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Application of wavelet packet image compression technique to particle image velocimetry

Hui Li[a], Masahiro Takei[b], Yoshifuru Saito[c] and Kiyoshi Horii[d]
[a]*Department of Mechanical Engineering, Kagoshima University, 1-21-40, Korimoto, Kagoshima 890-0065, Japan*
Tel.: +81 99 285 8252; Fax: +81 99 250 3181; E-mail: li@mech.kagoshima-u.ac.jp
[b]*Department of Mechanical Engineering, Nihon University, 1-8-14, Kanda Surugadai, Chiyoda-ku, Tokyo 101, Japan*
Tel.: +81 3 3259 0749; Fax: +81 3 3293 8254; E-mail: takei@mech.cst.nihon-u.ac.jp
[c]*Department of Electrical & Electonic Engineering, Hosei University, 3-7-2, Kajino, Koganei, Tokyo 184, Japan*
Tel.: +81 42 387 6200; Fax: +81 42 387 6200; Email: ysaitoh@ysaitoh.k.hosei.ac.jp
[d]*Shirayuri Women's College 1-25, Modorigaoka, Chofu-shi, Tokyo 182, Japan*
Tel.: +81 3 3326 7604; Fax: +81 3 3793 7461; E-mail: khorii@shirayuri.ac.jp

Abstract. Our motive of this study is to develop an application of the wavelet packet to PIV image compression processing in order to improve the spatial resolution and reliability furthermore. It was found that the reconstructed PIV image with a lower compression ratio might emphasize particle edges at a relatively high spatial resolution. The reconstructed PIV image with a higher compression ratio may display the large-scale motion of particles and may deduce noisy. In this study, the relative error of the wavelet packet image compression technique was lower than that of the standard wavelet image compression technique. The higher compression ratio of 64:1 can be realized without losing significant flow information in PIV processing. It could say that the wavelet packet could provide a better compression performance than the standard wavelet image compression technique when compressing PIV images.

1. Introduction

Particle Image Velocimetry (PIV) is a non-intrusive flow visualization technique and is now firmly established as a powerful fluid dynamics tool to measure flow velocity in the area of fluid mechanics. Even more important than this remarkably improved performance of the PIV technique, is its unique ability to capture instantaneous full-field flow and thus to allow the detection of spatial structures in unsteady flows quantitatively, which is not possible with other experimental techniques. Comprehensive reviews on the principles, the historical development and application of PIV were given by Adrian [1,2], and the details will not be repeated here.

It is a well-known fact that the evaluation of a PIV technique is often characterized by its accuracy and its spatial resolution. Much progress had been made in PIV technique, however, a certain number of erroneous vectors in the vector fields may generate with the use of PIV, which effects its spatial resolution.

One of factors may be related to poor quality of images. Therefore, it is becoming significant attention to improve spatial resolution and reliability in PIV technique. On the other hand, the storage capacity of the recorded PIV images and time evaluation becomes an important problem with the development of PIV technique. For example, a PIV system using a double-pulsed Nd:YAG laser and a cross-correlation CCD array camera can record a pair of images (1008×1016-pixel) with a frequency of 10 Hz. For obtaining turbulent flow statistics of one flow condition, 10,000 samples, i.e., 20,000 images containing the information of a flow field, are required to record in real-time to a very large hard disk. It does not only result in the larger physical storage, but also require a great deal time to transfer and process these images. Especially the need for reducing physical storage becomes significance when developing three-dimensional image velocity measurement techniques, such as Holographic PIV (HPIV).

The International Standard Organization (ISO) has proposed the JPEG standard for still image compression and MPEG standards for video compression. These standards employ discrete cosine transform (DCT) to reduce the spatial redundancy present in the images or video frames. We note that DCT has the drawbacks of blocking artifacts, mosquito noise and aliasing distortions at high compression ratios. However, the method of image compression that was often used in PIV is only to eliminate the low intensity pixels of image file. Because the low intensity pixels contribute little information about particle displacement, this type of image compression has very little effect on the accuracy of PIV. Recently, Hart [3] employed sparse array image correlation to realize compression ratios of 30:1 or greater and high processing speed of PIV. Freek et al. [4] evaluated the accuracy of the PIV measurement of mean RMS velocities when using a MJPEG image compression technique, and the compression ratio was achieved to 12:1.

Over the past decade the applications of discrete wavelet transform (DWT) have been gradually developed and become a popular technique for image processing in various fields. A wide variety of wavelet-based image processing has been reported in the literature. In the area of fluid mechanics Li et al. [5,6] developed an application of two-dimensional orthogonal wavelets to the turbulent image analysis, and the multi-scale turbulent structures and the coherent structure were clearly extracted. Li et al. [7] also applied the wavelet compression technique to turbulent image processing for reducing physical storage and extracting the compact dominant features. Ko et al. [8] employed the wavelet-based multiresolution method to enhance spatial resolution of PIV. Li et al. [9] developed an application of the wavelet-based image compression technique to PIV. The higher spatial resolution can be obtained by reducing noise in images, and the economy in storing, transmitting or further processing with high speed can be realized based on compressing the images. It has been proved that the wavelet image compression technique is effective in PIV system for improving spatial resolution and reliability.

Our purpose of this study is to develop an application of the wavelet packet to PIV image compression processing in order to improving spatial resolution and reducing the physical storage furthermore. The wavelet packet can provide a better compression performance than the standard wavelet image compression technique when compressing images.

2. Wavelet packet image compression

Wavelet decomposition simply re-expresses an image in terms of the wavelet basis. In wavelet decomposition we leave the high-frequency part alone and keep splitting the low-frequency part. In wavelet packet decomposition, we can choose to split the high-frequency part also into a low-frequency part and a high-frequency part. So in general, wavelet packet decomposition divides the frequency space into various parts and allows better frequency localization of images.

In general, the image compression is defined as the representation of image using fewer basis function coefficients than were originally given, either with or without loss of information. There are several methods to compress the image based on wavelets. The approach of wavelet packet image compression we employed in this paper is to setting wavelet packet coefficients of modes with insignificant energy to zero. The procedure of this compressed method can be summarized in three steps:

(1) Compute the wavelet packet coefficients representing an image in orthonormal wavelets basis.
(2) Specify the number of wavelet packet coefficients M to retain, that is, fix the compression ratio M/N where N is the total number of wavelet packet coefficients before compression and delete all other wavelet packet coefficients.
(3) Reconstruct the image from compressed wavelet packet coefficients using inverse wavelet packet transform.

We can then adjust the number of wavelet packet coefficients M to vary the compression ratio. For evaluating the compressed feature, the correlation coefficients between the original image and compressed image is employed in this paper.

From the distribution of wavelet packet coefficients, it was found that coefficients were highly redundant and we need to choose from among all the representation the one that represents the image most efficiently. By "efficient" we mean that an image can be represented by a small number of wavelet packets, the basis for the decomposition is chosen such that the weight of the coefficients is concentrated on a small number of wavelet packets and a large number of coefficients were close to zero.

3. PIV based on cross-correlation algorithm

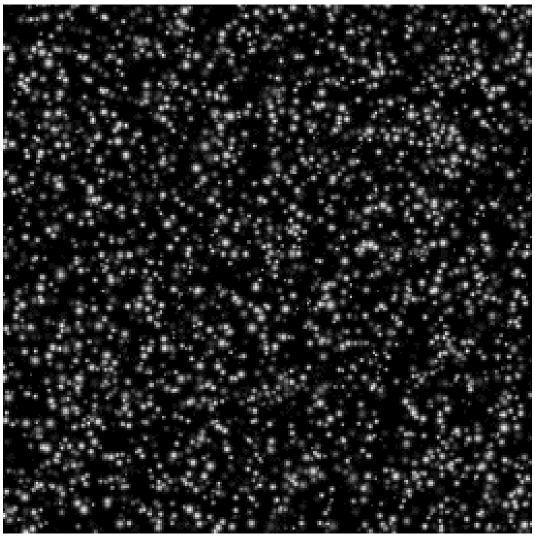
For typical method of Particle Image Velocimetry (PIV), instantaneous planar velocity vector is usually determined by cross-correlating the interrogation windows (or small image masks) in two successive PIV images separated by a known time interval. In typical approaches, the image data from a window taken in the first image and that from a window at the same position in the second image are cross-correlated. The discrete cross correlation coefficient is defined as

$$R(m,n)=\frac{\sum_i\sum_j f(i,j)g(i+m,j+n)}{\sqrt{\sum_i\sum_j f^2(i,j)\sum_i\sum_j g^2(i,j)}}$$

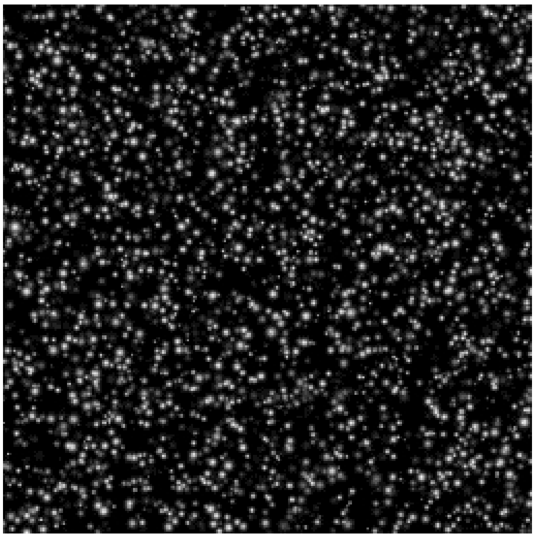
where $f(i,j)$ and $g(i,j)$ represent the pixel intensities of the interrogation windows at pixel locations (i,j) in the first and second images, respectively. The function $R(m,n)$ measures the correlation of the discrete functions $f(i,j)$ and $g(i,j)$ when they are relatively shifted by (m,n) pixels. The location of the maximum cross-correlation peak gives the mean displacement of the particles in the interrogation window within a known time interval. The instantaneous velocity vector at location (i,j) is calculated from this mean displacement.

4. Results

In order to evaluate the characteristics of compressed PIV image based on the wavelet packet image compression technique, a PIV standard image pair of a two-dimensional wall shear flow, which were



(a) At time T



(b) At time $T + \Delta t$

Fig. 1. Standard PIV Image pair of two-dimensional wall shear flow.

developed by the Visualization Society of Japan, were used in this study. Figure 1 shows two successive PIV images (256 by 256 pixels with an-8bit grayscale) within time interval $\Delta t = 0.033$ s.

To determine the effect of the choice of the wavelet bases, the standard PIV images were compressed by some known wavelet families, such as Daubechies, Coifman and baylkin families. It was found that the best subjective performance was obtained with high order wavelet bases (Daubechies wavelet with orders 16 to 20, Coiflets wavelet with orders 18 to 30, and Baylkin wavelet with orders 12 and 18). It was because a high order wavelet base can be designed to have good frequency localization that in turn increases the energy compaction. The regularity of wavelet also increased with its order.

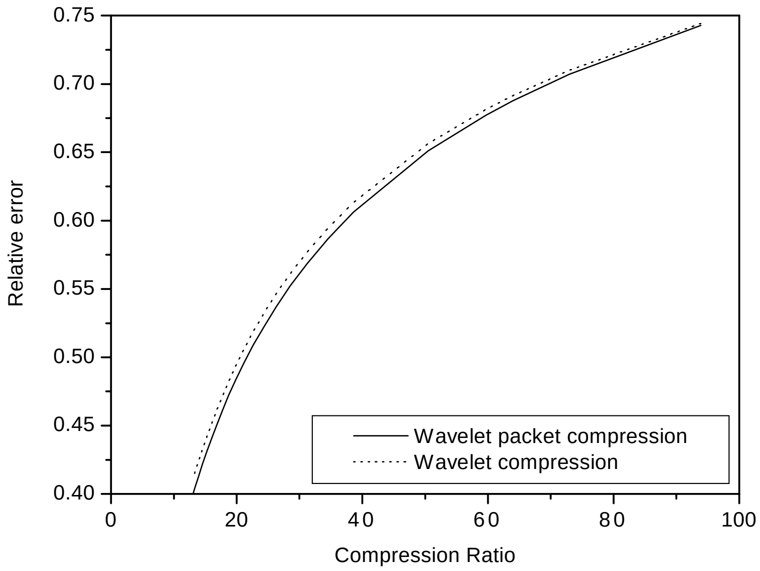


Fig. 2. Relative error of compressed PIV image with original PIV image as a function of compression ratio for wavelet packet technique and standard wavelet technique.

In addition, more vanishing moments can be obtained using a high order wavelet basis. On the other hand, although a low order wavelet base was expected to have a better space localization and therefore preserved the crucial edge information, low order wavelet bases for compressing PIV images shown the smaller correlation coefficients than that of high order wavelet bases at same compression ratios.

Figure 2 showed the relative error of compressed image with original image plotted as a function of the compression ratio when using the wavelet packet technique and standard wavelet technique. Daubechies wavelet with orders 20 was used. As illustrated in this figure, the relative error increased with increasing compression ratio and the relative error of the wavelet packet image compression technique was lower than that of the standard wavelet image compression technique. At the higher compression ratio range, the relative error of standard wavelet technique approached to that of wavelet packet technique.

Figure 3 showed a reconstructed image that is reconstructed from the remaining 1.56% of the 65536-wavelet packet coefficients with compression ratio 64:1. This figure having higher compression ratio given us the image of particle group since the compression of the image leaded to an increase in the particle-image size. Corresponding to the physically intuitive of physics of the flow, it exhibited the large-scale motion of particle-image and can be used to deduce noise in original images and describe the large-scale flow field.

The velocity vector field obtained from the compressed image pair of Fig. 3 using 24×24-pixel interrogation window was shown in Fig. 4. We prefer to present the raw data. The velocity vector obtained was almost consistent with the accurate solution, and represented a large-scale flow field. Although few of erroneous velocity vectors emerge, we are able to remove those vectors by the dynamic mean value method [10] that checks each vector individually by comparing a magnitude with the average value over its nearest neighboring reasonable vectors and replace the incorrect vector by this magnitude.

In fact, variations in particle image intensity and size, background noise, poor contract, insufficient illumination and optical aberrations effect the quality of experimental images and therefore cause low spatial resolution in PIV analysis. For testing the performance of wavelet compression technique of PIV in the real experiment, a simple experiment of planar jet was carried out in this work.

(a) At time T

(b) At time $T + \Delta t$

Fig. 3. Reconstructed PIV image pair with a 64:1 compression ratio and correlation coefficients 0.40 based on wavelet packet.

A planar jet was generated by a blower-type wind tunnel having flow-straightening elements, screens, and settling length, a 24:1 contraction ratio leading to a rectangular nozzle. The measurements were carried out at a Reynolds number (based on the nozzle width, mean exist velocity and air viscosity) of 5000. The nozzle width is $d_0 = 100$ mm and mean exist velocity is $U_0 = 0.7$ m/s. A plane of flow domain was illuminated by a double-pulse Nd: YAG laser and the images were recorded with a CCD camera (8 bits-640×480 pixels) with a frame rate of 30 frames/s. The spatial resolution of the images is about 0.4 mm/pixel and the physical dimensions of the images were about 256×192 mm (width x height). In Fig. 5, one of the two consecutive raw digitized PIV images is shown.

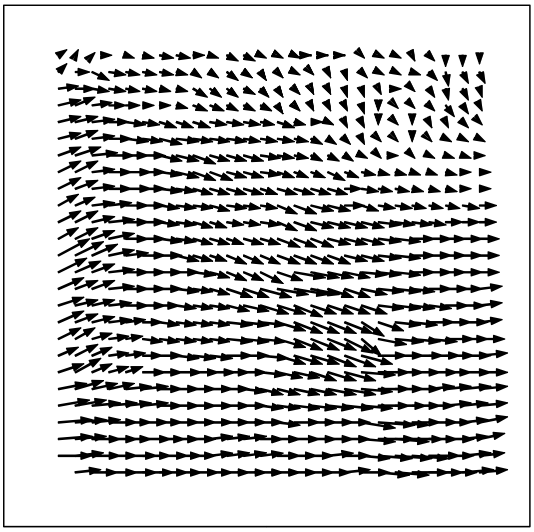


Fig. 4. Velocity vector field obtained from the cross-correlation of compressed PIV image pair.

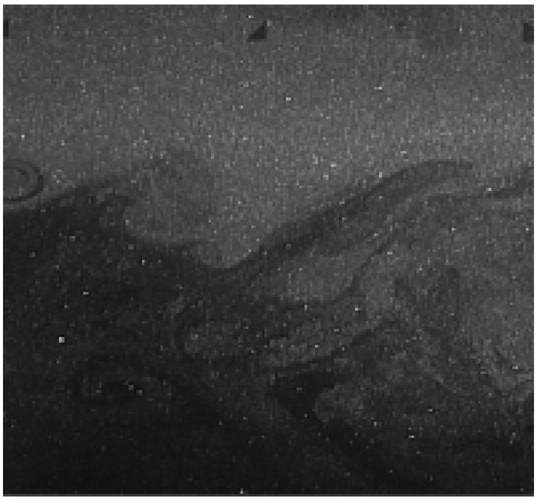


Fig. 5. Jet image.

A compressed jet image with a 16:1 compression ratio is shown in Fig. 6. As compared with the original image in Fig. 5, the noise in the image can be reduced and particles may be clearly observed. Then the windowed cross-correlation PIV method is used to process the original images and compressed images at a spatial resolution of 24×24-pixel with 50% overlap between adjacent interrogations. Figure 7 shows the result of velocity field that is obtained from the compressed images with compression ratio 16:1. For the purpose of comparison, the velocity vector field obtained from the original images is shown in Fig. 8. We prefer to present the raw data. A reduced number of erroneous vectors can be realized by the wavelet image compression technique in comparison with Fig. 8. We can easily remove these erroneous vectors by average neighboring reasonable vectors. This result indicates that the higher spatial resolution can be achieved by the wavelet image compression technique without losing information of

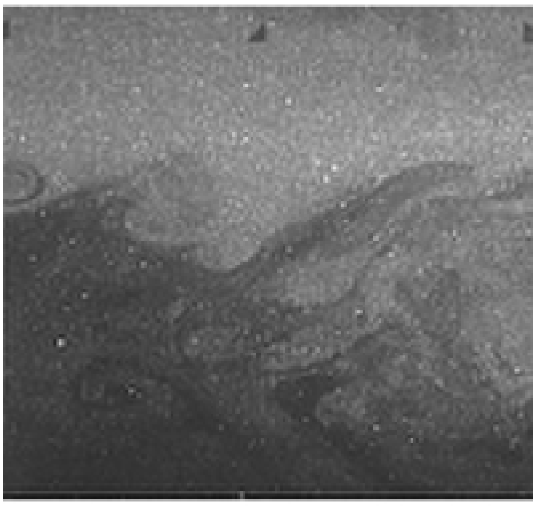


Fig. 6. Reconstructed jet image with a 16:1 compression ratio.

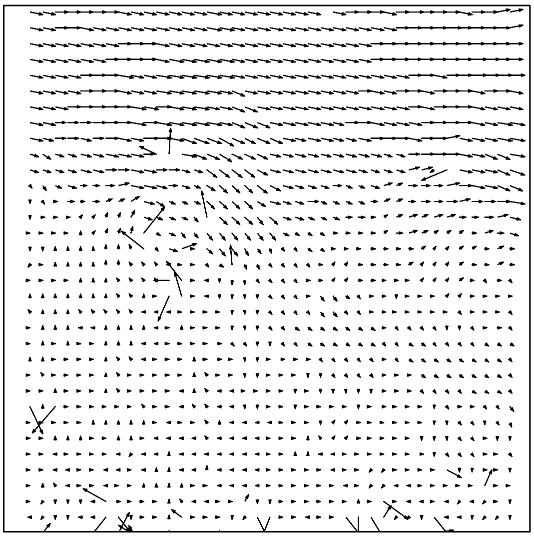


Fig. 7. Velocity vector field of jet obtained from compressed image pair with a 16:1 compression ratio.

flow field structure. Figure 9 shows the cleaned velocity vectors of jet that are obtained from compressed images with a 16:1 compression ratio after post-processing. It is evident that the reasonable velocity vectors of experimental jet can obtained even the images are compressed with the higher compression ratio.

5. Conclusions

(1) Wavelet packet technique could provide a better compression performance than wavelet compression technique in the image process.

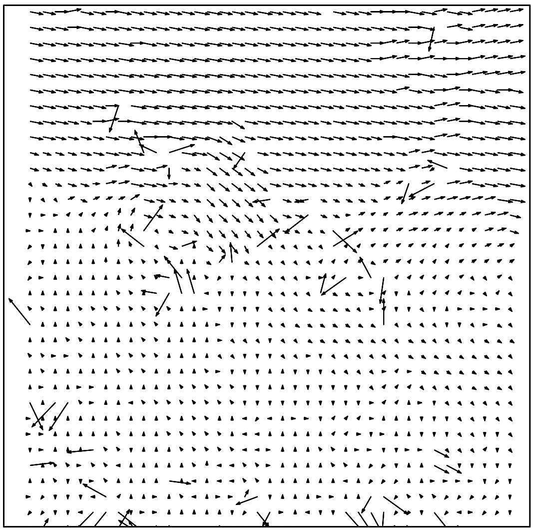


Fig. 8. Velocity vector field of jet obtained from original image pair.

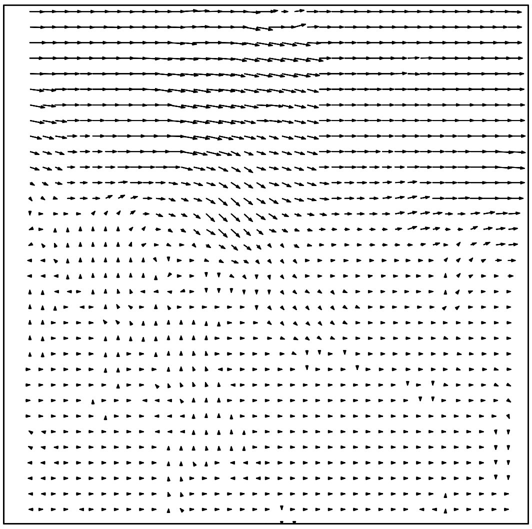


Fig. 9. Velocity vector field of jet obtained from compressed image pair with a 16:1 compression ratio, after cleaning.

(2) A higher compression ratio of 64:1 was realized without losing significant flow information in PIV processing.
(3) When wavelet packet compression technique was applied to the experimental PIV images of jet flow, a reduced number of erroneous vectors and higher compression ratio can be realized.

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