Simulation study of deflectometry systems

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A simulation tool for deflectometry (fringe reflection) systems is presented. The distorted reflection fringes and the phases are studied for noise-free and noisy data. The simulated shape errors are an excellent guide for measurement system design and evaluation, as well as algorithm development.

1 Introduction

Deflectometry utilizes the deformation of a fringe pattern after reflection from a test specular surface to infer the surface normal (or gradient) [1], in configurations similar to Fig. 1.

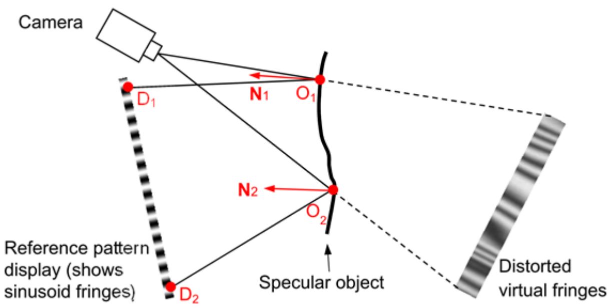

***Fig. 1** Principle of deflectometric measurement: surface normals **N** at object points **O** are calculated using the measured coordinates **D** on the reference pattern, which are viewed along the camera's lines of sight.*

A uniform fringe pattern is displayed on a TFT or other reference screen; the tested specular object reflects it towards the camera. Any deviations from a flat surface give rise to a distortion of the observed fringes, which can be evaluated quantitatively by virtue of the phase-shifting technique. With knowledge of the orientation parameters between the camera and the display, the object surface normal can be calculated from the phase distribution [2], [3]. The measurable area on the surface depends strongly on the position and shape of the object. Therefore the geometrical configuration of the measurement system must accommodate the test object. To construct a deflectometry system that can meet the measurement requirements of the specified surface, the parameters of the system elements, such as camera focal length, CCD size, display size and orientation, etc. must be correctly selected.

In this paper we present a method to simulate the whole measurement procedure. The parameters of the system elements, as well as some possible error sources, are simulated. The simulation output for the measured object shape can be compared with the pre-defined shape model, which enables us to directly study the random and systematic measurement errors.

2 Measurement set-up and measurable range

Fig. 2 shows the observed camera fringes reflected from different objects in an otherwise identical measurement set-up with some typical parameters, e.g. focal length 12.5mm, camera-object distance 410mm. etc.

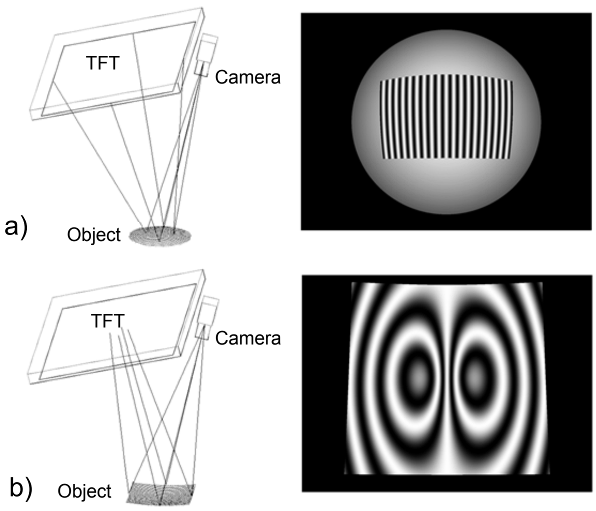

***Fig. 2** Simulated deflectometry setup (left) and fringes, as recorded by the simulated camera (right), reflected by a) convex sphere, b) concave hyperboloid.*

With these simulations, the measurable range on different object surfaces is easy to check and, if required, parameters (e.g. camera-display angle, camera-object distance, display & CCD size, etc.) can be adjusted to allow measurement of the entire object surface.

3 Test of orientation & evaluation algorithms

For an assessment of the calibration and surface-reconstruction algorithms, we first orientate the set-up presented in Fig. 2. That means we calculate the system geometry parameters from the

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simulated fringe phases which are reflected from a standard object, e.g. a plane.

Measurements of a plane and a sphere have been simulated for this set-up and evaluated using the calculated orientation parameters. The RMS error of the simulated absolute phase noise in orientation and object measurement is set to a (relatively high) value of 0.2 pixels on the display (or 1/500 fringe period when the fringe period is 100 pixels).

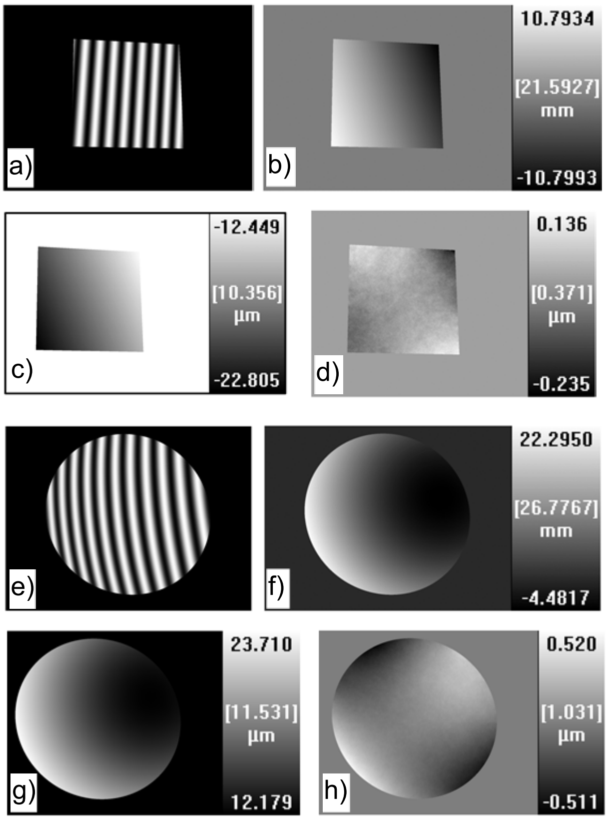

Fig. 3 *Simulated measurements of a tilted plane with an area of 100x100mm^2 (images a-d), and a sphere (R=300mm, ∅ 150 mm, images e-f), with phase noise. a), e) fringe image ; b), f) nominal height distribution; c), g) absolute shape error; d),h) relative shape error remaining after fitting with plane (d) and sphere model with fixed radius R=300mm (h).*

Fig. 3 shows the simulated measurement results of the plane and sphere, respectively. The absolute error is the difference between the calculated and ideal height distributions. And the relative error is defined as the remaining error after removing a best-fit object.

From the above simulations, we have found that the relative error, which describes the system's shape measurement performance, is much lower than the absolute error, including offset, tilting or shifting. For a typical deflectometry system like the one modeled here, and only considering phase noise, the relative error can reach the sub-micrometer range. The results demonstrate that the orientation and evaluation algorithms are effective and accurate, and also provide a lower limit for the achievable uncertainties.

4 Simulation of projector-based setup

An alternative deflectometry setup, suitable for measuring larger or strongly curved objects, utilizes a LCD projector and a flat screen, see Fig. 4(a). In this case the fringe period over the screen is usually not constant but chirped.

Like in section 3, we first simulate the system orientation and then a plane measurement, this time without phase noise. The resulting shape error is generated solely by the non-uniform fringe period. A strong saddle structure can be observed in the relative height error distribution, shown in Fig. 4(b).

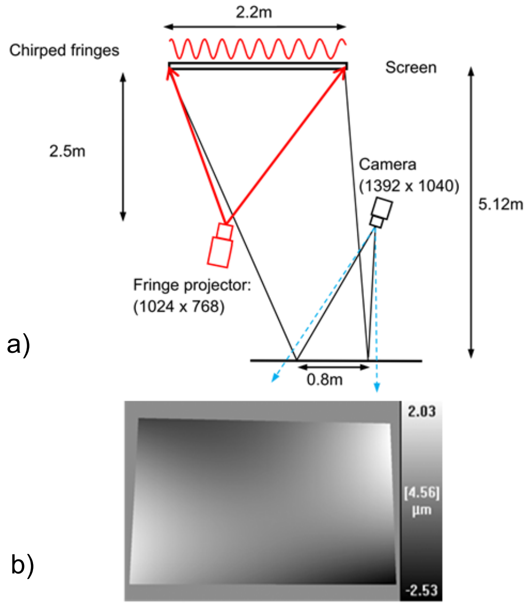

Fig. 4 *Deflectometry system using a projector and a screen instead of a TFT. a) system setup; b) relative shape error resulting from the chirped fringe period.*

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References

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