Investigations into modelling and assessment of theoretical profiles using capacitive sensor

A. Murugarajan

Department of Mechanical Engineering,
Sri Ramakrishna Engineering College,
Coimbatore-641022, India
E-mail: murugarajan@srec.ac.in

G.L. Samuel*

Department of Mechanical Engineering,
Indian Institute of Technology Madras,
Chennai – 600 036, India
Fax: +91-44-2257-5705
E-mail: samuelgl@iitm.ac.in
*Corresponding author

Abstract: Current developments towards assessment of surface finish using the area averaging technique have gained attention in the field of automotive manufacturing. In particular, use of tiny non-contact sensors plays a vital role during in-situ and online monitoring and process control. In this work, an attempt has been made for using non-contact capacitive sensor for characterisation of different theoretical (periodic) profiles. The capacitive response model is developed to predict equivalent theoretical capacitive displacement profile and relate accurately to a measured surface finish of the profile. The proposed model is simulated to predict dimensional parameters of various theoretical profiles. Furthermore, the feasibility to relate the capacitive response to dimensional and non-dimensional parameters of the theoretical profile is studied. The developed model is validated with the different theoretical profiles. Further, the model is validated with experimentally processed theoretical profiles using measurement setup. The results show that the observed and predicted non-dimensional parameters are well agreed with model output and measured output results. Further, it can be applied in non-periodic profile measurement using a sensor.

Keywords: capacitive sensor; theoretical profile; non-dimensional parameter.


Biographical notes: A. Murugarajan received his Bachelor’s degree in Mechanical Engineering from Bharathiar University in 1999, Master’s degree from Bharathiar University, Coimbatore in 2002 and PhD in Manufacturing Engineering from Indian Institute of Technology Madras, Chennai in 2012. He is pursuing PhD under Quality Improvement Programme at Indian Institute of Technology Madras, Chennai from Sri Ramakrishna Engineering College, Coimbatore. He is currently working as a Professor at the Mechanical
1 Introduction

Current development in the manufacturing and automotive engineering field has led to renewed interest in the use of non-contact sensor to measure the surface finish. The traditionally used contact techniques have limitations such as low speed measurement, contacting the part to be measured, requirement of vibration-free environment, etc. and not suitable for in-situ and on machine tool measurement environments. Non-contact techniques have several advantages compared to contact-stylus techniques such as the ability for in-process or in-cycle implementation, rapid measurement capability, non-contact nature of measurement, and the ability to provide information over a surface area. The non-contact measurement techniques such as using optical, capacitance/inductive, ultrasonic, machine vision and laser sensors are useful alternatives to the more traditional profiling method for predicting the surface parameters and to measure the surface finish in terms of a single representation from the profile to a real characterisation of the machined surface by Jiang et al. (2007). Area averaging techniques using a capacitive sensor has gained more attention in the recent years to estimate the surface finish quantitatively. In particular, with advent of newly developed tiny capacitive sensor with smallest sensing area plays a vital role in inspection of surface profiles. It is a potential technique to be used both online and offline assessment of surface profiles.

Few attempts have been carried out using the capacitive sensor to assess surface finish. Capacitive techniques have many advantages such as simplicity in operation and cost effectiveness when compared to other sensing techniques. Sherwood and Crookall (1967–1968) described a general theory for surface finish using capacitive instrument, which is quite simple for a flat plate system. They used a 0.135 in (3.42 mm) effective diameter electrode to measure the surface finish of ground surface and examined the
numerical relationship of a capacitance index to peak roughness height. A capacitive pick-up was proposed as an alternative to other sensing techniques (Brecker et al., 1977). The contacting probe area considered was fairly high, and hence, an average value that was obtained was in correlation with the standard stylus reading of a single trace. Shunmugam and Deshpande (1980) used a capacitance probe meter with a thin layer of coated polished probe surface for the assessment of surface finish. The authors observed that probe responded 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 was correlated with the functional properties of surface by Lieberman et al. (1988). In this process, a probe was held against the surface, with an insulator separating the probe and the surface. The process was basically contact type. A two-dimensional (2D) capacitance model was developed considering a probing element size of 2 mm × 16.8 mm flexible platen. The authors observed that electrical sensitivity of the instrument influences the measurement.

Williams et al. (1990) compared a capacitance-based surface roughness measurement system with stylus instrument results. The measurement technique, machining method and variables significantly influence the measurement results. The variations in capacitance of the field are generated by virtue of the change in distance while moving the probe along the surface (Garbini et al., 1992). Kiyono and Gao (1994) measured a machined surface with step-wise profile using capacitance type displacement probe. The results showed that profile evaluation error was related to the aperture diameter size of the displacement probe and the height of displacement profile. They used a 1.7 mm effective diameter displacement probe for measuring step-wise profile. Caiazzo et al. (1996) presented a capacitive sensor pad arrangement using different dielectric medium and characterised by static tests measuring the capacity against the roughness variability of the sample.

Perturbation theory-based approach has been proposed to predict the surface parameter from the capacitance of a rough and flat electrodes with a dielectric film on a conducting substrate by Guadarrama et al. (2003). The measurement procedure was proposed by Bruce and Garcia-Valenzuela (2005) to calculate the standard deviation from capacitive measurement and electrode probe geometry. Chang et al. (2007) developed a statistical model to predict surface roughness in real-time using cylindrical capacitive sensor mounted on the spindle of the machine tool. However, there are no suitable models available for representing the response of capacitance when scanning the machined profiles over the evaluation length. Most of the attempts carried out by the researchers are single location of measurement and not focused on the theoretical (periodic) surface profiles. It is essential to study the output response using the sensor for different periodic and non-periodic profiles. However, the attempt has been made by the authors for estimation of non-dimensional profile parameters for the ground (non-periodic) surfaces (Murugarajan and Samuel, 2010).

The present work investigates into modelling and assessment of different theoretical profiles using capacitive sensor. The model is developed based on the principle of operation of capacitive sensor. The triangular profiles with different shape have been considered for analysis. The simulated output of the sensor and estimated non-dimensional profile parameters for the profiles are presented in this paper. Further, the experimental results of triangular type profiles made using shaping processes have been measured using sensor and results are compared with the developed capacitance response model.
2 Analysis of theoretical profiles

For real engineering surfaces, the different theoretical profiles (periodic structure) used for representation of surfaces generated from the different machining process. These profiles are replicates of ground, shaped, side-milled and end-milled surfaces, as well as formed by different unconventional machining processes. The different theoretical profiles are formed in the base of the triangular wave pattern with different shapes. Figure 1 shows the different shapes of the triangular profiles have been considered for analysis. These profiles are replicates of shaped surfaces. The peak height was varying from 0.04 mm to 0.08 mm over the assessment length of 1 mm. However, it does not exactly represent the real engineering surface machined using shaping process. Also, these periodic profiles used for analysis the non-dimensional profile parameters to relate with capacitive output.

3 Capacitive response model

In this work, the tiny capacitive sensor is used to simulate the measurement surface finish of generated theoretical profiles. The sensor has a sensing element of 0.5 mm diameter and has the smallest effective sensing area available in the market. The capacitive sensor consists of a sensing element which acts as one of the conducting capacitor plates, while
A. Murugarajan and G.L. Samuel

the machined surface (target surface) forms the other conducting plate. When a potential
difference is applied to the sensing area and the target surface, an electric field is created
in the distance between them due to the opposite charging of surfaces as shown in
Figure 2. 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 (Sherwood and Crookall, 1967–1968). The capacitance is given by
equation (1)

\[
C = K \int_A \frac{dx dy}{Z} \quad \text{or} \quad \frac{KA}{Z_m}
\]

where \( K \) is the dielectric constant and \( Z_m \) is reciprocal of the mean value of \( 1/Z \) over an
area \( A \), expressed as equation (2)

\[
\frac{1}{Z_m} = \frac{1}{A} \int_A \frac{dx dy}{Z}
\]

Figure 2  Principle of capacitive sensing (see online version for colours)

The value of \( Z_m \) depends on the surface finish of the target surface. The magnitude of
variation decreases (i.e., average distance between the plates decreases) and there will be
a proportional increase of capacitance value result to smooth surface finish of the profile.
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 (Sherwood and Crookall, 1967–1968). 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 equation (3).

\[
\frac{1}{Z_m} = \frac{1}{A} \int_A \frac{dx dy}{a_d + f(x, y)}
\]

The sensor is positioned perpendicular to a target electrode (surface profile to be
measured) formed by a conductive surface. For the measurement of surface profile, the
capacitive sensor system will average over the area covered by the spot size (sensing
element) and diameter of sensing element \( (d_s) \) is 0.5 mm. The detail construction of the
sensor is shown in Figure 3. The measurement value can change as the probe or target is
moved across the surface depends on the structure of the profile. The magnitude of this
error depends on the nature and symmetry of the surface profile. The measured average displacement $Z_m$ is the reciprocal of the mean value of 1/z over an area $A$. The plane represented by $Z_m$ thus represents the effective position of the machined surface in terms of the observed capacitance and is called as capacitance plane as shown in Figure 4. In order to validate the model, the theoretical profiles are examined to predict the displacement. However, it is difficult to directly find the surface finish for the observed capacitive displacement. There is no method/solution that exists, to determine $f(x, y)$ even if $Z_m$ is known. The observed capacitive displacement of the sensor indicates the surface finish of the profile and smaller sensing area of the sensor gives a better prediction of the surface finish. To predict the capacitive displacement profile theoretically, it is essential to consider the 2D and three-dimensional (3D) profile data of the surface. Based on the profile data, the models are described as plane and surface area integral method.

Figure 3  Typical construction of capacitive sensor (see online version for colours)

3.1 Plane area integral method (2D model)

In this method, the 2D 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 is shown in Figure 4. $Z_i$ 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 the target surface. The area focused by the sensor and is assumed as line segment. The number of profile data points under the sensing area is based on the spatial resolution of the profile. The theoretical displacement on that location is predicted based on plane area integral method. It is determined by area integrated by the sensor on that location is given by equation (4).

$$\frac{1}{Z_m} = \frac{1}{d} \int_0^L \frac{1}{Z_i} dx.$$  \hspace{1cm} (4)

The Simpson’s algorithm (SA) is applied to area integration on the sensing element and is given by equation (5).

$$\frac{1}{Z_m} = \frac{\Delta x}{3d_i} \left[ z_1 + z_n + 4 \sum_{j=1}^{n-2} z_{2j-1} + 2 \sum_{j=1}^{n-2} z_{2j} \right]$$  \hspace{1cm} (5)

The observed displacement is an indication of the roughness of the surface at that location focused by the sensing element, it is named as capacitance surface roughness ($R_c$), and is expressed by equation (6).
Further, the sensing element of the sensor is moved continuously to scan the profile over the evaluation length. The observed displacement over the profile is predicted and change in the effective distance between sensor and target surface is obtained using equation (5). The predicted displacement profile data points such as $Z_{m1}$, $Z_{m2}$, ..., $Z_{mn}$ are used for evaluation of capacitive average roughness ($R_c$) value and maximum peak to valley displacement ($R_{tv}$) at different sampling intervals.

**Figure 4** Plane area integral method (2D model) (see online version for colours)

### 3.2 Surface area integral method (3D model)

In the proposed plane area integral method single cross-section or line of the profile of a 3D 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 focused on the 3D surface as shown in Figure 5. The sensor is focused area instead of a line or trace, which covers finite data points along $x$ and $y$ direction at that location. The surface profile data are $Z_{ij} = f(x, y)$. The sensing area focused on the surface of 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 equation (7).

$$Z = \int_{A} Z_{ij} \, dA$$

The number of profile data points under the sensing area in both directions is based on the spatial resolution of the profile. The 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 $x$ direction and it is represented mathematically by equation
Further re-applying the SA algorithm in my direction to compute the theoretical displacement and is given by equation (9).

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

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

Further, the sensor or target is moved continuous steps over the profile and 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 mainly depending on the 3D surface data of the target surface and complexity in integrating the surface data points over the length of the profile.

**Figure 5** Surface area integral method (3D model)

### 4 Non-dimensional parameter of the surface profile

In general, dimensional parameters such as average roughness \((R_a)\), maximum height of peaks \((R_p)\) and maximum depth of valleys \((R_v)\) and maximum peak to valley \((R_t)\) are extracted from the profile data to assess the quality of the surface. If the height of the profile \(y_1, y_2 \ldots\) and evaluation length \((L)\), \(R_a\) and \(R_t\) is expressed by equation (10) and equation (11).

\[
R_a = \frac{1}{L} \int_{x=0}^{x=L} |y| \, dx \tag{10}
\]

\[
R_t = |R_p| + |R_v| \tag{11}
\]

In area averaging technique, it is difficult to relate these parameters due to the finite number of irregularities are averaged on that location. The dimensional parameters such
as $R_p$ and $R_n$ cannot provide a full description of the surface. Particularly using surface area averaging techniques, height sensitive factors such as $R_p/R_n$ and $R_p/R_t$, are closely representing true profiles when studying idealised and real surfaces profiles (Zipin, 1981). In this work, it is significant to relate the height sensitive factors, i.e., non-dimensional parameters estimated from observed capacitive displacement. It is an indirect way to relate to dimensional parameters. Also, parameters are representing both the asymmetry of the profile peaks and the distribution of roughness (Sherwood and Crookall, 1967–1968). There is a significant similarity between $R_p/R_n$ and the fullness ratio $F$, derived from Abbott-Firestone (bearing area) curves. Such forms of sensitive factors are significant to relate the surface finish variations of the machined surface. In the present work, the distribution of capacitive average surface roughness ($R_c$) to maximum peak to valley height ($R_{pc}$) and maximum peak ($R_{pc}$) of the profile measured using the capacitive sensor called ‘profile height indices (PHI)’ are proposed to relate the surface finish of the profile. These non-dimensional parameters are evaluated from the observed displacement ($Z_{m1}, Z_{m2}, ..., Z_{mn}$) from both methods and given in equation (12) and equation (13). In this paper, the non-dimensional profile parameters are evaluated and to relate the capacitive displacement for theoretical profiles.

\[
R_c = \frac{1}{n} \sum_{n} |Z_{mi}|
\]  

\[
R_{pc} = |R_{pc}| + |R_{vc}|
\]

5 Results and discussion

5.1 Simulated results

The different theoretical profiles described in Section 2 were analysed using the proposed model. Figure 6 shows the predicted capacitive displacement profile using the proposed model. It is observed that the magnitude of variation considerable small over similar pattern of the profile. The predicted capacitive displacement profile does not closely trace the actual profile peak. It is mainly due to the nature of the method, the averaging effect suppresses the peaks and valleys of the profile. However, the predicted capacitive profile gives the information about the profile pattern of the theoretical profile. Furthermore, it is not feasible to compare the displacement profile observed and generated theoretically. Due to the area focused by the sensor on the profile instead of point contact method. However, the effective prediction of the profile is feasible by very small sensing area of the sensor. This method is reliable for quantitatively compare with different non-dimensional parameters of the actual generated profile and observed capacitive displacement profile. Instead of relating the dimensional parameters, proposed PHI are predicted to relate surface finish. The estimated PHI’s from the model and non-dimensional parameter value of the profile ($R_p/R_n$, $R_p/R_t$) are tabulated in Table 1. The values of actual non-dimensional parameters also fall in a same range of index. It is found that the computed PHI’s are moderately agreed with actual non-dimensional parameter values. However, percentage of deviation is larger variations for the profiles (b), (c) and (e). Figure 7 shows the comparison of estimated non-dimensional parameters of different theoretical profiles. The variation over the values is due to the
disposition of constructed theoretical profile peaks. The proposed indices give the distributed capacitive displacement and highest peaks of the surface profile.

**Figure 6** Predicted capacitive displacement profile by proposed models

![Predicted capacitive displacement profile](image)
Figure 6  Predicted capacitive displacement profile by proposed models (continued)
Figure 6  Predicted capacitive displacement profile by proposed models (continued)
Figure 7  Comparison of estimated non-dimensional parameters, (a) $R_a/R_t$ (b) $R_p/R_t$ (see online version for colours)
Investigations into modelling and assessment of theoretical profiles

Table 1: Estimated non-dimensional profile parameter values of different theoretical profiles

<table>
<thead>
<tr>
<th>S. no</th>
<th>Profile</th>
<th>Actual ( (R_e/R_b) )</th>
<th>Plane area integral method (2D model) PHI-1 ( = R_e/R_c )</th>
<th>Plane area integral method (3D model) PHI-2 ( = R_e/R_d )</th>
<th>% of deviation</th>
<th>Actual ( (R_e/R_b) )</th>
<th>Plane area integral method (2D model) PHI-2 ( = R_e/R_c )</th>
<th>Plane area integral method (3D model) PHI-2 ( = R_e/R_d )</th>
<th>% of deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a</td>
<td>0.26</td>
<td>0.32</td>
<td>0.21</td>
<td>23.08</td>
<td>0.80</td>
<td>0.70</td>
<td>0.57</td>
<td>12.50</td>
</tr>
<tr>
<td>2</td>
<td>b</td>
<td>0.15</td>
<td>0.25</td>
<td>0.44</td>
<td>66.67</td>
<td>0.50</td>
<td>0.49</td>
<td>0.67</td>
<td>13.64</td>
</tr>
<tr>
<td>3</td>
<td>c</td>
<td>0.29</td>
<td>0.34</td>
<td>0.35</td>
<td>17.24</td>
<td>0.70</td>
<td>0.54</td>
<td>0.69</td>
<td>100.00</td>
</tr>
<tr>
<td>4</td>
<td>d</td>
<td>0.30</td>
<td>0.29</td>
<td>0.32</td>
<td>0.33</td>
<td>0.65</td>
<td>0.37</td>
<td>0.43</td>
<td>103.13</td>
</tr>
<tr>
<td>5</td>
<td>e</td>
<td>0.21</td>
<td>0.30</td>
<td>0.43</td>
<td>42.86</td>
<td>0.43</td>
<td>0.46</td>
<td>0.48</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>f</td>
<td>0.24</td>
<td>0.26</td>
<td>0.45</td>
<td>08.33</td>
<td>0.51</td>
<td>0.51</td>
<td>0.72</td>
<td>13.33</td>
</tr>
</tbody>
</table>
5.2 Experimental results

Figure 8 shows the schematic representation of the capacitive sensor-based measurement system and photograph of the setup is shown in Figure 9. The capacitive sensor used in this work for measurement is shown in Figure 9(c). The authors have been made an attempt for estimation of non-dimensional profile parameters for the non-periodic surfaces (Murugarajan and Samuel, 2010) using the measurement setup. The measurement setup consists of a high precision XYZ axis linear stage arrangement, stage controller, capacitive sensor, sensor driver electronics and computer-based data acquisition system (DAQ). The sensor is placed in the sensor holder bracket and mounted on the vertical linear stage (Z-axis). It has a measuring range of $\pm 40 \mu m$ 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 target adjacent to the probe. Table 2 gives the brief description of the linear stages and capacitive sensor used in the present work. A computer aided DAQ is used for acquiring the real-time measurement of surface profile of the target surface while moving the linear stage. A LABVIEW programme is developed for acquiring the surface profile information at discrete time interval while moving the linear stage at a lower scanning speed. The measurement data obtained from the sensor is acquired and stored as ASCII format for further analysis. The five specimens are prepared by using shaping process and profiles formed as a triangular pattern of periodic profiles. The experiments were carried out using the developed measurement system using capacitive sensor.

**Figure 8** Schematic view of the experimental setup (see online version for colours)

Source: Murugarajan and Samuel (2010)
Figure 9 View of the experimental setup and capacitive sensor, (a) assembled view of the experimental setup and stage controller (b) capacitive sensor (c) computer-based (DAQ) and sensor electronics (see online version for colours)

Figure 10 shows the typical results of the measured and predicted profile of the shaped specimens. The measurement results were mapped with the roughness profile of the specimens. In area averaging techniques, it is difficult to directly relate the profile with stylus measurement. This is due to the nature of the method where the sensor averages the surface irregularities at the location. Although the sensor predicts valleys of the
profile, there is suppression by the averaging effect of the sensor. Hence, it is not accurate to compare the profile obtained using a capacitive sensor with the stylus profile. It is more significant to compare the proposed capacitive response model with equivalent capacitive displacement profile considering the 2D and 3D surface data of the specimen measured. In the present work, results of measured profiles using sensor and predicted profiles using capacitive response were mapped to the data points of a profile of the specimen measured using the stylus instrument. The profile of the specimen with a stylus Ra value between 35 \( \mu \text{m} \) to 60 \( \mu \text{m} \) was measured. The surface finish of the shaped specimen showed lower variation in magnitude. However, this also closely matches with proposed model results. Also, it is observed that the trend of the triangular pattern which is similar to the simulated results of the periodic profiles.

Table 2 Specifications of capacitive sensor and linear stage

<table>
<thead>
<tr>
<th>Details</th>
<th>Capacitive sensor</th>
<th>Linear stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>–40 to +40 ( \mu \text{m} )</td>
<td>Travel range</td>
</tr>
<tr>
<td>Standoff</td>
<td>100 ( \mu \text{m} )</td>
<td>Lead pitch screw</td>
</tr>
<tr>
<td>Output voltage</td>
<td>10 to –10 VDC</td>
<td>Resolution</td>
</tr>
<tr>
<td>Output sensitivity</td>
<td>0.25 V/( \mu \text{m} )</td>
<td>1/8 step: 0.156 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Linearity error</td>
<td>0.02 %</td>
<td>Speed range</td>
</tr>
<tr>
<td>Peak to peak resolution</td>
<td>33.46 nm</td>
<td>Load capacity</td>
</tr>
<tr>
<td>Sensing diameter</td>
<td>0.5 mm</td>
<td>Cable</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Driver</td>
</tr>
</tbody>
</table>

The observed displacement data \((Z_{m1}, Z_{m2},..., Z_{mn})\) from the measured profile was used for evaluation of the average capacitive roughness parameter. \( R_c \) was calculated for the displacement profile obtained from the proposed models. The sampling length of 0.8 mm was used for evaluation of the surface finish from the displacement profile over the evaluation length. Equation (11) was used for the evaluation of \( R_c \). It is significant to compare the surface finish values obtained from the measured displacement profile with proposed model values. It is observed the measured \( R_c \) values using sensor and theoretically calculated \( R_c \) using a plane area integral method shows significantly less variation compared to the surface area integral method. However, the percentage of variation shows the more significant difference in the proposed models due to surface profile data taken for analysis. Figure 11 shows the comparison of \( R_c \) values obtained by the capacitive sensor and proposed models with \( R_a \) values measured by a stylus instrument. The estimated parameters for shaped specimens (periodic profiles) are tabulated in Table 3. The result shows that the calculated \( R_c \) using plane area integral model agreed better than the surface area integral method for the machined surfaces. The results show close agreement with proposed model values of the specimens.
Figure 10  Measured and predicted displacement profiles for shaped surfaces, (a) Specimen 1 (b) Specimen 2 (c) Specimen 3 (d) Specimen 4 (e) Specimen 5 (see online version for colours)
Figure 10  Measured and predicted displacement profiles for shaped surfaces, (a) Specimen 1 (b) Specimen 2 (c) Specimen 3 (d) Specimen 4 (e) Specimen 5 (continued) (see online version for colours)
Investigations into modelling and assessment of theoretical profiles

Figure 10  Measured and predicted displacement profiles for shaped surfaces, (a) Specimen 1 (b) Specimen 2 (c) Specimen 3 (d) Specimen 4 (e) Specimen 5 (continued) (see online version for colours)

Figure 11  Comparison of measured and calculated surface parameter of the specimens using capacitive sensor, stylus and proposed methods (see online version for colours)
Table 3  Estimated profile parameter values of shaped specimen (periodic profiles)

<table>
<thead>
<tr>
<th>S. no.</th>
<th>Specimen</th>
<th>Measured $R_c$ ($\mu m$)</th>
<th>Plane area integral method</th>
<th>% of variation</th>
<th>Surface area integral method</th>
<th>% of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S1</td>
<td>8.35</td>
<td>6.85</td>
<td>17.96</td>
<td>7.04</td>
<td>15.69</td>
</tr>
<tr>
<td>2</td>
<td>S2</td>
<td>4.06</td>
<td>7.19</td>
<td>77.09</td>
<td>9.21</td>
<td>126.85</td>
</tr>
<tr>
<td>3</td>
<td>S3</td>
<td>7.72</td>
<td>7.53</td>
<td>2.46</td>
<td>9.39</td>
<td>21.63</td>
</tr>
<tr>
<td>4</td>
<td>S4</td>
<td>8.73</td>
<td>8.47</td>
<td>2.98</td>
<td>10.74</td>
<td>23.02</td>
</tr>
<tr>
<td>5</td>
<td>S5</td>
<td>9.43</td>
<td>9.19</td>
<td>2.55</td>
<td>12.02</td>
<td>27.47</td>
</tr>
</tbody>
</table>

6 Conclusions

In the recent years, there has been an increasing interest in characterisation of surface finish using the area averaging techniques. It has gained more attention in the field of automotive manufacturing and to develop a measurement system that deals with the fast scanning rate and numerically representing larger surface area for characterising the surface finish of the component. In this presented work attempt has been made using non-contact capacitive sensor for the assessment of different theoretical (periodic) profiles. The following conclusions were made from the results:

- An attempt has been made to investigate the modelling and assessment of different theoretical profiles using capacitive sensor. The capacitive response models were developed based on the principle of capacitive sensing.

- A capacitive response model for a surface was developed based on plane area and surface area integral methods to predict the equivalent theoretical capacitive displacement profile. The proposed methods effectively predicted capacitive displacement profile and the magnitude of displacement correlated with profile measured using capacitive sensor.

- The models were validated experimental results. The proposed PHI from the models are moderately agreement with non-dimensional parameters of the actual theoretical profile.

- Experiments were conducted and the displacement profile measured using the capacitive sensor agreed moderately with the predicted displacement profiles obtained using the capacitive response model. It was observed that the magnitude of capacitive displacement profiles from the model and sensor varied with surface finish of the specimen. The very rough surfaces have shown more variation in magnitude of displacement. This moderate deviation is due to the air-gap distance between the sensor and the target surface. The phase difference in the starting points of the measurement between the stylus and sensor also contributed to the deviation.

- However, the presented work is limited to a different triangular form of theoretical profiles. Moreover, the experimental results using sensor for non-periodic could be more significant compared to proposed model results.
Investigations into modelling and assessment of theoretical profiles

References


