CAVITATION, FLOW STRUCTURE & TURBULENCE IN THE TIP REGION OF A ROTOR BLADE

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LONG TERM OBJECTIVES

- Measure the flow structure and turbulence within a Naval, axial waterjet pump.
  - Create a database for benchmarking and validation of parallel computational efforts.
  - Address flow and turbulence modeling issues that are unique to this complex environment.
  - Measure and model flow phenomena affecting cavitation within the pump and its effect on pump performance.

- This presentation focuses on cavitation phenomena and associated flow structure in the tip region of a rotor blade.
FACILITY: For flow diagnostics and observations on cavitation, it is essential to have an unobstructed optical access to every section.

Pump blades (rotor and stator) are made of acrylic.

During PIV measurements, the test facility contains a concentrated solution of NaI in water, which has the same optical refractive index as the blades.

Blades become almost invisible.
The pump is driven by a 60HP AC motor through a 4.45cm diameter shaft. The shaft is supported by bearings at three points.

Honeycombs (flow straighteners) are installed in the settling chamber upstream of the pump.
WATERJET PUMP

Rotor tip diameter: 305mm, Tip clearance: 0.7mm.
Number of rotor blades: 7
Number of stator blades: 11

Selected flow conditions:

N=900 RPM

Flow rate \([Q]\) \(0.157\ \text{m}^3\text{s}^{-1}\)

Flow coefficient \([\phi = 2\pi Q\Omega^{-1}D^{-3}]\) \(0.37\)

Head coefficient \([\psi = (2\pi)^2gH\cdot(\Omega D)^{-2}]\) \(1.7\)

Torque coef. \(k_M = (2\pi)^2Me\rho^{-1}\Omega^{-2}D^{-5}\) \(0.14\)
BUBBLES CROSSING TO SUCTION SIDE AT MID BLADE

- At mid-chord, bubbles cross the tip clearance, and are entrained into the tip leakage vortex developing in the suction side.
TIP LEAKAGE VORTEX MIGRATION AND BREAKUP

- The tip leakage vortex migrates to the pressure side of following blade.
- Adverse pressure gradient causes vortex breakup/bursting.
SHEET CAVITATION IN TIP GAP

- Sheet cavitation occurs in the tip gap, demonstrating the strength of the tip leakage flow.
PIV MEASUREMENTS

Laser sheets

Prism filled with refractive index matched fluid
Early Stage – Instantaneous Flow – $s = 0.56c$

The tip clearance backflow collides with the main flow [point A] inducing a separated flow that follows the TLV outer branch.

Miorini et al. 2009
Wu et al. 2009
After TLV bursting – Instantaneous Flow $s = 1.06c$

- **Vortex sheet**
- **End-wall back flow** (no blade!)
- **Very localized clearance “recirculation”**
- **Very large scale (weak) vortical structure**
- **Main flow**
- **Incoherent vorticity distribution (TLV remnants)**

Incoherent vorticity distribution ($\vec{\omega}\vec{\omega}^*$): 
-1.38 -0.92 -0.59 -0.26 0.26 0.59 0.92

Trailing edge vortex

$\vec{U}/\vec{U}_{GAP} = 1$
Phase Averaged Circumferential Vorticity Component

- $s/c = 1.17$
- $s/c = 1.0$
- $s/c = 0.94$
- $s/c = 0.72$
- $s/c = 0.5$

Vortex bursting
In-Plane Components Of Turbulent Kinetic Energy

- $s/c=1.17$
- $s/c=1.0$
- $s/c=0.94$
- $s/c=0.72$
- $s/c=0.5$

Vortex bursting
Phase Averaged TLV --- Vorticity and TKE --- $s = 0.72c$

“Positive” vortices travel along the advancing front of the TLV generating large scale unsteadiness.

TKE peaks at the interface between the entrained end wall vorticity and the TLV.

High TKE is a direct result of vortex rope meandering.
In-plane Production of 2D-TKE --- $s = 0.72c$

Negative production due to rapid realignment of turbulence (via axial “stretch”) at the gap entry section (b)

Shear production in the vorticity sheet (c)

Positive production due to “compression” at the separation and later due to shear production in the advancing front of the TLV (b)

Note the absence of production in the (turbulent) core

$$P^*_{2D} = \frac{h}{(\bar{U}_{GAP})^3} \left( -u_z'u_z' \bar{S}_{zz} - u_r'u_r' \bar{S}_{rr} - 2u_z'u_r' \bar{S}_{zr} \right)$$
Details can be found in


