Despiking of Turbulent Flow Data in Gravel Bed Stream

Ratul Das

Abstract—The present experimental study insights the decontamination of instantaneous velocity fluctuations captured by Acoustic Doppler Velocimeter (ADV) in gravel-bed streams to ascertain near-bed turbulence for low Reynolds number. The interference between incidental and reflected pulses produce spikes in the ADV data especially in the near-bed flow zone and therefore filtering the data are very essential. Nortek's Vectrino four-receiver ADV probe was used to capture the instantaneous three-dimensional velocity fluctuations over a non-cohesive bed. A spike removal algorithm based on the acceleration threshold method was applied to note the bed roughness and its influence on velocity fluctuations and velocity power spectra in the carrier fluid. The velocity power spectra of despiked signals with a best combination of velocity threshold (VT) and acceleration threshold (AT) are proposed which ascertained velocity power spectra a satisfactory fit with the Kolmogorov "–5/3 scaling-law" in the inertial sub-range. Also, velocity distributions below the roughness crest level fairly follows a third-degree polynomial series.

Keywords—Acoustic Doppler Velocimeter, gravel-bed, spike removal, Reynolds shear stress, near-bed turbulence, velocity power spectra.

I. INTRODUCTION

SINCE several decades, significant progress has been made towards understanding the hydrodynamics of gravel-bed rivers. In fact, many studies can be found in the literature about the influence of bed roughness on flow parameters, but comparatively inadequate number of works has been performed in respect of the quality and confidence level of captured data for near-bed turbulence parameters in rough-bed streams. Therefore, decontamination of flow data with spike removing has received a great attention in recent years. Turbulent flow characteristics over spherical elements showed that the streamwise velocity distribution follows a linear profile below the spherical crests [10]. In another experimental study over a bed of angular crushed stones revealed that the Reynolds shear stress (RSS) reaches its maximum at the gravel crests [6]. Many researchers studied the double average (DA) Reynolds shear stress (RSS) of a gravel-bed and examined the pressure energy diffusion below the virtual bed level. They also applied double average methodology (DAM) and found the deviation of velocity distribution within the inertial ranges from logarithmic law [1], [14]. Moreover, many investigations [2], [5], [7], [9], [11]-[13] studied flow characteristics on rough-bed flows and applied the Reynolds

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equation for a steady flow over a rough-bed having zero-pressure gradient to determine total turbulent shear stress in the streamwise direction which can be can be expressed as

$$\mu \frac{du}{dz} + -\rho \overline{u'w'} = \tau_{via} + \tau_{turbulent} = \tau \qquad (1)$$

where, τ = total shear stress, τ_{vis} = viscous shear stress, $\tau_{turbulence}$ = turbulence shear stress, $-\rho\overline{u'w'}$ = Reynolds shear stress (RSS), μ = viscosity of fluid; and z = elevation with respect to the roughness crests. But limited works so far has been taken up to focus filtering the data and nature of velocity fluctuations at lowest bed level which is objective of the present study.

II. EXPERIMENTAL SET-UP

Experiments were conducted in Hydraulic and Water Resources Engineering Laboratory at National Institute of Technology, Agartala, India. An open channel of 14 m long, 0.60 m wide and 0.75 m deep was used for conducting experiments as shown in Fig. 1. Uniformly graded gravels with median diameters, d_{50} = 40 mm was used under uniform flow conditions. The experiment was run for a flow depth of 0.14 m (measured from the mean bed level) and a mean flow velocity of 0.21 m/s with stream wise bed slope of 0.1%. A Vernier point gauge with a precision of ±0.1 mm was used to check the flow depth at different points.

Fig. 1 Flume with gravel bed

S	0.001	Re	29400
h (m)	0.14	F	0.179
B (m)	0.6	u^*(m/s)	0.0306
U (m/s)	0.21	Re*	4284

S = Bed slope, h = flow depth, B = width of the flume, U = depth average velocity of flow, Re = Reynolds number, F = Froude number, u^* = shear velocity and Re* = particle shear Reynolds number. The prime objective of the present study is to focus the significance of despking the ADV data in an extremely rough bed in Low Reynolds number. To create the rough bed, uniform gravels (d_{50} = 40 mm) was used with a flow depth of 14 cm. The shear Reynolds number is well in agreement to describe the bed as hydraulically rough.

III. DATA POST-PROCESSING

Vectrino, manufactured by Nortek was used to capture the instantaneous velocity components. It is a 5 cm down looking high-resolution acoustic velocimeter used to measure the three-dimensional velocity in a wide range. It functioned with an acoustic frequency of 10 MHz and having a sampling rate of 100 Hz. The sampling rate could be magnified up to 200 Hz, but it was observed that the sampling rate of 100 Hz produced least noise in the signals. The sampling volume was cylindrical that had 6 mm diameter and 1–4 mm adjustable height. The acoustic sensor comprises of one transmitting transducer and four receiving transducers. Addition of a fourth receiver improves turbulence measurements and provides redundancy. As the measuring location was 5 cm below the probe, there was no significant influence of the Vectrino probe on the measured data. Vectrino also had provision to adjust transmit length 0.3 to 2.4 mm. In the present study the value of transmit length was adjusted to 0.3 mm near the boundary and 1.8 mm in away-bed flow zone. The effect of increasing transmit length was to increase signal to noise ratio. Reduced transmit length was used near boundary to reduce sampling volume. The processing module performed the digital signal processing required to measure the Doppler shifts. A real-time display of the data in graphical and tabular forms was provided by the data acquisition software. There was no requirement of seeding to the flow during the experiments, as the signal-noise ratio (SNR) was maintained equal to or above 15 due to the existence of ambient particles in the flow. The uncertainty analyses of Vectrino probe were performed for different experiments to test the data accuracy. In all experiments, the signal-to-noise ratio was maintained 15 or above. The signal correlations between transmitted and received pair of pulses were in general greater than 70%, which was the recommended cut-off value. However, on a number of occasions, the signal correlations close to the bed were dropped down by approximately 5% from its recommended cut-off value due to potentially steep velocity gradient within the sampling volume. The data measured by the Vectrino in the near-bed flow zone contained spikes resulting from the interference between incident and reflected pulses. So, the data were filtered by a spike removal algorithm based on the AT method [3]. This method was capable in detecting and replacing spikes in two phases. The threshold values (= 1 – 1.5) for despiking were chosen (by trial and

error) in such a way so that the velocity power spectra provided an acceptable fit with Kolmogorov "–5/3 scaling-law" in the inertial subrange [4]. Figs. 2 (a) & (b) show the typical stream wise velocity fluctuations measured with ADV before and after spike removal.
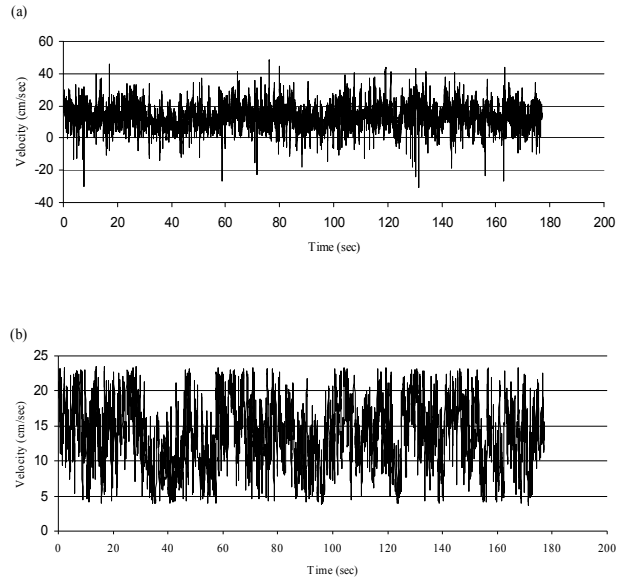

Fig. 2 Vectrino data (a) before spike removal (b) after spike removal

IV. RESULTS AND DISCUSSION

A. Power Spectral Density

Using the discrete fast Fourier transforms, the velocity power spectra $F_{ii}(f)$ were calculated, where f is the frequency. Fig. 3 present $F_{ii}(f)$ at z = 0.005 m before and after spike removal. The power spectra of despiked signals display a satisfactory agreement with Kolmogorov "–5/3 scaling-law" in the inertial subrange of frequency that occurs for frequencies $f > 1$ Hz. These features corroborate the adequacy of the *Vectrino* measurements in clear-water and mobile-bed flows. The power spectra exhibit similar relationships between the velocity components, where $F_{uu} \approx F_{vv} > F_{ww}$. It is however evident that discrete spectral peak was not observed for $f > 0.5$ Hz. It implies that the signals for $f \leq 0.5$ Hz contained large-scale motions; while those for $f > 0.5$ Hz had pure turbulence. The raw measured data were therefore decontaminated by using a high-pass filter with a cut-off frequency of 0.5 Hz, correlation threshold and spike removal algorithm. In this context, it is pertinent to mention that usually a cross-talk between fluid and suspended sediment particles to yield errors of between ±0.05 to 0.8% in time-averaged velocity and ±0.3 to 3.3% in rms of velocity fluctuations measured by a phase Doppler anemometer. As there were no suspended sediments in the present study, the measured data were free from any cross-talk.
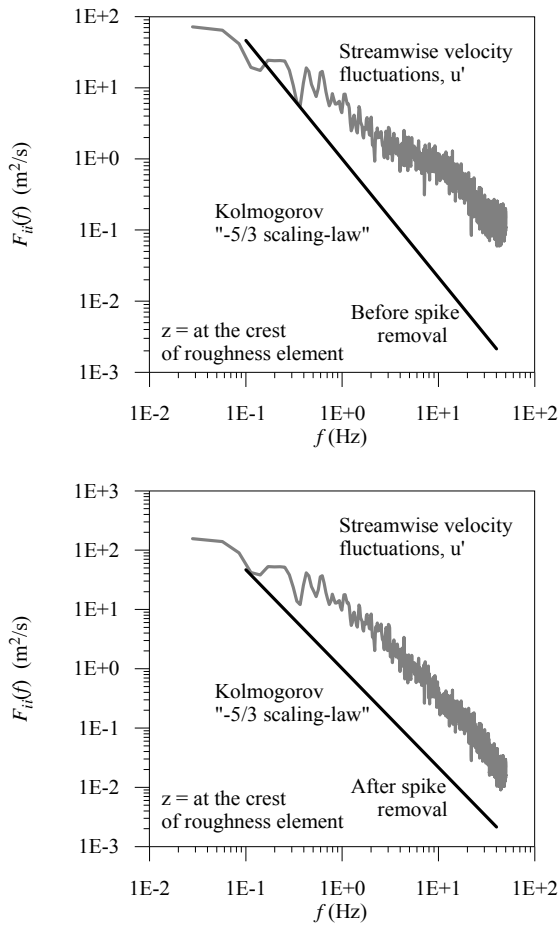
Fig. 3 Spectral of streamwise velocity fluctuations before spike removal and after spike removal

Fig. 4 Velocity power spectra $S_{uu}(k_w)$ and turbulent dissipation rate ε at crest level

In Fig. 4, the spectra $S_{uu}(k_w)$ $[= (0.5\,\overline{u}\,/\pi)F_{uu}(f)]$ as a function of k_w $[= (2\pi/\overline{u}\,)f]$ are drawn using the despiked instantaneous velocity data. The inertial subranges are satisfactorily characterized by Kolmogorov "–5/3 scaling-law". It corresponds to a sub range of k_w where the average value of $k_w^{5/3}S_{uu}$ is relatively constant (that is independent of k_w). Then, ε was estimated from (2):

$$\lambda_T = \left(\frac{15\upsilon\overline{u'u'}}{\varepsilon}\right)^{0.5}$$

(2)

$$\text{and } k_w^{5/3}S_{uu} = C\varepsilon^{2/3}$$

where ε = TKE dissipation rate and can be determined from the Kolmogorov's second hypothesis, k_w = wave number; $S_{uu}(k_w)$ = spectral density function for u'; and C = constant, being approximately 0.5 [7]. A typical spectrum $S_{uu}(k_w)$ $[= (0.5\,\overline{u}\,/\pi)F_{uu}(f)]$ versus k_w $[= (2\pi/\overline{u}\,)f]$ at the crest level by filtering the instantaneous u data is shown in Fig. 4.
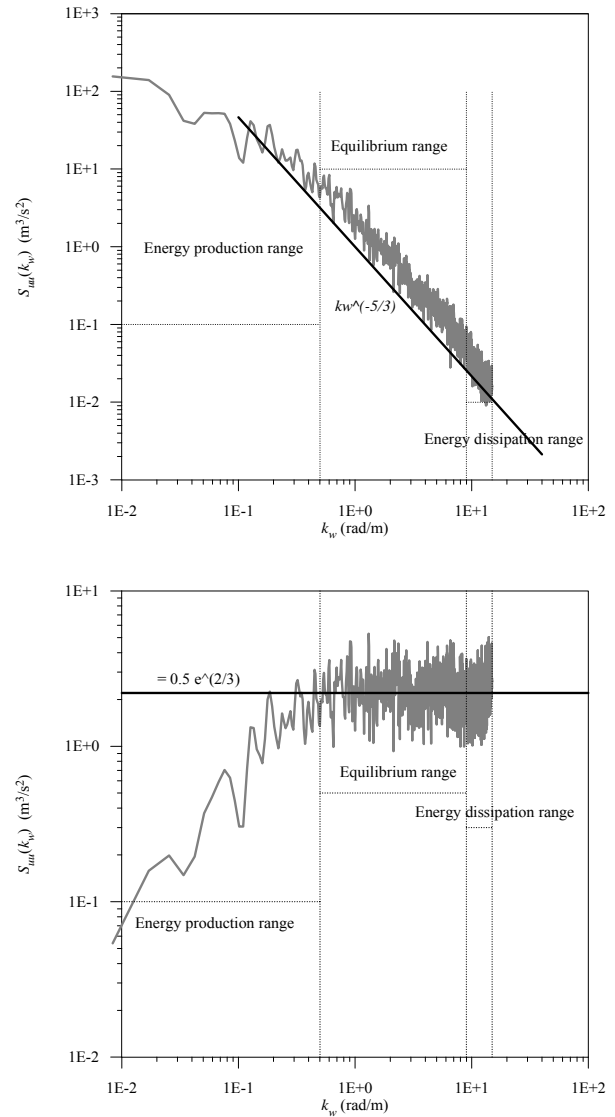
B. Stream-Wise Velocity Distributions

Fig. 5 (a) illustrates the vertical distribution of stream-wise velocity, u with depth z above and below the groove. In the carrier fluid, it is noted that, above the crest where the flow is not influenced by roughness element the profile is logarithmic. Below the crest level and within the groove velocity profile deviated from the logarithmic profile due to the direct influence gravel shape and compactness which necessitated the consideration of roughness geometry functions for examining the velocity profile below the crest. The velocity decreased to zero near the virtual bed level and further to negative values and thereafter increased to zero near the mean bed level. This is evident to the presence of rotational flows below the virtual bed level in the grooves. Fig. 5 (b) shows the vertical profile of the normalized stream-wise velocity $\widetilde{u}$ in the groove. To fit the data plots within the wall-shear layer ($z > 0$)

above the gravel crests to a logarithmic law (log law), $\bar{u}$ and z are scaled by u_* and Δz, respectively, such that $u^+ = \bar{u}/u_*$ and $z^+ = (z + \Delta z)/\Delta z$, where Δz = Nikuradse zero-plane displacement. To plot the experimental data, the log law was considered, as expressed in the following form:

$$u^+ = \frac{1}{\kappa}\ln\left(z^+\right) \tag{3}$$

where κ = Von Karman coefficient. To plot the data $u^+(z^+)$, Δz is taken as $0.25d_{50}$ and κ as 0.41. The value of u_* is obtained from τ_{uw} profile as $u_* = (-(\overline{u'w'}))^{0.5}$. The log law for u^+ within the wall-shear layer above the gravel crests ($z^+ > 1$) is therefore given by:

$$u^+ = 2.439\ln z^+ + 4.325 \tag{4}$$

On the other hand, the profile u^+ within the interfacial sub layer ($z^+ \leq 1$) fairly matches with a third-degree polynomial series given by:

$$u^+ = 2.0367 + 10.343z^+ + 5.3019z^{+2} - 4.3504z^{+3} \tag{5}$$

It is in conformity with [1] that the flows above the gravel crests ($z^+ > 1$) and within the interfacial sub layer ($z^+ \leq 1$) correspond to the log and the polynomial law, respectively.
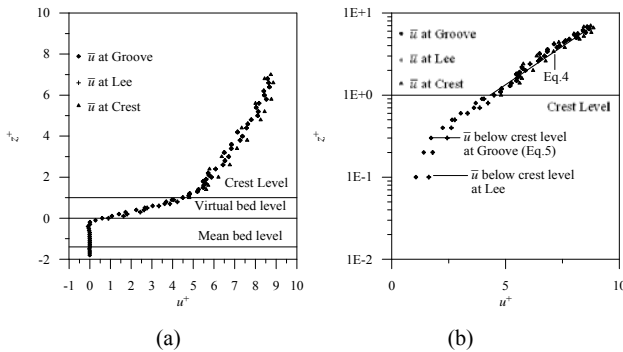

Fig. 5 Vertical distribution of stream-wise velocity, u with depth z above and below the groove

V. CONCLUSIONS

Turbulent characteristics over rough bed were studied. Time averaged stream-wise velocity and velocity power spectral densities after removal of spikes were studied and some important findings are summarized below:

- The velocity distribution in the outer layer was similar to that for flows over hydraulically smooth beds as stated by [8].

- In the region below the crest level the velocity profile deviated from the logarithmic profile due to the direct influence of the roughness elements.
- The velocity decreased to zero near the virtual bed level and further to negative values and thereafter increased to zero near the mean bed level. This is evident to the presence of rotational flows below the virtual bed level in the grooves. The spectral data showed no significant deviations at different horizontal locations. The spectral data was then analyzed at various vertical distances and three clear sub-ranges were identified.

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