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Automatic dimensioning model of contact profilometer based on linear fitting

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Abstract: Contact profilometer can measure the contours of various precision mechanical parts, which is of great significance to the industrial development. Aiming at the problem of automatic labeling of contact-type profilometer, the mathematical models of parameters such as slot width, distance between center of circle, Angle between oblique line and straight line and radius of circle are established by means of linear regression fitting and least square method. The contours of the measured workpiece under the tilt state are checked and corrected. The differences between the calculated values of the parameters of the workpiece under the two measurement states were analyzed to obtain more accurate and complete contour lines.

Keywords: Contact profilometer, Linear fitting, Automatic dimensioning model.

1. Introduction

In microelectronics, optoelectronics, MEMS and other semiconductor related fields, there are a lot of step structures in various devices. The height of step structure is closely related to device performance. Therefore, it is necessary to use a step height measuring instrument to monitor its magnitude. Step height measurement instruments used in semiconductor industry include contact profilometer, atomic force microscope, optical profilometer, etc. Compared with other instruments, contact profilometer has the advantages of large measuring range, high resolution, small measuring force, good repeatability and fast measuring speed, etc, which has been widely used in the semiconductor industry. Profilometer is a two-coordinate measuring instrument, which is composed of working platform, fixture, measured workpiece, probe, sensor and servo drive. The working principle of contact profilometer is as follows. The probe touches the surface of the measured workpiece and slides evenly, and the sensor senses the geometric changes of the measured surface. Samples are taken in the X and Z directions and converted into electrical signals. Through amplification and other processing, the electrical signal is converted into digital signals and stored in data files. At present, in the field of measurement, the research of contact profilometer mainly focuses on the development of step height standard sample to solve the calibration problem of instrument z-axis measurement performance. This enables the value of the instrument to be traceable to the measurement standard [1] through the standard sample, or to study the common faults of the profilometer [2], the error of the asphatic contact measurement of the profilometer [3] and the probe status of the profilometer [4-5]. Therefore, this paper studies the automatic labeling model of contactor from the perspective of mathematical modeling, which promotes the development of contactor calibration technology. In an ideal situation, the contour curve should be smooth. However, due to various problems with the contact profiler, the detected contour curve shows roughness. To simplify the problem, we assume that the contour line of the tested workpiece is a plane curve composed of straight lines and arcs [6].

2. Various parameter values of the wheel profile in the horizontal state

According to the measured data of workpiece 1 in the horizontal state and its contour line (as shown in Figure 1), we use Excel to make a line chart, as shown in Figure 2.

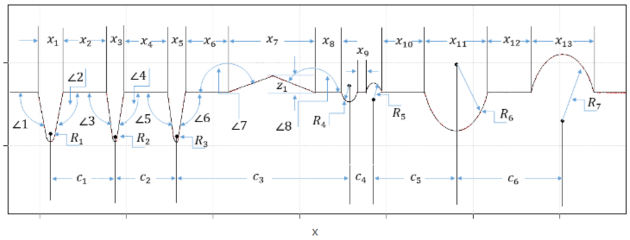

Figure 1. Profile of workpiece 1 measured in horizontal state

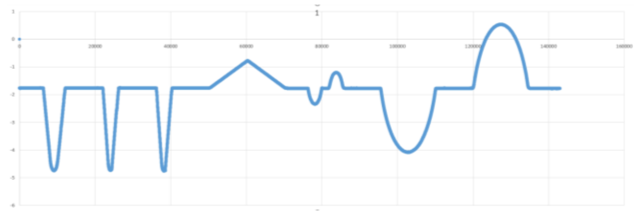

Figure 2. Line diagram of piece 1

It can be seen from the figure that the horizontal position of the contour line of the measured object and the trend of the scatter point are similar to the horizontal line. Take the data of 6338 of the first approximate horizontal line in Attachment 1, and calculate the z-axis average value of this group of data. The average value is $\overline{z} = -1.77013$. Use Excel to find the distance between each point and the z-axis average value $\overline{z}$. The z coordinates of the data for standard $\left|z - \overline{z}\right| < 0.005$ will be removed. Make scatter figure 3.

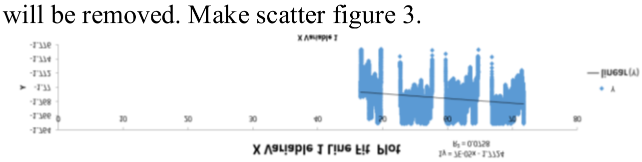

Figure 3. Linear fitting after data removal 1

The data of the first four approximate horizontal lines are fitted. Although the data is dense and compact, it still does not meet the expectations of this paper.

In consideration of the impact of missing values on the whole, the following treatments are made respectively in this paper.

1). eliminate the missing values. It's the distance between two points and the length 1 is the x-coordinate. The scatter figure 4 is obtained.

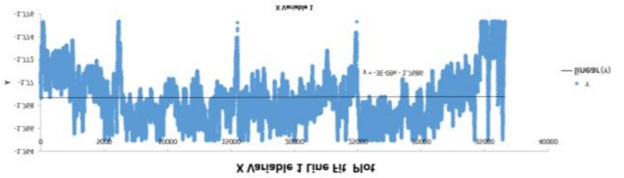

Figure 4. Linear fitting after data removal 2

Taking unit length 1 as abscissa, it can be seen intuitively that the slope of the fitting line tends to 0. However, we believe that the deviation caused by arbitrarily modifying the abscissa step between data points and the consequences of subsequent fitting are immeasurable. The step size between data points is about 0.001, so the deviation of 1 is too large to be adopted.

2). When missing values are excluded, the average step size between data points is 0.001 in abscissa. The scatter figure 5 is obtained.

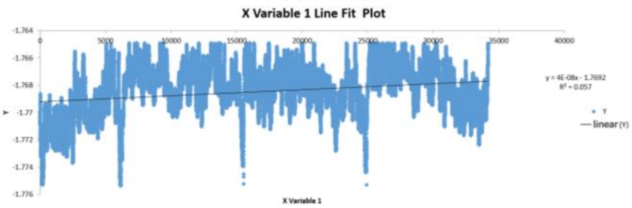

Figure 5. Linear fitting after data removal 3

By observing the scatter diagram, it can be seen that the data density can be increased by modifying the step size. However, for the trend of fitting regression line, it can be seen that the trend is monotonically increasing.

Due to the large amount of data removed, it is important to deal with the missing values. This directly affects the results of our model. This paper believes that the sample mean value $\bar{z} = -1.77013$ should be used to fill the missing value in the processing of missing value after eliminating data.

3). Missing value processing and mean filling missing value. Excel was used to remove and replace the removed data with the scatter diagram after sample mean value $\bar{z} = -1.77013$, as shown in FIG.

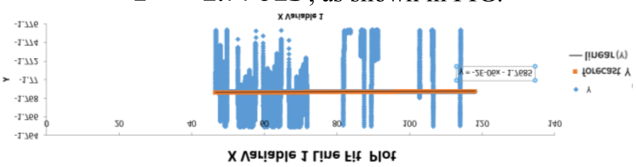

Figure 6. Linear fitting after data removal 4

By observing the scatter plot, it can be seen that the slope of the analytic formula of the regression fitting linear equation is -2×10^{-6}, it tends to 0. Therefore, in this paper, the intercept -1.7685 of the unitary linear regression equation after the mean processing of the missing value is used as the data horizontal line.

We first use Excel to make a broken line diagram of each diagonal line, and then make a linear regression equation of one variable for each diagonal line.

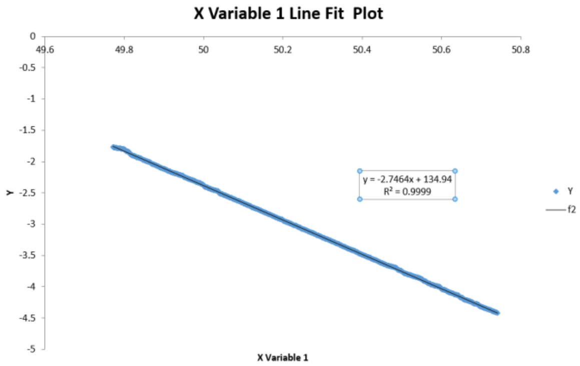

Figure 7. Linear fitting of the first oblique line

The equation of the first oblique line is $z_1 = -2.7464x + 134.94$, $P < 0.05$, $R^2 = 0.9999$

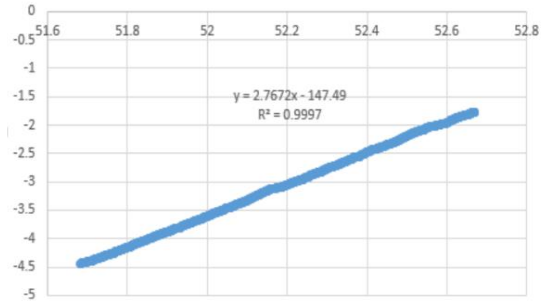

Figure 8. Linear fitting of the second oblique line

The equation of the second oblique line is

$z_2 = 2.7672x + -147.49$, $P < 0.05$, $R^2 = 0.9997$

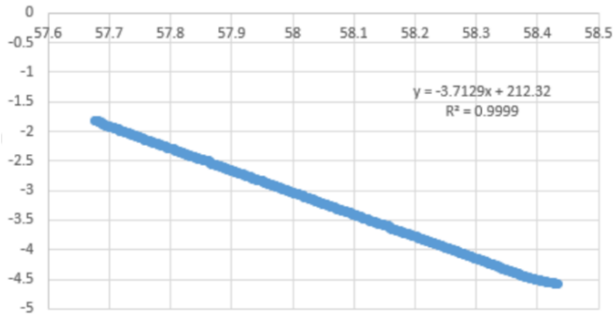

Figure 9. Linear fitting of the third oblique line

The third oblique line has the equation $z_3 - 3.7129x + 212.32$, $P < 0.05$, $R^2 = 0.9999$

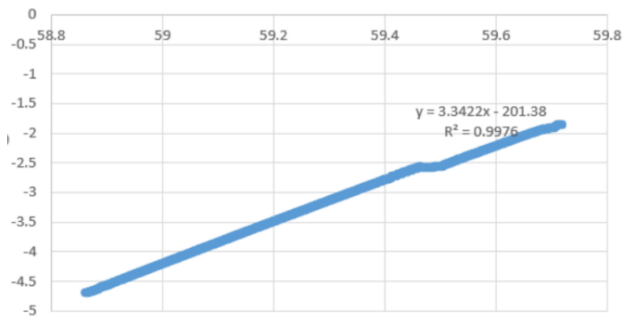

Figure 10. Linear fitting of the fourth oblique line

The equation of the fourth oblique line is zero $z_4 = 3.3422x - 201.38$, $P < 0.05$, $R^2 = 0.9976$

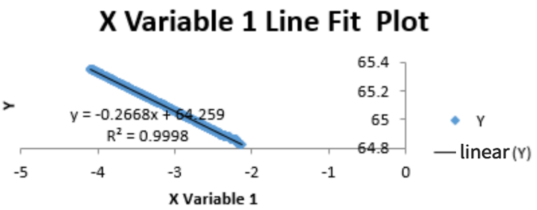

Figure 11. Linear fitting of the fifth inclined line

The equation of the fifth inclined line is $z_5 = -0.2668x + 64.259$, P<0.05, $R^2 = 0.9998$

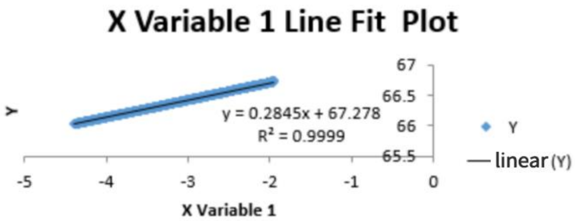

Figure 12. Linear fitting of the sixth oblique line

The equation of the sixth oblique line is $z_6 = 0.2845x + 67.278$, P<0.05, $R^2 = 0.9999$

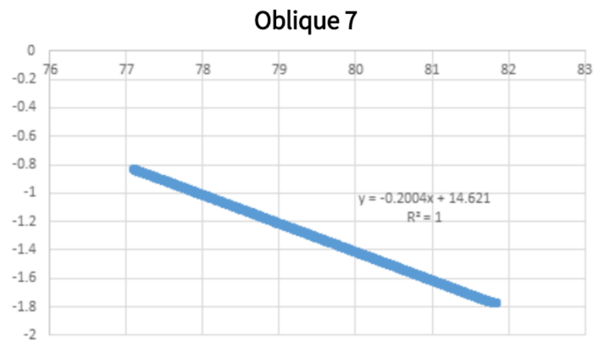

Figure 13. Linear fitting of the seventh inclined line

Article 7 The equation of an inclined line is $z_7 = -0.20004x + 14.621$, P<0.05, $R^2 = 1$

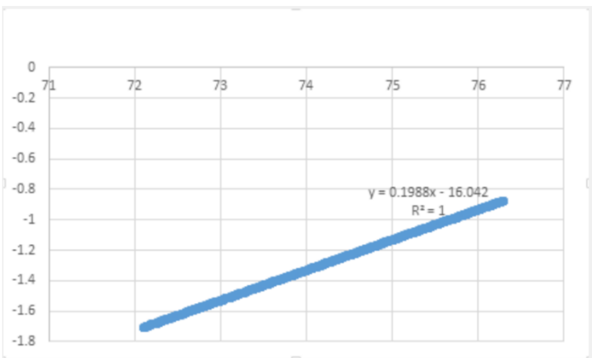

Figure 14. Linear fitting of the eighth oblique line

The equation of the eighth oblique line is $z_7 = 0.1988x - 16.042$, P<0.05, $R^2 = 1$

After obtaining all the equations of oblique lines, the coordinates of intersection points with horizontal lines can be determined, and the distance formula between two points can be used to obtain Model 1[7] :

$$L = \sqrt{\left(x_1 - x_2\right)^2 + \left(z_1 - z_2\right)^2} \qquad (1)$$

It finds the width of the notch, the length of the horizontal segment.

Model 2 was established:

$$x_{R_i} = \frac{J_1 + J_2}{2} \qquad (2)$$

We have the abscissa of the center.

Model 3 was established:

$$wjd = \left(x_{x_{R_i}}, 2.7672x_{R_i} - 147.49\right) \qquad (3)$$

The coordinates of the intersection of oblique lines are obtained.

By using the horizontal coordinate of the center of the circle, two intersection points of two oblique lines and the arc were obtained by using trigonometric transformation, and model 4 was established:

$$hz_i = \left(x_{R_i}, z_{hzi}\right)$$

$$kz_i = \left|\frac{J_2 - x_{R_i}}{-1.7685 - 2.7672x_{R_i} - 147.49}\right|$$

$$kz_j = -kz_i$$

$$\mathrm{kz}_j \bullet (\mathrm{yyx}_i - \mathrm{x}_{R_i}) + \mathrm{hzx}_i = -2.7464 \bullet \mathrm{yyx}_i + 134.94$$

$$yyz_i = -2.7672 \times yyx_i - 147.49$$

$$\mathrm{kz}_j \bullet (\mathrm{yzx}_i - \mathrm{x}_{R_i}) + \mathrm{hzx}_i = -2.7464 \bullet \mathrm{yzx}_i + 134.94$$

$$\mathrm{yzz}_i = -2.7464 \bullet \mathrm{yzx}_i + 134.94$$

$$(a - hzx_i)^2 + (b - hzz_i)^2 = (a - yyx_i)^2 + (b - yyz_i)^2$$

$$(a - hzx_i)^2 + (b - hzz_i))^2 = (a - yzx_i)^2 + (b - yzz_i)^2$$

(4)

MATLAB was used to obtain[8] the parameters of the contour in horizontal state, as shown in Table 1.

Table 1. Parameter values of contour line in horizontal state

Slit width	X1	X_3	X_5	X_7	X_{11}	X_{13}		
	2.8829	2.0639	2.0419	9.9907	7.2601	7.2385		
Arc radius	R_1	R_2	R_3	R_4	R_5	R_6	R_7	
	0.6448	0.3719	0.3534	0.9961	1.0078	4.0028	4.0002	
Center distance	C_1	C_2	C_3	C_4	C_5	C_6		
	7.4500	7.1103	93.6665	3.9766	14.0214	17.3264		
The length of the arc	L_1	L_2	L_3	L_4	L_5	L_6	L_7	
	0.9925	0.5814	0.5527	2.2538	2.2715	26.4115	26.3434	
The length of a horizontal line segment	X_2	X_4	X_6	X_8	X_9	X_{10}	X_{12}	
	5.0005	5.0102	5.0166	3.0714	1.0029	4.9979	5.0023	
The length of the slash segment	h_1	h_2	h_3	h_4	h_5	h_6	h_7	h_8
	3.0213	3.0153	3.0016	3.0550	3.2420	3.2792	5.1135	5.0742
intersection angle	∠1	∠2	∠3	∠4	∠5	∠6	∠7	∠8
	110.0072	109.8686	105.0739	106.6574	104.8459	105.9575	168.7562	168.6680
height	Z_1							
	0.9971							

3. Horizontal correction and difference analysis of wheel profile in tilting state

When the same workpiece is measured for different times, the calculated values of contour parameters will also be different due to different angles and positions of workpiece placement. When we get the measurement data of the contour line of work-piece 1 when it is tilted at an angle and has some horizontal displacement, we often need to calculate the tilt angle of the work-piece when it is measured, make horizontal correction, get the parameter values of the corrected contour line, and then compare the differences between the calculated values of the parameters of the contour line under the two measurement states. Using the same method above, we calibrated the horizontal line data under displacement state, and then substituted it into the above model to solve. Through linear fitting, we get that the horizontal line equation under displacement state is

$$z_{\text{tilt}} = -0.1308x + 7.788, \quad R^2 = 1$$

Table 2. The parameter values of the corrected contour lines

angle of inclination	7.4520							
Slit width	X_1	X_3	X_5	X_7	X_{11}	X_{13}		
	2.8957	2.0830	2.0606	9.9892	7.2540	7.2559		
Arc radius	R_1	R_2	R_3	R_4	R_5	R_6	R_7	
	0.6310	0.4848	0.6266	1.0167	1.0035	4.0083	4.0027	
Center distance	C_1	C_2	C_3	C_4	C_5	C_6		
	7.4736	7.0764	20.1419	2.9413	9.7690	12.7140		
The length of the arc	L_1	L_2	L_3	L_4	L_5	L_6	L_7	
	0.9761	0.7490	0.9218	2.3186	2.2868	26.4273	26.4006	
The length of a horizontal line segment	X_2	X_4	X_6	X_8	X_9	X_{10}	X_{12}	
	4.9934	4.9898	5.0074	3.0126	0.9879	4.9987	4.9968	
The length of the slash segment	h_1	h_2	h_3	h_4	h_5	h_6	h7	h8
	3.0146	3.0184	2.9990	3.0149	3.0267	3.0160	5.0203	5.0962
intersection angle	∠1	∠2	∠3	∠4	∠5	∠6	∠7	∠8
	110.0867	110.0873	105.0102	105.5163	104.8901	104.5303	168.6680	168.6790
Height	Z_1							
	1.0004							

Next, we analyzed the difference between the data in Table 2 and the parameters of the contour measured in the horizontal state. We substituted the two groups of data into Excel, and first calculated the sum, average and variance[9], as shown in Table 3. Then we conducted a one-way ANOVA, as shown in Table 4. Finally, we found that the two groups of data had significant correlation.

Table 3. Analysis of the sum, mean, and variance

Group	Number of observations	Sum	Average	Variance
Slit width	6	31.478	5.246333	11.30302
Arc radius	7	11.377	1.625286	2.703329
Center distance	6	143.5512	23.9252	1191.52
Arc length	7	59.4068	8.486686	149.8739
Length of horizontal line segment	7	29.1018	4.1574	2.454479
Oblique segment length	8	28.8021	3.600263	0.860986
included angle	8	979.8347	122.4793	818.1025
height	1	0.9971	0.9971	
Slit width	6	31.5384	5.2543	11.24886
Arc radius	7	11.7736	1.681943	2.558677
Center distance	6	60.1162	10.01937	35.00608
Arc length	7	60.0802	8.582886	148.7835
Length of horizontal line segment	7	28.9866	4.140943	2.480178
Oblique segment length	8	28.2061	3.525763	0.895143
included angle	8	977.4679	122.1835	828.3865
height	1	1.0004	1.0004	

Table 4. Results of the one-way ANOVA analysis

Difference source	SS	df	MS	F	P-value	F crit
Between groups	183623.4	17	10801.38	45.10606	2.13E-34	1.748804
Within group	19636.23	82	239.4662			
Total	203259.6	99				

4. Full profile lines based on the linear fit

In real life, when we detect the workpiece for many times, there will be deviations in the angle of workpiece placement, the starting point and the end point of measurement each time, which leads to that each measurement is actually to detect a part of the whole workpiece. Then we will calibrate the horizontal line data under displacement according to the 10 times of measurement data of workpiece 2, and substitute it into the previous model. Through linear fitting, we can get the horizontal line equation under displacement state, rotate it, and finally obtain the calibration data, as shown in Figure 15.

Using the Matlab model, you can get the parameter values of the contour line of workpiece 2 and its complete contour line, as shown in Table 5 and Figure 16.

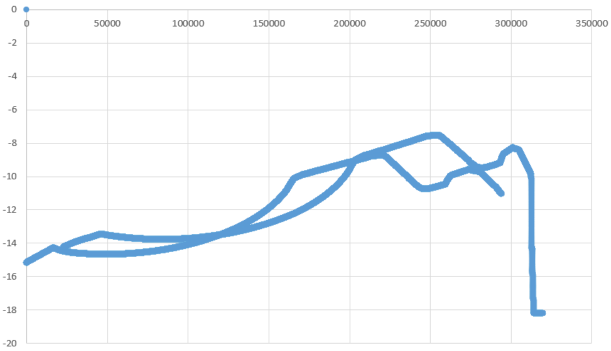

Figure 15. Calibration effect of workpiece 2 data 2

Table 5. Workpiece two parameters

Slit width	X21	X22	
	6.2137	1.2548	
circular arc radius	R_1		
	3.1069		
The length of the arc	L_1		
	18.9484		
The length of the slash segment	h_{21}	h_{22}	h_{23}
	3.2535	6.9497	6.7831
intersection angle	∠21	∠22	∠23
	81.0277	81.3152	50.6027

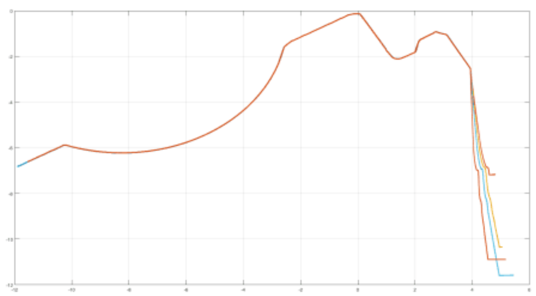

Figure 16. Calibration effect of workpiece 2 data 2

5. Conclusion

This paper analyzes the contour line data in the horizontal state, and then extracts the data from the points on the horizontal position. Using linear fitting, the intersection of oblique line and horizontal line is calculated. Using elementary mathematical methods, four models are established, and each parameter is solved using MATLAB programming. For the circular arc without oblique line intersection, the parameters such as the center radius of the circle can be obtained by using the least square method. For the contour line in the inclined state, first observe the data distribution of the scatter plot, directly fit the inclined horizontal line with a single linear fitting to obtain the slope of the regression equation, and then calculate the included angle and intersection coordinates, so as to obtain the rotation angle and the rotation center of the curve. Use Excel for data validation, and then calculate the values of each parameter. Finally, the two groups of data were analyzed by one-way ANOVA using Excel. Scatter plot analysis is also carried out for 10 groups of measured data in work-piece 2. The data of oblique straight line part are filtered out respectively for linear fitting, and then the tilt angle of two adjacent groups of data is measured respectively. After ignoring the tilt angle of odd pair of groups, the two groups of data are combined into five groups of data, and their data are calibrated one by one using the tilt angle and the rotation center. The model established in this paper can be generalized, and can be used in the calculation of arc, angle, groove width and other graphics, as well as in the calculation of the edge contour of buildings, cars and parts.

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