



Spatial resolution issues in rough wall turbulence

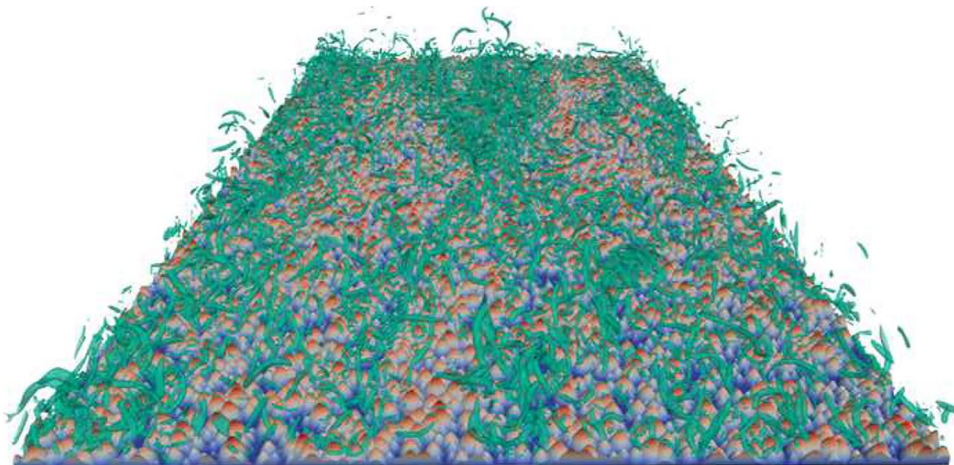
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Abstract

The question whether spatial resolution effects should be accounted for when performing hot-wire (or particle image velocimetry) measurements in turbulent wall-bounded flows over rough surfaces in the fully rough regime is addressed and answered by exploiting an existing direct numerical simulation database of open-channel flows at $Re_\tau = 500$ over a rough surface consisting of randomly distributed roughness elements. The results show sizeable attenuation effects of the streamwise velocity fluctuation intensity, similar to smooth-wall flows with up to 70% for a wire width of around 100 viscous units. A suitable correction scheme is applied to successfully compensate for the spatial resolution effects. Both results indicate that spatial resolution effects are relevant also in fully rough flows and can be corrected *a posteriori* when the state-of-the-art criteria on sensor size cannot be achieved in experiments.

Graphical Abstract



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1 Introduction

Accurate predictions of roughness effects on the hydrodynamic properties of turbulent flows remain one of the most challenging tasks of fluid mechanics research. Existing predictive tools mostly rely on the roughness function ΔU^+ , which describes the roughness-induced momentum deficit in the logarithmic layer of the viscous-scaled mean velocity profile. The equivalent sand-grain roughness height k_s is the standard parameter used to describe a rough surface and can be directly linked to ΔU^+ (Chung et al. 2021). As known from the classical Nikuradse diagram, the ratio between k_s and the boundary layer thickness δ (alternatively channel half height h or pipe radius R , respectively) determines the skin friction coefficient c_f . At sufficiently large Reynolds number Re , c_f approaches a constant value, which only depends on the ratio k_s/δ . This regime of Re -independent c_f is termed as fully rough. Despite k_s being a length scale, it does not describe a property of the rough surface but is rather a property of the turbulent flow, which thus needs to be determined empirically for every rough surface. Therefore, considerable research efforts have been and are devoted to finding a relation between k_s and geometrical surface properties, some of which are reported in the reviews by Jiménez (2004); Flack and Schultz (2010); Chung et al. (2021). In most of these investigations, the evaluation of k_s (or ΔU^+) is carried out under fully rough conditions, such that high Reynolds number flows are required.

Fully rough conditions are typically found for $k_s^+ \gtrsim 70$ (Chung et al. 2021). The viscous scaling, indicated here with the superscript $+$, refers to non-dimensionalization with the friction velocity $u_\tau = \sqrt{\tau_w/\rho}$ and the kinematic viscosity ν , where τ_w and ρ are the average wall-shear stress and the fluid density, respectively. Moreover, the physical roughness scale k has to be sufficiently smaller than δ in order for the log-law to remain of general validity and thus allow to reliably determine ΔU^+ . The suggestions for the required scale separation between δ and k vary in the literature. It should be noted that k is not uniquely defined but can refer to different geometrical properties of the rough surface. The recent review by Chung et al. (2021) states a requirement of $\delta/\bar{k} \geq 10$, where \bar{k} is the average peak-to-trough roughness height.

In consequence, laboratory experiments, just like direct numerical simulations (DNSs), for rough wall-bounded turbulence do not only require relatively high Re flows but also small physical roughness dimensions for an accurate determination of ΔU^+ . This results in spatial resolution challenges. In case of DNS, stricter resolution requirements than classical smooth-wall simulations apply (Schäfer et al. 2022). For experiments, the resolution

of small-scale turbulence poses the challenge which is addressed in the present paper.

2 Spatial resolution effects in smooth-wall flows

The problem of insufficient spatial resolution in hot-wire anemometry is well known and has been covered in classical literature (Bruun 1995) with respect to free-shear flows and in particular isotropic turbulence. Starting from the early works by Johansson and Alfredsson (1983) and Ligrani and Bradshaw (1987), it has been a rule of thumb for wall-bounded turbulent flows to keep the viscous-scaled active wire length l^+ below 20, in order to avoid significant spatial resolution effects on the measurements. Nonetheless, the severeness and implications of spatial resolution effects have long been underestimated causing a number of controversies regarding the Reynolds number scaling of near-wall statistics, e.g., regarding the near-wall peak in the streamwise variance $\langle uu \rangle^+$ profile (Örlü and Alfredsson 2012) or the existence of a second, so-called outer, peak (Alfredsson et al. 2011). Hereinafter, $\langle \cdot \rangle$ denotes averaging along the statistically homogeneous directions and time, while u is the streamwise velocity fluctuation. A seminal contribution in this respect is the work by Hutchins et al. (2009), which resolved some of the questions that were vividly discussed and established guidelines that have since then been followed in order to discern Reynolds number effects from spatial resolution effects.

Following the work by Hutchins et al. (2009), the effect of spatial resolution in hot-wire measurements has been further quantified on various turbulence quantities ranging from variance profiles (Chin et al. 2009; Philip et al. 2013b), through wall-shear stress measurements (Örlü and Schlatter 2020), higher-order moments and probability density functions (Örlü and Alfredsson 2010) to spectral density distributions (Chin et al. 2011) and multi-wire probes (Philip et al. 2013a; Baidya et al. 2019). These studies have established that the small-scale energy is universal, i.e., Reynolds number invariant throughout canonical wall-bounded flows (Marusic et al. 2010). This empirical finding has been exploited in various correction schemes for the variance (Monkewitz et al. 2010; Smits et al. 2011) and spectra (Philip et al. 2013b). Since similar spatial resolution effects have also been observed in particle image velocimetry (PIV) measurements (Shah et al. 2008), analogous correction attempts have also been provided for PIV, where the filtering effect acts in more than one direction (Segalini et al. 2014; Lee et al. 2016).

The aforementioned works have raised awareness that measurements in wall turbulence require either sufficiently small measurement probes (e.g., nanoscale thermal

anemometry probes, cf. Bailey et al. 2010) or large-scale facilities (e.g., the large pipe flow facility at CICLoPE, cf. Örlü et al. 2017) such that the measured small-scale energy in the flow is not attenuated. Whenever this cannot be guaranteed, results require corrections, or at least the comparison between different measurements at matched l^+ , in order not to mix spatial resolution effects with those under investigation, such as Reynolds number (Hutchins et al. 2009) or pressure gradient (Sanmiguel Vila et al. 2020) effects.

Since the effect of spatial resolution has only been well established in smooth-wall, canonical flows, correction schemes have not been applied to non-canonical flow cases, such as boundary layers exposed to pressure gradients or rough wall flows. One reason for this is that most of the aforementioned correction schemes are built on the finding that the small-scale energy in canonical wall-bounded flows is Re -invariant, which cannot be assumed to be directly transferable to other flows, see, e.g., the discussion in Sanmiguel Vila et al. (2020). Hence, most correction schemes are limited to the flow cases and parameter space they are calibrated against, see, e.g., Monkewitz et al. (2010), which is specifically designed for a wide range of parameters in zero-pressure gradient (ZPG) turbulent boundary layers (TBLs) or more general for canonical wall-bounded flows (i.e., pipe, channel and ZPG TBLs) as is the case for Chin et al. (2011); Smits et al. (2011).

The effect of insufficient spatial resolution is here demonstrated in Fig. 1, which shows the variance profile $\langle uu \rangle^+$ of the streamwise velocity fluctuations for a smooth open-channel flow simulated via DNS conducted at friction Reynolds number $Re_\tau = h^+ = 500$, where h is the gap height. Simulation details are given in Stroh et al. (2020), cf. Sect. 3. Following previous works (among others Chin et al. 2009; Segalini et al. 2011; Örlü and Schlatter 2013), the effect of spatial resolution in hot-wire anemometry is also simulated and depicted by spatially filtering the instantaneous velocity fields along the spanwise direction with a physical-space top-hat filter. As apparent, not only the near-wall peak is significantly attenuated but also the entire inner layer of the open-channel flow for longer wire lengths (filtering length $l^+ > 40$). Since most of the aforementioned correction schemes are designed to work for smooth, canonical wall-bounded flows (e.g., Smits et al. 2011), here, we have reconstructed the variance profile by utilizing the method by Segalini et al. (2011), which is not based on the small-scale universality observed in canonical flows, but utilizes a pair of differently attenuated profiles to reconstruct the fully resolved profiles. The results of six reconstructed profiles obtained by combining data with $l^+ = \{10, 21\}$ with data at $l^+ = \{42, 83, 104\}$ are shown in the same figure and agree remarkably well with the fully resolved DNS profile. This method is also

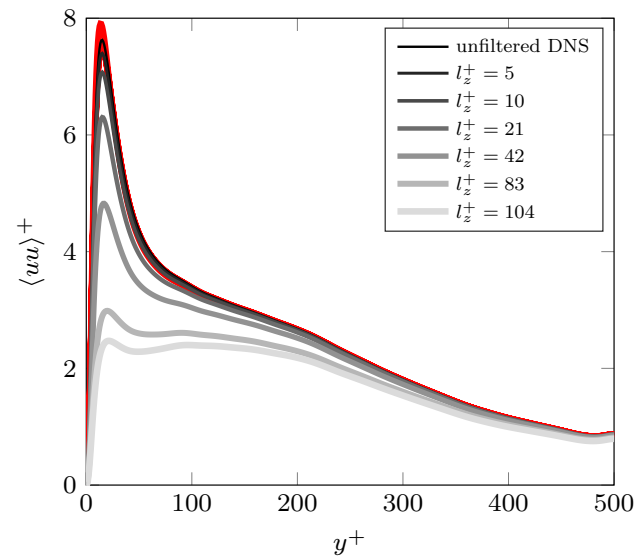


Fig. 1 Variance profiles $\langle uu \rangle^+$ of the streamwise velocity fluctuations for a smooth-wall turbulent open-channel flow at friction Reynolds number $Re_\tau = 500$. The solid lines in different shades of gray refer to different spanwise spatial filtering of the instantaneous velocity data prior to computing $\langle uu \rangle^+$. They range from black for the unfiltered data to the lightest gray for the largest filtering (see legend). The thick red lines are $\langle uu \rangle^+$ -profiles reconstructed with the method by Segalini et al. (2011) from filtered data as described in Sect. 2

extended to higher-order moments in Talamelli et al. 2013.

3 Spatial resolution effects in rough wall flows

While there is a clear understanding of the severity of spatial resolution effects in measurements of canonical smooth-wall flows, there has been little account on spatial resolution effects in rough wall flows so far. To the best authors' knowledge, the works by Shah et al. (2008) and Ghanadi and Djenidi (2021) are the only ones addressing this aspect and show contrasting evidence, prompting the present study. To address this gap in the literature, we are considering a fully rough, open-channel flow at the same friction Reynolds number $Re_\tau = 500$ as the smooth case in Fig. 1. Both numerical databases of the smooth and fully rough open channel have already been presented in Stroh et al. (2020). For the scope of the present manuscript, it is sufficient to recall that the rough surface is generated using the technique proposed by Forooghi et al. (2017), in which several discrete roughness elements are distributed randomly, creating a rough surface with prescribed statistics, which are here as follows: mean elevation $\langle k \rangle / h = 0.043$, maximum peak-to-trough roughness height $k_{\max} / h = 0.10$ (thus $h / \bar{k} > 10$), root-mean-square elevation $k_{\text{rms}} / h = 0.024$, skewness $Sk = 0.079$ and

kurtosis $Ku = 2.24$. The rough surface results in a roughness function of $\Delta U^+ = 7.6$. It was shown by Forooghi et al. (2017) that fully rough conditions can be achieved for surface roughnesses in this parameter range at $Re_\tau = 500$. It should be noted that the friction velocity used for the non-dimensionalization of the rough case properties is evaluated based on the effective wall-shear stress $\tau_{\text{eff}} = -h_{\text{eff}}P_x$, where the effective channel half-height $h_{\text{eff}} = h - \langle k \rangle$ and the imposed streamwise pressure gradient P_x are utilized. While this procedure can be performed in a straightforward manner for a numerical simulation, it may become challenging for an experimental study since a precise measurement of the effective channel height is required.

Applying the same filtering operation as done for the smooth-wall case (Fig. 1) on the rough wall case does yield a significant attenuation of the variance profile as apparent from Fig. 2. It should be noted that the attenuation, depicted in Fig. 3 as function of wall distance, is even more severe than for the smooth-wall case. This observation is qualitatively in agreement with the findings by Shah et al. (2008). In contrast, Ghanadi and Djenidi (2021) reported no attenuation of the streamwise variance with increasing wire length. In addition, Ghanadi and Djenidi (2021) observed that the application of the correction scheme of Smits et al. (2011) to the $\langle uu \rangle^+$ -profiles obtained from spatially filtered velocity data results in a strong over-correction that also produces an artificial near-wall peak for fully rough flows. With our data, we confirm that the correction scheme by Smits et al.

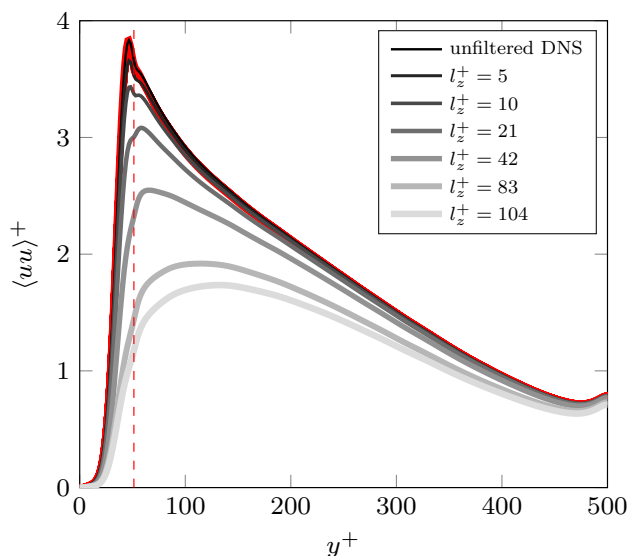


Fig. 2 Variance profiles $\langle uu \rangle^+$ of the streamwise velocity fluctuations for the fully rough turbulent open-channel flow at friction Reynolds number $Re_\tau = 500$ described in Sect. 3. Lines and symbols as in Fig. 1. The additional vertical dashed line shows the maximum roughness peak elevation $k_{\text{max}}^+ = 50$

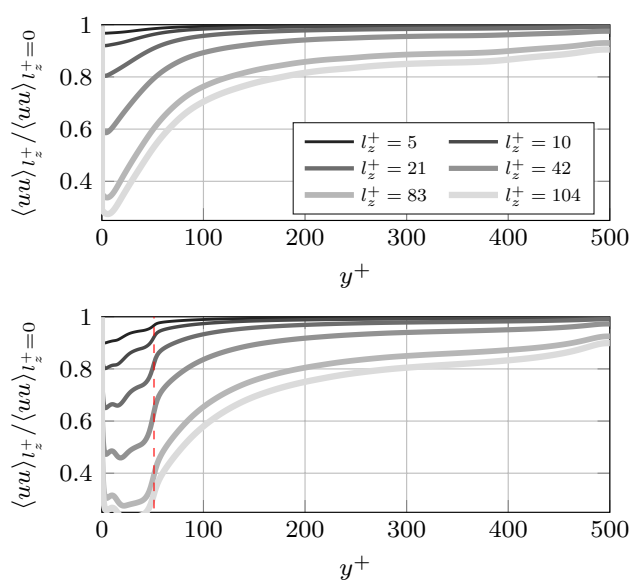


Fig. 3 Attenuation rate of the variance profiles computed as ratio between the filtered $\langle uu \rangle_{l_z^+}$ and unfiltered $\langle uu \rangle_{l_z^+=0}$ variance profile for the smooth-wall (top) and fully rough (bottom) turbulent open-channel flows. The additional vertical dashed line shows the maximum roughness peak elevation $k_{\text{max}}^+ = 50$

(2011) is not able to reconstruct the unfiltered $\langle uu \rangle^+$ -profile when applied to rough wall-bounded turbulent flows. It should, however, be noted that the correction scheme by Smits et al. (2011) was calibrated for canonical, i.e., smooth, wall-bounded flows, and is therefore neither deemed to be applied to rough wall flows, nor to other smooth non-canonical flows. The correction scheme developed by Segalini et al. (2011), on the other hand, is suitable for any turbulent flow and therefore utilized here, despite the fact that it requires two attenuated $\langle uu \rangle^+$ profiles measured with different l^+ . As shown in Fig. 2, the attenuated profiles can be successfully reconstructed to produce the fully resolved DNS results also in fully rough turbulent flows.

As shown in a number of spatial resolution studies (Hutchins et al. 2009; Chin et al. 2009, 2011), spatial resolution is linked to the attenuation of energy related to scales that are smaller/shorter than the sensing element. Turbulent, fully rough, wall-bounded flows still contain a considerable amount of small-scale energy, as shown in Fig. 4; hence, the measured variance profile is still strongly dependent on the wire length.

An interesting observation by Ghanadi and Djenidi (2021) was that their measurements did not show any effect of attenuation when increasing the wire length. The answer to this conundrum could lie in the type of fully rough flow they have considered, namely “a rough wall consisting of [a] series of transverse bar[s] spanning the entire width of the wind tunnel.” At particular locations downstream of

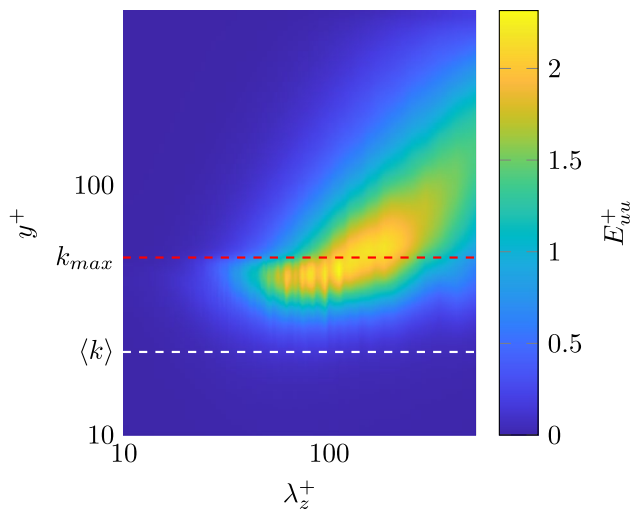


Fig. 4 One-dimensional spectra $E_{uu}^+(k_z)$ of turbulent streamwise velocity fluctuations as function of the spanwise wavelength k_z for the fully rough simulation considered in the present work. The horizontal lines indicate the mean roughness height $\langle k \rangle$ and the roughness tip height k_{max}

a transverse bar such a turbulent flow might exhibit a high degree of spanwise homogeneity even in the instantaneous turbulent flow field, which could explain the missing dependence of the variance profile on l^+ variations. In this context, one has to keep in mind that for a streamwise-periodic surface the position at which the turbulent statistics are measured via the hot wire becomes crucial, since the single-point statistics measured at a particular point may not be representative of the respective wall-parallel averages. Therefore, it might also be interesting to separately investigate the spatial resolution effect on Reynolds and dispersive shear stress contributions in rough wall flows. This is, however, beyond the scope of the present investigation.

4 Conclusion

In the present work, we address the question whether spatial resolution effects should be accounted for when performing hot-wire (or PIV) measurements in turbulent wall-bounded flows over rough surfaces in the fully rough regime. To this aim, we applied spatial filtering to an existing direct numerical database of smooth and fully rough open-channel flows at $Re_\tau = 500$. We observe that if a generic random rough surface is considered, it is not possible to neglect spatial resolution effects. In fact, spatial filtering significantly reduced the intensity $\langle uu \rangle$ of the streamwise turbulent fluctuations with an underestimation ranging between 3% for an equivalent hot-wire length $l^+ = 5$, through 18% for $l^+ = 21$ to sizeable 68% for $l^+ = 104$.

This result is in discrepancy with the evidence presented by Ghanadi and Djenidi (2021) showing no spanwise spatial resolution effects in a turbulent flow over spanwise-aligned square bars. We hypothesize that their result reflects a specific flow property above a “rough” surface with spanwise invariant surface properties. This issue calls for further studies on spatial resolution effects in turbulent flows with non-smooth walls. However, in light of the present result it is clear that no general statement can be made *a priori* on the lack of spatial resolution effects in turbulent flows above rough walls. Therefore, care should always be taken in respecting the current state-of-the-art criteria for the sensor size in experimental investigations, also over rough walls. This note of caution should also be extended to multi-wire (e.g., X and V) probes or PIV measurements. Since PIV spatially averages over the measurement area or volume depending on planar, stereo or volumetric measurements, its filtering effect for the various velocity components behaves rather similar to those encountered in single-wire measurements thereby attenuating the fluctuation levels (Segalini et al. 2014; Lee et al. 2016). The spanwise and wall-normal components measured via X- and V-wire probes on the other hand can result in amplified turbulence intensities contrary to measurements of streamwise velocity (Lee et al. 2016) which are attenuated. Further work is hence needed to extend the present analysis to the other velocity components/correlations in rough wall flows.

We also observe that the suggested relationship between the absence of near-wall, low-speed streaks in the fully rough regime and the lack of spatial resolution effects pointed out by Ghanadi and Djenidi (2021) is worth further discussion, for at least two reasons. On the one hand, the present fully rough results still show some energy content compatible with the presence of near-wall streaks. On the other hand, the small-scale energy content, whether triggered by streaks or by the rough surface itself, is sufficient for inducing spatial resolution effects. This means that the spatial resolution effects are dependent on the rough surface under consideration.

Finally, we report that the *a posteriori* correction developed by Segalini et al. (2011) can adequately compensate for the spatial resolution effects also in turbulent flows over rough walls. This correction would also lead to no artificial over-correction in case of 2D roughness elements as observed for other methods based on the small-scale universality (Ghanadi and Djenidi 2021), since it relies on at least two measured profiles with different l^+ . Hence, if measurements with two different l^+ yielded identical variance profiles, the scheme by Segalini et al. (2014) would not result in any unnecessary correction. In contrast, other correction methods relying upon small-scale universality in canonical flows or designed/calibrated for/in smooth-wall flows, such as the one developed by Smits et al. (2011), do not. This

is not surprising since these schemes were designed to be employed in smooth-wall flows only.

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