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PSP를 이용한 압력측정에서의 상관법에 의한 이미지 등록

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Correlation Based Image Registration for Pressure Sensitive Paint

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Abstract

A new algorithm, CBIR (Correlation Based Image Registration) was proposed to improve the resolution of image registration for PSP (Pressure Sensitive Paint). The local displacement vectors were obtained by finding the displacement which maximizes the cross-correlation between two interrogation windows of 'wind-off' and 'wind-on' images. A recursive multigrid processing was employed to increase the non-linear spatial resolutions. The variations of image were precisely measured without identifying the control points.

Key Words : Pressure Sensitive Paint(압력 감응 페인트), Image Registration(이미지 등록), Transform Function(변환 함수), Multigrid Method(다중격자 법), Control Point(기준점)

1. Introduction

Pressure measurement technique using pressure-sensitive paint (PSP) has made significant improvement during last decades. PSP is a luminescent surface coating for which the luminescence intensity is related to the surface air pressure. The main advantage of the PSP technique is that it can provide continuous 'field measurement' with high spatial resolution as opposed to the discrete 'point measurement' with conventional taps or transducers. Because the use of PSP can eliminate the need for a number of pressure taps, wind tunnel models could be constructed faster and with less expense (Bell *et al.*, 2001).

Most common technique using PSP is an intensity ratio method, where the surface pressure distribution is obtained by ratioing the intensity of two images between 'wind-off' and 'wind-on'. The undesirable effects of non-uniform coating thickness and non-uniform distribution of illumination can be eliminated by using the relative ratio between two images. However, a significant error of the intensity ratio can be induced if there is a small displacement or deformation between two images (Donovan *et al.*, 1993). In order to acquire accurate pressure distribution using the intensity ratio, the displacement and deformation of the model between two images should be corrected. This process of rearranging the pixels is called 'image registration' (Bell and McLachlan, 1996).

2. Conventional Method

In order to rearrange the pixels, it is usual to rely on a single global transformation between the coordinates of 'wind-off' (x', y') and 'wind-on'

(x, y). The most commonly used transform function is a polynomial transform function (Donovan *et al.*, 1993). The usual way to determine the coefficients is to measure the image coordinates (x,y) and (x',y') of fiducial marks,

$$x=\sum_{i,j=0}^{n} a_{i,j} x'^{i} y'^{j} \qquad (i+j\le n) \qquad (1)$$

$$y=\sum_{i,j=0}^{n} b_{i,j} x'^{i} y'^{j} \qquad (i+j\le n) \qquad (2)$$

called control points. In Eqs. (1) and (2), the number of unknown coefficients is ${}_{n+2}C_2\times 2$, and the required minimum number of control points for solving these equations is ${}_{n+2}C_2$. Once the coefficients are obtained, the intensity of each pixel in the original image is displaced

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to the transformed image with respect to the transform function. The main disadvantage of this approach is that the transform function is global. If the model movement contains nonlinear local deformation or warp, the higher-order polynomial is required. In that case, the accuracy of the transformation is limited due to the unstable nature of high-order polynomials.

The study of image registration using local information was made to overcome this limitation. For example, Shanmungasundaram and Samareh-Abolhassani (1995) developed a method using the Delaunay triangulation. The image is divided into triangle patches and then the pixels inside the triangles are parametrically transformed. This approach can give an accurate result for the case where local deformation is included. However, this method requires a number of control points and all control points should be matched between 'wind-off' and 'wind-on' images for the Delaunay triangulation. This can be an obstacle to apply the automatic detection of control points.

In the afore-mentioned methods, reliable identification of control points is the principal bottleneck in automated PSP data reduction. It is important to locate control points and establish the correspondence of control points in the 'wind-off' and 'wind-on' images precisely because an error in locating a single control point can have a global effect on the transformed image. Many fast automatic algorithms were developed (Le Sant *et al.* 1997), but few algorithms were robust enough to be successful more than 90% of the time (Bell *et al.*, 2001).

To remove the needs for control points, Weaver *et al.* (1999) proposed quantum pixel energy distribution algorithm with spatial anomalies used for embedded control points. They applied an aerosol mist of gray paint over the base coat before the application of PSP top layer. In this method, the image pixel is shifted pixel by pixel until the total count difference between all pixels in two images is minimized. However, the process of searching optimal value is extremely time-consuming and the complete optimization of this algorithm is not easy.

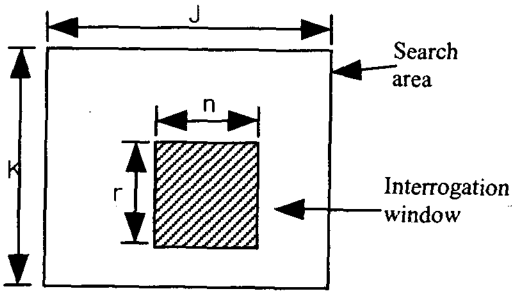


Fig.1 Relationship between search area and interrogation windows

3. Correlation Based Image Registration

In the present study, a new method of correlation based image registration (CBIR) for PSP image registration is proposed. In general, the maximization of

$$R(u,v)=\frac{\sum_{j=1}^{J}\sum_{k=1}^{K}I_1(j,k)\cdot I_2(j-u,k-v)}{\sqrt{\sum_{j=1}^{J}\sum_{k=1}^{K}I_1^{\,2}(j,k)\}^{1/2}}\cdot\sqrt{\sum_{j=1}^{J}\sum_{k=1}^{K}I_2^{\,2}(j-u,k-v)}} \tag{3}$$

cross-correlation between two images is widely used to estimate the motion of the object. In the PSP measurement, it has been thought that the pixel-intensity matching methods were not adequate for maintaining the intensity variations. However, the use of embedded control points made it possible to apply the pixel matching algorithm to the PSP measurement (Weaver *et al.*, 1999). In the present study, a layer of diffuse control points, called 'speckle coat' is formed by spraying gray paint coarsely over the base coat.

In the CBIR method, an image plane is divided into squares of n x n pixels (Fig. 1). Here, n is the m-th power of 2 and this square of pixels is called the 'interrogation window'. In each interrogation window, the displacement vector is obtained to represent the local motion of the object by calculating cross-correlation (Eq. (3)). The displacement of an interrogation window in the 'wind-off' image equals the displacement of the peak in the cross-correlation plane between the 'wind-off' and 'wind-on' images. To reduce time for computing the cross-correlation, a fast Fourier transform (FFT) is applied to both windows of the 'wind-off' and 'wind-on' images with the same size and position. The displacement of pixels inside the interrogation window is interpolated linearly with the displacement vectors of four nearest windows. This can be summarized as follows:

1. The 'wind-off' and 'wind-on' images are divided into n x n interrogation windows.
2. The FFT of both windows is calculated.

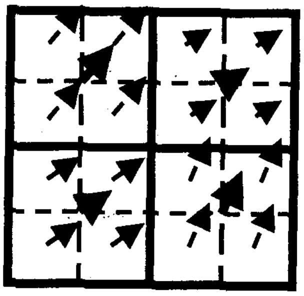


Fig.2 Application of coarse result (solid line arrows) to build a finer predictor (dotted line arrow)

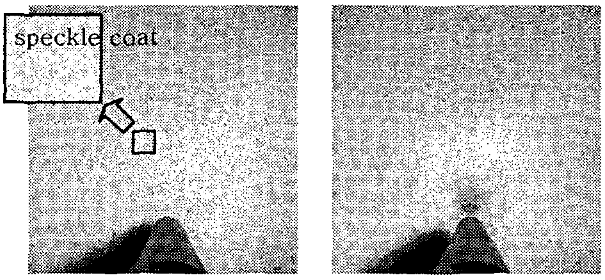
3. The cross product of window of the 'wind-off' image FFT and the window of the 'wind-on' image FFT conjugate is computed.
4. The location of the maximum is found in the correlation plane. (The displacement vector is determined.)
5. The displacement of the pixels inside the interrogation window is calculated with bi-linear interpolation with four nearest displacement vectors.
6. The 'wind-on' image is transformed pixel by pixel along the determined displacement vectors.

If the model motion is highly nonlinear, it is desirable to reduce the window size to minimize the linear interpolation error and to describe the local deformation precisely. However, the speckle-pair-loss due to the same window size and position of two windows makes the simple correlation unsuitable for a small window and due to aliasing of FFT, the minimum window size must be larger than four times of the window displacement. To overcome this problem, a recursive multigrid processing with discrete window offset (Scarano and Riethmuller, 1999) is applied in this study. The main idea of this method is to shift the window of the 'wind-on' image on the basis of predicted displacement. When the displacement vector $\delta = (\delta x, \delta y)$ is estimated, the window of the 'wind-on' image can be selected with a relative offset in order to maximize cross-correlation. To predict the displacement vector, the result with the coarse windowing is used as a predictor (Fig. 2). A finer windowing is made by halving the windows in both directions and the predictor is applied to the window offset by means of simple substitution of the previous iteration result.

In addition, the correlation based correction algorithm, which multiplies the correlation planes of two adjacent windows, is applied to increase SNR of the correlation plane (Hart, 2000).

4. Results

For the purpose of illustrating the operation of the CBIR method, an impinging jet on a flexible plate was set up. The plate material was vinyl film (thickness of 0.13mm) and four corners were fixed loosely so that some displacement and deformation are available. The impinging angle was 45° and the height was 1.5 times with respect to the nozzle diameter of 6mm. The exit velocity of the nozzle was 200m/s. Raw images of 'wind-off' and 'wind-on' with the impinging jet are shown in Fig. 3. Close inspection of Fig. 3 shows that speckles were coated on the plate.



(a) Wind-off (b) Wind-on

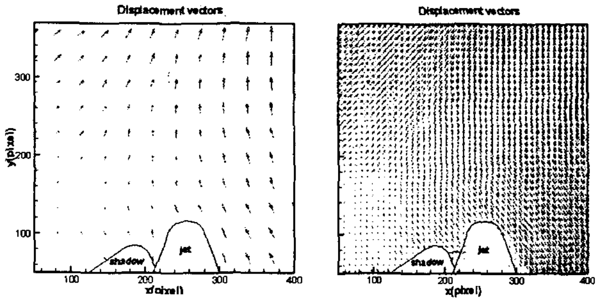
Fig.3 PSP with speckle coat: raw images of wind-off and wind-on condition

When an arbitrary displacement and deformation was given to the impinging surface by the jet, the displacement vectors were obtained by two methods in Fig. 4; (a) the standard correlation method, and (b) the recursive multigrid method. It is shown that the size of the interrogation window of the recursive multigrid method is reduced from 32x32 to 8x8 pixels and accordingly the spatial resolution was increased 16 times with desirable accuracy.

Figure 5 shows the comparison of the intensity ratio between 'wind-off' and 'wind-on' images. If image registration has not been applied, it is impossible to recognize the pressure distribution. However, in Figs. 5(b), and (c), clear image which represents the pressure distribution was obtained by image registration. In Fig. 5(b), image was registered by the 2nd order polynomial transform function with automatically detected 24 control points. In Fig. 5(c), the image was well-registered by the present CBIR method without any control points on the plate.

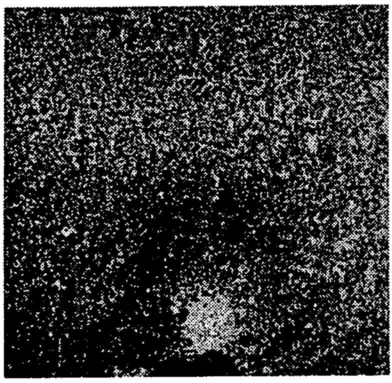
5. Conclusions

In the PSP measurement using intensity ratio method, it is essential to correct the motion between 'wind-off' and 'wind-on' images. The conventional image registration methods using the single global transform function have a limitation for describing a local

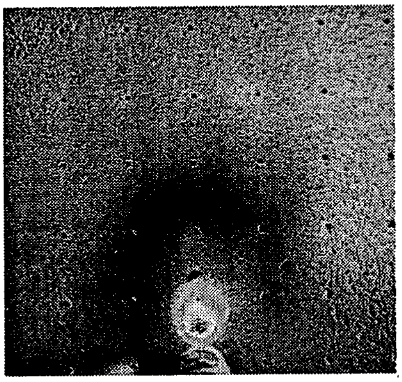


(a) Standard cross-correlation method (b) Recursive multigrid method

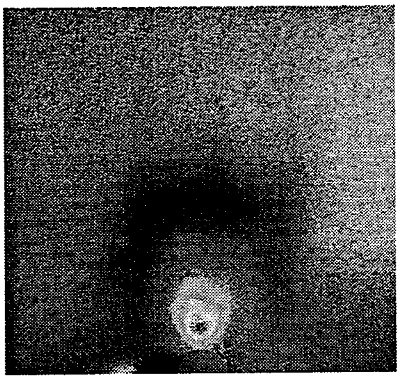
Fig. 4 Displacement vectors of interrogation



(a) No image registration



(b) Conventional method



(c) CBIR

Fig.5 Intensity ratio of the impinging jet

deformation. Moreover, the identification of control points interrupts the fully automated data reduction. In the present study, a new correlation based image registration (CBIR) was proposed for improving these drawbacks of conventional image registration methods. CBIR uses a cross-correlation between two interrogation windows in 'wind-off' and 'wind-on' images for finding local displacement vectors. A speckle coat which was sprayed over the base coat enabled to apply correlation method in a small interrogation window. A recursive multigrid processing was employed to increase spatial resolution and to describe a non-linear motion. It was found that well-registered images were produced by CBIR without any help of control points

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