Examination on Stall Characteristics inside the Diffuser of a Radial Pump

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Abstract. In this paper, the numerical simulation software ANSYS-CFX is used to simulate the flow field in the radial pump together with the SST k-ω turbulence model. The cross-power spectra analysis method is used to examine the internal rotating stall in the diffuser region. The rotating stall characteristics occurring in the part-load condition inside the vaned diffuser were discussed by using the cross-power spectra method.

1. Introduction
Rotating stall is a kind of unstable flow phenomenon which is common inside radial pumps. It usually occurs when radial pumps operate under low flow conditions, causing poor performance. With an increasing number of radial pumps operating on partial working conditions, the rotating stall phenomenon is particularly obvious. Therefore, it is of significant importance to investigate the rotating stall characteristics in a radial pump.

Zhang et al. [1] studied the unsteady rotational stall characteristics in the radial pump with slope volute at low flow rates. The results showed that the excitation frequency induced by the separation vortex structure inside the impeller varied at different flow rate. Li et al. [2], Lucius and Brenner [3], and Yuan et al. [4] found that the rotating stall group in the impeller extended to the inlet and outlet and transferred into adjacent flow channels, with the propagation direction opposite to the rotation direction of the impeller at the condition of 30% design flow rate. Some researchers also used, such as Zhang et al. [5] and Krause et al. [6], LDV and PIV to investigate the flow characteristics under the condition of rotating stall in the pump.

However, researches have been mainly focused on the behavior of rotating stall inside the impeller, and less on the rotating stall in the vaned diffuser. In this paper, the characteristic of the rotating stall in a vaned diffuser radial pump was revealed. It would supplement the research on the rotating stall of the radial pump, and provide scientific hydraulic design criteria for the parameter design of radial pump with vaned diffuser.
2. Numerical simulation

The pump model used in this study is a medium-low specific speed ($n_s=90.9$) radial pump taken from Ref [6]. It consists of an impeller with 5 backward curved blades, and a vane-less diffuser. The primary parameters of the pump model are shown in Table 1. A vaned diffuser is designed for the pump for the purpose of examination of rotating stall characteristics in that region [7]. The pump model is presented in Fig. 1.

Table 1. Parameters of pump model.

| Item                        | Parameter      | Reference |
|-----------------------------|----------------|-----------|
| Design flow rate $Q_0$ (m$^3$/h) | 47.5           | 600       |
| Design head $H_0$ (m)       | 4.3            | 90.9      |
| Design rotational speed $n_0$ (r/min) | 600           | 19        |
| Specific speed $n_s$        | 90.9           | 23        |
| Inlet angles of the blades $\beta_1$ (°) | 19           | 5         |
| Outlet angles of the blades $\beta_2$ (°) | 23           |           |
| Number of blades $Z$        | 5              |           |

The computational mesh of the pump shown partially in Fig. 2 is generated by ANAYS ICEM. The mesh number is about 3 million after a mesh independent study. The internal flow field of the model pump has been simulated using the commercial software ANSYS CFX 16.0. The detailed solving strategies are shown in Table 2. The time step of the unsteady calculation is set to the time corresponding to the impeller rotation of 3 degrees, and the maximum number of iterations in each time step is limited to 15.

Figure 1. Pump geometry.  
Figure 2. Mesh view.

Table 2. Numerical calculation settings.

| Item                        | Parameter      |
|-----------------------------|----------------|
| Turbulence model            | SST model      |
| Inlet boundary              | Total pressure |
| Outlet boundary             | Mass flow rate |
| Wall condition              | No-slip wall    |
| Convection term discretization | Second-order |
| Maximum residual value      | $10^{-4}$       |

3. Results and discussion

Figure 3 shows the flow field comparison between numerical simulation and experimental measurement [6] using TR-PIV at $0.5Q_0$, including stalled channel and non-stalled channel. It can be founded that the flow structure predicted by CFD shows good agreement with the experimental result: two big stall cells occur near the suction side of the blade for the stalled channel.
Figure 3. Flow structure for the pump with vaneless diffuser, at $0.5Q_0$.

Figure 4 shows the comparison of head curves between with and without vanes in the diffuser. In addition, the experimental result has been given for the case of vaneless diffuser. It can be founded that the induction of the vanes in the diffuser region has generally produced more energy loss in the diffuser region, resulting in a reduction in head. A hump region is found for the case with vanes in diffuser, probably due to the rotating stall in the vaneless diffuser.

The pressure fluctuation coefficient is used to analyze the pressure fluctuation at the monitoring point in the flow channel. It is dimensionless and the calculation formula is:

$$C_p = \frac{(p - \bar{p})}{(0.5 \rho U_z^2)} \times 100\%$$

Where $p$ and $\bar{p}$ are the unsteady pressure and averaged value, respectively, $\rho$ is the density, $U_z$ is the impeller tip speed.

Figure 5 shows the cross power spectrum analysis of the guide vane under different small flow conditions. The state of the vortex can be determined from Table 3. Under $0.41Q_0$ condition, an extremely high amplitude appears at a frequency of $0.005f_m$ with obvious periodicity and consistent phase difference of two monitoring points in time domain signal (Fig. 5(c)). It suggests that this frequency originates from the same disturbance source and appears as a rotating stall in the flow channel. Similarly, rotating stall also occurs under $0.5Q_0$ condition (Fig. 5(d)). Under $0.25Q_0$ condition without
highly relevant frequencies, however, it is not a rotating stall, or a stall group, or it may be a very complex turbulent flow (Fig. 5(a)). Conversely, under $0.35 Q_0$ condition with high amplitude but without consistent frequency, there may be several forms of stall vortex motion at the same time, and the specific flow structure must be analyzed by internal flow diagrams (Fig. 5(b)). In conclusion, it is not easy to be a rotating stall when the flow rate is smaller in the guide vane flow channel of the radial pump.

Figure 6 shows the streamline distribution in the inner flow field of the vane under the conditions of $0.41 Q_0$ and the number of vanes is 7, 8, and 9, respectively. It is found that the number of stall groups in the guide vane of three guide vanes is three. When the number of guide vanes is 7 and 8, the relative position of the stall groups changes with time as the impeller rotates (Fig. 6(a) (d) and (b) (e), e.g. from Ch1, Ch3, and Ch7 to Ch2, Ch4, and Ch7). Whilst the relative position of the stall groups is not changed at 9 vanes (Fig. 6(c) (f), Ch3, Ch6, and Ch9), i.e., the fixed stall phenomenon. Therefore, the type of stall in the guide vane may be affected by both the number of guide vanes and the number of stall groups. In addition, the number of guide vanes only affects the rotating frequency of the stall groups and does not change the stall form of the stall groups when the number of stall groups and the number of guide vanes are not an integer multiple.

**Table 3. Judgment of vortex.**

| Frequency domain plot | Time domain plot |
|-----------------------|-----------------|
| High amplitude        | Significant periodicity | Consistent phase difference |
| Consistent frequency  | Yes | Yes | Yes |
| Rotating stall        | Yes | Yes | Yes |
| Steady state vortex (fixed stall) | Yes | Yes | No |
| Unsteady vortex       | Yes | No | No |

![Diagram](a) $0.25 Q_0$

![Diagram](b) $0.35 Q_0$
Figure 5. Cross power spectrum analysis under different part flow conditions.

Figure 6. The streamline distribution in the inner flow field of the vane under the conditions of $0.41Q_0$ (Channels are named counter clockwise from Ch1).
4. Conclusion
In this work, the flow field inside diffuser of the radial pump was simulated to investigate the rotating stall. By using the cross-power spectra analysis it was possible to examine the internal rotating stall in the diffuser region. Rotating stall has been observed under the conditions of $0.41Q_0$ and $0.5Q_0$. In addition, both the number of guide vanes and the number of stall groups affect the type and the rotating frequency of stall groups, especially when the number of stall groups and the number of guide vanes are not an integer multiple, the rotating stall appears. Further research will be performed to explore the formation mechanism of rotating stall. Moreover, how to delay and eliminate rotating stall is a subject worth studying.

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