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Noise correction of turbulent spectra obtained from acoustic doppler velocimeters

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ABSTRACT

Velocity spectra are essential in characterizing turbulent flows. The Acoustic Doppler Velocimeter (ADV) provides three-dimensional time series data at a single point in space which are used for calculating velocity spectra. However, ADV data are susceptible to contamination from various sources, including instrument noise, which is the intrinsic limit to the accuracy of acoustic Doppler processing. This contamination results in a flattening of the velocity spectra at high frequencies ($\mathcal{O}(10)$ Hz). This paper demonstrates two elementary methods for attenuating instrument noise and improving velocity spectra. First, a "Noise Auto-Correlation" (NAC) approach utilizes the correlation and spectral properties of instrument noise to identify and attenuate the noise in the spectra. Second, a Proper Orthogonal Decomposition (POD) approach utilizes a modal decomposition of the data and attenuates the instrument noise by neglecting the higher-order modes in a time-series reconstruction. The methods are applied to ADV data collected in a tidal channel with maximum horizontal mean currents up to 2 m/s. The spectra estimated using both approaches exhibit an $f^{-5/3}$ slope, consistent with a turbulent inertial sub-range, over a wider frequency range than the raw spectra. In contrast, a Gaussian filter approach yields spectra with a sharp decrease at high frequencies. In an example application, the extended inertial sub-range from the NAC method increased the confidence in estimating the turbulent dissipation rate, which requires fitting the amplitude of the $f^{-5/3}$ region. The resulting dissipation rates have smaller uncertainties and are more consistent with an assumed local balance to shear production, especially for mean horizontal currents less than 0.8 m/s.

1. Introduction

Acoustic Doppler Velocimeter (ADV) data are commonly used for performing field measurements in rivers and oceans [1–5]. The ADV measures fluid velocity by comparing the Doppler phase shift of coherent acoustic pulses along three axes, which are then transformed to horizontal and vertical components. In contrast to an Acoustic Doppler Current Profiler (ADCP), the ADV samples rapidly ($\mathcal{O}(10)$ Hz) from a single small sampling volume ($\mathcal{O}(10^{-2})$ m diameter). The rapid sampling is useful for estimating the turbulent intensity, Reynolds stresses, and velocity spectra. Velocity spectra are useful in characterizing fluid flow and are also used as an input specification for synthetic turbulence generators (e.g., TurbSim [6] and computational fluid dynamics (CFD) simulations). These simulations require inflow turbulence conditions for calculations of dynamic forces acting on Marine and Hydro-Kinetic (MHK) energy conversion devices (see [7]). This study focuses on accurate estimation of velocity spectra from ADV measurements that are contaminated with noise, for application in CFD simulations for MHK devices.

ADV measurements are contaminated by Doppler noise, which is the intrinsic limit in determining a unique Doppler shift from finite length pulses [8–10]. Doppler noise, also called "instrument noise", can introduce significant error in the calculated statistical parameters and spectra. Several previous papers have addressed Doppler noise and its effect on the calculated spectra and statistical parameters [5,8–10,59]. These studies have shown that the Doppler noise has properties similar to that of white noise [8,9]. In the absence of noise, velocity spectra are expected to exhibit an $f^{-5/3}$ slope, in the inertial sub-range [11–13]. Nikora and Goring [8] showed that the spurious flattening at high frequencies is significantly greater for the horizontal u and v components of velocity as compared to the vertical w component of velocity, and is a result of the ADV beam geometry. Motivated by the many applications of velocity spectra, this study examines the effectiveness of two elementary techniques to minimize the contamination by noise in velocity spectra calculated from ADV data.

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ADV measurements are also contaminated by spikes, which are random outliers that can occur due to interference of previous pulses reflected from the flow boundaries or due to the presence of bubbles, sediments, etc. in the flow. Several previous papers have demonstrated methods to identify, remove and replace spikes in ADV data [14–18]. For example, Elgar and Raubenheimer [14] and Elgar et al. [16] have used the backscattered acoustic signal strength and correlation of successive pings to identify spikes. Once the spike has been identified, it can be replaced with the running average without significantly influencing statistical quantities [18]. Another technique that is commonly used to de-spike ADV data is Phase-Space-Thresholding (PST) [19]. This technique is based on the premise that the first and second derivatives of the turbulent velocity component form an ellipsoid in 3D phase space. This ellipsoid is projected into 2D space and data points located outside a previously determined threshold are identified as spikes and eliminated. The PST approach is an iterative procedure wherein iterations are stopped when no new spikes can be identified. There are several variations of this approach, such as 3D-PST and PST-L, detailed descriptions of which are given in [15,17]. In the present study, an existing method for despiking from [16] is applied, and we restrict our investigation to Doppler noise.

One existing technique to remove Doppler noise from ADV data is a low-pass Gaussian digital filter [10,20–23]. Although this technique is capable of eliminating Doppler noise from the total variance, the spectra calculated from filtered data exhibit a sharp decrease at high frequencies. In contrast, Hurther and Lemmin [24], using a four beam Doppler system, estimated the noise spectrum from cross-spectra evaluations of two independent and simultaneous measurements of the same vertical velocity component. After the correction, spectra obtained by Hurther and Lemmin [24] exhibit an $f^{-5/3}$ slope out to the highest frequency (Nyquist frequency).

The present study explores two different approaches for attenuating noise and thereby improving velocity spectra at high frequencies. The first approach, termed the “Noise Auto-Correlation” (NAC) approach, utilizes assumed spectral and correlation properties of the noise to subtract noise from the velocity spectra. The NAC approach is analogous to the Hurther and Lemmin [24] approach, but differs in that they estimate the noise variance using the difference between two independent measures of vertical velocity, whereas in this study the noise variance is estimated from the flattening of the raw velocity spectra. The second approach uses Proper Orthogonal Decomposition (POD) to decompose the velocity data in a series of modes. In POD, the maximum possible fraction of TKE is captured for a projection onto a given number of modes. Combinations of POD modes identify the energetic structures in turbulent data fields [25–29]. Low-order reconstructions of the ADV data are performed using a reduced number of POD modes which are associated only with the energetic structures in the turbulent flows. This eliminates the random and less energetic fluctuations associated with instrument noise.

The field measurements and raw velocity spectra are described in Section 2 and the methods to attenuate noise from velocity spectra follow in Section 3. Before detailing the NAC and POD approaches (Sections 3.1 and 3.2, respectively), the assumptions implicit to both methods are described in Sections 3 and 2.1. Results, in the form of noise-corrected spectra from both methods, are presented in Section 4. The noise-corrected spectra are compared with spectra from a Gaussian filter approach in Section 4.3 and evaluated for theoretical isotropy in Section 4.4. Finally, an example application is given in Section 5, where the NAC method is used to reduce uncertainties in estimating the turbulent dissipation rates from the field data set, especially during weak tidal flows. The NAC method estimates of dissipation rates are also more consistent with an assumed TKE budget, wherein shear production balances dissipation. Conclusions are stated in Section 6.

2. Field measurements

ADV measurements were collected in Puget Sound, WA (USA) using a 6-MHz Nortek Vector ADV. The site is near Nodule Point on Marrowstone Island at 48° 01'55.154'' N 122°39'40.326'' W and 22 m water depth, as shown in Fig. 1. The ADV was mounted on a tripod that was 4.6 m above the sea bed (the intended hub height for a tidal energy turbine), and it acquired continuous data at a sampling frequency f_s of 32 Hz for four and a-half days during spring tide in February 2011. The mean horizontal currents ranged from 0 to 2 m/s. The measurement location was sufficiently deep (17 m below the water surface at mean lower low water) where the influence of wave orbital velocities may be neglected. The measurement location is in close proximity to headlands, which can cause flow separation and produce large eddies, depending on the balance of tidal advection, bottom friction, and local acceleration due to the headland geometry. In a prior deployment at the same location, the tripod was instrumented with a HOBO Pendant-G for collecting acceleration data. Results indicate that tripod motion (e.g., strumming at the natural frequency) is unlikely to bias measurements. For further details about the measurement site location and data, see [5,30–32].

The raw data acquired from the ADV are shown in Fig. 2(a), where a few spikes are obvious in the raw data. The flow velocity did not exceed the preset velocity range of the ADV (see [5,30]), and there was no contamination from the flow boundary (ADV was positioned facing upward). Thus, these are treated as spikes and removed according to Elgar and Raubenheimer [14] and Elgar et al. [16]. The spikes constitute less than 1% of all data, thus a

Fig. 1. Regional map, bathymetry, and location of ADV measurements at Marrowstone Island site in Puget Sound, northwest of Seattle, WA.

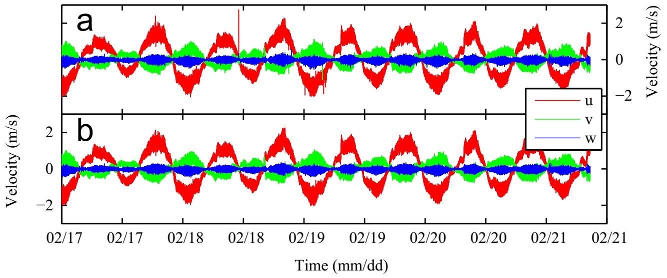

Fig. 2. Data from ADV: (a) raw velocity data and (b) velocity data after QC step.