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Application of PIV in the Flow Field Over a Fixed Dune Bed

by
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언덕이 있는 하상유동 계측을 통한 PIV기법의 수력학적 적용연구

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Abstract

The assessment of PIV to measure the mean velocity and turbulence was carried out over a train of fixed two-dimensional dunes. The agreement between the PIV and LDV is good enough even in regions of flow reversals and high shear. Though limited in the wall normal direction field-of-view, PIV provides instantaneous flow fields, which reveal the complex nature of flow over dunes, as well as more sophisticated analyses such as two-point space correlation and quadrant analysis with a reasonable accuracy. The present study is expected to be directly applied to more complex flow such as sediment transport.

요 약

반복적으로 나타나는 고정된 이차원 모래언덕에 의하여 생성되는 난류유동장을 해석하기 위하여 PIV 기법을 적용하였다. PIV 기법의 사정을 위하여 LDV 실험자료와 결과를 비교하였는데 유동박리 및 큰 전단유동 영역에 까지 좋은 결과를 보여주었다. 레이저 시트로 조사된 이차원 단면의 흐름을 이미징 테크닉으로 해석하는 PIV 방법이 갖는 고유의 단점들을 완전히 해결하지는 못하였으나, 전체적으로 LDV 결과와 매우 잘 일치하고 있었으며 특히 Two-point correlation 이나 Quadrant analysis와 같이 고차항까지를 추적할 수 있었다. 특히 기존의 일점계측법으로는 해석이 불가능한 순간유동장의 가시화 및 정량화가 가능하였으며 Time-series로 변환시킨 PIV 데이터의 신뢰성도 확인이 가능하였다. 추후 토사이동과 같은 복잡한 유동해석에도 본 기법을 그대로 활용할 수 있으리라 기대한다.

Keywords: PIV(입자영상유속계), Dune Bed(하상언덕), Turbulence(난류), LDV(레이저유속계).

1. INTRODUCTION

Particle image velocimetry(PIV) and Laser Doppler velocimetry(LDV) are now recognized as well established non-intrusive techniques for fluid velocity measurement. Since the first use of the LDV over three decades ago, LDV has now been used to make velocity

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measurements in a variety of complex flow fields and comprehensive descriptions of typical systems can be found in Goldstein [1996]. The ability of PIV to yield whole-field information will ensure its wide spread usage to extend further. One can obtain an indication of its usage and development from Adrian [1996], while PIV techniques are well described by Raffel et al.[1998]. As demonstrated in several recent studies, PIV provides a detailed and instantaneous flow field in complex flows (Cenedese et al.[1994]; Nakagawa & Hanratty[2001]). An important aspect of the PIV is its ability to evaluate spatial correlations (Nezu & Onitsuka[2001]). To some extent, the PIV still suffers limitations in the dynamic range of velocity measurement though significant improvements have been made (Adrian[1997]). Moreover, limitations on the quality of data are placed by the seed particle size, image quality and size, camera frame rate, processing software, etc.

A few researchers have used LDV and PIV jointly, but the assessment of relative merits and demerits are rather limited. Details of literature survey are available elsewhere (Hyun et al.[2002]). The present paper describes a comprehensive and quantitative assessment of PIV to measure mean velocity and turbulence in water flow. Analysis of the data is carried out using the LDV and the PIV measurements to demonstrate the relative usefulness of the two techniques.

2. EXPERIMENTAL SET-UP AND PROCEDURE

In order to study the relative performance of LDV and PIV to measure the mean velocities and the Reynolds stresses, the flow over a train of two-dimensional dunes attached to the bottom of a laboratory open channel flume was chosen. Fig. 1 shows a schematic of the various regions of the flow field and the coordinate system adopted in the present study.

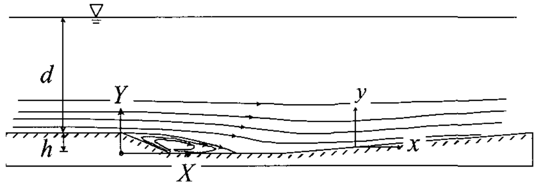

Fig. 1 Coordinates and schematic of flow field.

The flow field was generated in a rectangular cross-section (610 mm × 610 mm), 10-m long, recirculating open channel flume at IIHR-Hydroscience and Engineering facilities. A train of two-dimensional fixed dunes was attached to the bottom of the channel starting near the entrance to the flume and extending throughout the length of the flume. The shape of the dunes was geometrically similar to that used in earlier studies (Mierlo & Ruiter[1988]). LDV and PIV measurements were carried out in the flow between the 17th and the 18th dunes. The flow was also ensured to be periodic,. The Reynolds number based on the dune height ($Re = U_0h/v$) was 1.0×10^4. Here, U_0 is the maximum velocity, which occurs near the free surface.

A two-component filer optic LDA system was used to conduct the velocity measurements. A 2-W Ar-Ion Laser powers the LDA system. The flow was then seeded with 5 mm TiO2 particles. At each measurement location, a sample size of 15,000 validated samples was chosen. The uncertainty in the mean velocities (U and V) and turbulence intensities (u and v) was 1.5 % or less. The uncertainty in the Reynolds shear stress (uv) was 7 %.

A 5W Ar-Ion laser was used to power the PIV system. A system of mirrors and lenses were used to generate a 3-mm thick vertical light sheet at the measuring section. The Plexiglas dunes facilitated the transmission of light from below to illuminate the flow field.

After carefully filtering the water through a 5 mm filter bank, vinyl chloride polymer particles (specific gravity = 1.02 and mean diameter 30 micron) were introduced in the flow. The field-of-view was imaged with 640 × 480 pixel CCD camera. An acousto-optic modulator (AOM) was used to enhance the dynamic range of velocity tracking. The camera field-of-view was adjusted to yield images 120 mm × 80 mm in size. The time interval between two images was 1/200 sec and the exposure time was 1/450 sec. A commercial software (Thinkers Eyes 2-D) was used to perform the image analysis using a gray-level cross-correlation technique. Using an interrogation area of 20 × 20 pixels, the correlation peak is evaluated in a search area formed by a circle of radius equal to 17 pixels. To enhance the accuracy, a sub-pixel resolution method (Utami and Blackwelder [1991]) was adopted. Furthermore, an error vector elimination method (Hojo and Takashima[1995]) based on the continuous flow condition was adopted. A total of 1000 frames were used to compute the mean and turbulence quantities. The uncertainty in estimating the instantaneous velocity vectors is about 4 %. Details of the PIV system are available elsewhere (Hyun et al.[2002]).

3. RESULTS AND DISCUSSION

One of the advantages of the PIV technique is its capability to provide instantaneous flow field information. Fig. 2 shows a set of successive instantaneous flow fields. This figure serves to illustrate the usefulness of PIV in resolving complex flow regions. At time t = to, one can notice the formation of vortex below the separating streamline. As seen in the successive sketches, this vortex grows larger and is also simultaneously transported in the streamwise direction with a convection velocity, which is about 40% of U_o. One can notice the presence of strong ejection and sweep-type events that can have important implications in the transport of sediments. It is important to recognize that a fairly simple PIV system is capable of providing information in addition to that provided by complex LDV systems.

Fig. 3 shows the typical example of process mean velocity vectors and vorticity contours. High degree of vorticity is well concentrated just after separation point and developed through the limiting streamline, which clearly demonstrated the region of high velocity gradient.

Fig. 4 shows the mean velocity and turbulence profiles in the vicinity of the

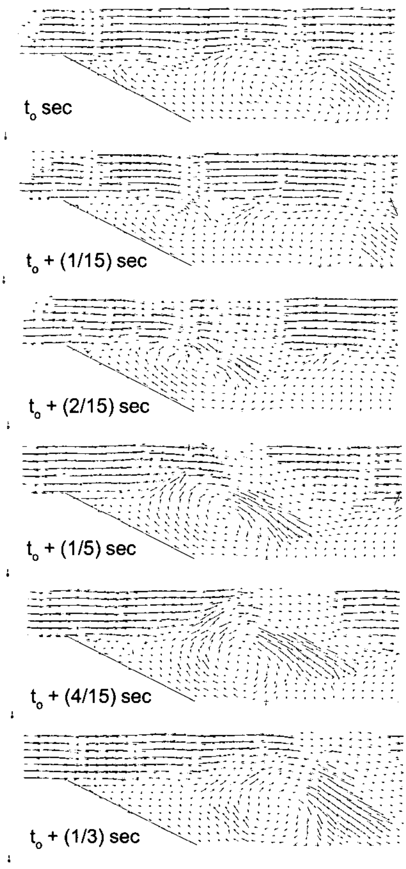

Fig. 2 Instantaneous velocity vectors.

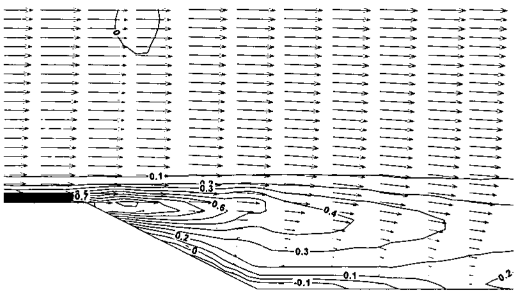

Fig. 3 Sample outputs of time-averaged flow field obtained by PIV.

reattachment region (x/h = 4) and serves to provide a typical assessment of the two measuring techniques. In the PIV measurements, due to limitations in the quality of the light sheet, the field-of-view in the wall normal direction is limited to y/d = 0.5. The LDV and PIV profiles show excellent agreement. Similar comparisons were made at other locations and details are available elsewhere (Hyun et al.[2002]). It should be remarked that even in regions of high shear and in regions where flow reversals are encountered, reasonable agreement could be found. Previously, disagreements have been noted between LDV and PIV profiles in such regions (Cenedese et al.[1994]).

Both LDV and PIV are capable of deciphering the important flow features. For example, the peak in the u profiles at y/d = 0.1 is due to the presence of the separating shear layer that is shed from the dune crest. Further, one can also notice a second peak away from the wall region (y/d ~ 0.35). This is remnant of the turbulence carried over from the shear layer shed from the previous dune. It should be noted that the absence of LDV data for v′ and u′v′ at y/d<0.12 was due to the difficulty of aligning laser beam near the dune surface in vertical directio.

To further explore the relative capabilities of LDV and PIV measurements, one can perform the more sophisticated data processing including two-point space-time correlation and quadrant analysis. Before doing these, PIV data should be transformed into the time series data at each field point. Fig. 5 shows some examples. Fig. 6 then demonstrates the typical results obtained by two-point space correlation, which show the extent of space correlation with a reference point near the

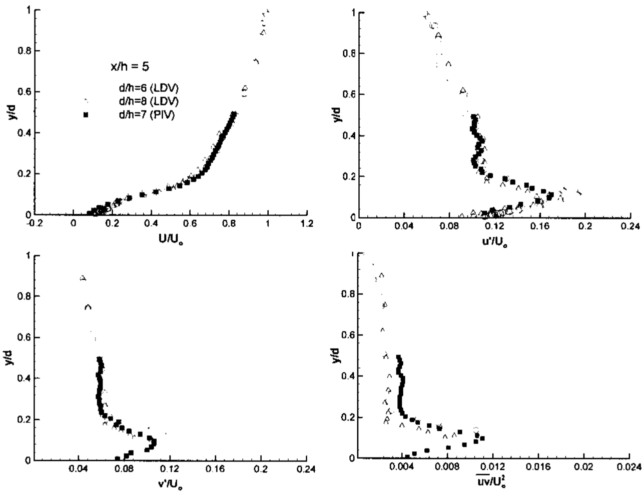

Fig. 4 Comparison of mean and turbulence between PIV and LDV.

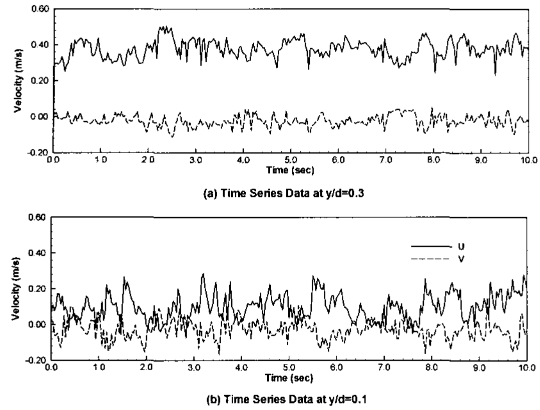

Fig. 5 Typical time-series data converted from PIV data.

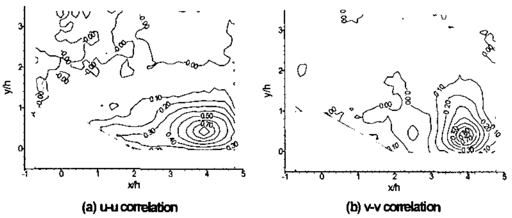

Fig. 6 Examples of two-point correlations for U-U and V-V.

reattachment point. This information is very useful to determine the various length scale of turbulence.

A quadrant analysis was carried out using the method suggested by Lu and Willmarth [1973]. Fig. 7 show examples of fluctuating velocities uv both outside and inside recirculating region.

To detect extreme events (large contributions), a detector indicator function, li(t) was defined such that:

$$\lambda_i(t) = \begin{cases} 1 & \text{when } |uv|_i \geq H\,(u)\,(v) \\ 0 & \text{otherwise} \end{cases}$$

Here, i denotes the quadrant of interest. The contribution to <uv> from a particular

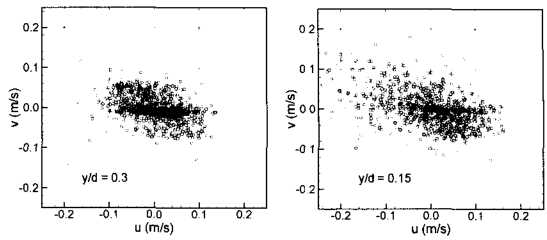

Fig. 7 Sample outputs of fluctuating velocities u'v'.

quadrant may then be written as:

$$\langle uv \rangle_i = \lim_{T\to\infty} \frac{1}{T} \int_0^T uv\ \lambda_i(t)\, dt$$

In this paper, results are presented for H = 2.0, which corresponds to events which are associated with (u)(v) > 5.5 <uv>. The fractional contributions by each one of the quadrants is shown in Fig. 8 for X/h = 4. Once again, the results of the two techniques compare very favorably. It is important to note that PIV is capable of providing information in the near-wall region (y/d < 0.1) while LDV provides information for y/d > 0.5. The quadrant-two events (ejections) make a larger contribution to the shear stress through most of the depth and indicate a peak in the region of the shear layer. The second peak in the quadrant-four (sweep events) profile occurs at a wall normal location that corresponds to a local minimum in the ejection event.

4. CONCLUSIONS

The assessment of LDV and PIV to measure the mean velocity and turbulence in a complex flow field indicates a very good agreement in the mean and turbulence profiles. The agreement is reasonable even in regions of flow reversals and high shear. In addition, PIV provides instantaneous flow fields, which

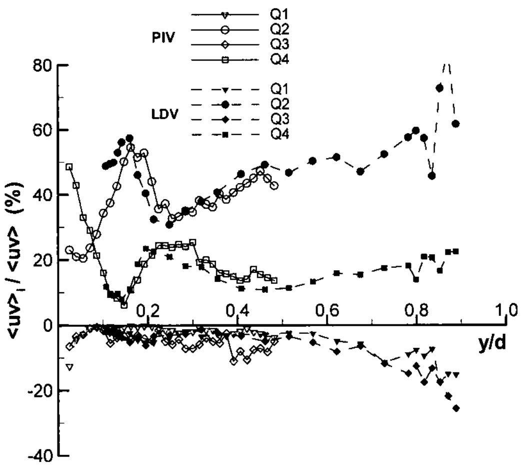

Fig. 8 Quadrant analysis for X/h=4.

reveal the complex nature of flow over dunes.

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