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Influence of motion compensation on lock-In thermographic investigations of fatigue crack propagation

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Lock-in thermography measurements are influenced by rigid body motion of the specimen due to the mechanical loading. These motion affects asymmetries in the measured temperature fields in the vicinity of the crack. This effect can be eliminated by a motion compensation procedure. Unfortunately, the results of the lock-in thermography are affected by this procedure, too. In this work the influence of the motion compensation procedure on fatigue crack propagation experiments, its gains and disadvantages are studied in a qualitative and quantitative manner. A new method for an automatic determination of the crack length in thermographic measurements is introduced and compared with potential drop measurements. Beside the known thermoelastic and dissipative effects, higher harmonic responses in the discrete Fourier transformation are analyzed and discussed.

1. Introduction

Infrared thermography is a contact free imaging method to measure temperatures on surfaces. This technique is widely used to gather information for a better understanding of plastic deformation and fracture of metallic materials. Haneef et al. [1] found that in tensile tests the temperature increase in the necking region rises with the strain rate. Amokhtar [2] and Ranc [3] used IR-thermography to investigate the formation and the dynamics of Portevin-Le-Chatelier bands in an aluminum alloy and a carbon-manganese steel. The IR thermography is often used to study the fatigue behavior of materials. Many authors use the measurement of the specimen temperature with IR thermography to determine the fatigue limit of steels [4–7]. For the determination of the fatigue limit with lock-in thermography methods were developed by Shiozawa [8] and Li [9].

Another interesting field of application for IR thermography is the evaluation of elastic stress fields according to the thermo-elastic effect [10] and the investigation of dissipative energies with the double frequency method proposed by Sakagami [11]. The determination of dissipated energy is used to evaluate the crack initiation [12–13] as well as effects in crack propagation experiments [14–17]. Previous fatigue experiments by Urbanek and Bär [18] showed deformed temperature fields at high loading levels. These deformations can be eliminated by a correction of the rigid body movement of the specimen. Unfortunately the results of the lock-in measurements are influenced by this motion compensation procedure. In this work the effects of the motion compensation on the results of lock-in thermographic measurements are studied in more detail. Furthermore, the higher harmonics of the discrete Fourier transformation are evaluated.

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2. Motion compensation and Lock-In-Algorithm

2.1. Motion compensation

For a lock-in evaluation a sequence of frames is recorded by a thermographic camera during a fatigue experiment. The recording frequency of the camera has to be higher than the loading frequency. The sequence contains several cycles and because the recording frequency is not an integer multiple of the loading frequency, the frames are taken at different loading levels. The mechanical loading leads to a shift of the specimen relative to the camera and therefore the correlation between a point on the specimen surface and a pixel of the camera changes with the loading. This specimen movement needs to be compensated to ensure a local alignment within a sequence and for all recordings of an experiment. A necessary condition is limited propagation of the crack. The crack propagation during a single measurement was in all experiment below 2 Pixel and mostly below 1 pixel. This slight crack propagation does not noticeable influence the results of the thermographic measurements.

Digital image correlation (DIC) with speckle pattern are common used for measuring strain field or deformations with good results. However, the speckle pattern strongly influences the emissivity of the specimen and thus the thermographic measurements. Sakagami mentioned a combined two step method of DIC with thermographic measurement [19]. The objective of this paper is to design a method that only requires a single measurement. Therefore, a motion compensation technique was chosen that combines both, detectability of motion and measurability of surface temperature.

The motion compensation algorithm used in this work is divided into four parts: firstly an edge detection, secondly a cross correlation, thirdly smoothing and averaging of the cyclic motion and at last the motion compensation.

For the edge detection the algorithm LoG (Laplacian of Gaussian), described by Fedorova [20], was used. In this algorithm, in the first frame of a sequence the temperature gradients are quantified, these are given by the edge of the painted area in the case of the specimen used in this work. Depending on those gradients a threshold is defined. Using this threshold, a Boolean image representing all edges was made for all frames. In Fig. 1 such a Boolean image is shown. Within the painted area nearly no significant gradients, due to the even-colored surface, are visible, whereas at the edge of the painting clear visible patterns are found.

For the following cross correlation a comparative pattern is needed. Therefore, two areas containing suitable patterns were defined by an upper and a lower alignment zone in the first frame of the first sequence of a recorded series (white rectangles in Fig. 1). For determining the shift between the different frames this pattern is searched in all frames and a convolution of the patterns with the first frame is made. The maximum of the convolution shows the best match between the two patterns, consequently the result is the present position of the frame. By comparing the position of the patterns with the position in the first frame, one gets the shift of the specimen. Fig. 2 shows the result of the movement of the lower alignment zone during a sequence of 990 frames recorded with a frame rate of 99 Hz in an experiment performed with a loading frequency of 10 Hz. In the loading direction a y-shift of up to 9 pixel is observed in this sequence.

Generally, in all experiments the difference in the y-shift between upper and lower alignment zone is below one pixel, hence strain can be neglected in the motion compensation procedure. For the best alignment near the crack, the average shift between upper and lower zone is calculated. The shift perpendicular to the loading direction (x-shift) is near zero due to the parallel guided grips of the testing machine and therefore it can be neglected. The Poisson effect is also neglected referring to the detected low strain.

Before the back shifting the determined shift values are smoothed by a sinusoidal fit. Fig. 3a shows the y-shift of the lower alignment zone (red[1] dots) and the corresponding sinusoidal fit (black line).

In Fig. 3b the deviation between the upper y-shift and the sinusoidal fit (deep blue dots) and the deviation between the lower y-shift and the sinusoidal fit (red crosses) is plotted. The magenta and light blue line represent the average deviation of the respective alignment zone. The deviation is below a half pixel and the mean deviation below a quarter pixel.

In the last step of the motion compensation all frames are shifted according to the sinusoidal fit.

2.2. Lock-In-Method

The core of the lock-in method is to connect a physical quantity with a constant lock-in frequency. In case of fatigue crack propagation experiments, the temperature effects are connected with the loading frequency. The specimen is loaded with a sinusoidal alternating force, therefore the mentioned responding temperature signal also has a sinusoidal form. At that point the discrete Fourier transformation (DFT) steps in. The DFT leads from a discrete sampled signal to a complex spectrum of sine functions representing the change of temperature.

The results of the DFT depend mainly on two parameters: the number of samples N (number of thermographic frames) and the sampling frequency f_s of the thermographic camera. The number of frames gives the number of complex sine functions and the sampling frequency refers to the maximum of the frequency complex spectrum. The frequency resolution is the sampling frequency divided by number of frames (Eq. (1)) [21]:

[1] For interpretation of color in Figs. 3 and 8, the reader is referred to the web version of this article.

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