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Evaluation of surface profile parameters of a machined surface using confocal displacement sensor

V Rishikesan[a], GL Samuel[b]*

[a]*Senior Research Fellow, Manufacturing Engineering Section, Department of Mechanical Engineering, IIT Madras, Chennai – 600036, INDIA*
[b]*Associate Professor, Manufacturing Engineering Section, Department of Mechanical Engineering, IIT Madras, Chennai – 600036, INDIA*

Abstract

This paper describes the use of non-contact type chromatic confocal displacement sensor for estimation of surface profile parameters such as R_a, R_q and R_t of different machined surfaces. The confocal displacement sensor can measure surface roughness of the order of 5 nm on conducting and non-conducting material. The surface irregularities of the profile measured over the evaluation length is related to the response of chromatic confocal displacement data. Confocal sensor response is analyzed to determine the displacement variations from the profile data points of the surface. Based on the confocal chromatic image principle, a new technique is used to measure the micro level surface finish. The new method is validated by measuring surface roughness of kwon specimen in the range of 1.6 - 3.2μm using an experimental setup developed and by stylus method. The estimated profile parameter values are in good agreement with the values obtained by stylus method and hence the confocal displacement based method can be implemented to measure surface roughness parameters.

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Keywords: Confocal displacement sensor; Surface roughness; Non-Contact type measurement

1. Introduction

It is well recognized that surface finish greatly influences the tribological properties of contacting parts. Precise understanding of this behavior is vital in many applications such as friction, lubrication and wear. Therefore, the

* Corresponding author. Tel.: +91-44-2257-4699; fax: +91-44-2257 4652.
E-mail address: samuelgl@iitm.ac.in

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characterization of surface roughness is being developed over the last 70 years. In general, average surface roughness (R_a) is mainly used as a dimensional index to determine the surface finish of a machined surface.

Nomenclature

R_a	standard Roughness
$R_{a(Stylus)}$	roughness measured by stylus based method
$R_{a(c)}$	roughness measured by confocal displacement based method

The measuring instrument can be divided into two broad categories: (1) contact types and (2) non-contact types. Traditionally used contact based instruments are not suitable for in-situ measurement environments and the traditional instruments have limitations such as low speed measurement, contact and require vibration-free environment, etc. Murugarajan and Samuel (2010) compared the contact and the non-contact instruments. They reported that non-contact instruments have several advantages in automated production and inspection systems in manufacturing sector, such as the ability for in-process implementation, rapid measurement capability, wear free measurements and the ability to provide information over a surface area. Jiang et al (2007) reported that the non-contact measurement instruments such as optical, capacitive/inductive, ultrasonic, machine vision and laser sensors are useful alternatives to the traditional profiling instrument to measure the surface finish of the machined surface. General considerations about measurement capabilities of these types of instruments can be summarized as in Table 1. Chin (1995) Compared the surface roughness measurements by stylus profiler, AFM and non-contact optical profiler.

Table 1: Surface microtopography instruments and their use for dimensional micro metrology by Bariani (2005).

Principle	Merits	Limitations	Examples of application
Stylus	Traceability Large range (XY and Z)	Mechanical contact force Tip geometry	Industrial surfaces
Autofocus	Point by point probing	Limited lateral resolution Max. detectable slope appr. 15°	Soft materials
White light interferometer	Fast High vertical resolution (sub-nm)	Max. detectable slope appr. 30°	Roughness of flat surfaces; Film thickness; Low aspect ratio; MEMS
Confocal	High aspect ratio structures Max. detectable slope up to 75°	Limited lateral resolution Limited vertical resolution	High aspect ratio; MEMS
SPM	nm resolution	Slow Limited range (X,Y and Z)	Nano surfaces

Hansen, et al. (2003) reported the comparison among a focus detection laser scanning profiler, a confocal scanning laser microscope and a white light interferometer for the measurement of plastic surfaces. Theilade (2005) reported a more thorough investigation of the focus detection profilometer where both random microstructures as well as deterministic microstructures were investigated. For all optical instruments, the noncontact nature is a clear merit. Few examples have been found where different instruments were actually compared based on measuring micro components. According to the comparison of all surface profile measurement instruments, we can conclude that the confocal displacement sensor is more suitable for evaluation of micro surfaces profile parameters.

In addition, the surface finish measuring techniques are classified into three categories (Vorburger, et al. 2002): line profiling technique, areal topography, and area integrating. In this paper, high-resolution confocal displacement sensor has been used to measure the texture over the surface by profiling technique. Izmailov and Kourova (1980) have studied the correlation between surface and profile parameters. Results reveal that the surfaces can be modeled with profile height and other surface profile parameters. Murugarajan and Samuel (2010) proposed a 2-D Discrete Point Method (DPM) to predict the theoretical response of capacitive displacement sensor of the measured surface profile. They also proposed non-dimensional 'Profile Height Index (PHI)' to relate the surface finish of the component. It was described by a numerical indication of the distribution of surface irregularities and peak height of the profiles measured using the sensor.

Samuel and Shunmugam (1999) have developed algorithms for evaluating the straightness and flatness form error based on computational geometric techniques such as the minimum zone and function-oriented evaluation. Fleishman, et al (2005) used least square curve fitting method to remove dimensional error data from the measurement signal and extract the surface information. This paper describes the detailed experimental work carried out for measuring the surface finish using the confocal displacement sensor based on the chromatic imaging principle system. A set of standard machined surfaces, namely, turned and milled surfaces with average roughness (R_a) values of 1.6, 3.2 and 6.3µm were used for measurement and analysis.

2. Development of Experimental Setup

The experimental setup used in this work comprises of three major components viz. confocal displacement sensor, high precision XYZ axis linear stage with controller and computer based data acquisition system as shown in Fig. 1. The confocal sensor is an ultra-precise non-contact displacement measuring system. The confocal sensor moves along Z-axis linear stage and micro component placed on the stage which can moves along X and Y-axis as shown in Fig. 2. Using confocal chromatic imaging principle, a polychromatic white light is focused onto the target surface by an optical system. This light reflected from the target surface is transmitted from the probe, through a confocal aperture and onto a spectrometer, which detects and processes the spectral changes and calculates distances. These distance measurements are related to surface irregularities.

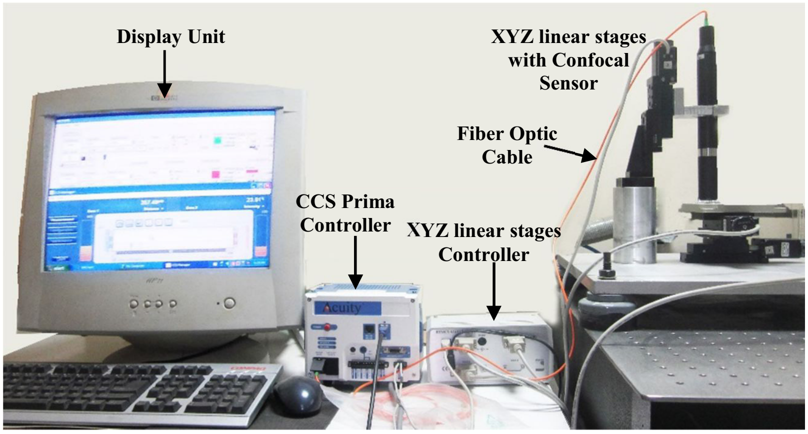


Fig. 1. Experimental setup for measurement of surface finish using confocal sensor

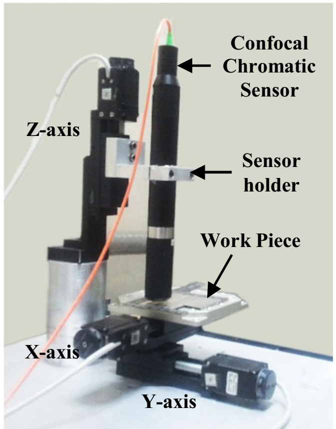


Fig. 2. XYZ Linear stages with confocal sensor

Table 2. Confocal Displacement Sensor Specifications

Prima Controller	
Measuring Frequency	100 - 5000 Hz;
Light Source	White light LED
Measuring Modes	Distance, Thickness;
Confocal Pen (CL1)	
Range (mm)	0.10
Range Beginning (mm)	3.3
Resolution (nm)	5

Linearity (mm)	0.02
Max. Target Tilt	+/- 43°
Spot Diameter (µm)	2
Measurable Thickness (mm)	7 (Minimum)

Table 3. Specifications of linear stage controller

Motion	
Resolution	full step, half step, 1/4, 1/8
Speed programmable	2-5000 step/s
Communications baud rate	up to 12 Mbps

Front-end Graphical User Interface (GUI) software are used for monitoring, control and storing the measured data. The stored data is analyzed and the profile parameters are evaluated. The specifications of the confocal displacement sensor are given in Table 2. The Specifications of linear stages and their controller are given in Table 3.

3. Estimation of surface roughness

In the present work, nine standard specimen (Turning, Vertical Milling and Horizontal Milling) with surface roughness values of 1.6 µm, 3.2 µm and 6.3 µm were considered to evaluate the surface profile parameters using confocal displacement sensor. The arithmetic average height and maximum peak to valley height of stylus profile were evaluated using Eq. 1 and Eq. 2 respectively.

$$R_{a(stylus)} = \frac{1}{L}\int_0^L |Z_x(h_i)|\,dx \quad \text{Eq. 1}$$

$$R_{t(stylus)} = |R_{p(stylus)}| + |R_{v(stylus)}| \quad \text{Eq. 2}$$

The arithmetic average height, maximum peak to valley height and root mean square of the confocal displacement profile were evaluated using Eq. 3, Eq. 4 and Eq. 5 respectively. The form error was filtered by polynomial regression method. The measured profile parameters such as R_a, R_q and R_t using stylus and confocal displacement sensor are given in Table 4.

$$R_{a(C)} = \frac{1}{n}\sum_{i=1}^{n}|Z_i| \quad \text{Eq. 3}$$

$$R_{t(c)} = |R_{p(c)}| + |R_{v(c)}| \quad \text{.Eq. 4}$$

$$R_{q(C)} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} Z_i^2} \quad \text{Eq. 5}$$

4. Results and Discussion

In the present work, the measured surface profiles using confocal sensor and stylus profilometer were plotted and compared in Fig. 3 – 5.

Table 4. Surfaces Profile Parameters of machined surfaces using confocal displacement Sensor and Stylus profilometer

Machining	R_a	Surfaces profile parameters (µm)					
		Confocal Displacement Sensor			Stylus profilometer		
		$R_{a(c)}$	$R_{q(c)}$	$R_{t(c)}$	$R_{a(stylus)}$	$R_{q(stylus)}$	$R_{t(stylus)}$
Turning	1.6	2.2250	2.6820	13.1266	1.736	1.990	7.93
	3.2	3.5662	4.0940	16.4505	2.243	2.569	9.53
	6.3	6.8455	7.9286	31.3377	5.739	6.487	24.02

Horizontal Milling	1.6	1.6898	1.9958	8.0386	0.445	0.549	2.68
	3.2	3.2905	4.1060	23.4659	0.509	0.770	3.08
	6.3	6.7000	7.7703	37.5313	1.428	2.018	13.37
Vertical Milling	1.6	1.9851	2.3965	12.1622	1.418	1.758	8.53
	3.2	3.5127	4.3704	20.6980	3.332	3.819	15.50
	6.3	6.1992	8.4885	50.6272	7.607	8.677	17.71

Fig. 3 shows the measured profiles of the turned surface. It was further observed that the magnitude of the profile varies with different turned surfaces. This leads to characterize the specimen based on the surface finish from the measured confocal displacement data. A similar trend is applied for the milled surface profiles as shown in Fig. 4 and Fig. 5. It can be seen that fine surfaces of the turned specimen and vertically milled specimen have the similar displacement profiles as obtained by both the methods. It can also be seen that, the confocal displacement sensor can measure more depth variation than the stylus method.

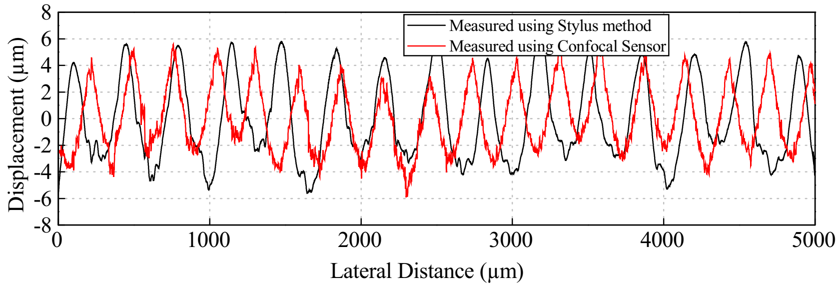


Fig. 3. Surface generated by turning

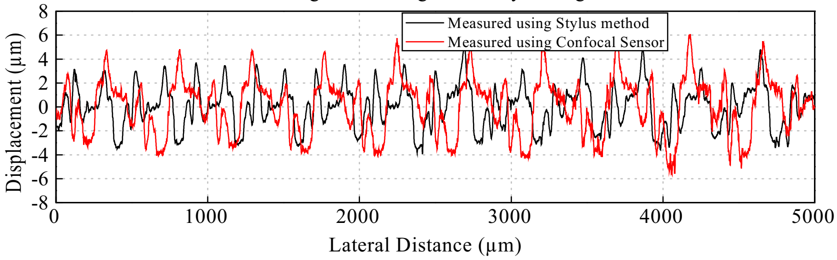


Fig. 4. Surface generated by vertical milling

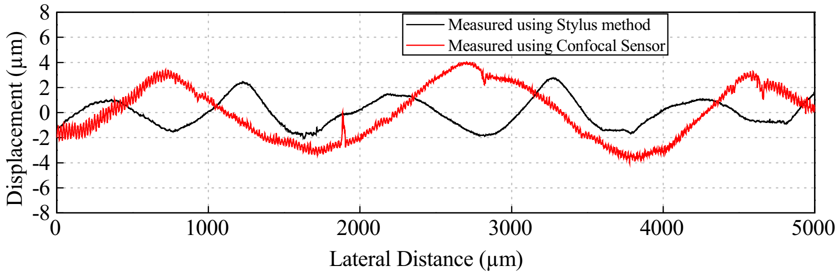
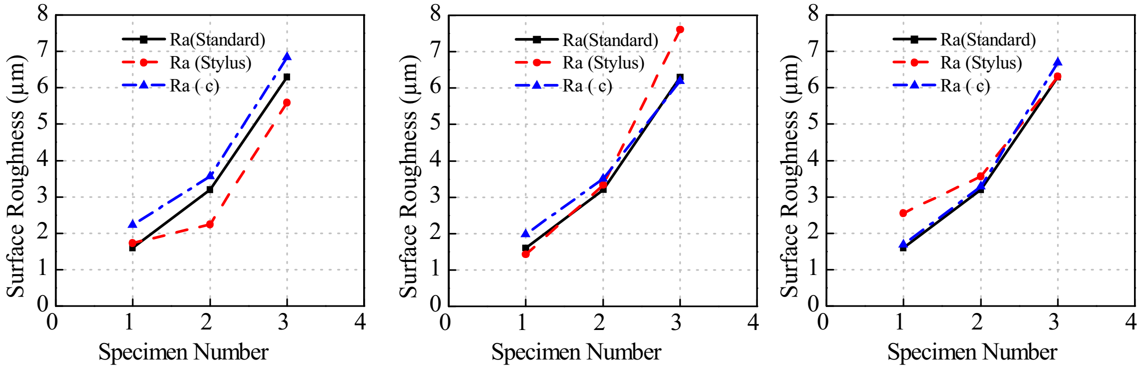


Fig. 5. Surface generated by horizontal milling

Fig. 6 (a), (b) and (c) show the comparison of measured $R_{a(c)}$ using confocal displacement sensor and measured $R_{a(stylus)}$ using stylus method with standard R_a for turned, vertically milled and horizontally milled surfaces respectively. To find the resemblance, it is significant to compare the surface finish values obtained from measured displacement with standard profile values. It is observed that the measured $R_{a(c)}$ values using confocal sensor and standard R_a values shows significantly less variation compared to the stylus method for the machined surfaces. It is also observed that, the sensor captures the surface undulations that are more dominant than surface roughness for fine and rough surfaces. This leads to large percentage variation between measured $R_{a(c)}$ using sensor and measured $R_{a(stylus)}$ using stylus technique.



(a) Surface generated by turning (b) Surface generated by vertical milling (c) Surface generated by horizontal milling

Fig. 6. Comparison of measured $R_{a(c)}$ (µm) using confocal displacement sensor and measured $R_{a(stylus)}$ (µm) using stylus method with standard surfaces

Fig. 7. shows the statistical relationship between measured $R_{a(c)}$ and stylus based $R_{a(stylus)}$. The measured $R_{a(c)}$ values were fitted by methods of least squares. The correlation coefficient (R^2) was obtained as 0.9716 for turned, 0.9965 for vertical milled and 0.9771 for horizontal milled specimen. It is observed that the coefficient for the roughness value gives better agreement for turned and vertical milled surfaces. The roughness of both turned and horizontal milled surface specimens range from 1.6 µm to 6.3 µm and correlate well with stylus based measurement.

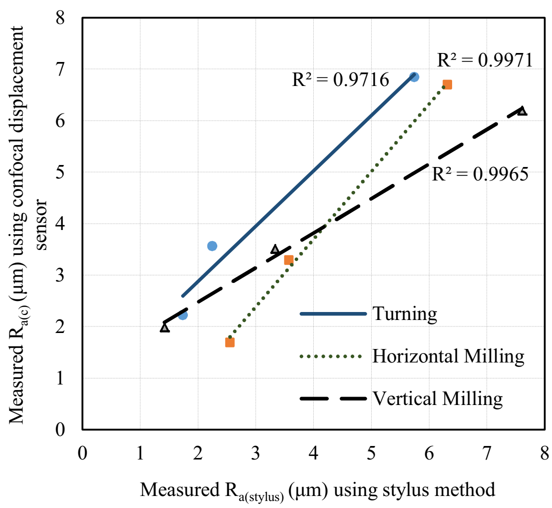


Fig. 7. Relation between measured $R_{a(c)}$ (µm) using confocal sensor and measured $R_{a(stylus)}$ (µm) using stylus for different machined surface

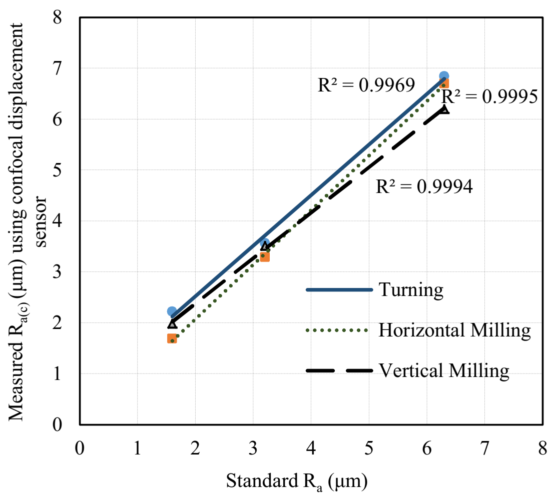


Fig. 8. Relation between measured $R_{a(c)}$ (µm) using confocal sensor and standard $R_{a(stylus)}$ (µm) of different machined surface

Fig. 8. shows the statistical relationship between measured $R_{a(c)}$ and standard R_a. The correlated data indicate that the surface parameter can be predicated from confocal displacement based surface parameter $R_{a(c)}$ and vice versa.

Correlation coefficients of 0.9969 for turned specimen, 0.9994 for vertical milled specimen and 0.9995 for horizontal milled specimen were observed using linear regression model. From the regression equation, the R_a can be predicated using the measurements from the sensor. The roughness values obtained directly from the measured $R_{a(c)}$ using sensor is influenced by the irregularities of the surface.

5. Conclusion

In this work, a non-contact measurement system has been developed to measure the surface profile parameter using confocal displacement sensor. The measurement taken using confocal displacement sensor and stylus method were compared with the standard specimen for turned, vertical and horizontal milled surfaces. The correlation coefficient values obtained for turned, vertical and horizontal milled surfaces with confocal method is 0.9969, 0.9994 and 0.9995 and with stylus method is 0.9716, 0.9965 and 0.9771 respectively. The results show that the surface finish measured by confocal method is in good agreement with the values obtained by stylus method.

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