Effect of probe size and measurement strategies on assessment of freeform profile deviations using coordinate measuring machine

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Abstract

Freeform profiles and surfaces have wider engineering applications. Designers use B-splines, Non-Uniform Rational B-splines, etc. to represent the freeform profiles in CAD, while the manufacturers employ machines with controllers based on approximating functions or splines that can cause deviations in manufactured parts. Deviations also creep in during the manufacturing operations. Therefore the manufactured freeform profiles have to be verified for conformance to design specification. Different points on the profile are probed using a coordinate measuring machine (CMM) and a substitute profile is established from the CMM data for comparison with design profile. The sample points are distributed according to different strategies. In the present work, two new strategies of distributing the points on the basis of curve length and dominant points are proposed considering the geometrical nature of the profiles. Metrological aspects such as probe contact and margins to be provided at the ends have also been included. The results are discussed in terms of form deviation with reference to substitute profile and positional deviation between design and substitute profiles, and compared with results of the strategies suggested in the literature.

1. Introduction

Freeform features are widely used in the design and manufacturing of dies and moulds, patterns and models, plastic products, etc. in many fields of engineering applications ranging from automotive/aerospace to biomedical and entertainment to geographical data processing [1]. The freeform features used in engineering applications are often specified with profile tolerances, which can be verified using contact or non-contact methods. The contact methods typically use coordinate measuring machines (CMMs) with touch probes for accurate measurement of a set of discrete sample points. This work considers CMMs with touch trigger probes where the scan rate is much less. However, this does not limit the scope of present work. The set of sample points are assumed to represent effectively the feature being measured. These sample points are used to create the substitute profile for the feature being measured. The substitute profile is compared with the design profile (CAD model) to determine conformance to the specification. It may be possible that the deviations of the sampled points may satisfy the given tolerance specification, but some of the non-sampled points may still be out of the tolerance range. It is intuitive that increased sample size could lead to better characterization of the profile; however, the sample size is often limited by cost and time constraints. Thus, for a given a sample size, the measurement strategy used must determine the locations of these measurement points such that the actual shape may be effectively characterized.

Measurement of freeform features is fundamental to both quality control and process troubleshooting; however, they are difficult to measure [2]. The common measurement strategy, especially in the inspection planning software, is to distribute the sample points in a uniform...
vectors and distributes the points along on patch size divides the surface into patches at the knot equally along sampling. First method distributes the sampling points combined patch size and patch mean Gaussian curvature based equi-parametric sampling, patch size based sampling, based on the surface normal identifies areas where further sampled surface and an iterative interpolation model of actual measurement points considering the probe ra-
ods. They have also presented a method for determination points and distributes them according to the above methods. They have also presented a method for determination of actual measurement points considering the probe ra-
dius. Edgeworth and Wilhelm [6] have taken an initial sampled surface and an iterative interpolation model based on the surface normal identifies areas where further samples may be required for a complete measurement.

ElKott et al. [7,8] proposed heuristic algorithms for equi-parametric sampling, patch size based sampling, patch mean Gaussian curvature based sampling, and combined patch size and patch mean Gaussian curvature based sampling. First method distributes the sampling points equally along U and V knot vectors. Second method based on patch size divides the surface into patches at the knot vectors and distributes the points along u and v parametric directions in proportion to the patch size. Third method based on patch mean Gaussian curvature, distributes the sample points according to curvature values with larger share of sample points for the patch with higher ranking. The second and third methods are combined to form a fourth method which allows the user to specify weights for each method. They also have presented an adaptive sampling strategy to minimize the maximum deviation between the design surface and substitute geometry using a genetic algorithm. Ainsworth et al. [9] proposed three methods based on chord length criterion, minimum sample density criterion and a parameterization based sampling criterion for sampling. The maximum deviation of the surface is specified to arrive at the chord length in the first method, while the second method specifies the maximum allowed distance between any two neighboring points on the surface. The third method uses the number of samples per knot span, as specified by the user.

Obeidat and Raman [10] suggested that first point with maximum Gaussian curvature, second point with mean Gaussian curvature and third point with average of the mean Gaussian and minimum Gaussian curvatures could be taken as critical points for each surface patch. Their first algorithm starts with samples at critical points in each patch and additional sample points are added to low density patches. The second algorithm considers the patch size and the share of sample points for a particular patch is propor-
tional to its size. If the share in a patch is three or more points, three critical points are selected first and the remaining points are added in the same way as in the first algorithm. The third algorithm adds the sampling points in an adaptive manner such that maximum difference between the substitute geometry and CAD model is less than the specified tolerance. It starts with a sample point in a patch with highest rank on the basis of patch mean Gaussian curvature and the remaining patches get sample points equal to or less than this number according to mean Gaussian curvature ratio. The computed maximum difference between the substitute geometry and CAD model is greater than the specified tolerance, the number of sample points in the highest ranked patch is increased by one and the procedure is repeated till the maximum permitted number of sample points in the highest ranked patch is reached. If the maximum difference between the substitute and model geometries is still greater than the specified tolerance, additional points are added based on patch size ranking and patch size ratio.

The literature reveals that most of the sampling methods are proposed for freeform surfaces, while limited information is available on the sampling of freeform profiles [7]. It is observed from the literature that the reported strategies lack the metrological sense, which emphasizes that the sample points cannot be located at the edges as the edge measurement is unreliable. Next important observation is that the effect of probe size on the measurement results is not reported and this is a very important factor as the probe may not contact the feature at the planned measurement point. These issues can cause errors in the measurement results in a practical environment. Other major observations are the dependency on user judgement of certain parameters and inefficiency in handling features with rapidly changing curvatures.

It is easier to visualize the measurement strategies in 2D and the issues mentioned above can be understood very well with freeform profiles [11]. As such, specific cross-sections of freeform surfaces can be measured using these strategies. Also extruded surface (referred to as 2½D feature in machining technology) created from 2D profile as obtained in contour milling or wire electro-discharge machining can be verified. The present work considers freeform profiles with different manufacturing deviations, investigates different measurement strategies and brings out the effect of probe size. In this paper, two new measurement strategies based on profile geometry are proposed. First strategy is based on the length of the curve and the second strategy is based on the concept of domin-
ant points. Three of the reported distribution strategies, namely uniform distribution along x-axis as well as u-
parameter direction and distribution based on segment size have also been implemented. The results are pre-
ented and discussed.

2. Design freeform profile

This paper uses the Non-Uniform Rational B-Splines (NURBS) for representing freeform profiles [12]. There are two fundamental reasons for using NURBS representation.
First reason is that it provides a more common mathematical representation for freeform features and its evaluation is straightforward, fast and computationally stable [13]. The second reason being its use as industrial standard for computer aided design (CAD), which is due to its ability to accurately represent various shapes including the primitives such as the spheres, cylinders, etc. to even very complex freeform features.

The design profile used in this work is represented using NURBS with \( C^2 \) continuity and its degree is taken to be 3. The data used for the example design profile is given below:

No. of control points: 5.
Control points (mm): (0, 70), (25, 20), (50, 90), (75, 20) and (100, 60).
Knot vector: \{0, 0, 0, 0, 0.3697, 1, 1, 1, 1\}.

3. Measurement strategies

The manufactured freeform profiles are measured at discrete points, called the sample points. Given the number of sample points, the sampling method has to distribute these points over the profile such that it is effectively characterized. The measured points are used to construct the substitute geometry for the profile being measured. The distance of the measured points from the substitute profile are evaluated in the linear and normal directions, as illustrated in Fig. 1. Then the substitute profile is compared with the design profile to determine the deviations between them.

The sampling methods reported in the literature use sample points at the ends of the profile to be measured. However, from metrological viewpoint, it is undesirable to have sample points at the ends, as these points cannot be measured precisely. This is likely to cause difference in a practical measurement scenario. Thus, the performance of all five methods presented here is studied for profile with 5% margin at both ends.

The general flowchart for the present work is shown in Fig. 2. The details of the measurement strategies are presented in the sub-section. All the measurement strategies start with a discretized profile of evenly spaced \((M + 1)\) points in Cartesian space. The spacing along the \( x \)-axis is taken as 10 \( \mu \text{m} \) and the corresponding parameter values and curvatures [14] are computed for further use.

![Fig. 1. Freeform profile showing a sample point and deviations.](image)

3.1. Uniform distribution in Cartesian space

This is considered to be the simplest method and CMM users prefer it in practice, as the measurements are directly in Cartesian space. However, its details are not covered in the literature, since researchers are always concerned with complex profiles and measurement strategies in parametric space. In this work, the sampling points are distributed with nearly equal spacing along the \( x \)-axis. The spacing between sample points depends on the feature size and the number of sampling points. The lower and upper bounds of the profile along the \( x \)-axis are obtained from the digitized profile and denoted as \( x_{\min} \) and \( x_{\max} \) respectively. These values correspond to minimum and maximum values of parameter \( u \). Then, the positions of all the sampling points can be obtained from the following equation:

\[
x_i^c = x_{\min} + (i - 1) \frac{x_{\max} - x_{\min}}{N_s - 1}; \quad i = 1, \ldots, N_s
\]

where \( N_s \) is the sample size. With the \( x_i^c \) value thus computed, the nearest point \( (x_i) \) on the digitized profile is obtained. Figs. 3a and 4a show uniformly distributed sampling positions in Cartesian space for sample sizes of 6 and 10 respectively.
3.2. Uniform distribution in parametric space

In this strategy, the sample points are distributed with nearly equal spacing along \( u \)-direction. The spacing between sample points depends on the range of the parameter and the number of sampling points. The positions of sample points \( (u'_i) \) can be obtained from the following equation:

\[
    u'_i = u_{\text{min}} + (i - 1) \frac{u_{\text{max}} - u_{\text{min}}}{(N_s - 1)}; \quad i = 1, \ldots, N_s
\]

where \( N_s \) is the sample size. The values of \( u_{\text{min}} \) and \( u_{\text{max}} \) are the minimum and maximum values respectively of parameter \( u \). After computing the \( u'_i \) value, its nearest point \( (u_i) \) on the digitized profile is obtained. Uniformly distributed sampling positions in \( u \)-direction are transformed to Carte-
sian space and shown in Figs. 3a and 4a for sample sizes of 6 and 10 respectively.

3.3. Distribution based on segment size

The patch size ranking algorithm proposed by Obeidat and Raman [10] has been modified by the authors for free-form profiles taking a fixed sample size and following segment size ranking. The given design profile is divided into segments using the design knot vector and segment size is computed as \((u_2 - u_1)\), where \(u_1\) and \(u_2\) are the bounds. Based on segment size, share of points for each segment is computed. If the share of points is 1 or more in a segment, the first sample point is placed at a point having the curvature \(k_{\text{max}}\). The sample points thus placed in all segments and the end points constitute the initial sample set. If it is required to add more sample points in a segment, the criteria of “high rank” and “low points density” are used and the sample points are located at points in the order of \(k_{\text{avg}1}, k_{\text{avg}2}, k_{\text{avgmin}1}, k_{\text{avgmin}2}\) and \(k_{\text{avgmin}3}\). The
required curvature values are computed using the following equation:

\[ \kappa_{arg1} = (\kappa_{max} + \kappa_{min})/2; \quad \kappa_{arg2} = (\kappa_{arg1} + \kappa_{max})/2 \]

\[ \kappa_{argmin1} = (\kappa_{arg1} + \kappa_{min})/2; \quad \kappa_{argmin2} = (\kappa_{argmin1} + \kappa_{min})/2 \]

\[ \kappa_{argmin3} = (\kappa_{argmin2} + \kappa_{min})/2 \]  \hspace{1cm} (3)

where \( \kappa_{max} \) and \( \kappa_{min} \) are the maximum and minimum curvatures respectively in a segment. For sample sizes of 6 and 10, the sampling positions on segment ranking are shown in Cartesian space in Figs. 3a and 4a respectively.

3.4. Proposed distribution based on curve length

In this method, total length of the curve \( L_t \) is computed first from the discretized profile. The length of the curve \( l_i \) between \( N_i \) sample points for this curve can be computed using the following equation:

\[ l_i = L_t / (N_i - 1) \]  \hspace{1cm} (4)

where \( L_t \) is given by \[ \sum [ (x_{j+1} - x_j)^2 + (y_{j+1} - y_j)^2]^{1/2}, \quad j = 1, \ldots, M - 1. \] It may be noted evenly spaced \((M+1) \) points represents the discretized profile in Cartesian space. Starting from \( x'_1 = x_{min}, x'_{M+1} \) is selected such that the curve length between \( x'_i \) and \( x'_{i+1} \) is nearly equal to \( l_i \), where \( i \) varies from 1, \ldots, \( N_i - 1 \). For each \( x'_i \), the position of the point \( (x_i) \) on the discretized profile is picked up. Figs. 3b and 4b show sampling positions based on uniform arc length in Cartesian space for sample sizes of 6 and 10 respectively.

3.5. Proposed distribution based on dominant points

A B-spline curve can be approximated using a reasonable number of key points that reflect certain characteristics of the curve, such as the curvature [15]. These key points are called the dominant points. The dominant points can be used with NURBS curves also, as the NURBS curves have all the characteristics of B-spline curves. The points with maximum local curvature are considered in this work as the dominant points. Along with these points, two more points defining the start and end points of the dominant profile are taken to form the initial set of sample points.

The initial sample points are used to form segments of the profile. Additional points can be added to each segment one at a time, starting with the longest segment, until the required number of sample points is placed. Within a segment, a new point is chosen in such a way that the curve lengths on either side of it are nearly equal. Figs. 3b and 4b show sampling positions in Cartesian space decided on the basis of dominant points for sample sizes of 6 and 10 respectively.

4. Simulation of manufactured profiles

In general engineering practice, various types of manufacturing deviations are encountered. The deviations are of different wavelengths. The long wavelength deviations come from various sources such as machine tool guide-ways and deflection of workpiece, while other wavelengths are due to vibrations, changing curvatures of profile machined, etc. The deviations due to conditions other than changing curvature can be simulated by using appropriate special type mathematical functions [16]. The special type form deviations include quadratic and sinusoidal deviations. Apart from these deviations, random deviations also occur that can be assumed to follow certain probability distribution. All these types of deviations are considered here for simulating the manufactured profiles.

4.1. Quadratic type form deviation \( (\delta_q) \)

The quadratic type form deviation, representing the deviation of form, can be approximated using a second-order polynomial as given in the following equation:

\[ \delta_q = b_0 + b_1 x_i + b_2 x_i^2 \]  \hspace{1cm} (5)

where \( b_0, b_1, \) and \( b_2 \) are the coefficients. In the present work, \( b_0 = 0.005, \ b_1 = -7.0(10^{-5}) \) and \( b_2 = -3.0(10^{-7}) \) are taken to give a maximum value of \( \delta_q \) at 0.010 mm.

4.2. Sinusoidal type form deviation \( (\delta_s) \)

The sinusoidal type form deviation can be approximated using a combination of sinusoidal functions as given in the following equation:

\[ \delta_s = A \sin(wx_i + \varphi) + B \cos(wx_i + \varphi) \]  \hspace{1cm} (6)

where \( w \) is given by \( 2\pi/j \) and \( j \) is the wavelength of the sinusoidal components. \( A \) and \( B \) are the amplitudes of sine and cosine components and \( \varphi \) is the phase lag. In the present work, the phase lag \( \varphi \) is taken as 0° and the values of both \( A \) and \( B \) are taken to be 0.005 mm. The wavelength \( j \) is assigned values of 1, 2, and 3 to simulate different sinusoidal form deviations. The maximum value of this component \( (\delta_s) \) is 0.010 mm.

4.3. Deviation due to changing machining conditions \( (\delta_m) \)

When cutting tool is machining different curvatures in a given profile, form deviations are introduced due to changing machining conditions. The distribution of this form deviation is computed on the basis of the curve as shown in the following equation:

\[ \delta_m = f_i (i - 0.5) \]  \hspace{1cm} (7)

where \( f_i \) is the maximum value of machining form deviation. Index \( i \) based on curvature of the profile is given by \( \lambda = (\kappa - \kappa_{min})/\lambda_{max} - \kappa_{min} \). The terms \( \kappa, \kappa_{min} \) and \( \kappa_{max} \) refer to the curvature, minimum curvature and maximum curvature of the profile respectively. A value of 0.010 is chosen for \( f_i \) so that the maximum value of this component \( (\delta_m) \) is 0.010 mm.

4.4. Random deviations \( (\delta_r) \)

The random deviations in a machining process can be obtained by appropriately conducting machine capability study. After adding this to systematic deviations, CMM
measurement can be simulated. The noise during CMM measurement also adds random deviations and information about relevant range of variation for this component can be obtained from CMM manufacturer’s calibration chart. In the present work, random deviations due to machining and measurement processes are combined and their effect ($\delta_c$) is characterized by a normal distribution with appropriate mean value and standard deviation. This work assumes that the random deviation follows the standard deviation of 0.001 mm.

4.5. Superimposition of the deviations

The simulated profile is obtained by superimposing all the components of deviations on the design profile. If $C(X_j, Y_j)$ is any point on the design profile, then its coordinates on the manufactured profile taking into account the effect of combined deviations will be $C_m(X_j, Y_j)'$, where $Y_j' = Y_j + \delta_q + \delta_t + \delta_m + \delta_c$. For arriving at the probe contact point during the measurement in a CMM, the coordinates given by $C_m(X_j, Y_j)'$ have to be used. Fig. 5 shows the plot of combined deviations taking $i = 1$ for the sinusoidal component. It can be observed that the magnitude of the combined deviations is 22.369 $\mu$m.

5. Computation of probe contact point

The computation of coordinates of probe contacting point is done in Cartesian space using a general method proposed by Shunmugam and Radhakrishnan [17]. Circular (section) profile of the probe is discretized with the same spacing used for discretizing the design profile. The spacing used in this paper is 10 $\mu$m. The resulting ordinates ($E_k$) of the probe section from the diameteral line, corresponding to the discretized points (marked as 0, 1, etc. in the figure), are computed. The notation $x_i$ refers to the $x$-coordinates on the simulated manufactured profile and $y_j'$ refers to the corresponding $y$-coordinates. The circular profile is placed such that the probe section marked with 0 (namely, its center) coincides with $x$-coordinate of the sample point $x_i$ under consideration. For each discretized $x$-coordinate, the sum of the ordinates ($y_j' + E_k$) is obtained. This results in an envelope as shown in Fig. 6 using dashed line. $y_{max}$ shows the point with maximum ($y_j' + E_k$) value on this envelope. The $x$-coordinate of probe contact point ($x_c$) is given by the location where $y_{max}$ occurs. The corresponding $y$-coordinate ($y_c$) is taken from the profile $C_m(x_i, y_j')$ obtained by superimposing the manufacturing deviations. The measured points are represented as $P_c(x_c, y_c)$. It should be noted that these are different from the initial sample points on the discretized profile.

6. Fitting of substitute profile

The degree, knot vector, number of control points and their weights for constructing the substitute profile are taken to be the same as that of the design profile. The substitute profile is fitted for the measured points by least squares method, as described below [12].

Let $\{P_i\}$ consist of a set of $N_i$ measured points that are to be approximated by a NURBS profile with $(n+1)$ control points, wherein $N_i > (n+1)$. The objective is to construct a substitute profile, represented as

$$C_i(u) = \sum_{i=1}^{n+1} N_{ip}(u)P_i; \quad u \in [0, 1]$$

Satisfying that,

- The end points are interpolated, i.e. $P_1 = C_i(0)$ and $P_{N_i} = C_i(1)$.
- The remaining points $P_{c(k)}$ are to be approximated in the least squares sense, i.e. $\sum_{k=2}^{N_i-1} |P_{c(k)} - C_i(u)|^2$ is a minimum; $\{u_k\}$ are the parameter values corresponding to measured points.
Table 1
Results for freeform profile (Control points: 5) with 5% margin and 10 μm discretization interval.

<table>
<thead>
<tr>
<th>Deviations considered</th>
<th>Dev. introduced (μm)</th>
<th>Sample size</th>
<th>Existing</th>
<th>Proposed</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Uniform x-axis</td>
<td>Unif. parameter</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Pos. dev.</td>
<td>Form dev.</td>
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<tr>
<td>(a) Linear deviations (μm) obtained by different measurement strategies</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>(i) Probe diameter: 0.0 mm</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>All dev. (k = 1)</td>
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<td>+9.961</td>
<td>0.614</td>
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<td></td>
<td>−9.434</td>
<td></td>
<td>−5.720</td>
<td>−3.148</td>
</tr>
<tr>
<td>All dev. + random</td>
<td>22.369</td>
<td></td>
<td>+8.813</td>
<td>1.780</td>
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<tr>
<td>(ii) Probe diameter: 1.0 mm</td>
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<td></td>
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<td></td>
<td>−5.824</td>
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<td>−5.940</td>
<td>−4.064</td>
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<td>(b) Normal deviations (μm) obtained by different measurement strategies</td>
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<td></td>
<td></td>
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<td>(i) Probe diameter: 0.0 mm</td>
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<td>All dev. (k = 1)</td>
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<td></td>
<td>−5.866</td>
<td>−3.944</td>
</tr>
</tbody>
</table>
The details of the algorithm for least squares fitting are given in Piegl and Tiller [12].

7. Computation of deviations

The deviation of a measured point from the substitute profile is computed in the vertical (linear) and normal directions as shown in Fig. 1. The distance between the measured point and corresponding point on the substitute profile along the y-axis gives the linear deviation. The shortest distance between the measured point and the substitute profile represents the normal deviation. Let \( e \) represent the deviation and \( (e_{\text{max}}, e_{\text{min}}) \) denote the maximum and minimum values of the deviations respectively.

The form deviation is taken to be deviation of the measured points from the substitute profile and it is computed as

\[
\Delta = |e_{\text{max}} - e_{\text{min}}| \tag{9}
\]

Depending on nature of the deviations considered, the form deviation \( \Delta \) may be expressed as linear or normal value.

The substitute profile established from the measured points may also be positioned differently with reference to the design profile. The distance between the substitute profile and the design profile are computed on a point-to-point basis as linear or normal values following the procedure outlined above. For quantifying the positional deviation, the maximum and minimum deviations are represented by \( p_{\text{max}} \) and \( p_{\text{min}} \).

8. Results and discussion

In the present work, the sampling points are selected considering the design profile. The measurement strategies involving uniform spacing in x- and u-directions as well as segment size are not affected by the manufacturing deviations superimposed. In case of other strategies involving curve length and curvatures, these deviations do not significantly affect the nature of the design profile and hence the computed values of curve length and curvature are altered very little. As the sampling positions are predetermined, the effect of probe size and measurement strategies can be conveniently studied. It may be noted that the measured points are on the profile with manufacturing deviations superimposed and the substitute profiles are established from the measured points.

Table 1 presents the results obtained for the freeform profile considered in the present work.

Initially the manufacturing deviations were not considered and the measured points were obtained with probe sizes of 0.0 and 1.0 mm according to different strategies for sample sizes of 6 and 10. When the substitute profiles were established from these measured points, their deviations from the design profile were zero at all points. In other words, form and position deviations were zero (not shown in Table 1), confirming that the substitute profile exactly matches with the design profile.

With superimposition of manufacturing deviations, the first step is to quantify the introduced deviation. This is done by the computing the deviations from the design profile following the procedure outlined in Section 7. The maximum values of deviations in the linear and normal directions are given in the second column of Table 1a and b respectively. The values are listed for sinusoidal type form deviation with \( \lambda = 1 \) superimposed on other manufacturing deviations. As expected the values listed in Table 1b are lower than that given in Table 1a, since the deviations are measured in the normal direction.

Ideally, the substitute profile established from the measured points must be able to capture the form deviation and lie close to the design profile. In practice, chosen measurement strategy should ensure that the form deviation obtained is as high as possible and the positional deviation as low as possible. It may be observed from Table 1a (i) that with zero probe size and sample size of 6 the existing strategies result in form deviation values ranging from 0.614 to 6.904 \( \mu \text{m} \) for a profile with all deviations, excluding random deviation, superimposed. Among the proposed strategies, the strategy based on dominant points gives a form deviation of 10.526 \( \mu \text{m} \). With the random deviation superimposed along with all other deviations, form deviation captured by this strategy is the highest. As the sample size is increased to 10, the form deviation values are higher than that obtained with a sample size of 6. The substitute profile established with higher sample size is more representative of the profile superimposed with manufacturing deviations. When the probe diameter is increased to 1.0 mm (Table 1a (ii)), a similar trend is observed and the form deviation values are slightly lowered. The increased probe size has a mechanical filtering effect with a slight reduction in the values obtained.

Two values are shown under positional deviations in Table 1. The upper value corresponds to \( p_{\text{max}} \) and lower value represents \( p_{\text{min}} \). The substitute profile lies between \( p_{\text{max}} \) and \( p_{\text{min}} \) with reference to the design profile. Taking the absolute sum of \( p_{\text{max}} \) and \( p_{\text{min}} \) as an indicator, it is seen from Table 1a (i) that the strategy based on segment size ranking gives minimum values of 10.911 \( \mu \text{m} \) and 11.434 \( \mu \text{m} \) for a sample size of 6, when the measurement is carried out using zero probe size on the profile superimposed with all deviations excluding random deviation and all deviations including random deviations respectively. The strategy of segment size ranking is actually based on algorithm [10] modified by the authors. The proposed strategy based on dominant points gives values very close to the minimum values obtained with segment size ranking strategy. This proposed strategy use points with maximum local curvature as dominant points and subsequent points are added on the basis of segment size ranking. A similar trend is observed in Table 1a (ii). The form and positional deviations based on normal deviation and listed in Table 1b always follow the trends given in Table 1a, but the values are lower than the values obtained in the linear direction.

9. Conclusions

In the present work, two new strategies for the distribution of given number of sample points in the measurement
of the freeform profiles have been proposed. The profiles superimposed with manufacturing deviations are taken and the metrological aspects like measuring probe size and margins to be provided have been considered. Identification of the contact point of the probe with the profile and assessment of the deviation in linear and normal directions are also dealt with.

The performance of the proposed strategies is compared with existing strategies, viz. uniform distribution along x-axis as well as u-parameter direction and distribution based on segment size. The third strategy is actually obtained by modifying the patch size ranking strategy for freeform surfaces to suit the objective of the present work. The probe size brings in mechanical filtering effect and hence the results are more reliable. The sample size also has a desirable effect of providing reliable results. For verification of freeform profile deviations, the deviations assessed in the normal direction are more appropriate as they represent conservative values.

The strategy based on dominant points is able to capture the higher values of form deviation with reference to the substitute profile and give lower values for positional deviation between the design and substitute profiles. Hence, the proposed strategy based on dominant points is more useful in the measurement of freeform profile. The work is being extended further to examine alternate measurement strategies and adaptive schemes for the assessment of deviations on the freeform features.

References