3-D Shape Measurement Using a Micro/Nano Speckle Method

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ABSTRACT:
When an object is placed at different distances from a camera lens, the resulting images are different in size due to perspective effect. If this effect can be quantitatively measured, it could be used to deduce the shape of a 3D object, because different part of the object occupies different position from the imaging lens. An equation for the perspective effect was derived by Sciammarella and Chiang in 1968 and verified using moiré fringes. It was then called the moiré gap effect and the equation was referred to as the moiré gap equation. An attempt was made in the present study to show that the moiré gap equation can be applied to the random speckle method for strain analysis as well. Furthermore an attempt was also made to use the effect to deduce the 3D shape of an object. Since speckles can be made in micro/nanometer size, one can use the technique to measure 3D shape of very small objects.

INTRODUCTION:
Stress analysis techniques based on 2 dimensional imaging that assumes plane specimens are well known. Including classical moiré and moiré interferometry [1], speckle interferometry [2] and digital image correlation techniques [3]. If the specimen is deformed along the optical axis or the specimen have curved surfaces (i.e. sphere), most of these techniques will suffer from errors caused by the out-of plane displacements due to perspective effect. This perspective effect is present in in-plane moiré [4] and speckle photography methods [5]. Sciammarella and Chiang derived an equation to take into account of this effect in moiré method [4]. Chiang and Asundi [5] showed that the same phenomenon prevails in speckle photography. They later used the effect to map the 3D displacement of the object. [6]. The idea was that de-focusing the image plane of a recording system will change the speckle pattern, causing fictitious strain. This information can be used to extract information about specimen’s position along the optical axis. The magnitude of fictitious strain of the specimen surface depends on de-focused distance. Thus it is directly related to the shape of the object. The purpose of this paper is to extend the application of the gap effect equation derived in [4] to speckle photography and use it to measure 3D shapes of small objects.

If we have a specimen as shown in Fig.1. Rigid body movement of this specimen along the optical axis by \( \Delta Z \) will cause a fictitious strain. The value of this fictitious strain is governed by

\[
\varepsilon_f = \frac{\Delta Z}{Z}
\]

which was introduced by Sciammarella and Chiang [4] for two moiré gratings with a constant gap. If the specimen surface is covered with speckles the fictitious strain can be calculated using CASI [2], provided that
good correlation is maintained. From Eq.1 it is seen that once $e_f$ is obtained, $Z$ can be calculated, thus leading to the 3D shape of the object.

**EXPERIMENTS:**

The experimental set-up consists of a CCD camera with 2048x2048 pixel resolution and divergent white light illumination. A speckle pattern of average speckle size being 0.2mm covers the specimen surface. To test the validity of gap effect we first applied the technique to flat plates of 45mmx45mm in size. Fig. 2 shows the schematic of experimental setup together with a typical set of displacement vector field and $u$ and $v$ displacement contours.

![Experimental Setup](image)

**Figure 2** - (a) Test setup for flat plate specimen with dimensions 45mmx45mm, (b) the displacement vector field as a result of the perspective effect, (c) displacement contours $u$ and $v$ along the x and y directions respectively.

These displacement contours are used to calculate the fictitious strain and compared with the predictions of Eq.1. As can be seen from the Fig. 3 experimental results are in good agreement with the theoretical predictions.

![Fictitious Strain vs Z](image)

**Figure 3** - Expansion of experimental results and theoretical prediction using the gap equation (1).
We then used an inclined plate (45° with respect to vertical plane) to check the validity of Eq.1. Fig 4 shows the experimental setup and the resulting fictitious strain field in terms of v displacement contours.

Strains along a vertical section were calculated and the values compared with the Eq.1 as shown in Fig. 5. We were first obtained the displacement field along vertical section. Then we fitted a polynomial function to the displacement field and find the strain by means of strain tensor using analytical methods.

DISCUSSION:
The preliminary results presented here indicate the gap equation derived from the in-plane moiré method can be indeed applied to the speckle method. But its usefulness for 3D shape measurement is not certain. We note that for the inclined plate experiment the experimental results, while indicates the trend, is
nevertheless off the predicted result. At the present time we are not certain as to the cause. Further research is needed to resolve the issue.

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