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Research paper

PIV and PTV measurements in hydro-sciences with focus on turbulent open-channel flows

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Abstract

PIV is one of the most popular measurement techniques in hydraulic engineering as well as in fluid sciences. It has been applied to study various turbulent phenomena in laboratory experiments related to natural rivers, e.g., bursting phenomena near the bed, mixing layers observed at confluences, wake turbulence around dikes and piers, and so on. In these studies, PIV plays important roles in revealing the space-time structure of velocity fluctuations and coherent vortices. This review article focuses particularly on the applications of PIV to turbulent open-channel flows, which have been conducted for the past decade in Hydraulics Laboratory of Kyoto University. In Section 2, we introduce our experimental setup and PIV/PTV algorithm. In Section 3, we apply the PIV measurements to reveal turbulence characteristics and coherent structures in open-channel flows as well as in vegetated canopy flows. For complex flow situations, various applications of PIV to compound open-channel flows and wind-induced water waves are considered to reveal coherent vortices. In Section 4, we discuss some advanced PIV measurements in open-channel flows. The free-surface-elevation fluctuations and velocity components were measured simultaneously with two sets of cameras to examine phase-averaged parameters of turbulence. A multi-layer scanning PIV was developed to reveal 3D turbulence structure in compound open-channel flows. Our discriminator PIV/PTV was applied successfully to sediment-laden open-channel flows and revealed the fluid/particle interaction and the relationship between coherent structures and sediment concentration. Finally, we conducted simultaneous measurements of velocity and dye concentration with a combination of PIV and LIF in vegetated open-channel flow, which enables us to examine turbulent scalar flux of a passive contaminant.

Keywords: PIV Measurements; Open-channel flow; Turbulence; Coherent structure

1. Introduction

Flow visualizations have been extensively conducted to investigate fluid motion, vortex patterns and turbulence in the fields of fluid dynamics, aeronautical mechanics and hydraulic engineering. The development of various useful methods has enabled us to conduct quantitative flow visualizations, in which fluid motion was evaluated by examining temporal variations of dye clouds, hydrogen bubbles and tracer particles. In PIV measurements of turbulent flows, seeding particles such as polystyrene (specific density is 1.02) have been used in water, together with a laser light sheet (LLS).

Two kinds of methods have been developed to obtain velocity vectors from the sequential digital images, i.e., one is the individual particle tracking and the other is the statistical cross-correlation of sequential narrow-window images. The former is called "particle-tracking velocimetry (PTV)" and the latter "particle-image velocimetry (PIV)". Various schemes for PTV are proposed to obtain velocity distributions. It is, however, very difficult to identify particle pairs in highly concentrated particle images, and thus PTV has been limited to low-concentration particle-laden flows. This implies that the number of velocity vectors obtained in space is comparatively small in PTV measurements. In contrast, PIV follows some patterns of

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particles by using a cross-correlation function between a pair of digital images in a narrow interrogation window.

PIV provides the velocity vectors of tracer particles illuminated by planar laser light. With the advent of powerful laser light sources, high-capacity computers and digital cameras, PIV instruments and the associated data processing techniques have progressed intensively. For example, Adrian (1991) has written a comprehensive review article about PIV techniques.

One of the most significant advantages of flow-visualization techniques such as PIV/PTV is that they are non-intrusive and thus do not disturb the flow at all unlike probe measurements. Nowadays, PIV techniques have spread widely and the advanced applications are conducted in various types of complex flows although each technique may be different in many fundamental and applied research fields including fluid engineering, medical science and industry flows, e.g., see Raffel et al. (2007) and Schroeder and Willert (2008). PIV has also become one of the most popular measurement techniques in hydro-sciences, and been applied to various flow fields related to rivers and ocean systems, such as open-channel flows, mixing layers, wakes around obstacles and so on. In these studies, PIV plays a vital role in revealing the space-time structure of velocity fluctuations and coherent vortices.

Although it was difficult for earlier PIV to capture high-speed near-wall flows, the development of double-pulse lasers and high-speed cameras has enabled us to measure turbulence structure and coherent vortices in both the inner and outer layers. Adrian et al. (2000) conducted PIV measurements of turbulent boundary layers, and found that the coherent structure is likely to be composed of vortex packets, in which several hairpin vortices are aligned in the streamwise direction. They divided the boundary layer into three sub-zone with approximately uniform momentum, and revealed that the normalized thickness of the three sub-zones depended on the Reynolds number, whereas the mean velocity of each sub-zone was almost independent of the Reynolds number. Later, Tomkins and Adrian (2003) conducted PIV measurements of horizontal planes at several heights in the buffer layer and the log-law layer to make three-dimensional (3D) examinations of boundary-layer structure. Their study supported the vortex packet model proposed by Adrian et al. (2000). Hurther et al. (2007) recognized that these coherent structures are also observed in the outer layers of open-channel flows. In the same manner, Sanjou and Nezu (2010) examined the effects of water waves on hairpin-vortex generation and decay processes using PIV measurements and Adrian et al. (2000)'s method.

It is well known that large-scale circulations and wake vortices such as the Karman vortex contribute significantly to hydrodynamic structures around dikes, aquatic vegetation, bridge piers and side cavities. For example, Kadota et al. (2007) conducted PTV measurements of flows around emergent tandem cylinders and captured both small- and large-scale vortex patterns. Further, one of PIV advantages is the comparatively easy extension to the large-scale fluid field in nature. Examples of this type include the visualization techniques for free-surface flow in rivers. Fujita et al. (1998) dubbed the "LSPIV" (large-scale PIV) as the most of measurements were taken over surfaces much larger than those in laboratory PIV. Further, Fujita et al. (2009) stressed an importance of LSPIV in river flow information.

Compound open-channel flows consist of two-stage channels, i.e., the main-channel and floodplains, as often observed in rivers during floods. Coherent horizontal vortices appear near the junction, and promote the transverse exchanges of mass and momentum between the main-channel and floodplains. A horizontal vortex was first visualized by Sellin (1964) using the aluminum-powder method. Later, Nezu et al. (1999b) found from PIV measurements that a twin-vortex structure, which consists of counter-rotating vortex pairs, appeared as the water depth reached 1.5 times the floodplain height. Meandering compound open-channel flow is also an area of high interest in river engineering. Sanjou and Nezu (2009) have developed a multi-layer scanning PIV system to reveal such complex flow structure. They found that significant secondary currents and horizontal vortices were generated due to an interaction between meandering inbank main-channel flow and straight overbank floodplain flow.

The other advantage of PIV is a possibility of simultaneous measurements between velocity components and scalar variables such as dissolved gas concentration and dye concentration. For example, Herlina and Jirka (2008) have successfully conducted simultaneous measurements of velocity and dissolved oxygen (DO) concentration using a combination between PIV and laser-induced fluorescence (LIF) near the air–water interface induced by oscillating grid turbulence. On the other hand, Okamoto et al. (2010) have conducted simultaneous measurements of velocity and dye concentration using a combination between PIV and LIF in vegetated canopy open-channel flow. Such an LIF provides a non-intrusive method of high-resolution measurements of mass concentration in water flows.

According to our experiences of PIV/PTV measurements, the present review article focuses on the application of PIV/PTV to turbulent open-channel flows, which have been conducted for the past decade in Hydraulics Laboratory of Kyoto University. In Section 2, we introduce our experimental setup and PIV/PTV algorithm. In particular, a discrimination method between fluid and sediment particles is proposed and discussed. In Section 3, we apply the PIV measurements to reveal turbulence characteristics and coherent structures over smooth and rough (vegetation) beds in open-channel flows. For complex flow situations, various applications of PIV to compound open-channel flows and wind-induced water waves are treated and discussed to reveal coherent vortices.

In Section 4, we discuss some advanced PIV measurements in open-channel flows. The free-surface-elevation fluctuations and velocity components are measured simultaneously with two sets of cameras to examine phase-averaged parameters of turbulence. Three-dimensional (3D) PIV is one of the most innovative techniques to be developed in the fluid measurement community, e.g., see recent review articles by Scarano (2010) and Ruck (2011). We have developed a multi-layer scanning PIV and applied it to compound open-channel flows. Our discriminator PIV/PTV was applied successfully to sediment-laden open-channel flows and revealed a fluid/