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Correlation analysis of spatio-temporal images for estimating two-dimensional flow velocity field in a rotating flow condition

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SUMMARY

Flow velocity estimation in actual rivers using image processing technique has been highlighted for hydrometric communities in the last decades, and this technique is called Large Scale Particle Image Velocimetry (LSPIV). Although LSPIV has been successfully tested in many flow conditions, it has addressed several limitations estimating mean flow field because of difficult flow conditions such as rotating, lack of light and seeds, and noisy flow conditions. Recently, an alternative technique named STIV to use spatio-temporal images based on successively recorded images has been introduced to overcome the limitations of LSPIV. The STIV was successfully applied to obtain one-dimensional flow component in the river for estimating streamflow discharge, where the main flow direction is known. Using the 5th order of central difference scheme, the STIV directly calculated the mean angle of slopes which appeared as strips in the spatio-temporal images and has been proved to be more reliable and efficient for the discharge estimation as compared with the conventional LSPIV. However, yet it has not been sufficiently qualified to derive two-dimensional flow field in the complex flow, such as rotating or locally unsteady flow conditions. We deemed that it was because the strips in the given spatio-temporal images from not properly oriented for main flow direction are not narrow enough or clearly visible, thus the direct estimating strip slope could give erroneous results. Thereby, the STIV has been mainly applied for obtaining one-dimensional flow component. In this regard, we proposed an alternative algorithm to estimate the mean slope angle for enhancing the capability of the STIV, which used correlation coefficient between odd and even image splits from the given spatio-temporal image. This method was named CASTI (Correlation Analysis of Spatio-Temporal Image). This paper described the step-by-step procedure of the CASTI and validated its capability for estimating two-dimensional flow field in the rotating flow. For this purpose, we generated artificial images for lid-driven cavity flow where true velocity field can be manipulated and validated with respect to the proposed CASTI algorithm. As a result, the CASTI was successfully performed to capture two-dimensional velocity vector in the given cavity flow.

1. Introduction

River discharge measurements during the flood event are crucial to build reliable a stage-discharge relationship, but have usually brought in various issues such as confronting unsafe field conditions and accuracy of the measurements due to lack of proper observation techniques. For instance, a float has been widely used to estimate mean flood velocity since it is cheap and easy in terms of field operation. However, the limitations of the float are well known such that the peak discharge can be missed by its sporadic measurement interval, thus continuous observation is nearly impossible. Recently, ADCPs have become a promising field instrument to precisely measure flow discharge, but they also have shown that it was very difficult to operate in the high flow conditions such as flood event, where its discharge estimates were not mostly reliable without proper quality control due to high turbulence, aeration, and bed movements.

As alternative ways of measuring flood discharge or velocity field, non-intrusive surface flow velocity measurement techniques have been considered for such high flow regimes. Among those techniques, Doppler radars and image-based method have been highlighted to measure free surface velocities. Doppler radars

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utilized Doppler shift between transformed and received electromagnetic waves to estimate surface flow velocity (Costa et al., 2006). Image-based method makes use of flow pattern recognition technique from consecutively recorded images, assuming that the surface flow patterns are continuously sustained by the flow velocity. In this paper, the image-based method was mainly handled. Historically, in the mid-1999s, the established indoor PIV technique (Adrian, 1991; Raffel et al., 2007) began to be applied to natural-scale river flows by Japanese researchers (Fujita and Komura, 1994; Aya et al., 1995; Fujita et al., 1997), and it became labeled as large scale particle image velocimetry (LSPIV). The LSPIV fundamentally differed from the conventional PIV in terms that it measures river surface velocity field using natural light, and usually requires ground reference points for the image ortho-rectification in order to deal with oblique angle of image. Afterward, such LSPIV has been successfully applied to measure flood discharge in various specified field conditions (Ettema et al., 1997; Fujita et al., 1998; Fujita and Hino, 2003; Creutin et al., 2003; Muste et al., 2005, 2008, 2011; Hauet et al., 2008; Jodeau et al., 2008; Le Coz et al., 2010; Dramais et al., 2011; Tsubaki et al., 2011; Kantoush et al., 2011; Kim et al., 2011). Up to now, however, the LSPIV still has substantially undergone continuous modification to properly handle a variety of more difficult field conditions such as illumination, lack of surface particle, insufficient light during night time, and measurement uncertainty (Kim, 2006; Kim et al., 2011; Muste et al., 2005, 2008; Hauet et al., 2008). Driven by such limitations, the LSPIV method has not been widely accepted by national agencies to measure stream flow. In addition, beyond the well-controlled high-end commercial video camcorder, the LSPIV recently began to be applied for more diverse measuring platforms such as CCTV, smart phones, and Airborne camera which usually provides unstable and mostly low quality images, thereby not easily processable by using conventional LSPIV algorithms (Fujita and Kunita, 2011). Therefore, there has been strong anticipation to enhance currently available LSPIV methodology to more reliably measure stream flow irrespective of difficult flow conditions as well as suitable for advances in the measuring platforms.

Before introducing a newly proposed algorithm in the present study, it would be meaningful to briefly address representative limitations and issues triggered by the conventional LSPIV method in more details, since they are good starting points to new developments. First, most of the embedded algorithms of the LSPIV have utilized finding a highest cross-correlation coefficient of rectangular patches divided from two consecutive images with a given time interval as likely as the indoor PIV technique. However, this approach sometimes gives rise to a couple of technical drawbacks because the PIV algorithm that worked well in the laboratory has confronted various unresolved issues when applied in the natural river. An main issue was that there were no standardized criteria to determine the size of patch (i.e., interrogation area) and searching area. In general, they should be carefully chosen in the consideration of the given surface conditions such as particle density to differentiate the image pattern within the patch against its surrounding pattern, thus the proper assignment of them usually requires highly experienced skills, otherwise resulting in unidentifiable user-dependent outputs. Second, when the tracking particles in some part of the given image are relatively very sparse owing to irregular distribution of the particles, the quality of the results becomes very poor. Third, when the flow speed is very slow, there can be few noticeable variation between two pairs of successive images. This case usually resulted in zero velocity with partially erroneous non-zero velocity. Finally, when it should deal with a barely recognizable surface image pattern such as the night time operation with insufficient light (even using infrared image), it is not easy to obtain reliable velocity data. In fact, this limitation mainly drives the LSPIV method hard to be adapted for the seamless streamflow observation system.

From the perspective of dealing with such limitations of the conventional PIV algorithm, the spatio-temporal image velocimetry (STIV) firstly proposed by Fujita et al. (2007) provided a noteworthy idea in terms of working better in such difficult flow or image conditions, as well as enhancing various technical drawbacks of LSPIV. Rather than using image patches (i.e., the interrogation area) in the two successive images, the STIV is designed to build the spatio-temporal image which comes from tracking temporal variation of the pixel value along an interrogation line (rather than interrogation area) for a user-defined direction such as a streamwise direction in the successive multiple images (see Fig. 1a). The spatio-temporal image is typically represented to contain oblique strips that correspond to the movement of surface particles along the interrogation line (see Fig. 1b). This sort of the spatio-temporal image has been conventionally utilized in the robotic visionary area in order to track an object migration (Jahne, 1993; Bigun, 2006). Based upon the spatio-temporal images, the STIV estimated the average slope angle of strips in the image, and finally calculated a component of velocity per each interrogation line. Given that many interrogation lines are simultaneously drawn along a cross-section, horizontal distribution of streamwise velocity can be obtained to be utilized for discharge calculation.

Fujita and Hara (2010) reported that the angle of strip (i.e., velocity) from the STIV was more sensitive enough to capture the velocity than the correlation coefficient driven by LSPIV. Thus, it better analyzed the noisy flow patterns driven by the low flow or insufficient surface particle driven by lack of seeding and lighting. Also, computational efficiency of the STIV was much enhanced, as ten times greater than LSPIV. It was successfully applied for a real flash flood discharge measurement in Toga River, Japan (Fujita et al., 2013).

It seems clear, therefore, that the STIV can be evaluated to be more suitable for assessing stream flow discharge than conventional LSPIV. However, in the current version of the STIV, we deem that there are still rooms for enhancement. Here, we point out two potential issues of the STIV. First, whereas obtaining a streamwise component is sufficient enough to derive flow discharge, it could be limited to provide two-dimensional velocity field in the complex flow. It was speculated that the algorithm currently used in the STIV might have limitations to properly estimate the velocity component that does not follow streamwise direction (e.g., spanwise direction), and thus the derived spatio-temporal images do not contain clear strips. Second, it is subsequently difficult to identify the main flow direction in the field condition or in the complex flow where the main flow direction continuously alters. In this paper, we thereby attempted to develop a specified algorithm named correlation analysis of spatio-temporal image (CASTI) designed to measure time-averaged two-dimensional velocity field for the complex flow based on the main flow direction that was defined automatically. The developed algorithm was validated by using artificially-generated cavity flow where the true velocity was known.

2. Methodology of CASTI

2.1. Spatio-temporal image and previous issues

In this section, since the CASTI stems from the STIV, we firstly reviewed the STIV method in detail to provide a new alternative algorithm that overcomes its potential drawbacks. The core of the STIV method was to utilize the spatio-temporal images generated on the basis of a line of pixels outputted by drawing an interrogation line on a given image, and cumulate the lines taken throughout the recorded successive images (Fig. 1a). Then, the cumulated image strips constitute a spatio-temporal image