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ORIGINAL ARTICLE

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Optimal adjustment of a machine tool for improving the geometrical quality of machined parts

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Abstract The manufacturing industry has to improve the quality of its manufactured products. It is the reason why industry needs tools and methods that make the control of that quality possible. In this paper, we propose a method that allows an optimal adjustment of the machine tools in order to respect at best a set of standard functional requirements applied to a part. The requirements have to use the maximal material requirement defined by ISO standard.

The proposed method works out a geometrical model. Interchangeability boundaries enriched with adjustment parameters constitute the basis of the model. Comparison between this geometrical model and a first manufactured part allows us to obtain the variations of adjustment parameters. These variations directly correct the machine tool being certain that the following parts respect at the very best the functional requirements. At least, this method brings the first step to statistically control a process.

Keywords Adjustment · Geometrical quality control · Machining · Tolerancing

1 Introduction

Nowadays the market fluctuation and the fashion ask for more and more new and different patterns. As the batch size decreases, it is necessary to design and manufacture the best quality products at lower cost while reducing delays. So the concept of concurrent engineering [1–3] must be used, it is now well known in industry as well as in academic areas. The design of the parts, the process planning, even the production system must be made simultaneously.

Figure 1 shows the different items involved in integrated design and manufacturing. In manufacturing engineering, we see the interactions between the product (or the workpiece), the manufacturing process (machining, forming, assembly, etc.) and the manufacturing resources (machines, tools) in order to obtain the manufacturing process, but also the manufacturable workpiece and even the manufacturing system. The aim of the product design consists of defining all the operations, resources and processes necessary for obtaining a real mechanism (set of assembled parts) that best fits functional requirements. This integration must answer to several objectives: quality of the product, due time, production reactivity, etc., and constraints: cost, market, safety, laws, etc. In order to solve this wide problem, methods, models and tools can be used. Each of them must be representative for each user (design office, manufacturing, marketing, production, etc.) and coherent along the several phases of the product life cycle.

In this paper, we are focused on the geometrical quality of manufactured products. One way of improving product quality is in controlling the geometrical tolerancing by:

- Either adjusting machine tools in order to respect at the very best a set of standard functional requirements applied to a part.
- Simulating the geometrical effect of manufacturing fault causes and adjustment parameters in the respect of functional requirements.

Therefore, we propose some tools and methods that allow us to solve this first point. We work in a manufacturing context where mechanisms are mass-produced. The parts have common dimensions (a few hundred millimetres) and every type of part is produced apart from each other. We suppose they are rigid concerning the local distortion and the global distortion. This is the reason why adjustment and tolerancing are able to control only manufacturing faults greater than the real distortion (a few hundredths of a millimetre at least). Moreover, we are able to link the value of adjustment parameters to the value of functional requirements, which are applied to a part of a mechanism. In this way, the aim is to control the adjustment parameters on the machine tool , which allows it to satisfy the functional requirements.

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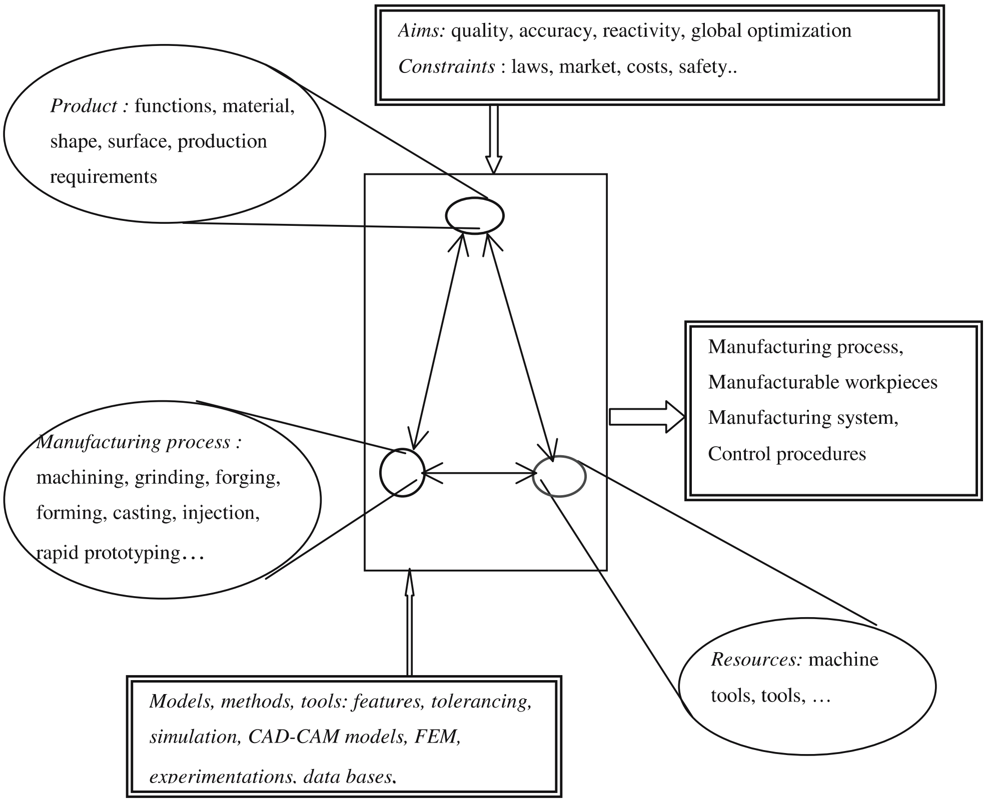


Fig. 1. Reference diagram of our approach

2 Adjustment task compared with tolerancing task

To understand the problems of adjustment, at first we have to define the tolerancing task. Tolerancing task is a subset of the geometrical definition of a mechanism.

Limited to the geometrical point of view, design products need two studies (Fig. 2).

- A first one consists of choosing designed solutions and manufacturing processes which will carry out a real mechanism. The real mechanism is the answer to the functional requirements. The main aim of this study is to obtain a technical drawing. The drawing takes finely into account all the relations between parts and especially the manufacturing generations.
- The second study analyses and validates the result of the previous study. Two aspects of the mechanism are studied at the same time.
  - A dimensioning that defines the nominal geometry.
  - A tolerancing that takes an interest in the small deviations between the real geometry and the nominal geometry.

Thus, we are able to give now the aim of tolerancing according to the product design [4]:

The aim of tolerancing consists in controlling the small deviations between the real geometry and the nominal geometry of a mechanism in order to respect at the very best its functional requirements.

If the problem is to control the effect of small deviations before manufacturing, we have to solve a simulation in which product drawings show the result.

If the control of small deviations takes place during manufacturing, we have to adjust machining-tools.

Thus, adjustment is the practical and technical aspect of the general tolerancing problem. Adjustment and tolerancing have the same aim.

3 Adjustment of machine tools

3.1 Functional requirements and ISO language

Regarding the definition of adjustment, optimal adjustment needs a direct expression of functional requirements. Usually, assembly and positioning are two functional studied requirements having a geometrical expression.

The concept of boundary cleverly translates the assembly condition. A part of a mechanism fits all the other parts if none of its manufactured points violate the interchangeability boundary. ISO standard [5] allows the use of the virtual condition with the maximum material requirement. This condition describes almost perfectly the concept of boundary and so the functional requirement of assembly. A manufactured part fits for use if it is entirely on the good side of the interchangeability boundary. A part is all the better if its matter is near the boundary without violating it. Therefore, the deviation, and more exactly, the smallest devia-

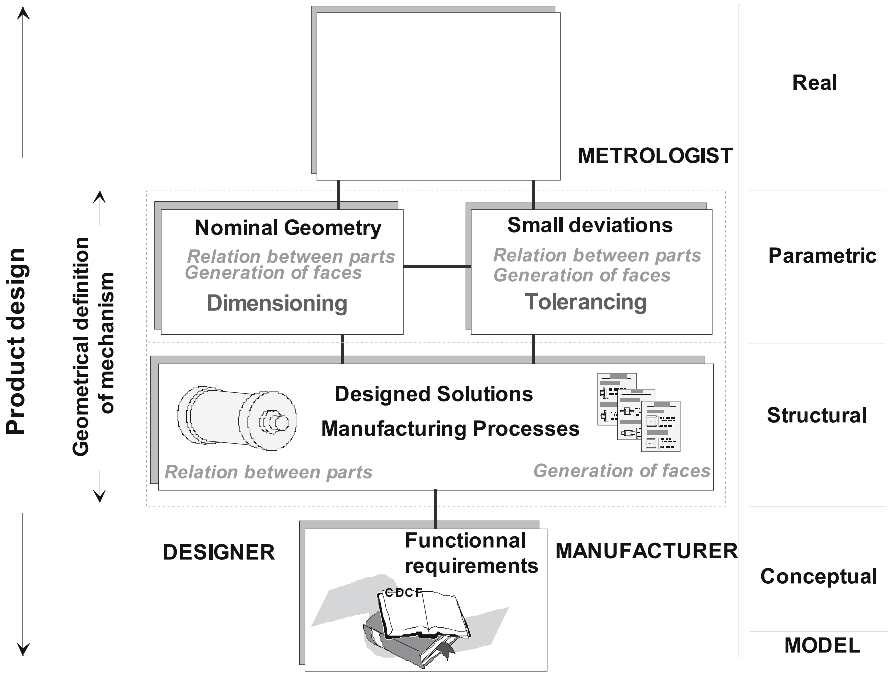


Fig. 2. Geometrical definition of mechanism

tion between the part and the boundary evaluates numerically the respect of the function.

On the other hand, the ISO standard language is not able to translate correctly the functional requirement of positioning. In fact, the standard language is not able to take strictly into account the influence of variation of form or the influence of local distortion. The principal effect is that good parts according to the technical drawing do not fit the other parts and good parts according to the function are refused [4]. Thus, the product is not optimal.

Actually, no one is able to optimally adjust machine tools according to the positioning condition expressed in ISO language. The ISO geometric model of tolerances takes into account the maximal form deviation of a feature but not the form fault distribution in the tolerance zone. Thus, the position deviation between two parts in an assembly is not predicable with a realistic correlation. It is the reason why this paper proposes a method taking into account only the assembly condition. Moreover, the assembly condition must use the maximum material requirement and the virtual condition in order to tend towards optimum.

3.2 Manufacturing deviations, adjustment parameters and measurement

Figure 3 shows the different quantities appearing in the adjustment and uncertainties (Δ) disturbing adjustment for a part machined.

Adjusting a machine tool demands connecting the active part of the tool with the machined surface. This does not succeed the first time because there are a lot of errors or uncertainties due to the adjustment operation and the machining process as well as the static or dynamic behaviour of the machine tool (the tool or the workpiece). These uncertainties are the causes of manufacturing deviations. To control the influence of some uncertainties as screw, displacement reversibility or slideway defects, machine-tool builders put some adjustment parameters into the numerical control unit or adjustable stops on conventional machine tool. The modification of these parameters allows movement of the uncertainty zone compared to its nominal position. The dimension of this displayed quantity (adjustment parameter) is the length.

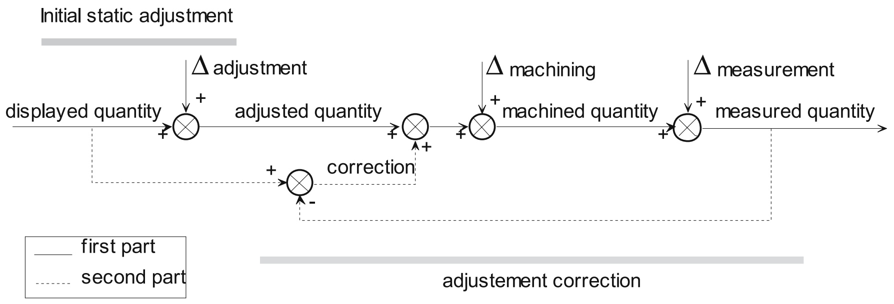


Fig. 3. Adjustment: quantities and uncertainties

In return, the dimension of the machined quantity is more complicated, it assures the respect of the functional requirement. So in practice, for adjustment corrections, these requirements must be translate into a dimension compatible with a length (dimension of displayed quantity). Therefore, the aim of the measurement task is to evaluate the respect of the function and to give a measured quantity compatible with the adjustment parameters. The difference between displayed quantity and measured quantity gives the value of the adjustment parameter correction.

3.3 Adjustment model for the determination of the correction

We define a model built on a geometrical representation of the interchangeability boundary. Variation of some dimensions, which correspond to adjustment parameters, allows us to distort the model. For example, this allows us to fit the best adjustment model to the geometry given by the measurement of the first (or a couple of) manufactured part on the coordinate measuring machine. After moving and distorting the model, the variations of dimension give the direct value of the corrections of the adjustment parameters. Therefore, after having introduced these corrections, the following manufactured part has more chances to fit the best interchangeability boundary and consequently the functional requirement.

4 Geometric adjustment method

To explain the proposed method, we use an application that is representative of the industrial adjustment problem. The following technical drawing (Fig. 4) defines a manufactured part (a cover) in accordance with the words of the ISO 2692 standard. Its first function is to respect an assembly condition: when the cover lies on the A plane and when a shaft goes through the C cylinder, two screws have to fit with the part. The cover is manufactured on a conventional machine tool, it lies on the A plane, a drilling tool drills both holes with a diameter of 12.5 mm. A boring tool finishes the diameter of 28 mm. Three adjustable longitudinal stops put each tool in its work position. The machine gives the other cross-position and the direction of drilling.

There is no difference with a numerical machine tool; only we deal with numerical stops.

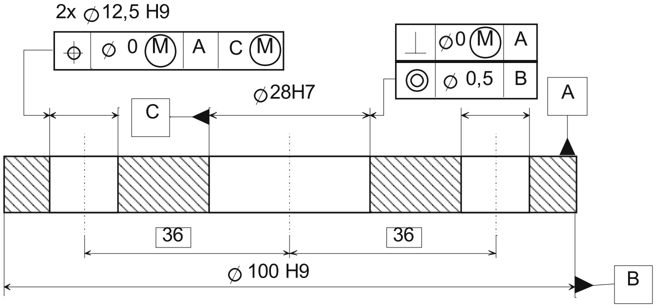


Fig. 4. Technical drawing of the cover

4.1 Geometrical adjustment model

The geometrical adjustment model is a construction of geometrical features based on the virtual condition. The features lay on exact positions. This model must include the feature (here the C cylinder) defining a datum using a maximal material requirement (M). Minimal geometrical reduction elements and dimensional characteristics represent each feature (point, vector, and radius for cylinders; point and vector for plan) (Table 1).

Then the model is parameterised according to the adjustment possibilities of the machine tool. An L1 and L2 quantity parameterises the longitudinal hole positions. R1, R2 and R3 parameterise hole diameters (Fig. 5). L1, L2, R1, R2, R3 are characteristics in harmony with ISO 17450-1, in other words, they are near key process parameter according to Boeing's definition [BOI-00]:

$$\overrightarrow{O1O2} = L1 \cdot \overrightarrow{k}\,, \quad \overrightarrow{O1O3} = L2 \cdot \overrightarrow{k}\,.$$

4.2 Initial adjustment, drilling, and measurement

First, the machine tool is initially adjusted according to the nominal dimensions of the part. Next, a first part is machined. A measurement by using a coordinate measuring machine extracts points from the surface of the manufactured part. Now, a set of measured points Mi represents each feature ($\mathrm{Mi}_{\mathrm{Pl1}}$, $\mathrm{Mi}_{\mathrm{Cy1}}$, $\mathrm{Mi}_{\mathrm{Cy2}}$, and $\mathrm{Mi}_{\mathrm{Cy3}}$).

4.3 Deviation between the adjustment model and the extracted points

We search now for the best fit between the adjustment model and the extracted points. We have to specify the deviation between a measured point Mi and its own point I belonging to the adjustment model. For this purpose we use the principle of a mowing

Table 1. Geometrical features of the part

Feature	Minimal geometrical reduction element Point	 Vector	Paramter
Pl1	O2	$\vec{k}$	none
Cy1	O1	$\vec{k}$	R1
Cy2	O2	$\vec{k}$	R2
Cy3	O3	$\vec{k}$	R3

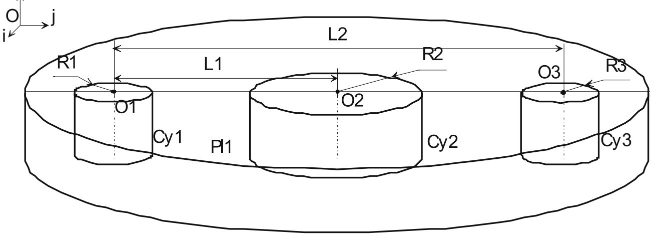


Fig. 5. Geometrical adjustment model

of the initial adjustment model [5], but using the small displacement torsor defined by the moving ($\overrightarrow{Di}$) of point I (Fig. 6). We use a direct expression of the deviation (ei) between the measured point and the nominal point of the moved model.

This method presents the constraint to be able to determinate the nominal point of the moved model by the knowledge of the measured point and the geometrical properties of the nominal feature. However, this is always possible with the usual machined feature (analytically defined geometric shapes): plan, cylinder, sphere, cone, parabola, gearwheel surface, etc.

The knowledge of the minimal geometrical reduction elements in their initial position defines the initial adjustment model. A small displacement torsor (SDT) (relation 1) expresses formally the moving of the initial reduction elements.

$$\{\mathscr{T}_{\mathrm{pd}}\} = \left\{ \underset{S/R}{\vec{\theta}} \left| \begin{matrix} \alpha \\ \beta \\ \gamma \end{matrix} \right. , \underset{O \in S}{\vec{D}} \left| \begin{matrix} u \\ v \\ w \end{matrix} \right. \right\}_{O,R} \qquad \text{relation 1}$$

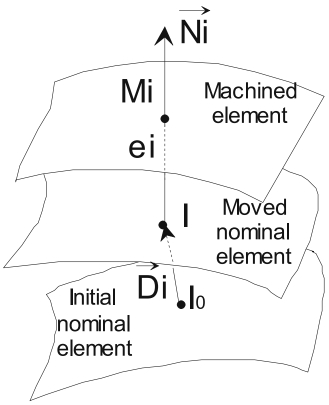
This relation gives the displacement parameters at the point O projected on the base R:

- α, β and γ are the components of the small angular displacement of S in R base,
- u, v and w are the components of the small displacement in translation of point O belonging to S.

This SDT can also be described by a 4 × 4 matrix (relation 2) in homogeneous coordinates.

$$[D] = \begin{bmatrix} \mathbf{0} & -\gamma & \beta & u \\ \gamma & \mathbf{0} & -\alpha & v \\ -\beta & \alpha & 0 & w \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} \end{bmatrix}_{S,R} \qquad \text{relation 2}$$

Fig. 6. Adjustment principle



These mathematical relation allows us to easily calculated the different models (nominal, moved, etc.) of each feature (defined by its geometrical reduction elements) and its particular parameters (characteristics) attached to the part definition.

The moved reduction elements describe the adjustment model. The deviation (ei) between the measured point (Mi) and the nominal point (I) is formally evaluated from the moved reduction elements. The original parameters of the initial model allow its distortion by addition of a variation (equations 2):

$$\begin{aligned} &R1_{\text{initial}} \rightarrow R1 = R1_{\text{initial}} + \Delta R1 \\ &L1_{\text{initial}} \rightarrow L1 = L1_{\text{initial}} + \Delta L1 \\ &R2_{\text{initial}} \rightarrow R2 = R2_{\text{initial}} + \Delta R2 \\ &L2_{\text{initial}} \rightarrow L2 = L2_{\text{initial}} + \Delta L2 \\ &R3_{\text{initial}} \rightarrow R3 = R3_{\text{initial}} + \Delta R3 \qquad \text{equations 2} \end{aligned}$$

Thus, for every shape (plane, cylinders), the deviation (ei) expresses itself from the reduction elements of the initial model, the measured points, the unknowns (α, β, γ, u, v, w) of the small displacement torsor and the variations of the original parameters of the model (ΔL1, Δl2, Δr1, Δr2, Δr3).

Figure 7 shows the different operations that yield the deviation (ei) between each measured point (Mi) and its nominal point (I).

The model represents the nominal part attached to the machine tool, the original parameters correspond to the adjustment parameter (corrections) of the machine tool, and each gap (ei) describes the deviation between the first part and the nominal part.

The unknowns (α, β, γ, u, v, w) allow us to fit the different datum of the machine tool and the coordinate measuring machine.

A variation of unknowns and parameters alters each deviation (ei).

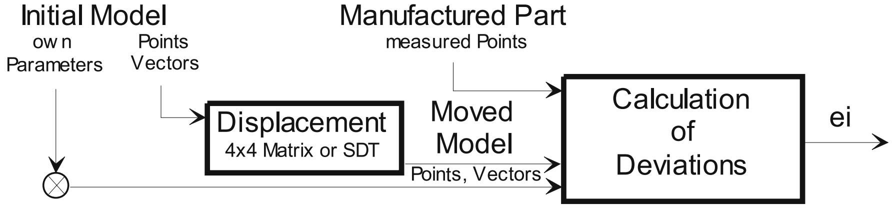
4.4 Working out the corrections of the adjustment parameters

The working out the corrections is equivalent to the resolution of an optimisation problem under constraints. The target of the resolution is to find the moved and distorted model that best fits the measured points. Nevertheless, the measured points do not violate the limits of the model.

The mathematical description is:

Target best fit between part and adjustment model
we search the minimum of the maximal deviation: [max(|ei|)] minimum.

Fig. 7. Deviations working out



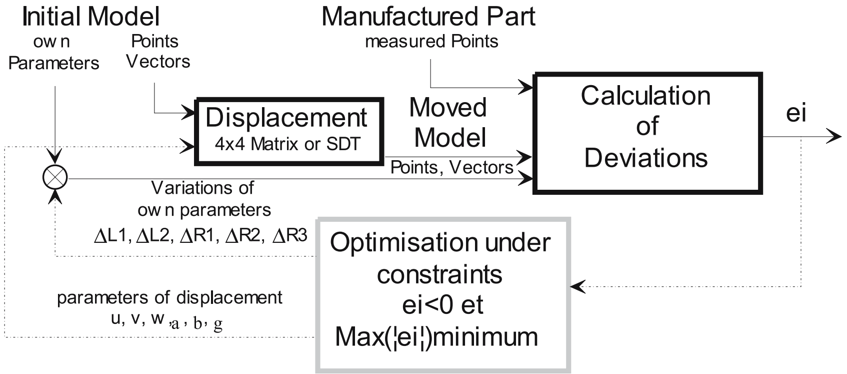


Fig. 8. Optimisation

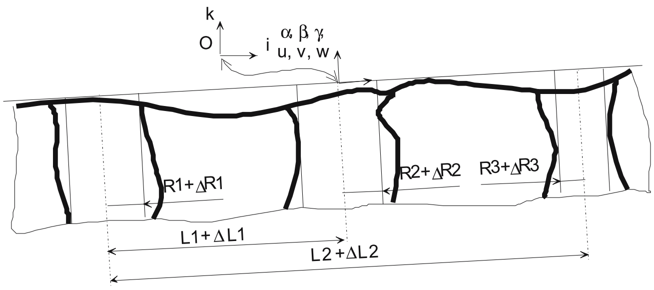


Fig. 9. Best fitting of the adjustment model according to the part

Constraint	none of the measured points violate the limits of the model ∀i, ei⩽0, if the direction of normal vector goes out of the matter.
Parameters	unknowns of the SDT (α, β, γ, u, v, w) and its particular parameters of the model (ΔL1, Δl2, Δr1, Δr2, Δr3).

The result of the optimisation under constraints directly gives the values of it particular parameters (corrections) so that the following part best fits the function requirement. Use of classical solver software can solve this optimisation analytically or numerically.

Figure 8 shows the return of the improvement loop.

The Fig. 9 shows the final relative position at the best fit between the adjustment model and the first part.

We have applied this method on some real machining. We note a consequent immediate improvement of the machine tool adjustment after the first part. Indeed, this procedure corrects the initial static adjustment deviation but leaves a little fault corresponding to the machining deviation of the first part. Generally, the static adjustment fault is greater than the manufacturing fault. We have defined a strategy to improve the machine tool adjustment and correct the residual machining fault, taking into account the following parts. With simple cases, the correction c_j of a parameter p after the jth part is equal to the opposite variation of the parameter p_j obtained with the jth part, divided by j

$$c_j = -\frac{p_j}{j}\,. \qquad \text{equation 3}$$

5 Concluding remarks

The proposed method is optimal since we evaluate the corrections of adjustment parameters at the very best according to the functional requirements. With this method, we are able to control the three-dimensional aspect of the manufactured parts although each correction belongs to a one-dimensional space.

The method permits us to control the influence of the deviation causes even if they do not correspond to the adjustment parameter. It is not necessary to characterise those deviations. For instance, an increase in the radius of the holes will control an angular deviation between the drilling tool and the support plan; however, we do not have to determinate it.

The application of the method is enough to control tolerancing. The simulation of tolerancing is not a technical need. The adjustment method and experience allows us to control manufacturing deviations according to the functional requirements. Parts are manufactured at best according to a practical choice of a process.

At least, this method is the first step to statistically control a process. The deviations correspond to the surveillance parameters; adjustment parameters control the process.

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