HEATED PLATE TEMPERATURE MEASUREMENT USING ELECTRONIC SPECKLE PATTERN INTERFEROMERY

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ABSTRACT

In this work, we present an original technique for heated plate temperature measurement using electronic speckle pattern interferometry (ESPI). A Fourier Transform Method algorithm is proposed to analyze fringe patterns in order to extract the phase from which one can get the unknown temperature.

KEYWORDS: *Temperature measurement, ESPI, Fourier Transform Method, phase.*

I. INTRODUCTION

In the field of temperature measurement, the knowledge of the temperature distribution has become crucial in many branches of science and engineering. With the development of modern and new technologies, new methods of temperature measurement have emerged, among which optical techniques play an important role, as they have incomparable advantages. These techniques exploit the change of the optical property that is caused by the change of the temperature to measure and calculate the physical quantities.

There are a large number of optical techniques, such as, classical interferometry , holographic interferometry [1,2], speckle shearing interferometry [3], speckle photography [4], Talbot interferometry [5], , shearing interferometry [6], Lau phase interferometry [7,8], Moiré deflectrometry [9], digital holographic technique [10,11], effect mirage[12] and electronic speckle pattern interferometry (ESPI) [13], which have been used to measure the temperature.

ESPI is one of several promising optical non contact, whole field laser techniques available for measuring surface displacements. It is a well established non destructive evaluation tool used in optical metrology applications. It utilizes the speckle pattern produced by an optically rough surface when illuminated by laser light. ESPI is also known as : digital holography, electronic holography and TV holography. Its development as an experimental technique originates with Holographic Interferometry (HI). Laser speckle noise was regarded as the bane of holography, but the speckle phenomenon became the stepping stone for the speckle metrology. Butters and Leendertz developed the technique in 1970, since then it has been used in a variety of engineering and other applications.

In this paper, we present a method for heated plate temperature measurement by using ESPI. A Fourier Transform Method algorithm is proposed to analyze fringe patterns in order to extract the phase from which one can get the unknown temperature.

II. BASIC THEORY

2.1 Fringe formation

ESPI or Television holography (TVH) as it is also known is a well established optical metrology technique. Over the past two decades, it was successfully used in a wide range of applications, such as deformation measurement, vibration analysis, surface contouring, fluid flow visualization and nondestructive testing.
The principle of the standard ESPI is based on the recording of a holographic speckle patterns sequence on the photosensor of a TV camera.
ESPI can be described as an image holography (an image hologram is recorded of the real image of the object instead of the object itself), with an in-line reference beam, where the TV target replaces the film as the recording medium. The reconstruction process is performed by the computer.
We consider now an interferometer like the one presented in Figure.1 [14]. Basically, the ESPI system consists of a continuous He-Ne laser, a CCD camera, a monitor and a computer with an image processing board. The light coming from the laser is coupled with a single mode fiber. A fiber optics 10 /90 directional coupler splits the light into the signal and the reference beams.
A beamsplitter cube, placed between the photo sensor and the imaging lens, couples the light diffused by the object to the reference beam. The pattern recorded by the TV camera is then stored in a digital memory.

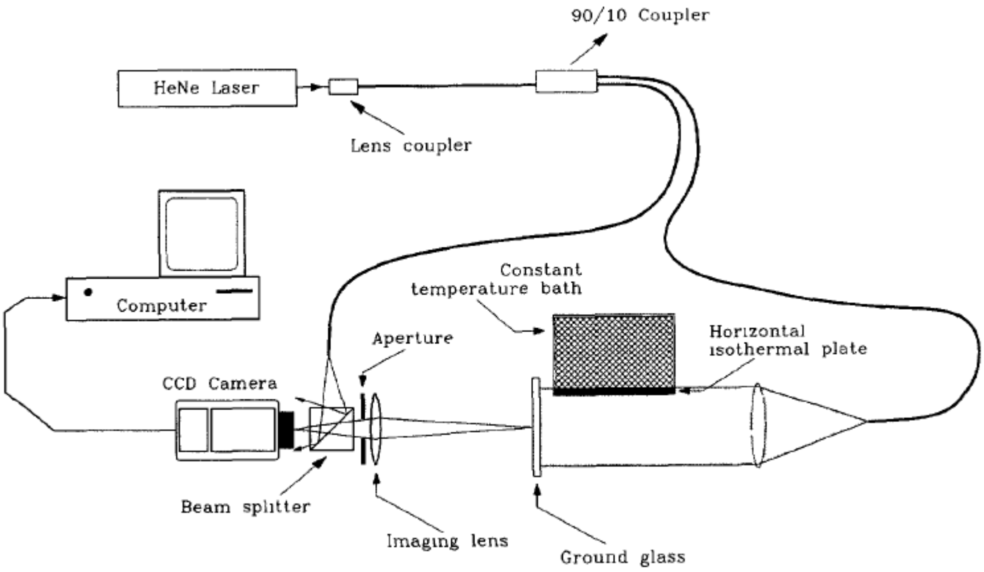

Figure 1. ESPI set-up

If a squared difference is performed between tow intensity speckle patterns, recorded at different times, the resulting pattern can be described as [14]:

$$I(x,y) = 8I_0(x,y)I_r(x,y)\sin^2[\vartheta(x,y) + \frac{\Delta\varphi(x,y)}{2}] \times \{1 - \cos[\Delta\varphi(x,y)]\} \quad (1)$$

Where $I_0(x,y)$ and $I_r(x,y)$ are the objet and reference beam intensities, $\vartheta(x,y)$ is the speckles random phase and the interference phase $\Delta\varphi(x,y)$ contains the desired information about temperature variation. The multiplicative noise interference term $\sin^2[\vartheta(x,y) + \Delta\varphi(x,y)/2]$ can be reduced by taking an average operation over many speckles. Assuming that the following relation holds

$$\left\langle \sin^2[\vartheta(x,y) + \frac{\Delta\varphi(x,y)}{2}] \right\rangle = \frac{1}{2} \quad (2)$$

Where the angle brackets denote the averaging operation, Eq. (1) can be rewritten as:

$$I(x,y) = 4I_0(x,y)I_r(x,y)\{1-\cos[\Delta\varphi(x,y)]\} \quad (3)$$

Eq. (3) is equivalent to the classical interferometry equation. It describes perfect correlated fringes without speckles. In practice, due to speckle decorrelation, fringe visibility is always <1. Fringes visualization on a monitor is sufficient for qualitative investigation. For quantitative evaluation, the temperature information has to be numerically extracted.

2 .2 Fringe analysis

In this section we describe phase extraction from fringes correlation patterns using Fourier Transform Method [15].
A fringe pattern, f(x,y) captured by a CCD camera can be expressed as

$$f(x,y) = a(x,y) + b(x,y)\cos(\Delta\varphi(x,y)) \quad (4)$$

Where a (x, y) and b(x, y) describe background variation and local contrast of the pattern respectively. The input fringe pattern is rewritten in the following form for convenience of explanation:

$$f(x,y) = a(x,y) + c(x,y) + c^*(x,y) \quad (5)$$

With
$$c(x,y) = \frac{1}{2}b(x,y)\exp(i\Delta\varphi(x,y)) \quad (6)$$

i is the imaginary unit and the asterisk denotes the complex conjugate.
The interference phase $\Delta\varphi(x,y)$, containing the residual deformation, can be evaluated by Fourier analysis.
Now, Eq. (5) can be described by the 2-D Fast Fourier Transform (FFT) as follows:

$$F(u,v) = A(u,v) + C(u,v) + C^*(u,v) \quad (7)$$

where the capital letters indicate the Fourier spectra, and *u* and *v* are the spatial frequencies in the *x* and *y* directions. The amplitude spectrum of Eq. (7) is a tri-modal function with A(*u*,*v*) forming a broad zero peak, and two peaks C(*u*,*v*) and C*(*u*,*v*) located symmetrically with respect to the origin. By means of bandpass filtering, the zero peaks A(*u*,*v*) and C*(*u*,*v*) are removed. The remaining spectrum is no longer symmetric and will yield a non-zero imaginary
part after inverse transformation. Then, using inverse FFT for the phase distribution, $\Delta\varphi(x,y)$ can be calculated by :

$$\Delta\varphi(x,y) = \arctan\left(\frac{\mathrm{Im}[c(x,y)]}{\mathrm{Re}[c(x,y)]}\right) \quad (8)$$

where Re[*c*(*x*,*y*)] and Im[*c*(*x*,*y*)] are the real and imaginary parts of *c*(*x*,*y*), respectively. With Eq. (8) based on FFT using only one image, a recovery of the phase $\Delta\varphi(x,y$ can be obtained. The phase distribution is wrapped in to this range and 2π jumps occur for variations of more than 2π. Using Eq. (8) and taking in to account the signs of $\mathrm{Im}[c(x,y)]$ and $\mathrm{Re}[c(x,y)]$, the phase principal values ranging from $-\pi$ to π are obtained. These discontinuities can be corrected by adding or subtracting 2π according to the phase jump ranging from π to $-\pi$ or vice versa. A practical phase unwrapping algorithm developed by Macy [16] is used for processing module 2π phase maps of Eq. (8) in reasonable times.

III. METHOD FOR TEMPERATURE MEASUREMENT

Now, let us consider a light beam through a test section of length l . The unwrapped phase is related to the variation of the refractive index of air on top de the plate surface by:

$$\Delta\varphi = \frac{2\pi l}{\lambda}\Delta n \quad (9)$$

Where λ is the wavelength.

The change in the refractive index of air is usually related to a temperature variation through a factor approximately constant, if the temperature changes are small, the so-called Gladstone-Dale constant. The refractive index of air at 632.8 nm can be evaluated with greater precision by :

$$n-1=\frac{0.292015\times10^{-3}}{1+0.368184\times10^{-2}T} \tag{10}$$

Where T is in degrees Celsius. This equation is based on the Gladstone-Dale relation, with wavelength dependence calculated according to Meggers and Peters and small corrections due to Tilton.

Hence $$\Delta n=-\frac{1.075152\times10^{-6}}{(1+0.368184\times10^{-2}T)^2}\Delta T \tag{11}$$

From Eq. (9) and Eq.(11) we easily obtain :

$$\Delta T=\left[-\frac{1,075152.10^{-6}}{(1+0,368184.10^{-2}T)^2}\right]^{-1}\frac{\lambda}{2\pi l}\Delta\varphi \tag{12}$$

Owing to the linear relationship between ΔT and $\Delta\varphi$ (Eq.(12)), measurements of ***T*** may be made automatically from the unwrapped phase of the interferogram.
Figure 2 [14] show ESPI fringes above a central section of a horizontal aluminum plate $(0.7cm\times25cm\times25cm)$. The interferogram is digitized in 512 x 512 x 8 bit data, with a magnification factor such that 1 pixel = $40\times10^{-6}m$.

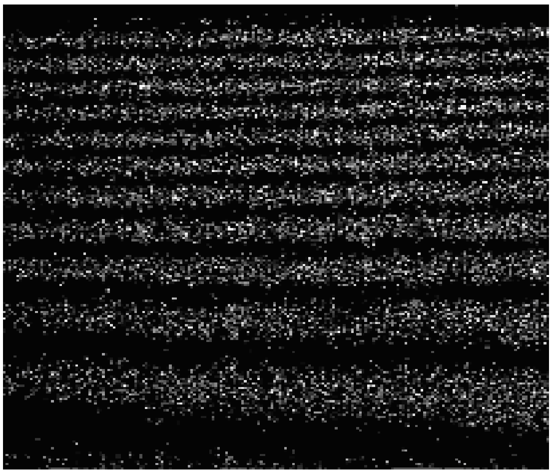

Figure.2: Electro-optic holography fringes relative to the central section of the plate. The temperature of the plate was $325\pm0.2K$. Room temperature was $295\pm0.2K$.

The phase of the object is calculated using Eq. (8). After obtaining accurate phase values, the continuous phase needed for the evaluation of the temperature is given by the phase unwrapping algorithm.
Processing figure. (2) with the Fourier transform as described in the previous section gives the wrapped phase shown in figure.(3) and then, by using the Macy algorithm [16], the relative unwrapped phase (see figure.4).

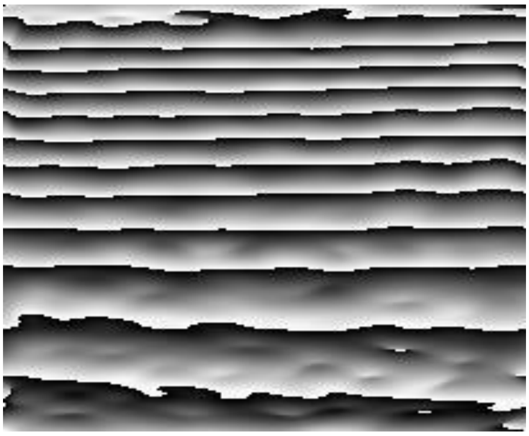

Figure 3. The wrapped phase of the speckled interferogram

Figure 4. The unwrapped phase map relative to the fringes of figure 3.

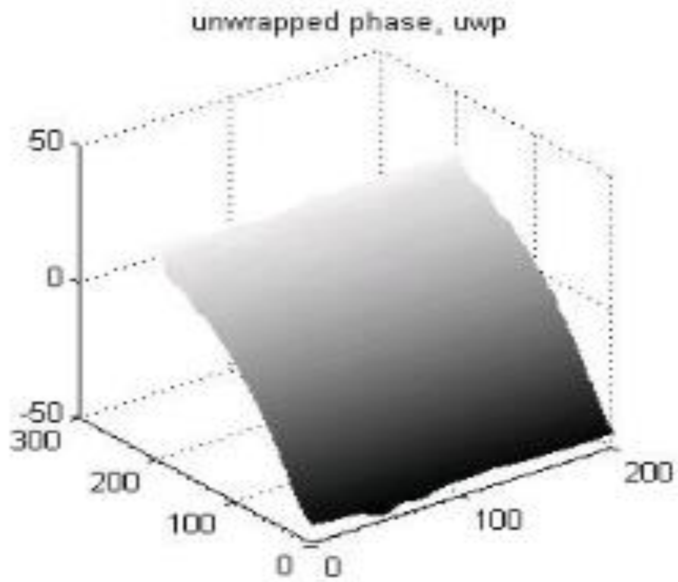

Figure. (6) shows the temperature variation with distance from the plate as calculated from the corresponding unwrapped phase.

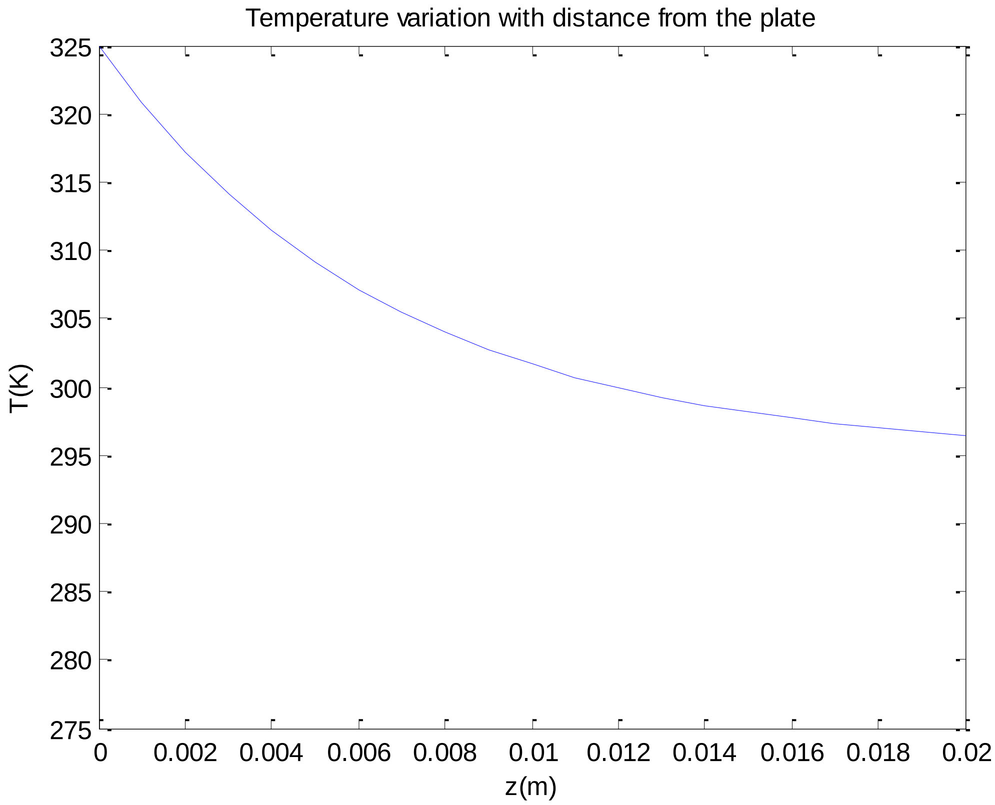

Figure 6. Temperature variation with distance from the plate.

Figure. (7) shows the temperature variation with distance from the plate obtained by G. Schirripa Spagnolo and al [14].

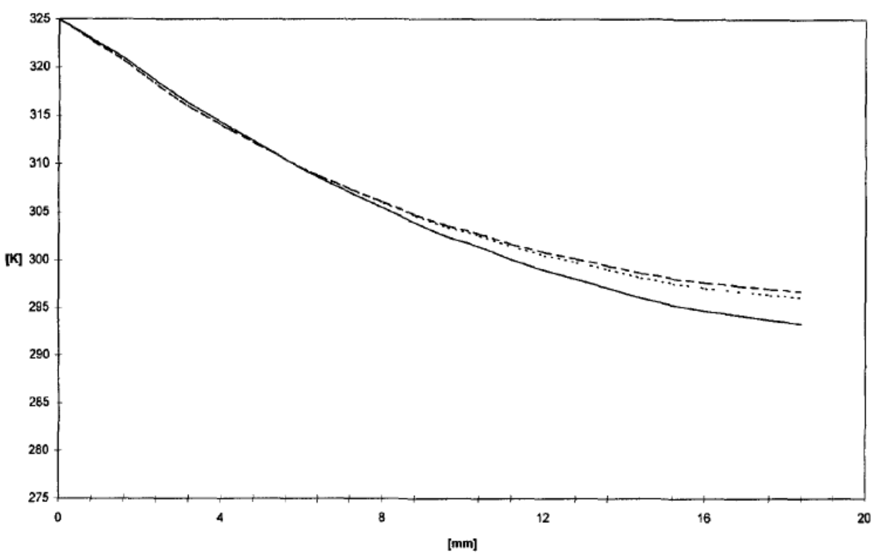

Figure 7. Temperature variation with distance from the plate obtained by G. Schirripa Spagnolo and al.

The accuracy of the proposed method depends on errors in plate and room temperature determination, plate length measurement and phase evaluation. Error in phase determination encloses computational errors, optical non linearities and electronic noise. In our case, computational errors (due to signal discretization and quantization by CCD) give the most relevant contribution. We assumed an error of 1mm on the plate length measurement and an error of $\lambda/20$ on the phase determination. The total error in temperature determination depends on the distance from the plate, and was about $\pm 0.4K$ near the plate surface and $\pm 0.57K$ at a distance of about 3 cm from the plate.

IV. CONCLUSION AND FUTURE WORK

In this work, we present an original technique for heated plate temperature measurement using electronic speckle pattern interferometry (ESPI). A Fourier Transform Method algorithm is proposed to analyze fringe patterns in order to extract the phase from which one can get the unknown temperature.

we made a comparison with the results of G.Schirripa Spagnolo [14], we obtained results that agree relatively well within the margin of experimental error and was about 0.4 K near the plate surface and 0.57 K at a distance of about 3 cm from the plate. We note that our results render fairly experimental reality knowing that our method is relatively simple and inexpensive.

The future research proposed in the present study includes: heated plate temperature measurement using digital holography and windowed Fourier transform method of fringe pattern analysis.

ACKNOWLEDGEMENTS

We want to thank Dr. Daniel Francis, Department of Engineering Photonics at Cranfield University for his constructive and helpful comments.

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