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Machine-tool setting: Algorithm for passing the adjustment by points to the adjustment on dimensions

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Abstract*—The setting of machine tool is to position the machined surfaces to each other relative to the reference of the machine. Traditionally the position of each cutting tool is corrected after each machining operation to get a conform part. The Total Inertial Steering (TIS) allows correcting in one time all deviations of the measured points on the work piece relative to the CAD model. In the case of the production by machine tool with numerical control, it seeks to link the parameters part to adjustable parameters on the machine (tool offsets). The relationship between part parameters and tool offsets is obtained thanks to the incidence matrix. This matrix is easily and automatically calculable in the case of matrix connecting points to tool offsets. This is not the case for a matrix linking a parameterization of the surface with dimensions to tool offsets. This paper proposes an algorithm to pass from the matrix on the points to the matrix on the dimensions, in order to obtain it automatically. This original approach allows exporting the TIS approach to apply it to the geometric tolerancing. An example of a relatively simple 2D part is used to illustrate this problem.

Index Terms— **Adjustment, machine-tool setting, steering of the machining, tool offsets, Total Inertial Steering.**

I. INTRODUCTION

The objective of steering machines is to bring back as close as possible the actual work piece to its original model defined in design office. For doing that, the machine must be initially adjusted to correct position of cutting tools and regularly to compensate for wear. On this subject, several methods and strategies have been developed to enable the machine tool to produce parts with dimensional quality required. Due to the very approximate initial setting tools, Kibe [1] proposed an in-situ measure approach to adjust tools. The author Anselmetti [2] has shown that it can reduce the cost of adjustment by acting on the manufacturing dimensions chosen by ΔL method [3]. Upstream of setting the machine in the machine-shop, the GPS tolerancing (Geometrical Product Specification) [4] has been developed to allow manufacturers of mechanical parts to produce conform parts. That why the authors Goldschmidt [5] and Boukar [6] conscious of the interest offered by the GPS tolerancing to ensure the conformity of products, have used this tolerancing for setting machines. Boukar [7] showed that we can reduce the influence of measured points on the surfaces on corrections to the tools. Others, however, such as Del Castillo and Min-Chiang [8],[9] proposed statistical approaches to adjust machines. The steering approach by control charts was initially introduced by Shewhart [10] to detect out of control situations. Works on inertial approach for steering machines were carried out by Pillet [11] in the context of inertial tolerancing [12].

There are in the literature several methods for steering machines [13],[14],[15], which is generally to swing the part in the machine to better correct the deviations. But the approach of the total inertial steering, whose principle is explained in the next section can not only balance the part, but all tool paths to be as close as possible to the target dimension.

Starting from a CAD file, it shows that with probing points on it, the incidence matrix of dimensions can construct and this in a quasi-automatic

II. PRINCIPLE OF TOTAL INERTIAL STEERING

The Inertial steering approach allows establishing a direct link between the tool offsets and position of the machined surfaces spotted in a reference frame linked to the machine. In the case of machining, especially in the case of 3D machining, identification of good corrections to be made is complex because there are dependencies between the dimensional and corrections. The TIS approach establishes this dependence by the incidence matrix (refer to 2) of tool offsets on the probed points and calculates the steering matrix (refer to 3). This matrix allows passing to vector of deviations on the points to vector of correction on the tool offsets.

We retain the illustrative example of the part below in figure 1.

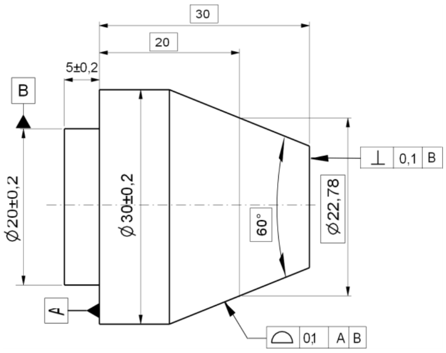
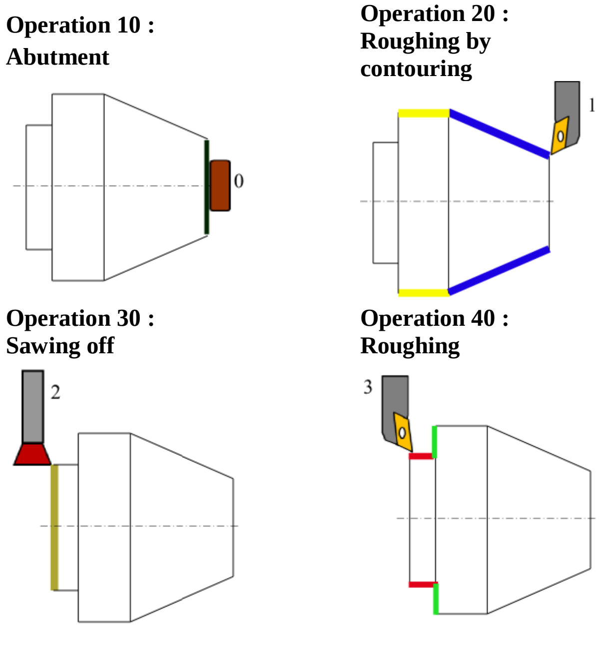


Fig.1. Specification of the finished part

All machining operations are performed in a single turning center, from the abutment (operation 10) until the Sawing off of the work piece by the tool 3 (operation 40). Figure 2 shows the manufacturing process of the part.


Operation 10 : Abutment

Operation 20 : Roughing by contouring

Operation 30 : Sawing off

Operation 40 : Roughing

Fig. 2. Manufacturing process of the part

A. *Choice of the points for the expression of dimensions*

For doing inertial steering of digital machines, it must be measured points on the work piece. It is then necessary to correct their position by acting on the correctors in CNC. For this example of the part, points were chosen two to two diametrically opposed on cylinders S3 and S5, and then on the cone S2. For plane surfaces it was decided to take a single point on each to position the tool on the Z axis like is shown to Fig. 3.

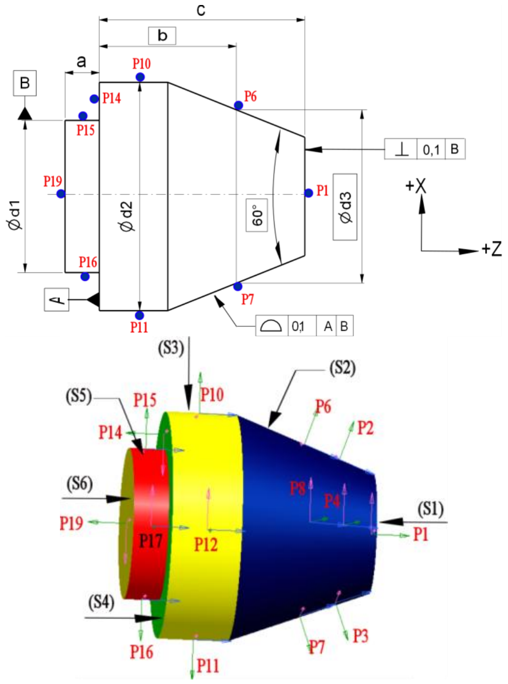


Fig.3. Representation of probed points

This choice has the advantage to delimit each dimension by two opposite points such as in the case where the diameter is measured using a multi-dimensions or a vernier calliper. The dimensions were designated by letters (refer to Fig. 2) to facilitate the explanation in the rest of this paper.

The coordinates X, Y, Z and the normal components *ai*, *bi*, *ci* of surfaces at these points shown in Table 1.

Table1.Coordinates and normal's of probed points

Surface	Point	X	Y	Z	ai	bi	ci
S1	P1	0	0	30	0	0	1
S2	P2	11.39	0	20	0.866	0	0.5
	P3	-11.39	0	20	0.866	0	0.5
	P4	11.39	0	20	0.866	0	0.5
	P5	-11.39	0	20	0.866	0	0.5
	P6	9.51	0	25	0.866	0	0.5
	P7	-9.51	0	25	0.866	0	0.5
	P8	9.51	0	25	0.866	0	0.5
	P9	-9.51	0	25	0.866	0	0.5
S3	P10	15	0	5	1	0	0
	P11	-15	0	5	1	0	0
	P12	15	0	5	1	0	0
	P13	-15	0	5	1	0	0
S4	P14	12	0	0	0	0	-1
S5	P15	10	0	-2.5	1	0	0
	P16	-10	0	-2.5	1	0	0
	P17	10	0	-2.5	1	0	0
	P18	-10	0	-2.5	1	0	0
S6	P19	0	0	-5	0	0	-1

Coordinates and normal's are used in the following sections to calculate the incidence of tool offsets on dimensions.

B. *Incidence matrix of tool offsets on points*

To construct this matrix, it is necessary to identify the tool offsets that act on the surfaces and to determine the relationship between them and the tool offsets.

- The abutment (0) with (tool offset T0z) which positions surface S1 is fixed to prevent the simultaneous movement of all the tools that will effectively move the next work piece.
- The tool 1 which machines the surface S2 and S3 must be axially adjustable by acting on the tool offset T1z and radially by T1x. In the example, the concerned axes are Z axis for the lengths and the X axis for diameters. The incidence of tool offset is calculated according to the normal to the target surface.

The impact of tool offset is 1 for plane and cylindrical surfaces in the direction of concerned correction. If we move the tool to 1, the points of the surface move from 1.

For the cone, the impact of the tool 1along Z (T1z) is given by the equation 1:

$$T1z = \Delta z \qquad (1)$$

and its impact on X (T1x) is given by the equation 2:

$$T1x = \Delta z.\tan(30°) \qquad (2)$$

Figure 4 shows graphically like example the calculation of the impact of tool offsets on the cone.

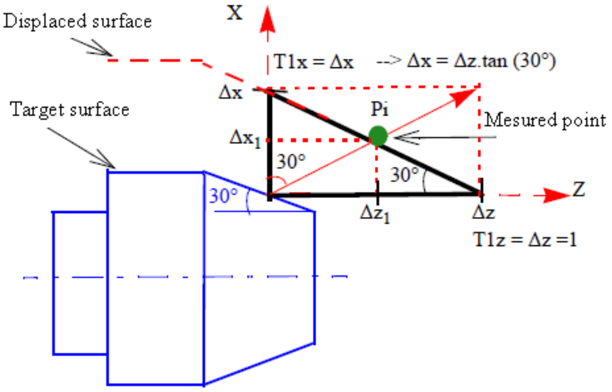


Fig.4. Calculation of the incidence on the cone

- The tool 2 is axially adjustable using tool offset T2z.
- Finally tool 3 will be adjusted axially by T3z and radially by T3x.

The method of small displacements [16] allows establishing the mathematical relationship between the correctors and points of surfaces. The displacement of each point can be calculated using this method, which, by its assumption of small displacements with regard of the curvatures of the surface, allows linearize the deviation of the point relative to its target surface according to equation 3.

This equation is simplified because of the absence of rotation of the tool relative to the work piece and vice versa, allowing removing components in rotation in the second member of the equation 3.

$$ei = \xi i + aiTx + ciTz \qquad (3)$$

Where:

ξi : initial deviations relative to the target points

ei :final deviations after correction

Tx, Tz: corrections of position of the tool

ai, ci: direction cosines of the local normal $\overline{ni}$ to the target surface

The incidence matrix on points [a] is given in Table 2 (columns Tix... Tiz).

Table 2.Total incidence matrix in inertial [a]

Surface	Point	T1x	T1z	T2z	T3x	T3z
S2	P2	0.289	0.5	0	0	0
	P3	0.289	0.5	0	0	0
	P4	0.289	0.5	0	0	0
	P5	0.289	0.5	0	0	0
	P6	0.289	0.5	0	0	0
	P7	0.289	0.5	0	0	0
	P8	0.289	0.5	0	0	0
	P9	0.289	0.5	0	0	0
S3	P10	1	0	0	0	0
	P11	1	0	0	0	0
	P12	1	0	0	0	0
	P13	1	0	0	0	0
S4	P14	0	0	0	0	-1
S5	P15	0	0	0	1	0
	P16	0	0	0	1	0
	P17	0	0	0	1	0
	P18	0	0	0	1	0
S6	P19	0	0	-1	0	0

Equation 3 allows deducing the general expression of the matrix (refer to 4) which can gives the incidence matrix [a].

$$(e) = [a](C) + (\xi) \qquad (4)$$

Where:

e: vector of deviations on the points

C: vector of correctors.

III. ALGORITHM OF TRANSITION FROM INERTIAL INCIDENCE MATRIX TO THE MATRIX ON DIMENSIONS

A. Step 1: Total incidence matrix in inertial

The first step of the algorithm consists in listing points of the surfaces involved in the dimensions with normal of each surface, and to define the axes of displacement of tools in which the corrections are made. This matrix is gived in the table 2.

B. Step 2: Definition of the dimensions by the two concerned points

This step is to define each dimension by two points that constitute each part of the dimension. The incidence on each part of the dimension is calculated in step 3. The definition of diameters is made by two opposite points on the same surface of revolution (see section 2.1). To correct the position of the cone, it has been positioned by a gauge plane approximately at the middle of the cone. This type of specification has the advantage of making independent adjustment of the position of cone to its angle. The cone and the cylinder with diameter d2 are made by the same tool (Tool 1). To correct its position, this tool is adjusted radially by measuring the diameter d2 and axially by measuring the position of the gauge plane to the length b (sees Fig. 3). Diameter d3 is not piloted here since the diameter d2 and *b* can already position the tool respectively in X and Z. It is also assumed that the cone has no coaxiality default which will not be measured and the angle of the cone is a program parameter controllable by the adjuster, it is not piloted here. Table 3 gives piloted dimensions obtained by combining points.

Table 3.Definition of dimensions by two points

Dimension	Part 1of the dimension	Part 2of the dimension
a	P19	P14
b	P14	P6
c	P14	P1
Ø d1	P16	P15
Ø d2	P11	P10

C. Step 3: Calculation of the incidence on both parts of the dimension

To calculate the incidence on the two parts of the dimension expressed in Table 3, it must copy the lines of the points that define the dimension in the incidence matrix (Table 2). Incidence of tool offset on a point is calculated using equation 4.

For length dimensions:

- In part 1, i.e. the point left or bottom of the dimension, the displacement of a point is made in the negative direction of the axis of correction (-X or -Z). In this example, we are concerned by the Z axis. The coefficient of displacement is equal to -1. Dividing the incidence of the matrix (coefficients Tix, Tiz of the incidence matrix in Table 2) by the normal component (components ai, bi, ci, in Table 1) to the surface at that point in the concerned direction and multiplying by the coefficient (-1) of the vector of negative displacement (equation 5):

$$a_{ij} = -\frac{T1z+T2z+T3z}{ci} \qquad (5)$$

- In part 2, i.e. the point of right or top of the dimension, the displacement of a point is made in the positive direction of the axis of correction (+X or +Z). In this example, we are concerned by the Z axis. The coefficient of displacement is 1. Similarly, is multiplied the incidence by the normal component to the surface at that point in the concerned direction and by the coefficient (+1) of the vector of positive displacement (equation 6):

$$a_{ij} = \frac{T1z+T2z+T3z}{ci} \qquad (6)$$

With:
$sign\,(X,Z)$: is the sign function which gives the sign of displacement of the tool along the axis X or Z of the machine.
a_{ij}: coefficient in row i and column j of the incidence matrix.

For diameter dimensions**:**

Correction of diameters is assigned to the XY plane; if the X axis is corrected then the associated Y axis will be automatically corrected so axisymmetric. It is considered that the correction is made to the radius, which allows obtaining an incidence of 2 on the diameter (see Table 5).

The incidence is calculated by the following (7).

$$a_{ij} = \frac{T1x + T3x}{ai} \qquad (7)$$

See Table 1 for the values of ai, bi, ci):

Table 4.Incidence matrix on the part 1 of the dimension

Dimension	Part 1	T1x	T1z	T2z	T3x	T3z
a	P19	0	0	-1	0	0
b	P14	0	0	0	0	-1
c	P14	0	0	0	0	-1
Ø d1	P16	0	0	0	1	0
Ø d2	P11	1	0	0	0	0

Table 5. Incidence matrix on the part 2 of the dimension

Dimension	Part 2	T1x	T1z	T2z	T3x	T3z
a	P14	0	0	0	0	1
b	P6	0.577	1	0	0	0
c	P1	0	0	0	0	0
Ø d1	P15	0	0	0	1	0
Ø d2	P10	1	0	0	0	0

D. Step 4: Calculation of the incidence matrix on dimensions

The incidence matrix on dimensions is obtained by adding the two incidence matrices on both parts of the dimension previously calculated in Tables 4 and Table 5. Table 6 shows the incidence matrix on dimensions.

Table 6. Incidence matrix on dimensions

	T1x	T1z	T2z	T3x	T3z
a	0	0	1	0	1
b	0.577	1	0	0	-1
c	0	0	0	0	-1
Ø d1	0	0	0	2	0
Ø d2	2	0	0	0	0

The objective of adjustment of the machine is to bring the dimensions to their target. Knowing the deviations on dimensions a, b, c, Ø d1 and Ø d2, it is possible to calculate the values of tool offsets to reduce initial deviations (ξi).

IV. SYNTHESIS

In the previous sections the algorithm was presented with an example. This section presents the application of the algorithm in general on a manufacturing process using a flowchart (refer to fig. 5). This flowchart leaves two possibilities for steering. If the measurement means is to measure points, then the total inertial steering is used.

In the case where the steering machine is by measuring dimensions on the part, then the algorithm allows to pass to the steering by dimensions. However, this approach requires the knowledge of the direction of correction. This algorithm needs to be improved in order to deal the most complex 3D parts.

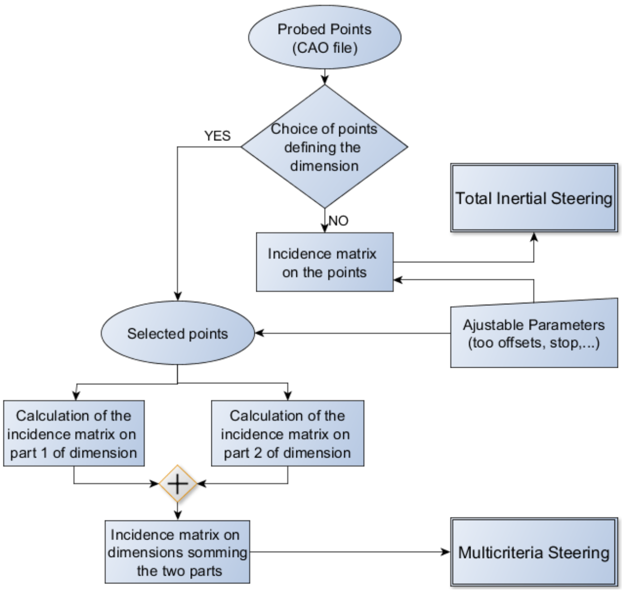


Fig.5. Flowchart of the algorithm

V. CONCLUSION

The article showed the passage of incidence matrix of tool offsets on points (Total Inertial Steering) to an incidence matrix of tool offsets on dimensions (Traditional Steering). The approach has been demonstrated through an example of a simple part in the 2D case, but its use for complex geometries like 2D or 3D is fast and the principle remains the same.

However, there remains a generalization work of this algorithmic approach for transforming automatically the incidence matrix on the points to the incidence matrix on dimensions whatever the work piece.

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