Influence of wavy surfaces on coherent structures in a turbulent flow

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Keywords: PIV, Wall bounded flows, Surface roughness effects, Coherent structures

We describe how outer flow turbulence phenomena depend on the interaction with the wall. We investigate coherent structures in turbulent flows over different wavy surfaces and specify the influence of the different surface geometries on the coherent structures. The most important contribution to the turbulent momentum transport is attributed to these structures, therefore this flow configuration is of large engineering interest. In order to achieve a homogeneous and inhomogeneous reference flow situation two different types of surface geometries are considered: (i) three sinusoidal bottom wall profiles with different amplitude-to-wavelength ratios of $\alpha=2a/\Lambda=0.2$ ($\Lambda=30$mm), $\alpha=0.2$ ($\Lambda=15$mm), and $\alpha=0.1$ ($\Lambda=30$mm); and (ii) a profile consisting of two superimposed sinusoidal waves with $\alpha=0.1$ ($\Lambda=30$mm). Measurements are carried out in a wide water channel facility (aspect ratio 12:1). Digital particle image velocimetry (PIV) is performed to examine the spatial variation of the streamwise, spanwise and wall-normal velocity components in three measurement planes. Measurements are performed at a Reynolds number of 11200, defined with the half channel height h and the bulk velocity U_B. We apply the method of snapshots and perform a proper orthogonal decomposition (POD) of the streamwise, spanwise, and wall-normal velocity components to extract the most dominant flow structures. From this orthogonal decomposition of velocity fields we find similar large-scale structures in the vicinity of the complex surface. These large-scale structures are identified as streamwise-oriented, counter-rotating vortices exhibiting a characteristic scale in the spanwise coordinate direction. We quantitatively describe this spanwise scale by applying the proper orthogonal decomposition onto the streamwise velocity component in the (x,z)-plane. We found similar spanwise scales in the order of $\Lambda_z=1.5H$ for the basic wavy surfaces of different amplitude-to-wavelength ratios in the first two eigenmodes. This scale is observed to be slightly smaller for $\alpha=0.2$ ($\Lambda=15$mm) and slightly larger for $\alpha=0.2$ ($\Lambda=30$mm). In addition, the oscillation and the location of the first two streamwise-averaged eigenfunction extrema are nearly identical. This scaling indicates that the size of the largest structures neither depends solely on the solid wave amplitude, nor on the wavelength. For the profile described by the superposition of two sinusoidal waves a spanwise scale of $\Lambda_z=0.85H$ was identified for the first eigenmode. This scaling is not confirmed by the second eigenfunction where a spanwise distance of $\Lambda_z=1.3H$ is observed. The location of the extrema of the second eigenmode is shifted by a spanwise distance of $z/H=0.4$. The eigenvalue spectra from the orthogonal decomposition in the (x,y)- and (x,z)-plane become increasingly broader for the profile with doubled amplitude ($\alpha=0.2$ ($\Lambda=30$mm)), half the wavelength ($\alpha=0.2$ ($\Lambda=15$mm)), and the superimposed waves. Thus by increasing the surface complexity more modes contribute to the energy containing range. We conclude that by increasing the complexity of the bottom surface and thus altering the flow homogeneity from homogeneous in spanwise coordinate direction as for the basic wave profiles to completely inhomogeneous as for the superimposed waves the energy spectrum of the turbulent flow and the number of significant modes is increased. The flow over the superimposed waves can be described as the superposition of dominant eigenmodes with different spanwise scales.
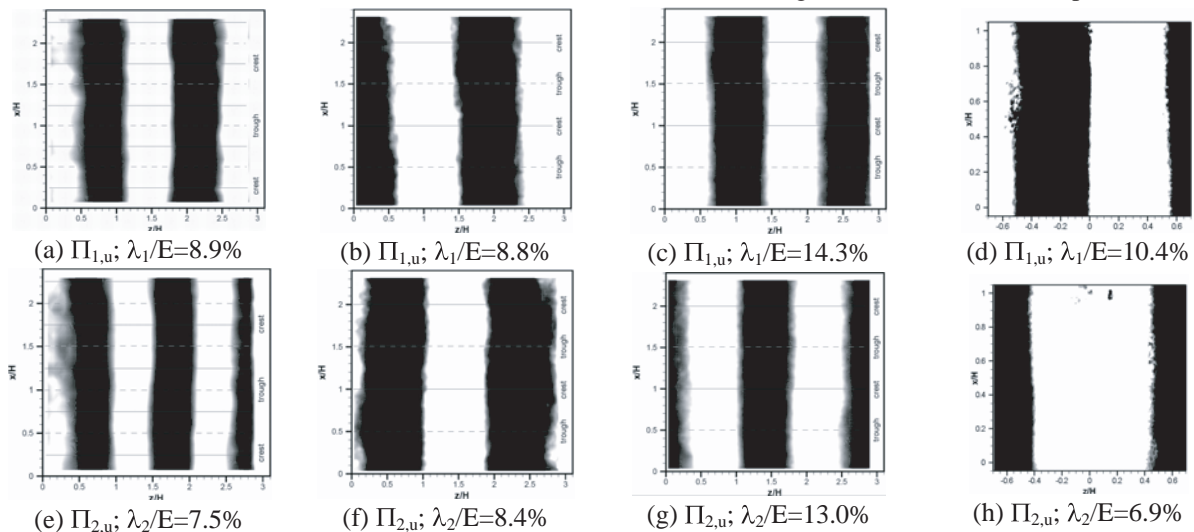

Fig. 1 Comparison of the first two eigenfunctions for a decomposition of $u/U_B(x,y/H=0.26,z,t)$ for $\alpha=0.2$ ($\Lambda=15$mm) (first column), $\alpha=0.2$ ($\Lambda=30$mm) (second column), $\alpha=0.1$ ($\Lambda=30$mm) (third column), and the superimposed waves (fourth column), $Re_h=11200$.