Intelligent Sampling for Inspecting Cylindrical Surfaces

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Abstract

The goal of our research is to reduce the number of inspection points for cylinders and bell shapes while maintaining almost the same tolerance zone, so the time and cost is reduced. According to Cantilever Beam Theory that states the maximum deflection on the cylinder being machined using lathe machine, occurs at the free end of the cylinder. Hence the maximum dimensional error can be expected to be at the free end of the cylinder being machined. A big reduction in the number of the inspection points has been achieved. It reached, in cylinders, to about 74.9% with a difference in a tolerance zone of 3.7%. A big reduction, also, has been achieved in sampling bell shapes. It reached to about 66.75% with a difference in a tolerance zone of 1.6%. So number of inspection points can be expected to be maximum at that region. The same thing can be said for the maximum deflection of the cutter used in cutting the bell shape. The cutter deflection will be maximum at the free end of the cutter, so maximum dimensional error can be expected to be at the bottom of the bell shape. Hence the sampling points are expected to be dense close to that region.

Key Words: Sampling cylinders, sampling bell shapes, end milling, CMM.

1.0 Introduction

Part inspection is a very important step in the manufacturing cycle. This inspection process is non-value added and is time consuming. In this work, the manufacturing error is mainly caused by the cutter's deflection and cylinders' deflection. Those errors are verified experimentally. There are many factors that affect the surface error, such as, tool deflection, tool wear, cutter runout, thermal effect, geometry of the surface created, and the manner in which the part is created. DeVor et al. [1] studied the surface error of the workpiece created by end milling process. Sutherland and DeVor [2] studied the cutting operation in flexible end milling systems. They depended on the model created by DeVor et al. [3], but they applied the model on flexible end milling systems where the cutter is long and flexible and the workpiece is thin.

1.1 Sampling Strategies

In coordinate metrology, surfaces are sampled using discrete points and fixed sampling strategies. The fixed strategies include aligned systematic, random and Hammersley methods, Kim and Raman [4]. The sampled points are then fitted using form – fitting methods. The least square method (LSQ) and the minimum zone method (MZ) are the most common methods employed to determine the form error of surfaces. Often these methods rely on large sample sizes and yet large parts of the object being inspected can be ignored during sampling. At very large sample sizes, the fitting algorithms may be of less impact, Dowling et al. [5, 6]. Lin and Chen [7] created algorithms to find the measuring point positions for the basic features that the surface is composed of, and then finding the positions of the measuring points for the entire surface using those algorithms.

In general, as the accuracy requirement increases, the sample size has to be increased, Namboothiri and Shunnugam [8]. Yau and Menq [9] stated that as the tolerance is tighter the sample size increases, and the sample size decreases if the manufacturing process used to create the part is suitable for that type of surface. Woo et al. [10] studied the flatness and the roughness of surfaces and used Hammersley, Halton-Zaremba, Uniform and Stratified methods for sampling of the measuring points. They
concluded that the uniform, random and stratified methods are not the best strategies based on the sample size and the error approximation. Zhang et al. [11] studied the effect of three factors on the sample size using artificial neural networks: the machining process type, geometrical and dimensional tolerance, and the size of the part created. Uppliaapapan et al. [12] studied the sampling process of cylinders in particular. They used the equi-distant sampling and spiral sampling processes in their work. They studied the relation between the form error and the sampling algorithm and the fitting algorithm used to fit the substitute geometry. 

Cho and Kim [13] developed an inspection planning strategy for sculptured surfaces using a coordinate measuring machine (CMM). They determined the optimum measuring point locations based on the mean curvature analysis and a region selection ratio constant. They also used various methods to determine the optimum probe path that minimizes the inspection time and the measuring errors. Pahk et al. [14] developed an inspection system integrated with a CAD environment for manufacturing molds. They used uniform distribution sampling, curvature of the surface, and a hybrid technique of both in sampling the points on the surface. The surfaces are divided into subintervals and the points after that were distributed randomly. Fan and Leu [15] developed an AutoCAD-based inspection planning system that evenly samples points using the dimensions of the part being inspected; however, it does not consider the complexity of the part surfaces or the part tolerances. Lee et al. [16] integrated Hammersley sequence and a stratified sampling method to develop a sampling strategy for geometric features on a surface. They compared between the effectiveness of Hammersley method, uniform sampling and random sampling. A quadratic reduction in the number of sample points using the derived sampling strategy based on Hammersley sequence was achieved compared with the uniform sampling method at the same level of accuracy. Badar et al. [17] presented an adaptive sampling procedure, which reduces the sample size. They found the regions of the maximum error based on the error profile of the surface, and determined the initial points to start search to find other inspection points that give almost the same accuracy as the population measurement points. Also, Badar et al. [18] made an experimental analysis to check the performance of the adaptive sampling procedure in both straightness and flatness verification. They used face and end milling to create flat plates, and they studied the effects of different factors on the sample size and on the error: manufacturing process and step size in the search technique in straightness and the search strategy and search algorithm in flatness. Obeidat and Raman [19] developed three strategies to inspect free form surfaces depending on the free form surfaces geometry. They reduced the number of sampling points based on the critical regions on the manufactured surface. Recently, Obeidat and Raman [20] and Obeidat et al. [21] developed methods for inspection end milled flat plates depending on the way the part is made. Those methods helped reduce the number of inspection points with minimum error in the tolerance zone.

2.0 The Experimental Work

Four cylinders have been manufactured using lathe machine as shown in figure 1; two of them (A, C) manufactured at same parameters but different lengths, where length of C= 200 mm and length of A= 100 mm to show the effect of the cylinder length on the dimensional error and on the number of sampling points. The same for cylinders (B, D) where length of B=100 mm and length of D=200 mm. the cutting parameters are shown in table 1.

**Figure 1:** The cylinder after machining
Table 1: Cylinders dimensions and manufacturing parameters

<table>
<thead>
<tr>
<th>Cylinder #</th>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>Depth of cut (mm)</th>
<th>Speed (rev/min)</th>
<th>Feed (mm/rev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100</td>
<td>30</td>
<td>2</td>
<td>480</td>
<td>0.164</td>
</tr>
<tr>
<td>B</td>
<td>100</td>
<td>30</td>
<td>2</td>
<td>700</td>
<td>0.141</td>
</tr>
<tr>
<td>C</td>
<td>200</td>
<td>30</td>
<td>2</td>
<td>480</td>
<td>0.164</td>
</tr>
<tr>
<td>D</td>
<td>200</td>
<td>30</td>
<td>2</td>
<td>700</td>
<td>0.141</td>
</tr>
</tbody>
</table>

The two Bell shape were manufactured by CNC Milling Machine (End milling) with 2 cutting tools. Each tool of specifications shown in Table 2 to show the effect of cutting tool length and its diameter on the dimensional error and the number of sampling points. For the two cutters, spindle speed and feed were the same (5000 rpm or at a feed rate of 40mm/min) to make workpiece number 1 and 2 of the bell shape.

Table 2: Tool Dimensions

<table>
<thead>
<tr>
<th>Tool Name</th>
<th>Tool Length(cm)</th>
<th>Diameter of cutter (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 ( 10 HSS )</td>
<td>9.5</td>
<td>0.85</td>
</tr>
<tr>
<td>T2 ( 8 HSS )</td>
<td>8.8</td>
<td>0.70</td>
</tr>
</tbody>
</table>

2.1 Cylindricity

Cylindricity measurement is specified as \( (r_i, \theta_i, z_i) \). If the axis of cylindrical feature is well aligned with the z-axis, then the deviations with reference to the assessment cylinder are given by:

\[
e_i = r_i - (R_o + x_o \cos \theta_i + y_o \sin \theta_i + l_i \cos \theta_i + m_i \sin \theta_i).
\]

Where \((x_o, y_o, z_o)\) refers to the center of the assessment sphere whose radius is \(R_o\). The least square method has been used to use cylindricity.

Based on cantilever beam theory which states that the deflection of a point on a cantilever beam is proportional to the distance the load applied, that is, the deflection of the beam due to the cutting load applied is maximum at the free end of the beam where the cutting load is applied. In the manufacturing processes, the deflection caused by the cutting load is also proportional to the distance from the fixed end and is maximum at the free end, deflections on this area are higher than those on the other regions figure 2.

In manufacturing process, many factors affect the overall manufactured part specifications and quality. Tool deflection is one of them. While the tool passes through the manufactured part, a force is affecting on the workpiece from the cutter and the same force is affecting on the cutter causing a cutter deflection. This causes a workpiece deflection too. So a dimensional error on the workpiece is presenting there as a result of the deflection of the workpiece and the cutter made.

Figure 2: FEA Model/Deflection of cutting tool.
This theory was the guide to derive more effective inspection strategies which focuses on those areas of manufactured parts that is expected to have the highest manufacturing errors (critical areas) instead of taking the whole part to inspect, which leads to minimizing the total number of points inspected and thus minimizing cost and time, increasing quality, and remove non added values as mentioned earlier.

3. Results and Discussion

Let \((\varphi, r_i, z_i)\) be the coordinates on the manufactured cylinder. The measurement plane is

\[
R_o + X_o \cos(\varphi) + y_o \sin(\varphi) + L_o z_i \cos(\varphi) + m_o z_i \sin(\varphi)
\]

This part was produced by lathe machine using the cutting parameters mentioned above. The Coordinate Measuring Machine (CMM) was used to inspect the part. To inspect the part a huge number of inspection point has been taken and then a surface fitting has been made to fit a reference surface to compare with. This huge number of points is around, for this sample, 385 points. This operation takes a lot of time and consumes a lot of energy. So smaller number of points is needed to minimize the time and cost and in the same time achieving a close tolerance zone to that we get when the whole surface is inspected.

The deviation \(e_i\) for each point is calculated by the following equation:

\[
e_i = r_i - (R_o + X_o \cos(\varphi) + y_o \sin(\varphi) + L_o z_i \cos(\varphi) + m_o z_i \sin(\varphi))
\]

To apply this equation, \(r_o, x_o, y_o, l_o\), and \(m_o\) were calculated using least square method.

The least square method has been applied to find \(x_0, y_0, l_0\), and \(m_0\) that equal to -0.978, 3.1619, 1.8128, -5.6327, 0.8292 respectively.

The deviation equation for this piece is:

\[
e_i = r_i - (0.8292 + 0.978 \cos(\varphi) + 3.1619 \sin(\varphi) + 1.8128 z_i \cos(\varphi) - 5.6327 z_i \sin(\varphi))
\]

A quality control is used to eliminate outlier points. The upper control limit (UCL) and lower control limit (LCL) based on \(\bar{X}\) chart have been calculated to compensate for measurement error from CMM. In order to calculate UCL and LCL the following equation has been applied:

\[
\text{UCL} = \bar{e} + 3\sigma \\
\text{LCL} = \bar{e} - 3\sigma
\]

\(\bar{e}\): the average deviation.
\(\sigma\): the standard deviation.

The average deviation \(\bar{e}\) is 4.97657E-05 and the standard deviation \(\sigma\) is 0.004351578, so the UCL and LCL are 0.0131045 and -0.013004968 respectively. Then we removed the deviation above 0.0131045 and below -0.013004968, after that we found that \(e_{\text{max}}\) and \(e_{\text{min}}\) are equal to 0.009240093 and -0.008111555 respectively, and \(h(t)_{\text{before}} = |e_{\text{max}}| + |e_{\text{min}}| = 0.017351648\).

Based on that, the number of inspection points has to be reduced to save time and cost. Those points have to be guided by the cantilever beam theory mentioned above. So the points will be dense on the area close to the free end of the cylinder. 97 points have been collected. The distribution of those points are shown in figure 3.
The same calculations of the inspection points before reducing the points have been made:

$$c_{\text{max}} = 0.008050207 , \ c_{\text{min}} = -0.00805557 \text{ and } h(t)_{\text{after}} = 0.016105777$$.

The percentage difference between the deviation for inspection points before elimination and after elimination is ($h(t)_{\text{before}} - h(t)_{\text{after}} / h(t)_{\text{before}}$) * 100% = 7.18%.

The percentage reduction of the number of inspection points after elimination and all inspection points is (385 - 97 / 385) * 100% = 74.8%. So the number of inspection points have been reduced by 74.8% to get a difference in a tolerance zone of 7.18%. The same calculations have been made for the other cylinders. Table 3 shows the percentage difference in number of points and in the tolerance zone.

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>No. of Population points</th>
<th>No. of sampling points</th>
<th>$h(t)_{\text{before}}$ (mm)</th>
<th>$h(t)_{\text{after}}$ (mm)</th>
<th>Percentage of difference in tolerance zone (%)</th>
<th>Percentage of reduction in inspection points (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>385</td>
<td>97</td>
<td>0.0174</td>
<td>0.0161</td>
<td>7.18</td>
<td>74.8</td>
</tr>
<tr>
<td>B</td>
<td>400</td>
<td>100</td>
<td>0.0237</td>
<td>0.0217</td>
<td>8.4</td>
<td>75</td>
</tr>
<tr>
<td>C</td>
<td>534</td>
<td>134</td>
<td>0.0176</td>
<td>0.0169</td>
<td>3.7</td>
<td>74.9</td>
</tr>
<tr>
<td>D</td>
<td>818</td>
<td>205</td>
<td>0.0270</td>
<td>0.0291</td>
<td>7.8</td>
<td>74.94</td>
</tr>
</tbody>
</table>

Figures 4, 5, and 6 show the distribution of the inspection points after applying cantilever beam theory. Those figures show that most of the inspection points are close to the free end of the cylinder being machined.
Figure 4: The regions have maximum error on the surface for cylinder B

Figure 5: The regions have maximum error on the surface for cylinder C
A bell shape, shown in figure 7 has been produced using end milling process to study the effect of the cutter length and diameter on the dimensional error. The cutting parameters used in cutting two pieces of bell shape are shown in table 2. The same procedure has been used to reduce the number of inspection points.

The same calculations have been made for the two pieces of bell shape. The results are shown in table 4.

<table>
<thead>
<tr>
<th>bell #</th>
<th>No. of Population points</th>
<th>No. of sampling points</th>
<th>( h_{\text{before}} ) (mm)</th>
<th>( h_{\text{after}} ) (mm)</th>
<th>Percentage of difference in tolerance zone (%)</th>
<th>Percentage of reduction in inspection points (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>394</td>
<td>131</td>
<td>0.0136</td>
<td>0.0172</td>
<td>1.6</td>
<td>66.75</td>
</tr>
<tr>
<td>2</td>
<td>1241</td>
<td>413</td>
<td>0.0332</td>
<td>0.0307</td>
<td>7.4</td>
<td>66.72</td>
</tr>
</tbody>
</table>
Figures 8 and 9 show the distribution of the points based on the cantilever beam theory.

**Figure 8**: The regions have maximum error on the surface for bell # A

**Figure 9**: The regions have maximum error on the surface for bell # A

4. Conclusion

The goal of our research is to reduce the number of inspection points for cylinders and bell shapes while maintaining almost the same tolerance zone, so the time and cost is reduced.

According to Cantiliver Beam Theory that states the maximum deflection on the cylinder being machined using lathe machine, occurs at the free end. Hence the maximum dimensional error can be expected to be at the free end of the cylinder being machined. So number of inspection points can be expected to be maximum at that region. The same thing can be said for the maximum deflection of the cutter used in cutting the bell shape. The cutter deflection will be maximum at the free end of the cutter, so maximum dimensional error can be expected to be at the bottom of the bell shape. Hence the
sampling points are expected to be dense close to that area. So, reduction in time and cost can be achieved using the sampling techniques used.

5. References


