Tip Leakage Vortex Structure and Turbulence in the Meridional Plane of an Axial Pump

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ABSTRACT

Particle image velocimetry (PIV) measurements are performed in the tip region of a water-jet pump rotor blade, in an optically index-matched facility, in order to study the structure and evolution of the flow. Data are used to examine the evolution of the tip leakage vortex (TLV) by means of the swirling strength to map the spatial distributions of multiple secondary vortices. Turbulence statistics are computed with a Reynolds average approach from instantaneous and rotor phase averaged velocity maps.

1. MOTIVATION AND FACILITY

1.1 Tip leakage flow and vortex

The flow in the tip region of a rotor blade is extremely complex due to the simultaneous occurrence of numerous phenomena, including a 3D background flow, tip leakage flow and vortex, boundary layers on blade and casing, etc. The leakage flow is driven through the clearance between the tip of the blade and the casing end-wall by the pressure difference between the pressure side (PS) and suction side (SS). The clearance flow, which rolls up into the tip leakage vortex, generates boundary layers on the blade tip and stationary wall of the casing, both of which feed vorticity into the flow within the blade passage (Tan [4]). Associated flow phenomena adversely affect the performance of a turbomachine, as well as cause noise and cavitation. Due to the complex geometry, it is difficult to measure the development of a TLV, and even PIV probing has been limited to measurements away from boundaries (Liu [2]). Several numerical studies involving RANS have also been performed describing the occurrence of the TLV bursting, e.g. Furukawa et al. [1].

1.2 Facility, setup and procedures

To fully resolve the flow within turbomachines a peculiar facility was developed, in which the fluid (62%-64% by weight solution of sodium iodide in water) has the same optical refractive index as the transparent acrylic blades and casing (Uzol et al. [5]). This facility has been upgraded recently to accommodate a water jet pump, and enables totally unobstructed PIV measurements anywhere within the machine, including the flow in the tip region (Wu et al. [6]). A compound illustration of the experimental setup in the present experiments is presented in Figure 1. The pump rotor is driven by a 44.8 kW AC motor, and experiments are performed at a rotor frequency \( \Omega = 15 \) Hz (900rpm), corresponding to a blade tip velocity \( U_t = 14.36 \) m/s (tip chord-length Reynolds number equal to \( 5.15 \times 10^5 \)) and flow rate \( Q = 0.157 \) m³/s. The geometrical characteristics of the rotor are: 7 blades, tip chord-length \( c_t = 258.5 \) mm, casing radius \( R = 152.4 \) mm, nominal tip clearance \( c_t = 0.7 \) mm, actual tip clearance in measurement site \( c_t = 1 \) mm and blade pitch \( = 136.8 \) mm. The flow and head coefficients are \( \phi = 2\pi\Omega^3D^3 = 0.37 \) and \( \psi = (2\pi^2gH(\Omega D)^3 = 1.7 \), where \( D = 2R \). The ability to vary and control the loop pressure enables observations on cavitation. PIV measurements are performed in the vertical meridional plane (Figure 1). The light source is a 50 mJ/pulse Nd: YAG laser, the flow is seeded with 11 mm, silver-coated hollow glass spheres that have a specific gravity of 1.6, slightly less than that of the liquid (1.8). Images are recorded on a 2048×2048 pixel CCD camera using a 105 mm lens. The field of view is 40×40 mm². The PIV system is synchronized with the rotor, which facilitates measurements at desirable orientations of the blade. Locations of data planes are characterized by the chord fraction, \( s/c \), where \( s \) is a circumferential curvilinear coordinate following the blade tip centerline. Twenty-five sections are investigated, separated by \( s/c = 0.055 \) (14.36 mm along the tip) and the database consists of 1000 instantaneous, 2D velocity distributions in each plane. Image filtering includes masking and median high-pass filtering to remove dim blade traces (due to a slight refractive index mismatch), and external bright spots, a particle trace equalization (Uzol [5], Roth [3]), and a Gaussian filtering. Cross correlation analysis is performed using LaVision software. The present interrogation window size is \( 32 \times 32 \) pixel, 50% overlap, which provides 128×128 vectors with spacing of 0.34 mm, the typical interrogation window contains at least 6 particles (Figure 2). The number of realizations is selected to achieve convergence of mean flow and turbulence properties.

2. FLOW VISUALIZATION AND MEAN FLOW CHARACTERISTICS

2.1 Flow visualization

As a preliminary step, cavitation is used to visualize the TLV.

![Figure 1. Schematics of the waterjet pump rotor and stator with the position of the meridional plane, the CCD camera and the investigated area.](image-url)
The low pressure in a vortex core attracts bubbles and is prone to cavitation inception. A sample image (Figure 3) shows that the TLV first appears at mid-chord, and detaches from the blade SS immediately after rolling up. As they migrate towards the pressure side of the neighbor blade, multiple structures wrap around each other near the core, and wind spirally, eventually causing breakup/bursting into a massive cloud of bubbles.

2.2 Phase averaged flow

Figure 4 shows both the rotor phase averaged velocity and circumferential vorticity distributions in two planes, illustrating the process of vortex rolling up and detachment. The velocity is normalized with the $U_t$, and the vorticity with $U_t / h$. The tip leakage “jet”, whose spatially averaged axial velocity in the tip gap is 4.45 m/s (0.31 $U_t$), and the vorticity layers that are generated as it interacts with the solid boundaries are clearly evident. Upon leaving the tip gap, a shear layer extends from the blade. Besides the rolling up of the blade-generated vorticity into the vortex core, the casing boundary layer is entrained into the outer branch of the vortex, as it induces flow separation at the end-wal. The location of vortex centers along the blade passage is summarized in Figure 5. Variations in the total circulation in different regions of the flow, including the separating shear layer, the vortex core, and the layer with opposite vorticity surrounding the core are presented in Figure 6. Also included is the circulation of an additional, separated vortex that rolls up downstream of the blade trailing edge, while the original structure interacts strongly with the neighboring blade pressure side. As is evident, the main leakage vortex circulation increases initially, but then reaches a plateau at $s/c = 0.611$, and decays downstream of the trailing edge. In the region of vortex strength plateau, the circulation within the separating shear layer increases rapidly until the trailing edge. Subsequently, the shear layer rolls up to another vortex, and remaining circulation diminishes rapidly.

Figure 3. Tip leakage vortex visualization by means of cavitation bubbles. The blades are moving from top to bottom, and mean flow is from right to left. The dashed yellow line highlights the winding of vortex core; bubbles pass through the tip clearance and are entrained into the vortex.

Figure 4. Phase averaged in-plane normalized velocity ($u/U_t$) and out-of-plane vorticity ($\omega_\theta / h U_t$) at (a) $s/c = 0.500$, and (b) $s/c = 0.722$. Vectors are diluted in the horizontal direction for clarity.

Figure 5. Location of the tip leakage vortex center at different chord fractions, the center location is defined as the point of maximum out-of-plane vorticity; coordinates are defined in Figure 4a.
3. UNSTEADY FLOW AND TURBULENCE

3.1 Distribution of vortices
A sample instantaneous velocity and vorticity map demonstrating the presence of multiple vortex “ropes” of opposite signs is presented in Figure 7a. To identify and characterize these flow structures, the “swirling strength” $\sigma$ is computed as defined in Zhou et al. [7], and illustrated in Figure 7b. Defining the location of the vortex center as the local maximum of $\sigma$, Figure 8 shows ensemble averaged scatter plots of the centers. The plots illustrate vortices of opposite sign to prove that the blade tip feeds vortices into the vortex core, whereas the casing boundary layer vortices remain along its outer branch in this plane. Further along the passage, as vortex bursting occurs at $s/c \approx 0.8$, vortices with positive sign are entrained into the TLV center. The average number of (negative) vortices within the vortex core in each plane increases with $s/c$ (Figure 9) reaching its maximum close to the trailing edge of the blade. The corresponding phase averaged circulation in a vortex (not shown because of space limitations), as determined by integrating the vorticity, peaks at mid chord, and then gradually decreases. The vortex average diameter also peaks at mid chord, but remains fairly constant at ~2$h$.

3.2 Turbulence
Sample distributions of in-plane turbulent kinetic energy $k_{2D}$ normalized with $U_t^2$, are presented in Figure 10. Regions with elevated turbulence include the vortex center, the shear layer separating from the tip of the blade, which extends with the chord fraction, and the region containing positive vorticity fed from the casing boundary layer, starting from the point of flow separation. Of course, some of this kinetic energy is a result of vortex meandering, especially near the vortex center, and the vorticity layer fed from the casing. At $s/c = 0.500$, the kinetic energy peak generated by the casing is small and confined to an area located above the vortex. Beyond the trailing edge, as the positive vorticity layer wraps around the vortex, this region expands substantially. An analysis of the terms contributing to turbulent kinetic energy production (not shown) indicates that flow compression near the point of separation, as two layers of fluid collide and detach, is a major contributor to the high turbulence level. These layers consist of the primary flow in the passage on the right side, and the jet associated with the leakage flow on the left side. Shear production is the primary contributor to turbulent kinetic energy in the separating shear layer. There is little turbulence production in the vortex core, due to the low shear strain-rate, suggesting that the turbulence there is a result of shear layer entrainment, as well as “pseudo-turbulence” associated with vortex meandering. Future efforts will focus on distinguishing between them.
4. CONCLUSIONS

The unsteady flow in the tip region of a waterjet pump rotor has been investigated in a refractive index matched facility by means of 2D PIV. Instantaneous data as well as phase averaged flow and turbulence statistics obtained in 25 meridional planes elucidate the rolling up and subsequent development of the tip leakage vortex. Included are interactions among multiple large scale structures, formation of a “wall jet” in the gap between the blade tip and the casing, entrainment of vorticity sheet extending from the blade tip into the vortex, vortex-induced flow separation and entrainment of a vorticity sheet with opposite sign. Statistics describe the evolution of the circulation in the rotor passage, and regions with elevated turbulence.

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REFERENCES


