Progress in Numerical Simulation of Turbulent Cavitating Flow in an Axial Waterjet Pump

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Abstract. A progress made in numerical simulation of turbulent cavitating flow in an axial waterjet pump (ONR AxWJ-2) is presented. The computational approach is designed to resolve the interaction between the rotor and the stator both in time and in space comprising the full 360° sector of the pump, using a scalable finite-volume-based Navier-Stokes solver. Unsteady Reynolds-Averaged Navier-Stokes (URANS) and a hybrid of URANS and Large Eddy Simulation (LES) are employed for turbulence modeling and also for directly capturing some of large-scale coherent structures in the flow. A continuum mixture approach based on phasic volume-fraction is adopted along with a finite-rate mass-transfer model. It is shown that both the major quantities of interest (QOI) of waterjet pumps and the salient features of the flow such as tip-leakage vortex (TLV) cavitation can be predicted with a commendable accuracy.

1. Introduction
There have been attempts to numerically predict performance of axial waterjet pumps, with more recent ones employing URANS [1,2,3]. Still, the complex physics of three-dimensional turbulent cavitating flow in axial waterjet pumps has evaded an explication of various flow phenomena such as thrust-breakdown.

This article concerns the turbulent cavitating flow in an axial waterjet pump, AxWJ-2, that has a 6-bladed rotor and a 8-bladed stator. The rotor-stator assembly is housed in a cylindrical shroud with the rotor-tip clearance of 0.7 mm. The pump was tested in the 36-inch cavitation tunnel at the Naval Surface Warfare Center Carderock Division (NSWCCD) [4,5]. It was also tested separately in the Rolls-Royce pump loop facility [6]. The AxWJ-2 model of 12-inch diameter was used by the group at the Johns Hopkins University (JHU) for detailed measurements and visualizations of the flow-fields [7]. In tandem with the experimental works, a high-fidelity computational capability has been developed aiming at simulating the entire pump and resolving the interaction between the rotor and the stator both in time and in space comprising the full 360° sector of the pump. The goal was to be able to predict not only the global quantities of interest (QOI) such as thrust, torque and head but also to capture the salient features of the turbulent cavitating flow including different types of cavitation (e.g., sheet cavity, tip-leakage vortex cavitation) and their impacts on the pump performance.

In the following, the key elements of the computational approach are summarized first. The progress made to date will be discussed along with the challenges, lessons learned, and future work.

2. Computational Approach – Finite-Volume Method with Continuum Approximation
A homogeneous equilibrium mixture model is adopted to describe two phases (water liquid and vapor). The individual phases can be modeled as incompressible or compressible fluid, which allows us to
resolve shock and acoustic waves generated by cavitating flows. The phase compositions are represented by volume-fraction, with the phase change modeled using, among others available, a finite-rate mass transfer model derived from a modified Rayleigh-Plesset’s equation [8]. An implicit, finite-volume-based projection algorithm is employed for a coupled system of equations for velocity, pressure and volume-fraction. A sliding-grids method [1] is used to pursue time-accurate solutions for rotor-stator interaction. The details of the computational method and validations can be found in the references [1,8].

For turbulence modeling, URANS approach is usually sufficient to predict the global quantities and to capture the gross features of the flow. The URANS computations for the AxWJ-2 pump have been made to date using the family of linear k-ω models, although more sophisticated models such as nonlinear or explicit algebraic k-ω models and differential Reynolds-stress models can potentially improve the accuracy of URANS predictions. Capturing large-scale coherent structures requires a “scale-resolving” approach. To that end, we chose to employ a hybrid URANS-LES approach based on the Improved Delayed Detached Eddy Simulation (IDDES)[9].

3. Results

3.1. Computational Details

URANS computations have been carried out to simulate the NSWCCD’s 36-inch tunnel experiment which covered a wide range of cavitation number and flow-rate including thrust-breakdown at the rotor speed of 2000 RPM and the inlet flow velocity around 11 m/s. Three computational grids with 2.2M-element, 4.3M-element and 11M-element grids were used for the computations. All the computations were made using the second-order spatial and temporal discretization schemes. An implicit time-marching algorithm with nonlinear iterations was employed to advance the solutions with the time-step size of $2 \times 10^{-5}$ second. With this time step size, one revolution of the rotor is resolved by 1500 time steps (0.24° per time step). For RANS turbulence modeling and near-wall treatment, we started with a pragmatic approach, namely, a combination of an isotropic eddy-viscosity model (Menter’s SST k-ω) and wall functions.

Additional computations were made using the IDDES on the 11M-element grid in order to capture some of the large-scale turbulent structures in the flow. A smaller time-step size of $5 \times 10^{-6}$ was used for the IDDES computations.
3.2. **Thrust and Torque on the Rotor**

Figure 1 shows the time-averaged $K_T$ and $K_Q$ obtained from the URANS computations with the 4.3M-element grid. In addition, the results from the 11M-element grid are shown for the two lowest cavitation (Thomas) numbers ($\sigma = 0.350, 0.362$). It was found that the overall difference between the predictions 2.2M-cell and the 4.3-cell grid was roughly 4%, with the difference further decreasing between the 4.3M-cell and the 11M-cell grids. The scatter of all the URANS predictions done so far using different turbulence models and numerical schemes seems to be around 6% from the tunnel data, which is fairly reasonable in view of the complexity of the flow. More importantly, the figure shows that the URANS closely captures the trend associated with the thrust-breakdown.

3.3. **Cavitation Pattern and Dynamics**

The tests conducted at the NSWCCD, Rolls-Royce and JHU, albeit with all different rotor speeds ($N = 2000, 1200, 900$ RPM, respectively), have revealed the occurrence of the TLV and the sheet cavitation on the suction side of the rotor. The TLV cavitation is illustrated in Figure 2(a) by the photograph taken in the NSWCCD’s 36-inch tunnel at $N^* = (p_t - p_v)/p_n^2D^2 = 0.994$ and $Q^* = Q_J/nD^3 = 0.803$, where $p_t$, $p_v$ and $Q_J$ are the inlet static pressure, the saturation pressure and the flow rate, respectively. The figure, depicting an instantaneous snapshot, portrays the characteristic shape of the TLV cavity expected in the near and post-breakdown regime – the “delta”-like overall shape and the shedding of cloud cavity, which is believed to reflect the interaction between the TLV and the vortices emanating from the suction side of the rotor. The shedding of vortices in the wake of the TLV cavity, which are oriented largely perpendicular to the blade surface, was also observed in the JHU’s experiment [7], They dubbed it “perpendicular cavitating vortex” (PCV). Both the URANS and the IDDES predictions, shown in Figures 2(b) and 2(c) using two iso-surfaces of volume fraction at 0.5 (mixture of 50% liquid and 50% vapor) and 0.9 (mixture of 90% liquid and 10% vapor), are seen to reproduce the main features of the TLV cavitation. In particular, the IDDES captures finer cavitating structures associated with the vortices shed from the TLV cavity and the trailing edge of the rotor. Interestingly, cavitating vortices resembling the PCVs observed and discussed at length by the JHU group seem to be captured by the IDDES. Among other features captured by the URANS and IDDES are the small pockets of cavitation near the tips of the stator blades (seen in the figures) and the cavitating hub vortex (not shown here), which were also observed in the experiment [6].

Although not shown here due to space limitation, the URANS and IDDES results provide detailed space-time maps of the pressure distribution on the blade surfaces. The change in the surface pressure distribution with the progress of thrust-breakdown offers a crucial information that sheds light on what causes thrust-breakdown. The question comes down to how different types of cavitation in the pump
contribute to unloading the pressure side of the rotor blades. Based on the numerical results, it is 
surmised that the elliptic nature of pressure plays an important role in unloading the pressure side, as 
discussed in [1] using the Poisson’s equation for pressure. The computational results show that the 
pressure unloading mainly starts from the leading edge of the rotor blades rather than around the 
trailing edge. In view of this, the elliptic nature of pressure appears to work in a way that the suction 
side’s low pressure (saturation pressure) is impressed upon the adjacent (incoming) pressure side, 
causing the unloading of the pressure side.

4. Summary and Conclusion
The URANS predictions were shown to predict the pump characteristics including the thrust-
breakdown with a decent accuracy. In view of the complex nature of the flow such as the large 
streamline curvature and swirl, the accuracy URANS predictions may well be improved by resorting to 
more advanced turbulence models. The hybrid URANS-LES approach (IDDES) seems to be able to 
capture finer details of the turbulent cavitating flow without incurring an excessive computational cost. 
The elliptic nature of pressure appears to be responsible for thrust-breakdown, inasmuch as it can lead 
to unloading the pressure side of the rotor blades by the suction side’s low pressure “impressed” on to 
the neighboring pressure side. Among our future work are computations with high-order RANS 
turbulence models, hybrid URANS-LES computation on a finer grid, and comparison with the 
experimental data in terms of the flow-fields such as the mean velocity and Reynolds’ stresses.

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References
[1] Kim S E and Schroeder S 2010 Numerical study of thrust breakdown due to cavituation on a 
hydrofoil, a propeller, and a waterjet 28th International Conference on Naval Ship 
Hydrodynamics, Pasadena, California September 12-17
[2] Lindau J W Pena C Baker W J Dreyer J J Moody W L Kunz R F and Paterson E G 2012 
Modeling of cavitating flow through waterjet propulsors. International Journal of Rotating 
Machinery 2012
[3] Ahn S J and Kwon O J 2013 Numerical investigation of cavitating flows for marine propulsors 
using an unstructured mesh technique International Journal of Heat and Fluid Flow 43 259-
267
[4] Michael T Schroeder S and Becnel A 2009 Design of the ONR AxWJ-2 axial flow water jet 
pump”, Hydromechanics Department Report NSWCCD-30-TR-2008/066
[5] Chesnakas C J, Donnelly M J Pfitsch D W Becnel A J Schroeder S D 2009 Performance 
evaluation of the ONR axial waterjet 2 (AxWJ-2) Hydromechanics Department Report 
NSWCCD-50-TR-2009/089
[6] Andersson L 2010 ONR AxWJ-2 Pump Loop Test Report PR-1223 Rolls-Royce 
Hydrodynamic Research Ceneter
[7] Tan D, Li Y, Miorini R, Vagnoni E, Wilkes I and Katz J 2012 Role of large-scale vortical 
structures in the rotor passage of an axial waterjet pump in performance breakdown 30th 
Symposium on Naval Ship Hydrodynamics, Hobart, Tasmania Australia November 2-7 2012
[8] Kim S E 2009 A numerical study of unsteady cavituation on a hydrofoil 7th International 
Symposium on Cavitation CAV2009 Ann Arbor Michigan August 17 – 22
[9] Travin A K, Shur, M L, Spalart, P R and Strelets, M K 2006 Improvement of delayed detached-
eddy simulation for LES with wall modelling. In ECCOMAS CFD 2006: Proceedings of the 
European Conference on Computational Fluid Dynamics, Egmond aan Zee, The 
Netherlands September 5-8