Precision dimensional analysis in CAD design of reliable technologies

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Abstract. The paper presents a schematic diagram of interactive synthesis of a unit TP workflow based on structural synthesis of links and its subsequent precision dimensional analysis. It describes the method of building shock schemes to check the compliance with technical requirements of a drawing, to calculate diametric operational parameters and allowances for machining. It also demonstrates the method to define precision types and classes of devices necessary to implement the designed machining technology of turning gauging equipment.

1. Introduction

The integrated CAD systems provided for considerable reduction of costs and terms of developing new products, which are composed of computer-aided-design systems of technological processes (CAD TP). Their benefits, first of all, include cost-effective technologies, and second, reliable technologies that ensure surface precision and roughness [1, 2].

Cost-efficiency of a technological process is defined by various options, calculation of technical and economic indicators and their comparison resulting in the most favorable option.

Reliable precision means that such technological processes guarantee precision parameters of manufactured products as early as their design stage [3, 5]. Therefore, the reliability of technological processes (TP) of a workpiece machining is understood as their property to ensure precision and quality of parts specified in the drawing at different stages of their production provided the required technical parameters are preserved within the prescribed limits at all stages and taking into account workpiece machining in specific sequence, using proper equipment, sufficient industrial facilities, necessary tooling and under the given operating modes [6, 7, 8].

It is possible to assess the TP reliability against precision parameters expected during its operation according to the precision margin index [9]. It characterizes the relation ($\psi = IT_{Xi} / \omega_{Xi}$) of allowable change ($IT_{Xi}$) of TP precision parameter ($X_i$) against its failure ($\omega_{Xi}$) expected during TP operation. In other words, according to [9], the TP reliability may be connected with the reliability of ensuring the required precision of workpiece machining without failures. Provided $1 < \psi \leq 1.2$ and even at $\psi > 1.2$, it is possible to guarantee the TP reliability against precision parameters. The greater this indicator, the higher the expected TP reliability is (it will only depend on correct setting of Machining operation and its technical condition when a TP is implemented in real operating conditions). It is only possible to calculate the precision margin index for every size and technical specification (misalignment, runout) after precision dimensional analysis of a technological process designed using CAD TP. Therefore, the
synthesis of technological structures with their subsequent precision dimensional analysis shall become the main design method of reliable technologies within these systems in order to consider specific features of produced parts. At the same time, to assess the TP reliability against precision parameters the system shall ensure certain design levels of workflow technology connected with the solution of problems of automated determination (choice) of technological bases and machine accessories, as well as TP dimensional synthesis and analysis. Due to the fact that solution of certain tasks is still not completely formalized the operating mode within such systems remains interactive [6, 7].

2. Interactive TP synthesis

The interactive TP synthesis includes surface machining plans, definition of workpiece machining stages, distribution of mechanical and non-mechanical machining stages, composition analysis of operating complexes, locating chart, applied tools and equipment.

The specifics of a technological design is to find the most effective solution within a large scope if there is a need to consider a large number of factors and restrictions. This caused the need to decompose the general task and to implement its solution in several stages thus forming the hierarchical structure. The sequence of stages is defined by predetermined strategy with information feedback only between adjacent stages [10, 11, 12]. The design of a technological process (in this case its workflow) is ensured alongside with gradual specification and adjustment of design solutions. Considering the specified features, the schematic diagram of the workflow design system of a specific TP is given in Figure 1.

The reliability of TP against precision parameters is ensured at the third, fourth and fifth design levels (Figure 1). Let us explain the features of solving some of such tasks in case of automated design of a TP workflow.

The following influence the manufacturing precision:

- workpiece locating;
- precision of accepted mounting rotation surfaces;
- precision of linear technological values;
- precision types and classes of applied tools.

At present, the synthesis of technological bases for plane elements is carried out manually by a process engineer since this process is not yet well studied, and for rotation elements – according to the developed formalized rules based on design and technical characteristics on these elements [10, 11, 12] provided that for plane elements the bases are already specified.

The direction of synthesis of technological bases happens from the last TP operations to the first ones since the last operations include the machining of the most critical surfaces, generally having
positional relationship and common design linear dimensions. In particular situations, such orientation allows applying certain standards of rationality depending on their priority and applicability. Such criteria are accepted as follows [10, 11, 12]:

- minimization of locating failure for plane and rotation elements ($\Delta \theta \rightarrow \min$);
- minimization of the number of technological bases for the entire TP ($\{T_Bi\} \rightarrow \min$);
- minimization of allowance variations ($\Delta Z_i \rightarrow \min; \Delta B_{ij} \rightarrow \min$).

The adjustment of precision of rotation surfaces accepted as the bases is made closer to (or up to) the average economic precision of equipment where they are formed, according to recommendations described in [11, 12] provided the precision of such surfaces, which was defined at the first design level, is lower the recommended value. This is strongly required since the initial shocks of machined surfaces and unevenness of machining allowances decrease, and in some cases the precision of mounting rotation surfaces directly affects the positional relationship requirements (PRR) of surfaces specified by the designer. However, the increase in precision of these surfaces shall not increase the cost of supporting operations.

The required types and classes of workpiece precision for final machining thus complying with positional relationship requirements between the machined surfaces specified by the designer shall be defined with regard to the value of such requirements using ratios obtained on the basis of analytical study for various schemes that ensure surface PRR in case of their final machining [11, 12]. For primary machining of workpieces it is advisable to define the precision class according to the precision of mounting surfaces using the recommendations described in [11, 12].

One of the major and critical stages of manual and automated design of technological processes is the synthesis of dimensional schemes and precision dimensional analysis of TP workflow (in this case the fourth and fifth levels of TP workflow design, see Fig. 2), which makes it possible to assess the reliability of designed TP against precision parameters and to control the manufacturing quality at TP design stage.

The quality of TP design and decrease in commissioning terms of designed technologies mainly depends on the accuracy of this analysis. This also leads to considerable reduction of tangible costs caused by the need for TP development using pilot workpiece batches, and TP implementation will be connected with the development and specification of cutting modes in the production of one or two parts from a batch with subsequent production of all parts without failure.

![Figure 2](image_url)

**Figure 2.** Levels of automated workflow design for reliability evaluation of the workflow through precision characteristics
3. Precision dimensional analysis of TP workflow

The objectives of precision dimensional analysis of TP workflow include the following:

1. Calculation (definition) of all operational dimensions and machining allowances;

2. Analysis of a possibility to ensure design dimensions and positional relationship requirements of elements with specified precision using the necessary equipment automatically when setting a workpiece with or without adjustment.

The precision dimensional analysis of TP is inseparably linked with synthesis of corresponding dimensional schemes. For turning gauging equipment it is necessary to design schemes of linear dimensions and shock schemes.

The scheme of linear dimensions is used to analyze the possibility of ensuring precision of design dimensions, to calculate the linear operational parameters and machining allowances. At the same time the following standards of rationality are considered:

– complete interchangeability between design and technological dimensions excluding failures;
– smaller tolerance of dimensions;
– minimum dimensional variations of allowances in a workpiece batch.

To ensure reliability of TP against precision parameters and compliance with the specified standards of rationality the synthesis of operational dimensions implies the following rational structure of technological dimensional chains: not more than three-link components in a dimensional chain with design dimension being its master link; not more than four-link components in a dimensional chain with allowance being its master link.

The scheme of shocks arising during the entire technological process is used to check the possibility of complying with technical PRR of rotation elements, to define unevenness of allowances, to calculate diametric operational dimensions and machining allowances.

The structure of technological PRR of rotation surfaces is presented as the shock scheme of rotation elements in initial workpiece, primary, being machined and machined rotation elements of a relatively ideal surface within the initial workpiece or the center line of a spindle formed around [10, 12]. The shock scheme is presented as an array of numbers automatically formed by a special algorithm. The formalized method of PRR synthesis is described in [10, 12]. One of the features of this method is accounting of residual shocks since they exert direct impact on the compliance with technical requirements, especially in instrument making having more stringent technical requirements in comparison with mechanical engineering.

The analysis of a possibility to obtain the given precision of design linear dimensions is carried out by a formalized method [11]. It includes the formalized rules of assigning precision to operating dimensions depending on the precision of design dimensions, number of constituent dimensions in linear dimensional chains and dimension intervals regarding design and technological dimensions. The method is developed on the basis of a method of complete interchangeability and criterion – the precision of operational dimensions shall be equal or not more than two tolerance grades rougher than the machining method or the used equipment.

The max/min method is accepted to calculate the technological dimensional chains. Design dimensions and allowances are accepted as master links, while technological dimensions are accepted as constituent links [11].

The shocks of rotation surfaces obtained within a primary workpiece are defined according to oscillations of these surfaces and displacement of their axes from the reference target position, and for holes obtained through casting the misalignment of their axes is also considered [10, 12]. The shocks of primary surfaces are determined by empirical formulas [13], which features are given in [12]. The shocks of machined surfaces are defined by automatic design of dimension shock chains with desired shocks being its master links, and shocks of primary and machined surfaces, as well as surfaces within a primary workpiece being its constituent links. These shock chains are assessed taking into account vector properties of constituent links via the quadratic summation method [10, 12]. The shocks of machined surfaces are defined via adjustment coefficients specified in reference books [14].

Once the possibility of ensuring PRR set by the designer via the formalized method presented in
is established, the intermediate allowances and diameters of rotation elements are calculated based on the minimum estimated allowance, which size ensures normal cutting. Its value is defined by the sum of three components: height of microroughnesses and depth of a defective layer obtained after preceding machining of a surface, as well as the total value of spatial deviations $e_{\text{max}}$ arising within a considered and preceding operations and including uncontrolled failure of a workpiece shape, i.e. allowance unevenness. Since the shock vectors of one and the same rotation surface in different states coincide in direction, then the value $e_{\text{max}}$ is defined as a half of arithmetical difference between shock values of rotation elements being machined and already machined. The intermediate diameters are calculated through a finishing zone of machining identified in certain cases to consider the reasons for overlapping. There are various reasons for this: pitches of a workpiece obtained by forging, stamping or casting; lack of distinct preliminary condition of a rotation element; combination of rough and semifinish machining in one operation; considerable interoperable allowance unevenness, which may exceed the allowance value to get the required quality of a surface within its single machining. For these cases the $e_{\text{max}}$ is calculated using the adjustment coefficient [14]. Knowing the diameter of a considered machining stage ($D_i$), the minimum estimated allowance ($z_{\text{min}}$) removed when receiving $D_i$, as well as the deviation of a diameter of a preceding machining stage ($e_{(i-1)}$ – for a shaft, ($ES_{(i-1)}$) – for a hole), it is possible to define the nominal diameter of the preceding machining stage ($D_{(i-1)}$) using one of the following formulas:

$$D_{(i-1)} = D_i + 2z_{\text{min}} + |e_{(i-1)}| \quad \text{for a shaft;}$$

$$D_{(i-1)} = D_i - 2z_{\text{min}} - ES_{(i-1)} \quad \text{for a hole.}$$

After the nominal diameters of intermediate machining stages are defined for each rotation element, the actual minimum and maximum machining allowances are automatically calculated.

4. Conclusions

Currently, not enough attention is paid in production to these design stages due to their labor-consuming nature, shortage of time and, in fact, lack of the necessary software tools.

Therefore, the solution of the problem related to automation of synthesis of TP dimensional schemes and its subsequent precision dimensional analysis was and still remains an urgent task. Thus, to reduce time of automated design of technologies ensuring reliability of machining against precision parameters, the process engineers shall use the corresponding tools – software systems.

The case in point is the TIS-Tsep’ system (ITMO University) making it possible to design linear dimensional chains, to calculate them and to display the scheme on a computer screen.

However, to check the possibility of PRR compliance and to define the unevenness of allowances the process engineers do not possess the corresponding tools and do it manually. Therefore, there are numerous studies devoted to the creation of a system of interactive synthesis and calculation of shocks [10, 12] based on the method of synthesis of dimensional schemes and TP precision dimensional analysis [10, 11, 12].

Such system provides for the quality increase of production planning and design manufacturing technologies of turning gauging equipment ensuring the given precision of design dimensions and PRR with a certain margin, which guarantees reliability against precision parameters, as well as for lower costs of machining and commissioning using pilot and consistency batches.

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