RESEARCH ARTICLE

A FULL METHOD FOR OPTIMIZING THE QUALITY OF MANUFACTURING BY CNC MACHINE-TOOL.

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Abstract

In the steering methods of CNC machine tool presented in the literature, none use both the geometry and the cutting parameters to adjust the machine. In the steering methods of machine that we previously presented in our works, we always use an incidence matrix built from linear relationships between a collection of geometric deviations and a collection of correctors available in numerical control (NC). This matrix makes it possible to find the adjustment to be made on the tools which guarantees the geometric quality of the workpiece. Now, more and more machine tools are monitored by sensors (vibration, temperature, load, ...), and it is interesting to watch how we can connect this new collection of parameters to another new collection of possible corrections which would be the feeds, the speeds, the depths of pass, ... In this article, we present new feeds in the field of steering taking into account the relations between new collections of parameters which are, the load, the torque and the feed rate. It is possible to determine from an experimental assembly the linear relationships that exist between these new collections of parameters to apply a more "global incidence matrix". If we know the measurement of the parameters obtained thanks to the experimental assembly and the measurement of the geometry of the part, it is then possible to find a more global setting which optimizes the whole of the process on all the parameters and to get the best quality possible regardless of the complexity of the part.

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Introduction:-

Due to the origins of the very complex and very varied manufacturing uncertainties related to the part/tool/machine system, several researchers have worked to try by different ways to maintain the quality of the processes. Some authors such as Sergent et al., 2010 Tichadou et al., 2007 have attempted to solve the problem of machining defects, by modeling the machining defects by torsors of small displacements presented by Clement and Bourdet, 1988. Others authors, such as Girardin, 2010, sought instead to model the dynamic behavior of the machining system in the case of milling, and used a frequency analysis of the cutting force to monitor the machining process. Similar work in monitoring of the machining by monitoring of tool wear has been done by Huseyin et al., 2004, and monitoring of
tool wear by acoustic emissions has been done by Marinescu et al., 2008, and even work on monitoring of tool wear by electric power has been done by Faleh et al., 2005.

Many other problems with the part / tool / machine system persist, such as the setting of manufacturing process. In this subject, several authors have published approaches to effectively steer the process. Due to the very approximate initial setting of the tools, Kibe et al., 2007 proposed to adjust the initial position of the tools using an in-situ measurement. The authors Bourdet, 1982 and Anselmetti and Bourdet, 1993 have shown that if we can act on the correctors of the machine to reduce the difference between the theoretical part and the machined part, it can also be reduced by acting on the optimal dimensions chosen intelligently. The authors Goldschmidt 2009 and Pairel et al., 2011 implemented the Copilot-Pro® methodology that allows the adjustment of all cutting tools, including roughing tools. Their method determines the “range of setting” or the “range of monitoring” in a manufacturing step and allows determining the manufacturing dimensions to be measured to adjust a maximum of cutting tools per step.

There are methods in the literature to determine the manufacturing dimensions necessary for the good adjustment of the machine, but the methods proposed by Goldschmidt 2009 and Pairel et al., 2011 differs in that because these dimensions are determined taking into account the constraints related to manufacturing process. The authors Goldschmidt et al., 2007, and Boukar et al., 2012, conscious of the interest offered by the geometric tolerancing to ensure the conformity of the products, exploited this tolerance for setting the machines. Pillet et al., 2014 proposed a multivariate setting approach using both Hotelling’s T² and an incident matrix between the tool correctors and the points probed on the part. However, his method is limited only to the use of column information of the incidence matrix. Pairel et al., 2014 also presented a multivariate setting approach using a linear program. He showed that we can optimize the setting by optimizing a parameter of distance introduced in the program. Work on the matrix setting approach of machines has been conducted in particular by Boukar et al., 2014; Boukar et al., 2015; Boukar et al., 2017; Pillet and Pairel 2011 in the context of inertial tolerancing introduce by Pillet, 2001.

In this article, we propose an extension of the inertial steering method that we previously proposed by going beyond the geometrical parameters of the part to steer the machine. In addition to steering the geometrical parameters, we introduce the control of the cutting force and the torque measured from an experimental assembly.

**Input / Output System**

The quality of the machining depends on the correct configuration setting between the input and output parameters, that is to say on the one hand, between the dynamic parameters (load, torque, ...) and the cutting parameters (depth of pass, feed per revolution, cutting speed, ...) and on the other hand, between the adjustment parameters of the numerical control and the geometry parameters of the part. Figure 1 shows a systemic view of the production system. In this system, we measured δ at the output (δ is a centering between the target and the measured value) + a variability σ. The goal of the steering is to eliminate, if not to reduce as much as possible the centering and to control the variability.

![Systemic view of a production system](image-url)
To present this work, we base ourselves on the case of drilling of a part chosen voluntarily simple to present the approach. Five (5) holes of 10 mm in diameter are made equidistantly along a circumscribed circle in the part (see Fig. 2). The holes were made on XC48 steel of 40 mm in diameter. The depth \( h \) of the hole is \( h = 12 \) mm. Figure 2 shows the drilling geometry.

**General’s tolerances ISO 2768 m-k**

![Drawing definition of the part](image)

**Steering Methods**

Steering by the geometry of the part

The drilling surfaces are generated by the same drill. This drill can be adjusted by acting on its axial position corrector \( T_z \) (along the Z axis) which adjusts the position of the \( h \) depth of the hole. Its radius corrector (\( R \)) is not corrected. If the drill is worn, it is either sharpened or replaced. Similarly, the angular offset is not corrected, it is an editable parameter in the program. Anyway, displacement variables \( T_x \) (translation along the X axis) and \( T_y \) (translation along the Y axis) are introduced into the program to allow the machining reference to be repositioned on the part reference to refocus the machined shapes on their targets (Fig. 3).

Thus, to correct the machining we acts on \( T_x \), \( T_y \) and \( T_z \). The difference between the target surfaces and the machined surfaces is measured at several points by distances following the normal of the points of the surfaces. Thus, we arbitrarily decided to measure five points on each hole (four on the sidewall that positions the shapes on the circle and one on the bottom that allows correcting the depth of the hole).

![Representation of the target holes and offsetting machined holes](image)

Table 1 gives the coordinates of the probed points and the components of the local normals expressed in the part reference as well as the deviations measured at these points according to the normals (column \( e^0_i \)).

| Point | X  | Y  | Z   | ai | bi | ci | \( e^0_i \) |
|-------|----|----|-----|----|----|----|------------|
| P1    | 19 | 0  | -4  | -1 | 0  | 0  | -0.1818    |
| P2    | 14 | 5  | -4  | 0  | -1 | 0  | -0.1807    |
| P3    | 9  | 0  | -4  | 1  | 0  | 0  | 0.1847     |
| P4    | 14 | -5 | -4  | 0  | 1  | 0  | 0.2106     |
To steer the machining by the drill, we use the approach of Total Inertial Steering presented by Boukar et al., 2014 which makes it possible to establish and to use the direct link between the correctors and the position of the machined surfaces defined in a reference linked to the machine. So we use all the raw information on the points without going through a geometric parameter by dimension which makes us lose the precision of setting. If we consider \(\mathbf{e}_{n,1}^0\) the matrix of initial deviations measured on the points and \(\mathbf{e}_{n,1}^1\) the matrix of the next deviations (after setting) on these points. The goal of the setting is to find the offset to be made on the points to minimize \(\mathbf{e}_{n,1}^1\). This results in the relation of equation (1):

\[
\mathbf{e}_{n,1}^1 = \mathbf{e}_{n,1}^0 + \mathbf{d}_{n,1} \tag{1}
\]

With \(\mathbf{d}_{n,1}\) : matrix of offset on \(n\) points

The offsets on the points are computed by the method of small displacements proposed by Bourdet et al., 1988 which consists in calculating the translation of the real point according to the displacement \(\{\mathbf{D}(O), \mathbf{D}(O)\}\) of the trajectory of the tool relative to the part (equation 2):

\[
d_i = \mathbf{D}(\mathbf{P}_i) \cdot \vec{n}_i \tag{2}
\]

This is expressed by:

\[
\mathbf{D}(\mathbf{P}_i) \cdot \vec{n}_i = \left(\mathbf{D}(O) + \vec{n} \wedge \mathbf{OP}_i\right) \cdot \vec{n}_i
\]

Where, \(O\) is the origin of the reference of trajectory of the tools and rotations \(R_x, R_y\) and \(R_z\), respectively around the \(X, Y\) and \(Z\) axes. The development of equation (2) gives equation (3):

\[
d_i = a_i T_x + b_i T_y + c_i T_z + L R_x + M R_y + N R_z \tag{3}
\]

With:
- \(a_i, b_i, c_i\): direction cosines of the local normal \(n_i\) to the target surface;
- \(L, M, N\): components of the vector \(\mathbf{OP}_i \wedge \vec{n}_i\);
- \(T_x, T_y, T_z\): translation respectively along \(X, Y\) and \(Z\) axes;
- \(R_x, R_y, R_z\): rotations along \(X, Y\) and \(Z\) axes.

Since for the part, only \(T_x, T_y\) and \(T_z\) are corrected, equation (3) is simplified and becomes (4):

\[
d_i = a_i T_x + b_i T_y + c_i T_z \tag{4}
\]
This equation can be written in the following matrix form (see equation 5):

\[ [d_{n,1}] = [m_{n,p}] \cdot [c_{p,1}] \]  

(5)

With:
- \([m_{n,p}]\): matrix of incidence of the correctors on the points (n lines, p columns);
- \([c_{p,1}]\): matrix of corrections on the correctors (p rows, 1 column).

The adjustment consists of making an offset opposite to the initial deviation to cancel the deviation of each point and to bring back the machined surfaces on their target. This gives for all the points the following matrix system (6):

\[ [-e_{n,1}^0] = [m_{n,p}] \cdot [c_{p,1}] \]  

(6)

This matrix system (with 25 rows and 3 columns) has no exact solution because the number of points (n = 25) is greater than the number of correctors (p = 3). The multi-linear regression then makes it possible to obtain the values of \( T_x \), \( T_y \) and \( T_z \) which minimize the sum of the squares of the next offsets. It consists in its simplest presentation, to multiply the matrix of initial deviations \( [e_{n,1}^0] \) by the pseudo-inverse \( [m_{n,p}]^+ \) of the incidence matrix according to equation (7):

\[ [c_{p,1}] = [m_{n,p}]^+ \cdot [-e_{n,1}^0] \]  

(7)

With:
- \([m_{n,p}]^+ = ([m_{n,p}]^T \cdot [m_{n,p}])^{-1} \cdot [m_{n,p}]^T\)

Knowing the deviations of the points reported in Table 1, we obtain the values of \( T_x = 0.188 \), that of \( T_y = 0.193 \) and that of \( T_z = 0.191 \) which minimize the geometric differences on the next piece. The corrections obtained make it possible to estimate the new deviation values on the next part thanks to equation 8.

\[ [e_{n,1}^1] = [e_{n,1}^0] + [m_{n,p}] \cdot [c_{p,1}] \]  

(8)

Figure 7 presented below shows the deviations before and after adjustment of the geometry.

**Steering by cutting parameters**

To take into account the loads and the cutting conditions in the incidence matrix, measurements are made using an experimental assembly.

**Experimental assembly for measuring cutting force and torque**

For drilling, we used a DECKEL MAHO milling center: DMC 635V and a HSS drill ("High Speed Steel") without cutting in the center. Figure 4 shows the machining assembly of the part.

![Machining assembly of the workpiece](image)

The steel sections are placed and tightened between the 3 jaws of the vice. Then the depth between the top of the test part and the base is measured with vernier caliper in order to perform the offset of the machine and to inform the position of its origin (0, 0, 0).

**The acquisition chain**

The input parameters that we measure experimentally are the cutting force \( F \) and the torque \( C \). The measurement of the loads (\( F \) and \( C \)) is carried out by an acquisition chain consisting of four (4) main elements (1-Dynamometer, 2-charge amplifiers, 3-multimeters, 4-card and PC-based processing software) shown in Figure 5. The acquisition system used is the UNIGOR SET 304 PC.
The well-known setting parameters for the drill operation are the cutting speed and the feed per revolution. The cutting speed characterizes the relative speed between the workpiece and the tool at the point of contact, while the feed per revolution naturally characterizes the state of surface obtained (see Chibane et al., 2011).

During machining, the cutting speed was set at 10 m/min and the values of the cutting force and the torque were measured by varying the spindle feed rate and the depth of the hole h = 4, +2, +2, +2, +2 (= 12 mm). The program allows recovering the values of the force and the torque provided by the machine. These values are given in Volt thanks to the amplifiers, a coefficient of 20000 to obtain the torque in (N.mm) and 5000 for the force in (N) as given in Table 2.

**Table 2**: Measures of cutting force and torque according to the feed rate.

| f (mm/rev) | F (Volt) | C (Volt) | 5000 | 20000 |
|------------|----------|----------|------|-------|
| 0,080      | 0,294    | 0,075    | 1470,000 | 1500,000 |
| 0,100      | 0,316    | 0,097    | 1580,000 | 1940,000 |
| 0,125      | 0,353    | 0,112    | 1765,000 | 2240,000 |
| 0,160      | 0,397    | 0,126    | **1985,000** | **2520,000** |
| 0,200      | 0,412    | 0,139    | 2060,000 | 2780,000 |

Figure 6 shows the influence of the feed rate on the cutting force and torque provided by the machine. The cutting force and the torque increase according to the feed rate, which requires a better adjustment of the latter.

**Relationship of dependence between cutting force, torque and feed rate**

The relationships between cutting force, torque and feed rate in the case of drilling are given respectively by equation (9) for the cutting force and by equation (10) for the torque:
With:

\( f \): spindle feed rate (mm / rev).
\( d \): tool diameter (mm).
\( K_{cc} \): specific cutting force coefficient (N / mm²)
\( K_{ca} \): specific axial force coefficient (N / mm²)

Equations (9) and (10) can respectively be simplified by the following equations (11) and (12):

\[
F = K_{ca} \cdot f \cdot d \\
C = K_{cc} \cdot f \cdot d^2
\]  

(9)  
(10)  

(11)  
(12)

Where \( K_1 = K_{ca} \cdot d \), and \( K_2 = K_{cc} \cdot d^2 \)

The specific force coefficient \( K_{ca} \) and \( K_{cc} \) indicate the criterion of machinability of the material, they vary according to the cutting parameters and the geometry of the section. In our case, these parameters were determined experimentally as a function of the feed rate for a diameter of 10 mm, for the drill HSS (see Table 3).

Table 3: Specific cutting forces according to the feed rate

| \( f \) (mm/rev) | \( D \) (mm) | \( K_{ca} \) (N/mm²) | \( K_{cc} \) (N/mm²) |
|-----------------|------------|---------------------|---------------------|
| 0.080           | 10         | 2056.25             | 480                 |
| 0.100           | 10         | 1745                | 460                 |
| 0.125           | 10         | 1544                | 430.4               |
| 0.160           | 10         | 1303.13             | 381.25              |
| 0.200           | 10         | 1107.5              | 338                 |

Global Optimization Of Manufacturing

The overall setting of the machine involves both the adjustment of the workpiece geometry and the setting of the cutting condition for overall optimization of production. The "overall" incidence matrix between deviations of the points probed on the part and the tool correctors, on the one hand, and between the loads and the feeds, on the other hand, can be expressed by the following matrix relation (see equation 13):

\[
\begin{bmatrix}
-e_{n1}^0 \\
-F_{i1} \\
-C_{i1}
\end{bmatrix} =
\begin{bmatrix}
\mathbf{m}_{n1} & 0 & 0 \\
0 & \mathbf{K}_{11} & 0 \\
0 & 0 & \mathbf{K}_{21}
\end{bmatrix}
\begin{bmatrix}
f_{i1}
\end{bmatrix}
\]

(13)

With:

\( \mathbf{F}_{i1} \) = Matrix of cutting forces
\( \mathbf{C}_{i1} \) = Matrix of torques
\( \mathbf{f}_{i1} \) = Matrix of feed per revolution.

\( \mathbf{K}_{11}, \mathbf{K}_{21} \) = respectively, Matrices of the specific axial force coefficients and specific cutting force coefficients.

Discussions:-

Determination of the best feed adjustment

The overall optimization of the process is done on all the collections of parameters. The approach for optimization by geometry is presented in section III (in point A), which is simply reported its incidence matrix in the "Overall" incidence matrix obtained by equation 13 (see Table 4). As for the geometry parameters, the measured values of \( F, C, K_1 \) and \( K_2 \) are also reported in the "Overall" incidence matrix that is given in Table 4.

Table 4: "Overall" Incidence Matrix

| Tool offsets | Feed per revolution |
|--------------|---------------------|
| \( T_X \)    | \( T_Y \)  | \( T_Z \)  | \( f_1 \) | \( f_2 \) | \( f_3 \) | \( f_4 \) | \( f_5 \) |
This matrix contains 35 rows and eight (8) columns, so it is not invertible. The system does not have an exact solution. The pseudo-inverse of Gauss given by the equation 14 thus makes it possible to find an approximate solution of setting of the values of the correctors and feeds which optimizes at the best the production.

\[
\begin{pmatrix}
c_{\text{p},1} \\
[e_{\text{f},1}]
\end{pmatrix} = \begin{pmatrix}
[m_{\text{n},p}]^+ & 0 & 0 \\
0 & [K_{1i}]^+ & 0 \\
0 & 0 & [K_{2i}]^+
\end{pmatrix} \begin{pmatrix}
-e_{\text{p},1} \\
-F_{\text{f},1} \\
-C_{i,1}
\end{pmatrix}
\]  

(14)

With:

\[ [m_{\text{n},p}]^+ = ([m_{\text{n},p}]^T [m_{\text{n},p}])^{-1} [m_{\text{n},p}]^T \]
\[ [K_{1i}]^+ = ([k_{1i}]^T [K_{1i}])^{-1} [k_{1i}]^T \]
\[ [K_{2i}]^+ = ([k_{2i}]^T [K_{2i}])^{-1} [k_{2i}]^T \]

Knowing the deviations measured on the points, the measured cutting forces and the torques reported in Table 4, we obtain the values of the adjustment parameters given in Table 5.

**Table 5**: Values of the adjustment parameters to be made

| Tool offsets | Feed per revolution |
|--------------|---------------------|
| Tx | Ty | Tz | f1 | f2 | f3 | f4 | f5 |
| -0.188 | -0.193 | -0.191 | 0.037 | 0.048 | 0.059 | 0.075 | 0.092 |
The corrections obtained make it possible to estimate the new deviation values on the next workpiece which is calculated by equation 8 and the next values of cutting forces and torques given in Table 6.

Figure 7 shows the deviations before and after adjustment of the geometry. It is also noted in this figure that the geometric deviations after adjustment have been greatly reduced and therefore we have a better quality of the part.

![Fig 7: Representation of the measured deviations before and after adjusting the machine](image)

Table 6 gives the values of cutting forces and torques before and after adjustment according to the feed rate.

| Before adjustment | After adjustment |
|-------------------|------------------|
| f (mm/rev) | Cutting force (N) | Torque (N.mm) | f (mm/rev) | Cutting force (N) | Torque (N.mm) |
| 0.080 | 1470 | 1500 | 0.037 | 699,123 | 299,494 |
| 0.100 | 1580 | 1940 | 0.048 | 737,881 | 279,913 |
| 0.125 | 1765 | 2240 | 0.059 | 851,810 | 305,575 |
| 0.160 | 1985 | 2520 | 0.075 | 1006,108 | 343,892 |
| 0.200 | 2060 | 2780 | **0.092** | **1037,688** | **340,012** |

It can be seen here that the cutting force and the torque increase according to the feed rate. The question is to determine among the configurations of feed rate obtained for the adjustment, which is the best solution of adjustment of the feed rate to use for the machining of the part?

The authors Chibane et al. 2011 and Dib et al. 2015 seeking to optimize the cutting parameters have shown that the most influential parameter on the surface quality of the workpiece is the feed rate, followed by tool nose radius presented by Dib et al. 2015, or depth of pass and output of the tool presented by Chibane et al. 2011. They show that when the feed rate is high, the surface quality is better. Too much feed rate increases the force and may damage the cutting tool. Too little feed rate tends to degrade the surface quality of the part. On the one hand, on their work, and on the other hand, on the result obtained given in Table 6, we retain the value of **0.092 mm/rev** calculated by the incidence matrix for the machining of this part. Because, it seems to be a compromise between the experienced feeds of **0.08 mm/rev** and **0.100 mm/rev**.

**Possibility Of Monitoring The Cutting Force By The Shewhart Control Chart**

Knowing the values of the fixed feeds, the cutting force and the torque, it is interesting to monitor the cutting force to avoid a sudden increase in its value which would be due for example to the tool wear which disturbs the process. To this end, a “Shewhart control chart” presented by Shewhart, 1931 is designed to judge the importance of variability. It is considered that the process is under control if it is subjected only to random variations (sum of small variations which with the central limit theorem lead to a distribution law of Gauss). In this case it is not necessary to intervene on the process. The zone of random variation is determined by the "control limits". These control limits...
are traditionally set within ±3σ of the target value, so we take a risk α = 2 x 0.135% = 0.27% of disrupting a well-centered process. The control limits are calculated for n = 1, by equation 15:
\[
\begin{align*}
\text{LCL}_F &= \text{cible} - u_\alpha \sigma \\
\text{UCL}_F &= \text{cible} + u_\alpha \sigma
\end{align*}
\]  
(15)

With \( u_\alpha = 3 \), standard Gauss variable for the risk \( \alpha = 0, 27\% \)

LCL\(_F\): Lower control limit of cutting force.
LCS\(_F\): Upper control limit of cutting force.

The Shewhart control chart amounts to considering that the cutting force is negligible within the control limits. The standard deviation is to be estimated by measuring the cutting force on some machined parts. If we consider that the standard deviation is equal to 10 Newton for example, the limits of control of the cutting force for the feed rate chooses of 0.092 mm/rev are calculated:
\[
\begin{align*}
\text{LCL}_F &= \text{1037.688} - 3 \times 10 = 737.688 \text{ Newton} \\
\text{UCL}_F &= \text{1037.688} + 3 \times 10 = 1337.688 \text{ Newton}
\end{align*}
\]

Between 737.688 Newton and 1337.688 Newton, there is no risk of decentering the process due to special causes, for example the wear of the cutting tool. Beyond these limits, the process would be out of order and must be corrected.

**Conclusion:**

In this paper, we have proposed an original approach to more global setting machine to optimize all parameters throughout the manufacturing process. The approach was presented based on a part made by milling. However in this article, we open two research perspectives to improve this work:

1. The first on the control of the cutting force by the control charts, because here we arbitrarily chose the standard deviation on the effort, it would be interesting to calculate a true standard deviation from the measurements of the cutting force.
2. The second perspective would be to also consider in the study the quality parameters of the piece such as roughness ... to obtain a much global incidence matrix.

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