Generating the cloud of points from the phase images

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Abstract. This article deals with the generating the cloud of points from the phase images. These phase images are similar to phase images which are generated during non-destructive testing using an infrared camera. In the first step the model of sample with the defects is created in the CAD software. Next the lock-in method is applied to the results from the numerical thermal FEM analysis and the phase images are created in the software MATLAB. Phase image representing the 2D image of the material at a certain depth under the surface of the model. From these phase images the coordinates of the cloud of points are generated in the MATLAB.

1. Introduction

With the greater availability and effectively falling price of thermal cameras, in the last years thermography has developed from a rarely used technique towards an increasingly popular investigation method. There are a number of techniques evaluating the time dependence of temperature distribution. An infrared camera (IRC) can also be used as a detector for these measurements.

Using the synchronizations of the infrared camera with the exciting harmonic loading events is possible to do thermoelastic analysis [1–6], determining the dissipative energy estimation in fatigue tests [7–13], to do nondestructive testing [14–17] and analysis of vibration and determination of resonance frequencies and modal shapes [18, 19, 20]. The method for the processing of the thermal images, which are generated during the record with thermal camera, is named the lock-in method.

Technically the cloud of points is a database containing points in the three-dimensional coordinate system. Important thing is, that cloud of points is a very accurate digital record of an object in the space. It is saved in form of a very large number of points that cover surfaces of a sensed object.

Points in a point clouds are always located on the external surfaces of visible objects, because this are the spots, where ray of light from the scanner reflected from objects.

2. Lock-in method

The lock-in method is the technique of signal processing, in which the signals have to be extracted from statistical noise. Prerequisite to using this technique is that the primary signal, have to be
periodically pulsed or anyhow else amplitude-modulated with a certain frequency called “lock-in frequency” $f_{\text{lock-in}}$ and the response to this excitation is detectable at the same frequency $f_{\text{lock-in}}$.

The lock-in method is using in the non-destructive testing by infrared thermography to detect the hidden defects in the sample.

Lock-in method can be described as a multiplication of detected signal $F$ by a weighting factor $K$. This process is usually called lock-in correlation procedure. Output signal $S$ for synchronous correlation is obtained by linear averaging over $n$ lock-in periods ($L$ is phase position, $N$ is number of frames in one period) [5, 6]:

$$S = \frac{1}{nN} \sum_{L=1}^{N} K_j L \sum_{j=1}^{N} K_j^L F$$  \hspace{1cm} (1)

The correlation function optimum to achieve the best signal to noise ratio is the harmonic function. When the sine wave with amplitude $A$ and its phase $\varphi$ is used this equation is get [5, 6]:

$$F(t) = A \sin(2\pi f_{\text{lock-in}} t + \varphi) = A \sin(2\pi f_{\text{lock-in}} t) \cos \varphi + A \cos(2\pi f_{\text{lock-in}} t) \sin \varphi$$  \hspace{1cm} (2)

and weight factors are:

$$K_j^{0^\circ} = 2 \sin \left( \frac{2\pi(j-1)}{N} \right)$$  \hspace{1cm} (3)

$$K_j^{90^\circ} = 2 \cos \left( \frac{2\pi(j-1)}{N} \right)$$  \hspace{1cm} (4)

Using the addition theorem of equation (2) and equations (3) and (4) the results of correlation are:

$$S^{0^\circ} = A \cos \varphi$$  \hspace{1cm} (5)

$$S^{90^\circ} = A \sin \varphi$$  \hspace{1cm} (6)

Then, the amplitude the phase is [5, 6]:

$$A = \sqrt{(S^{0^\circ})^2 + (S^{90^\circ})^2}$$  \hspace{1cm} (7)

$$\varphi = \tan^{-1} \left( \frac{S^{90^\circ}}{S^{0^\circ}} \right)$$  \hspace{1cm} (8)

3. Numerical thermal FEM analysis

In the first step the model of sample with the defects is created in the CAD software SpaceClaim. The defects are designed like the blind holes 10×10 mm with the square cross section with the different depth under the surface the model (figure 1).

![Figure 1. Design of the sample with the defects.](image-url)
The material used in the FEM analysis is called „Onyx” and it is a composite material which is defined by the producer (Markforged) as nylon mixed with chopped carbon fiber. The thermal properties of this material are:

- density \( \rho = 1.18 \, \text{g cm}^{-3} \),
- isotropic thermal conductivity \( \kappa = 0.23 \, \text{W m}^{-1}\text{K}^{-1} \),
- specific heat \( c_p = 1510 \, \text{J kg}^{-1}\text{K}^{-1} \).

The front face of the sample with the defects (figure 1) is excited by the heat flux with the cosine amplitude in the program Ansys workbench. The heat flux in this thermal analysis represents the using of the halogen lamp. This thermal analysis represents an experiment in which is used optical excited lock-in thermography. The principle is shown in the figure 2.

![Figure 2. Principle of the Optical excited Lock-in Thermography [21].](image)

On the front surface of the sample is applied the heat flux \( M \). Maximum of the heat flux amplitude is \( 12.8 \, \text{W m}^{-2} \) which is computed from the data of power of halogen lamp. On the other surfaces of sample is applied the convection which represent a natural heat transfer between the object and the ambient air and it value is \( 20 \, \text{W} \, \text{m}^{-2}\,\text{K}^{-1} \). On the front surface of numerical model is created the mapped mesh \( 176 \times 176 \) nodes. The final numerical mesh contains \( 635 \, 072 \) nodes, \( 133 \, 125 \) elements and is made up of the hexahedral linear elements. The boundary conditions are shown in the figure 3.

![Figure 3. Boundary conditions.](image)
The ten FEM analysis are created with the different excitation time. The heat flux in each analysis consists of two cosine waves. Excitation times are computed from the different lock-in frequencies. Lock-in frequency is same like the frequency of the excitation thermal wave (heat flux). Lock-in frequency is using to determine reaction at the certain depth $h$ under the surface of the measured sample [22]:

$$h = \frac{2\kappa}{\sqrt{2\pi\rho c_p f_{\text{lock-in}}}}$$  \hspace{1cm} (9)

In this paper are defined the ten depths under the surface of the sample. From these depths are using the equation (9) calculated lock-in frequencies (table 1).

| Table 1. Defined depths and the corresponding lock-in frequencies. |
|---------------------------------------------------------------|
| **Depth $h$** (mm) **|** **Lock-in frequency** (Hz) **|** **Excitation time** (s) |
| FEM 1 | 0.1 | 2.8648 | 0.70 |
| FEM 2 | 0.2 | 0.7162 | 2.79 |
| FEM 3 | 0.3 | 0.3183 | 6.28 |
| FEM 4 | 0.4 | 0.1790 | 11.17 |
| FEM 5 | 0.5 | 0.1146 | 17.45 |
| FEM 6 | 0.6 | 0.0796 | 25.13 |
| FEM 7 | 0.7 | 0.0585 | 34.19 |
| FEM 8 | 0.8 | 0.0448 | 44.64 |
| FEM 9 | 0.9 | 0.0354 | 56.50 |
| FEM 10 | 1.0 | 0.0286 | 69.93 |

Heat flux data are defined in the FEM analysis using the discrete points and are calculated follow:

- time vector is linearly spaced to 60 discrete points and the start point is 0 and end point is Excitation time (see table 1),
- the values of Heat flux are calculated using the equation:

$$M = \frac{12.8}{2} \times (1 - \cos(2\pi f_{\text{lock-in}}t))$$  \hspace{1cm} (10)

At the end of the FEM simulation are export the temperatures of the nodes on the front surface to the text files. The 60 text files for the one FEM simulation are created because the time vector has the 60 discrete points. This group of 60 text files is created for each of the ten FEM analysis.

The group of 60 text files is imported to the MATLAB and using the equation (9) is calculated the phase image. This phase images shows if the defects are at the certain depth $h$ under the surface of the sample.

Next is applied the image processing to these phase images and there are converted to binary images, based on threshold. Phase images in the binary scale are shown in the figure 4.
In the next step is created the MATLAB script which generate the XYZ coordinates of the cloud of points (figure 5). These coordinates are written to the text file. Finally this cloud of points can be used for reverse engineering to create the CAD model, for example using the freeware software MeshLab.
4. Conclusion
The aim of the paper is to generate the cloud of points from the phase images. At the beginning of the paper the theory of the lock-in method is explain. Next the workflow of the ten FEM analyses are clarify.

The output from the FEM analyses are the 10 group of files. Each of these groups contain the 60 text files of the values of the temperatures. The 10 phase images are generated using the data from the 10 groups of text files. The phase images are processed and converted to binary scale. At the end the MATLAB script are created which use the phase images in the binary scale. This script is able to generate the coordinates of the cloud of points and export it to the text file. This cloud of points can be used to reverse engineering.

These results will be used for the comparison with the experimental measurement where the sample will be printed by the 3D printer MARK TWO and the optical excited lock-in thermography will be used.

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