Towards full-field photothermoelastic microscopy using a CCD camera

J. Charnay, D. Teyssieux, B. Cretin
FEMTO-ST, 32 rue de l’Observatoire, F-25044, BESANCON, cedex France
Jerome.charnay@femto-st.fr

Abstract. We report on a new method which allows extracting thermoelastic images by full-field method using in-plane measurement. The aim of this work is to show that it is possible to extract the in-plane thermoelastic field. Recently, a vibrometric measurement method has been developed at FEMTO-ST Institute for measuring in-plane displacement with nanometer and sub nanometer resolutions. The use of this method with thermography imaging allowed us to extract thermal expansion of micro samples heated by photothermal or thermoelectrical excitation. In this paper, we present an innovating technique to image thermoelastic field of these investigated samples. This technique is based on a CCD (charge-coupled device) camera which has been optimized for the previously presented applications.

1. Introduction

It had been demonstrated in the seventies that the out-of-plane thermal expansion can be measured with several methods. Most studies about photothermoelastic measurements were based on out-of-plane methods. Due to maturity of these methods, a lot of results have been shown. On one hand there are local methods which consist in scanning samples with a local probe to give a 2D map of the out-of-plane displacements. For example, Cretin et al used a very sensitive interferometer in order to extract the out-of-plane thermoelastic field of samples heated by photonic excitation [1, 2]. On the other hand there are full-field methods. Jumel et al with interferometry [3] and Grauby et al with thermoreflectance study and interferometry [4] managed to extract out-of-plane deformations of membranes or metallic layers. From our knowledge, the in-plane information of the thermal expansion has not been investigated and we proposed to test this technique with new low cost full field sensors. Our photothermoelastic method is based on two processes using the same CCD camera.

The first step consists in thermographical imaging. The full-field thermographical imaging system used has been already characterized in other papers [5, 6]. It operates with visible and near infrared radiations and it reaches high spatial resolution (about 450nm).

The second step of the method consists in measuring in-plane expansion of heated samples. Processing to extract these data is explained in the following sections.
2. Theory of in-plane displacement measurement

References about image processing are full of rigid displacement measurement techniques. Here the main problem is that most displacement detection algorithms are inaccurate for measuring very small thermal expansion.

The phase difference between the Fourier Transforms of two images representing the same object allows us to estimate the displacement between two positions of this object. Three 1D profiles of imaged object are plotted on figure 1. The blue solid line profile is the reference signal. The red dashed profile represents the reference signal with a two pixels displacement. The green one is an expanded profile. If profiles have the same shape, displacement between these profiles can be directly estimated by the phase difference algorithm (blue and red). This method does not work for extracting thermal expansion information between blue and green profiles, cause displacements between the two front edges and the two back edges are different. Theses displacements have to be calculated singly. Then the thermal expansion can be deduced.

To calculate separately these displacements, we first generate “perfect” profiles to simulate two rigid displacements. Theses new profiles can be generated from our data (here blue and green lines) by doing a symmetry. On figure 1, we have taken, for example, the abscissa 14 for symmetric axis. Let’s name S1 the blue profile and S2 the green one.

From the 1st to the 14th position we can write:

\[
S_1(x) = 0 \forall x \in [1 \, 11], \quad S_1(x) = 1 \forall x \in [12 \, 14] \\
S_2(x) = 0 \forall x \in [1 \, 19], \quad S_2(x) = 1 \forall x \in [10 \, 14]
\]

Then symmetry gives:

\[
S_1'(x) = S_1(x) \forall x \in [1 \, 14], \quad S_1'(x) = S_2(2 \ast 14 - x) \forall x \in [15 \, 2 \ast 14] \\
S_2'(x) = S_2(x) \forall x \in [1 \, 14], \quad S_2'(x) = S_1(2 \ast 14 - x) \forall x \in [15 \, 2 \ast 14]
\]

Two other profiles (for back edge) can be generated with \( x > 14 \). We call them S3’ and S4’. S1’ and S2’ have the same shape, S3’ and S4’ too, the algorithm can be used in the best conditions. On figure 2, S1’, S2’, S3’ and S4’ are plotted. With the phase difference algorithm we get d1 and d2 (front and back edges phase difference). (d1 + d2) is the information about thermal expansion of the object.

The phase difference algorithm has been tested for measuring Atomic Force Microscopy probe vibrations. Subnanometer resolution has been reached [7].

Fig. 1, blue profile is the reference, red one is the same profile with a two pixels displacement, the green one is an expanded profile.
3. Experimental setup

The aim of this experiment is to extract the correlation between thermal field and expansion of the sample under test.

The sample is a platinum strip (≈100nm thickness) on a Pyrex substrate. For using the algorithm described in section 2 we need sharp edges. So we engraved our strip using FIB (Focused Ion Beam) in order to have a lattice (figure 3.)

We have heated the sample with a dynamic electrical excitation. We have chosen high amplitude pulse wave excitation to enable high power differences. In order to investigate each part of the excitation time we have also used a stroboscopic light. In this setup, for each run, two series of images are acquired. The light pulses have a phase difference of π. It means that for each run we study the strip thermal expansion for two opposed excitation levels.

The measured thermal time constant \( \tau \) of the sample is about 15ms. So the excitation frequency has been set to 10Hz. We have expected to have in half an excitation period a first order system which can reach its maximum thermal expansion.

As we can note on figure 3, the platinum strip is divided into six smaller strips. Four of them have the same width (6.3 µm). We have studied the profile evolution of these four strips (named T1, T2, T3 and T4) versus phase difference between excitation and light pulses. On figure 3, red rectangle represents the working area, green lines represent front edges of profiles of strips which have been our references and yellow lines represent back edges.

Fig. 2, four “perfect” profiles generated from the reference profile and the expanded one

Fig. 3, Lattice engraved on Pt layer
4. First results

4.1. Measurement of the thermal expansion of the strips

4.1.1. Versus power. We have measured the thermal expansion for different values of the excitation power. Light pulses have a phase difference (with excitation) about -10° (and +170°) in order to have the wider amplitude gap between the two series of images. Figure 4 shows the evolution of the thermal expansion along each strip while power supply decreases. The evolution seems effectively related with the power.

4.1.2. Versus phase difference. Here, we set the supply amplitude to 10V. Then we scan the phase difference between excitation and light pulses in order to obtain the excitation profile shape. We noticed in figure 5 that for negative phase difference we have got the maximum amplitude of thermal expansion (as in subsubsection 4.1.1). Then for values near τ, expansion is closed to zero (the difference of power between the two sequences of images is weak). Finally, for larger phase difference, amplitude expansion increases up to the maximum. Values of thermal expansion are negative, because the reference strip for algorithm is here the most excited one.
4.2. Thermoelastic field

The thermal response and the expansion response to the excitation signal are plotted in figure 6. There is a correlation showing that these phenomena are linked. It seems too early to claim we can get thermoelastic field. Getting the in-plane expansion field was only the first step toward in-plane thermoelastic microscopy.

5. Conclusion

First results are encouraging. We have demonstrated that working with both thermography and vibrometric methods allows extracting information about sample properties. Taking longer images sequences should make us able to reach better resolution and so have a larger field of operation in term of power, frequencies and temperatures. (for a number N of images, the SNR - Signal Noise Ratio – depends on $\sqrt{N}$).

Now, only thermal expansion can be mapped with our setup. Next step could consist in extracting the entire thermal expansion field (not only with strips edges). We have already studied evolution of a Fourier Transform of a lattice profile during thermal expansion of the entire Pt strip, so of this lattice.

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