Analysis of S Characteristics and Pressure Pulsations in a Pump-Turbine With Misaligned Guide Vanes

Hui Sun

e-mail: sh0929@163.com

Ruofu Xiao¹

e-mail: xrf@cau.edu.cn

College of Water Resources
and Civil Engineering,
China Agricultural University,
Beijing 100083, China

Weichao Liu

Dongfang Electric Machinery Co., Ltd.,
Deyang, Sichuan Province 618000, China
e-mail: hustlwc@163.com

Fujun Wang

College of Water Resources
and Civil Engineering,
China Agricultural University,
Beijing 100083, China
e-mail: wangfj@cau.edu.cn

Growing environmental concerns and the need for better power balancing and frequency control have increased attention in renewable energy sources such as the reversible pump-turbine which can provide both power generation and energy storage. Pump-turbine operation along the S-shaped curve can lead to difficulties in loading the rejection process with unusual increases in water pressure, which lead to machine vibrations. Pressure fluctuations are the primary reason for unstable operation of pump-turbines. Misaligned guide vanes (MGVs) are widely used to control the stability in the S region. There have been experimental investigations and computational fluid dynamics (CFD) simulations of scale models with aligned guide vanes and MGVs with spectral analyses of the S curve characteristics and the pressure pulsations in the frequency and time-frequency domains at runaway conditions. The course of the S characteristic is related to the centrifugal force and the large incident angle at low flow conditions with large vortices forming between the guide vanes and the blade inlets and strong flow recirculation inside the vaneless space as the main factors that lead to the S-shaped characteristics. Preopening some of the guide vanes enables the pump-turbine to avoid the influence of the S characteristic. However, the increase of the flow during runaway destroys the flow symmetry in the runner leading to all asymmetry forces on the runner that leads to hydraulic system oscillations. The MGV technique also increases the pressure fluctuations in the draft tube and has a negative impact on stable operation of the unit. [DOI: 10.1115/1.4023647]

Keywords: pump-turbine, S-shaped characteristics, MGV, pressure pulsation

1 Introduction

As electrical systems develop, large thermal and nuclear power plants account for a large proportion of the total supply. Such plants are used to meet the demands for electricity despite their poor peaking capacity. Pumped storage power stations have good dynamics and can provide high-quality energy with good economics. Reversible pump-turbines are the core equipments in pumped storage power stations with a critical influence on stable operation of the power plant. The S characteristics of the pump-turbine operation area was first pointed out by Tanaka and Tsunoda [1] and shown in the elliptical area of the characteristic curve in Fig. 1. The operating curve for a given opening per unit flow Q_{11} rapidly bends downward and almost vertical to the horizontal axis n_{11} . This results in an S-shaped bend as n_{11} decreases, which is commonly referred to as the S characteristics. The S-shaped characteristic curve is not unique to pump-turbines, but the complex operating conditions and the frequent starting and stopping made the S characteristics particularly evident for pump-turbines. Once operating on the S-shaped curve, the pump-turbine may become unstable and may switch back and forth between the generating mode and the reverse pumping mode which resulted in unit and network problems when the system cannot provide the load after load rejection [2]. In the S-shaped curve region, the same speed corresponds to three different flow conditions as shown in Fig. 1. At one point, the slope is positive, so there will be both positive and negative torque, which can easily damage the pump-turbine components. The flow near the no-load operating condition is very complex with the flow dominated by backflow and vortices

in all parts of the turbine [3]. The dynamic characteristics of the rotating stall [4,5] are also very important and often occur in pumps and turbines. In addition, the pressure fluctuations then directly affect stable operation of the pump-turbine. Water pressure fluctuations are one of the most important reasons leading to hydraulic unit vibrations. Therefore, the pressure fluctuation should be controlled to improve the S characteristics. These fluctuations have been analyzed using time-frequency transformations in vassal studies [6,7].

Many authors have shown that pump-turbines with S-shaped operating characteristics near runaway can experience unstable behavior during load rejection. Martin [8,9] concluded that the stability of a pump-turbine in turbine mode can be related to the slope of the n_{11} - Q_{11} at runaway, with a positive slope yielding unstable operating conditions. Hasmatuchi et al. [10,11] experimentally measured the flow characteristics using PIV with a numerical investigation of a scale model pump-turbine model at off-design operating conditions in generating mode. Recent publications such as Widmer et al. [12] showed that the S-shaped curve can be traced back to flow recirculation and vortex formation within the runner and the vaneless space between the runner and guide vanes. Zhang and Wang [13] simulated the flow in the S region using commercial software and concluded that many large eddies existed in the vanes and runner which wasted much of the water energy and reduced the turbine output. Zobeiri et al. [14] explained how pressure fluctuations at the blade passage frequency (BPF) and its harmonics vary along a distributor channel of the pump-turbine. Recent experience with a single stage reversible pump-turbine published by Billdal and Wedmark [15] introduced the concept of MGVs to overcome difficulties with aligned guide vanes to obtain a stable speed after load rejection. Shao [16] used the internal characteristic theory of turbomachinery and the original model characteristic curves without MGVs to denote internal characteristics of a pump-turbine with MGVs and showed

¹Corresponding author.

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Fig. 1 Characteristic pump-turbine operating curves

Fig. 2 Pump-turbine components and part of the computational grid for the flow field

that the MGVs can improve the stability of reversible pump-turbines in the no-load mode. Qian et al. [17] studied the influence of misaligned guide vanes on pressure pulsations in Francis hydraulic turbines to show that the new rotor-stator interaction between the MGVs and the runner increases the high-frequency pressure pulsations in the guide vane and spiral casing.

This paper focuses on the flow in the S-shaped region with MGVs to improve the S characteristics. First, the model test and the CFD simulation with aligned guide vanes and MGVs are achieved. Then the CFD results are compared with experimental data to analyze the S characteristics and pressure pulsations.

2 Simulation Model

The CFD simulations model included the spiral case, stay vanes, guide vanes, runner, and draft tube. Each component of the pump turbine is shown in Fig. 2 along with a partial enlargement of the computational grid. The grid was generated using the commercial software ICEM CFD v14.0. A tetrahedral mesh was used in the spiral case with the other four domains using hexahedral meshes. A grid independence study used five different sizes of grids with elements from 600,000 to 1,500,000 nodes. The numerical simulations show that the results are more accurate with smaller elements. However, the differences in the CFD results were less than 0.2% with the meshes having more than 1,200,000 nodes. Hence, the meshes with 1,200,000 nodes were used for the calculations. The pump-turbine specifications are listed in Table 1.

Table 1 The main pump-turbine characteristics

Runner blade number	N	9
High-pressure side diameter of runner	D_1	515.4 mm
Low-pressure side diameter of runner	D_2	300 mm
Rotation speed	n	1200 rpm
Guide vane number	Z_1	20
Stay vane number	Z_2	20

3 Analysis of the S Curve Characteristics

3.1 S Characteristics Without MGVs. The simulations used wicket gate openings of 4 deg, 6 deg, and 8 deg. The boundary conditions were:

- Constant discharge at the inlet of the spiral case.
- Averaged relative pressure of 0 Pa at the outlet of the draft tube.
- Solid surfaces: smooth no slip walls and general grid interface (GGI) to connect different domains and meshes.
- Turbulence model: SST $k-\omega$.

Figures 3 and 4 compare the computational results and model test data for low flow conditions, which is in the typical S-shaped characteristic region for openings from 4 deg to 12 deg. The good

Fig. 3 Comparison of predicted and measured performance curves

Fig. 4 CFD performance curves

agreement between the measured and simulated results show the reliability of modern CFD methods for complex, unsteady flow structures. Both the simulation results and the experimental results clearly show the S-shaped characteristics. The operating conditions change frequently in pumped storage power stations, which can induce oscillations in the hydraulic system in the unstable S region.

3.2 S Characteristics With MGVs. The MGVs technique is widely used to control the stability of machines operating in the S region. The aligned guide vanes and the misaligned guide gates are first opened simultaneously from their closed position

to some small opening. Then several (usually an even number) MGVs are changed to their full preopening angles, often 20 deg to 28 deg. The MGVs improve the stability of the reversible pump-turbines in the no-load mode and in the turbine startup mode and also reduce pressure surges during turbine load rejection. In this paper, the simulations and the experimental tests used preopening of the 2, 7, 12, and 17 guide vanes with openings of 20 deg and 28 deg. The vane locations are shown in Fig. 5. As seen in Fig. 6, the simulation results agree well with the measured data with no S characteristic curve in any case. In Fig. 4 the slope was positive at runaway with the aligned guide vanes, while with the MGVs, the slope is always negative. Thus, the instabilities are related to the S-shaped curve with a positive slope at runaway.

3.3 Internal Flow Analysis of the S Characteristic. Figure 7 shows the S1 stream surface at all 8 deg guide vane openings for flow rates $Q_{11} = 0.01, 0.02, 0.06$, and $0.087 \text{ m}^3/\text{s}$. The streamlines in Fig. 7 show the vortex flow structure in the runner passages and even near the entire leading edge near the no-load operating condition (runaway) in turbine mode. The vortex structure almost disappears for $Q_{11} = 0.06$ and $0.087 \text{ m}^3/\text{s}$ because of the centrifugal force and the large incident angle at the low-load conditions which lead to the large vortices between the guide vanes and the blade inlets and strong recirculation inside the vaneless space. They are the main factors that lead to the S-shaped operating characteristics.

The characteristic curves in Fig. 6 lead to the conclusion that the S characteristics can be improved when the pump-turbine operates with several guide vanes at different opening angles. The streamlines on the blade-to-blade surface are compared in Fig. 8 for the aligned guide vanes and the MGVs. When the guide vanes are aligned, as shown in Fig. 8(a), the vortex causes the S characteristics by

Fig. 5 Schematic diagram of the MGVs

Fig. 6 Comparisons of the CFD results with experimental data for MGVs

Fig. 7 Streamlines on the runner

Fig. 8 Streamlines on the runner for aligned guide vanes and MGVs

observing Figs. 8(b) and 8(c), showing that preopening some of the guide vanes increases the flow and reduces the vortices.

4 Pressure Fluctuations With MGV

Further analysis considered unsteady flow for the same model with 6 deg and 8 deg guide vane openings. Since the S characteristic are effectively improved by MGVs, the following study focuses on predicting the radial forces on the runner and the pressure pulsations in the draft tube.

Since the unsteady simulations require much time and computing resources, several operation conditions near no-load were chosen for further calculations. Figure 8 shows the conditions chosen for the three different aligned guide vane openings, with the MGVs preopenings set to 20 deg and 28 deg, while the rest were maintained at the original angle. The boundary conditions were the same as in steady calculations with the steady flow results used as the initial conditions. The time step was $\frac{1}{100}$ of a rotation period ($\Delta t = 0.0005$ s) with the total time including 20 rotations. The investigation focused on the effects of the pressure fluctuations in the draft tube, with 16 monitoring points in four different planes in the draft tube, with each of the four points evenly distributed around the circumference on each plane as shown in Fig. 9. Locations 1, 2, 3, and 4 in the first plane were nearest the runner outlet at a distance of $0.25D_2$. The other planes were $0.5D_2$, D_2 , and $1.5D_2$. In the following analysis calculations, with aligned guide vanes and MGVs, the analysis condition is near the runaway condition.

4.1 Radial Force on the Runner. The fluctuation of the radial force on the runner is the primary reason for the unstable conditions. The fluctuations of the radial force plotted in the time domain in Fig. 10 shows that the fluctuations significantly increased with preopening of the misaligned with larger preopen-

Fig. 9 Simulation conditions in the draft tube

ing angles giving larger forces. The amplitudes and main frequencies listed in Table 2 show that:

1. The amplitude is 3 times higher with a 20 deg preopening than with no MGVs and almost 16 times higher with the 28 deg guide vane opening. This substantial increase in the amplitude of the radial forces causes significant fluctuations of the runner and vibrations, resulting in unstable operation of the unit.

Fig. 10 Forces and amplitude spectra on the runner

Table 2 Radial force amplitudes and frequencies at different guide vane openings: fn is the runner rotating frequency, Fr is the main frequency, and Fr' is the second main frequency

Guide vane opening	8 deg	20 deg MGVS	28 deg MGVS
$\Delta F_{\max}$ (N)	78	247	1233
F_r/fn	6	9	8
F_r'/f_n	4		9.6

2. The main frequency with the 20 deg preopening is $9fn$, where fn is the runner rotational frequency. $9fn$ equals the number of passing blades, so the results indicate that the unstable conditions mainly come from the runner interference effect.

Thus, the MGVS increase the amplitude of the radial force, which results in unit vibration. The mechanism producing the unstable operation can be seen in the S1 stream surfaces for the runaway conditions shown in Fig. 11. The CFD simulations show that near the no-load condition, the vortices in the runner and in the vaneless space between the runner and the guide vanes are the main cause of the unstable S characteristics, with the backflow blocking the flow, as shown in Fig. 11(a). A significant part of the vortices are between the blades which contributes to the forces on the runners with the asymmetric vortices as one important reason for the unstable conditions at no-load condition in pump-turbines. In the aligned guide vane conditions the flow in the adjacent flow channel is relatively uniform, so the pressure of the radial force is smaller than that of the MGVS condition since the S characteristics were improved by preopening some of the guide vanes, with the guide vane angle increasing the flow rate increases as well, which reduces the vortex structures in the opened guide vanes as shown

in Figs. 11(b) and 11(c), then the uniform flow will be destroyed, which leads to rapid increase in radial force.

4.2 Analysis of Pressure Fluctuations in the Draft Tube. The following discussion focuses on monitoring point 3 to analyze the impact of the pressure fluctuations. The pressure pulse waveforms and spectra for the aligned guide vane and MGVS cases are shown in Fig. 12, with the detailed amplitudes and the main frequencies listed in Table 3.

The results in Fig. 12 and Table 3 show that:

1. The pressure amplitudes are 1.7 times higher for the 20 deg MGVS than for the aligned guide vanes, and almost 13 times higher for the 28 deg MGVS. This substantial increase in the amplitude of the pressure fluctuations shows that the MGVS technique increases the pressure fluctuations which negatively impacts the stable operation of the unit.
2. For the aligned guide vane conditions, the main frequency is $1fn$ and the second frequencies are $20fn$, $2fn$, and $4fn$, which are all integer multiples of the runner rotating frequency. Thus, pressure fluctuations in the draft tube are mainly caused by the rotations.
3. For the 20 deg MGVS position, the main frequency is $9fn$ and the second frequency is $20fn$, where 9 is equal to the number of runner blades and 20 is equal to the number of guide vanes. For a preopening angle of 28 deg, the main frequency is $1.33fn$ and the second frequencies are $2.33fn$ and $9fn$. Thus, preopening of some of the guide vanes results in the pressure fluctuations containing rotating frequency components of the impeller caused by the rotor-stator interactions in the generating mode with more significant effect as the preopening angle increases. Thus, the 28 deg guide vane preopening angle includes many low frequency components.

Fig. 11 Streamlines in runner for various MGVS

Fig. 12 Pressure fluctuations and amplitudes in the draft tube at monitoring point 3

Table 3 Pressure fluctuation amplitudes for different guide vane openings

Guide vane opening	8 deg	MGVs for 20 deg	MGVs for 28 deg
$\Delta P_{\max}$ (Pa)	442	688	4940
Fr/f_n	1	9	1.33
Fr'/f_n	20, 2, 4	20	2.33, 9

5 Conclusions

Experimental data and CFD simulations results are given to analyze the S characteristics and the effect of MGVs to improve unstable operation of pump-turbines at no-load conditions. The flow in the pump-turbines near the no-load conditions becomes very complex so both steady and transient simulations were performed to predict the features of the internal flow and the pressure fluctuations. The main conclusions are:

- The good agreement between the experimental data and the CFD simulations shows that the CFD simulations provide accurate results that can be used to identify the internal flow for runaway conditions.
- Comparison of the curves for the aligned guide vane and MG cases from the steady-state simulations show that the MG technique eliminates the S-shaped performance characteristics. Thus, the MGVs can improve the S characteristics of pump-turbines.
- The radial forces predicted by the transient simulations for the aligned guide vanes and the MGVs show that the radial forces are increased by the preopening of some guide vanes resulting in significant fluctuations of the forces on the runner and vibrations. The MGVs destroy the flow symmetry in the runner leading to asymmetric forces on the runner and system oscillations.
- The increased pressure fluctuation demonstrate that the MG technique induces pressure fluctuations in the draft tube and can cause unstable operation of the unit.

Thus, although the MGVs improve the S characteristics of the pump-turbines, the unbalanced radial forces on the runner and the pressure fluctuations both lead to unstable operation at the no-load conditions. Hence, further research of the effect of MGVs is needed for practical applications.

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Nomenclature

N = runner blade number
 D_1 = high-pressure side diameter of runner (mm)

D_2 = low-pressure side diameter of runner (mm)

n_1 = nominal rotational speed (rpm)

Z_1 = guide vane number

Z_2 = stay vane number

Q = computational flow (m^3/s)

H = computational head (m)

Q_{11} = unit flow (m^3/s) $Q_{11} = Q/D_1^2 \sqrt{H}$

n_{11} = unit speed (rpm) $n_{11} = nD/\sqrt{H}$

$\Delta F_{\max} = F_{\max} - F_{\min}$ (N)

$\Delta P_{\max} = P_{\max} - P_{\min}$ (Pa)

f_n = runner rotating frequency (Hz)

F_r = main frequency (Hz)

$F_{r'}$ = second main frequency (Hz)

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