Thickness Correction for Edge Detection of Optical Coordinate Measuring Machines

Jiyou Fu and Robert Hocken
Precision Metrology Lab, University of North Carolina at Charlotte, Charlotte, NC 28223

Abstract: Edge detection is essential to ensure the accuracy of geometrical measurement in optical CMMs. In this paper, an edge model of a thick part is introduced and the approach to calculate the edge shift due to the thickness of the part is explained. In the end, the experimental data show that the bi-directional measurement error for parts with thicknesses larger than 3mm and measured at lens magnification 6.6 times is always near 3μm.

Key words: Optical CMM, OTF, edge shift, bi-directional measurement

1. Introduction

As the dimensions of microchip features shrink, the demand for high accuracy measurement in lithography grows rapidly. Optical coordinate measuring machines (CMM), also called video-based CMMs, are becoming widely used tools due to their non-contact and fast two-dimensional measurement [1]. In spite of many advantages, their measurement accuracy is degraded by improper illumination and characteristics of the part [2].

All measurements using optical CMMs are based on the coordinates of the measured points, specifically the edge position in the image. In bi-directional measurement, the variations in edge definition are added together when the two edges are taken from different sides, so the errors in bi-directional measurements are much larger than that from uni-directional measurement. This study focuses on bi-directional measurement, such as diameter measurement of ring gauges, width measurement of gauge blocks, etc.

Our test results have shown that the measurement variance due to different lighting conditions, such as top lighting and backlighting, is about 1μm for the same part. If the lighting intensity is controlled properly, the variance is less than 1μm. Surprisingly, we also found those the measurement error of a part is always about 4μm, no matter if its thickness is 5mm or 30mm. To explain why the same optical CMM, which can measure a thin part with error less than 1μm, produces such a constant bias error, an image acquisition model of an optical CMM will be introduced.

2. Image acquisition model of optical CMM [3]

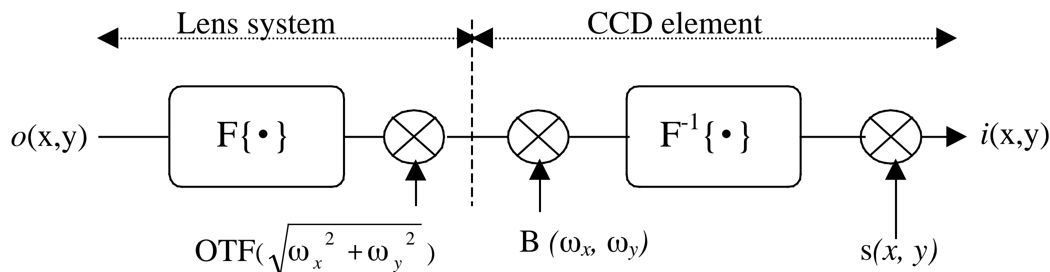

Fig.1 An image acquisition model of optical CMM

In this model, o(x,y) represents an incoherently illuminated object. The diffraction-limited lens system acts as a low-pass filter, and its filtering effect can be described by the Optical Transfer Function OTF[4]. The OTF depends on the numerical aperture of the objective lens divided by the wavelength of light (NA/) and on the degree of defocusing. F{•} denotes the Fourier transform. The image intensity after the lens system can be obtained by multiplying the object intensity in the Fourier domain by the OTF.

The input o(x,y) filtered by the OTF is then sampled by the pixels of the CCD elements. This can be expressed by first a convolution with a block function representing the size ($P_{size_x} \times P_{size_y}$) and shape of the pixels followed by a multiplication with the rectangular grid of unit impulse function P (ω_x, ω_y) (spaced by $P_{spacing_x} \times P_{spacing_y}$) representing the position of the pixels. The convolution with a block function in the spatial domain equals to a multiplication with B(ω_x, ω_y) in the Fourier domain, where B(ω_x, ω_y) is the Fourier transform of the block function b(x,y). The result is then sampled by multiplication by s(x,y), a rectangular grid of the unit impulse function (•), which is the same as a convolution with S(ω_x, ω_y) in the Fourier domain. The block and sample functions in the both spatial and Fourier representation are listed in Table 1.

Table 1 the block function of a CCD pixel and the sampling function of CCD surface both in spatial and Fourier representation

Spatial domain	Fourier domain
$b(x,y) = \begin{cases} 1 & \lvert x\rvert < \frac{P_{size_x}}{2}, \lvert y\rvert < \frac{P_{size_y}}{2} \\ 0 & else \end{cases}$	$B(\omega_x,\omega_y) = \sin c(P_{size_x} ?\omega_x) \sin c(P_{size_y} ?\omega_y)$ here, sinc(x)=sin(x)/x
$s(x,y) = \sum_{m}\sum_{n} \delta(x - m\ P_{size_x})\ \delta(y - n\ P_{size_y})$	$S(\omega_x,\omega_y) = \sum_{m}\sum_{n} \delta(\omega_x - m\ P_{size_x})\ \delta(\omega_y - n\ P_{size_y})$

m, n are pixel number along horizontal and vertical direction of CCD chip respectively.

Assuming the object is thin with respect to the depth of the focus of the optical system and treated it as two-dimensional (2D), the Fourier representation of the given model is:

$$I(\omega) = \{O(\omega)\quad OTF(\omega)\quad B(\omega)\}\quad S(\omega) \tag{1}$$

here = (ω_x, ω_y), indicating continuous spatial frequency in reciprocal meters. And denotes a convolution.

3. Edge formation model for a thick part

Once the part becomes thicker than the depth of the field of the objective, the effect of finite thickness will change the intensity distribution in the edge transition area and therefore introduce measurement error using current edge detection methods, such as derivative and threshold methods. A thick part can be modeled as a stack of 2D object planes separated along the z axis by small intervals, Δz. The image of each object plane at the CCD surface is degraded by the OTF at varying degrees of focus. Thus the image is a sum of information from in focus as well as out of focus object planes[5]. This relation can be modeled with the equation

$$I_{thick}(\omega) = \sum_{j=0}^{j=d/\ z} \{O(\omega, j\ \ z) \cdot OTF(\omega, j\ \ z) \cdot B(\omega)\}\quad S(\omega) \tag{2}$$

here we assume the part has the thickness d and the object plane at j = 0 is where the CCD camera is focused.

In order to compensate for the error due to the thickness of part, the relation between edge shift and part's thickness is required. To avoid calculating the complex $OTF(\omega, j\Delta z)$ and Fourier transformation, we built up the new $I_{thick}(x,y)$ by adding all the intensity distributions of edge transition area at consecutive $j\Delta z$ positions. Clearly, the width of edge-transition area W_j increases as the out of focus $j\Delta z$ increases. Also, W_0 , the width of edge transition area at the focus plane, is the smallest one. Knowing that the intensity decreases at the squared ratio of W_j/W_0, $(W_j/W_0)^2$ should be used as the weight coefficient when adding the intensity. Supposing the edge position at $j\Delta z$ plane as P_j, we define the edge shift at $j\Delta z$ plane is $E_j = P_j - P_0$. Thus the relation between edge shift and part's thickness $T(d)$ could be calculated by

$$T(d) = \frac{\sum_{j=0}^{j=d/\Delta z} \left(\frac{W_j}{W_0}\right)^2 E_j}{\sum_{j=0}^{j=d/\Delta z} \left(\frac{W_j}{W_0}\right)^2} \tag{3}$$

4. Experiment and result

By using an *Voyager* 12×12 optical CMM [6] with lens magnification 6.6, NA=0.185, and CCD size 11μm, we took 200 images of a very thin edge pattern (thickness around 0.1μm) at consecutive z positions with the interval Δz = 0.01mm and backlight intensity 70 units. Starting from the focus position, the total z travel range is 2mm. For each image, the edge position P_j was found by the derivative method and its edge shift E_j equals to(P_j - P_0). The width of edge transition area W_j can be found by counting the pixel number in the edge transition area. To simplify W_j's calculation, we treated W_j as a arithmetic series due to the equal z interval. By fitting the previous W_j series, we obtained the new W_j series with the common difference about 0.6 pixel. Then the edge shift $T(d)$ could be calculated by formula (3). All data at each z position were the average results from 10 measurement of the same image(Table 2).

Table 2 Edge shift data

$j\Delta z$ (mm)	E_j (pixel)	W_j (pixel)	$T(d)$ (pixel)
0	0	2	0
0.01	0.03951	2.6	0.014688
0.02	0.080085	3.2	0.027574
0.03	0.141876	3.8	0.041588
0.04	0.16683	4.4	0.052082
…	…	…	…
1	11.99884	62	0.56989
1.01	11.05717	62.6	0.572724
…	…	…	…
1.9	18.33217	116	0.77231
1.91	20.02384	116.6	0.773791
…	…	…	…

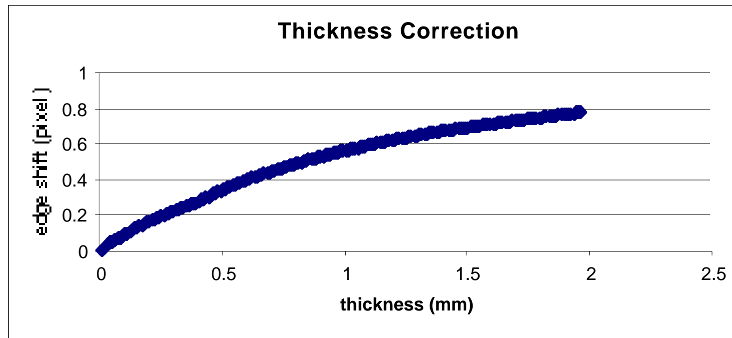

Fig.2 Relation between the edge shift and the thickness of a part

Figure 2 shows the thickness correction curve for this lens. By further extending the curve with geometrical progression the edge shift will converge to around 0.83 pixel, which means the maximum thickness compensation is about 2.8μm for this specific measurement configuration.

5. Conclusion

Depending on the illumination conditions and characteristics of the part, measured edge position can shift. The thickness of a part may also introduce larger measurement errors than the illumination. Based on the edge formation model of a diffraction-limited optical system, thickness correction plot which describes the relation between the edge shift and the thickness can be obtained by summing the edge shifts at varying degrees of defocusing. For the lens magnification 6.6 and NA=0.185 under backlighting 70 unit, the edge shift increases from zero to 3mm as the thickness grows from zero to larger than 3mm.

Acknowledgment: Help from Warren Lin at GSI Lumonics Inc. is gratefully acknowledged.

Reference:

[1] Garces A. et al, “Performance Test Procedures for Optical Coordinate Measuring Probes”, Final Project Report, Part I, European Communities Brussels Contract No. 3319/1/0/159/89/8-BGR-D (30), July 1993
[2] Thakkar H.E, “Characterization of Hybrid Coordinate Measuring Machines”, Master Thesis, UNC Charlotte, 1998
[3] Frank R Boddeke, Lucas J van Vliet, “Autofocusing in microscopy based on the OTF and sampling”, Bioimaging, 2 (1994) 193-203
[4] Goodman, Joseph W., “Introduction to Fourier optics”, McGraw-Hill Inc., 1988
[5] Michael A. Oliva, Miguel Bravo-Zanoguera, Jeffrey H. Price, “Filtering out contrast for microscopy autofocus”, Applied Optics, Vol.38, No.4, p638-646, February 1999
[6] “Software manual: Voyager software version 5.0”, GSI Lumonics Inc., 1997