Volumetric Flow Rate Measurement using Surface Imaging Techniques

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Abstract

The purpose of our research is to validate an experimental method developed by Johnson and Cowen (2016) aimed at measuring volumetric discharge in an open channel using Surface particle image velocimetry (SPIV) combined with turbulent boundary layer analysis to infer the bathymetry and calculate volumetric flow rate, ultimately extending this work to natural systems (Hendrickson, 2020).

1 Introduction

The United States Geological Survey conducts thousands of streamflow measurements in rivers annually using *in situ* methods that typically employ intrusive techniques that may affect measurement quality. More modern methods (e.g. acoustic Doppler current profilers, multi-beam echosounders) used to measure channel bathymetry provide access to larger bodies of water, but rely on *in situ* measurements across the channel.

The technique developed by Johnson and Cowen (2016) leverages particle image velocimetry for streamgaging. It utilizes coherent turbulent structures in the instantaneous velocity field, which connect the bed to the free surface, to infer channel bathymetry. The strength of this technique lies in its unobtrusive nature, which allows for reliable and cost-effective data collection across large regions, and thus greater insight about turbulent dynamics across a stream than can be provided by point measurements.

2 Methodology

Tests were performed in a 30 m long, 1.5 m wide, and 0.8 m high outdoor flume with several flow rates. Surface flow and boundary layer data were collected via SPIV and acoustic Doppler velocimetry (ADV), respectively. SPIV data were captured by a downward-facing JAI GO 5000M camera above the flume centerline. The time between images, Δt, ranged from 16 to 33 ms. An ADV placed downstream of the SPIV field of view (FOV) was used to construct the velocity profile (Hendrickson, 2020).

Floating seed particles were used for SPIV measurements. The outdoor setting posed major illumination issues during data collection; surface reflections affected particle detection, and shadows on the flume bed obscured the contrast between particles and background. To enhance particle detection, an adaptive binarization algorithm was applied. The surface velocity field was then obtained using PIVlab (Thielicke and Stamhuis, 2014). The volumetric flow rate is calculated using:

$$Q = \sum_{i=1}^{N} \overline{U}_{B_i} A_i \tag{1}$$

where Q is the total discharge, A_i is the ith (or local) cross-sectional area of the n segments into which the entire cross section has been divided, and U_{B_i} is the corresponding ith mean velocity measurement. Each local velocity component, $\overline{U}_{B_i}$, was obtained from the relation $U_B = kU_{\text{surf}}$ (where k is index velocity and U_{surf} is surface velocity). Index velocity varies with flow characteristics (Johnson and Cowen, 2017); thus k

was determined at the centerline using U_B constructed by the ADV data and the surface velocity at the same location. Last, k is used with local, spanwise U_{surf} to obtain local depth-averaged velocity across the FOV.

The local depth across the channel was obtained from the surface velocity field. The integral length scale was used to connect surface dynamics with bathymetry. The integral length scale, $\mathscr{L}$, provides streamwise ($\mathscr{L}_{11,1}$) and spanwise ($\mathscr{L}_{22,1}$) eddy sizes. Sparse seeding due to illumination issues affects the averaging process, yielding values of $\mathscr{L}_{11,1}$ and $\mathscr{L}_{22,1}$ outside the theoretical range. $\mathscr{L}_{11,1}$ and $\mathscr{L}_{22,1}$ were used with measured flow depth to build a linear relationship and obtain local flow depths across the FOV.

3 Results & discussion

Test	$L_{11,1}$ % difference	$L_{22,1}$ % difference	$Re = U_B L/\nu$
1	0.07	47	38800
2	114	34	89500
3	62	18	118600
4	14	7	133500
5	22	30	59000

Table 1: Percent difference between estimated and measured discharge (Hendrickson, 2020). ν is the kinematic viscosity of water, and L is the hydraulic radius (area over wetted perimeter).

The flow rate estimation using $\mathscr{L}_{22,1}$ for obtaining local flow depths, H_i, provides a better approximation than $\mathscr{L}_{11,1}$, in particular at high Re. The large uncertainty in results (Table 1) can be attributed to the difficulty in obtaining high quality images due to seeding inconsistencies and surface reflections, suggesting a need to continue to improve PIV algorithms for sparse data in field applications.

4 Conclusions

SPIV measurements were collected in an outdoor channel, in which inconsistent illumination produced sparse seeding and incomplete data sets, following binarization methods to improve image quality. This affected the quality of SPIV analysis and the integral length scale. The correlation in the velocity fields is sensitive to factors such as wind, flow dynamics, and seeding, affecting the averaging process and yielding integral length scale values outside the theoretical range. In addition, our aspect channel aspect ratio of almost 1:1 produced a negative slope for the linear relation between $\mathscr{L}_{22,1}$ and channel depth, whereas Johnson and Cowen's application in a shallow water channel yielded a positive slope for the same relation.

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References

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