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Application of correlation curve fitting to improve the absolute displacement measurement using speckle correlation

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ABSTRACT

Displacement measurement using a database of speckle patterns is one method for producing a low cost, non-contact, high resolution displacement measurement. However, this method requires a large number of database patterns that limits the measurement range and speed, especially in two dimensions. Appropriate curve fitting helps reduce the number of required database patterns, making it feasible to develop an absolute scale for machine tools based on speckle correlation. The curve used for fitting is the autocorrelation function of the speckle pattern, referred to here as the correlation curve.

1. Introduction

Speckle patterns are complex intensity distributions, which occur when an optically rough surface is illuminated with a coherent light. Scattered light waves from illuminated points of the surface, interfere and create the speckle pattern. Speckle patterns were first observed using candle-light, in 1877 by Exner, and Lord Rayleigh evaluated the first order statistics of the speckle intensity in 1919 (Dainty and Chen, 2011). The introduction of the laser in 1960 brought deeper investigations for understanding speckle properties (Tiziani and Pedrini, 2012), when the phenomenon was known to be troublesome. Many studies were performed to develop methods for speckle reduction.

In 1970, Leendertz applied the speckle phenomena to displacement measurement on rough surfaces. This was the birth of Speckle Interferometry (SI). Since then, many investigations have applied speckle techniques to the measurement of position and displacement (Patzelt et al., 2012), deformation (Charrett and Tatam, 2014), stress and strain (Matsumoto et al., 2014), surface roughness (Wiesner et al., 2012), and vibration analysis (Bianchi, 2014). Multiple review articles have been published that cover the theoretical and practical characteristics of these technique as well as their development over time (Tiziani and Pedrini, 2012; Jacquot, 2008).

This research introduces a curve-fitting technique that can improve one of the common methods of displacement measurement using speckle phenomenon. One way to use speckle phenomenon for absolute displacement measurement is to use a laser to illuminate an optically rough surface and capture the speckle patterns using a camera (Fig. 1).

Shifting the sample or the optical head in incremental steps, capturing and storing the speckle patterns at each step creates a database of speckle patterns. This is the process of calibrating the displacement scale based on speckles. Afterwards, finding an unknown position of the sample is possible by capturing the speckle pattern at an unknown sample position and determining the correlation of this pattern with all the database patterns. The sample position associated with the correlation peak reveals the position of the sample (Fig. 2). The correlation criterion used in this research is explained in Section 2.

In the literature, displacement measurement using a database of speckle patterns is applied to high resolution displacement measurement (Patzelt et al., 2012) and to investigating the possibility of alignment of work pieces with relocation uncertainty in micrometer order (Goch et al., 2005). However, this method requires a large number of database patterns. For precision measurement, the distance between adjacent database patterns should be less than the resolution of the scale. The large number of required database patterns limits the measurement range, especially in two dimensions. This paper describes a curve fitting technique that helps reduce the number of required database patterns and makes it feasible to create an absolute scale for machine tools based on speckle correlation

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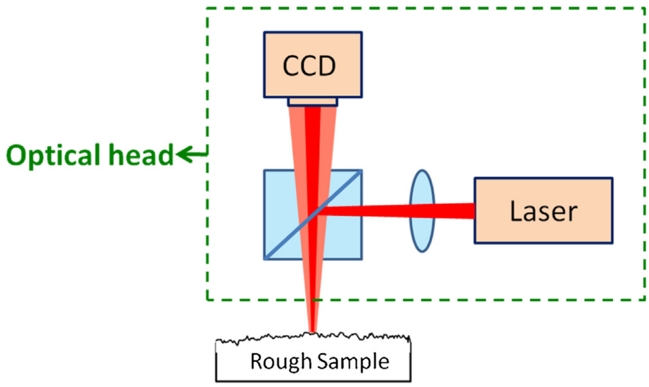

Fig. 1. Typical speckle correlation setup.

in Section 2. The curve used in this technique depends on the characteristics of the measurement system and is called the correlation curve.

Section 3 compares the results of the correlation curve fitting method with the one that uses a large number of database patterns, and with fitting a Gaussian curve. The target resolution for all the methods is one micron. Hence the method with a large number of database patterns requires one database pattern every micron. The other methods require one database entry every 10 microns, and the sample position in between is determined by fitting a curve to the 10 micrometer intervals. Using the correlation curve fitting reduces the number of required database patterns, which helps increase the speed and the range of absolute measurement using speckle correlation. The preliminary results of this research have already been reported (Farsad et al., 2013).

2. Theory

Comparing two speckle images is one of the main steps of the measurement method discussed in this research. Correlation coefficient is a value that quantifies the similarity of two images. There are different ways of determining this quantity. The correlation coefficient used here is based on the Zero-normalized cross-correlation (ZNCC) criterion (Pan et al., 2009) as follows

$$C_{ZNCC} = \sum_{i=-M}^{M}\sum_{i=-M}^{M}\left\{\frac{[f(x_i,y_i)-f_m]\times\left[g(x_i',y_i')-g_m\right]}{\Delta f \Delta g}\right\} \quad (1)$$

where

$$f_m = \frac{1}{(2M+1)^2}\sum_{i=-M}^{M}\sum_{i=-M}^{M} f(x_i,y_i),$$

$$\Delta f = \sqrt{\sum_{i=-M}^{M}\sum_{i=-M}^{M}[f(x_i,y_i)-f_m]^2}$$

$$g_m = \frac{1}{(2M+1)^2}\sum_{i=-M}^{M}\sum_{i=-M}^{M} g(x_i',y_i'),$$

$$\Delta g = \sqrt{\sum_{i=-M}^{M}\sum_{i=-M}^{M}\left[g\left(x_i',y_i'\right)-g_m\right]^2}$$

In Eq. (1), f and g are the pixel intensities of the two different images (F and G) of the same size. Each image has $(2M+1)$ rows and columns. The variables x_i and y_i show the position of the ith pixel in the image F, and x_i' and y_i' show the pixel position in the image G. The advantages of ZNCC criterion is that it is robust to disturbances and insensitive to offset and scale in illumination lighting. Because this method compares the two images pixel by pixel, the distance between the two images should be less than the speckle size.

The correlation curve used here is the autocorrelation function of the speckle pattern, which is a measure of mean speckle size (Li and Chiang, 1992). Another way to determine this curve is to determine the correlation of one of the database patterns with its neighbors. The autocorrelation of a speckle pattern in subpixel scale or the correlation of one of the database patterns with its neighbor database patterns gives a correlation distribution (discrete points). In order to obtain a continuous curve, an interpolation method is required, for example a cubic spline interpolation between adjacent correlation coefficients or a Guassian fit to the data. Fig. 3 compares the spline fit correlation curve for the sample position at 10 μm over a 20 μm range, with the second order polynomial and the Gaussian fit over the same range. The polynomial shares three points with the correlation curve at sample positions 0, 10, and 20 μm (three points can define a unique second order polynomial). The Gaussian distribution with y offset of 0.19, width of 7.29, amplitude of 0.807, and x offset of 10.065 fits the data almost indistinguishable from the spline fit and may be used as the correlation curve.

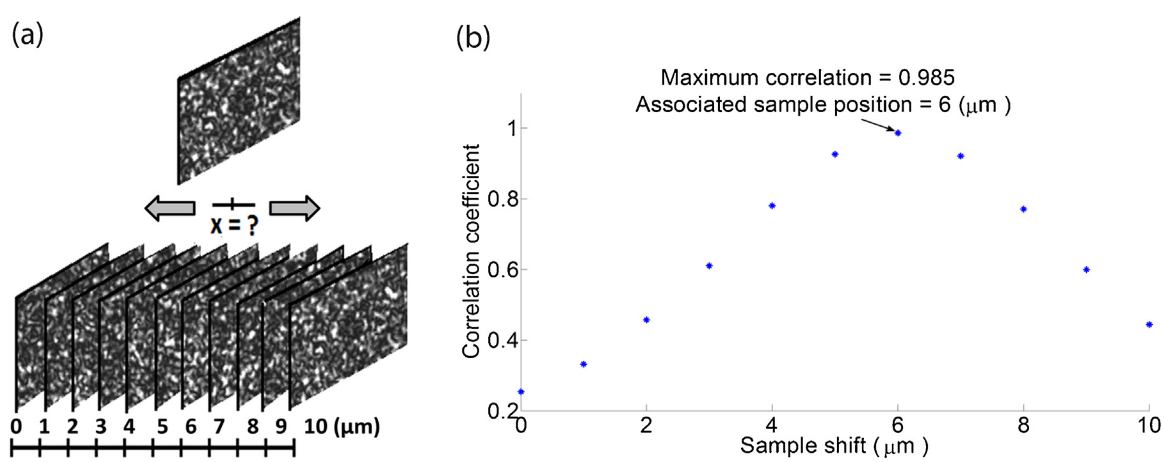

Fig. 2. Absolute position measurement using speckle pattern correlation. (a) The database of speckle patterns and the corresponding sample positions. (b) Correlations between the speckle pattern at an unknown position and the database patterns. The correlation peak shows the sample position.