FREE SURFACE BEHAVIOR IN TURBULENT OPEN-CHANNEL FLOWS

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Summary Laboratory experiments were conducted to investigate characteristics of the free surface behavior and its influences on turbulence structures in an open-channel shear flow. The results show that the streamwise spectrum of water surface fluctuations follows the –10/3 power low, and that the surface influence layer is approximately less than 20 percent of the mean water depth and its thickness becomes large as the wavelength of the surface fluctuation increases but small as the Froude number increases.

INTRODUCTION

Understanding the roles of turbulent flows around water surfaces is of increasing importance from the perspective of environmental fluid mechanics because turbulence structures near the surfaces may considerably influence free surface phenomena, such as gas transports, momentum exchanges, self-aeration etc., which are essential to aquatic ecosystems. In this study, laboratory experiments were conducted to investigate characteristics of the free surface behavior and its influences on turbulence structures in an open-channel shear flow. A simultaneous image measurement method was used to measure instantaneous velocity vectors and the corresponding water surface profile in a vertical cross section of the open-channel flow. The proper orthogonal decomposition (POD) was applied to the measurement data of the water surface fluctuations to extract their predominant fluctuation patterns. Then, interactions between the predominant water surface fluctuations and the turbulence structures were examined by calculating their space correlations. Based on the knowledge obtained above, the streamwise spectrum of the water surface fluctuations and the influence range of the free surface were discussed.

EXPERIMENTS

Figure 1 shows instantaneous velocity vectors and the corresponding water surface profile measured by the simultaneous image measurement method proposed by Miyamoto and Kanda [1]. In the measurement method, we utilized images, in the same flame of which both the flow field and the water surface profile were visualized by a laser light sheet, an image extracting technique to detect the location of the water surface, and particle image velocimetry (PIV) to measure the velocity vectors. As for the hydraulic conditions, we kept a Reynolds number Re_* based on the friction velocity a constant (= 500), whereas we changed a Froude number Fr based on the mean bulk velocity and the mean water depth from 0.53 to 1.23 (subcritical to supercritical). In this study, since we can obtain both the velocity vectors and the water surface profile, we investigate the 'free surface – turbulence structures' interactions from the viewpoint of the turbulence from the water surface toward the inside fluid.

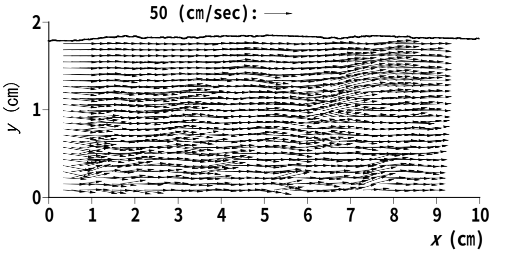

Figure 1 Instantaneous velocity vectors with the corresponding water surface profile (Re_* = 505, Fr = 1.23).

RESULTS AND DISCUSSION

Space correlation structures of predominant water surface fluctuations with turbulence

The POD is applied to the measurement data of the water surface fluctuations to extract their predominant fluctuation patterns. The result of the POD analysis shown in Fig. 2 successfully reveals that most of the principal components are sinusoidal wave shapes. Therefore, the fluctuation distribution of the water surface is almost completely represented by the superposition of the sinusoidal waves. By using the modal amplitudes of the POD eigenvectors, then, we calculate space correlation coefficients between the amplitudes and the velocity fluctuations. Figure 3 shows the contour map of the space correlation coefficients, representing the typical distribution pattern. The result clearly shows that there exists a thin surface influence layer near the water surface in which the turbulent flow seems to be parallel to the wavy surface due to the kinematic

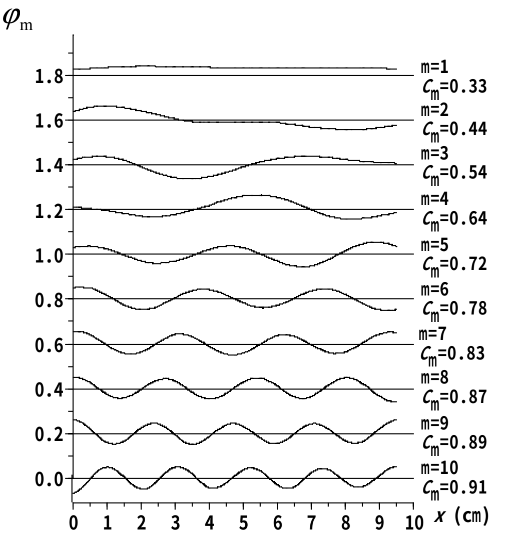

Figure 2 POD eigenvectors of the water surface fluctuations. The vertical axis is modified in 0.2 between two successive modes, m and m+1. Re_* = 505, Fr = 1.23.

boundary condition at the surface, and also that there is the specific interaction between the water surface fluctuations and the large-scale turbulence structures having the same longitudinal scale. The surface influence layer experimentally obtained here is supposed to be almost the same as the blockage layer numerically obtained by Shen et al. [2].

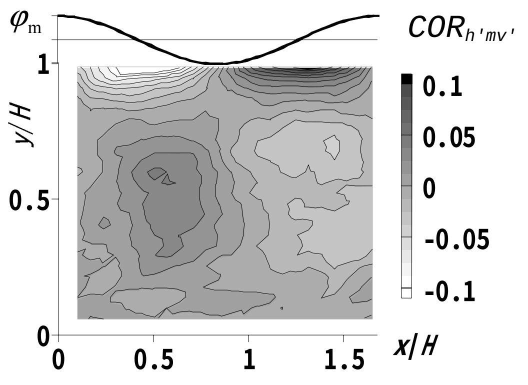

Figure 3 Spatial correlation coefficients of the surface fluctuation component of the eigenvector and the vertical component of the velocity fluctuations. The profile of the corresponding eigenvector is indicated above the contour map. POD mode m = 7, $Re_* = 505$, $Fr = 1.23$.

Streamwise spectrum of water surface fluctuations

The POD analysis in the previous subsection is equivalent to the spectrum analysis since most of the eigenvectors are sinusoidal waves with wavelength L_m. Therefore, the POD contribution ratio c_m corresponds to the value of the spectrum at wave number $k_m = 2\pi/L_m$. From the result in Fig. 3, on the other hand, it is revealed that there is a specific interaction between the surface fluctuation h'_m and the large-scale turbulence structure with the same scale L_m. Thus, if we assume a physical mechanism on which the pressure fluctuation p'_{Lm} due to the large scale turbulence u'_{Lm} with L_m makes the surface fluctuation h'_m with the same scale L_m, we can conjecture that in the Fourier space the $\rho\, u'^{2}_{Lm} \sim p'_{Lm} \sim \rho\, g\, h'_m$ have the same slope in the spectral distributions. Consequently, when the spectrum of u'_{Lm} follows the well known –5/3 power low, the streamwise spectrum of h', which is equivalent to c_m in this study, follows the –10/3 power low. Figure 4 shows the streamwise spectrum of h' obtained through the above consideration. It is evident that there exists a range which follows the –10/3 power low in each case and that the range of the –10/3 power low becomes large as the Froude number Fr increases.

Influence range of water surface

From the distribution of the space correlation coefficients in Fig. 3, we evaluate the range of the surface influence layer by defining a vertical scale measure of the layer δ_m. The result shown in Fig. 5 indicates that the surface influence layer is approximately less than 20 percent of the mean water depth H and its thickness δ_m became large as the wavelength of the surface fluctuation L_m increases but small as the Froude number Fr increases.

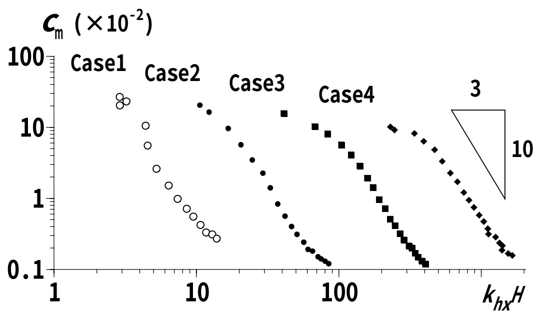

Figure 4 Streamwise spectrum of the water surface fluctuation. The values in horizontal axis are modified by multiplying 5, 5^2, 5^3 in Case2, 3, 4, respectively. Fr = 0.54, 0.64, 0.85, 1.23 in Case1,2,3,4, respectively.

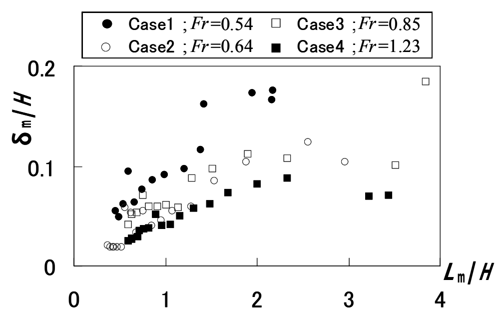

Figure 5 Relationship between the thickness of the surface influence layer and the wavelength of the surface fluctuation. $Re_* = 505$, $Fr = 0.54 – 1.23$.

CONCLUSIONS

The main conclusions obtained in this study are as follows. (1) There is a layer near the water surface where the turbulence is strongly affected by the water surface fluctuations. In the surface influence layer, the turbulent flow seems to become parallel to the wavy surface. (2) There is a specific interaction between the surface fluctuation and the large-scale turbulence structure having the same streamwise scale. (3) The streamwise spectrum of water surface fluctuations follows the –10/3 power low. (4) The surface influence layer is approximately less than 20 percent of the mean water depth and its thickness became large as the wavelength of the surface fluctuation increases but small as the Froude number increases.

References

[1] Miyamoto, H. and Kanda, T.: Simultaneous image measurements of velocity field and water-surface wave in open-channel flows, *Proc. Hydraulic Measurement & Experimental Methods Conference 2002*, ASCE, Colorado, 2002.

[2] Shen, L., et al.: The surface layer for free-surface turbulent flow, *J. Fluid Mech.* **386**:167-212, 1999.