Numerical analysis of misaligned guide vanes effect pressure oscillations in a prototype pump turbine

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Abstract. The unsteady Reynolds-averaged Navier-Stokes equations with the $k$-$\omega$ based SST turbulence model were solved to model the unsteady flow within the entire flow passage of a large Francis Pump turbine with misaligned guide vanes (MGV) device under the rotated speed. Four MGV with three different MGV openings are chosen to analyse the influence of pressure pulse in turbine modes. This study investigates the characteristics of the dominant unsteady flow frequencies in different parts of the pump turbine for various MGV openings. The hydraulic performance and pressure fluctuations were predicted numerically. The computed result shows that the MGV can decrease the relative amplitude in the state part of flow passage, but not for the rotator runner blades.

1. Introduction

With the process of the development of pump storage plant in current China, the stability of pump turbine units were paid more attention. The hydraulic interaction between runner blades and guide vanes is a well-known cause of vibration and noise in pump turbines\cite{1}. The phenomenology of Rotor Stator Interactions (RSI) may be considered as a combination of inviscid flow, potential, and viscous flow, wake, interactions\cite{2}. The application of MGV for pump storage turbine brought a new hydrodynamic research topic\cite{3,4}, including the new RSI between the MGV and runner. MGVs can improve the stability of the pump turbine in no-load mode and turbine startup mode and cut down the surge pressure rises under turbine load-rejections\cite{5}. In order to achieve a more widely application of MGVs in pump turbine, the influence of pressure pulses with MGVs in turbine modes were proposed. The 3D flow mechanism of pump turbine can be investigated numerically. It is a great significance for in-depth understanding of the inherent mechanism of pump turbine vibration, to improve the whole hydraulic performance, improving the operation stability of pump turbine.

2. Prototype Francis pump turbine

The Francis pump turbine under consideration has a 3.9 m diameter runner. The designed water head in turbine mode is 500 m, with 7 runner blades is, 20 stay vanes and guide vanes. The rotated speed is 500rpm. The computed flow domain includes the entire turbine flow passage as shown in Figure 1.
The position of four MGVs is shown in Figure 2. Three different of MGV opening 0, 5 and 15, with the other GV opening keep the same of 9 degree, are chosen to analysis the influence of the MGVs. The parameters of three operating conditions are list in Table 1. For the three operating conditions, the rotating speeds are just the same of rotated speed, the water head are all 500 m.

| Operating Conditions | No. of MGV | MGV opening | Rest GV opening |
|----------------------|------------|-------------|-----------------|
| MGV0                 | —          | 0°± 9°      | 9°              |
| MGV5                 | 3, 4, 13, 14 | 5°± 9°      | 9°              |
| MGV15                | 3, 4, 13, 14 | 15°± 9°     | 9°              |

An unstructured mesh was used so that the cell density could be controlled manually based on the flow features. The spiral case region had a relatively coarse mesh, with the mesh further refined downstream as the flow accelerated. Particular attention was paid to the discretization near the stay vanes, guide vanes and the runner blades to correctly represent the local large velocity gradients. The mesh had about 540,000 nodes, 1,600,000 elements. The mesh for three MGV openings cases is shown in Figure 3.

The $k$-$\omega$ based SST model accounts for the transport of the turbulent shear stress and gives highly accurate predictions of the onset and the amount of flow separation with adverse pressure gradients\cite{6}. A second-order Backward Euler scheme was used for the convection terms with a central difference scheme for the diffusion terms in the momentum equations. The model was implemented in the ANSYS CFX13.

![Figure 1. The prototype France pump turbine.](image1)

![Figure 2. Position of four MGVs.](image2)

![Figure 3. Three cases mesh in stay vane and MGV part.](image3)
For unsteady simulation, the time step was related to the runner rotational speed with one complete runner revolution is performed every 100 time steps. The data was recorded every 2 time steps. The long period for the irregular fluctuating flows were analyzed for 2,000 time steps for each case with data sampled for the last 1,000 steps. The pressures were converted to head.

3. Results and analysis

3.1 Performance

Steady numerical results are shown in Fig. 4 for the discharge, power and efficiency for the three cases. For case MGV0, the turbine operated with small guide vane openings without a different MGV opening, with a predicted discharge of 24.5 m$^3$/s with a hydraulic efficiency of 66% and a runner power of about 79 MW. For cases MGV5 and MGV15, the discharge increased to 27.9 m$^3$/s and 34.3 m$^3$/s, the efficiency increased to 70% and 74%, and the runner power increased to 96 MW and 124 MW. The increasing MGV opening increased the flow area inside the guide vanes which increased the discharge, the turbine power and the hydraulic efficiency.

![Figure 4. Steady performance results for 3 cases.](image)

3.2 Pressure analysis in diversion parts

During the calculations, the flow data was saved at the points inside the spiral case, stay vane and guide vane, as shown in Figure 5. Among these, 5 were on spiral case (named sp1–sp5), 4 were on stay vanes (named sv1–sv4), 4 were on pressure side of guide vanes (named mv1–mv4), 4 were on suction side of guide vane (named gv1–gv4), above four-point are evenly arranged along the circumferential direction. Near the two MGVs, 4 were on the MGVs suction side (named gv5–gv8). All of these points were located on the middle span plane (0.5span) along the height of the blade. These points were in a stationary reference frame.

![Figure 5. Monitoring points in diversion parts.](image)
The pressure was recorded at 21 points in the spiral case, stay vane and guide vane in the unsteady predictions. The relative peak-to-peak amplitudes of the pulses are listed in Table 2 and 3 under three different MGV openings. The calculated results show that, for all three cases, along the flow direction, the relative pressure amplitude increasing in spiral case. And at the same monitoring point in spiral case, the pulse amplitude decreased with the opening increasing of MGV. With the radius decreased, the relative pulse amplitude increased from spiral case to stay vane and the pressure side of guide vane, while it increased dramatically in the suction side of guide vane.

Table 2. Relative pulse amplitudes in spiral case and stay vane at 13 points for three cases.

| OC4p-to-p(%) | sp1 | sp2 | sp3 | sp4 | sp5 | sv1 | sv2 | sv3 | sv4 | mv1 | mv2 | mv3 | mv4 |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| MGV0         | 1.56| 2.41| 4.21| 5.38| 8.49| 7.30| 8.07| 8.20| 10.16| 9.08| 9.95| 9.09| 10.93|
| MGV5         | 0.82| 1.33| 2.58| 4.07| 5.39| 7.10| 6.74| 8.18| 7.59| 8.46| 7.88| 9.93| 8.64|
| MGV15        | 0.92| 1.40| 3.36| 5.48| 4.78| 6.92| 6.88| 7.91| 7.59| 8.44| 8.37| 8.84| 8.81|

Table 3. Relative pulse amplitudes in suction side of guide vane at 8 points for three cases.

| OC4p-to-p(%) | gv1 | gv2 | gv3 | gv4 | gv5 | gv6 | gv7 | gv8 |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|
| MGV0         | 39.85| 42.53| 43.60| 39.55| 38.24| 40.43| 34.43| 36.11|
| MGV5         | 45.92| 38.31| 44.99| 41.13| 35.99| 30.75| 30.45| 32.16|
| MGV15        | 46.22| 16.87| 42.79| 17.52| 30.45| 18.52| 16.71| 16.30|

On stay vane and guide vane, three pairs of four-points, sv1 to sv4, mv1 to mv4, and gv1 to gv4, are evenly arranged along the circumferential direction. The results in Table 2 show that the pulse amplitude is less than 12%, and little difference between the four values. The relative pulse amplitude increased dramatically in the suction side of guide vane, almost larger than 40%, as shown in Table 3. The results show that the amplitudes for the four symmetric points (gv1 to gv4) are changed a lot in case of MGV15. That means the MGV lead to non-uniform flow along the circumferential direction, and then causes the big amplitudes difference between the 4 points.

The MGV0 case pressure pulse and the amplitude spectrum show that the dominate frequency is a low frequency of $0.732f_n$ for each point (sp5 to gv4) in diversion parts. For the case of MGV5, the dominate frequency is still the low frequency, but it changed to $1.07f_n$ with obvious $0.54f_n$. For the case of MGV15, the dominate frequency changed to $0.63f_n$, with obvious $1.27f_n$. And also contain the frequencies of $7n f_n$ for all three cases of those points. That frequency, 7 times the runner rotational frequency which corresponds to the number of blades on the runner, is due to the rotor-stator interference between the runner and the guide vanes.

3.3 Pressure analysis for runner blade passage

There were also 8 points rotating with the runner between the two runner blades (named rv1-rv8) as shown in Figure 6. The unsteady numerical flow analyses included 8 monitored points rotating with the runner in the blade passage to record the pressure pulses. The peak pulse amplitudes at the 8 rotating points in the blade passage are shown in Table 4, also including three MGV opening cases.
These results show that the pulse amplitudes decreased gradually from point rv1 to rv8 in cases of MGV0 and MGV5. For case MGV15, the first three points increased from 40% to 50%, then decreased gradually from rv3 to rv8. At the same point, the pulse amplitudes increased gradually from case MGV0 to MGV15. That means, the MGV can reduce the pulse amplitudes in the stay parts of the pump turbine flow passages, but can increase the pulse amplitudes within rotating runner blade passages. For those rotating points (rv1 to rv8) of case MGV0, the dominate frequency is 20f_n, instead of low frequency in diversion parts. For cases of MGV5 and MGV15, the dominate frequencies are 2nf_n with strong amplitudes. Those rotating points also contain the frequency of 20f_n. And the amplitudes of 20f_n pulse amplitudes decreased gradually from point rv1 to rv8, indicating that the influence of the cascades becomes weaker along flow direction.

3.4 Pressure analysis in draft tube
The flow data was also recorded on 3 sections (named, dt1-dt3) in the upper tube, with each sections having 4 points near the wall. Point 1 on the dt2 plane was named dt21 with the other points named in the same way, as shown in Figure 7. These points were in a stationary reference frame.

![Figure 6. Monitoring points in runner passage.](image1)

**Table 4.** Relative pulse amplitudes at the 8 rotating points in runner blade passage.

| OC\A_p,\% | rv1 | rv2 | rv3 | rv4 | rv5 | rv6 | rv7 | rv8 |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|
| MGV0      | 31.57 | 26.14 | 18.68 | 15.30 | 10.83 | 7.88 | 4.99 | 5.99 |
| MGV5      | 34.10 | 34.93 | 31.42 | 18.88 | 15.36 | 9.84 | 5.90 | 4.45 |
| MGV15     | 45.65 | 50.39 | 53.23 | 36.42 | 24.59 | 16.91 | 10.88 | 6.05 |

![Figure 7. Monitoring points for simulations in draft tube.](image2)
Table 5. Relative pulse amplitudes at the 3 sections in draft tube.

| OC A_{p-\text{to-p}}(\%) | dt11 | dt12 | dt13 | dt14 | dt21 | dt22 | dt23 | dt24 | dt31 | dt32 | dt33 | dt34 |
|---------------------------|------|------|------|------|------|------|------|------|------|------|------|------|
| MGV0                      | 2.73 | 2.89 | 2.95 | 3.28 | 2.56 | 2.48 | 2.73 | 2.28 | 2.01 | 1.95 | 1.74 | 2.01 |
| MGV5                      | 2.76 | 2.48 | 2.71 | 2.61 | 1.72 | 1.94 | 1.66 | 1.95 | 1.04 | 1.11 | 1.19 | 1.05 |
| MGV15                     | 2.46 | 2.06 | 2.46 | 1.90 | 1.60 | 1.60 | 1.55 | 1.66 | 1.21 | 1.16 | 1.21 | 1.13 |

The pressure at 12 survey points along the cone tube (from section dt1 to dt3) were recorded with the relative peak-to-peak amplitudes listed in Table 5. At each section, the relative pressure pulse amplitudes at four points near the wall are almost the same. The maximum amplitude reaches 4% for dt14 in case of MGV0. The relative amplitudes decrease gradually along the flow direction from section dt1 to dt3 for all three cases. According to the results in draft tube, the misaligned guide vanes can reduce the pulse amplitude, with the MGV opening increases, the pulse amplitude decreases more. For draft tube point dt11, the dominant frequency is still the low frequency of 0.732f_n for case MGV0 and it changed to 0.54f_n in case MGV5, and 0.63f_n in case MGV15.

4. Conclusions
The pressure pulses in a Francis pump turbine were predicted numerically for turbine operating conditions for the rated rotational speed at different misaligned guide vane openings.

The numerical results show that the misaligned guide vanes significantly reduce the pulse amplitudes in the stationary parts of the turbine, with larger amplitude decreases at the misaligned guide vane opening increases. However, the misaligned guide vane increases the pulse amplitudes within the rotating runner blade passages with the pulse amplitudes increasing more with increasing misaligned guide vane opening.

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