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Improvement of Acoustic Doppler Velocimetry in bubbly flow measurements as applied to river characterization for kinetic turbines

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ABSTRACT

Acoustic Doppler Velocimetry (ADV) can measure flow velocities in three directions in experimental facilities and field applications. Based on the Doppler shift effect, ADV can accurately resolve the quasi-instantaneous flow field at frequencies of up to approximately 200 Hz. However, this technique is sensitive to operating conditions that can lead to contaminated signals containing large amplitude spikes, a disadvantage of ADV. Aliasing of the Doppler signal creates these spikes. Such a situation occurs when large particles intersect the sampling volume or acoustic waves. For example during the characterization of river velocities, sediments floating near the riverbed cause aliasing from particles, and more importantly, surface entrained air bubbles contaminate the ADV signal. Spikes due to air bubbles not only increase the standard deviation of the velocity, but also corrupt the autocorrelation and power spectra. As some of these spikes appear like velocity fluctuations, developing accurate despiking procedures is an important requirement during post-processing of ADV velocity measurements in bubbly flow applications. A new hybrid method is introduced which has advantages over conventional despiking methods such as the acceleration thresholding method and the phase-space thresholding method when using ADV in bubbly flow. ADV river velocity measurements near kinetic turbines demonstrate the proposed method. This method is applicable to other bubbly flow applications to characterize the liquid phase using ADV.

1. Introduction

Acoustic Doppler Velocimetry (ADV) measures local flow velocity in 3-D. This technique uses the Doppler frequency shift between the emitted and reflected acoustic waves from scattering particles in the sampling volume to calculate the instantaneous velocity of the flow. Sampling rate frequencies of up to 200 Hz enables ADV to capture the velocity fluctuations required to characterize turbulence of the flow. Having the sampling volume away from the probe allows measurements not to interfere with the flow. Compared to optical and laser techniques, ADV is simple and compact, as the acoustic emitter and receivers are installed within a common device. Additionally, acoustic waves penetrate deeper in water when compared to light or laser beams (Duraiswami et al., 1998). Because of these advantages, ADV is widely used by researchers for flow velocity measurements in laboratory and field applications (Chansona et al., 2008; Sarker, 1998; Trevethan et al., 2007; Trowbridge and Elgar, 2001; Wilcox and Wohl, 2006).

Although measuring velocity with ADV has advantages over other velocity measurement methods, this technique is sensitive to operating conditions and often requires further processing. For example, measured signals may contain Doppler noise due to aliasing of the return signal above the Nyquist frequency. This happens if the velocity of the flow rises above or below the velocity range of the instrument (Goring and Nikora, 2002). Velocity shear in the sampling volume creates Doppler noise generating a large velocity gradient in the direction of the acoustic beam (Rodriguez et al., 1999). Conventional filtering algorithms, including Tukey's method (Otnes and Enochson, 1978) and Wavelet Thresholding (Daubechies, 1992), are available for low amplitude and high frequency noises. In addition to noise, the signal can contain large amplitude spikes. There can be ambiguity for the root cause of these spikes. However, most studies that report spike issues are related to the measurements of high turbulent flows (MacVicar et al., 2007; Rehmel, 2007), surf zones (Rodriguez et al., 1999; Farmer et al., 2001; Mori et al., 2007), bed areas (Strom and Papanicolaou, 2007), and downstream of flow steps (Wilcox and Wohl, 2006). In these studies bubbly flow occurs: the flow contains air bubbles except in the bed area where the existence of air bubbles has a much lower probability.

When particles are small compared to the acoustic wavelength, Ishimaru (1977) showed that as the results of the almost isotropic scattering, the scattering amplitude is constant. The signal processing mathematics of the isotropic scattering is considerably simple and is used in ADV. Large particles compared with the acoustic wavelength have an anisotropic scattering and they scatter mostly

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in the forward direction. The signal processing method of the ADV recognizes the anisotropic scattering identical to the case of strong fluctuations in turbulence. According to the theory of wave propagation and scattering in random media, the size of particles play a main role in back scattering and signal quality of the ADV receiver. Large sediments near the bed area and large air bubbles close to the surface of the flow may disturb the ADV velocity dataset. Still, air bubbles have more effect on the signal than sediments and other solid particles because the acoustic cross section of air bubbles is three or four times larger than their geometrical cross section (Medwin, 1977). Although air bubbles are one of the main sources of these spikes, limited information is available on how air bubble induced spikes influence the turbulence statistics when using ADV in bubbly flow applications to characterize the liquid phase velocity.

Spikes in a dataset not only increase the noise energy (Anderson and Lohrmann, 1995), but also change the turbulence statistical properties such as autocorrelations, power spectra and standard deviation. Despiking is required not only for more accurate turbulence statistical properties measurement, but for void fraction measurement in applications such as water treatment, piping, and biochemistry. For example, the difference between the turbulence statistical properties of a raw dataset and a spike-free dataset is an adequate parameter to infer the void fraction of a gas–liquid mixture.

Understanding the behavior of spikes is the first step in developing an appropriate despiking procedure to allow 3-D liquid-phase velocity measurements of the liquid phase in bubbly flow applications. Similarity between spikes and natural fluctuations in the turbulent flow complicates despiking algorithms. The signal-to-noise ratio (SNR) parameter provides an assessment of the quality of the ADV received acoustic signal. Although the back scattered signal from air bubbles has a lower SNR than that of solid particles (Nielsen et al., 1998), the SNR value is not a proper despiking criterion, since it varies with the turbulence intensity of the flow. In addition, experience shows that low SNR values and spikes in the velocity dataset occasionally appear at different times. One of the conventional despiking methods is the acceleration thresholding method. This method limits the acceleration and deceleration of particles in the flow due to physics. In a recent despiking method development proposed by Goring and Nikora (2002), and later modified by Wahl (2003), an ellipsoid defined in the phase-space filters the spikes. The performance of these proposed methods changes in different conditions and they may not be able to detect all the spikes in the velocity dataset when applied in various bubbly flow applications. For datasets with low spike density, the phase-space thresholding method is satisfactory; however, the efficiency of this method decreases when the density of spikes is considerable.

As part of research in renewable energy generation using river kinetic turbines, ADV is used in situ and a new despiking algorithm is required to process velocity data because of the significant presence of air bubbles. A comprehensive investigation was required with focus on the generation of spikes in the velocity dataset when air bubbles intersect the sampling volume and the acoustic beams. Current methods tested to filter the spikes from the dataset are not accurate. From the analysis, it became apparent that improvements could be made in the phase-space thresholding method by removing the high amplitude spikes, which are different from the velocity fluctuations. The improved "hybrid method" performs better at despiking bubbly-flow data sets for measuring the liquid-phase and the method applies to other bubbly-flow applications.

2. Field study

The high frequency flow velocity measurement is essential for understanding the flow dynamics for kinetic turbines for river and ocean applications. Other than mean velocity, turbulence characteristics of the flow—such as turbulence intensity and turbulence length scales—are important for river kinetic turbine performance analysis. Mean velocity affects the total available power in the flow, while the turbulence characteristics influence the output power of the turbine by affecting its performance. For an optimal design, turbulence characterizing is required as a first step. In the study of river flows, velocity measurement at a high temporal frequency is an important source of information for turbine sighting and power production predictions. ADV is a common tool to measure 3-D velocity in laboratory and field settings, while other measurement techniques such as laser Doppler anemometry and particle image velocimetry are less appropriate outside laboratory settings (Sarker, 1998). Other methods like propeller gauges and Pitot tubes are not accurate for this application and do not provide turbulence quantities. Hot film has difficulties operating at velocities above 2 m/s.

When the transducer of the ADV transmits periodic short acoustic pulses, scatterers reflect a small fraction of the energy back. Scatterers phase must be different from the transmission medium. Air bubbles, suspended sediments, microorganisms, or seeding particles in the river reflect a fraction of the acoustic waves; receivers detect acoustic echoes if they originate at the sampling volume. The instantaneous velocity at any spatial point is calculated for the Doppler shift from the reflected signal. ADV has one transmitter and several receivers capturing the reflected acoustic waves from particles contained in the sampling volume. Seeding particles used for ADV measurement require to be small in comparison with the acoustic wavelength, otherwise large spikes occur in the velocity dataset. In addition to the spiky velocity dataset, the velocity of small particles represents better the instantaneous fluctuations of the flow; large particles are unable to respond as quickly to velocity fluctuations due to their higher moment of inertia or buoyancy.

Fig. 1 shows the ADV measurements conducted in the Winnipeg River in front of a 25 kW vertical New Energy Corporation kinetic turbine positioned 1 m below the water surface (Bibeau et al., 2009). Field measurements in Fig. 2 show that in addition to noise, large amplitude spikes occur in the velocity dataset. Measurements repeated at different water depths show that large amplitude spikes remained in the velocity dataset. An underwater video camera reveals significant amounts of air bubbles entrained in the flow before the turbine. The camera detects numerous air bubbles larger than the sampling volume size. A laboratory test apparatus was then developed for testing filtering algorithms to allow measuring turbulence characteristics upstream and downstream of kinetic turbines where the density of entrained air bubbles is comparable to other bubbly flow applications.

3. Experimental setup

University of Manitoba's water-tunnel facility can assess the effects of air bubbles on the quality of the ADV velocity dataset. The water-tunnel test section is 61.0 cm in width, 76.2 cm in height, and 182.9 cm in length. We position the ADV horizontally at the mid-depth and mid-width of the test section. A Vectrino Nortek AS ADV measures the water velocity. This type of ADV has four receivers in parallel and allows data collection rates of up to 200 Hz. The sampling volume for this ADV model is a cylinder 0.6 cm in diameter and 0.9 cm in height, and is located 10 cm away from the ADV transmit transducer. A 10 MHz frequency transmitter emits acoustic waves. This high acoustic frequency has a wavelength of 0.01 cm, which is sensitive to particles larger than this wavelength. An air bubble generator positioned below the ADV sampling volume generates large bubbles in the water tunnel. The generated bubbles pass through the sampling volume. The