Instability analysis of a pump-turbine in vaneless space by turbulence kinetic energy production term

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Abstract. Unsteady flow in a high head pump-turbine was simulated using the Partially-Averaged Navier–Stokes (PANS) method. To study the improvement of "S" characteristics of a pump-turbine with misaligned guide vanes (MGV), turbulence kinetic energy production term and pressure fluctuations are numerical studied, comparing with results of pump-turbine with synchronized guide vane (SyV). Instability in the vaneless space of the model pump-turbine is analyzed based on turbulence kinetic energy equation. The maximum value of turbulence kinetic energy production(P_k) with MGV is doubled compared with the maximum value with SyV, which are in accordance with the increase of the amplitude of pressure fluctuation compared with SyV. The change of P_k is determined by the change of the normal stress term. The change of normal stress term will influence the amplitude of pressure fluctuation. The maximum value of 3D term with MGV increases compared with the result with SyV. It may be caused by the nouniform flow with MGV.

1. Introduction

Pressure fluctuation, resulting from the interaction be-tween the Rotor-Stator Interaction(RSI), is one of charac-teristics of the flow instability in a pump-turbine in the vaneless space[1]. This RSI phenomenon can be consid-ered as the combination of two mechanisms, potential flow interaction and wake interaction [2,3].

For pump turbine, the purpose of using MGV is to im-prove instability in "S" characteristics of pump-turbines during the starting period. However, it could also influ-ence the pressure fluctuations in vaneless space. Xiao et al. [4] found that the pressure fluctuations in vaneless space close to synchronous opening guide vanes reduced signifi-cantly, while Liu [5] found that the pressure fluctuations close to the misaligned opening guide vanes increased. There is a strong correlation between vibrations and pres-sure fluctuations in vaneless space, which deserves more investigation with regard to flow–structural interaction. At present, the influence of the relative opening of pre-opened guide vanes on the instability of a pump turbine in "S" characteristics was still unclear.

The study of instability of a pump-turbine should over-come the difficulties in the simulation of strong vortex and separation flow. For predicting the fluctuation of the dominant scale of vortexes, Partially-Averaged Navier-Stokes (PANS) [6] has been found to be better than that of the LES in flow

regions where simulations suffered from poor near-wall resolution. Ji [7] studied the unsteady cavitating tur-bulence flow around a highly skewed model marine pro-peller based on the PANS method.

In this paper, a nonlinear PANS turbulence model [8] was used to calculate the flow in the vaneless space and the transportation of turbulence kinetic energy equation was used to analyze the instability of the flow.

2. Pump-turbine geometry

Parameters of the model pump-turbine are shown in table 1.

The structure of MGV is shown in figure 1. The pre-opening angle of the misaligned guide vanes is 21 °and 4 pre-opened guide vanes are axial symmetry.

Table 1. Parameters of the model pump-turbine

rated head (m)	52.4
rated discharge (m^3/s)	0.45
rotational speed (rpm)	1200
runner inlet diameter (m)	0.3
numbers of blades	9
numbers of vanes	20
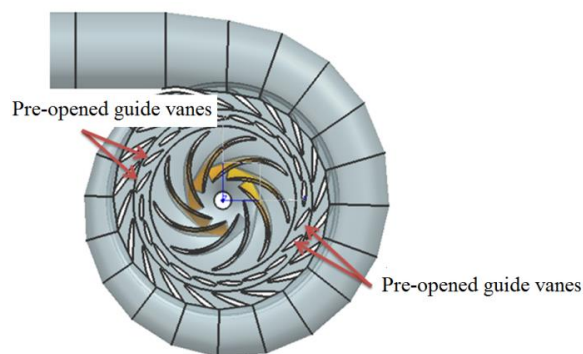
Figure 1. Structure of MGV.
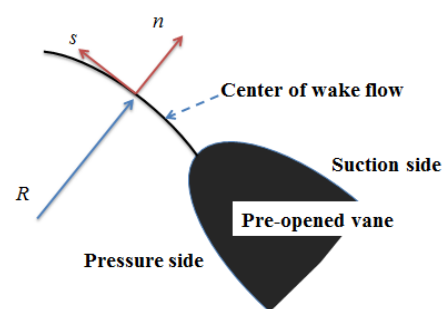
Figure 2. (s，n，z) coordinate system

3. Turbulence kinetic energy transport equation

In order to analysis the flow interaction between pre-opened guide vanes and runner inlet, a curvilinear coordinate system (s, n, z) located on the wake flow of the pre-opened guide vanes is created. z coordinate is the same as the original (x,y,z) coordinate system. s is the tangential direction of the centerline of the wake flow. n is the normal direction of the centerline of the wake flow. The origin of coordinate locates at the crossover point between the curve of guide vanes and the centerline of the wake flow. The (s, n, z) coordinate system is shown in figure 2, R is the radius of the centerline of the wake flow.

The turbulence kinetic energy transport equation in the curvilinear coordinate system is shown in equation (1)[8].

$$\frac{\partial}{\partial t}(k) = -\left[\frac{1}{h}\overline{u_s}\frac{\partial}{\partial s} + \overline{u_n}\frac{\partial}{\partial n} + \overline{u_z}\frac{\partial}{\partial z}\right](k) + \left[-\frac{1}{h}\overline{u_s'^2}\left(\frac{\partial \overline{u_s}}{\partial s} + \frac{\overline{u_n}}{R}\right) - \overline{u_n'^2}\frac{\partial \overline{u_n}}{\partial n}\right]$$

$$-\overline{u_s'u_n'}\left(\frac{\partial \overline{u_s}}{\partial n} + \frac{1}{h}\frac{\partial \overline{u_n}}{\partial s}\right) + \frac{1}{h}\overline{u_s'u_n'}\frac{\overline{u_s}}{R} - \left(\overline{u_s'u_z'}\frac{\partial \overline{u_s}}{\partial z} + \overline{u_n'u_z'}\frac{\partial \overline{u_n}}{\partial z}\right) - \left(\frac{1}{h}\overline{u_s'u_z'}\frac{\partial \overline{u_z}}{\partial s} + \overline{u_n'u_z'}\frac{\partial \overline{u_z}}{\partial n} + \overline{u_z'^2}\frac{\partial \overline{u_z}}{\partial z}\right) \quad (1)$$

$$-\frac{1}{h}\frac{\partial}{\partial s}\left(\overline{u_s'\frac{u_i'u_i'}{2}}\right) - \frac{1}{h}\frac{\partial}{\partial n}\left(\overline{hu_n'\frac{u_i'u_i'}{2}}\right) - \frac{\partial}{\partial z}\left(\overline{u_z'\frac{u_i'u_i'}{2}}\right) + \frac{1}{2}\left(\Pi_{ii} + V_{ii} - \varepsilon_{ii}\right)$$

In which, u_s', u_n' and u_z' are the velocity fluctuations along s, n and z axes. $\overline{U_s}$, $\overline{U_n}$ and $\overline{U_z}$ are the phase averaged velocity component along s, n and z axes. $h = 1 + \frac{n}{R}$. The section headings are in boldface capital and lowercase letters. Second level headings are typed as part of the succeeding paragraph (like the subsection heading of this paragraph).

4. Instability analyze by turbulence kinetic energy

The wake flow of the pre-opened guide vanes is one of the main reason for causing the instability in vaneless space, so the wake flow is analyzed. Lines for analysis are shown in figure 3. s is the distance far away from the trailing edge of the guide vane. c is the chord length of the guide vane. n is the distance from the analysis point to the centerline, $n>0$ at the left part of the centerline in figure 3(b).
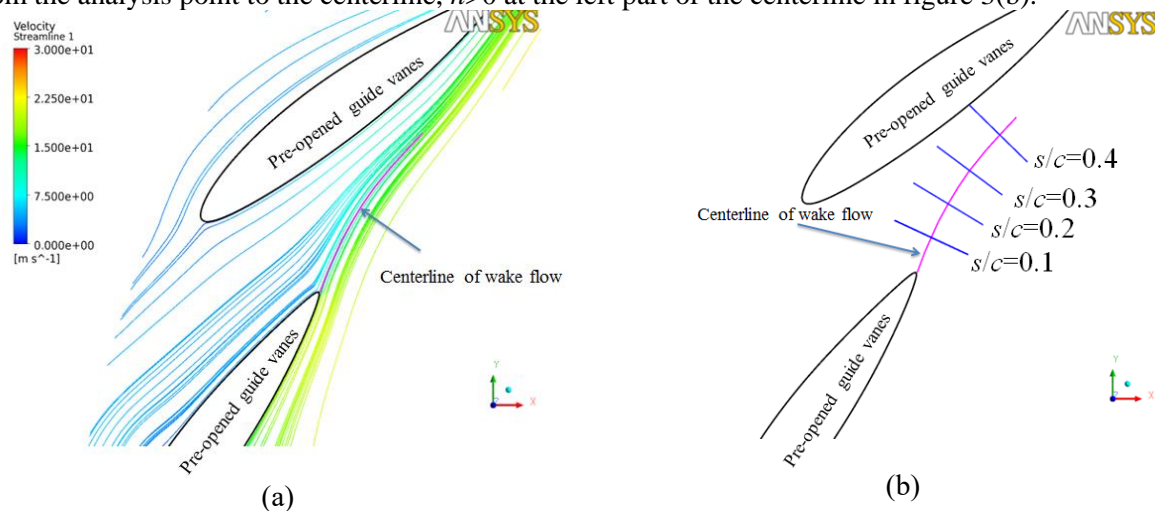
**Figure 3.** Lines for analysis on centerline of the wake flow of pre-opened guide vane.

Velocity distributions along the direction of centerline of wake flow $\overline{u_s'^2}$ were shown in figure 4. The wake flow was influenced by upstream flow when s/c=0.1,0.2. When s/c=0.3, The wake flow was mainly affected by the rotating runner and it can be interpreted by the rotor-stator interaction, especially when s/c=0.4. The use of MGV increase the $\overline{u_s'^2}$ in the vaneless space.

(a) MGV   (b) SyV
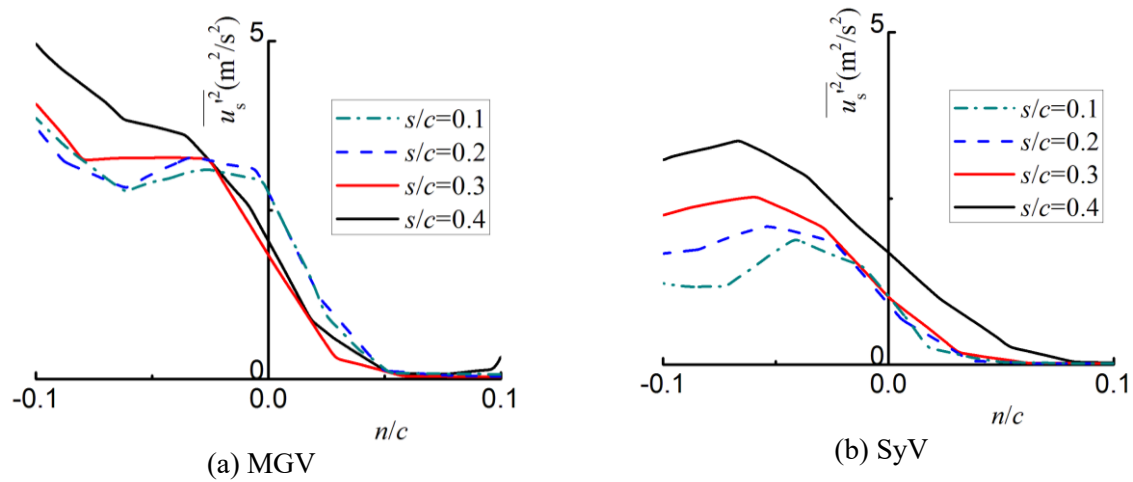
Figure 4. $\overline{u_s'^2}$ distribution**.**

The distribution of normal stress term in vaneless space is shown in figure5. When s/c≤0.3, lines of normal stress term coincide with MGV, while the value of normal stress term change significantly when s/c=0.4 and n/c<0.01. The wake flow with MGV is interfaced by the runner inlet at the position of s/c=0.4, which leading the change of normal stress term. The maximum value of normal stress term with MGV at s/c=0.4 is twice of the maximum value when s/c≤0.3. The position of maximum value of normal stress term with MGV locates at inside the centerline of wake flow and it is close to the runner inlet. When n/c>0.01, normal stress term with MGV is 0. The normal stress term with SyV at s/c=0.4 is less than other lines when n/c<0.01. It may be caused by the uniform flow in the vaneless space with SyV. The use of MGV destroy the uniform flow in the vaneless space, leading the increase of the normal stress term at the position close to the runner inlet.

The distribution of shear stress term in vaneless space is shown in figure 6. The position of maximum value of shear stress term with MGV when s/c≤0.3 is close to the runner inlet. The maximum value of shear stress term with MGV is four times of the result with SyV, and it is small when s/c=0.4. The maximum value of shear stress term with SyV locates at the position close to s=0.


(a) MGV   (b) SyV
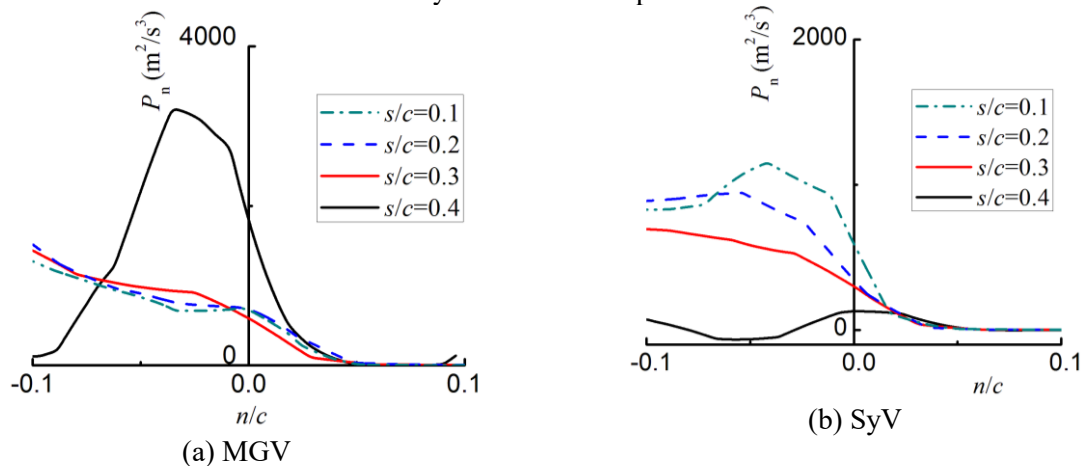
Figure 5. Distribution of normal stress term**.**

(a) MGV   (b) SyV
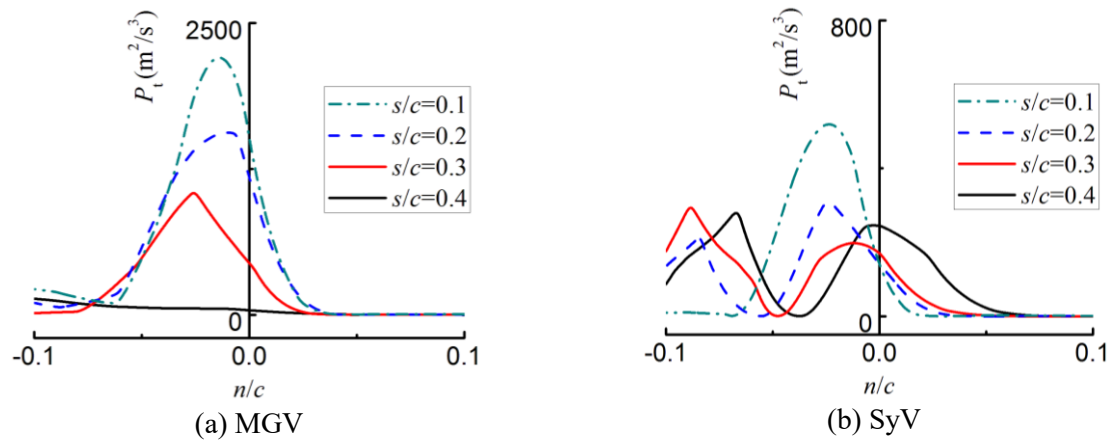
Figure 6. Distribution of shear stress term**.**

The distribution of curvature term in vaneless space is shown in figure7. The position of maximum value of curvature term with MGV when $s/c \leq 0.3$ is close to the runner inlet. Monotone change can be seen when $s/c=0.4$ with MGV. When $n/c \geq 0.05$, the value of curvature term is 0. There has negative value with SyV at the position close to the runner inlet.

The distribution of 3D term in vaneless space is shown in figure8. The use of MGV causes the monotone change of the 3D term. The maximum value of 3D term with MGV increases compared with the result with SyV. It may be caused by the nonuniform flow with MGV.

(a) MGV   (b) SyV
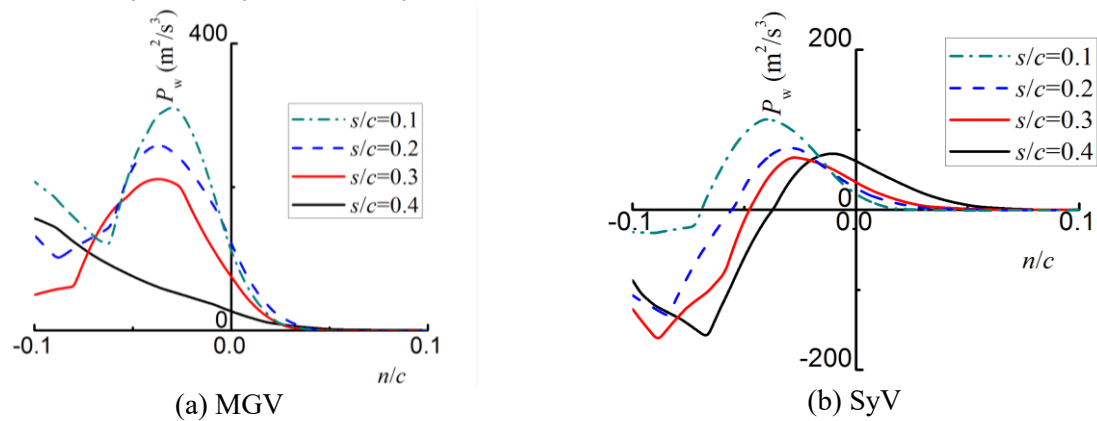
Figure 7. Distribution of curvature term**.**

(a) MGV   (b) SyV
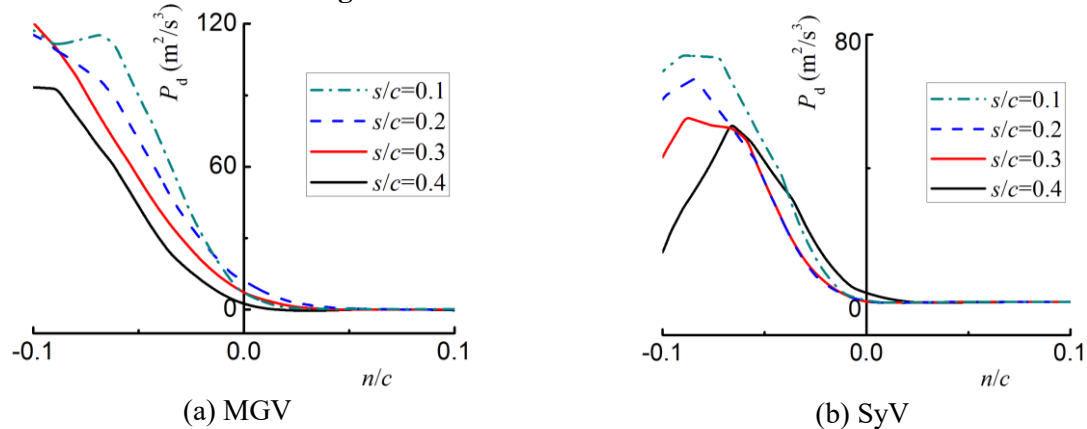
Figure 8. Distribution of 3D term**.**

The distribution of the production of turbulence kinetic energy(P_k) in the vaneless space between the pre-opened guide vanes and the runner inlet was shown in Figure9. When $s/c \leqslant 0.2$, P_k with MGV is twice of the SyV. When $s/c \geqslant 0.3$ P_k with MGV is three times more than the maximum value with SyV. The maximum value of with MGV is doubled compared with the maximum value with SyV, which are in accordance with the increase of the amplitude of pressure fluctuation compared with SyV. The change of P_k is determined by the change of the normal stress term. The change of normal stress term will influence the amplitude of pressure fluctuation.

(a) MGV   (b) SyV
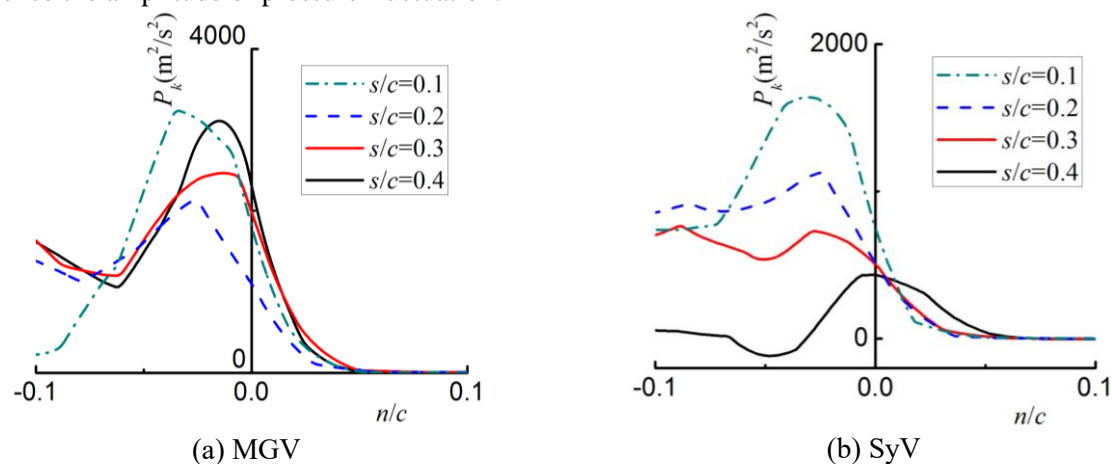
Figure 9. Distribution of the production of turbulence kinetic.

5. Conclusion

The use of MGV may increase the maximum value of P_k, and the maximum value with MGV is twice of the value with SyV. The increase of P_k has a relationship with the increase of the amplitude of pressure fluctuation. The maximum value of P_k with MGV is doubled compared with the maximum value with SyV, which are in accordance with the increase of the amplitude of pressure fluctuation compared with SyV. The change of the P_k can be used to predict the change of the amplitude of pressure fluctuation in vaneless space. The change of Pk is determined by the change of the normal stress term. The change of normal stress term will influence the amplitude of pressure fluctuation. The maximum value of 3D term with MGV increases compared with the result with SyV. It may be caused by the nouniform flow with MGV. The use of MGV destroy the uniform flow in the vaneless space, leading the increase of the normal stress term at the position close to the runner inlet.

Acknowledgment

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