TOPOLOGICAL MODELLING OF THE PART GEOMETRY IN MANUFACTURING

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Abstract: - Nowadays the design methodology is based on the individual tolerancing of the surfaces which compose a part, using dimensional chain in order to assure the functional performance in mechanical structures. In this paper is proposed the replacement of the tolerancing way used in present with an original concept based on the topological structures. According to the new concept certain of the part’s surfaces are grouped regarded as a whole. This determines the replacement of the dimensional chain with chain of topological structures. This approach simplifies the next stages of identification and modeling. The topological structures include all the elements which have constraints regarding the shape, dimensions and relative position. We have to notice that the topological structure isn’t limited to the surfaces generated in the current operation.

In order to topological modeling the geometry is necessary to group the surfaces constraint from point of view of relative position of surfaces. These constraints may have as reference a surface machined in the current operation or in a previous operation. Each constraint regarding the shape, position or dimensions represent a topological structure’s parameter.

In paper are presented methods developed by authors in order to topological modeling the geometry of part as so as the specialized software developed by authors in the MatLab program.

Key-Words: - Topological modeling, Dimensional control, Tolerancing, Topological structure, Genetic algorithms, Neural network

1 Introduction

The dimensional control problem is one of the more important due of the increased request for customized products, machined in small production batch.

In the manufacturing process, the compliance regarding quality must be monitored in real time and, also, the error correction must be integrated in the manufacturing process [5].

Nowadays, the machine tools are able to generate very complex surfaces, and as follow, the main problem isn’t to machine this kind of surfaces but to control the geometry of these surfaces.

It is noticeable that the deviation compensation strategy tends to replace the error reducing strategy.

The literature highlights that not exist an unitary approach regarding generation, inspection and tolerancing of part’s surfaces regarding its position in the assembly.

Due of these reasons we may state that the current standards regarding the dimensional and position deviations are not properly to the recent evolution in the design and machining domain of machine tools manufacturing.

This aspect is highlighted more by fact that the form, position and dimensional deviations evaluation is based on two main standards: ISO/FDIS 1101:2000 (E) „*Geometrical specification of the product—Geometrical tolerance—Form, orientation, position and beat tolerances*” and ISO/TR 5460:1985 „*Geometrical tolerances —Form, orientation, position and beat tolerances — Guiding principles*”.

A deep analysis of these standards highlighted that occur ambiguity from mathematical point of view.

Since each coordinate measuring machine producer may understand in different ways these standards is possible that the software used for the surfaces identification to show different data at the measuring of the same parts [4].

This fact may be highlighted by the following example: According to ISO/FDS 1101:2000 (E) standard, for a cylindrical surface, the cylindrical tolerance zone is limited at two coaxial cylinders with radius difference *T*. In the same time, the standard show that the surfaces cylindricality is regarded as correct if this surface is content between two coaxial cylinders with radius difference *T*. Regarding the two cylinders axis position and the radius value, the two cylinders may be selected

in a such manner that the difference between it's radius to have the smaller possible value [3].
In figure 1 are presented the two cases, first with the two coaxial cylinders A_1 with z_1 axis and radius difference Δr_1, and the second case with the to coaxial cylinders A_2 with z_2 axis and having the radius difference Δr_2. The standard don't mention nothing regarding the way in which the two cylinders are determined, if the cylinders have to approximate in an optimal way the real surface unevenness or if exist zones where these unevenness overcome the cylinder surface. These ambiguities are generated due to the facts that are not used rigorous mathematical methods to describe these surfaces.

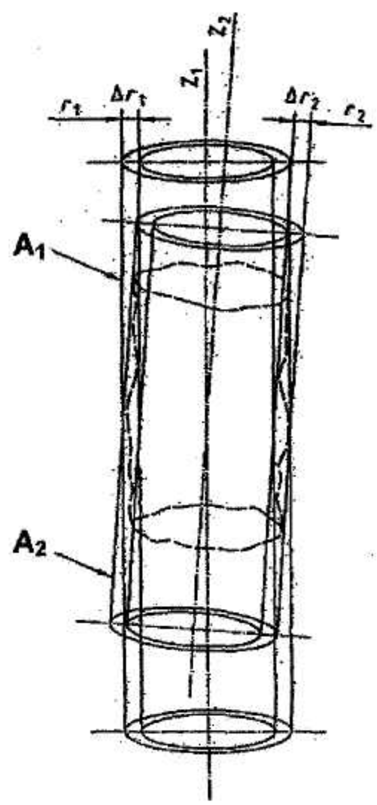

Fig. 1. Coaxial cylinders which bound the actual surface

Similarly, may be regarded the case of two plane surface distance and position tolerancing. If the two plane surfaces are not parallels, which is a real case, the distance between the two surfaces may have only an ambiguous definition.
The conclusion of the above presented facts is that in the form, position and dimensions deviations definitions, according to the standards, are introduced errors of which value and nature are impossible to be determined and which affect the measurement results.
As result is necessary a standards system which define in a more correct way, from mathematical point of view, the interpretation of the points cloud gathered from the machined surface.
Analyzing the structure of a part we may remark that it have some surfaces which compound the interface with the rest of the assembly. This interface is composed by those surfaces which fulfill the functional role of a unique complex surface having a form-counter form type relation with another complex surface in the assembly.
The topological structure may be defined as the surfaces assembly geometrically interconnected so belongs to the same complex surface.
We may affirm that the part geometry topological modeling is closer to reality than the individual modeling of the surfaces which compose the part. The topological modeling of the part geometry proposes the surfaces assembly modeling which form the interfaces between the parts from the assembly component. By this way to regard the part surfaces is minimized the error appeared at surfaces identification.
Is important to highlight that the topological structures have to be selected in such a way to consider these surfaces important form point of view of the piece's working. These working importance represent the first criterion for the surface's selection which will form the surfaces assembly [1], [2].
The second criterion is the clamping type for machining. The surface's assembly may be regarded as being composed by these surfaces which are machined in a single clamping and the surfaces on which are made the part clamping.
The topological structure model construction presumes the following of two stages:
- determination of the part geometrical elements equations, considering the dimensions of these elements at their the nominally values (values established at design);
- at those dimensions which are tolerated are adding variations, representing the mathematical model parameters, determined from the tolerance values;
Finally we will obtain so many parameters like tolerated dimension deviations are in the part specification.
In this paper are presented the techniques developed by the authors in order to topological modeling the part geometry.
In rest the paper is organized as follow:
- in section 2 is presented the topological modeling concept;
- in section 3 is show the way to determine the part numerical value of the model parameters;
- the section 4 is reserved for the presentation of numerical examples regarding the topological structure identification by the various presented methods;
- the section 5 is dedicated to the conclusions which result from this paper;

2 Topological modeling concept

The geometrical form of any machined surface is always different to the nominal form. In order to assure the exchangeability and to fulfill the functional requirements the geometrical tolerancing is established for certain surfaces. To determine the machined surfaces quality the surface are inspected and are gathered points which will be processed according to an algorithm which will allow to verify the condition established by the designer.

In industry the tolerancing is made on these piece surfaces which will be in contact with another surface's group constituting a couple on type form and counter-form.

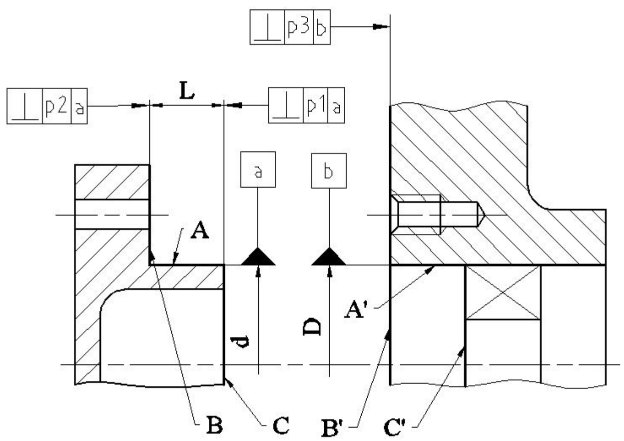

Fig. 2. Shape—counter shape surfaces

The tolerancing have the goal to assure the overlap good enough between form and counter-form.

Let's consider the case of a bearing cover presented in figure 2.

The functional surfaces of this are *A*, *B*, and *C* surfaces which are in contact with surfaces *A*' and *B*' on the cradle and respectively *C*' on the bearing.

As follow are rational to make the *ABC* surfaces assembly inspection, simultaneous processing three point clouds to obtain the *A*, *B* and *C* surfaces model.

The surfaces assembly tolerancing will be made by limiting some of the surfaces assembly deviations.

In the presented example will be tolerated the *A*-*C* distance, the *B* surfaces diameter, the perpendicularity of the *A* surface regarding the *B* and the parallelism between *A* and *C*.

These are the surface's assembly deviation parameters.

The topological approach of these deviations will give more precisely results regarding the individual study of each of these deviations. These results represent better the correspondence between the assembly surfaces.

2.1 Topological structuring of the part geometry

We can affirm that by the topological modeling are made the modeling of a surfaces structure regarded as a unique geometrical complex element. This way to regard a mechanical part is based on three main motivations:

Firstly the piece is characterized by an interface with the rest of the mechanical construction. This interface is composed by more surfaces which geometrically work like a unique complex surface in relation of type form counter-form with another complex surface belongs to the mechanical structure. From this point of view the topological structure represents an assembly of geometrically inter-conditioning surfaces so to belong to the same interface.

Secondly, the tolerances from the technical specifications, usually, don't refer to a single surface but to more surfaces, some being tolerated surfaces and another being reference surfaces. In the real cases these reference surfaces have errors too, errors which will affect the modeled surface. Hence the individually modeling are criticizable, haven't possibility to exactly know the reference surface. The reference surfaces by itself are change from sample to sample.

Thirdly, some of the geometrical deviations may be defined only modeling more surfaces. As example we may regard the thickness of a plate. Never isn't established which is the reference and the modeled surface. In order to model this case is necessary to model a structure composed by two planes, parallel at nominal level, and only after this we may model the distance between these planes. Similarly, for the two cylindrical surfaces model is necessary to model two cylinders with parallel ax at nominal level. Hence the dimensions of the assembly surfaces will have initial the model dimensions at nominal values.

2.2 Construction of the topological structure model

The technical requirements impose constraints regarding certain model parameters. Will not be restricted all the deviations but only those considered important for the part functional role accomplishment.

All these aspects need to establish of a strategy for the model construction. In the numerical model defining we propose to browse two main stages:

The first stage is to determine the mathematical equations of the geometrical elements which compose the model. In these equations initially we consider that the surfaces dimensions are at nominal values namely at those values established in design phase.

In the second stage we add at these dimensions the model parameters which are tolerated in the technical specifications. In this way is obtained a numerical model of the part, characterized by a number of parameters equal with the number of tolerated dimension established at design.

This model represents the topological structure model.

In figure 3 is presented a topological structure composed by two holes with diameters D_1 and D_2 and three plane surfaces *P*, *Q* and *R*. The conformity parameters are the model's parameters of the topological structure idle the holes diameters variations D_1 and D_2, the distance between the D_1 hole center and the *Q* plane deviation (distance *A* deviation), the distance between the hole centers deviation (distance *B* deviation), the angle between the holes ax and the distance between *P* plane and the holes center variation (distance *C* variation).

The part program for the surfaces generation contains the points 1…10 (see figure 3) which determine the tool's path.

The piece's measuring is making on the measuring system similarly with the generating process by replace the tool with a touch probe. In the measuring sequence in part program the touch probe will follow the path needed to gather point's coordinates.

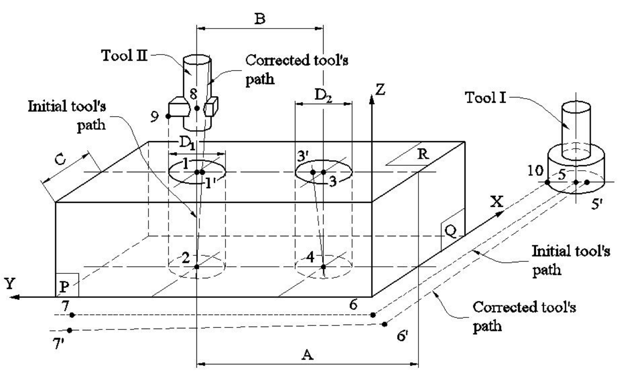

Fig. 3. Topological structure

3. Model parameters determination

As we previously shown, in order to determine the machined surfaces quality, the point cloud coordinates are measures and after this, the coordinates are processed by some method. In following are presented some of the methods for the topological structures identification.

The algorithm proposed for topological structure identification presumes to follow three steps:

1. Grouping of the part surfaces which will be in contact with another surfaces group belong to the mechanical construction where it is mounted the piece, forming a surfaces assembly on type form counter-form. This surfaces group will represent the topological structure.
2. Gathering of an ordered points cloud on each of the surfaces which form the topological structure.
3. Processing of these data for computing the deviation values which are tolerated in the technical specifications in order to determine the piece conformity with the CAD model.

For the data processing are proposed two methods: the genetic algorithm based method and the neural network based method. These methods allow the in-cycle dimensional verification with a great precision and a reduced calculus effort.

The topological structure is established based on the form, dimension and position constraints criteria. We have to notice that the topological structure isn't limited solely to these surfaces machined in current operation.

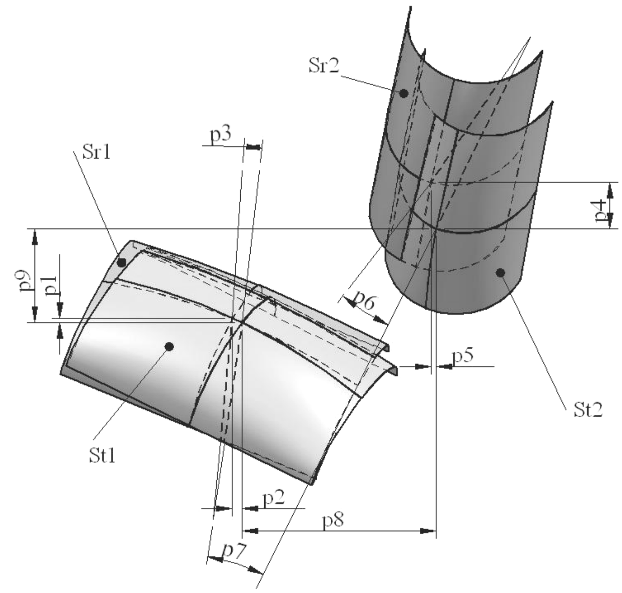

Fig. 4. Deviations of the topological structure surfaces

Each of the topological structure surface is characterized by model and conformity parameters which describe the similitude between the real piece's surfaces and the model (p_1, p_2, ... p_n parameters, see figure 4).

Each of the p_i parameters from the technical specifications signify a tolerance representing the variations limits.

In figure 4 are shown a topological structure, selected based on this criterion and composed by two theoretically surfaces S_{t1} and S_{t2}. Due of the machining errors we may consider that are obtained the S_{r1} and S_{r2} real surfaces, the position of these surfaces being determined by parameters p_1, p_2, p_3 and respectively p_4, p_5 and p_6.

Presuming that in technical specifications was restricted the relative position between the two surfaces by parameters p_7, p_8 and p_9 it is interesting that the values of these parameters are inside the tolerance field.

Each of the form, position and dimensions restrictions, established in design phase, will be one of the conformity parameters of the topological structure.

As example we can consider the piece presented in figure 3, machined on a reconfigurable machining system.
The important dimensions are the tolerated ones.
These dimensions will be identified using the neural network based method.
The piece's measuring is made on the same machine as the manufacturing. For the measuring stage the cutting tool is replaced with a touch probe which will be moved on a certain path.
After the points cloud gathering is realized the topological structure model parameters are determined by minimizing an objective function. More over, we will not identify each of the topological structure parameter but only the links between the measured point's coordinates and the dimensional deviations of the topological structure surfaces.
We have to notice that all of the measured coordinates must be influent regarding the dimensional deviations. If this condition isn't accomplished the neural network identification will have very poor results.
If exist dimensions which are not influenced by some of the coordinates, these dimensions must be individual identified by another neural network.

4 Numerical examples

In following are presented some of the methods applied for the mechanical structures identification based on the topological approach.
The numerical examples are based on specialized software developed by authors in MatLab program, version 7.

4.1 The cylinder-cylinder topological structure modeling using genetic algorithms

The genetic algorithms based technique was applied for the assessments of the parameters of a topological structure formed by two holes with radius R=10 mm and the distance between ax d=50 mm (see figure 5).
In order to simulate the real surfaces inspection was used software which generates two points' clouds (one on each surface) with 7 points on each surface.
For the cylindrical surfaces were used the equations:

$$X_1 = \begin{Vmatrix} R\cdot\cos(\alpha) \\ R\cdot\sin(\alpha) \\ p\cdot\alpha \end{Vmatrix};\ X_2 = \begin{Vmatrix} R\cdot\cos(\alpha)+d \\ R\cdot\sin(\alpha) \\ p\cdot\alpha \end{Vmatrix}. \qquad (1)$$

Let's presume that the surfaces ax have angular deviations φ_1 and φ_2 regarding the theoretically position. In this way the point's coordinates are:

$$x_i = \omega_2^T(\varphi_i)\cdot X_i,\ i=\{1,2\}, \qquad (2)$$

where

$$\omega_2(\varphi_1) = \begin{Vmatrix} \cos(\varphi_i) & 0 & -\sin(\varphi_i) \\ 0 & 1 & 0 \\ \sin(\varphi_i) & 0 & \cos(\varphi_i) \end{Vmatrix},\ i=\{1,2\}. \qquad (3)$$

In order to define the objective function was applied the less squares method.
So, the objective function becomes:

$$d = \sum_{i=1}^{7}\left(X_i^2 + Y_i^2 - R^2\right)^2 + \sum_{i=8}^{14}\left[\left(X_i - d\right)^2 + Y_i^2 - R^2\right]^2. \quad (4)$$

As solving program were used the Genetic Algorithm Toolbox from MatLab version 7.
In table 1 are presented the results obtained for various values of the φ_1 and φ_2 angles.
The Genetic Algorithm Toolbox options were established at: Population Size=20; Elite Count=2; Crossover Fraction=0.8; Migration Interval=20; Migration Fraction=0.2.

Table 1. Numerical results

φ_1 actual [°]	φ_1 calc [°]	φ_2 actual [°]	φ_2 calc [°]	$\Delta\varphi_1$ [°]	$\Delta\varphi_2$ [°]
1	1.00238	-2	-2.00038	0.00238	0.00038
2	2.0021	-1	-0.99045	0.0021	0.00955
-0.5	-0.4971	-1	-1.00215	0.0029	0.00215
-1	-0.9954	0	-0.00553	0.0046	0.00553
-1.5	-1.495	0.5	0.50494	0.005	0.00494

4.2 A complex topological structure modeling using neural network

Was selected a piece with plane and cylindrical surfaces and were established the dimensional and positioning deviations which appear between the functional surfaces (see figure 5).

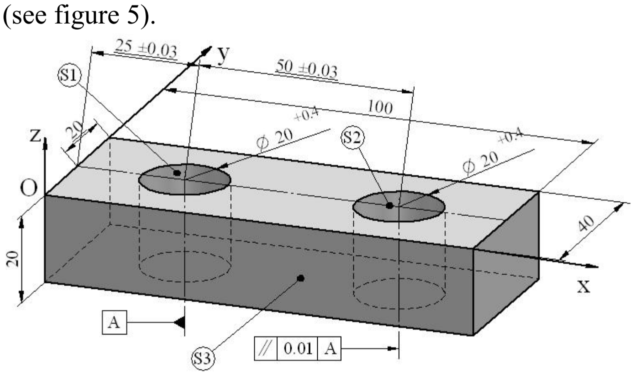

Fig. 5. Part with dimensions assembly

As functional surfaces was considered the holes with diameters of 20 mm (S_1 and S_2) and the plane surface S_0.
Was considered as important the holes diameter, the position of these holes regarding the plane surface S_0, the position regarding the *yOz* plane of the reference system and the distance between the holes ax.

In order to simplify the neural network use we consider that the parameter set is formed by

$$\{\varphi_1, x_{02}, y_{02}, \varphi_2\}, \quad (5)$$

where:

φ_1 — rotation around Ox axis of the S_1 axis;

x_{02} — displacement of the S_2 hole center regarding the S_1 hole center on Ox axis;

y_{02} — the hole S_2 center displacement regarding the S_1 hole center on Oy axis;

φ_2 — angle between the S_1 and S_2 holes ax in plane yOz;

At the neural network training for each i point was applied a coordinates transformation in a reference system modified with the conformity parameters and were calculated the value of f function as deviation of points position regarding the cylindrical surface:

$$f = (x + X_0)^2 + (y + Y_0)^2 - R_0^2, \quad (6)$$

where X_0 and Y_0 are the theoretically coordinates of the cylindrical surface center and R_0 is the theoretically radius of this cylinder.

The x_{02} and y_{02} parameters have deviations in domain ± 0.4 mm and angular parameters φ_1 and φ_2 have deviations in domain ± 0.03 °.

It was obtained a data base with

$$M = \prod_{i=1}^{4} v_i = 5^4 = 625, \quad (7)$$

records, each record having 38 fields (34 values of f function and 4 values of the parameters set).

In table 2 is presented the precision for interrogation of the neural network. The interrogation parameters are in the training domain.

Table 2. Neural network precision

Parameter	Actual	Calculated	Error
φ_1 [°]	-0.02	-0.0202	0.0002
x_{02} [mm]	0.1	0.10442	0.00442
y_{02} [mm]	-0.3	-0.3045	0.0045
φ_2 [°]	0.01	0.0093	0.0007

5 Conclusion

Is proof the fact that the part geometry topological modeling allows to eliminate the ambiguity in the dimensional deviations definition.

The numerical results obtained by simulations proof that the topological modeling leads to better results regarding the individual modeling fact that demonstrate that its useful.

The calculus efforts are smaller then in case of individual identification due of fact that is determined the whole conformity parameters set in the same identification action.

The proposed methods are feasible, being sustained by dedicated software, developed by authors and which proof the expected results.

Is imposed the conceptual modification of the standards which describe the dimensional deviations.

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