PIV 3-Dimensional Measurements of the Volume Flow Field in Pump Sump

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Abstract Particle image velocimetry was applied for measurements of the flow fields inside sump structure including a vertical axial flow pump bell-tube and suction passage. The measurement results under two typical operational conditions of flow rate show that at the operation condition of design flow rate, the velocity-field distribution in the impeller inlet section is symmetrical, the axial velocity uniformity of the section is about 87%, and vortex was not occurred, the flow regime in the bell-tube and the impeller inlet can meet the design requirement; The distribution of the velocity field in the impeller inlet-section at large flow rate is asymmetric, the axial velocity uniformity of the section is only 70%. A pair of strong vortex formed at each section in both the bell-tube and the space below the bell mouth, which finally entered the impeller and induced vibration. By analyzing the detailed flow structure of vortex core zone, we reveals the distribution regularity of circular velocity components in the vortex core that the components at the center of the vortex core are close to zero, and increase with the increase of the vortex core radius, in the radius range of 5 mm the velocity gradient is the largest, the characteristics of forced-vortex are evident.
Keywords: PIV; pump; Flow field; sump, vortex

1 Introduction

In recent years the rapid development of CFD technology makes and numerical simulation technology widely used in the field of the study on the flow simulation. But due to the limitation of the numerical simulation technology, the presence of complex vortex movement often leads to large deviation in the results of numerical simulation calculation, especially in the water with spiral (vortex rope) occurs.

Experimental measurement is the only means to directly obtain the actual velocity field, which is also the necessary means of validation of numerical simulation. There are a lot of limitations in the flow measurement with interference on actual flow, such as measuring accuracy and synchronicity. Modern laser technology and the rapid development of information technology makes the noninterference measurement of flow velocity is possible and continuous development. Much work has been done in recent 10 years in the application of three-dimensional laser particle imaging velocimetry to internal flow of centrifugal pumps and axial flow pumps system. But most measuring ranges are smaller and the integrity of the results, systematic and precision still cannot meet the requirement of engineering practice.

In order to obtain the velocity field of pump sump and bell tube a high frequency, high resolution, high power of three-dimensional PIV was applied to the measurements of detail velocity field in an axial flow pump sump to reveal the complex flow structure in pump intake region and vortex generation.*10th Pacific Symposium on Flow Visualization and Image Processing*
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2 Test system and equipment

2.1 Test systems

Test apparatus is shown in Figure 1. The whole system includes a vertical axial flow pump as test pump, a centrifugal pump as the auxiliary pump, intake pool, outlet tank, the circulation pipe line, flow meter, etc. A high frequency DC type three-dimensional PIV system was adopted for the measurements, which consists of the main equipment Dual Power laser, CMOS cameras and image processing system. The optical thickness of laser sheet light is 1.0 mm and through input optimization the light uniformity is good.

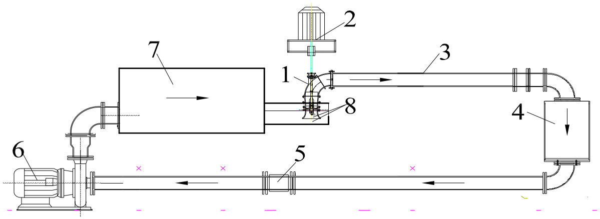


Fig.1 Vertical axial flow test loop
1 test pump, 2 motor, 3 pipe line, 4 tank, 5 flow meter
6 auxiliary pump,7 intake pool, 8 measurement zone

2.2 The main measuring equipment

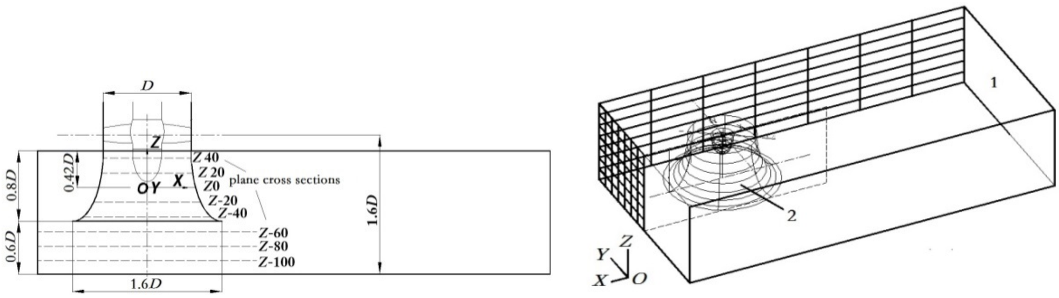
The camera resolution is 2400 pixels by 1800 pixels, shooting frequency is 480 frames/s. Camera with a built-in CMOS image sensor, Due to the limitation of test framework, selected sampling area is 300 mm× 200 mm.

Image processing system adopts Dynamic Studio software platform for measurement and control, calibration, data acquisition, processing, etc., suitable tracer particles are chosen for seeding with the density near the water density, so the particles can follow the fluid movement well.

3 the velocity measurement scheme

3.1 Intake geometry parameters and measurement area

Intake structure including the sump and bell tube, is made of organic glass, as shown in Figure 1 and Figure 2..



（a） （b）

Fig.2 Pump intake layout
(a)Profile (b) 3 d wire frame
1 inlet of sump, 2 bell tube

Velocity measurement sections are parallel to the longitudinal plane, as shown in Figure 3. The 15 measurement sections were symmetrically arranged on both sides of the bell tube center profile of which the interval are (0.07-0.2) D. The laser light sheet covered the entire section, the measurement work efficiency was greatly improved.

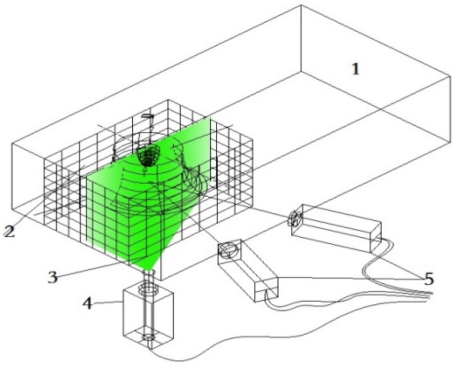


Fig.3 Illustrating of the measurement system
1 inlet 2 sampling area 3 lighting 4 laser 5 cameras

3.2 the velocity measurement condition

According to the performance of axial flow pump system, under the rated speed the large flow rate 1.2 Q0 was selected for the measurement. In case of the constant water level of the intake, the flow fields in the sump and bell tube were measured at each section. The layout of PIV measurement system is shown in Figure 3. The laser source projected to the measuring zone from the bottom of the sump.

4 velocity measurement data processing and result

4.1 PIV measurement data processing

The measured velocity data were analyzed using TECPLOT. In order to display the complete pump water flow structure, including the sump and the bell tube. Using the measurement in primary area (in side of bell tube, and below the bell mouth), through the relevant methods to calculate the velocity field outside of main area, to show the full field velocity field within the intake structure. Flow field analysis is focused on the measurements of the main areas, involving the impeller inlet condition and vortex formation, development and rotating motion.

4.2 Three-dimensional velocity field

According to the measurement data the velocity fields in the whole space of the intake structure were obtained after the computation, which is also called the volume velocity fields, shown in Figure 4 (shown with ratio of z direction velocity component v_z to the cross section axial average flow velocity $\bar{v}_a$). Figure 4 means at all nodes in the three-dimensional space of the intake structure have the velocity value. In order to show the pump the velocity field of bell tube the flow field around to the tube was hidden. The volume flow velocity field can not only show the three-dimensional flow characteristics of the intake structure, but also be very convenient to intercept any cross section of the velocity distribution for analysis of the flow characteristics.

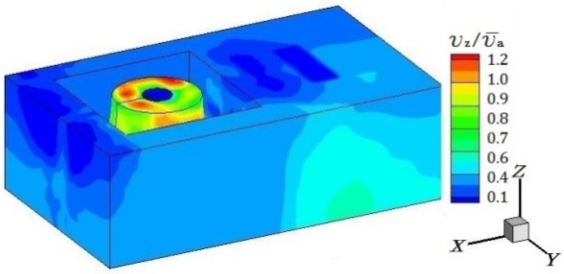


Fig.4 3D-volume flow field of the pump intake

4.3 The velocity field of the typical section

4.3.1 The velocity distribution of impeller inlet

Pump impeller inlet section was 10 mm below the impeller chamber, as shown in Figure 2a cross section z40. For convenience of analysis, according to the flow direction (x axis direction) the locations are defined as the left and the right, marked in Figure 5. In Figure 5 the distribution of velocity is expressed as the ratio of axial velocity to the section average flow velocity. The index to judge velocity distribution usually applies the velocity distribution non-uniformity or uniformity.

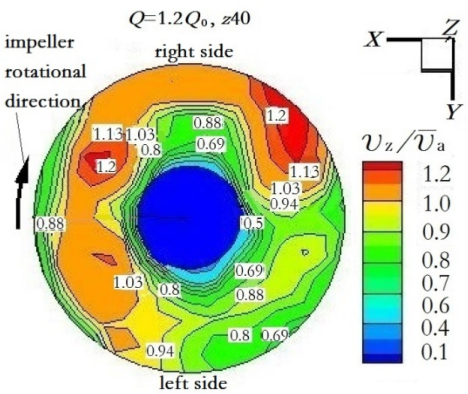


Fig. 5 Axial velocity $v_z/\bar{v}_a$ distribution of Impeller inlet section

In cases of large flow rate the velocity distribution at impeller inlet is asymmetric. The higher velocity greater than 1.0 is towards to the right side. The highest velocity reaches 1.2. Low flow velocity distribution appears on the left side of the section. This on the one hand, with the increase of flow velocity, the water flows into the pump impeller with the direction change from horizontal to vertical, under strong inertia which is trying to increase the turning radius of curvature, the water further concentrated toward the back of the section; On the other hand because of the flow direction effect the water inflow angle at right side of impeller inlet increased, while inflow angle at the left side of the inlet section reduced which results directly in the lower axial velocity at left and the higher axial velocity at right.

The axial velocity non-uniformity of the impeller inlet section velocity was calculated as 0.24, which means the velocity uniformity is 0.76. The operation efficiency of axial flow pump in the large flow rate conditions may decline from BEP condition.

4.3.2 The longitudinal section y0 velocity field

In Figure 6 the cloud shows the axial velocity distribution of the longitudinal profile (y0), the streamlines show the composition of flow velocities v_x and v_z.

The longitudinal profile section is the center section of the intake structure and parallel to the flow direction, where coordinate value y is 0.

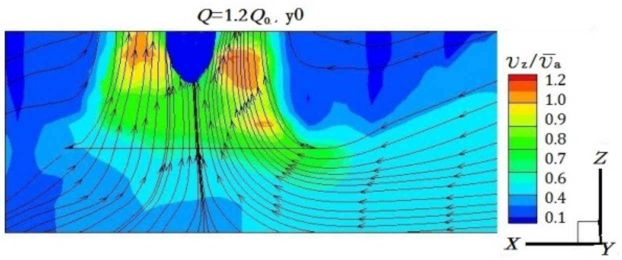
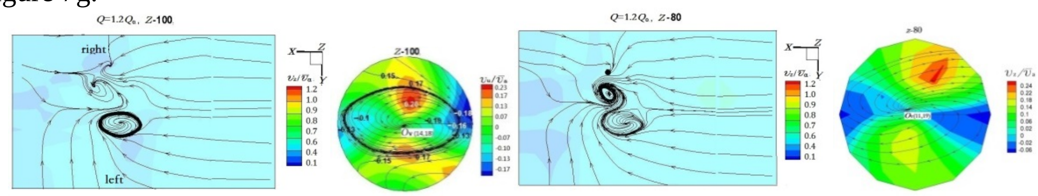


Fig.6 Velocity distribution of the longitude sections y0

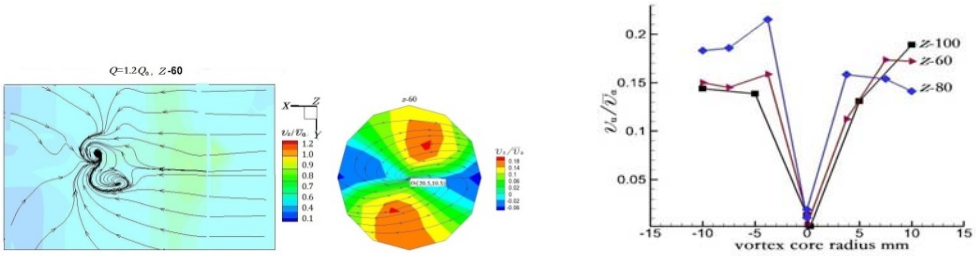
Under large flow rate the longitudinal profile streamline looks smooth, but the gradients of flow velocity and direction change increase; and the streamline below the bell mouth, near the center singularity area is relatively concentrated.

4.3.3 The velocity field below bell mouth

Figure 7 is the velocity field in the area below the bell tube, the cloud is for the axial velocity distribution, and the streamlines show the composition of flow velocities v_x and v_y. Three horizontal cross-sections, z-100, z-80 and z-60, are selected from the bottom of the sump to the pump bell mouth for the analysis of the velocity distribution. The study was focused on to find the spiral conditions near the bottom of the sump where the water flow into the turbulent mixing zone, easy to form the spiral, Figure 7a, 7c, and 7e show the flow fields of three horizontal sections below bell mouth. The axial velocity component gradually increased along with the main flow. However there has been a marked change in the plane movement. At the bottom of the bell mouth a pair of large vortex appeared in the center of the area. The left side vortex rotates clockwise, the right side vortex rotates counterclockwise, which reveals the special way for the flow to accumulate the rotational kinetic energy and finally form vortex. The closed streamline formation vortices were found in all three sections. Flow trace clearly shows the development of the vortex. From the cross section, z-100 to z-80 and to z-60 in the space between the bell mouth and the bottom, the geometry size of single vortex average diameters respectively are reduced gradually from 20 mm to 18 mm and to 16 mm; the diameters of vortices core are about 5-8 mm. It is also clearly observed that underwater vortex occurred began at the bottom and ended in the bell tube. This makes the flow conditions deteriorate, and seriously affects the normal operation of the pump unit. Also, in order to explore the inner flow structure of the vortex core region, take the left side single vortex to analyze the change of the relative magnitude of the velocity of circumferential component ($v_u/\bar{v}_a$) within the vortex core, as shown in Figure 7b, 7d and 7f. The circumferential component at the vortex core center is close to zero, and rapidly increases with the increase of the vortex core radius. The rotating flow in a vortex core has obvious characteristics of forced vortex. The maximum circumferential component velocity is about 0.2, see Figure 7g.



（a） （b） （c） （d）



(e) (f) (g)

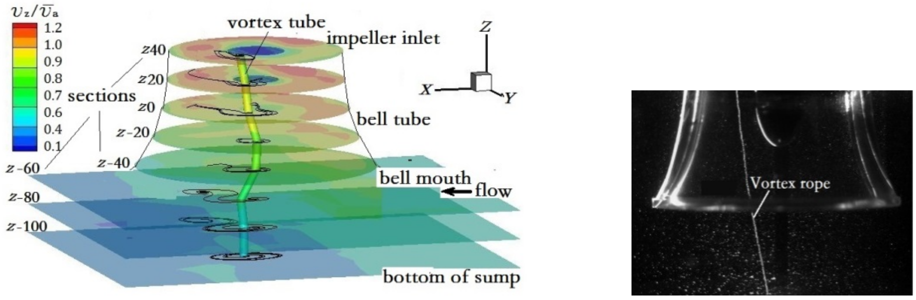
Fig.7 The axial distribution, streamlines of the sections below bell-mouth and tangential velocity distribution in vortex cores

(a)z–100 (b) vortex core (c) z–80 (d) vortex core (e) z–60 (f) vortex core (g) tangential velocity distribution

In the investigation of the rotating flow under the bell tube, we can see that the vortices come in pairs with inverse rotation direction. This means that the spiral energy exchange between the two vortices to overcome resistance of the rotation and maintain the development of vortex for sustainable. After the water flow into the bell tube the vortex pattern almost remains as before. For each pair of main vortex, the rotational intensity of one vortex is weak and another is strong which means the transfer of rotational energy and form stronger vortex.

3.4 Vortex tube forms

Based on the analysis of the vortex core on the left side of pump shaft centerline the of vortex tube form was obtained, which can also be referred to as the numerical value of vortex tube, as shown in Figure 12a. The center line of vortex tube passes through the center points of the vortex cores, and extends from the bottom of the sump to the impeller inlet section. It similar to the vortex rope photograph taken by the CMOS camera, as showed in Figure 12b. Theoretically the vortex tube is not able to end inside the fluid, which must begin from a border, and ends at another border, here again, validated by experiment. The most obvious characteristics of vortex motion in reality of the intake structure are instability. Vortex is very sensitive to flow boundary condition, the vortex change the form instantaneously. The vortex appears intermittent when the strength is weak, and appears continuously when the strength is strong. Decisive conditions generating a powerful vortex are that the rotational energy accumulation in the process of flow is greater than the energy dissipative and sustained growth, suitable space and enough time, etc.



(a) (b)

Fig.8 The developing of the vortex rope in the pump intake under large flow rate(1.2Q0)

(a) numeric vortex tube by PIV measurement, (b) reality of the vortex rope photo by CMOS camera

5. Conclusions

(1) Three-dimensional PIV laser velocimetry was applied to measure the internal flow of the vertical axial flow pump intake structure including pump bell tube, the full three-dimensional velocity fields were obtained under large flow rate condition.

(2) The velocity distribution in the cross section of the pump impeller inlet is asymmetric and the axial velocity uniformity is 0.70. The water regime of impeller inlet and bell tube is poor; On both left and right sides close to the pump shaft centerline there were continuous vortices appeared which form visible vortex ropes into the impeller, and lead to severe vibration of pump unit.

(3) The detailed flow structure of vortex core regions was analyzed. Through the velocity conversion a numerical form of vortex tube was presented. The distribution of the circumferential velocity component in vortex core was revealed. The circumferential velocity component at the center of the vortex core is close to zero, and increases rapidly along radius direction. The vortices have obvious characteristics of forced vortex..

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