Hydrodynamic Analysis of the Flow Field Induced by a Symmetrical Suction Elbow at the Pump Inlet

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Abstract. The paper investigates the hydrodynamic field generated by the symmetrical suction elbow at the pump impeller inlet. The full three-dimensional turbulent numerical investigation of the flow in the symmetrical suction elbow is performed using FLUENT then the flow non-uniformity generated by it is numerically computed. The numerical results on the annular cross section are qualitatively and quantitatively validated against LDV data. A good agreement between numerical results and experimental data is obtained on this cross section located downstream to the suction elbow and upstream to the pump impeller. The hydrodynamic flow structure with four vortices is identified plotting the vorticity field. The largest values of the vorticity magnitude are identified in the center of both vortices located behind the shaft. The vortex core location is plotted on four annular cross sections located along to the cylindrical part between the suction elbow and the pump inlet. Also, the three-dimensional distribution of the vortex core filaments is visualized and extracted. The shapes of vortex core filaments located behind the pump shaft agree well with its visualization performed on the test rig. As a result, the three-dimensional complex geometry of the suction elbow and the pump shaft are identified as the main sources of the flow non-uniformity at the pump inlet.

1. Introduction

The large pumping units are widely used in industry to store energy [1-3], to ensure cooling or heating in different systems [4] and to transport water [5]. The solutions for large pumps are different than regular one [6]. A suction elbow with complex three-dimensional geometry is installed upstream to the impeller of large pumps [1], the pump-turbines [3] and the first impeller of the multistage pumps [7]. The cavitating vortices are visualized at the pump inlet during its operation [8-10]. The suction elbow generates circumferential non-uniformity in velocity distribution at the impeller eye due to the geometry and the flow around the shaft [11]. Consequently, the flow with pre-rotation is experimentally and numerically identified over roughly one half of the impeller eye and counter-rotation in the second half [12-14]. This non-uniform flow is ingested by the impeller leading to hydrodynamic and mechanical problems [15-17].

Therefore, a symmetrical suction elbow is manufactured and installed upstream to a centrifugal pump with characteristic speed of \( n_q = n Q^{0.5} / H^{0.75} \sim 30 \). The global performances of the centrifugal pump...
with symmetrical section elbow are investigated on the test rig available at Politehnica University of Timisoara [18], Fig. 1a. Two cavitating vortices were visualized downstream to the symmetrical suction elbow, Fig. 1b. In this paper, the hydrodynamic field induced by a symmetrical suction elbow is explored in order to elucidate the source of the non-uniformity generated at the impeller eye.

Fig. 1 Test rig available at Politehnica University of Timisoara (a) and visualization of the vortex pairs generated by the suction elbow at the pump inlet (b).

Section 2 summarizes the three-dimensional computational domains, boundary conditions and numerical setup. The numerical results are validated against LDV data in Section 3 on an annular cross section. Next, the hydrodynamic field generated by the three-dimensional geometry of the suction elbow is analysed. The paper conclusions are drawn in the last section.

2. Numerical investigation of the three-dimensional flow field in the suction elbow

2.1. Numerical setup

The three-dimensional computational domains correspond to the inlet pipe together with the suction elbow, the impeller pump model with five blades, the volute together with the outlet pipe installed on the test rig, Fig. 1. A mixing interface technique was applied in our previous numerical investigations in order to couple the steady flow fields between rotating and fixed domains [19, 20]. A full three-dimensional unsteady flow computation is performed from upstream to downstream of the centrifugal pump with suction elbow as on the prototype case [14] in order to avoid the limitations introduced by mixing technique [20]. However, the time computation is up to one order of magnitude larger in this case than previous one. A structured grid with 2M cells is considered on the inlet pipe and suction elbow domain, around 1.2M cells on the pump impeller domain and 1M on the volute together with outlet pipe. The suction elbow-impeller and the impeller-volute interfaces are employed in the computation [21], Fig.2. In this case, the inflow boundary condition is imposed on the pipe inlet corresponding to the discharge together with turbulence quantities (the hydraulic diameter of 0.08 m and the turbulence intensity of 2%, respectively). The discharge value of 40.2 l/s corresponding to 1.3Qn and the impeller speed of 3000 rpm are imposed in correlation with experimental conditions where the cavitating vortices are visualized, Fig. 1b. The static pressure value measured on the test rig is imposed on the outlet section displaced in the outlet pipe. The flow computation is performed with k-ω turbulent model using FLUENT [22]. The second order schemes and SIMPLE algorithm for
coupling velocity-pressure fields are selected. The threshold values for numerical solution on pressure, velocity components and turbulence quantities convergence are imposed below to 1e-6. The time step of 1 ms is considered in this computation with 20 inner iterations on each time step.

![Fig. 2 Three-dimensional computational domains: suction elbow (red), impeller (yellow) and volute (blue). A detailed view with structured mesh used in numerical simulation.](image)

2.2. Numerical results against experimental LDV measurements

Particularly, a cylindrical part is installed between symmetrical section elbow outlet and impeller inlet in order to install the optical window for LDV measurements. The annular cross section selected for LDV measurements is located at 50 mm (denoted z=0.05 m in Fig. 3) with respect to the section elbow outlet (labelled z=0 in Fig. 3). Let us examine now the flow field on this annular section with a casing diameter of $D_c=103 \text{ mm}$ and a sleeve diameter of $D_s=40.5 \text{ mm}$, respectively. In this case, the ratio between the sleeve and casing diameters is $D_s/D_c=0.4$. The flow angle $\gamma$ is defined in eq. (1) being the flow deviation with respect to the pump axis, Fig. 3a.

$$\gamma = \arctan \left( \frac{V_u}{V_z} \right) \text{[°]}$$

![Fig. 3 Positions of annular cross sections with respect to the suction elbow outlet (z=0) (a); Five radial sections defined on the annular cross section ($b=0/1$ near to sleeve/casing) (b);](image)
Five radial sections are defined on the annular cross section in order to quantify the flow non-uniformity, Fig. 3b. The distance between the sleeve and casing is quantified using $b$ parameter defined by eq. (2)

$$b = \frac{D_c - D_s}{D_c - D_s} \quad [-].$$

The radial sections located closed to the sleeve are labelled with values around zero ($b \approx 0$) while near to casing with values are around unit ($b \approx 1$), respectively.

Fig. 4 presents the qualitative assessment of the flow angle map ($\gamma$) between numerical results and LDV data measured by Draghici et al. [12] on the annular cross section displaced at $z=0.05$ m (see Fig. 3). One can observe that the detailed features of flow field are recovered in numerical simulation providing a good agreement against experimental data.

![Fig. 4](image)  
**Fig. 4** Numerical flow angle map validation against LDV data [4] on the annular cross section located at $z=0.05$ m (see Fig. 3a).

![Fig. 5](image)  
**Fig. 5** Flow angle validation against experimental data on five radii displaced on annular section ($b=0$ near to hub and $b=1$ near to casing see Fig. 3b).

Negligible flow angle deviation provides the best hydrodynamic conditions on the annular cross section at the pump inlet. However, it can be easily observed in Figs. 4 and 5 that the flow field is
strongly non-uniform. The most significant variation of the flow angle on the annular surface of the outlet suction elbow is generated near the boundaries (in vicinity of sleeve and casing, respectively), see Fig. 5. One can see that the largest flow non-uniformity of $\pm 39.62^\circ$ is computed near to the sleeve from $0^\circ$ to $180^\circ$. However, a significant flow non-uniformity of $\pm 33.15^\circ$ is quantified near to the casing corresponding to the region from $-180^\circ$ to $0^\circ$. In this case, two regions are identified with extreme values of the flow non-uniformity: (1) the region located near to the casing from $-180^\circ$ to $0^\circ$ and (2) the region located behind to the sleeve. Consequently, two different sources of the flow non-uniformity can be assumed for this case: (1) the three-dimensional geometry of the suction elbow which generates the flow non-uniformity near to the casing; (2) the flow over the sleeve induces the non-uniformity behind it.

The flow angle ($\gamma$) numerically computed is validated in Fig. 5 against experimental data on five radii displaced on annular cross section. These five radii are located as follow (Fig. 3): $b=0.05$ (near to sleeve), 0.26, 0.48 (near to mid cross section), 0.73, 0.96 (near to casing). The numerical results (lines) agree quite well with experimental data (points) validating the numerical computation.

3. Hydrodynamic field analysis in the suction elbow

3.1. Hydrodynamic field analysis on the annular cross section $z=0.05$ m

A flow structure with four vortices is revealed on annular cross section displaced at $z=0.05$ m in the cylindrical part, Fig. 6, using numerical analysis.

![Flow field computed on annular cross section located at $z=0.05$ m: (a) flow field structure (b) vorticity map (c) pressure coefficient map together with the vectors of the flow field (red arrows).](image-url)
Two vortices are located in the upper side (V1 and V2) with respect to plane R1-R2, see Fig. 6a, and other two vortices in the lower side (V1m and V2m), respectively. Both V1 and V2m are right-hand vortices while other two (V2 and V1m) are left-hand vortices, respectively. The vorticity reaches the largest values in the core of vortices V1 and V1m. The flow vectors marked with red arrows are overlap on the static pressure field in Fig. 6c in order to prove that the minimum pressure is reached in the center of vortices (with blue spots). Moreover, the lowest pressure coefficient values are obtained in the center of V1 and V1m vortices in agreement with flow visualization on the test rig. The pressure coefficient is defined according to the following equation:

$$c_p = \frac{p - p_{ref}}{\rho g H} \quad [-].$$

where \(p\) is the static pressure, \(p_{ref}\) reference static pressure selected on the outlet section, \(\rho\) water density, \(g\) the gravity acceleration and \(H\) the pumping head, respectively.

3.2. Hydrodynamic field analysis in three-dimensional geometry of the section elbow

The flow structure with four vortices is identified along to the cylindrical part. This flow structure is plotted on four annular sections displaced at 0.025 m, 0.05 m, 0.075 m and 0.1 m with respect to the outlet section of the suction elbow denoted \(z=0\) in Fig. 3a. Further, the analysis is focused on two vortices (V1 and V2) located in upper side. Both centers of these vortices are marked with red spots in Fig. 7. Each center is located on a strip with negligible tangential component marked with blue color. Clearly, one can observe a modification of each vortex center position from one section to another. Two geometrical parameters (e.g. radial and angular coordinates) associated to each vortex center are introduced to quantify the position distribution along to the suction elbow and cylindrical part, respectively.

![Fig. 7 Flow field structure on four annular sections located along to the cylindrical part (see Fig. 1): (a) \(z=0.025m\) (b) \(z=0.05m\) (c) \(z=0.075m\) (d) \(z=0.1m\). The blue lines correspond to the negligible tangential velocity component.](image-url)
The vorticity maps are plotted on all five annular cross sections displaced on the cylindrical part, Fig. 8. Also, the vortex core filaments associated to V1 (blue) and V1m (red) generated by the symmetrical section elbow are visualized on the cylindrical part. One can observe a very good qualitative agreement between the distributions of both vortex cores filaments (V1 - blue and V1m - red) along to the cylindrical part plotted in Fig. 8 and the cavitating vortices visualized on the test rig in Fig. 1.

**Fig. 8** Vortex core filaments in the cylindrical part generated by the symmetrical suction elbow: V1 (blue vortex core) and V1m (red vortex core)

The vortices can be automatically detected using a technique developed by Haimes and Kenwright [23, 24] or Sadlo et al. [25]. As a result, the vortex core identification technique presented by Stuparu and Susan-Resiga [26] is employed using the visualization expert software TECPLOT on numerical data provided by FLUENT commercial software. The algorithm returns a set of vortex core segments with associated vorticity magnitude (vortex core strength) values. Consequently, the third parameter associated to the vortex core is vorticity magnitude. This parameter is a hydrodynamic one.

The vortex core filaments are identified in the three-dimensional flow through the symmetrical suction elbow and the cylindrical part are sketched in Fig. 9. The red vortex core filaments correspond to V1 and V2m vortices while blue vortex core filaments are associated to V1m and V2 vortices, respectively. In the axonometric view, it is revealed that the red filaments correspond to right-hand vortices whilst the blue filaments to left-hand vortices. The flow particles injected near to outer wall of the elbow generate the V1 and V1m vortices located behind to the sleeve. In the meantime, the flow particles closed to the inner wall induce V2 and V2m vortices. The vortex core filaments are generated by the three-dimensional geometrical configuration of the symmetrical suction elbow. These vortices start on the suction elbow wall being ingested by the pump impeller.

The geometric and hydrodynamic parameters are defined to characterize both V1 and V2 vortex core filaments. As a result, these parameters are plotted in terms of the axial coordinate along to the symmetrical suction elbow and cylindrical part in Fig. 10. The radial coordinates (r1 and r2) and the angular positions (θ1 and π-θ2) are used to identify the geometrical locations of the vortex cores on each annular cross section. It can be observed that geometric parameters (r and θ) computed for both vortex core filaments are quite similar along to the cylindrical part.

The vorticity magnitude on both vortex filaments is plotted against axial coordinate in Fig. 10c. The vorticity magnitude associated to vortex core filament V1 is approximately twice larger than V2. As a result, the minimum static pressure value in the center of the vortex V1 is lower than in the center.
of vortex V2. This statement is supported by the static pressure map plotted in Fig. 6c, as well as the visualization of the cavitating vortices on the test ring, Fig. 1.

Fig. 9 Vortex core filaments on three-dimensional geometry of the section elbow: V1 and V2m right-hand vortices (blue vortex cores) and V1m and V2 left-hand vortices (red vortex cores). The blue and red circles correspond to minimum radial coordinates of the vortex core filaments.

Fig. 10 Distribution of the vortex core parameters: (a) radial coordinate, (b) angular position and (c) vorticity magnitude associated to V1 and V2 vortices along to the suction elbow and the cylindrical part.
On the other hand, the vorticity magnitude (vortex strength) monotonically increases along to the vortex core filament up to a maximum value, Fig. 10c. After that, the vorticity magnitude monotonically decreases up to the outlet section of the cylindrical part. The minimum radial coordinate of each vortex core filament is identified based on the position of the maximum vorticity magnitude value (maximum strength) according to the Kelvin’s theorem. The physical explanation for this observation is that the vortex spins faster/slower being stretched/squeezed once the radial coordinate associated to the vortex core filament is diminished/enhanced. The previous statement is supported by V1 evolution from a gathered vortex on z=0.025 m section (Fig. 6a) to a scattered one on section located at z=0.1 m (Fig. 6d) taking into account that the radial coordinate associated to its core is monotonically enhanced.

4. Conclusions

The hydrodynamic flow field generated by the symmetrical suction elbow of the large pump is explored in this paper. The geometries of the suction elbow, impeller and volute correspond to the components installed on the test rig. The three-dimensional computational domains (suction elbow with pipe inlet, impeller and volute with pipe outlet) are defined. The numerical setup and boundary conditions are briefly presented. The three-dimensional turbulent flow is computed using FLUENT code. The numerical results obtained on annular cross section displaced downstream to the suction elbow were validated against LDV measurements. A good agreement between numerical results and experimental data is obtained on this cross section. A hydrodynamic structure with four vortices is revealed. Therefore, a detailed analysis of the flow field is performed on this cross section. Two regions with the extreme values of the vorticity magnitude are identified. One region is located near to the casing while other region is situated behind to the sleeve being produced by it. Next, the vortex core filaments are extracted using the flow field. The three-dimensional distribution of the vortex core filaments in the suction elbow geometry is plotted. According to expectation, the root of the vortex core filaments is located on the suction elbow. However, these locations are clearly identified based on numerical investigation. In the future, different geometrical configurations of the suction elbow can be explored to improve the hydrodynamic conditions at the pump inlet in order to reduce the maintenance cost and to extend the lifetime of mechanical parts.

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