MEASUREMENT, MODELING AND EVALUATION OF SURFACE PARAMETER USING CAPACITIVE-SENSOR-BASED MEASUREMENT SYSTEM

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Abstract

Surface roughness parameter prediction and evaluation are important factors in determining the satisfactory performance of machined surfaces in many fields. The recent trend towards the measurement and evaluation of surface roughness has led to renewed interest in the use of newly developed non-contact sensors. In the present work, an attempt has been made to measure the surface roughness parameter of different machined surfaces using a high sensitivity capacitive sensor. A capacitive response model is proposed to predict theoretical average capacitive surface roughness and compare it with the capacitive sensor measurement results. The measurements were carried out for 18 specimens using the proposed capacitive-sensor-based non-contact measurement setup. The results show that surface roughness values measured using a sensor well agree with the model output. For ground and milled surfaces, the correlation coefficients obtained are high, while for the surfaces generated by shaping, the correlation coefficient is low. It is observed that the sensor can effectively assess the fine and moderate rough-machined surfaces compared to rough surfaces generated by a shaping process. Furthermore, a linear regression model is proposed to predict the surface roughness from the measured average capacitive roughness. It can be further used in on-machine measurement, on-line monitoring and control of surface roughness in the machine tool environment.

Keywords: capacitive sensor, surface roughness, machined surfaces.

1. Introduction

Current developments in the manufacturing and automotive engineering field have led to renewed interest in the use of non-contact sensors to measure the surface roughness. With the advent of newly developed tidy non-contact sensors play a vital role in quality inspection of surfaces and process monitoring [1]. Current techniques of surface measurement use the profiling or stylus instruments and area averaging techniques using a sensor to estimate the nature of the surfaces. The major disadvantage of using a stylus instrument for such measurements is that it requires direct physical contact with the surface, which limits the measuring speed and scratches the surface. In addition, the instrument readings are based on a limited number of line samplings, which may not represent the real characteristics of the surface under investigation. It is also limited to a sampling length which may not represent the overall surface. Due to these drawbacks, contact-type instruments are not suitable for high-speed automated inspections. Area averaging techniques such as optical, ultrasonic, machine vision and laser scanning methods are useful alternatives compared to the more traditional profiling methods for specifying the surface parameter. These techniques mostly use the non-contact type sensing methodologies to measure the roughness parameter of the surface. Generally, area averaging techniques yield a single parameter that is representative of the statistical properties of the surface roughness/undulations, sampled over the entire area of the probe rather than profile on a single line of cross section.

Several research works have been reported on characterizing the various engineering surfaces by area averaging techniques. Optical methods adopt light triangulation [2], light sectioning [3], light scattering [4-6], or a laser speckle and fibre optic sensor [7, 8] to measure surface roughness parameter of the engineering surfaces. Machine vision techniques are employed for acquiring the image of the machined surfaces and to analyze the image for prediction of surface parameters. Few investigations have been carried out by researchers based on machine vision technology. The statistical parameters were derived from the grey level intensity histogram of the machined surface image and correlated them with the average surface roughness (R_a) value determined from the stylus method [9, 10]. Kiran et al. [11] used the machine vision system to capture the images the surfaces manufactured by various processes including shaping, milling and grinding. The new optical parameters for roughness evaluations based on the process parameter have been introduced using machine vision for different manufacturing surfaces such as shaping, milling and grinding [12]. The machine vision system created to acquire an image of the machined surface during cutting process and image is analyzed using wavelet transform to correlate with surface roughness parameters [13]. Adamczak et al. [14] describe the application of Fourier and wavelet transform for the analysis of geometrical surface irregularities. However, optical and machine vision techniques depend on the detecting angle, the angle of inclination, lighting, reflectivity of the surface, calibration against standard roughness specimen, optics arrangement and a correlation chart. Also they are influenced by the lay pattern of the surface produced by the different machining process. The ultrasonic method applies an ultrasonic sensor to transmit a pulse to the surface and measure the amplitude of the returned signal. However, this technique has limitations for use of frequency range, offset distance, transmitter range, measurement speed and properties of the surface [15].

Area averaging techniques using a capacitive sensor have gained more attention in the recent years to estimate the surface roughness quantitatively. In particular, the current scenario in advent of newly developed high sensitivity non-contact capacitive sensors plays a vital role in quality inspection of surfaces. It is a potential technique to be used both on-line and off-line assessment of surface roughness. Few attempts have been carried out using the capacitive sensor to predict the surface roughness of the machined surface [16, 17]. They have used a 0.135 in (3.42 mm) effective diameter electrode to measure the roughness. Shunmugam and Deshpande [18] used a capacitance probe meter with a thin layer of coated polished probe surface for assessment of surface finish. The authors observed that the probe responds quickly to the changes in the surface finish of different specimens prepared by different machining processes. The output of the capacitive sensor on the location has been correlated with functional properties of the surface by Lieberman et al. [19]. Here a probe is held against the surface, with an insulator separating the probe and the surface. The process is basically contact-type.

An attempt has been made to measure the surface profile using fringe field capacitance by Garbini et al. [20] and Nowicki et al. [21]. The variations in capacitance of the field are generated by virtue of the changing distance while moving the probe along the surface. This is basically a contact-type technique and it is affected by the swarf or burrs present on the workpiece. Williams et al. [22] compared a capacitance based surface roughness measurement system with stylus instrument results. The measurement technique, machining method and variables significantly influence the measurement results. Varghese and Radhakrishnan [23] developed a pulse jet capacitance instrument to measure the surface roughness of different machined surfaces. This method is restricted by jet velocity, effective diameter of electrode, dielectric medium and sensitivity of the instrument.

Gao and Kiyono [24] measured a machined surface with step-wise profile using a capacitance-type displacement probe. The results showed that the profile evaluation error is

connected with the aperture diameter size of the displacement probe and height of the displacement profile. They have used a 1.7 mm effective diameter displacement probe for measuring a step-wise profile. A perturbation-theory-based approach was proposed to predict the surface parameter from the capacitance of a rough and flat electrode with a dielectric film on a conducting substrate [25]. The measurement procedure has proposed to calculate the standard deviation from capacitive measurement and electrode probe geometry (Bruce and García-Valenzuela [26]). Chang et al. [27] developed a technique to predict the surface roughness in real time using a cylindrical capacitive displacement sensor mounted on the spindle of the machine tool. From the literature, it is observed that there is an increasing trend towards measurement of surface finish using the capacitive sensor based assessment method. However, the method is hard to directly correlate the surface profile of the measured surfaces from the output response of the sensor. This is due to the effective area, resolution, sensitivity of the probe and necessity of a suitable model to explore surface characteristics from the capacitive response.

In this paper, an attempt has been made to use the smallest available effective sensing area of the capacitive sensor for prediction of the surface parameter of various surfaces obtained by a different machining process. A model has been developed based on the principle of capacitive sensing, and reconstruction based on area integral method to predict the theoretical capacitive response for 2D and 3D surface profiles. The stylus measurement technique was used to generate the profiles which quantitatively describe the surface topography of each specimen. These profiles are the input of the physical model to predict the capacitive response profile for each specimen. The proposed models are validated with capacitive and stylus measurements using 18 specimens. The surface parameter values determined from the model, and sensor are correlated. Also a linear regression model is proposed to relate the roughness value obtained by stylus measurement and obtained by the proposed model and capacitive measurement. The details of the measurement setup, proposed models and analysis of the results and conclusions are presented in this paper.

## 2. Measurement setup using a capacitive sensor

Fig. 1 shows the schematic representation of the capacitive sensor based measurement system and photograph of the setup. The measurement setup consists of high precision XYZ axis linear stage arrangement, stage controller, capacitive sensor, sensor driver electronics and computer based data acquisition system. The base plate supports the linear stage arrangement of the setup. The setup base is mounted on four anti-vibration mounts to isolate ground vibrations. Fig. 1 (c) shows the capacitive sensor used in this work for measurement. The measured workpiece or target surface is placed on a linear stage (X-axis linear stage) and can be moved in X and Y directions. The linear stages have a travel range of 50 mm and provide motion with 0.15 µm resolution. The stages are driven by a stepper motor with quadrature encoder for obtaining feedback about the position of the stage. The motion controller is operated using SMCVieW software with the help of a computer system. Also it can be accessed through LABVIEW software. The speed of measurement is limited by the scanning speed of the stage. In the present setup the minimum speed is 0.1 mm/s. The maximum traverse speed of the stage is 3.5 mm/s. The straightness error of the stage is 400 µrad for the whole range of 50 mm, which has been reported by the manufacturer. Table 1 gives a brief description of the linear stages and capacitive sensor used in the present work.
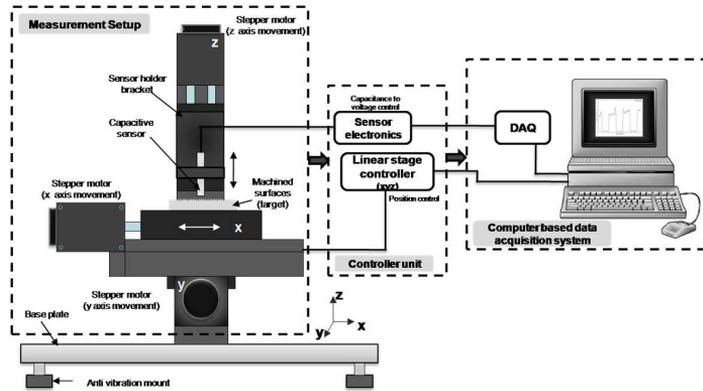
(a) Schematic view of the measurement setup
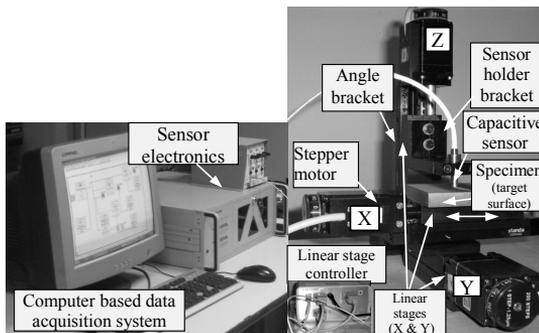
(b) Photographic view of the measurement setup
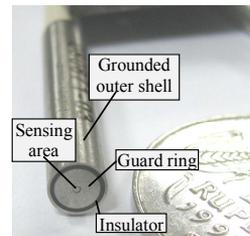
(c) Capacitive sensor

Fig. 1. Measurement setup using a capacitive sensor.

The sensor is placed in the sensor holder bracket and mounted on the vertical linear stage (Z-axis). It has a measuring range of ± 40 µm and a peak-to-peak resolution of 33.46 nm. The footprint or spot size (effective sensing area) of the sensing element is 0.5 mm and it is surrounded by a concentric guard ring which prevents sensing of targets adjacent to the probe. Guard rings are used for focusing the electric field towards the target. The sensor is normally used to measure conductive targets.

Table 1. Specifications of capacitive sensor and linear stage.

Capacitive sensor		Linear stage	
Details	Specified values	Details	Specified values
Range	-40 to +40 µm	Travel range	50 mm
Standoff	100 µm	Lead screw pitch	0.25 mm
Output voltage	10 to -10 VDC	Resolution	Full step: 1.25 µm / 1/8 step: 0.156 µm
Output sensitivity	0.25 V/µm	Speed range	0.1-3.5 mm/s
Linearity error	0.02 %	Load capacity	Horizontal: 3 kg Vertical: 2 kg
Peak to peak resolution	33.46 nm	Cable	Integrated, 1.6 m length
Sensing diameter	0.5 mm	Driver	1.5 A Micro step driver with USB interface

The sensor used in the present work is calibrated for flat metallic targets [28]. The calibrated sheet is provided by the manufacturer. The sensitivity is 0.24 V/μm and the linearity error is 0.11%. The combined uncertainty of measurement for the vertical axis is 0.0127 μm. The capacitive sensor is compensated to minimize thermal drift in the working range of 22.2°C to 35°C. In this temperature range the errors are less than the 0.5% of the full scale range of measurement.

Also it is important to identify and remove noise generated from different sources such as driver electronics, data acquisition hardware and processing of acquired data. The instantaneous error in the output voltage and the typical noise of the capacitive sensor for the sampling frequency of 1 kHz is identified as 98 Hz and it is removed using a low pass filter. A computer-aided data acquisition system (DAQ) is used to acquire the real time measurement of surface irregularities of the target surface while moving the linear stage. A LABVIEW program is developed to acquire the sensor output in terms of a voltage signal at discrete time intervals, while moving the linear stage at minimum scanning speed. The measurement data obtained from the sensor is acquired and stored in ASCII format for further analysis.

3. Experimental details

The measurements were carried out for specimens prepared using three different manufacturing processes, grinding, milling and shaping. Six specimens were prepared using each manufacturing processes. The roughness values were measured using a PC-based stylus roughness measuring instrument, *MarSurf XR 20*. The profile and digital data points on the profile are stored for further analysis. The evaluation length selected for measurement is 5.6 mm and the sampling length is 0.8 mm. The spatial resolution of the profile measured is 1 μm. The details of the specimens and surface roughness values are tabulated in Table 2.

Table 2. Surface roughness value of specimen using stylus instrument.

Machining process/ Specimen	Roughness value, R_a (μm)					
	1	2	3	4	5	6
Ground (G)	0.05	0.10	0.22	0.41	0.80	1.56
Specimen no.	7	8	9	10	11	12
Milled (M)	0.49	0.98	1.15	1.26	1.66	2.06
Specimen no.	13	14	15	16	17	18
Shaped (S)	12.37	35.04	35.13	46.21	54.35	58.88

The experiments were carried out using the proposed measurement setup. The target surface placed on the stage is moved across the lay pattern of the surface perpendicular to the sensing direction of the sensor. A standoff distance of 60 μm between the sensor surface and target surface is maintained by adjusting the Z axis stage. The sensor signal is acquired at the rate of 1 kHz. Measurement is carried out at the speed of 0.1 mm/s. If the measurement speed is high, the sensor has difficulty to detect fine irregularities of the target surface can arise. If the stage is travelling at lower speed across a surface, the sensor measures the fine irregularities of the surface. For example for a probe or target travelling at 1 mm/s across a surface, a sampling rate of 1 kHz is required if data points are to be read at l μm intervals. In the present work, the data is acquired at the 0.1 μm intervals and stored data is used for further evaluation of surface roughness of the surfaces. Care has been taken to measure the profiles at the same location on the specimen for both stylus and capacitive sensor measurements, using a fine marking made on the specimen with indelible ink.

4. Capacitive response model

The capacitive sensor used to measure the surface roughness consists of a sensing element which acts as one of the conducting capacitor plates, while the machined surface (target) forms the other conducting plate. If the sensing area and dielectric conductivity are both held constant, the capacitance (C) will be inversely proportional to the average distance (Z_m) between the two conductive plates (Fig. 2). The capacitance is given by

$$C = K \iint_A \frac{dxdy}{Z} \quad or \quad \frac{KA}{Z_m}, \tag{1}$$

where: K is the dielectric constant and Z_m is reciprocal of the mean value of $1/Z$ over area A, expressed as

$$\frac{1}{Z_m} = \frac{1}{A} \iint_A \frac{dxdy}{Z}. \tag{2}$$

The value of Z_m depends on the surface roughness (irregularities) of the target surface. With decreasing roughness, the average distance between the plates decreases and there will be a proportional increase of capacitance value. If the surface finish is represented by the function $z = f(x,y)$ then the distance between the plates is given by $Z = a_d + f(x,y)$, where a_d is the standoff distance normally fixed for a given sensor by means of zero setting arrangement of the driver electronics. The plane represented by Z_m represents the effective position of the machined surface in terms of observed capacitance [15]. It is called as capacitance plane. The observed displacement for a nominal separation by the sensor between a machined surface and the sensor surface is given by

$$\frac{1}{Z_m} = \frac{1}{A} \iint_A \frac{dxdy}{a_d + f(x,y)}. \tag{3}$$
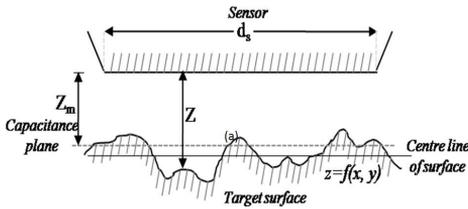
Fig. 2. Principle of capacitive sensing.
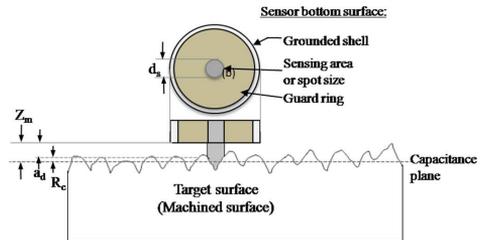
Fig. 3. Capacitive sensor for measurement of surface profile.

If the standoff distance a_d is zero, the observed displacement directly represents the roughness of the surface measured by the spot size of the sensor. If the observed capacitive displacement is measured and the sensing area is known, in principle it is possible to determine the profile of the surface $f(x,y)$ at that location. In general there is no method/solution that exists to determine $f(x,y)$ even if Z_m is known. Since the sensor gives the average surface irregularities in terms of displacement at that location, it is difficult to predict displacement of each point of the profile. However, the observed capacitive displacement by the sensor indicates the measure of irregularities on the machined surface and a smaller sensing area of the sensor gives better prediction irregularities of the surface. In the present work, the sensing area of the capacitive sensor is 0.5 mm, used for measuring the surface

irregularities of the machined surface. The schematic cut section view of the sensor surface and sensor focusing the target surface are shown in Fig. 3.

The observed displacement is an indication of the roughness of the surface on that location spotted (focused) by the sensing element and it is named as capacitance surface roughness (R_c).

$$R_c = Z_m - a_d .\qquad(4)$$

The observed displacement on that location can further be compared with the displacement obtained over the evaluation length of the profile. To observe the displacement over the evaluation length a physical model is needed to accurately relate the measured capacitance roughness to the surface profile. In this work a model has been developed and validated by comparing the measurements made with a capacitive sensor and stylus profiler on 18 different surfaces. The stylus technique was used to generate profiles which quantitatively describe the surface topography of each specimen. These digitized profiles were used as input to the model to calculate the value of R_c from the observed displacements. Since the capacitive sensor is focused on a finite area, the model has been developed considering the two-dimensional profile and also three-dimensional topography of the specimen.

The models are described as plane area and surface area integral method. Predictions were made for both the change in the displacement over the evaluation length of the profile and effective changes in the sensor to surface distance due to the surface topography of the specimen. From the observed displacement over the length, the roughness parameter R_c is calculated for both 2D and 3D models. It is determined by calculating the height difference from the highest peak to the mean-line over that sampling interval range. The R_c values for the various sampling intervals are averaged over the entire evaluation length of the surface profile. To validate the model, calculated R_c values are compared with measured R_c values obtained using the capacitive sensor.

4.1. Plane area integral method

In this method, the two-dimensional profile of the surface is considered. The height of the profile z_i over the evaluation length L and a schematic representation of the plane area integral model are shown in Fig. 4, where z_i is the distance from the sensor surface to the height of the profile. The displacement is evaluated based on the air gap or standoff distance maintained initially between the sensor and target surface.
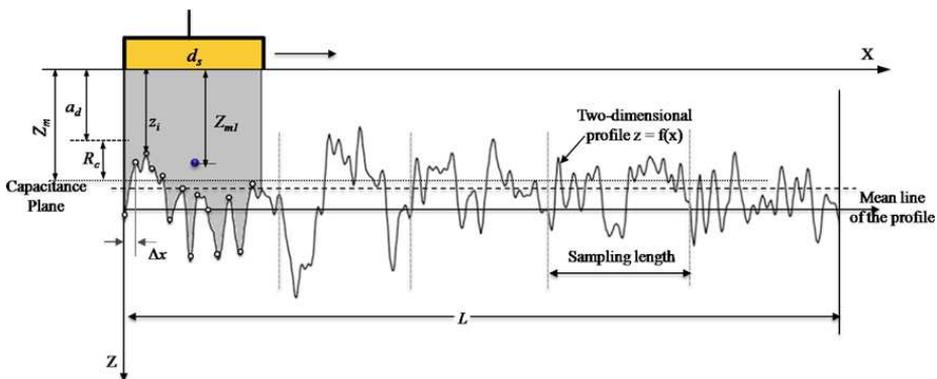

Fig. 4. Plane area integral method (2D model).

The shaded portion is the area focused by the sensor and is assumed as a line segment. The number of profile data points under the sensing area is based on the spatial resolution of the profile. In the present measurement, the resolution of the data points of the profile is 1μm and the diameter of the sensing element is 500 μm, hence approximately 500 data points are under the sensing element at that location. The theoretical displacement on that location is predicted based on the plane area integral method. It is determined by the area integrated over the sensor below the sensing element and is given by

$$\frac{1}{Z_m} = \frac{1}{d_s} \int_0^{d_s} \frac{1}{Z_i} dx.$$ (5)

The Simpson's Algorithm (SA) is applied for area integration on the sensing element and is given by

$$\frac{1}{Z_m} = \frac{\Delta x}{3 d_s}\left[z_1 + z_n + 4\sum_{j=1}^{\frac{n-2}{2}} z_{2j-1} + 2\sum_{j=1}^{\frac{n-2}{2}} z_{2j} \right].$$ (6)
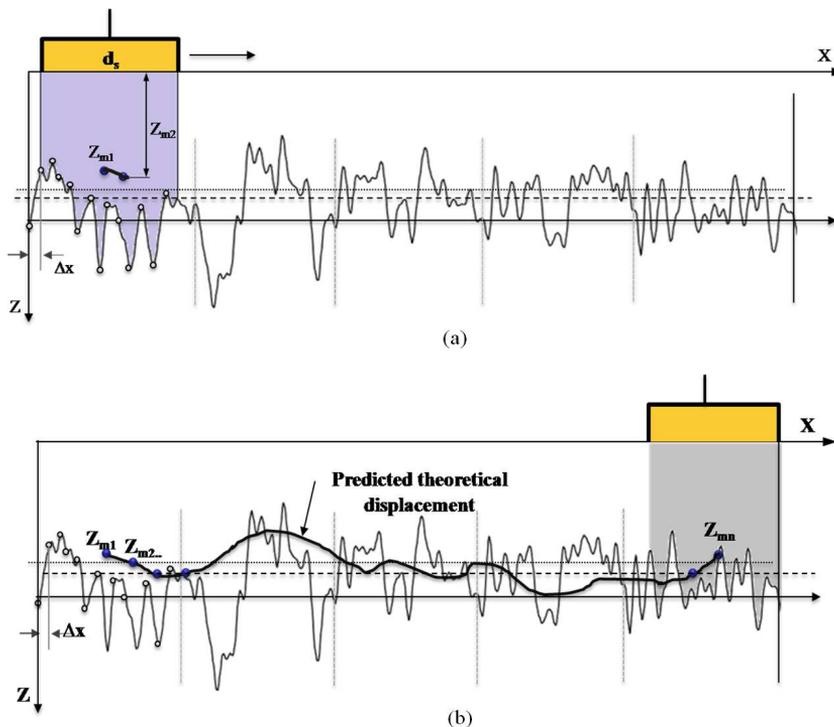

Fig. 5. Predicted/theoretical displacements when the sensor scanned the data points of the profile.

Further, the sensing element of the sensor is moved continuously to scan the profile over the evaluation length as shown in Fig. 5. The observed displacement over the profile is predicted and the change in the effective distance between sensor and target surface is obtained using Eq.(6). Fig. 5(b) shows the predicted/theoretical displacement profile obtained

by the proposed model. The predicted displacement profile data points such as Z_{m1}, Z_{m2}….Z_{mn} are used for evaluation of capacitive average roughness value at different sampling intervals.

4.2. Surface area integral method

In the proposed plane area integral method, a single cross section or line of the profile on a 3-D surface is considered. In general, this is not realistic to be representative of that surface as a whole. However, in reality the capacitive sensor is focusing on the 3-D surface as shown in *Fig. 6*. The sensor is focusing an area instead of a line or trace, which covers finite data points along the x and y directions at that location.
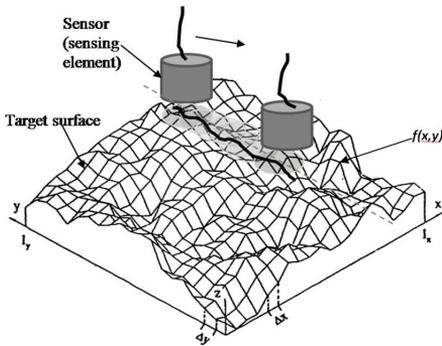

Fig. 6. A schematic view of the capacitive sensor focus on the surface.
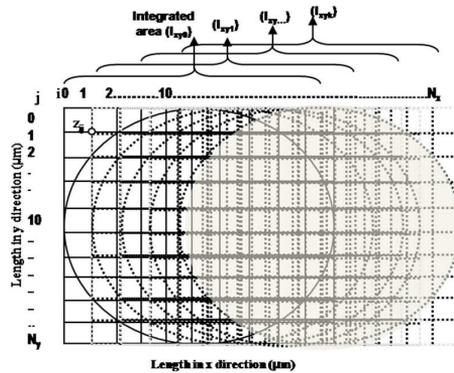
Fig. 7. Two-dimensional representation of sensing element on the surface.

The irregularities of the surface are considered along the *x* and *y* directions and the surface is represented by $z = f(x,y)$. The surface consists of *N* parallel profiles in a main measurement axis direction, at regular spacing, Δy in an orthogonal direction to that profile. Each profile has a spatial resolution of Δx and the number of data points is N_x. The surface characterized by a matrix of N_y lines and N_x points and each data point (x_i, y_j) has a surface height of z_{ij}. Then the distance between the sensor surface and target surface at x_i and y_i is $Z_{ij} = a_d + f(x_i, y_j)$. The sensor focused on the surface at the location is represented by grid pattern arrangement of the target surface and the shape of the sensing element is a circle. Fig.7 shows the two-dimensional representation of the sensing element on the surface in a grid pattern arrangement.

The sensing area focused on the surface by the sensor is integrated using the data points. The sensor gives an average displacement of irregularities at the location. The predicted/theoretical displacement is determined at the location focused by the sensor expressed as

$$\frac{1}{Z_m} = \frac{1}{A}\iint\limits_A \frac{dxdy}{Z_{ij}}. \tag{7}$$

The number of profile data points under the sensing area in both directions is based on the spatial resolution of the profile. In this method, approximately 500×500 data points are under the sensing element at the location in both x and y directions (as shown in Fig. 7). Simpson's Algorithm (SA) has been applied for performing the numerical computation to predict the displacement at the location. The inner integral is an evaluation of displacement in the *x* direction and it is represented mathematically by

$$f_x(y_i) = \frac{\Delta x}{3}\left[f(x_0, y_i) + f(x_n, y_i) + 4\sum_{j=1}^{\frac{n-2}{2}} f(x_{2i-1}, y_i) + 2\sum_{j=1}^{\frac{n-2}{2}} f(x_{2i}, y_i) \right]. \qquad (8)$$

Further re-applying SA algorithm in the y direction to compute the theoretical displacement and it is given by

$$\frac{1}{Z_m} = \frac{\Delta x \Delta y}{9A}\left[f_x(y_0) + f_x(y_n) + 4\sum_{j=1}^{\frac{n-2}{2}} f_x(y_{2j-1}) + 4\sum_{j=1}^{\frac{n-2}{2}} f_x(y_{2j}) \right]. \qquad (9)$$

Further, the sensor or target is moved in continuous steps over the profile and the displacement is predicted. The predicted theoretical displacement profile data points are further used for evaluating the average capacitive surface roughness of the surface. However, this method is mainly depending on the 3-D surface data of the target surface and complexity in integrating the surface data points over the length of profile.

5. Results and discussion

A total of 18 specimens prepared by different machining processes such as grinding, milling and shaping were measured using the proposed measurement setup. The displacement profiles were predicted theoretically using the proposed plane area and surface area integral method using data points of the profile measured. The surface roughness parameter is evaluated using the displacement profile obtained from the sensor, models and it is further analyzed to predict the relationship among the measured and predicted roughness parameter of the machined surface.

5.1. *Measured and predicted profile using sensor and proposed models*

Fig. 8 shows the typical results of the measured and predicted profile of the different specimens. The measured and predicted profiles are plotted along with the data points of a profile of the specimen measured using the stylus instrument. The results show that the magnitude of a predicted profile represents the surface irregularities of the specimen. Also it is observed that the measured profile does not relate closely the finer irregularities of the profile. This is due to the nature of the capacitance sensor, which averages the irregularities of the target surface. The sensor also fails to capture the valleys of the profile. Hence, it is not suitable to compare directly the profile obtained using a capacitive sensor with a stylus profile. It is more significant to compare the stylus profile with the profile obtained from capacitive response modeling.

Fig. 8 (a) and (b) shows the measurement results of ground specimens with a stylus; R_a values are 0.1 and 1.6 µm respectively. It shows that the profile which is closely matching with the proposed model results of the specimen. Also the magnitude of the displacement profile is varying with the profile of the specimen. A similar trend can be observed for milled and shaped specimen profiles shown in Fig. 8 (c)-(f). It can be seen that the fine surfaces of ground and milled specimen are much closer to predict the displacement profile obtained by both models. The rough surfaces of the order of more than $R_a > 2$ µm have shown variation and also the phase differences showed the causes of measurement results. It is mainly due to the nature of the measurement method where the stylus contacts a single point on the surface and the sensor focuses the area. Also it is difficult to measure at the same location of the specimen where a stylus measurement is carried out.

The plotted results are shown with the roughness profile of specimens mapped using measurement results obtained from the sensor. The predicted profiles from the models are closer due to data points of the considered profile. In the present work, predicted displacement profile from surface area integral method considered the 2D profile data points stacked over the length of sensing element. It leads to a lower variation over the plane area integral method.
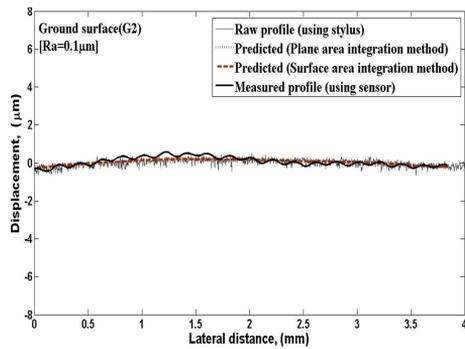
(a) Ground surface (Specimen no.: 2)
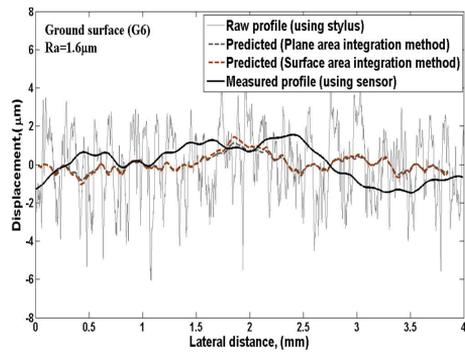
(b) Ground surface (Specimen no.: 6)
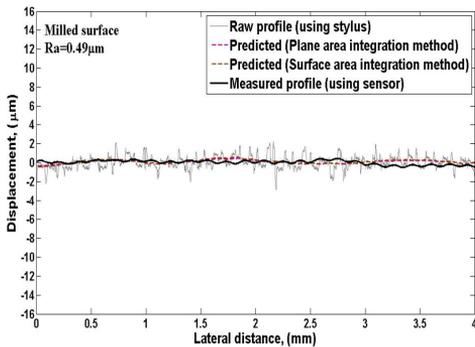
(c) Milled surface (Specimen no.: 7)
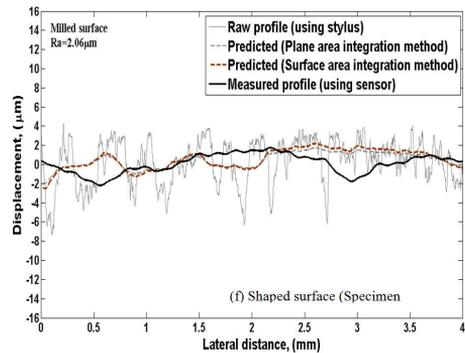
(d) Milled surface (Specimen no.: 12)
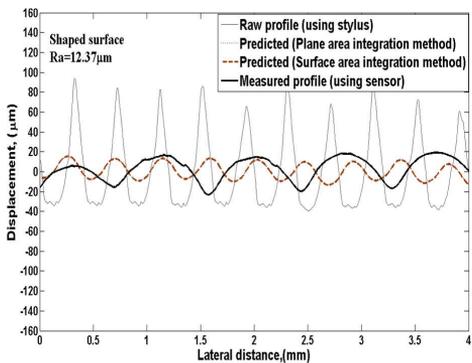
(e) Shaped surface (Specimen no.: 13)
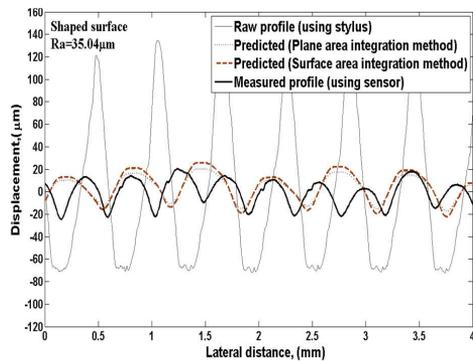
(f) Shaped surface (Specimen no.: 14)

Fig. 8. Typical results of measured profile using a capacitive sensor, stylus and predicted profile obtained from proposed models of different machined surfaces.

5.2. Measured and calculated average capacitive roughness (R_c)

The R_c from the predicted and measured displacement profile obtained using the proposed model and sensor is summarized in Table 3. A sampling length of 0.8 mm is used for evaluation roughness parameter from the displacement profile over the length. Fig. 9 shows that the R_c values obtained by the capacitive sensor and proposed models are compared with R_a values measured by a stylus instrument. The result shows that the calculated R_c using a plane area integral model agrees better than the surface area integral method for the machined surfaces. However, the measurement results shows a close agreement with proposed model values of the specimens.

Table 3. Description of surface and evaluated average capacitive roughness values.

S. No	Surface description	Specimen	Measured R_c (µm)	Calculated R_c (µm) using the proposed capacitive response model	
				Plane area integral method	Surface area integral method
1	Ground	G1	0.08	0.04	0.05
2		G2	0.07	0.08	0.10
3		G3	0.11	0.12	0.15
4		G4	0.10	0.09	0.11
5		G5	0.17	0.23	0.33
6		G6	0.29	0.32	0.40
7	Milled	M1	0.11	0.15	0.19
8		M2	0.29	0.34	0.43
9		M3	0.54	0.57	0.62
10		M4	0.50	0.56	0.71
11		M5	0.70	0.74	0.78
12		M6	0.73	0.67	0.85
13	Shaped	S1	0.93	1.71	2.41
14		S2	8.35	6.85	7.04
15		S3	4.06	7.19	9.21
16		S4	7.72	7.53	9.39
17		S5	8.73	8.47	10.74
18		S6	9.43	9.19	12.02

Fig. 9(a) shows that the result of ground specimen surfaces, R_a values about 0.05 µm and 0.1 µm are close to the calculated and measured R_c. It shows that the sensor effectively measures the very fine surfaces which are less than 0.1 µm R_a for ground surfaces. However, the resolution of the sensor plays a vital role in the prediction of the surface parameter of very fine surfaces. Fig. 9(b) and (c) shows the results of milled and shaped specimens. It is observed that the rough surfaces measured by the sensor have shown the differences. The results obtained from the plane area integral method closely agree with R_c values of the specimen. Further the measured R_c values were correlated with the calculated R_c from both proposed models.

Figs. 10-12 shows the correlation between measured and calculated R_c values for ground, milled and shaped surfaces respectively. The measured and predicted R_c values were fitted by the method of least squares. The correlation coefficient (R^2) was obtained as 0.90 for ground, 0.97 for milled and 0.79 for shaped specimen by the plane area integral method. Similarly using the surface area integral method, the correlation coefficients are 0.85 for ground, 0.96 for milled and 0.66 for shaped specimen. It is observed that the correlation coefficient for the roughness values obtained from the plane area integral method gives better agreement for ground and milled surfaces. The roughness of both surface specimens ranges from 0.05-2 µm and is well correlated with measurement results. However, the very rough surfaces have variation

with fitted results because the order of the roughness range can be taken out of the measurement range of the sensor.

From the observation, correlated data indicate that the capacitance-based surface parameter R_c is predictable from the surface profile measured using a stylus instrument. Fig. 13 shows the relationship between the measured Rc and Ra. The correlated data also indicate that the surface parameter can be predicted from capacitance-based surface parameter R_c and vice versa. The resulting correlation coefficients of 0.97 for ground specimen, 0.89 for milled specimen and 0.78 for shaped specimen were observed using the linear regression model. From the regression equation, the R_a values can be predicted using the measurement results by the sensor. The roughness values obtained directly from the measured R_c using a sensor are influenced by the irregularities of the surface. Although the sensor measurement results attribute the R_a values from R_c and it is based on the sensing size of the sensor. It gives more 3-D surface information about the surface than the profile measurement.


(a) Results of ground specimens

(b) Results of milled specimens

(c) Results of shaped specimens
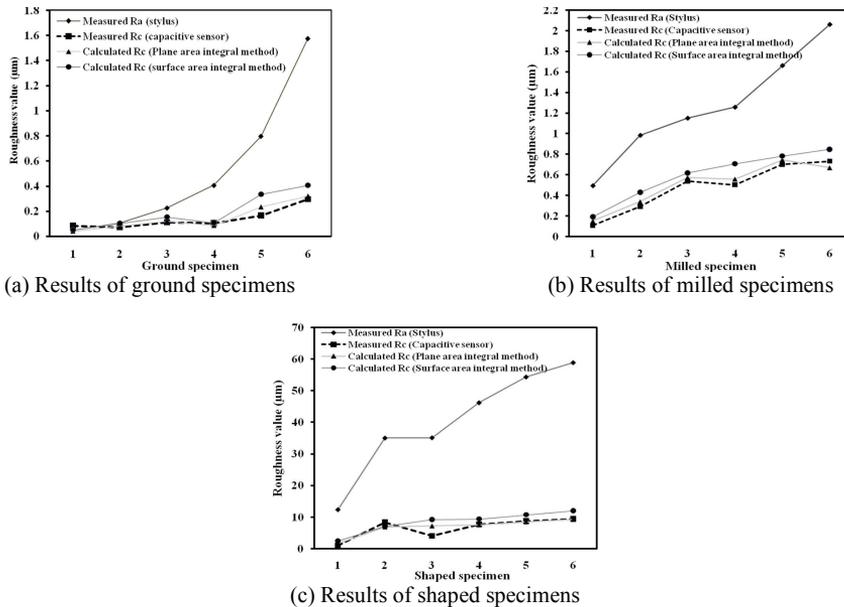
Fig. 9. Measured and calculated surface parameter of the specimens using capacitive sensor, stylus and proposed model.


(a)

(b)
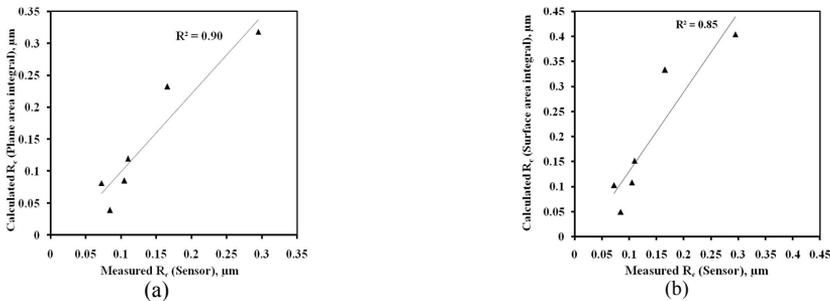
Fig. 10. Correlation between measured R_c using capacitive sensor and calculated R_c using (a) plane area integral model (b) surface area integral model for ground specimen.
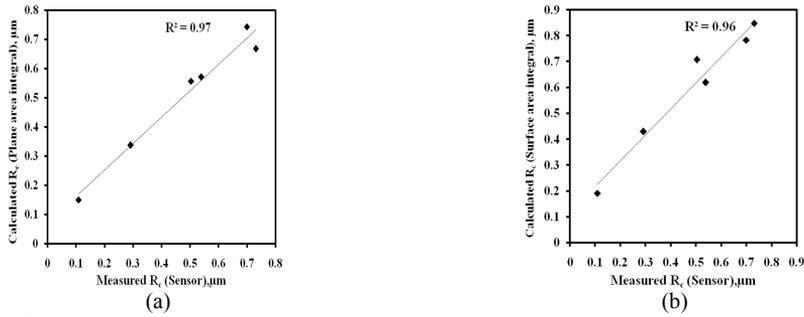
Fig. 11. Correlation between measured R_c using a capacitive sensor and calculated R_c using
(a)   plane area integral model (b) surface area integral model for milled specimen.
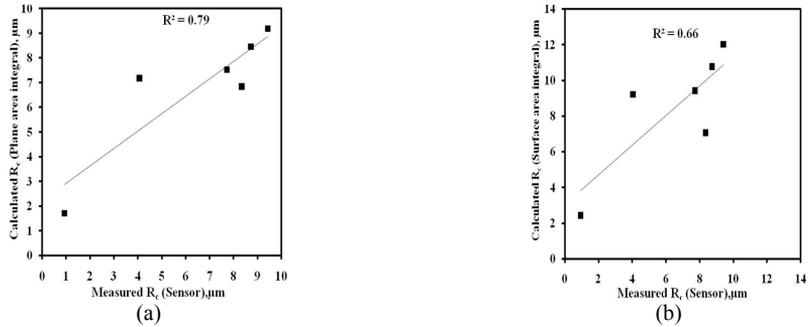

Fig. 12. Correlation between measured R_c using a capacitive sensor and calculated R_c using
(a) plane area integral model (b) surface area integral model for shaped specimen.
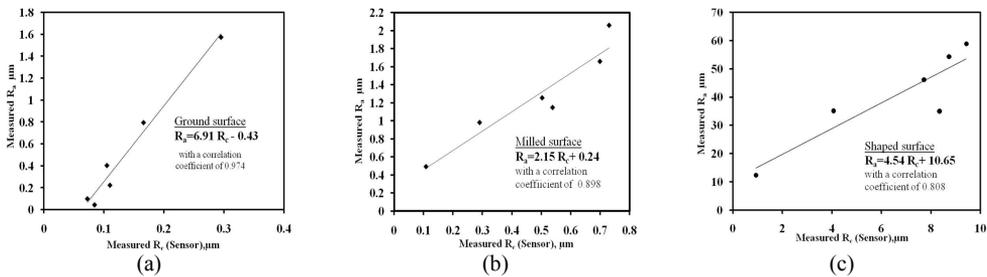
Fig. 13. Relationship of measured R_c using a sensor and R_a using a stylus with different machining processes
(a) grinding (b) milling (c) shaping.

6. Conclusions

In this paper, an attempt has been made to use a capacitive sensor for effectively measuring the surface parameter of different machined surfaces. The proposed non-contact sensing method quantitatively relates the roughness to conventional surface parameters by the stylus technique. The measurements were carried out for 18 manufactured surface specimens. In order to validate the measurement results, a model was developed using the plane and surface area integral method to predict the capacitance response profile from the given stylus profile. The predicted and measured results are in good agreement with the proposed models. The results show that the non-contact sensor system is capable of assessing the surface finish parameter.

The average capacitive roughness height (R_c) and measured roughness height (R_a) using stylus method were compared. It is found that surface roughness increases with an increase in capacitance roughness. The correlated values of the ground and milled surface have shown good agreement with stylus values and the correlation coefficient (R^2) values for ground, milled and shaped surfaces are 0.97, 0.89 and 0.80 respectively. The results show that a capacitive sensor can effectively assess surface finish of fine and moderately rough surfaces compared with very rough surfaces by shaping processed surfaces. The proposed measurement system is cost effective, portable and further, it can be extended to adapt in an on-machine, in-process machine tool environment for inspecting the surface finish parameter of the component.

Acknowledgement

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