Assessment of the impact of calculation methodologies on defect determinations in manufacturing

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Abstract: Many research works on methods to determine manufacturing defects have been developed. Obtained results from these studies can be used for improving product qualities. If manufacturing defects are classified according to causes of errors, it might include: machining defects (machine tool, cutting tool, tool-path, machining program), positioning defects (work-holder errors, datum errors (surface deviations from a previous setup), errors of contacts between work-piece and work-holder) [KV], thermal errors, and skill operation procedure of technicians, or it could be errors of calculation methods, which are used to determine the defects from measured data. In this article, impact of calculation methodologies on manufacturing defects is assessed. Firstly, the basic concept of calculation methods is presented. Secondly, different calculation methods used for determining manufacturing defects in an experimental application are proposed. Finally, influences of the different calculation methods on results are estimated.

Key words: machining defect, positioning defects, impact, calculation methodology, Small Displacement Torsor (SDT).

1- Introduction and literature review

In recent years, many research works on methods to determine manufacturing defects have been developed. Among the methods, their results can be used to predict sources of defects in order to improve product quality in fabrications. If the manufacturing defects are characterized according to causes of errors, it might be illustrated in figure 1. Model of Manufactured Part (MMP) [VV1, VV2, and VV3] that is proposed by Villeneuve and Vignat is used to simulate the manufacturing process in terms of deviation. This model can be used in tolerance analysis and synthesis. Manufacturing defects are considered using two independent components: machining and positioning deviation. In order to separate the machining and positioning dispersions, Tichadou et al. [TL] proposed a double measurement of the work-piece.

Considering errors of cutting tools, Larue et al. [LA] observed defects of cutting tool during flank milling, and calibration method are then used to minimize uncertainties of manufacturing. Besides, cutting parameter is also a factor affecting products, some experimental results are available, such as Sun et al. [SW] presented strategies and algorithm on how to select width of cut, feed rate and spindle speed; Beauchamp et al. [RM1] investigated effects of six independent variables (cutting speed, feed rate, depth of cut, tool nose radius, tool length and type of boring bar) on surface roughness in a lathe dry boring operation. In addition, Ramesh et al. [RM2, BC] focused on effects of geometric, cutting-force induced, fixture-dependent and thermal errors on accuracy of a machine tool. Geometric, kinematic are considered as a basic inaccuracy of a machine tool; or changes in temperature of the various machine elements are causes of increasing inaccuracy of machine tools; work-piece displacements on a fixture are also taken into account and could be reduced using tool-path compensation.

In general, manufacturing defects are determined using different calculation methods from measured data. Different calculation methods can give different results; consequently, proposed methods should be assessed to be able to choosing...
a suitable method. However, there are few studies on influences of calculation methods on obtained results in manufacturing. This article considers impacts of different methods that are used to determine manufacturing defects. Concretely, sensitivity of the calculation methods is shown in an experimental application.

2- Basis concept of calculation methods

The methods used for determining the manufacturing defects are based on the Small Displacement Torsor (SDT) concept, which has been developed since the seventies by Bourdet and Clément [BM, EB]. This concept is based on an assumption of small displacements of a rigid body. It allows solving a general problem of the fit of a geometrical surface model to a set of points. A SDT is represented using two vectors: vector R includes three small rotations \( r_x, r_y, r_z \) and vector L includes three small translations \( t_x, t_y, t_z \). Thank to the SDT concept, Villeneuve et al. [VV4] have extended to manufacturing process where machining deviations were obtained using measurement of relationships between a nominal part (perfect surfaces) and a real part. A SDT can be used to show different surfaces, for instance: two rotations and one translation (along a normal vector of a plane) in a SDT are used for plane, or two rotations and two translations (along two axes, which are perpendicular with cylinder axis) are used for a cylinder SDT, etc.

Let \((OXYZ)\) be the origin system of a plane, which has a normal vector along \(Z\). A SDT of this plane is expressed using three components, which are differences between an associated plane and a nominal plane (figure 2). The plane SDT is shown as in equation (1).

\[
T_{\text{plane}} = \begin{bmatrix} R & L \end{bmatrix}_{(O, X, Y, Z)} = \begin{bmatrix} r_x & 0 & 0 \\ r_y & 0 & 0 \\ r_z & 0 & 0 \end{bmatrix}
\]

(1)

According to this concept, SDTs of two machined planes and a SDT relation of two planes are obtained in the following experimental application.

3- Experimental application

A batch of 50 parts is machined using CNC machine (DMG-Deckel Maho DMU 50). Different defects can occur during a manufacturing process. In particular, the two following principal defects are considered in this study.

- A positioning variability of work-pieces on a fixture,
- A machining variability of machined parts,

Variability of positioning and machining are determined using the two following independent measurements.

- The first measurements are carried out inside a machine tool during machining.
- The second measurements are carried out on a CMM.

The drawing of a work-piece and a machined part are illustrated in figure 3. Two planes of a part, which is fixed on a fixture on the CNC machine, are machined using an end-mill (Ø20).

As previously mentioned, a double measure is carried out in order to determine the manufacturing defects. The first measurement (figure 4a) is carried out inside the CNC machine after machining without disassembly the machined part out of the fixture. A CMM (Mahr-Vision MS222) (figure 4b) is then used to measure 50 machined parts, which are marked in execution order from 1 to 50.
It is important to notice that a locating plane cannot be measured in the first measurement (CNC). Consequently, an OXY plane (a perfect plane) of a coordinate system of a machining/measuring programme (figure 5) is used to define a part’s coordinate system in this case. Conversely, a locating plane of a machined part can be measured using the CMM. Measured points of a cylinder and machined planes of each part are obtained for analysing positioning and machining defects.

4- Calculation methodologies

Here, three components in a SDT of each plane (two rotations around X and Y; one translation along Z) are obtained. The best-fit least-square method presented by Alistair [A] is used to reconstruct machined planes and a cylinder of a part from measured points, namely associated planes and associated cylinders.

Centroid of a machined plane (figure 6) is used as an origine of a reference frame for expressing a plane SDT. Therefore, centroids of machined planes are needed to identify.

SDTs of machined plane 1 and 2 are expressed in frames \( R_{o1} \) and \( R_{o2} \) as in equation (1).

\[
T_{PL1} = \begin{bmatrix}
    r_{x1} & 0 \\
    r_{y1} & 0 \\
    0 & t_{z1}
\end{bmatrix}_{(G_1R)} \text{ and } T_{PL2} = \begin{bmatrix}
    r_{x2} & 0 \\
    r_{y2} & 0 \\
    0 & t_{z2}
\end{bmatrix}_{(G_2R)}
\]

(1)

The two SDTs can be expressed in a frame \( R_O \) as in equations (2) and (3), where \( O \) is a centroid of a locating plane.

\[
\bar{D}_{O1} = D_{O1} + \bar{\Omega}_{O/R} \wedge G_1O
\]

(2)

\[
\bar{D}_{O2} = D_{O2} + \bar{\Omega}_{O/R} \wedge G_2O
\]

(3)

\[
\Rightarrow T_{PL1} = \begin{bmatrix}
    r_{x1} - d_{O1r_{x1}} \\
    r_{y1} - d_{O1r_{y1}} \\
    0 - \frac{3}{4} \pi R_{r_{x1}} + t_{z1}
\end{bmatrix}_{(O,R)}
\]

(4)

\[
\Rightarrow T_{PL2} = \begin{bmatrix}
    r_{x2} - d_{O2r_{x2}} \\
    r_{y2} - d_{O2r_{y2}} \\
    0 - \frac{3}{4} \pi R_{r_{x2}} + t_{z2}
\end{bmatrix}_{(O,R)}
\]

(5)

where \( d_{O1} \), \( d_{O2} \) are distances between machined planes 1, 2 and a locating plane.

Furthermore, relationships of machined plane 1 and 2 can be expressed using the following SDT (8).

\[
\Rightarrow T_{PL1+2} = \begin{bmatrix}
    r_{x1} - r_{x2} - d_{O1r_{x1}} + d_{O2r_{x2}} \\
    r_{y1} - r_{y2} - d_{O1r_{y1}} + d_{O2r_{y2}} \\
    0 - \frac{3}{4} \pi R_{r_{x1}} - t_{z1} - \frac{3}{4} \pi R_{r_{x2}} - t_{z2}
\end{bmatrix}_{(O,R)}
\]

(8)

It is important to emphasize that components of a SDT are variations of defects of 50 parts. Thus, translation and rotation defects of 50 machined parts are determined, and their variations are then obtained.

4.1 – Determination of rotation components

Two different coordinate systems defined for analysis defects are a coordinate system of machine (MCS) and a coordinate system of part (PCS) as in figure 7.

- MCS is defined using three axes of a machine (XYZ) and its origin is:
  - An intersection point of a cylinder and locating plane of the fixture (on the CNC machine),
  - A point that is moved along Z machine 15mm (radius of parts) from an intersection point of locating plane and an end-plane, which is perpendicular with part’s cylinder axis, of a V-block (on the CMM),

- PCS is defined as follows:
  - Z-axis is a work-piece’s associated cylinder axis.
  - X, Y are the same direction with X and Y machine.
4.2 – Determination of translation components

Three different methods are proposed in order to determine translation components of SDTs using the two coordinate systems (MCS and PCS).

4.2.1 – Projection ZM method

In this method, centroid of each associated plane is projected on the Z axis of the MCS (ZM) (figure 9.a). Variations of the projected points of plane 1 and 2 then are obtained. These are translation components of the SDTs of the two machined planes.

4.2.2 – Projection ZP method

Here, centroids of associated planes are projected on an associated cylinder axis in the PCS (ZP) (figure 9.b). The translation components of SDTs of the machined planes are variations of the projected points of plane 1 and 2.

4.2.3 – Intersection method

A point intersection of an associated plane and an associated cylinder axis is considered in the PCS (figure 9.c). Variations of these points are obtained as translation components of SDTs.

Some remarks are derived as follows:

- Results obtained on the CNC machine are machining defects. d₀₁ and d₀₂ are notations of translation defects of machined planes and plane 0 (locating plane). In this case, defects of locating plane equal zero.

- Results obtained on the CMM might include: machining defects of machined planes, contact defects between work-pieces and the fixture on the CNC machine, and defects of work-piece’s locating planes.

Hence, there are differences of the two above results (d₀₁, d₀₂), which are obtained using two different machines. Relationships of two machined planes are estimated using a deviation d₁₂.

4.3 – Presentation of results

The following results show components of SDTs, which its rotation defects are determined using only one method, while translation defects are determined using three different methods.

4.3.1 – Rotation components

Rotation components of SDTs in table 1 are obtained using measurements on the CNC machine and the CMM.

<table>
<thead>
<tr>
<th>Name</th>
<th>fₓ₀</th>
<th>fᵧ₀</th>
<th>fₓ₁</th>
<th>fᵧ₁</th>
<th>fₓ₂</th>
<th>fᵧ₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNC</td>
<td>-</td>
<td>-</td>
<td>5.529</td>
<td>4.546</td>
<td>5.568</td>
<td>4.969</td>
</tr>
<tr>
<td>s (rad⁻¹)</td>
<td>×10⁻³</td>
<td>×10⁻³</td>
<td>×10⁻³</td>
<td>×10⁻³</td>
<td>×10⁻³</td>
<td></td>
</tr>
<tr>
<td>CMM</td>
<td>30.386</td>
<td>30.312</td>
<td>6.152</td>
<td>5.716</td>
<td>6.004</td>
<td>5.554</td>
</tr>
<tr>
<td>s (rad⁻¹)</td>
<td>×10⁻³</td>
<td>×10⁻³</td>
<td>×10⁻³</td>
<td>×10⁻³</td>
<td>×10⁻³</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Rotation components (in the PCS)

*: Standard deviation; **: Variance, --: undetermined values

As it can be seen, differences of variances (fₓ₁, fᵧ₁; fₓ₂, fᵧ₂) from the two different machines are insignificant. However, variances of rotation defects (fₓ₀, fᵧ₀) obtained on the CMM are greater than machining defects (fₓ₁, fᵧ₁; fₓ₂, fᵧ₂). In other
words, the positioning defects are significant; consequently these defects are taken into account in calculations of translation components.

4.3.2 - Translation components

As it is mentioned, influences of calculation methods as well as positioning defects are assessed using the following results. In this present study, influence of measuring machines is not taken into account. However, noise measurements are verified and these are insignificant.

1- “Rough” results of measurements on the CNC machine and results of measurements on the CMM

Figure 10 represents the results obtained on the CNC machine. The results show translation variations of the two machined planes ($s^2_{d01}$, $s^2_{d02}$) and the work-piece’s locating planes (planes 0). As it is mentioned in the section 3, variations of the work-piece’s locating planes equal zero ($s^2_0 = 0$).

![Figure 10: Translation components by measurements on the CNC machine (Intersection method)](image)

![Figure 11: Translation components by measurements on the CMM (Intersection method)](image)

Table 2: Translation defects

<table>
<thead>
<tr>
<th>Translation defects</th>
<th>d01</th>
<th>d02</th>
<th>d12</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Name</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Projection Z_m method</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CNC</td>
<td>$4.25 \times 10^{-5}$</td>
<td>$3.15 \times 10^{-5}$</td>
<td>$4.352 \times 10^{-5}$</td>
</tr>
<tr>
<td>CMM</td>
<td>$3.54 \times 10^{-5}$</td>
<td>$4.54 \times 10^{-5}$</td>
<td>$3.016 \times 10^{-5}$</td>
</tr>
<tr>
<td>Projection Z_p method</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CNC</td>
<td>$3.13 \times 10^{-5}$</td>
<td>$1.04 \times 10^{-5}$</td>
<td>$3.450 \times 10^{-5}$</td>
</tr>
<tr>
<td>CMM</td>
<td>$4.36 \times 10^{-5}$</td>
<td>$4.78 \times 10^{-5}$</td>
<td>$4.09 \times 10^{-5}$</td>
</tr>
<tr>
<td>Intersection method</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CNC</td>
<td>$4.11 \times 10^{-5}$</td>
<td>$4.95 \times 10^{-5}$</td>
<td>$7.72 \times 10^{-5}$</td>
</tr>
<tr>
<td>CMM</td>
<td>$4.29 \times 10^{-5}$</td>
<td>$4.13 \times 10^{-5}$</td>
<td>$7.84 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Table 2 shows variances of translations of 50 parts. These variances are obtained using the three different methods on the two different machines.

Two planes of a part are machined using two different machining processes and different tool paths. In other words, the two processes are independent. Consequently, machining defects obtained are independent. These are verified by the following step.

a) Verification of relations:

According to properties of variance and covariance in probability theory and statistics, two random variables whose covariance is zero are called uncorrelated. These apply to the results of measurements on the CNC machine in order to verify relations of two variables ($s^2_{d01}$, $s^2_{d02}$). If the two variables are independent, then their relations can be shown as in equation (11).

$$s^2_{d12} = s^2_{d01} + s^2_{d02}$$  \hspace{1cm} (11)

The results obtained on the CNC machine are verified using equation (11), but they are not satisfied. Moreover, figure 10 shows that the translation defects of the two machined planes increase together during machining times (from the 1st part to the 50th part). It means that these defects are dependent. It could be due to temperature variations, which are not taken into account in the present study. In addition, the spindle of the CNC machine has not a thermal compensation device. Consequently, these drift should be corrected. In a previous study [SD], results show that evolution of temperature depends on measuring times.

In general, a measurement error has two components: random and systematic. The random component causes a spread in the results of measurement, whereas the systematic
component causes a bias in the results. The drifts of \(d_{01}\) and \(d_{02}\) in figure 10 are systematic errors. Consequently, these should be corrected.

b) Differences of the results on the two different machines:

It can be seen that differences between variances of the machined planes on the CMM and the CNC machine are significant (figures 10, 11 and table 2). These can be explained by the two following sources:

- Positioning defects of work-pieces on the fixture in the CNC machine,
- Defects of locating planes of work-pieces (plane 0).

These two points will be detailed later.

c) Differences of the results on the same machine:

Results obtained on the same machine with the three methods are differences. Thus, influences of the methods on the obtained results are significant. A sensitivity of these methods will be considered in the section later.

2- Correction of the “rough” results on the CNC machine

As the previous conclusions, the results obtained on the CNC machine are corrected using systematic components. These components are determined using trendlines of measured data.

\[
d_{\text{corr}}^k = d_{\text{meas}}^k - \delta_i^k
\]

where \(d_{\text{meas}}^k\) is a translation defect of the machined plane \(i\) of the \(k\)th part.

\(d_{\text{corr}}^k\) is a translation defect of the machined plane \(i\) of the \(k\)th part after correction.

\(\delta_i^k\) is a drift of the machined plane \(i\) of the \(k\)th part. This is calculated using a power equation as follows:

\[
\delta_i^k = a_k m^k
\]

\(k\) is a part number \((1, 50)\).

a) Verification of relation:

In table 3, translation defects are corrected using the systematic components.

\[
\begin{align*}
&\text{Corrected translation defects} \\
&\begin{array}{|c|c|c|c|}
\hline
\text{Name} & \text{d01} & \text{d02} & \text{d12} \\
\hline
\text{Projection ZM method} & \begin{array}{c}
\text{CNC} \\
0.741 \\
1.195
\end{array} & \\
& \begin{array}{c}
0.454 \\
1.0 \times 10^{-3}
\end{array} & \\
& \begin{array}{c}
1.0 \times 10^{-3} \\
1.0 \times 10^{-3}
\end{array} \\
\hline
\text{CMM} & \\
20.44 & \\
20.30 & \\
10 \times 10^{-3} & \\
\hline
\text{Projection ZP method} & \begin{array}{c}
\text{CNC} \\
3.049
\end{array} & \\
& \begin{array}{c}
2.887 \\
5.936
\end{array} & \\
& \begin{array}{c}
10 \times 10^{-3} \\
10 \times 10^{-3}
\end{array} \\
\hline
& \begin{array}{c}
20.32 \\
20.24
\end{array} & \\
& \begin{array}{c}
10 \times 10^{-3} \\
10 \times 10^{-3}
\end{array} & \\
\hline
\text{Intersection method} & \begin{array}{c}
\text{CNC} \\
0.711
\end{array} & \\
& \begin{array}{c}
0.499 \\
1.209
\end{array} & \\
& \begin{array}{c}
10 \times 10^{-3} \\
10 \times 10^{-3}
\end{array} \\
\hline
& \begin{array}{c}
20.39 \\
20.96
\end{array} & \\
& \begin{array}{c}
10 \times 10^{-3} \\
10 \times 10^{-3}
\end{array} & \\
\hline
\text{Projection ZM method} & \begin{array}{c}
\text{CNC} \\
5.490
\end{array} & \\
& \begin{array}{c}
2.065 \\
7.555
\end{array} & \\
& \begin{array}{c}
10 \times 10^{-3} \\
10 \times 10^{-3}
\end{array} \\
\hline
& \begin{array}{c}
41.78 \\
41.19
\end{array} & \\
& \begin{array}{c}
10 \times 10^{-3} \\
10 \times 10^{-3}
\end{array} & \\
\hline
\text{Projection ZP method} & \begin{array}{c}
\text{CNC} \\
0.93
\end{array} & \\
& \begin{array}{c}
0.834 \\
1.763
\end{array} & \\
& \begin{array}{c}
10 \times 10^{-3} \\
10 \times 10^{-3}
\end{array} \\
\hline
& \begin{array}{c}
41.28 \\
45.11
\end{array} & \\
& \begin{array}{c}
10 \times 10^{-3} \\
10 \times 10^{-3}
\end{array} & \\
\hline
\text{Intersection method} & \begin{array}{c}
\text{CNC} \\
5.049
\end{array} & \\
& \begin{array}{c}
2.485 \\
7.354
\end{array} & \\
& \begin{array}{c}
10 \times 10^{-3} \\
10 \times 10^{-3}
\end{array} \\
\hline
& \begin{array}{c}
41.58 \\
43.91
\end{array} & \\
& \begin{array}{c}
10 \times 10^{-3} \\
10 \times 10^{-3}
\end{array} & \\
\hline
\end{array}
\end{align*}
\]

Table 3: Corrected translation defects

After correction, the results of two methods (projection \(Z_{\text{M}}\) and intersection method) are satisfied, therefore the corrections of a systematic component are necessary.

b) Differences of the results on the same machines:

Despite the systematic correction, there are still differences of the obtained results by the methods. It means that influences of the methods are significant.

c) Differences of the results on two different machines:

The systematic component corrections are not sufficient to obtain similar results by two different machines. Hence, the two factor effects (plane 0 and positioning defects of work-pieces) will be considered in the next section.

3- Influence of positioning defects on the translation components

In order to quantify a sensitivity of the calculation methods and positioning defects (on the CNC machine), correlation coefficients of the translation defects and rotation defects of the work-pieces on the fixture are obtained as in table 4.

\[
\text{Correlation coefficients}
\]

\[
\begin{align*}
\text{Name} & & \text{RotCyl of Projection ZM method} & & \text{RotCyl of Projection ZP method} & & \text{RotCyl of Intersection method} \\
\hline
\text{d01} & & 0.38 & & 0.47 & & 0.50 \\
\text{d02} & & 0.18 & & -0.41 & & -0.07 \\
\text{d12} & & 0.21 & & 0.47 & & 0.49 \\
\hline
\end{align*}
\]

Table 4: Correlation coefficients

The results show that all the correlation coefficients are less than or equal to 0.5. It means that relationships between the translation defects and positioning defects are weak. Thus, the influences of positioning defects on the calculations of translation components are insignificant.

4- Influence of locating planes on the translation components

The workpiece’s locating planes are used to establish the LCSs, which are used to obtain defects. Thus, these planes can influence the obtained results. The following table (5) shows correlation coefficients of translation defects and the rotation defects of these planes.

\[
\text{Correlation coefficients}
\]

\[
\begin{align*}
\text{Name} & & \text{Rot0 of Projection ZM method} & & \text{Rot0 of Projection ZP method} & & \text{Rot0 of Intersection method} \\
\hline
\text{d14} & & -0.03 & & -0.01 & & -0.09 \\
\text{d20} & & -0.15 & & -0.16 & & -0.08 \\
\text{d12} & & 0.31 & & 0.34 & & -0.07 \\
\hline
\end{align*}
\]

Table 5: Correlation coefficients

It can be seen that the correlation coefficients are small. Therefore, influence of the workpiece’s locating planes is insignificant on the translation defects.

5- Conclusions

As examination of experimental results, the calculation methodologies strongly influence the measurement
results. Conversely, effects of the work-piece’s geometrical errors and the positioning defects on the calculations of translation defects are insignificant.

This study presents that choice of numerical analysis methods for identification defects can influence on quality of measurement results. Therefore, data analysis methods are important in controlling product quality.

The results also indicate that, in some experiments, the measurement variability is a sum of a random dispersion and a systematic dispersion. Then the systematic component should be corrected in order to retain only the random component.

This study deal with the problem of relative position of two parallel planes. This seems trivial, but it has not been analysed.

6- References


