in the horizontal direction. Furthermore, the force in the z-direction has much higher values in comparison with the horizontal forces because the main flow through the runner is in the axial direction. RVR-produced pressure pulsations at PL cause higher peak-to-peak amplitude of axial force oscillations in comparison to the oscillations of horizontal forces. The amplitude has an average value of 150 N. The torque around the z-axis, seen in figure 4b, shows similar behaviour as the axial force. The torque oscillations due to the RVR with an average peak-to-peak amplitude of 8 N·m are transmitted to the shaft.



(a) Axial force (b) Torque about the z-axis

Figure 4: Axial force and torque on the runner

Figure 5 shows the time evolution of the bending moment on the runner about the x-axis (figure 5a) and y-axis (figure 5b). In the first two seconds, there are high-frequency oscillations around a mean moment value as a result of rotor-stator interaction at BEP. From $t = 2$ s to $t = 6$ s, when the guide vanes are closing, the magnitude of the mean values of both moments is decreasing. This is happening due to the fact that with flow reduction, as a consequence of closing the guide vanes, the flow-induced forces on the rotor surfaces decrease. The moment about the x-axis is a consequence of flow-induced forces acting in the y and z-directions and due to their orientation and the location of the origin, it decreases to a mean value which is still negative. The flow-induced forces in the x and z-directions cause the moment around the y-axis with a positive mean value. In the period of $t = 6\,\text{s}$ to $t = 9\,\text{s}$, the RVR is forming which can be seen in the developing fluctuations of the bending moment. The values of the moment fluctuate between positive and negative values which means that the direction in which forces tend to bend the rotor is changing. This consequentially changes the direction of the loads on the bearings fixing the shaft. After $t = 9\,\text{s}$, the RVR is well-developed and it causes the moment to oscillate regularly with an average peak-to-peak amplitude of $6\,\text{N·m}$. The values of the bending moment about the horizontal axes are significantly lower than those of the torque about the z-axis. In an ideally axisymmetric flow field, the values of the bending moment about the horizontal axes would be zero. However, similar to the horizontal forces, they are not because of the imperfections of the flow distribution of the spiral casing and flow formations inside the draft tube.



(a) Moment about x-axis (b) Moment about y-axis

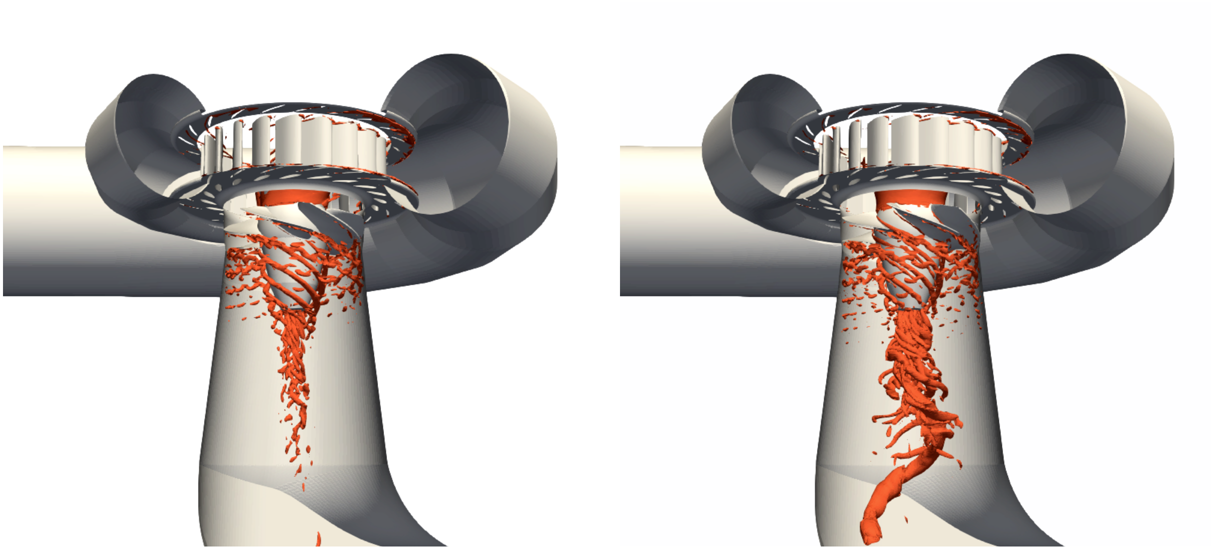
Figure 5: Bending moment on the runner

In order to better understand the presented results, the vortical flow structures are visualised in figure 6 through the iso-surface of $\lambda_2 = 5000\,\text{s}^{-2}$. λ_2 criterion is a vortex core detection algorithm that is used to identify vortices from a three-dimensional fluid velocity field [19]. Figure 6a indicates an axial flow field after the runner in the draft tube with no significant swirl, which is a characteristic of the BEP condition. However, in figure 6b, the RVR is clearly visible. The RVR forms at the part load operating condition and causes large pressure oscillations which produce persistent low-frequency high-amplitude pulsating forces, as seen in figures 3 and 4a. Such pulsating forces have a significant negative impact on the lifetime of the machine, which is why the results shown in this paper are of great importance for understanding the effects of regulating the operating conditions of the turbine.

5. Conclusion

This paper gives a brief description of the evolution of the forces, bending moment and torque on the runner, and formation of oscillating flow structures during load reduction of a Kaplan turbine model. The load reduction, i.e., the transition from BEP to PL, was performed by closing the guide vanes while the angle of the rotor blades was kept constant throughout the operation. The computations were performed using the OpenFOAM open-source CFD code.

It was shown that forces, bending moment and torque experience high-frequency oscillations around a stable mean value at BEP due to rotor-stator interaction. The formation of the RVR at PL causes high-amplitude fluctuations in horizontal forces and bending moment about the



(a) Best efficiency point (b) Part load

Figure 6: Flow structures in the draft tube at BEP and PL conditions visualised using λ_2 iso-surfaces

horizontal axes. A well-developed RVR causes repeating low-frequency oscillations of forces, bending moment and torque at PL. Flow structures in the draft tube during BEP and PL were visualised using λ_2 iso-surfaces and the formation of the RVR was clearly observed.

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