Determination of sheet topography using Shadow Moiré method

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ABSTRACT: The Shadow Moiré method can be applied to characterize the surface topography and the dimensional instabilities of paper. Among other capabilities, the technique can be used to determine the influence of cyclic humidity on cockle. For a copy paper subjected to cyclic humidity conditions for six complete cycles, the surface topography was measured after each humidity cycle with the Shadow Moiré method. The results show that the most severe cockle occurs during the first cycle, after which the change in cockle is relatively slight. The tool is also useful in measuring not only curl but also the directionality of curl. Several types of filtering and computational techniques can help to separate curl from cockle and characterize these defects in terms of an appropriate length scale.

Application: The Shadow Moiré method can characterize dimensional instability problems in lightweight papers in a noncontact, nondestructive manner.

Editor's note: *The limitations of black and white printing compromise the quality of the figures in this paper, which are intended to be viewed in full color. TAPPI members can access full-color versions of Figures 2-5 at* <http://www.tappi.org/index.asp?pid=32225&ch=1>

For many grades, sheet flatness is a critical quality parameter. Detrimental nonflatness may take the form of small-scale roughness to large-scale deformations such as cockle, wrinkles, curl, and warp. For other papers, specific topographies are desired in the sheet surface, such as in embossing or fluting, but uniformity is still required. To evaluate sheet flatness, one must first measure the surface topography and then analyze the results.

We have used the noncontact Shadow Moiré method to measure sheet surface topography. In this method, the surface is measured in a natural state. Because of the full-field measurement capability, the surface topography can be captured quickly, and transient changes in the shape of the sheet can be measured.

Here, we describe the measurement principle and the capabilities of the Shadow Moiré method. We also give examples of the way the tool is used to characterize sheet topography. The tool is useful for measuring not only curl but also the directionality of curl, and there are techniques for separating the measurements of curl and cockle.

Measurement Principle of Shadow Moiré System

The word "Moiré" was first used by the French to describe the surface of a specific type of silk fabric that had a watered or wavy pattern. In experimental mechanics terminology, the term corresponds to the interference fringes that are developed from the superposition of geometric patterns [1]. In the Shadow Moiré method, these fringes are developed by the superposition of a line space pattern, or grating, with the shadow of that grating projected onto a surface.

Figure 1 illustrates how the system works. As the spatial elevation of a surface changes, the shadow is distorted. The superposition creates light and dark fringes that correspond to contours representing constant elevation. The change in elevation represented by one fringe, Δh, is obtained from Eq. 1 [2]:

$$\Delta h = P/[\tan(\alpha) + \tan(\beta)] \quad (1)$$

where

P = pitch of the reference grating

α = angle of illumination

β = angle of observation.

For the system described in Eq. 1, the angles α and β were 35° and 90°, respectively, with respect to the reference grating, or the glass plate for the reference grating. The resolution of the measurement system can easily be improved by increasing the pitch of the reference grating, where the pitch is the center-to-center distance between two adjacent lines. Increasing the pitch could cause a problem in areas with very large variations in surface topography, however, because the fringes would be spaced so closely together that they could not be discerned.

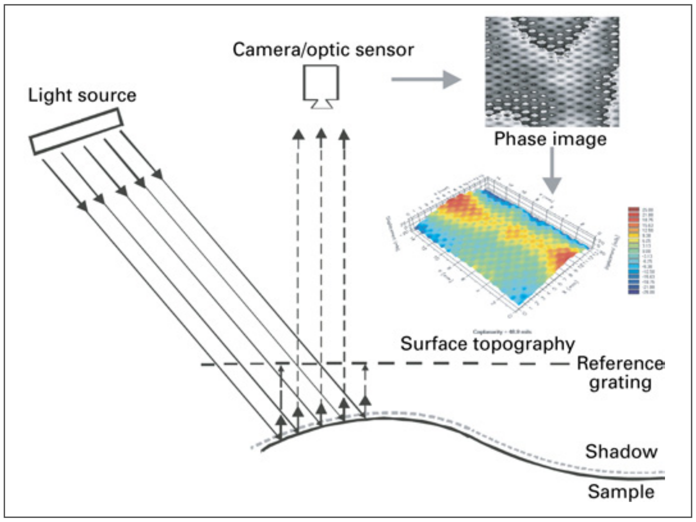
Figure 1 shows how the phase image is captured by the CCD camera (where CCD stands for "charge-coupled device"). This image is converted to a three-dimensional image that represents the surface topography of the sheet.

Verification of Measurements

The Shadow Moiré system is calibrated with a proportionality constant to convert the phase images to out-of-plane displacement values. Since the position of the light source and the camera are fixed, the calibration of the system generally remains unchanged. For the system used in this study, the angle between the light and the reference plate was about 35°. This angle produced a fringe sensitivity of 363 µm (14.3 mils) per fringe for the plate at 100 lines per inch (2.54 cm). After the phase stepping technique was applied, the resolution of the system was on the order of 3.81 µm (0.15 mils).

To verify the resolution and accuracy of our measurements, we fabricated a block consisting of several grooves of various dimensions on one surface of an aluminum plate. The depth of the grooves ranged from 25.4 µm to 3.81 mm (1 to 150 mils), and the width ranged from 1.27 mm to 7.93 mm, or 50 to 312 mils (1 mil = 25.4 µm).

The surface topography of the calibration plate was also measured by a Coordinate-Measuring Machine (CMM), and by an optical sensor called "PaperMap" (CyberMetrics, Alpharetta, GA). In general, the differences between the results obtained by the shadow Moiré method and those from these systems for the non-steep grooves were less than 3%.



1. Scheme of the experimental setup for the Shadow Moiré system.

Filtering and analysis of filtered data

When characterizing the sheet topography, one needs to obtain some measure for comparison between samples. Often the topography data will be a complex combination of several different types of deformation. These types of deformation could be characterized in terms of their length scales and directionality.

Several types of filtering techniques were utilized to separate some of these different types of deformation. A 2-D FFT was used to obtain the topography data as a function of different wavelengths, thus, allowing certain frequency components to be isolated or removed from the data [3]. The computational method of a moving average was used to separate the data into high and a low wavelength components. In addition, polynomial equations were fitted to the data to isolate curl or warp. For samples that were mainly composed of curl, we approximated the global curvatures of the sheet using a polynomial fit of second order:

$$w(x,y) = k_x x^2 + k_{xy} xy + k_y y^2 + Ax + By + C \qquad (2)$$

where the first three coefficients are the curvatures, x and y are the spatial dimensions along the horizontal and vertical directions at the region of interest. The coefficients k_x, k_{xy}, …, and C are unknown coefficients to be determined by the least square method.

In the least squares method, the sum of the squares of the errors is minimized as follows:

$$E = \sum\sum[w(x_i, y_j) - z(x_i, y_j)]^2 \qquad (3)$$

where

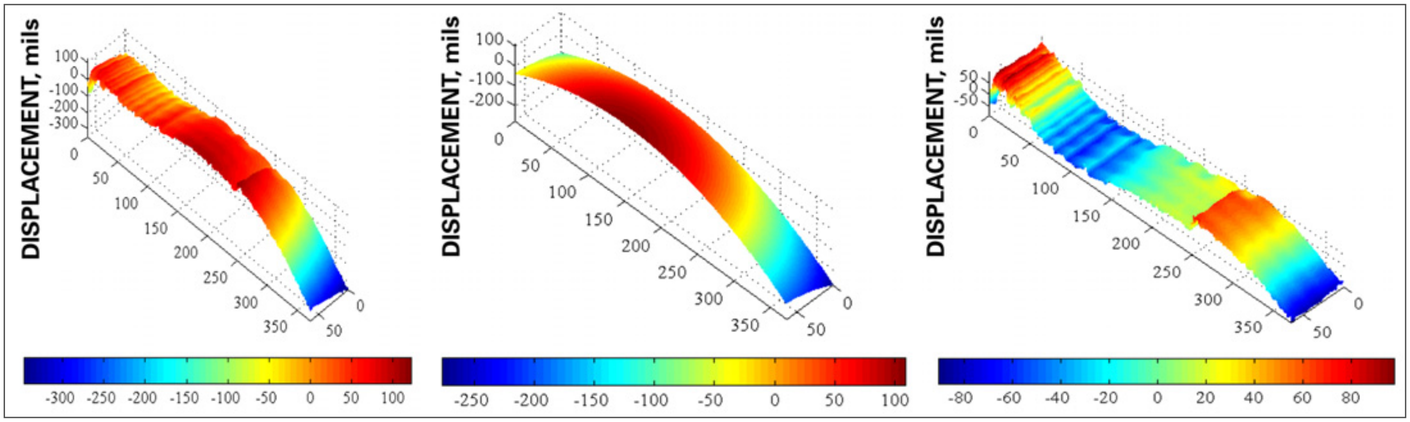
$i = 1, 2, \ldots, m$
$j = 1, 2, \ldots, n$
m = number of points in the horizontal direction
n = number of points in the vertical direction.

The term $z(x_i, y_j)$ represents the heights measured by Shadow Moiré system at each location. E can be minimized by setting its partial derivatives with respect to each of the constants (k_x, k_{xy}, ..., C) equal to zero. This results in a system of six linear equations that are solved numerically.

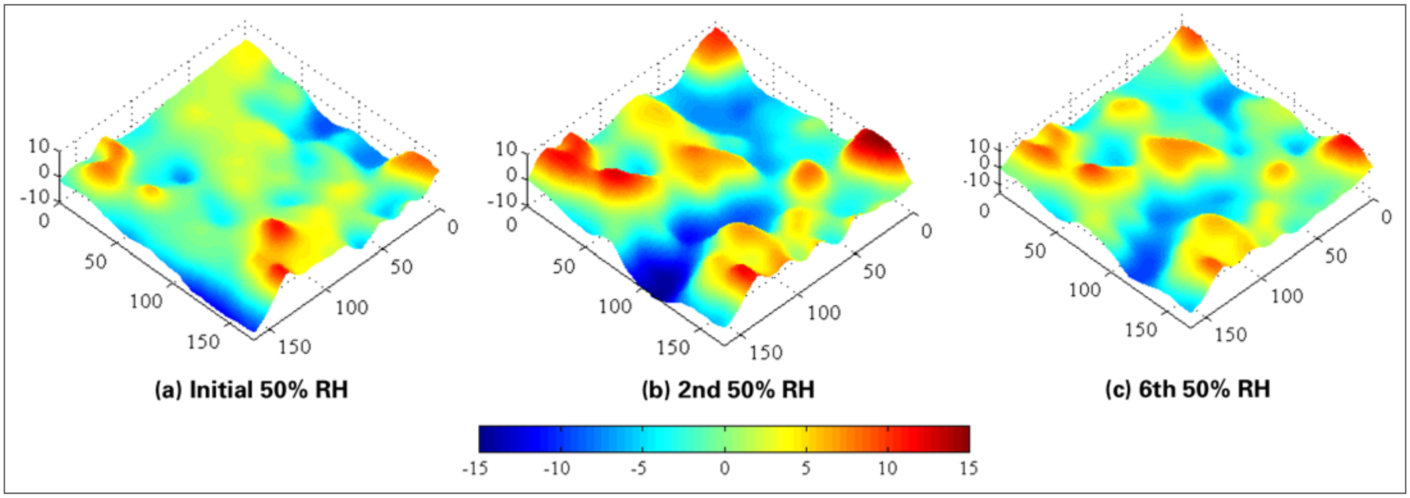
It is not possible to adequately express the surface topography of a paper sample or any other material by using only one parameter. Many parameters have been developed for this purpose, and some parameters may be used more than others, depending on the specific application [4, 5]. In future studies of cockle and analysis of dimensional instability problems during drying of paper materials using the shadow Moiré method, we will employ maximum peaks, minimum valleys, standard deviation, and volume per unit area to analyze surface topography. (The volume per unit area is the average of the absolute value of the surface height.)

Sheet Topography Measurements

The Shadow Moiré system can distinguish features over a wide range of size scales for a variety of materials. The following figures provide examples of the types of surface topographies that



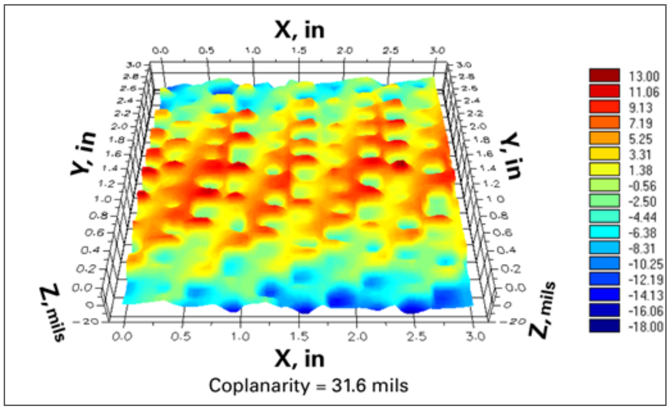
2. A strip from a corrugated container composed of curl and wrinkle (left image), the global curvature of the sheet (middle), and the wrinkles (right). The vertical axis represents height in mils (25.4 µm) and the scales along the x and y axes are pixels (each pixel corresponds to 0.6 mm).



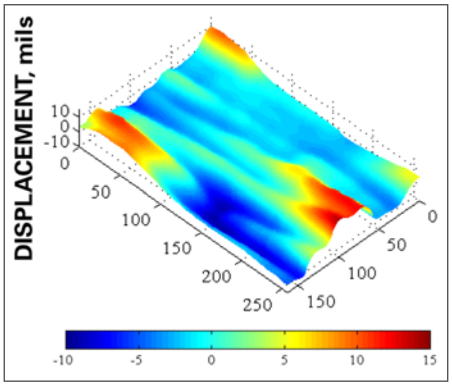
3. Surface topography of a 10.16 cm square (4 in. × 4 in.) of the sheet as measured after the first cycle, the second cycle, and the sixth humidity cycle. The vertical axis represents height in mils (25.4 µm) and x and y axes are pixels (each pixel corresponds to 0.6 mm).

can be imaged with the Shadow Moiré system.

Curl and wrinkle. **Figure 2** presents the results obtained for a sample that is composed of curl and wrinkle. We separated the curl and wrinkle using a MatLab program developed on the basis of the second-order polynomial fit mentioned earlier. This particular sample appears to have a higher-order curve to it, and a more accurate fitting could probably be obtained with a higher-order polynomial.



4. Washboarding in the top liner of a corrugated board.



5. Fluting of a lightweight coated sheet in web-offset printing.

Cockle. In another experiment, a sheet of copy paper was subjected to cyclic humidity conditions ranging from 50% to 85% RH for a total of six complete cycles. The ambient temperature was constant at 22°C. The surface topography of a 10.16 cm x 10.16 cm (4 in. × 4 in.) piece of the sheet was measured after each humidity cycle. The results show that the most severe cockle occurs during the first cycle; after that, the change in cockle is stable.

Figure 3 presents a comparison among sheet topography at the initial, second, and the sixth cycles starting at 50% RH. The axis perpendicular to the plane of the sheet represents the out of plane deformation (cockle) in mils (25.4 µm or 0.001 in). The axes in the plane of the sheet are in pixels, where each pixel corresponds to 0.6 mm.

The results of these cyclic humidity experiments indicated that the most severe cockle occurred during the first cycle (Fig. 3a). Comparison of the results obtained after the second cycle (Fig. 3b) with those obtained after the sixth cycle (Fig. 3c) shows that the change in cockle after the second cycle is relatively small. Therefore, if the relative humidity of warehouses and storages containing paper materials goes through cyclic humidity changes, a significant dimensional instability problem may occur during the first stages of humidity cycling.

Fluting and washboarding. **Figure 4** shows washboarding in the top liner of a corrugated board sample. The flute tips and the buckling or washboarding between the flutes tips can be seen easily. Coplanarity value of 31.6 mils (802.6 µm) shown in this figure corresponds to difference between the maximum height and minimum depth of the board.

Figure 5 shows an image of fluting that occurred during web-offset printing on lightweight-coated paper. This fluting occurs during the drying and usually in the printed area. This sample had black ink printed on both sides.

CONCLUSIONS

The Shadow Moiré method can be used as a tool for studying not only sheet topography but also dimensional instabilities. It is a quick and accurate technique for examining out-of-plane deformations such as cockle and curl. The data collected are

+filtered with statistical techniques to obtain meaningful parameters that are then compared to visual rankings. Very small variations in sheet topography can be detected in the Moiré images. Future studies will analyze the effect of drying variables during manufacturing of paper materials in cockle. **TJ**

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INSIGHTS FROM THE AUTHORS

Dimensional stability is an important aspect of paper quality. To study problems such as curl and cockle, we need a simple way to measure topography. The Shadow Moiré method is a practical and simple approach.

The Shadow Moiré instrument gives us a quick and accurate way to evaluate differences in cockle in sheets as a function of sheet structure and drying conditions. The most difficult aspect of this research was determining how to manipulate the collected data to obtain meaningful parameters. We used several different filtering techniques, calculated many different parameters, and compared the calculated results to visual rankings.

We were not sure how well the method would work when the sheet had very small out-of-plane deformations. However, we were pleasantly surprised to find we could detect those small variations in sheet topography in our Moiré images.

This apparatus is available in the paper physics group at IPST-GIT for use by companies to evaluate their paper samples. In the meantime, our research on dimensional stability continues. We are applying this technique in analyzing dimensional instabilities developed during the drying process. Our drying studies have already given us new insights on the effects of nonuniformities in paper formation and nonuniformities on the dryer surface.

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Hojjatie

Coffin