A NEW MOTION COMPENSATION TECHNIQUE FOR INFRARED STRESS MEASUREMENT USING DIGITAL IMAGE CORRELATION

T. Sakagami, N. Yamaguchi, S. Kubo
Department of Mechanical Engineering, Graduate School of Engineering, Osaka University
2-1, Yamadaoka, Suita, Osaka 565-0871 Japan

T. Nishimura
JFE Steel Corporation
1, Kawasaki-dori, Mizushima, Kurashiki 712-8511 Japan

ABSTRACT
A new technique was developed for motion compensation in thermoelastic stress measurement. Brindled pattern with different infrared emissivities was applied on the test sample for the motion analysis. Infrared images of the brindled pattern were taken under the same loading condition as the thermoelastic stress measurement. Displacements and deformations on the test sample were analyzed by the digital image correlation method based on the information of the movement of the brindled pattern. Automatic motion compensation was conducted in the subsequent thermoelastic stress measurement based on the results of displacement measurement. Another motion compensation technique without the brindled pattern was proposed, in which visible images were taken by the digital camera as well as the infrared camera. The field of view and the framing sequence of the visible and infrared camera were completely synchronized. The full field displacement measurement was conducted by the digital image correlation method using visible images, then the motion compensation of the infrared images were carried out based on this displacement data. The feasibility of the proposed motion compensation techniques was experimentally demonstrated.

Introduction
Numerical stress analysis techniques such as the finite element method (FEM) and the boundary element method (BEM) enabled us to evaluate stress distribution of structural components even with complicated shapes. However, we often encounter difficulties in conducting numerical stress analyses in actual components, because loading conditions or boundary conditions of the objective components cannot be easily prescribed. Experimental techniques of stress evaluation are then very important. Thermoelastic stress analysis (TSA) has been widely used as full-field experimental stress evaluation method [1]. Especially it is employed as a useful tool for the evaluation of stress concentration at notches or welding parts in the components. In the TSA techniques, however, displacement sometimes causes an experimental error in infrared stress measurement, when a large deformation or a steep stress change is observed in the field of view (FOV). Thus motion compensation techniques, such as optical techniques with moving mirrors or lenses, or computational techniques by the post data processing based on the movements of characteristic points in infrared images, have been developed and have been installed to the commercially available stress analysis systems. However, it is not possible to conduct full field motion compensation. In this study, two full field motion compensation techniques are proposed based on the digital image correlation method.

Full Field Motion Compensation Technique Based on Digital Image Correlation
In this paper, two different full field motion compensation techniques are proposed based on digital image correlation method. One technique uses only infrared images measured by the infrared thermography. The digital image correlation for the motion analysis is applied only to the sequential infrared images. The other technique uses both visible images and infrared images. Visible sequential images are taken by the high speed digital video camera synchronized to the sequential infrared images. Motion analysis by the digital image correlation is applied to the visible data and the analyzed displacement data is forwarded to the infrared stress analysis. Details of these two methods will be described below.
In the motion compensation using only infrared images, brindled pattern with different infrared emissivity values is applied on the test sample. This brindled pattern is used for the motion analysis for avoiding unsuccessful digital image correlation due to nondescript infrared images without any characteristic pattern. In laboratory experiments, infrared images of the brindled pattern are taken under the same loading condition as the thermoelastic stress measurement. Displacements and deformations on the test sample are analyzed by the digital image correlation method based on the information of the movement of the brindled pattern. In the subsequent thermoelastic stress measurement, the brindled pattern is removed and flat-black paint is applied on the sample surface. Automatic motion compensation is conducted in the thermoelastic stress measurement based on the results of displacement and deformation measurement. This motion compensation technique requires infrared data acquisitions twice in the same loading condition for motion analysis and thermoelastic stress analysis. One might encounter the difficulties that experiment can not be conducted twice, in the case of nonrecurring experiments such as random loading experiment or impact loading experiment. It is noteworthy that experiment can be carried out in one time in the following cases. (1) If the emissivity correction is conducted for the brindled emissivity pattern, the infrared intensity distribution can be accurately calibrated by the post processing. (2) The brindled pattern contains spots made by flat-black paint, where the emissivity value is almost one. By the full field motion compensation and the identification of the flat-black spots, accurate thermoelastic stress measurement can be conducted at least on these flat-black spots. As the result, stress distribution can be sparsely obtained. A complete stress distribution can be constructed by interpolating this sparse stress distribution.

The other motion compensation technique uses both visible images and infrared images. This technique doesn't require application of any brindled emissivity pattern. Instead sequential visible images are taken by the high speed digital video camera whose FOV and framing time are completely synchronized with those of infrared images. Full field displacement measurements are conducted in every captured frame by the digital image correlation method using visible images, then the motion compensation of the infrared images were carried out based on this displacement data.

**Experimental Setup**

In this paper the experimental results obtained by the full field motion compensation technique using infrared data with brindled emissivity pattern are shown.

Configurations of the employed steel specimen with a circular hole are shown in Figure 1. Material of the specimen was 590MPa class hot rolled steel. Brindled pattern with different emissivity values was installed using spray lacquer of flat-black and gray colors as shown in Figure 2. Infrared camera with InSb array sensor (Indigo Phoenix Mid) was employed. The noise equivalent temperature difference of this camera was 25mK. The framing speed was set to be 100 frames/s.

![Figure 1 Configurations of employed specimen](image1.png)

![Figure 2 Test sample with brindled pattern drawn by black and gray spots](image2.png)
In the digital image correlation, generally used subset comparing technique was employed. Hierarchical computation, that is a rough estimation by the subset matching followed by parameter identification by the Newton-Raphson method [2], was employed. In the rough estimation, only subset’s rigid motion without deformation was assumed. The most plausible displacement of the subset center was searched based on the least-squares residual criterion. The following square sum of residuals $R$ was calculated for variously assumed displacement of the subset.

$$R = \sum_{i} (F(x, y) - G(x^*, y^*))^2$$  

Here $(x, y)$ denotes the coordinate of the subset center, $u$ and $v$ are the displacement for the subset centers in the $x$ and $y$ directions respectively. $(x^*, y^*)$ denotes the coordinate of the subset center in the second image after the displacement. $F(x, y)$ and $G(x^*, y^*)$ are infrared intensity values at $(x, y)$ and $(x^*, y^*)$, respectively. Square sum was calculated for all pixels in the subset.

In the second stage, the Newton-Raphson method was employed for more precise image correlation. In this stage, deformation of the subset was considered in addition to the rigid motion. $(x, y)$ and $(x^*, y^*)$ were related by the deformation occurred between capturing two infrared images as follows.

$$x^* = x + u + \frac{\partial u}{\partial x} \Delta x + \frac{\partial u}{\partial y} \Delta y$$

$$y^* = y + v + \frac{\partial v}{\partial x} \Delta x + \frac{\partial v}{\partial y} \Delta y$$

where $\Delta x$ and $\Delta y$ are the distances from the subset center to point $(x, y)$. The most plausible displacement of the subset obtained by the rough estimation was set as the initial values of the displacement in the correlation search by the Newton-Raphson method. The size of subset was set to be $36 \times 36$ pixels. The image correlation was performed to determine values of displacement and gradient terms based on the following correlation function $R$.

$$R = \frac{\sum_{i} F(x, y) \cdot G(x^*, y^*)}{\sqrt{\sum_{i} F^2(x, y) \cdot \sum_{i} G^2(x^*, y^*)}}$$

**Experimental Results of Motion Compensation**

Feasibility investigation of the full field motion compensation was started from simple experiments, in which motion compensation was conducted under parallel movement condition without deformation. Plate specimen with brindled pattern was installed on the parallel moving stage, and the FOV was set on the area which didn’t contain circular hole. Specimen was moved back and forth for the distance which was equivalent to 19 pixels in the FOV. Experimental results are shown in Figure 3. Figure 3(a) is the infrared image before displacement, and Figure 3(b) is the infrared image after displacement without motion compensation. It is found that brindled patterns in the FOV do not coincide due to the displacement. Digital image correlation was applied to these two infrared images and motion compensation was conducted for the infrared image after displacement. The result is shown in Figure 3(c). It is found that the location of the brindled pattern after displacement coincides very well with that before displacement.

Further the feasibility of the full field motion compensation was investigated under the elastic deformation condition. Plate specimen with brindled pattern was installed to the hydraulic servo test machine. The FOV was set on the area which didn’t contain circular hole. Fully reversed tension and compression cyclic load (stress ratio $R=-1$) was applied to the specimen. Loading range was set to be from -9.8kN to 9.8kN. Infrared images were captured at every 1.96kN increment of the applied load, and the motion compensation was conducted for all infrared images. Obtained experimental results are shown in Figure 4. Figure 4(a) is the infrared image obtained at no-loading, and Figure 4(b) is the infrared image obtained at 9.8kN loading.
without motion compensation. In this case it was found that maximum displacement due to deformation and rigid movement was 9 pixels. Figure 4(c) shows the result of motion compensation by the digital image correlation. Very good coincidence of the brindled pattern is found in the infrared image with motion compensation demonstrating the feasibility of the motion compensation under elastic deformation.

![Figure 3 Results of motion compensation under parallel movement without deformation](image)

![Figure 4 Results of motion compensation using infrared images for brindled pattern under tensile load](image)

**Experimental Results of Infrared Stress Analyses with Full Field Motion Compensation**

Feasibility of the full field motion compensation was investigated in the thermoelastic stress analysis as well as in the 2f lock-in analysis for local plasticity identification [3]. Experiments were conducted under two different loading conditions, i.e., an elasticity condition and a local plasticity condition. In the elasticity condition, fully reversed tension and compression cyclic load (stress ratio $R = -1$, loading frequency 10Hz) was applied to the specimen. The loading amplitude was set to be 9.8kN, so that no plastic deformation was found at the stress concentrated notch root. In the local plasticity condition, on the other hand, the loading amplitude increased to 13.8kN, so that local plasticity was observed at the notch root. Framing rate of the sequential infrared images was set to be 140 frames/s, and lock-in data processing for the thermoelastic stress analysis and the 2f lock-in analysis was performed for sequential infrared data in 4 cycles.

Experimental results obtained under the elasticity condition are described first. Results of lock-in data processing without motion compensation are shown in Figure 5. Significant edge effect noises are found at circular notches both in the thermoelastic result and in the 2f lock-in result. It is found that the distributions of lock-in values are very noisy due to spot-like noises in the stress concentrated area. Results of lock-in data processing with motion compensation are shown in Figure 6. It is found that the edge effect noises disappear in the both images, and the spot-like noises in the stress concentration area are reduced. Successful noise reduction can be conducted by the full field motion compensation using digital image correlation.

Experimental results obtained under the local plasticity condition are shown in this paragraph. Results of lock-in data processing without motion compensation are shown in Figure 7. It is found that the edge effect noises become significant due to the increasing displacement at the edge of the circular hole. Spot-like noises also become significant. On the other hand, results of lock-in processing with motion compensation are shown in Figure 8. It is found that edge effect noises and spot-like noises are drastically attenuated by the motion compensation processing in the both cases. Especially it is noteworthy that concentration of 2f lock-in values, indicating the existence of local plasticity, can be observed at the notch root. Accurate 2f lock-in measurement was not possible until using motion compensation technique. Detection of very small temperature change due to the heat generation induced by plastic deformation became possible, since accurate measurement of the
infrared intensity distribution was conducted by the full field motion compensation technique. Further the distribution of the lock-in values in the thermoelastic analysis on the line A-B in Figure 8 is shown in Figure 9. The broken line shows the lock-in values without motion compensation, and the solid line shows the lock-in values with motion compensation. It is found in the figure that successful noise reduction is conducted by the motion compensation technique using the digital image correlation.
Conclusions

In this paper, two different full field motion compensation techniques for the infrared stress measurement were proposed based on the digital image correlation method. One technique uses only infrared images measured by the infrared thermography. The digital image correlation for the motion analysis is applied only to the sequential infrared images taken for objects with brindled emissivity pattern. The other technique uses both visible images and infrared images. Visible sequential images are taken by the high speed digital video camera synchronized to the sequential infrared images. Motion analysis by the digital image correlation is applied to the visible data and the analyzed displacement data is forwarded to the infrared stress analysis. The feasibility of the motion compensation technique using infrared images of the brindled emissivity pattern was experimentally demonstrated for the thermoelastic stress measurement as well as the 2f lock-in measurement for the local plasticity identification.

Acknowledgments

This research was partially supported by the Grant-in-Aid for Exploratory Research (Project Number 17656041) by the Japan Ministry of Education, Culture, Sports, Science and Technology. The authors are grateful to Prof. Izuru Nishikawa of Osaka Institute of Technology for his instruction and cooperation in developing digital image correlation programs.

References