Investigation of vortex in pump sump by V3V measurements

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Abstract. The aims, scope and conclusions of the paper must be in a self-contained abstract of a single paragraph with 60-120 words. The abstract must be informative and not just indicative and contain a summary of the significant results reported in the paper. No references should be cited. Avoid mathematical expressions as far as possible. Just below the abstract, up to six keywords should be provided. The vortex may appear in the sump when the pump inlet is not properly designed or the pump suction pipe is not deeply submerged enough, not only will the pump's energy performance and cavitation performance be significantly reduced, but it may also cause the pump unit to vibrate and fail to operate properly. The water surface vortex is the most common vortex into the sump, and it is also a vortex that has a great influence on the operation of the pump. According to the development process of the water surface vortex, it is divided into four shapes: A-shape vortex: the water flow rotates slowly, forming only a shallow sunken; the B-shape vortex: the water flow rotates faster, the sunken becomes deeper as a funnel, and the air intermittently enters the water pump. It has only influence on the performance of the pump; C-shape vortex: the rotation speed of the water flow is very fast, the funnel has penetrated into the suction pipe, the air continuously enters the water pump, and the pump unit generates strong vibration, which has a serious impact on the operation of the water pump; D-shape vortex: The water flow rotates sharply around the suction pipe. A large amount of air enters the water pump, and the pump unit generates severe vibration, which is impossible to operate. The pump unit generates severe vibration and cannot run. In this paper, the vortex of the sump is measured by the V3V volumetric field three-dimensional laser velocimetry to study the mechanism and development of vortex under the flow rate at the BEP of the pump. The measurement results show that the distribution of the circumferential velocity $V_u$ of the vortex region in the vortex core is characterized by the value at the center of the core being close to zero, and the circumferential velocity of the vortex increasing with the increase of the radius, At a certain value the circumferential velocity is gradually reduced as the radius increased, and there is a maximum value during this change. At each stage of the development of the vortex, the regularity of the circumferential velocity of the vortex changes with the radius is the same that circumferential velocity increases in the vortex core, then decreases gradually outside of vortex core. The 3D vortex is obtained. The circumferential velocity gradient is quite large in the vortex core region. The maximum value is not on the water surface, but at a small depth below the water surface. The dissipation of vorticity is much rapid than its accumulation, which is shown as Instantaneous collapse of the vortex (less than 1 s). When the vorticity of the vortex reaches a certain value, it often causes severe vibration of the pump unit.
1. Introduction
In the case of improper design of the pump sump or insufficient submerged water depth of the pump suction pipe, the pump sump may generate eddies. Not only will the pump's energy performance and cavitation performance be significantly reduced, but it may also cause the pump unit to vibrate, affecting safe operation. The surface vortex is one of these shapes. Usually, the surface vortex is divided into 4 shapes, A-shape vortex: the water flow rotates slowly, forming only a shallow funnel; B-shaped vortex: the water flow rotates faster, the funnel is deeper, and the air is intermittently introduced into the water pump. The influence is small; C-shaped vortex: the water flow rotates very fast, the funnel has penetrated into the suction pipe, and the air continuously enters the water pump, which has a serious impact on the performance of the water pump; D-shaped vortex: the water flow rotates sharply around the suction pipe, and a large amount of air enters the water pump. The pump unit is vibrating and cannot operate. The existence of vortex has a great influence on the safe and economic operation of the pumping station. Therefore, studying the mechanism of vortex generation and the law of development can provide a more practical method for engineering design to optimize the design to reduce the vortex.

2. Experimental device and equipment

2.1 Experimental device
The experimental equipment includes a vertical axial flow pump, a water inlet tank, an outlet pipe, a torque meter, a flow meter, a laser flow meter, and a circulation line, as shown in figure 1. The vertical axial flow pump has an impeller diameter of 120mm, a number of blades of 4, a pump running speed of 2400 rpm, a water inlet bell mouth submerged depth of (50-80) mm, and a sink and a pump inlet bell tube made of plexiglass. The transparency is used for laser measurements.

![Figure 1. Vertical axial flow pump water inlet experimental device](image)

1 axial pump 2 torque meter 3 pump sump 4 flow meter 5 3-camera 6 laser head 7 outlet pipe

2.2 Introduction to V3V Measurement
V3V measurement, like PIV, is also a non-contact online laser full-field measurement. It is characterized by the illumination of the body light source system, which can capture the instantaneous flow particles in a specific measurement area and obtain the instantaneous flow characteristics of the regional flow field. It is integrated into a single probe with three cameras, coplanar and triangular. The three cameras capture particles from different angles of view. The entire measurement volume is completely visible. The measurement volume can be as deep as 140×140×100mm. The position of the laser and the laser can be flexibly arranged to meet different test requirements.
The key to the V3V test measurement is three-dimensional calibration. The three-dimensional calibration is performed using the INSIGHTV3V-4G software, as shown in figure 3, where figure 3(a) shows the image when the calibration plate is in the reference plane position. After software calibration calculation, the results are shown in figure 3(b). The particle imaging on the calibration image should be triangular and similar. The three magnification calibration curves should be below the reference curve and the change is smooth; the results of the three small hole imaging calibration curves should be between 0.95 and 1.05 and the change is smooth; the three mechanical calibration curves should be less than 0.25 pixels and the curve should change smoothly.

The test calibration results meet the test technical requirements. Data collection for test measurements can be performed after the calibration work is completed.

The V3V system captures the error of the positional movement of the tracer particles in water, with an accuracy of 10 μm in the X and Y directions and 40 μm in the depth Z direction. According to the information provided by the manufacturer, the error of the flow rate measurement is ± (0.5-1.0)%.
2.3 V3V measuring area

The surface vortex of the inlet tank usually occurs on the left rear side and the right rear side of the water pump, and the area selected for measurement according to the observation is as shown in figure 4.

![Figure 4. V3V flow rate measurement area](image)

(a) elevation view   (b) plan view

1 Axial flow pump 2 pump sump 3 measurement area

3. The formation of surface vortex in pump sump

During the test, the process of generating and evolving free surface eddies was observed while maintaining the water level in the pump sump, the rotational speed of the axial flow pump, and the flow rate. Using particle image flow field display technology and photographing method, the morphological photos of different development stages of vortex are obtained. As shown in figure 5, the left side is the V3V particle image, and the right side is the photo taken by the camera.

After a period after the pump was started, the water flow in the pump sump was stable and there was no obvious rotational flow phenomenon. As the flow rate increases, the water surface around the suction pipe begins to rotate, the rotation is slow, there is no obvious vortex center, and the water surface is stable. As time goes by, the rotation gradually accelerates, forming the center of the vortex, the rotation speed is still very slow, and the surface of the smooth water surface is concave, and the shape is as shown in figure 5(a). After the rotation center is formed, the rotation speed is obviously accelerated, and the center of the vortex appears to be obviously concave, forming a deep concave vortex, and the shape is as shown in figure 5(b). With the development of time, the rotation of the vortex is accelerated, the surface depression is deepened, and the shape of the arc is changed into a funnel shape. At the end of the funnel, granular small bubbles are detached and enter the horn nozzle to form a discontinuous air vortex, as shown in figure 5(c) shown. The vortex is further developed, and the bubbles falling off at the end of the funnel are gradually integrated into a continuous scroll. The scroll extends to the mouth of the horn to form a continuous suction vortex. The scroll enters the impeller and the blade contacts, causing cracking and noise. The form of the continuous inhalation vortex is shown in figure 5(d).
4. Vortex velocity field analysis
The flow rate data file of the obtained V3V measurement is imported into Tecplot software for processing to obtain the required cloud image and curve.

4.1 Surface vortex evolution

4.1.1 A-shape vortex
A-shape vortex is the initial surface rotation phase of the evolution of free surface vortices. Under the condition of \( Q = 25 \text{L/s} \), the sections with different depths were taken at intervals of \( \Delta h = 5 \text{mm} \) water depth, and the three sections of \( h = 10 \text{mm} \), \( h = 15 \text{mm} \) and \( h = 20 \text{mm} \) were taken from the water surface downward to obtain the water flow. The axial velocity distribution cloud diagram as shown in Figure 6.

![Figure 6. Axial velocity and streamline at 3 section](image)

Figures 6 and 7 reflect the development process of A-shape vortex. When the free surface vortex is in the \( Z = 60 \text{mm} \) section, it can be seen from the streamline diagram that the vortex generated by the surface vortex centered on the vortex core is relatively large. Then slowly gather toward the center of the vortex core. When the vortex is 10 mm below the water surface and reaches the \( Z = 50 \text{mm} \) section, it can be seen from the streamline diagram that the A-shape vortex phase disappears.
4.1.2 B-shape vortex

When the free surface vortex evolves into a concave vortex on the surface, the morphological changes of the vortex tube on different depths of water are shown in figure 8.

![Figure 8. axial velocity and streamline of 4 sections](image)

Figures 8 and 9 show the evolution of the free surface vortex to B-shape vortex. The B-shape vortex is smaller than the A-shape vortex, and the vortex range centered on the vortex core becomes smaller. The disturbance on the water surface is weakened, but the depth below the water surface is deepened, and the surface vortex reaches the underwater depth of 25 mm.

4.1.3 C-shape vortex

When the free surface vortex evolves into a discontinuous aspiration vortex, the morphological changes of the vortex tube at different depths of the water surface are shown in figure 10.

![Figure 10. axial velocity cloud diagram and section streamline diagram](image)

Figures 10 and 11 reflect the evolution of the free surface vortex to the C-shape vortex. It can be seen from the streamline diagram in the figure that the vortex has discontinuity in the adjacent section during
the generation process. The swirling vortex tube of this process is longer, reaching 60 mm below the water surface, and the surface vortex has an enhanced effect on the water flow below the water surface.

4.1.4 D-shape vortex
When the free surface vortex evolves into a continuous inhalation vortex, the morphological changes of the scroll at different depths of the water surface are shown in figure 12.

Figure 12. axial velocity cloud diagram and section streamline diagram

| (a) Z=60mm | (b) Z=50mm | (c) Z=35mm | (d) Z=0mm |

Figure 13. Continuous suction vortex tube

Figures 11 and 12 reflect the evolution of the free surface vortex to the D-shape vortex. Currently, the surface vortex reaches the water depth of 110 mm, the length of the vortex tube is the longest, and the vortex development is stable. As can be seen from the streamline diagram, the D-shape vortex has a strong disturbance to the water surface and underwater. As shown in figures 6 to 12, the shape of the scroll obtained by the three-dimensional body flow field data analysis is very short when the water surface begins to generate the free surface vortex stage, that is, the surface rotation stage. The free surface vortex to the cross-section Z= 50 mm, that is, the underwater depth of 10 mm, the surface vortex evolved into a form of surface depression. The shape of the scroll of the surface concave vortex is distorted during the extension to the underwater, and the scroll is also slightly longer than the length of the surface rotating vortex. The free surface vortex to the cross-section Z= 35 mm, that is, the underwater depth of 25 mm, the surface concave vortex evolved into the form of intermittent suction vortex. At this time, in the process of cross-section analysis, it can be found that when the cross-section analysis is below Z=35 mm, the generation of the vortex does not have continuity, and the length of the scroll has a significant increase. The free surface vortex to the cross-section Z= -10 mm, that is, the underwater depth of 70 mm, the intermittent suction vortex evolved into the form of a continuous inhalation vortex. At this time, the length of the scroll is the longest, reaching 110 mm below the depth of the water. The evolution of the free surface eddies obtained by data analysis is basically similar to that of vortex photographs taken with high-speed photography.

4.2 Velocity analysis of vortex core region
In the process of free surface vortex evolution, velocity is an important parameter reflecting the characteristics of vortex motion. By analyzing the data obtained by V3V measurement, the variation law of circumferential velocity along the radial direction at different development stages and the development law of the maximum circumferential velocity along different depths are obtained. In the process of vortex evolution, the circumferential velocity distribution of vortices in different development stages is different. This section analyzes the variation of the vortex in the radial direction at different stages. According to the experimental data, in the process of free surface vortex evolution,
four distinct stages of vortex flow structure were detected, namely the surface rotation phase, the surface concave phase, the intermittent inhalation phase and the continuous inspiration phase.

In order to quantitatively analyze the water flow rotation of the free surface vortex, the flow around the intersection of the water flow traces is examined. In each of the analysis sections analyzed in figures 6-8, the center of the vortex core is at the center of the vortex convergence. The center of the circle takes the data of a circular area with a radius of 15 mm for analysis, and converts the flow velocity component of the XY plane of the Cartesian coordinate into a circular component or a tangential component of the polar coordinate (polar axis $r$, polar angle $\theta$) with the center of O Radial component, which is calculated as:

$$V_u = V_x \sin \theta + V_y \cos \theta$$

$$V_r = V_x \cos \theta + V_y \sin \theta$$

(1)

4.2.1. A-shape vortex. When the free surface vortex evolution develops into the surface rotation stage, the water surface at different depths is analyzed from the top to the bottom in three sections: $Z=60\text{mm}$, $Z=55\text{mm}$, $Z=50\text{mm}$, and the circular section of the vortex core center intercept radius of 15mm is analyzed. figure 14 and figure 15.

(a) $Z=60\text{mm}$, (b) $Z=55\text{mm}$, (c) $Z=50\text{mm}$

**Figure 14.** The circumferential velocity at the center of the vortex core

**Figure 15.** The circumferential velocity distribution of different sections
4.2.2. **B-shape vortex.** When the free surface vortex evolves into a concave vortex on the surface, the circumferential velocity changes with radius on different depths of water as shown in figure 16 and figure 17.

![Figure 16. Circular velocity at the center of the vortex core](image)

(a) Z=60mm, (b) Z=50mm, (c) Z=45mm, (d) Z=35mm

![Figure 17. Circular velocity profile of different sections](image)

4.2.3 **C-shape vortex.** When the free surface vortex evolves into a discontinuous inspiratory vortex, the circumferential velocity changes with radius as shown in figure 18 and figure 19 on different depths of water.

![Figure 18. Circumferential velocity at the center of the vortex core](image)

(a) Z=60mm, (b) Z=50mm, (c) Z=25mm, (d) Z=0mm
4.2.4. D-shape vortex. When the free surface vortex evolves into a continuous inhalation vortex, the circumferential velocity varies with radius on different depths of water as shown in figures 20, 21 and 22.

![Figure 19. Circular velocity profile of different sections](image)

![Figure 20. Circumferential velocity at the center of the vortex core](image)

(a)Z=60mm, (b)Z=50mm, (c)Z=35mm, (d)Z=25mm, (e)Z=15mm, (f)Z=0mm, (g)Z=-30mm, (h) Z=-50mm
From figure 14 to figure 22, the variation of the circumferential velocity of the surface vortex along the radial direction at different stages of development is shown. It can be seen that the distribution of the velocity $V_u$ in the vortex core is characterized by the fact that the value of the center of the vortex core is close to zero, and the circumferential velocity of the vortex increases with the increase of the radius, and then decreases to a certain extent and then decreases. Small, there is a maximum in this change. The law of the vortex's circumferential velocity changing with the radius does not change with the vortex development stage, that is, the variation of the circumferential velocity with the radius is a similar law. It can be seen from the analysis that the surface vortex is at different stages of evolution, and the variation of the maximum circumferential velocity in the depth direction is basically similar. As the depth of the taken section increases, the circumferential velocity increases substantially first. After the value is gradually reduced, its maximum speed is not on the water surface, but a depth below the water surface.

5. Conclusion
(1) Using V3V measurement technology to accurately measure the complete development process of the free surface vortex in the pump sump, the three-dimensional field is obtained, and the vortex numeric form at different development stages is given.
(2) The velocity distribution of the vortex core region has the characteristics of forced vortex. The flow velocity about the core center is close to 0, rapidly increases along the radial, and reaches a maximum
at a radius (5-10) mm. The vortex at different stages has similar velocity profiles at different horizontal sections.

(3) The flow velocity of the vortex core section increases first and then decreases with water depth from the surface, reaching a maximum at a certain depth (10-40) mm below the water surface. This indicates that the energy of the vortex is gradually accumulating during the development process until the vortex touches the impeller and collapses.

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Nomenclature

- $Q$: flow rate
- $h$: water depth
- $A, B, C, D$: the type of vortex
- $X, Y, Z$: Cartesian coordinate axises
- $r, \theta$: polar coordinate (polar axis, polar angle)
- $V_x, V_y, V_z$: flow velocity components
- $V_x, V_y, V_z$: tangential component of the flow velocity

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