Research and application of flow visualization technique in large-scale hydraulic models

Wen Cheng¹,², Bao-wei Hu³,⁴, Tian Wan², Zhang-bin Wang², Fujio YAMAMOTO⁴

¹ State Key Laboratory of Multiphase Flow in Power Engineering; Xian Jiao tong University, Xian 710049, China
² Key Laboratory of Northwest Water Resources and Environmental Ecology of Education Ministry; Xian University of Technology, Xian 710048, China
³ ShaoXing University, ShaoXing, 312000, China
⁴ Fiber Amenity Engineering Course, Graduate School of Engineering, University of Fukui, Bunkyo 3-9-1, Fukui 910-8507, Japan

wencheng@xaut.edu.cn; emiwbp22@163.com; hbw@zscas.edu.cn

Abstract. With the rapid development of computer and optical technique, as a powerful measuring method in hydrodynamics, flow visualization technique is able to get much flow field information in practical engineering. It also has an important meaning to projects and environmental areas. The image processing is the key to flow visualization for gaining flow field information. In terms of the PIV principles, the algorithm of PIV based on Fast Fourier Transformation (FFT) is studied, and the image mosaic program based on genetic algorithm has been compiled. The flow field of seabuckthorn flexible dam has been calculated and analyzed by using those methods as above-mentioned, and in the meanwhile, the application of flow visualization technique to measure the outdoor flow field has been studied exploringly, which proves that it is feasible to apply this technique to measure the large-scale outdoor flow field.

1. INTRODUCTION

Flow visualization is the major method to study the field of fluid dynamics. Its basic principle is that some matters are released in transparent or semitransparent fluid medium, and then make the flow field visualizable by optical function. It is the most intuitionistic and effective tool to study the basal flow phenomena, to realize characteristics of flow, and then to deeply explore its physical mechanism. (X. Liu. 2006) This technique attracts many human eyes and plays an important role in the study of fluid dynamics. Long before 1914, Hot Wire Film Anemometer was invented, which made great contributions to fluid measurement. However, this method interferes with flow field for its contacted measuring. Laser Doppler Velocimeter developed in 1960s has achieved contact free less measurement to flow field, but it is a single point measuring technique which is applicable for steady-state or unsteady-state flow field, but not for the study of time-variant one (L. Xu, et al. 2003). Since 1980s, quantitative flow visualization technique has been developed rapidly with the noticeable development of electronic technique, image processing methods and signal analyzing theory. Particle
Image Velocimetry (PIV) was developed this time. Based on fluid visualization, it is the newest fluid measurement means developed by introducing the research achievements of modern computer technique, optical technique and image analysis technology (Y.Murai, 2008). PIV can not only show the physical pattern of flows, but also supply quantitative information of instantaneous whole flow field, which makes the study of flow visualization produce a qualitative leap forward.

As the most advanced technique of flow visualization, PIV can be widely used in engineering and environmental applications, especially in studying flow velocimetry of large-scale experimental models in irrigation projects and natural waters. The velocimetry theory of single-phase two-dimensional flow field in lab has been developed maturely by 30 years’ research. However, for the limitation of its experimental setup and conditions, so far, many domestic researchers have been major in studying the application of PIV/PTV to indoor mini-type experiment table, and the application of visualization technique to outdoor flow field observation is singular. In order to extend this advanced velocimetry technique to outdoor and explore its effect in sea buckthorn flexible dam, this paper studies the changing modality of flow field in field observing sea buckthorn flexible dam by applying the PIV.

2. METHOD OF PARTICLE IMAGE VELOCIMETRY

The basic principle of PIV can be described in the following operations (Y.Murai, et al. 2007): the nearly noise-free tracer particles with good traceability and dispersion are seeded to the flow field, particle velocity is used to represent the flow velocities at the corresponding positions in the flow field, and the powerful lighting system is used to illuminate a measurement plane in the flow field. The photographing method is used to record the positions of those particles which get exposure twice or more times, then the displacement of each particle are available by the image analysis techniques. As a result, the velocity vector of each point in the flow can be obtained from the displacement and exposure time interval, and other motion parameters can also be calculated, whereby the local motion laws of fluid can be derived (X. Wang, et al. 1998; Wen Cheng, et al. 2005). It can be expressed as the following equation:

\[
\begin{align*}
  u(x, y) &= \frac{S_x \times k}{dt} \\
  v(x, y) &= \frac{S_y \times k}{dt}
\end{align*}
\]

(1)

The performance of the whole flow field is evaluated by Eq. (2):

\[
C = \frac{\sum (\phi_n \cdot \phi_n)}{\sqrt{\sum \phi_n^2 \cdot \sum \phi_n^2}}
\]

(2)

The PIV technique includes three steps as follows: (1) Acquisition of the digital images; (2) Compiling the PIV programs; (3) Data post-processing. Based on the principle of PIV, using CCD cameras to constantly shoot the flow field, and then the digital images can be obtained. The FFT-based Gray level cross-correlation method is adopted in the images, and then, the tracing images can be divided up from the measured ones in experiment by compiled programs. Finally, the algorithms can be achieved by using MATLAB to compile programs.

3. THE APPLICATION OF FLOW VISUALIZATION IN PRACTICAL ENGINEERING

The sea buckthorn flexible dam mainly makes use of the principles in fluid dynamics that the drag reduced flow formed by flow obstacle preventing water, flow rate reduction and silt settlement caused by flood sediment retardation, and pressure head going through the interspaces between main branches of sea buckthorn. Planting sea buckthorn in gully between mountains, and when flood bringing with silt goes through the sea buckthorn, the silt will be lagged in the upper or middle reaches of sea buckthorn cluster, which can control water and soil loss of gullies and intercept silt(Ri-jun Zhang, 2006).
Explored and studied for more than 20 years, many qualitative results have been obtained. In order to deeply realize the watertight effect of sea buckthorn, and explore the flow property and the effect low of sea buckthorn to flow rate alteration, this paper observes the flow field changing form of sea buckthorn in field with recently advanced PIV technique. In order to get the data of basic images, a flow rate observation experiment was carried out successfully in experimental base of sea buckthorn in Hua County, Shaanxi Province, China in November, 2006. This paper mainly uses 2# sea buckthorn dam as the research object to explain that it is feasible to observe the outdoor flow field by applying the PIV technique.

3.1 Experimental Setup

This test uses daylight as light sources. The tracing particles are circle white foams with good light rain reflecting characteristics and small density, which diameter is about 5mm. Fig.1 shows the test system.

![Fig. 1 The layout for the test facilities (m)](image)

The frequency of camera used in experiments is 30frame/s. The images in this paper employ one frame every 3 frames. Two continuous moments at some state in test are intercepted to shoot the flow field. The whole length of 2# sea buckthorn dam is 9.64m. The camera is fixed on the 3.5m-high scaffold. With the limitations of experimental conditions such as the performance and objective distance of camera, three cameras are used to cover the whole bed in this test, and in the meanwhile, the spillway face is divided into three sections, which is upper, middle and bottom, respectively. Fig 2 shows the flow field image of each section.

(a) The instantaneous image and flow velocity vector graph of the dam in the upriver

(b) The instantaneous image and flow velocity vector graph of the dam in the middle reach
3.2 Experimental results and Analysis

3.2.1 Calculation of flow field
The flow changes in flexible dam for test process are simulated by the water level variation of the impounding reservoir which supplies water to the dam. Fig.3 shows the time variation of discharge in impounding reservoir.

![Fig. 3 The time variation of discharge in impounding reservoir](image)

In order to calculate the whole flow field of the flexible dam, this paper studies the method of image mosaics in the pre-processing stage. The basic principle of this method is used for reference, and the flow field is calculated. On the basis of this data, the digital flow field is mosaic. Fig.4 shows the result. The discharge is 0.11m³/s. The water is flowing from left to right. L represents the length of the dam bed, while B is width. The arrows in the field vector graph represent the velocity of tracing particles, and the length expressed the size of velocity (1mm=0.34m/s), while the arrows represent the direction. Comparing to the real flow field, it is shows that the field vector graph obtained by PIV can fundamentally reflect the flow movement characteristics such as the field states and the size of velocity.

![Fig.4 The whole flow field shown as vector graph in 2# dam](image)

3.2.2 The analysis of the results
Through analyzing the distribution of the flow field, the energy dissipation produced by the flexible dam can be reflected.

(1) **The velocity distribution along the flexible dam bed for the same discharge**

In order to explore the change in the velocity along the flexible dam bed for the same discharge, on the basis of the embarking time and order of the tracing particles in the image sequence, the discharge of the tracing particles embarked each time and its corresponding velocity in each cross section can be deduced by combining the outflow processing curve of impounding reservoir. Fig. 5 shows the flow velocity changing process along the 2# dam bed in 5 types of different discharges.

Fig. 5 shows that the variation in the velocity for each discharge along the dam bed is decreasing. When the water flow comes into the sea buckthorn flexible dam, the velocity curve presents descending trend, especially in the first row. The changing characteristic of Fig. 5 shows that the water flow velocity is continuously reducing because of the existence of the sea buckthorn, which explains the preventing water effect of the sea buckthorn. This conclusion is in concordance with the results obtained in the indoor lab flume in Sin kiang Agricultural University, China. (Y. Cheng, et al 2003, 2004)

Observing from the discharge angle, the effect of the sea buckthorn on the flow is presenting certain laws because of the different orders the flow coming into the sea buckthorn dam. As the discharge is small in the beginning stage of the test, the sea buckthorn is not lodging and the backwater phenomenon doesn’t appear in the flexible dam, which shows that the flood detention action of the dam is not remarkable. With the discharge becoming heavier, the detention function will come to be very obvious. Fig. 5 shows that the velocity in the discharge of 0.12m$^3$/s is as same as that in the discharge of 0.04m$^3$/s in the later stage, which explains that the flood peak discharge is delayed by sea buckthorn flexible dam. This result is the same as the conclusion obtained by Wang Cun (2003) in Hohai University, China who studies the effect of the plants on the flow.

(2) **The variations of velocity in the same monitoring cross section**

In order to know the flow rate variation in the same cross section of the whole outflow process, the outflow discharge of impounding reservoir is calculated by volume method, and the locations that 1m downstream of entrance region and 3m, 5m, 7m away from the dam site are set as 4 monitoring cross sections. After measurements are made once per 30s in these sections, and 8 times each section, then the average flow rate is calculated. The result is shown in Fig.6.
The velocity at 1.0m section is drafted as inlet velocity. Fig. 6 shows that the flow rate variation trend at each section is the same as the outflow changing trend of reservoir. The velocity in the first cross-section takes a maximum value of 1.10m/s, at which the sea buckthorn doesn’t have remarkable influence on the entrance region water flow. Compared with the first cross-section, the flow rate at the middle section is reducing obviously. It can be explained that according to the principle of the continuity of flow movement, the backwater region appears in the dam for the existence of the sea buckthorn. Because of the interactions of the backwater flow before the dam and the flexible features of the dam body, the flow at the last monitoring cross-section in the middle and lower parts reaches has changed to be steady, which is beneficial to the sediment disposition. Every monitoring cross-section has undergone the same outflow process; however, because of the existence of the sea buckthorn, the flow rate at each cross-section seems to be reduced step by step, which explains that it is feasible to employ the PIV to observe the flow field of flexible dam (Zhang-bin Wang et al. 2008).

3.3 Effect of the sea buckthorn flexible dam on distribution of soil grain size
In order to know that when the flow conditions in channal are changed by sea buckthorn flexible dam, whether the soil can be sorted and intercepted naturally, a certain research about the distribution of soil grain size in spacial and time have also be done in this paper. Three sections of 2# dam in upstream, middle reaches and downstream are employed to correspond with the above-mentioned research. And five soil layers in each section are used to sample soil, which is 0~20, 20~40, 40~60, 60~80, 80~100cm respectively. The soil samples are graded by sieving method after drying. Fig.7 shows the result.

![Fig.7 The cumulative mass percentage of sediment grain size bigger than 0.1mm in each layer of different sampling sections](image)

---

Fig.6 The time variation of flow rate in different monitoring cross-section of 2# dam bed
The content of soil particles whose grain sizes are larger than 0.1mm is increasing layer by layer. The main reason is that the water flow is held back by the sea buckthorn, and the flow rate is decreasing along the dam, then the coarse particles cannot move with water (Tao Zhang. 2008). The existence of the sea buckthorn has changed the flow pattern, then the distribution of the soil grain size can also be changed, which has greatly improved the erosion resistant of the soil.

5. CONCLUSIONS
The basic principle of flow visualization is studied in this paper. The flow field measurement with flow visualization technique is used in the practical engineering, and the following conclusions have been obtained.
(1) Through analyzing the digital flow field measured by PIV, it can be seen that the sea buckthorn has remarkable influence on the flow characteristics, especially on the velocity, and the flow rate in the dam is obviously smaller than that before the dam. It means that the water flow energy loss caused by the resistance of the sea buckthorn flexible dam to flow is mainly concentrated in the water-saturated stage, and it is most possible for silt depositing in this area, which provides the theoretical basis for controlling soil erosion of gully channel with sea buckthorn flexible dam.
(2) By analyzing the distribution of soil grain size in the channel with the existence of the sea buckthorn, it also can be obtained the sand-blocking effect of the flexible dam.
(2) The feasibility of the PIV technique to be used in field test site has been verified, which provides the technological supports for outdoor flow field observation in the future.

ACKNOWLEDGEMENTS
The authors thank Prof. Huai-en Li of Xi’an university of Technology and Prof. Yamamoto of University of Fukui for useful discussion.

NOMENCLATURE

\( S_x \)  Displacements of particles in water flow direction \([\text{m}]\)
\( S_y \)  Displacements of particles in the direction normal to water flow direction \([\text{m}]\)
\( k \)  Scale
\( dt \)  exposure time. \([\text{s}]\)

Greek Letters

\( \varnothing \)  target variable

Subscripts

th  theoretical value
R  reconstruction value

REFERENCES
X. Liu.(2006). "Study on particle image velocimetry and inverse analysis in aeration tank,"M.D. Xi’an University of Technology ,Shaanxi,CHINA

L. Xu,et al.(2003) "Study on development of Particle Image Velocimetry" J. Advance of Dyn. 33(04),pp. 533-540

Yuichi Murai.(2008) "Increase of effective viscosity in bubbly liquids from transient bubble deformation,"Fluid Dynamics Research. 40(7-8):565-575
X. Wang, et al. (1998) "The Initial exploration of particle image velocimetry (PTV-PIV) in two-phase flow," J. Dyn. 30(01), pp. 121-125

Yuichi Murai, Kazumasa Inaba, Yasushi Takeda (2007) "Skin friction reduction by large air bubbles in a horizontal channel flow," 19(2), pp. 223-229

Wen Cheng, et al. (2005) "Bubble velocity measurement with recursive cross correlation PIV technique," J. Fluid Measurement and Instrumentation. 16, pp. 35-46

R. Zhang (2006). "The water flow experiments of seabuckthorn flexible dam," M.D. Xi’an University of Technology, Shaanxi, CHINA

Y. Cheng, et al. (2003) "Experimental study on Hydrodynamic behavior of channel vegetation," J. Sin kiang Agricultural University, 26 (2), pp. 59-64

Y. Cheng. (2004) "Hydrodynamic characteristics of plant flexible dam based on experiment," M.D. Sin kiang Agricultural University, Sin kiang, CHINA

C. Wang. (2003) "The water flow test study of river channel with vegetations," M.D. Hohai University, Jiangsu, CHINA

Z. Wang, et al. (2008) "Research and application of flow visualization technique in the fluid measurement of Sea buckthorn plant flexible dam," J. Hydro. Eng. 27(1), pp. 28-31

Z. Wang. (2008) "Research and application of flow visualization technique in Sea buckthorn plant flexible dam outdoor fluid measurement," M.D. Xi’an University of Technology, Shaanxi, CHINA

T. Zhang. (2008) “Experimental research on sand-blocking and ecological benefit of sea Sea buckthorn plant flexible dam," M.D. Xi’an University of Technology, Shaanxi, CHINA