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Time average synchronization in thermoelastic stress analysis

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Abstract

Thermoelastic stress analysis is noncontacting technique used to obtain stress field on the material surface by measuring changes of the surface temperature by infrared camera. Roughly 1 MPa change in stress state causes a temperature change of 1 mK in steel. Because of extremely small temperature measurement it is necessary to reduce noise. Thermoelastic stress analysis expects adiabatic conditions so that the specimen is usually loaded by cyclic load. Lock-in principle is most frequently method used to extract signal from statistical noise. However, it is necessary to ensure a synchronization link between IR camera and loading machine. In the case of large displacement of the test object it is necessary to be eliminated. In the contribution is presented an algorithm which requires only knowledge of the temporal signal and identification of displacement by using Lock-in technology and time average synchronization to determine infrared field.

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Keywords: thermoelastic stress analysis; lock-in method; time average synchornization

1. Introduction

In the last years thermography has developed from unusually used technique to more popular research method. There are a couple techniques evaluating the time dependence of temperature distribution. The example of this type of dynamic thermography is lock-in thermography. In lock-in method, the heat introduction occurs periodically with a lock-in frequency. Surface temperature is evaluated and averaged over a number of periods [1].

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2. Thermoelastic stress analysis

Lock-in thermography is method which is used in thermoelastic investigations. Thermoelastic stress analysis describes the relation between stress changes and temperature changes of a body in specimens. When the tensile deformation is in the elastic field specimen's temperature increases, on the other hand when there is a pressure load it decreases. In the elastic part it is possible under adiabatic conditions to determine the value of the first stress invariant on the material surface by measuring changes of the surface temperature [2]. Adiabatic conditions are ensured by frequency higher than 2 Hz for steel specimens and more than 20 Hz for aluminum specimens [3].

The equation of thermoelasticity is derived from heat equation ignoring thermoplastic effect [4]:

$$\rho C_\varepsilon \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + T_0 \sum \frac{\partial \sigma_{ij}}{\partial T} \dot{\varepsilon_{ij}}^e \; for \; i,j = 1,2,3, \tag{1}$$

where ρ is the material density, C_ε is specific heat capacity at constant deformation, T is absolute temperature, t is time, k is thermal conductivity, x, y and z are spatial coordinates, T_0 *i*s the initial temperature, σ_{ij} stress tensor, $\dot{\varepsilon_{ij}}^e$ is the rate of change of elastic deformation [5].

To evoke the thermoelastic effect it is standard to load object cyclically so that no heat conduction takes place. Therefore the first term on the right side of (2) can be neglected. Using simple mathematical operations we obtain final form of thermoelastic equation [6]:

$$\Delta T = -\frac{\alpha}{\rho C_p} T_0 \sum_{i=1,2} \sigma_{ii}. \tag{2}$$

where ΔT is temperature change, σ_{ii} are changes in the principal stresses, α is linear coefficient of thermal expansion, C_p is heat capacity at constant pressure.

This equation gives the basics to thermoelastic stress analysis. Roughly 1 MPa change in stress state causes a temperature change of 1 mK in steel. Because of extremely small temperature measurement it is necessary to reduce noise. The software ALTAIR LI (FLIR) provides thermograms of stress fields using thermoelastic effect, which is based on a linear relationship between the temperature changes induced mechanical load and stress at the surface of the material. ALTAIR LI software is associated with the lock-in method that is used to extract the signal from noise and for synchronization signal load to signal measured data.

2.1. Lock-in method

Lock-in method is the technique used in measurement, where it is necessary to extract signal from statistical noise. An important condition for using this method is that the primary signal must be periodically pulsed or anyhow else amplitude modulated with lock-in frequency (loading frequency)f_{lockIn}. Another using of lock-in method is in thermoelastic stress analysis when it is necessary to synchronize the cyclic loading with measured data. Infrared camera picks up a series of thermal images and temperatures are compared by extraction of sine wave of each pixel. Lock-in method requires recording at least 4 phases in the same distance in one period. The minimum sampling frequency is greater than quadruple of loading frequency [1]. User interface of ALTAIR LI software is presented in Fig. 1.

Lock in method can be described as a multiplication of detected signal *F* by a weighting factor *K*. Usually this process is called lock-in correlation procedure. Output signal *S* for synchronous correlation is obtained by linear averaging over nlock-in periods (*L* is phase position, *N* is number of frames in one period) [7]:

$$S^L = \frac{1}{nN} \sum_{i=1}^{n} \sum_{j=1}^{N} K_j{}^L F. \tag{3}$$

The correlation function optimum to achieve the best signal to noise ratio is the harmonic function. When we use sine wave with amplitude A and its phase Φ we get [7]:

$$F(t) = Asin(2\pi f_{lock-in}t + \Phi) = Asin(2\pi f_{lock-in}t)cos\Phi + Asin(2\pi f_{lock-in}t)sin\Phi \tag{4}$$

and weight factors are:

$$K_j^{0^\circ} = 2sin\left(\frac{2\pi(j-1)}{n}\right), \tag{5}$$

$$K_j^{90^\circ} = 2cos\left(\frac{2\pi(j-1)}{n}\right). \tag{6}$$

Using the addition theorem of equation (4) and equations (5) and (6) the results of correlation S^{0° and S^{90° are:

$$S^{0^\circ} = Acos(\Phi), \tag{7}$$

$$S^{90^\circ} = Asin(\Phi). \tag{8}$$

Value A is corresponded to the maximum value of the radiation and when we consider calibration data for specific camera we can determine maximum value of temperature change ΔT for each pixel. Finally, due to equation (2) it is possible to obtain extremely value of the first stress invariant in each pixel ("points") of measured object.

However, it is necessary to ensure a synchronization link between IR camera and loading machine to determine the lock-in frequency. This frequency is usually obtained by external signal for example it is distribution of loading forcefor loading machine. It is not always possible to acquire this external signal. Hence an algorithm which requiresonly knowledge of the recorded thermograms or raw radiation data is possible to use.

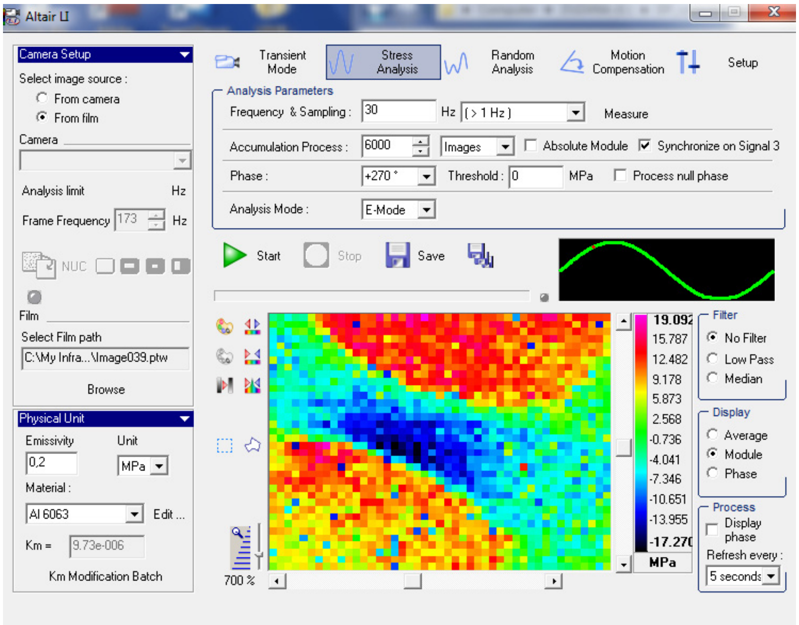

Fig. 1. Print screen of user interface of ALTAIR LI software,
green curve (sin wave) represents external signal for determination of lock-in frequency.

3. Experimental part

In experimental part concrete beam is cyclically loaded. Concrete beam is reinforced by steel rebar. Part of beam is removed for the purpose of visibility of reinforcement (Fig. 2). Cycling concrete beam was scanning by infrared camera. Output signal was processed in appropriate software.

Fig. 2. Measuring process.

Loading frequency is determined from recorded video. Area of pixels was selected and plotted average distribution of raw data in time for recorded video. Period of lock-in process was obtained from this distribution. On the Fig. 3 is marked the period of the loading signal. The time of one period in recorded signal is 0.501 s. Rounded value of loading frequency (lock-in frequency) is 2 Hz.

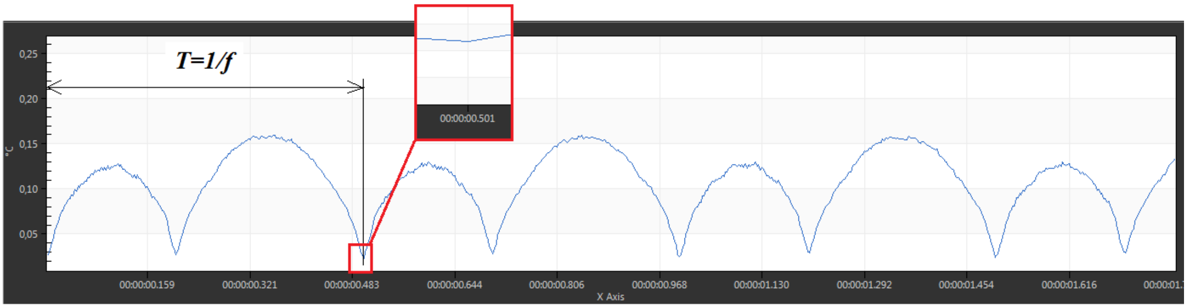

Fig. 3.Temperature distribution in time.

Software FLIR ResearchIR Max is set to record the measured temperature data from IR camera. In Fig. 4a we can see print screen of the recorded video in the software, in which concrete beam is loaded. Color stripes indicated the reflection of radiation from surroundings too. We use to deduct the first frame from each following frame to reduce color stripes (Fig. 4b). However the quality of thermogram is low. The level of noise is very high in frames. We have to use time average synchronization to improve image quality, to reduce noise and to suppress necessary to know emissivity in wavelength of camera for testing object [7].

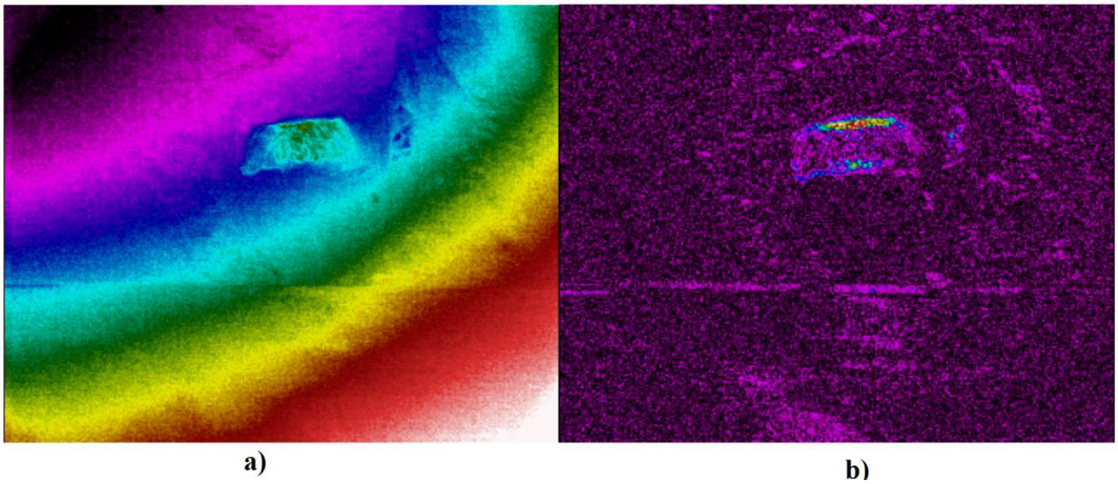

Fig. 4. a) Raw frame b) Frame after submission of the first frame.

3.1. Time average synchronization

Time average synchronization is a statistical method of processing of measured data to reduce noise. Specimen is loaded by cyclic loading. A series of infrared images (frames) of cycled specimen is recorded. Main part of infrared camera is infrared detector, which reacts to infrared radiation. An important parameter of each detector is a resolution. This characterization indicates the number of points in which scanning area is distributed. In our measurement, the resolution of 256×320 was set. It means that each frame consists of grid with 256×320 pixels. Each pixel can be marked as $x_{k1,k2}$, where $k1$ and $k2$ are position in grid and contains radiation data. Because it is numerical problem, data were exported to MATLAB.

Algorithm of time average synchronization was used to reduce noise. Each period contains *N* frames. Number of frames in one period is counted from period and sampling frequency, if the sampling frequency is 383 Hz and period is 0.501 s, there are 192 frames in each period. Number of period *n* is given by record length. The longer the record is the better image processing is. Time averaging is made by picking frames in the same position of sin wave. These values are suddenly summed and divided by number of periods:

$$ {}^{aver}x_{k1,k2} = \frac{1}{n}\sum_{i=1}^{N-1}\sum_{j=1}^{n} {}^{i+N*(j-1)}x_{k1,k2}. \tag{9} $$

where $x_{k1,k2}$ is pixel with position $k1$ and $k2$ in frame, N is number of frames in one period (in our experiment $N = 192$), n is number of period (in our experiment $n = 52$).

For example we choose 48$^{\text{th}}$ frame. It contains grid with 256×320 pixels. Next frame added to averaging will be j multiples of number of frame in one period ($j = 1$ to number of period). Every pixel of the frame will be averaged independently. Synchronizing algorithm with resultant averaged thermogram of 48$^{\text{th}}$ frame is in Fig. 5.

This procedure can be repeated for each frame in period and subsequently we obtain a sequence of frames for one period of loading cycle. After raw radiation data transformation to temperature changes we can use equation (2) for one period.

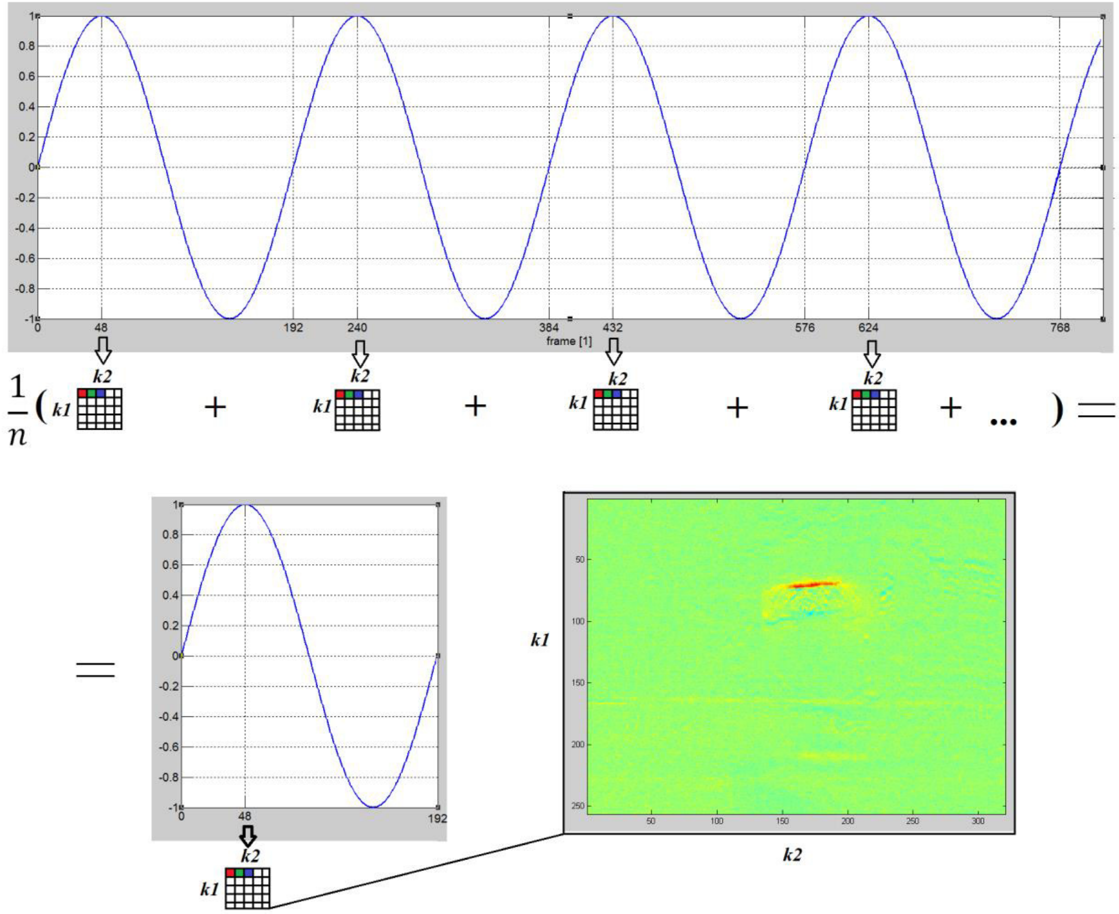

Fig. 5. Time average synchronization for 48th frame in period.

4. Conclusion

Thermoelastic stress analysis is noncontact technique connected to infrared camera. We can obtain stress field on the material surface by mentioned equipment. However, it is necessary to ensure a synchronization link between IR camera and loading machine. It is not always possible to connect infrared camera with loading machine. This frequency is usually obtained by external signal for example for loading machine it is distribution of loading force. It is not always possible to acquire this external signal. Hence an algorithm which requires only knowledge of the recorded thermograms or raw radiation data is possible to use. This contribution shows determination of lock-in frequency and using of time average synchronization. Although process of time average synchronization is included in lock-in process, it is suitable to make it independently for example if we want to obtain filtered record for one loading period. From time average synchronization it is possible to obtain a sequence of temperature changes in time and from these values can be calculated stress values by thermoelastic equation. This approach allows comparing stress fields obtained from thermoelastic stress analysis with other method e.g. finite element method FEM [8–10]. Lock-in relationships give only maximum stress values. Results of this work will be used for further processing of thermograms.

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