Simulation of hydropower flow measurement accuracy as a function of sensor density and placement

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Abstract

The following paper addresses the simulation of Acoustic Time of Flight and Current Meter instrumentation using nearest neighbor, inverse distance weighting, and kriging methods to sample computationally modeled flow fields of the Unit 4 intake at the Lower Granite Hydroelectric Plant. Sensor simulation is important in this setting because the intake geometry and flow field do not meet the requirements of hydraulic turbine performance test codes. In such cases, usefully-accurate measurement of turbine flow is impossible in the absence of special effort and expense to address the deviations of intake and flow-field geometry from code-specified conditions. Simulation provides a comprehensive technique to gauge the effectiveness of different arrangements of acoustic time of flight and current meter sensors for such intakes. The sensor simulation technique and permutations of the computational fluid dynamic models that will be developed in support of this is presented in addition to preliminary results associated with this research. This work quantifies the evolution of flow measurement accuracy as increasing numbers of flow sensors are applied; and demonstrates that current meter accuracy increases from 89.3% to 98.3% and acoustic time of flight accuracy increases from 95.6% to 99.2 when exposed to the simulated hydraulic conditions.

1. Introduction

Accurate flow measurement is an important component of hydroplant operation because of its capability to indicate overall plant health; demonstrate contractual performance requirements and inform multi-unit optimization within the plant.[3] Significant effort has been expended on the development of standardized techniques measure the flow rate given its level of influence on plant operation, however these techniques are not applicable to a specific subset of hydroplants which contain short converging intakes (SCI).[1][6][9] This is because the length of the SCI intake is insufficient to allow the flow profile to become fully developed and therefore the information from flow sensors, which detects point or transect information, cannot be reliably converted to a flow rate.[11] Development of a technique which allows for accurate flow measurement within SCI is important because this represents roughly 10% of the United States hydropower capacity.[5]

To this end the following paper investigates the simulation of Current Meters and Acoustic Time of Flight instrumentation in computational fluid dynamic (CFD) models of Unit 4 of Lower Granite Lock and Dam (Fig. 1). Lower Granite is a United States Army Corps of Engineers (USACE) facility located on the Snake River in Washington State and is comprised of 6 135MW Kaplan turbines.[13] This facility was selected for the research not only because the plant has a SCI but also due to the fact that the plant was willing to share operational test data from Unit 4. This data enabled the authors to not only investigate the measured flow rate evolution but also the change in the recorded unit characteristic curve that this causes.

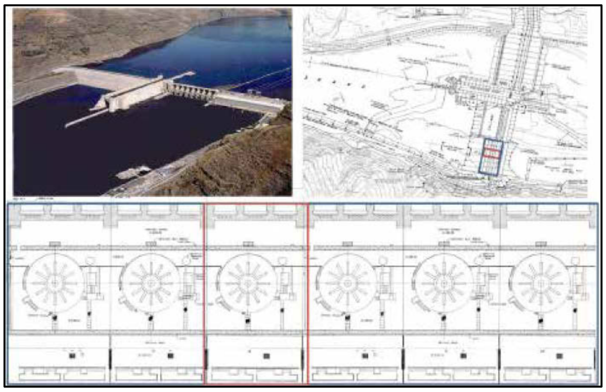

Fig. 1: Lower Granite Lock and Dam

2. Proposed Methodology

The work to simulate the impact of acoustic time of flight and current meter sensor resolution can be largely discretized into three primary parts: 1) CFD Modeling, 2) Sensor Simulation, and 3) Characteristic Curve Impact.

2.1 CFD Modeling

Creation of CFD models of the intake represents a critical component of the research as the data provided will act to inform the sensor simulation. The research will focus on the development of models for 6 discrete flow rates (291, 368.88, 487.47, 429.93, 561.61 and 632.26 m^3sec^{-1}) where performance data was collected by the USACE during unit testing. The number of points was selected because it represents the number of points required to fit a 5^{th} order polynomial to the dataset as a goal of this reaserach is to demonstrate the change in the characteristic curve that occurs and this is the order required for curve generation by the test codes.[1][9]

The CFD tool being used for the analysis is Star-CCM+ and the turbulence closure models being used are steady state K-ε and K-ω. The computational domain represents a region 20 meters upstream of the intake to the beginning of the draft tube and the solids model representing this region was developed using geometry provided by the USACE. Given the extent of the model the mesh produced for the CFD ranges between 3.2 and 7.9 million cells depending on the point in the mesh independence study. One of the largest challenges in computationally representing the flow field in the intake using CFD is determining the appropriate upstream and downstream boundary conditions. As such a series of models will be produced with different boundary conditions at each flow rate to fully capture the range of possible hydraulic conditions. These will include:

1: Strictly axial mass flow inlet and pressure outlet.
2: Axial and Left mass flow inlet and pressure outlet.
3: Axial and Right mass flow inlet and pressure outlet.
4: Axial, Right and Left mass flow inlet and pressure outlet.
5: Hydrostatic pressure inlet and mass flow outlet.

At each combination of boundary condition and flow rate a mesh independence study will be performed and the resulting flow data will be validated using the appropriate industry standards and field measurements that were taken during the operational testing of Unit 4.[2]

2.2 Sensor Simulation

The data from the CFD modeling will then be used to inform the subsequent modeling of the sensor response to the flow hydraulic conditions present within the intake and the corresponding flow rate that would be recorded. This will be done through the development of two separate post processing code sets capable of reading in the raw data from the CFD model, the first to model current meters and the second acoustic time of flight sensors. Current meters are modeled as idealized points in space (Fig. 2) whereas the acoustic time of flight pulses are modeled as a series of points along the acoustic path length (Fig. 3). It is apparent that in both cases the values provided by the CFD model must be used to determine the hydraulic characteristics at the points relevant to the simulation. To this end the authors have developed three separate post-processing codes for both of the sensor types, each employing different numerical techniques. The first technique utilizes a basic nearest-neighbor, the second uses an inverse distance weighting, and the third ordinary kriging. The different methods are used to fully understand the effect of the numeric technique of the sensor simulation and therefore minimize its impact. Each of the post-processing codes allows the user to actively select the downstream location and number of sensors to be modeled; the code then determines the appropriate spatial placement and converts the sensor recorded velocities to a flow rate using the test code prescribed numeric method. The research that is being performed assumes the placement of the current meters in the gate slot and the acoustic time of flight meters immediately downstream of the unit's bulkhead.

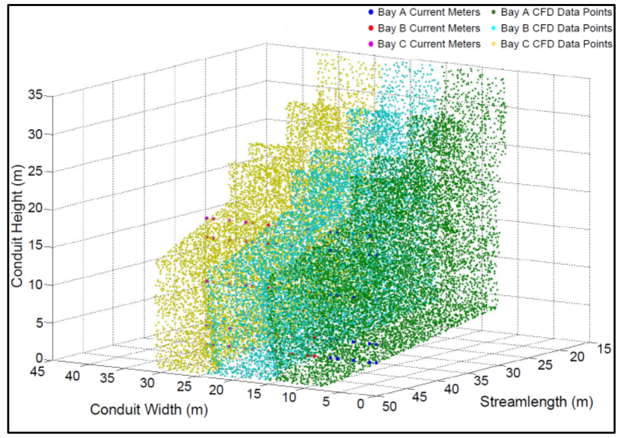

Fig. 2: Current Meter Simulation

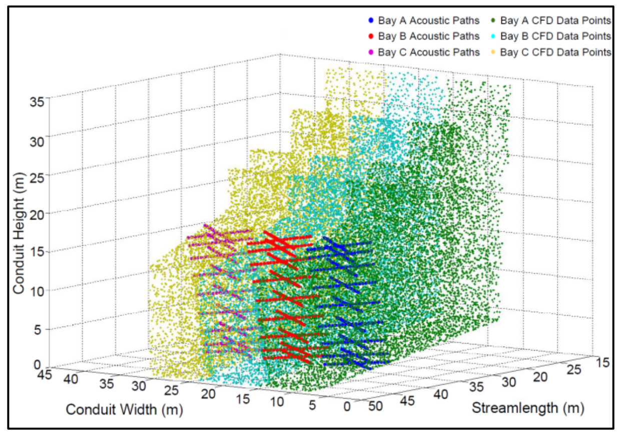

Fig. 3: Acoustic Time of Flight Simulation

The research is also takes into account the impact that local hydraulic characteristics have on velocities recorded by the flow sensors. In the case of current meters this focuses on the impact of turbulence and oblique flow. This is informed using a series of studies which subjected different types of current meters to both hydraulic characteristics as demonstrated in Fig. 4 and Fig. 5. [7][8][10][12] Using this information the post processing code allows for the simulation of the response of several different types or an idealized one which strictly records the downstream component of the flow without the influence of turbulence. In regards to acoustic time of flight simulation the primary attribute that is taken into account is the impact of oblique flow on the velocity recorded by the acoustic pulse because this acts to alter the transit time of the pulse and thereby impact the recorded flow rate. Given this the time of flight simulation code allows for the simulation of acoustic paths in each direction as well as dual acoustic paths.

The post processing tool will be used to investigate the increase in flow measurement accuracy as a function of the number of applied sensors over a range of applied instruments. The minimum number of current meters that will be investigated is a grid with a 5 by 5 resolution as this is the least that is supported by the test code.[9] Increasing levels of resolution will be investigated until there is a nominal increase in increased flow measurement accuracy. The minimum number of time of flight paths that will be simulated is a single path and this will similarly be expanded upon until minimal increases in accuracy are achieved.

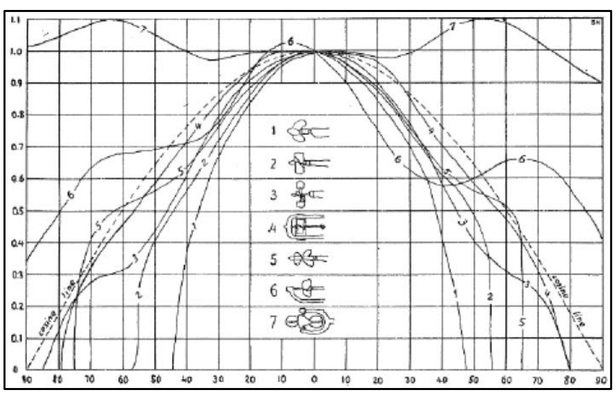

Fig. 4: Current Meter Oblique Flow Response

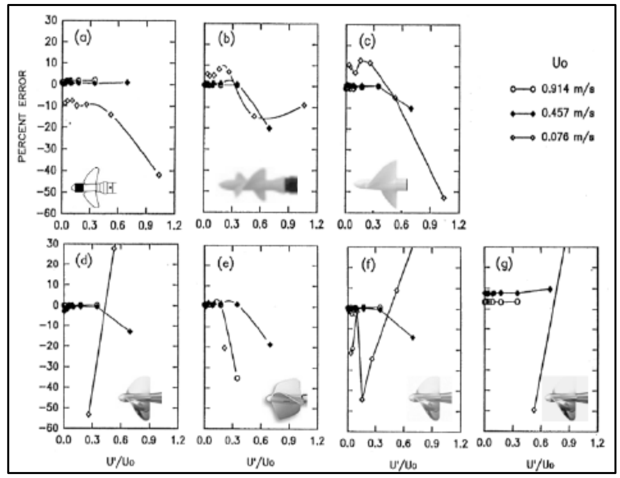

Fig. 5: Current Meter Turbulent Response

2.3 Characteristic Curve Impact

The flow rates recorded by the simulated instrumentation will then be combined with the unit performance data provided at each of the simulated flow rates to demonstrate how the recorded efficiency curve changes based on the number of applied flow meters. In addition to this, the known flow rate will be used in combination with the performance to develop a reference characteristic curve.

3. Preliminary Results

Preliminary results associated with this research were developed using CFD models of the intake using axial mass flow velocities and pressure boundary conditions at the upstream and downstream boundaries respectively and developed with a mesh of 4.5 million cells. The numeric method used for sensor simulation was the nearest neighbor technique and idealized sensor response was assumed. Across the range of simulated sensors it was observed that the sensors over predicted the flow rate, however the extent of this decreased as the number of sensors simulated increased.

Current meter simulation was performed at horizontal and vertical resolutions ranging from 5 to 15 meters at an increment of 2 sensors. The results of this demonstrated significant similarities in accuracy resulting from the same quantities of meters across the range of flow rates (0.16% mean difference). As such the results for each level of sensor resolution are addressed as a function of the mean percent reference flow rate (PRFR) which is found in Table 1. An interesting aspect that can be observed from this is the importance of adequate vertical and horizontal current meter resolution as demonstrated in Fig. 6. This figure demonstrates the importance of achieving sufficient resolution in both the vertical and horizontal directions; with higher levels of accuracy occurring at ratios which have horizontal resolution equivalent or higher than vertical resolution.

Table 1: Mean Current Meter PRFR

		Horizontal Current Meter Resolution					
		5	7	9	11	13	15
Vertical Current Meter Resolution	5	110.65	107.28	106.36	105.94	105.82	105.50
	7	106.92	104.03	103.26	102.86	102.69	102.47
	9	106.58	103.61	102.86	102.43	102.33	102.05
	11	106.38	103.40	102.62	102.29	102.12	101.88
	13	106.49	103.45	102.66	102.37	102.16	101.97
	15	106.03	103.15	102.47	101.99	101.78	101.66

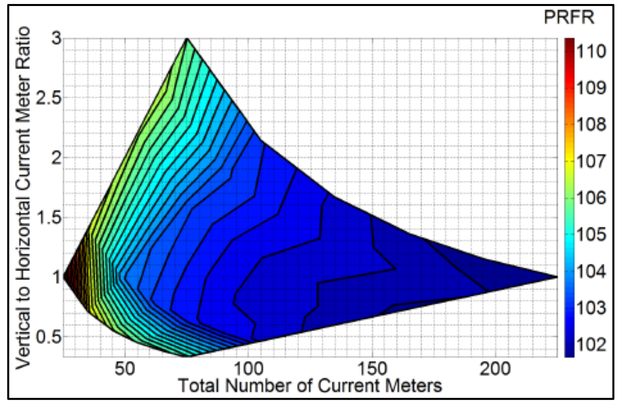

Fig. 6: Current Meter Resolution Ratio Effects

Acoustic time of flight simulations were performed for both the single direction paths and the dual paths from a range of 1 to 9 paths. The acoustic paths in both directions were found to have a nominal difference (0.42 CMS) and therefore the dual path results were used for the subsequent analysis. The PRFR resulting from different quantities of dual paths at different flow rates are demonstrated in Table 2. From these results it can be observed that the flow rate has a minimal impact on the PRFR rather the number of acoustics paths is significantly more important. Interestingly, it appears that there are two inflection points in the increase in accuracy that occurs; the first at 3 paths and the second at 7 paths. An inspection of the hydraulic structure that the acoustic paths travel though demonstrated that these discontinuities were a result of fortuitous placement of the paths. Additionally when observing these, it is important to take the extent of the accuracy differential into account with a 0.2 PRFR difference occurring between 3 and 4 paths and 0.5 PRFR occurring between 7 and 9 paths.

Table 2: Dual Path PRFR

Number of Dual Acoustic Paths	Flow Rate (m^3sec^{-1})					
	291.0	368.9	429.9	487.5	561.6	632.3
1	104.55	104.49	104.48	104.48	104.45	104.45
2	103.84	103.80	103.78	103.76	103.75	103.73
3	101.46	101.46	101.45	101.44	101.44	101.44
4	101.64	101.63	101.60	101.60	101.62	101.61
5	101.53	101.49	101.48	101.46	101.46	101.45
6	100.92	100.89	100.89	100.87	100.86	100.85
7	100.36	100.29	100.29	100.26	100.25	100.24
8	100.75	100.69	100.68	100.65	100.64	100.63
9	100.82	100.79	100.78	100.77	100.78	100.77

The results of the flow measurement investigation were then combined with the performance data provided by the USACE to produce the characteristic curve that would be recorded if the different quantities of flow sensors were used. Naturally due to the over prediction of the flow rate, the efficiency curves of the turbines under predict the actual efficiency of the turbine. The extent of this can be found in Fig. 7 and Fig. 8 for current meters and acoustic time of flight paths respectively. It should be noted that for brevity the current meter analysis is limited to equivalent horizontal and vertical resolutions. In this it can be observed that the mean difference between the reference curve and the minimal level of instrumentation is 9% and 3.7% for current meters and acoustic time of flight respectively.[3][4]

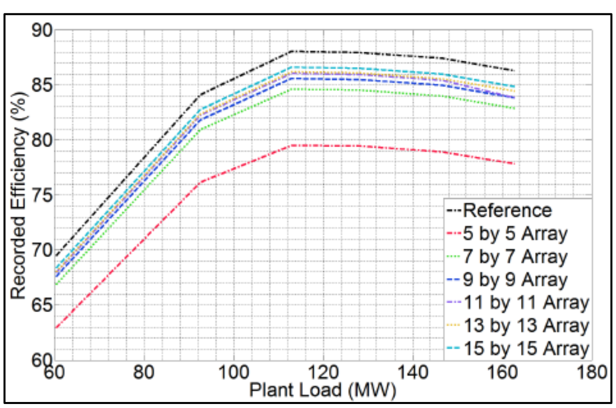

Fig. 7: Current Meter Recorded Efficiency

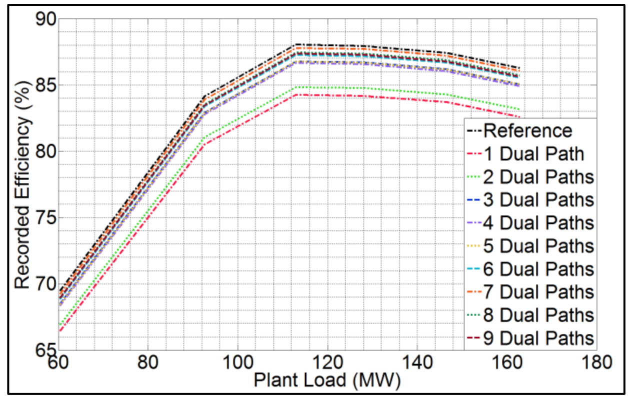

Fig. 8: Acoustic Time of Flight Recorded Efficiency

4. Conclusions

The paper above demonstrates the research process developed to investigate value of flow measurement accuracy in SCI; which is performed in support of a Department of Energy research thrust into Hydropower Asset Management.[3] While the research is specifically directed toward Lower Granite, the computational techniques developed can easily be applied CFD models of other intakes. Preliminary results of the investigation into accuracy demonstrate that the simulated instrumentation over predicts the flow rate and thereby under predicts the unit efficiency. The number of sensors was found to have the largest impact on accuracy; whereas the flow rate in which the sensors were simulated had a relatively minimal effect suggesting that the hydraulic structure of the flow was relatively consistent. Future research will include a comprehensive investigation of the range of boundary conditions and their impact on the calculated hydraulic structure of the intake. These models will then be used to investigate impact of flow sensor quantity on recoded flow measurement accuracy using the three different sensor simulation numerical models. Further work will later be performed to analyze the implications of flow measurement accuracy in regards to plant optimization developing insight into the overall value of flow measurement instrumentation in short converging intakes over a range of plant loadings.

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