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Development of Uncertainty Quantification Method for MIR-PIV Measurement using BOS Technique

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1. Introduction

Matching Index of Refraction (MIR) is frequently used for obtaining high quality PIV measurement data. Therefore, quantification of the MIR uncertainties is one of the prime factor for high PIV measurement accuracy. Even small distortion by unmatched refraction index of test section can result in uncertainty problems. In this context, it is desirable to construct new concept for checking errors of MIR and following uncertainty of PIV measurement. This paper proposes a couple of experimental concept and relative results. The details are presented in the following sections.

2. MIR-PIV Uncertainty Quantification Method

This paper proposes several steps of experiment process. The first step is a background oriented schlieren (BOS) technique. Background image distortion due to change of refraction index between the image and camera makes it possible to determine displacement vector field of that space. One background image with a refractive disturbance and another without it compose a BOS image pair, which can be analyzed using cross-correlation tools.

The second step is a stereoscopic background oriented schlieren (SBOS) technique. The enlargement of the experiment through two cameras makes them possible to take simultaneous pictures. The two cameras capture the same target at different viewpoints. The test section of PIV experiment is composed of fixed solid materials which are unable to separate from it, so BOS technique would not be applicable. Therefore SBOS technique is considered as a significant factor for the successful experiment.

Two images from individual two cameras should be matched as similar scale for the precondition of cross-correlation. Therefore image processing using MATLAB plays an essential part in SBOS experiment.

The third step is mapping. The verification of SBOS experimental data can be rationalized by mapping it with BOS data. For the average percentage of difference between SBOS and BOS, SBOS data can be rationalized by a certain factor.

As the last experiment step, MIR-PIV Uncertainty Quantification will be conducted. Two digital cameras for SBOS and one CCD camera for PIV are used to capture the same boundary of test section. Both velocity field and MIR errors can be detected by this set-up. Finally, revised velocity value which enhance PIV accuracy are available.

At this step, artificial uniform vector field by BOS also used to certificate whether the errors are checked as precise level.

3. Experimental Set-up

Overall experiment is conducted on the condition of background image, camera(s), quartz tube, tank which is filled with mineral oil. The background image is managed by a computer, hence tank contact with monitor screen preventing the interference between LCD and camera lens. The refractive index of mineral oil is well matched with the refractive index of quartz tube, so the distortion by quartz tube is only seen at the border of the tube.

3.1 BOS Set-up

At the first step, there is no distortion of the background image, because camera image is only taken through tank and mineral oil. Then, with object in mineral oil, image distortion due to change of refraction index at the border of the tube makes slightly different camera image.

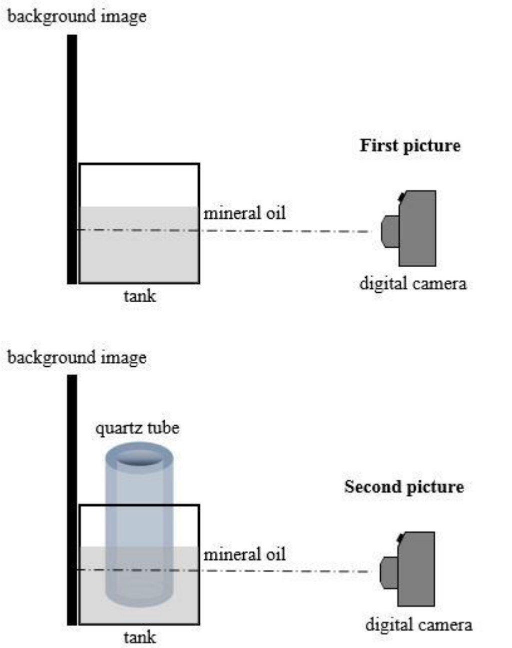


Figure 1. Schematic diagram of BOS set-up

3.2 SBOS Set-up

Two cameras take simultaneous picture of distorted background image. Same type of camera and tripod should be used. The two camera operate by remote controlled.

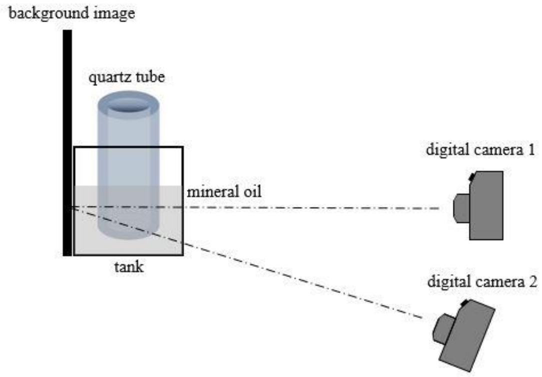


Figure 2. Schematic diagram of SBOS set-up

Camera 1 is located at the front of the test section, and camera 2 is located aside. To cross-correlate both image, the image from camera 2 should be transformed as front view. This process is done by MATLAB code. Section **4** will introduce stereo matching tool in MATLAB, which identify whether the two images are well matched. In other words, the tool gives information whether the image from camera 2 is well transformed to front view.

3.3 PIV-SBOS Set-up

Three cameras are used to obtain both velocity and displacement vector fields. Two digital cameras are for BOS analysis, and One CCD camera is for PIV measurement.

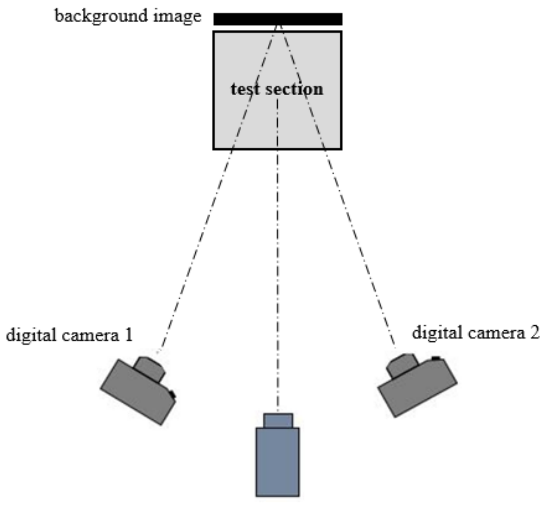


Figure 3. Schematic diagram of PIV-SBOS set-up

The test section is composed of twisted tape and tube filled with mixture oil. There are a number of seed particles in mixture oil whose refraction index is well matched with the twisted tape.

Two digital cameras focus on the background image behind the test section, and estimate the degree of distortion. The CCD camera focuses on the center of the test section that can measure the average flow velocity data.

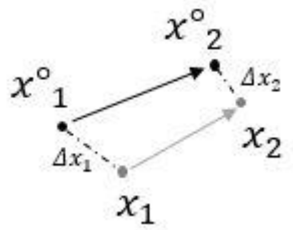
3.4 MIR-PIV Uncertainty Verification Set-up

There are two ways of defining uncertainty. A mathematic uncertainty is one of them. The mathematic uncertainty of MIR-PIV can be distinguished by the following equation:

$$\frac{\Delta x_2 - \Delta x_1}{\Delta t}(uncertainty) = v \cdot \nabla(\Delta x) \quad (1)$$

v is velocity field which can be obtained by PIV, and Δx is displacement vector field induced by refractive disturbance, which can be obtained by BOS.

The derivation of uncertainty is followed.



x°_1 : Original particle location at 1st shot

x°_2 : Original particle location at 2nd shot

x_1 : Distorted particle location by MIR errors at 1st shot,

$$x_1 = x^\circ_1 + \Delta x_1$$

x_2 : Distorted particle location by MIR errors at 2nd shot,

$$x_2 = x^\circ_2 + \Delta x_2$$

v° : Original particle velocity, $v^\circ = (x^\circ_2 - x^\circ_1)/\Delta t$

v : Experimental particle velocity, $v = (x_2 - x_1)/\Delta t$

$v - v^\circ$: Errors of MIR, $v - v^\circ = (\Delta x_2 - \Delta x_1)/\Delta t$

With the equation below:

$$\Delta x_2 = \Delta x_1 + (v\Delta t)\cdot\nabla(\Delta x) \quad (2)$$

Errors of MIR can be derived as equation (1).

Also, according to a definition of uncertainty, MIR-PIV uncertainty can be obtained by subtracting original vector field from distorted vector field. It is an experimental uncertainty. To specify the uncertainty, artificial uniform vector field is generated instead of the flow.

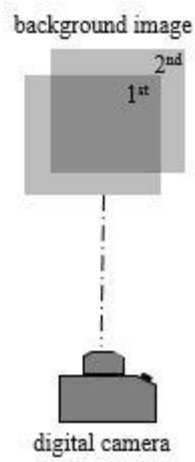


Figure 4. Schematic diagram of generating artificial uniform vector field

After taking the first picture, the background image is moved slightly, then the second picture is taken with transferred\background image. The cross-correlation of the both image makes uniform displacement vector field.

To obtain distorted vector field, the same experiment is conducted in the case of object existence.

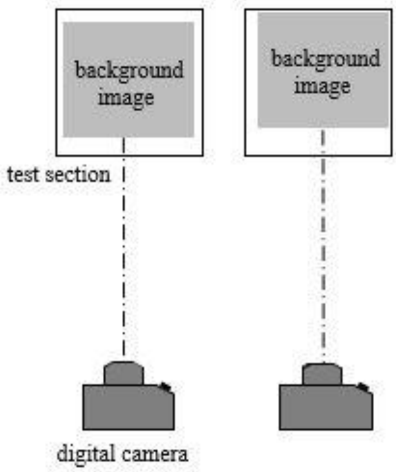


Figure 5. Schematic diagram of generating artificial distorted vector field

The experimental uncertainty data finally proposes the reference criteria for the mathematic uncertainty which associated with PIV and SBOS techniques.

4. Results and Discussion

For experimental results, PIV analysis program and MATLAB are used.

4.1 BOS

Cross-correlation is done between two images by PIV program.

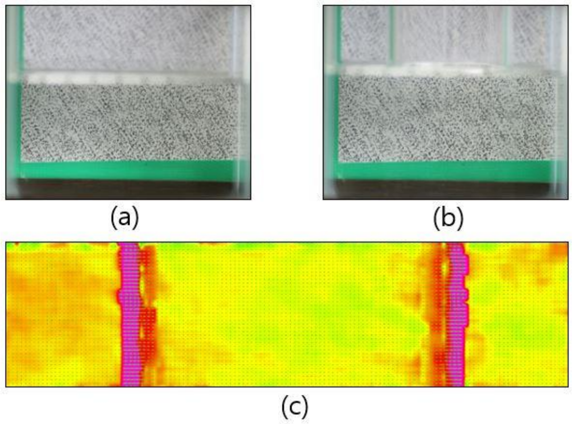


Figure 6. BOS result: (a) Original background image; (b) Distorted background image with quartz tube in mineral oil; (c) Cross-correlation result of (a) and (b) over the mineral oil area

4.2 SBOS

Above of all, the image from camera 2 should be transformed as similar level of the image of camera 1. Transformation can be conducted by MATLAB code [1]. Also, image transformation is checked by stereo matching tool in MATLAB.

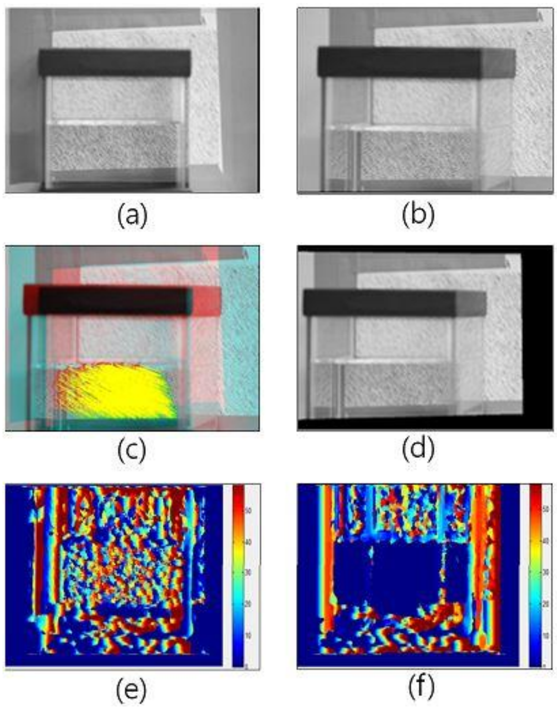


Figure 7. Image transform process: (a) Front view; (b)

Aside view; (c) Matching points in respect of projective conversion between (a) and (b); (d) Revised image of (b) as front view; (e) Matching graph between (a) and (b); (f) Matching graph between (a) and (d)

As the matching result (f) of transformed image (d) and original front image (a) shows ‘zero’ value at test section region, it can conclude that transformed image is almost exact front view, and can be used for cross-correlation.

Cross-correlation result of the two (a), (d) images is shown at Figure 8.

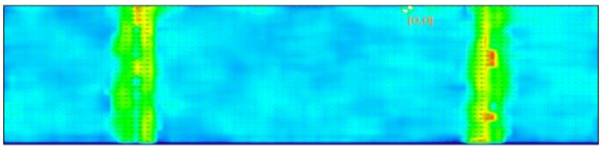


Figure 8. SBOS result

4.3 Mapping

Comparisons of the displacement vector value of BOS and SBOS was performed over the same line. Average difference percentage between BOS and SBOS can be quantified.

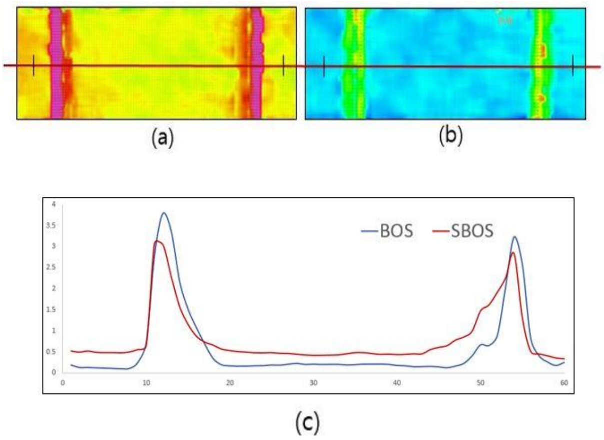


Figure 9. BOS-SBOS mapping: (a) BOS result; (b) SBOS result; (c) mapping (a) and (b)

The mapping result (c) shows that SBOS presents average 0.75% displacement values of that of the BOS. This result should be considered at the following experiment.

Eventually, SBOS technique is established.

4.4 MIR-PIV Uncertainty Quantification

The SBOS and PIV experiment was carried out on the same test section. The upper part of the twisted tape within the quartz tube was taken by both SBOS and PIV cameras.

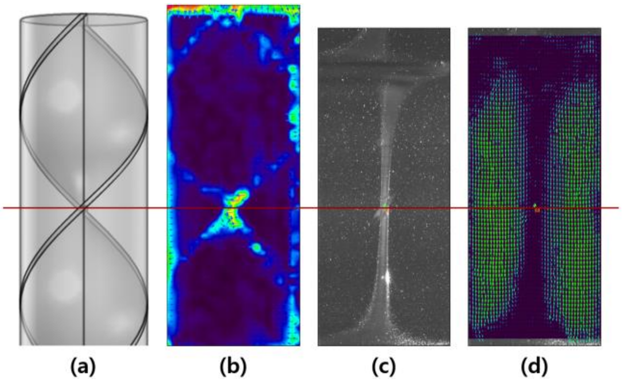


Figure 10. All figures lie on the same center line (red traverse line). (a) CAD model of the test section; (b) SBOS result; (c) a picture of PIV camera; (d) PIV cross-correlation result of (c) and its pair.

The SBOS result (b) illustrates the remarkable distortion along the edge of the twisted tape.

The column at the center of the PIV original picture (c) is due to the reflection of the laser. Although this column makes the picture seem to be taken for the quite different region from (a), (c) have the exact same boundary with (a) and (b). The PIV result (d) demonstrates the downstream of the particles.

A synthetic northeastward vector field was generated instead of the particle flow. Error of the MIR, $v - v^{\circ}$, can be calculated by subtracting the distorted vector field from the original vector field.

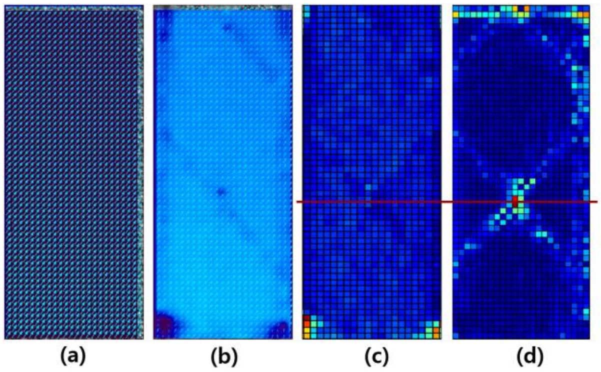


Figure 11. The synthetic northeastward vector field and calculated uncertainty: (a) Original vector field without test section; (b) Distorted vector field with test section; (c) The result uncertainty of the subtraction between (a) and (b); (d) Calculated uncertainty from Fig.10

$v - v^{\circ}$ is demonstrated at (c) and $v \cdot \nabla(\Delta x)$ is demonstrated at (d). As shown at Figure 11, (c) and (d) indicate the same center line and represent similar uncertainty shape. Hence, the verified MIR errors are demonstrated at Figure 11. (d).

The final result shows trivial difference of the two errors, which validates that the uncertainty quantification method proposed is reliable.

5. Summary

This study developed an MIR uncertainty quantification method for PIV measurement using SBOS technique. From the reference data of the BOS, the reliable SBOS experiment procedure was constructed. Then with the combination of SBOS technique with MIR-PIV technique, velocity vector and refraction displacement vector field was measured simultaneously. MIR errors are calculated through mathematical equation, in which PIV and SBOS data are put. These errors are also verified by another BOS experiment. Finally, with the applying of calculated MIR-PIV uncertainty, correct velocity vector field can be obtained regardless of MIR errors.

ACKNOWLEDGEMENT

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