Digital image correlation and distortion correction for creep deformation measurement of high temperature components

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Abstract This paper presents a new high temperature DIC system for creep measurement. A telecentric lens is used to acquire sequential images of a test piece at high temperature. An Adaptive Image Filtering (AIF) algorithm is developed to suppress image distortion while maintaining the spatial resolution of the original images. Following AIF, an optimal image is formulated to represent each set of sequential images, which are acquired over different time periods. DIC is used to calculate the strain between different image pairs. Preliminary results from controlled high temperature tests have demonstrated the effectiveness of the technique.

Introduction

The conventional method of measuring the variation of creep properties is to take small samples, and carry out individual creep tests in which the strain response of the test sample with time is measured using extensometers or high temperature strain gauges. Such deformation data is incorporated into finite element creep simulation analyses by many researchers [1, 2]. However, it may not be feasible to extract reasonably sized test samples from the required regions. Moreover, it may be argued that due to the change in constraint conditions, the behaviour of the extracted samples will be different from the behaviour of the same material in situ. Hongo et al [3] successfully developed a system based on a moiré interferometry technique to measure the creep strain distribution in a thick welded joint but this required tedious specimen preparation and interruption during the creep tests. As one of the non-contact measurement methods, the digital image correlation (DIC) technique was successfully employed by many researchers to map the strain variation spanning cross-weld specimens during room temperature tensile tests [4,5]. In general, for high temperature measurement, the air flow-field located between the test specimen and the camera optics is characterised by a turbulent velocity superimposed on the bulk natural convective flow-field. This flow-field is driven by the temperature gradient. For creep measurement, the recorded images will be affected by this turbulence, which randomly changes the refractive index along the optical transmission path, generating geometric distortion, in the form of a space and time varying blur. Several signal processing approaches have been proposed to solve this problem [6-7]. The approaches attempt to restore a single high-quality image from an observed frame sequence distorted by air turbulence. Most research performed to date has been carried out under the assumption that both the test sample and the image sensor are static. Hence, the distortion is due to the air turbulence alone. This imaging process can be described as:

$$G_n[x] = \left(F \otimes h_{n,x} \otimes h\right)[x] + N_n[x] \qquad (1)$$

where $\otimes$ represents a convolution operator. The vector $x = (x, y)^T$ denotes a 2D spatial domain. F, G_n, and N_k denote the ideal image, the n-th observed image, and the noise, respectively. $h_{n,x}$ is the spatial varying point spread function (PSF) for the position x in the n-th frame. h is the spatial invariant diffraction limited PSF, typically due to sensor optics and settings. Restoring the high-quality image F is a challenging task, because a static object is deformed in an observed image by the optical turbulence, and this deformation is not constant for the image position or over time. Therefore, the unknown $h_{n,x}$ is changing both spatially and temporally. High shutter speed is favoured to avoid motion blurring caused by air turbulence. The Adaptive Imaging Filtering (AIF) method is developed and used to find a single high-quality image from an observed image sequence distorted by air turbulence.

Adaptive Imaging Filtering (AIF) methods

When there is no motion blurring and the spatial invariant diffraction is limited, the object appearance can be estimated by simply averaging the observed frames in the image sequence. The averaging operation of the frames without global motion is equivalent to the Gaussian convolution of the ideal image, if the local motion effect caused by the air turbulence is a normal distribution with zero mean and standard deviation σ:

$$\frac{1}{N}\sum_{k=1}^{N} G_k(H(x, p_k)) \approx F(x) \otimes N(0, \sigma^2) \qquad (2)$$

where $G_k(H(x,p_k))$ denotes the observed k-th frame in total N frames with the local motion effect of $H(x,p_k)$. $F(x)$ represents the ideal image appearance. $N(0,\sigma^2)$ is a Gaussian kernel of zero mean and standard deviation of σ.

Although the averaged image obtained from an image sequence tends to eliminate the local motion effect caused by the air turbulence, simple averaging also results in a loss in image details. This means that the motion effect caused by the optical turbulence cannot be assumed to have a normal distribution with zero mean and standard deviation σ. To address this problem and improve the image quality, a new method, adaptive image filtering (AIF) has been developed. With the AIF technique, image vectors (xk) are used to form an image data matrix. Each column in this matrix is an image vector. It is understood that when an object is subjected to high temperature, the image intensity of every pixel will change randomly over time. However for the majority of the time, the image pixels will remain at a fixed location. By plotting the grey scale intensity of each single pixel taken from each independent observed frame into a frequency (probability) domain, a stochastic model can be created. Thereby, instead of assuming a normal distribution with zero mean and standard deviation σ, the true probability distribution of each pixel can be analysed and the statistical mode of each pixel set recorded to reconstruct the ideal image. This stochastic image analysis process is termed, Adaptive Image Filtering (AIF).

AIF experimental test

A simulated high temperature experiment was performed in which a P91 creep test specimen was heated to 650°C. A regular grid (speckle) pattern was fabricated on the surface of the specimen by laser micro cladding. Figure 1 shows the experimental setup. A Phantom V9.1 high speed camera was used to capture the video images during the test. Two video clips were recorded at a frame rate of 1,000 fps and a spatial resolution of 1600x1200 pixels. The first video clip covered a time period of 40 seconds. Approximately 40 minutes later, the second video was taken, which covered a time period of 50 seconds with the same camera and experimental settings as the first video clip. Still images were then extracted from the video clips for strain analyses.

Figure 1 Experimental setup in a simulated high temperature test.

Effectiveness of AIF

The incremental strain field between the two image sequences was calculated using the Istra 4D software system (Dantec Dynamics GmbH, Germany). Figure 2(a) shows the strain distribution from the two mean images. Figure 2(b) shows the result from the two AIF images. Overall, both results show similar strain distributions. However, the result from AIF images has a higher spatial resolution compared to the result obtained from the mean images. This is because simple averaging will tend to smooth out the spatial details of the image. In contrast, the AIF algorithm will maintain the spatial details, while suppressing the air flow disturbance. This has demonstrated the effectiveness of the AIF algorithm for creep strain measurement.

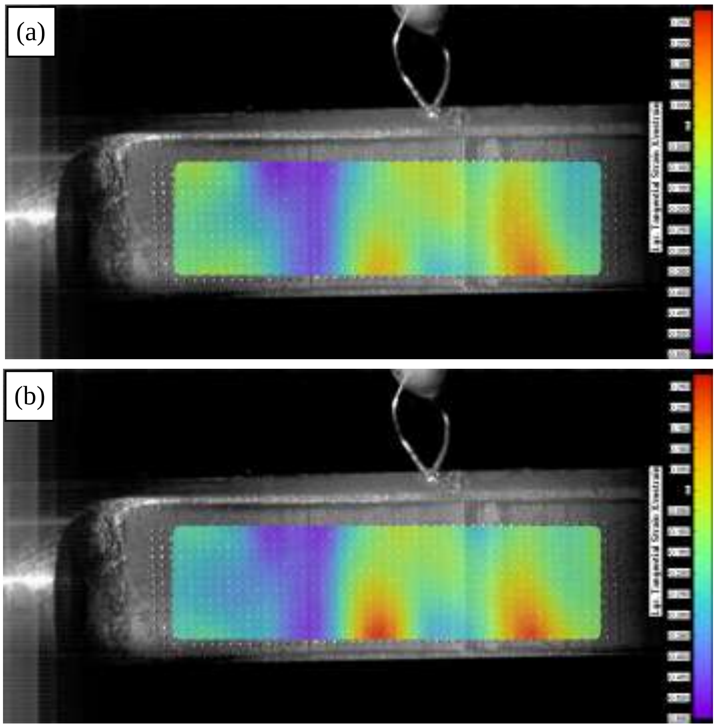

Figure 2 Incremental strain field between two image sequences. (a) Strain distribution calculated from mean images. (b) Strain distribution calculated from AIF images

Conclusions

This paper presents a new high temperature DIC system for creep measurement. A Canon macro lens is used to acquire sequential images of a test piece at high temperature. An Adaptive Image Filtering (AIF) algorithm is developed. It is based on probability of intensity distributions, and has the advantage of suppressing image distortion while maintaining spatial resolution of the original images. After AIF, an optimal image is formulated to represent each set of sequential images which are acquired over different periods of time. DIC is used to calculate the strain between different image pairs. Preliminary results from controlled high temperature (600-700°C) experiments on P91 steel samples demonstrated the effectiveness of the technique and algorithm.

References

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