Transfer method of geometric tolerance items based on assembly joints

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Abstract
In order to reduce the uncertainty in the selection of geometric tolerance items, a qualitative method for top-down transfer of geometric tolerance items is proposed. The assembly joint which is composed of two mating surfaces with functional requirements or structural constraints is acted as the basis of geometric tolerance items transmission. According to the structural characteristics, the assembly joints are divided into meta-assembly joints and composite assembly joints, and the priority rules for assembly joints are proposed. The transfer path of part-level geometric tolerance items is established according to the functional requirements and structural constraints among parts. On this basis, by adding information about the composition and constraint types of assembly joints between parts and the position constraint relationship of the general structure surface in the part, the transfer path of part-level geometric tolerance items is extended to the transfer path of geometric feature surface-level. With the development of product design, the initial functional requirements will be transformed into structural constraints between parts and geometric feature surfaces, and the structural transformation model of functional requirements is constructed. The generation specifications of geometric tolerance items based on structural constraints and the transfer specifications of datums are established. And based on the above specifications, the mapping relationship between functional requirements, structural constraints, and geometric tolerance items is defined. The synchronous transmission of geometric tolerance items along with the product design process are realized which provides an effective analysis tool for the top-down design of geometric tolerance items. Finally, the effectiveness of the method is verified by taking the transmission parts and connection parts in the crankshaft-piston mechanism as an example.

Keywords Geometric tolerance items · Assembly joints · Transfer path · Functional requirements · Structural constraints

1 Introduction

With the continuous development of high-precision machinery and equipment, geometric tolerance design has become a key link that must be considered in the product design stage [1, 2]. In traditional tolerance design, the selection of geometric tolerance items often depends on the designer’s experience, which has great uncertainty. It also affects the quality characteristics of parts such as mating and service life. How to analyze the functional characteristics and structural attributes of the product itself according to the design requirements, provide a qualitative method for geometric tolerance design, and realize the top-down transfer and generation of geometric tolerance items is an important problem in this field [3].

To solve the abovementioned problems, a top-down design method of geometric tolerance items is proposed in this paper. The transfer mechanism from geometric tolerance requirements of product to the corresponding tolerance items of geometric features based on functional requirements and structural constraints is given. The structural transformation model of functional requirements is constructed, based on which the unified expression of geometric tolerance semantics is proposed; the transfer path of part-level and geometric feature surface-level is established, and the generation specification of geometric tolerance items is constructed, which provides a theoretical basis for the generation and transfer of geometric tolerance items.

The remainder of the paper is organized as follows. An overview of related works is provided in Section 2. The related concepts of assembly joints are introduced in Section 3.
The details of the proposed transfer path and transfer method of geometric tolerance items are explained in Section 4 and Section 5, respectively. The transfer process of geometric tolerance items based on assembly joints is introduced in Section 6. Section 7 takes the crankshaft-piston mechanism as an example to illustrate the effectiveness of the method. Section 8 ends the paper with a conclusion.

2 Related works

At present, scholars at home and abroad have done a lot of work on the generation of geometric tolerance items. The proposed methods can be roughly divided into the following three types: position rule method, theoretical rule method, and case-based inference method.

2.1 Position rule method

The core points of the position rule method are to establish tolerance model and design specification of geometric tolerance and generate the tolerance items according to the assembly and position information of geometric features. For example, by analyzing the functional requirements corresponding to the joints between components, a method of generating functional specifications and functional tolerances based on position features was proposed by Anselmetti [4]; Cao et al. [5] proposed a scheme for functional specifications, which decomposed a geometrical functional requirement on a complex mechanism into geometric specifications defined on key parts; through studying the expression and decomposition methods of geometric functional requirements, and by using improved assembly directed graphs [6], a functional tolerance design method based on the evolution from geometric functional requirements to geometric specifications was presented by Yang et al. [7]; by classifying and sorting the position features, and using the position table [8] to describe the assembly position of the parts, the tolerance specification method of the position features in the datum reference system was given by Gong et al. [9]; Zhang et al. [10] proposed a method of generating tolerance specifications and tolerance domain types based on assembly position, which used polychromatic set theory and its normative verification method, which improves the accuracy and efficiency of geometric tolerance design; by using the crawler graph to identify the position of the functional surface, a 3D manufacturing tolerance synthesis algorithm based on technology and topology-related surface rules [13] was adopted by Jaballi [14]; in order to analyze error and its stack-up of mechanical product effectively, Zhang et al. [15] presented an integrated modeling method of unified tolerance representation based on key features (KFs) [16] and graph theory [17] in order to deal with these types of tolerances simultaneously; By starting from the basic spatial relationship between geometric elements, the description logic of geometric tolerance, the judgment algorithm, and the automatic generation algorithm of the tolerance type were proposed by Qin et al. [18]; to realize the automatic generation of the geometric tolerance area in the CAD system, a method based on description logic was proposed by the research group [19, 20]; Zhong et al. [21, 22] used description logic to construct a meta-model of assembly tolerance items and automatically generated tolerance items based on the ontology. This method reduces the uncertainty of geometric tolerance items through the rules of description logic; Zhao et al. [23] proposed a tolerance specification of the plane feature based on the independent axiom. The minimum information axiom is introduced for the optimum mapping rules, and the tolerance types are selected; Zhao et al. [24] proposed a novel method for computer-aided tolerance specification to evaluate static factors and dynamic factors. Those factors are assessed by the rule-based algorithm and axiomatic design algorithm; a product structure graph with tolerance items [25] is generated and stepwise enriched by design knowledge and rule-based as well as manually entered tolerancing information; Zhang et al. [10] proposed a new reasoning algorithm for assembly tolerance specifications and corresponding tolerance zone types, which realized the systematization and computerization of ATS and TZT design.

2.2 Theoretical rule method

In this method, a series of theoretical models are introduced to normalize the inference experience of geometric tolerance items selection, and the tolerance items are generated based on this. Armillotta [11] proposed a method of generating tolerance specifications based on product data. This method realized the reasoning of geometric tolerance items based on assembly requirements; Jiang et al. [12] presented a geometric tolerance information inference based on polychromatic set theory and its normative verification method, which improves the accuracy and efficiency of geometric tolerance design; by using the crawler graph to identify the position of the functional surface, a 3D manufacturing tolerance synthesis algorithm based on technology and topology-related surface rules [13] was adopted by Jaballi [14]; in order to analyze error and its stack-up of mechanical product effectively, Zhang et al. [15] presented an integrated modeling method of unified tolerance representation based on key features (KFs) [16] and graph theory [17] in order to deal with these types of tolerances simultaneously; By starting from the basic spatial relationship between geometric elements, the description logic of geometric tolerance, the judgment algorithm, and the automatic generation algorithm of the tolerance type were proposed by Qin et al. [18]; to realize the automatic generation of the geometric tolerance area in the CAD system, a method based on description logic was proposed by the research group [19, 20]; Zhong et al. [21, 22] used description logic to construct a meta-model of assembly tolerance items and automatically generated tolerance items based on the ontology. This method reduces the uncertainty of geometric tolerance items through the rules of description logic; Zhao et al. [23] proposed a tolerance specification of the plane feature based on the independent axiom. The minimum information axiom is introduced for the optimum mapping rules, and the tolerance types are selected; Zhao et al. [24] proposed a novel method for computer-aided tolerance specification to evaluate static factors and dynamic factors. Those factors are assessed by the rule-based algorithm and axiomatic design algorithm; a product structure graph with tolerance items [25] is generated and stepwise enriched by design knowledge and rule-based as well as manually entered tolerancing information; Zhang et al. [10] proposed a new reasoning algorithm for assembly tolerance specifications and corresponding tolerance zone types, which realized the systematization and computerization of ATS and TZT design.

2.3 Case-based inference method

This method is based on the existing successful cases for analogy and learning, so as to form a generation method of geometric tolerance items. For example, Sarigecili et al. [26] mapped the geometric dimensions and tolerance information of the product from STEP to the OWL-based model [27] and used the ontology-based model to explain tolerance analysis; Goetz et al. [28] presented a novel ontology-based approach combining knowledge from the product design and tolerancing domains to enable an automated tolerance specification of product concepts; this method realized the automatic generation of geometric tolerance items by analogy. In paper [29], the semantic web rule language is used to define and code the tolerance analysis specifications extracted from the ontology, based on which the automatic reasoning of semantic
information is realized; based on the similarity between the topological relations of target and previous cases, an ontology-based similarity measure for computing the similarity between target and previous cases is designed in [30].

The above method has largely solved the uncertainty in the geometric tolerance design process and provided reliable models and related inference rules for the selection of geometric tolerance items. However, there are still some limitations. Among them, the position rule method is mostly based on the functional requirements of the assembly joints between the parts to select geometric items, but the structural correlation between the general structure surfaces in the parts was ignored; the theoretical rule method has problems of accuracy and adaptability, and most of the rules are generated based on the structural constraints between the geometric feature surfaces, ignoring the geometric tolerance specifications generated based on the functional requirements; the case-based inference method has high efficiency, but the pertinence is not high. For the parts with special structure, the variation may appear in the process of analogy, which leads to the error of the recommended tolerance items. The focus of those three methods is mainly to generate tolerance items according to the structural correlations between parts, the transfer path of part-level geometric tolerance items is constructed, and the unified expression of geometric tolerance items transfer, and the composition and constraint types of assembly joints are introduced.

To solve the above problems, a top-down transfer and design method of geometric tolerance items based on assembly joints was proposed. The main work of this paper is as follows:

1. The assembly joint is used as the basis of geometric tolerance items transfer, and the composition and constraint types of assembly joints are introduced.
2. According to the functional requirements and the structural correlations between parts, the transfer path of part-level geometric tolerance items is constructed. On this basis, by adding the composition of the assembly joints between the parts, the constraint type of the general structural surfaces and the transfer path of geometric feature surface-level geometric tolerance items are established.
3. The structural transformation model of functional requirements is constructed, and the unified expression of geometric tolerance information is realized. The generation specification of geometric tolerance items and transfer specification of datum based on structural correlation were established.

### 3 Basis of the geometric tolerance item transmission

#### 3.1 Definition of assembly joints

In the design of the product structure, the assembly relationship is realized through several pairs of mating constraints.

The assembly joint is used as the basis of assembly connection and geometric tolerance item transmission, which expresses the spatial shape and position relationship and the mating characteristics between mating parts. Complex assembly joints are often composed of simple assembly joints.

Definition 1 meta-assembly joint: The mating surface pair formed by the functional requirements or structural constraints of two geometric feature surfaces between parts is called meta-assembly joint.

The type of mating surfaces and the mating constraints are the basic elements of meta-assembly joints. In engineering, common mating surfaces mainly include plane, cylinder, and spherical, and the mating constraints mainly include fit, coaxial, and tangent. The meta-assembly joint can be obtained by adding the corresponding mating constraint between the mating surfaces. The common meta-assembly joints are shown in Table 1.

The meta-assembly joint can be expressed as:

\[
MJ_{is,jt} = F_{is} \rightarrow T_{is} F_{jt}
\]

where \(F_{is}\) represents the \(s\)-th mating surface of the part \(P_i\), \(F_{jt}\) represents the \(t\)-th mating surface of the part \(P_i\) that has a mating constraint with \(F_{is}\), and \(C_{is,jt}\) represents the mating constraint between the surface \(F_{is}\) and \(F_{jt}\).

Definition 2 composite assembly joints: The set of multi-component assembly joints with a certain spatial position constraint between two parts to ensure the realization of specific functions is called composite assembly joint; composite assembly joints can be transformed into a set of meta-assembly joints constrained by a certain spatial position.
The composite assembly joint $J_{i,j}(f_m)$ between the $P_i$ and the $P_j$ for the completion of a specific function $f_m$ can be expressed as:

$$J_{i,j}(f_m) = MJ_{i_{1,j1}} \rightarrow T_{i,1} \rightarrow MJ_{i_{2,j2}} \rightarrow T_{i,3} \rightarrow T_{n-1} \rightarrow MJ_{i_{n,jn}}$$  \hspace{1cm}(2)$$

where the constraint $T_{n-1}$ is mainly used to describe the direction and position constraints between the meta-assembly joints $MJ_{i_{n-1,jn-1}}$ and $MJ_{i_{n,jn}}$, including the direction constraints (parallel, vertical, inclined) and position constraints (fit, coaxial, symmetrical).

The common composite assembly joints are shown in Table 2.

### 3.2 Priority of assembly joints

When there are multiple meta-assembly joints between mating parts, in order to determine the priority of tolerance transmission, the priority of the assembly joints should be ordered. The essence of part assembly is to restrict the freedoms of the parts, so as to realize the position and assembly of the parts. Obviously, the more the DOFs (degrees of freedoms) restricted by the assembly joint, the higher the priority of the assembly joint, and the higher the priority of the transfer path through the joint. And according to the order of limited DOFs from more to less, the primary assembly joint, secondary assembly joint, and third assembly joint are defined in turn.

As shown in Fig. 2a, there is a meta-assembly joint $MJ_{11,21}$ formed by large planes fit and a meta-assembly joint $MJ_{12,22}$ formed by short cylinders coaxially. There are 3 DOFs limited by large planes and 2 DOFs limited by short cylinders; therefore, $MJ_{11,21}$ is the primary assembly joint, and $MJ_{12,22}$ is the secondary assembly joint. In Fig. 2b, there is a meta-assembly joint $MJ_{11,21}$ formed by small planes fit and a meta-assembly joint $MJ_{12,22}$ formed by long cylinders coaxially. There is 1 DOF limited by small planes and 4 DOFs limited by long cylinders; therefore, $MJ_{1,21}$ is the secondary assembly joint, and $MJ_{12,22}$ is the primary assembly joint.

When the inherent attributes (surface type, size, etc.) of the mating surface are consistent, the contact form between the mating surfaces affects the limited degree of freedoms. The DOFs limited by plane contact is the largest, followed by the DOFs limited by line contact, and the least is DOFs limited by point contact. As shown in Fig. 3, $MJ_{11,21}$ and $MJ_{12,22}$ are all meta-assembly joints formed by large planes fit. In Fig. 3a, under the action of gravity, the meta-assembly joint $MJ_{11,22}$ is approximately plane contact, limiting 3 DOFs, while the joint $MJ_{11,21}$ is approximately line contact, limiting 2 DOFs. Therefore, the former is the primary assembly joint, and the latter is the secondary assembly joint. In Fig. 3b, the screw makes the meta-assembly joint $MJ_{11,21}$ approximate to plane contact, limiting 3 DOFs; $MJ_{12,22}$ is approximate to line contact, limiting 2 DOFs. Therefore, $MJ_{11,21}$ is the primary assembly joint, and $MJ_{12,22}$ is the secondary assembly joint.

### 4 Transfer path of geometric tolerance items

#### 4.1 Transfer path of part-level geometric tolerance items

The transfer path of geometric tolerance items is first generated based on the correlation between the parts. The part with the initial requirement is used as the start point of the transfer path of part-level geometric tolerance items. And it is directed to the lower part with structural constraints or functional requirements in turn, until the lower part is the last part. The transfer path of part-level can be divided into four basic forms: series path, parallel path, star path, and triangle path. On this basis, a mixed path which may be composed of multiple basic paths can be formed.

The series path is shown in Fig. 4a, and the path is $P_1 \rightarrow P_2 \rightarrow P_3$. The parallel paths include single-input parallel paths (Fig. 4b) and multi-input parallel paths (Fig. 4c). The star paths (Fig. 4d) refer to multiple unrelated parallel parts that have functional requirements or structural constraints with the same upper part. In the process of tolerance transfer, both parallel paths and star paths have a number of one-way paths with common nodes. In order to simplify the expression of the tolerance transfer process, it is necessary to expand the common nodes to obtain several series paths. For example, the parallel path shown in Fig. 4b can be decomposed into two series paths: $P_1 \rightarrow P_2 \rightarrow P_3 \rightarrow P_4$ and $P_4$.  

| Common meta-assembly joints | plane | cylinder | spherical |
|-----------------------------|-------|---------|----------|
| fit                         | tangent | tangent |
| coaxial                     | tangent |
| tangent                     | tangent |
| tangent                     | tangent |
| tangent                     | tangent |

Table 1: Common meta-assembly joints
In the triangle path (Fig. 4e), there are loops of upper and lower parts. In the construction of the path, different parallel parts can be selected in turn as the last part to obtain several series paths. In Fig. 4e, the triangle path can be decomposed.
into two series paths: $P_1 \rightarrow P_2 \rightarrow P_3$ and $P_1 \rightarrow P_3 \rightarrow P_2$. Based on the connection characteristics of triangle paths, polygonal paths can be derived.

### 4.2 Transfer path of geometric feature surface-level geometric tolerance items

According to the correlation between geometric feature surfaces, the transfer path of part-level can be further expressed as the transfer path of geometric feature surface-level. It consists of the geometric feature surface, the relationship between the surfaces, and the information about start position and direction. It can be constructed according to the following steps:

1. **Structural transformation of initial functional requirement**

   The initial design requirement is determined according to the functional requirements, and it can be transformed into a constraint correlation between the two related feature surfaces $F_{i,m}$ and $F_{j,n}$; here, the constraint correlation is mainly reflected as the distance requirement, position requirement, and orientation requirement.

   For example, the initial requirement is the distance requirement between the surface $F_{1,1}$ and $F_{1,3}$, as shown in Fig. 5.

2. **Establish transfer path of part-level**

   (1) If $i=j$, that is, the surfaces $F_{i,m}$ and $F_{j,n}$ belong to the same part $i$. Part $i$ is not only the start part but also the end part. The mating constraint between the parts is traversed, and the transfer path of part-level is established.

   (2) If $i \neq j$, part $i$ and part $j$ are set as the start part and end part respectively. The mating constraint between the parts is traversed, and the transfer path of part-level is established. For example, there are two series paths of part-level, in Fig. 5a and Fig. 5b:

$$P_1 \rightarrow P_2$$

### Fig. 3
(a) Assembly joint under gravity (b) Assembly joint under tightening force

### Fig. 4
(a) series path (b) single-input parallel path (c) multi-input parallel path (d) star path (e) triangle path

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Establish transfer path of geometric feature surface-level

(1) Establish transfer path of extended part-level

Based on the transfer path of part-level, the correlation information of the mating surface pairs is added to the path, and the transfer path of extended part-level is obtained. The path is shown in Fig. 5a.

Transfer path a1 of extended part-level:

\[ P_1 \xrightarrow{F_{1,1}} P_2 \xrightarrow{F_{2,1}} P_3 \] (5)

Transfer path a2 of extended part-level:

\[ P_1 \xrightarrow{F_{1,2}} P_2 \xrightarrow{F_{2,2}} P_3 \] (6)

(2) Establish transfer path of geometric feature surface-level

In addition to the transfer between the mating surfaces of different parts, the constraint correlation between the general structural surfaces in the parts is also an important link in the transfer of design requirements. The spatial position constraint between the general structural surfaces in the transfer path of extended part-level is added to form a continuous path of complete geometric tolerance.

The spatial position constraint between the general structural surfaces is expressed as follows:

\[ \dot{L}_{im, in} \xrightarrow{F_{im}} F_{in} \] (7)

where \( \dot{L}_{im, in} \) refers to the spatial position relationship between the general structure surfaces \( F_{im} \) and \( F_{in} \) in the part \( P_t \).

\( L_{im, in} \) includes fit constraints such as fit, coaxial, and tangent and position constraints such as vertical, parallel, and inclined.

Taking Fig. 5a as an example, the vertical constraint between the general structural surfaces \( F_{2,1} \rightarrow L_{21,22} F_{2,2} \) and \( F_{3,1} \rightarrow L_{31,32} F_{3,2} \) is an important link in the transfer of design requirements; therefore, they are added to the transfer path between mating surfaces to obtain the complete transfer path of geometric feature surface-level:

Transfer path b1 of geometric feature surface-level:

\[ F_{1,1} \xrightarrow{C_{11,21}} F_{2,1} \xrightarrow{L_{21,22}} F_{2,2} \xrightarrow{C_{22,12}} F_{1,2} \] (8)

Transfer path b2 of geometric feature surface-level:

\[ F_{1,3} \xrightarrow{C_{13,31}} F_{3,1} \xrightarrow{L_{31,32}} F_{3,2} \xrightarrow{C_{32,12}} F_{1,2} \] (9)

(3) Analysis of transfer path of geometric feature surface-level

Based on the above paths, in order to clearly express the transfer process of geometric tolerance between parts, the complex transfer paths such as parallel, star, and triangle paths are decomposed; that is, several independent series paths of part-level are obtained based on the expansion of common parts; on the basis, the mating constraints between the mating surfaces and the spatial position constraints of the general structure surface are added, and several transfer paths of geometric feature surface-level are obtained.

Due to the existence of common mating surfaces, correlation often exists between the abovementioned paths; it is necessary to combine those multiple transfer path of geometric feature surface-level. That is, when the same surface exists in multiple transfer path of geometric feature surface-level, it is used as a link to connect with the mating surfaces in the initial path in sequence. As shown in formula (8) and formula (9), \( F_{1,2} \) forms mating surface pairs with \( F_{2,2} \) and \( F_{3,2} \) in different paths, respectively. Therefore, \( F_{1,2} \) can be used as a common
mating surface to establish the correlation between two series paths b1 and b2. In this process, the combined path inherits the surface composition, the relationship between the surfaces and the transfer direction on the initial paths b1 and b2. The combined path is as follows:

\[
\begin{align*}
F_{1,1} & \xrightarrow{C_{11,21}} F_{2,1} & \xrightarrow{L_{21,22}} F_{2,2} & \xrightarrow{C_{22,12}} F_{1,2} \\
F_{1,3} & \xrightarrow{C_{13,31}} F_{3,1} & \xrightarrow{L_{31,32}} F_{3,2} & \xrightarrow{C_{32,12}} F_{1,2}
\end{align*}
\] (10)

### 4.3 The order for transfer paths of geometric tolerance items

For the same design requirement, when there are multiple transfer paths of part-level or geometric feature surface-level, the order of transfer paths is important to the transfer process of geometric tolerance items. In order to determine the priority of multiple transfer paths, the following principles are proposed:

**Principle 1:** Principle of key part. Key part refers to the part that undertakes main functions, and it is correlated with other parts in the path. For the part-level path, the priority of the path containing the key part is high; when the key parts exist in multiple paths, the path priority of the main function is the highest.

**Principle 2:** Principle of primary assembly joint. For several transfer paths of geometric feature surface-level extended from the same part-level path, the transfer path containing the primary assembly joint has a higher priority.

**Principle 3:** Principle of the shortest path. For transfer paths of part-level (or geometric feature surface-level) that have the same start part (or surface) and end part (or surface), they contain key parts and primary assembly joints as well, and the path with fewer parts (or surfaces) has higher priority.

### 5 Generation and transfer of geometric tolerance items

#### 5.1 Structural transformation of functional requirements

To ensure the realization of specific functions, multiple topological constraints often exist between product constituent units.

In the process of top-down design, the function decomposition and reconstruction is carried out. And the geometric features can be generated according to the sub-function and the correlated constraints; this process is embodied in a hierarchical structure, as shown in Fig. 6. Firstly, based on the existing design knowledge, the function planning is carried out through multivariate conflict resolution to produce the functional combination of products or units. This is the first level. Then, the functional planning scheme is extended to obtain the concept combination of parts to meet the functional requirements. This is the second level. On this basis, the information of geometric features is extracted to form the functional structure attributes between the geometric feature elements. This is the third level. Finally, the shape and position constraints between the geometric feature elements are defined, and the transformation between function and geometric features is established. This is the fourth level.

Based on the above process, the function constraint indirectly acts on the combination process of the sub-feature units, which transforms the target functions into the mating structures and the mating behaviors. And then they are transformed into the shape and position constraints between the parts. These shape and position constraints can be further transformed into specific structural requirements such as distance, direction, shape, and position between geometric features; thus the structural transformation of functional requirements and their correlations are fulfilled.

#### 5.2 Generation of geometric tolerance items based on structural attributes

The design requirements are divided into functional requirements and structural constraints. The structural transformation method of functional requirements is given in 5.1, based on which the unified expression of functional requirements and structural constraints can be realized. On this basis, the generation of geometric tolerance items can be realized based on the correlation specifications between geometric tolerance items and structural attributes.

During design process, the product structure attributes that directly affect the generation of geometric tolerance items mainly include the structural correlations between the parts or the surface, as well as the attributes of the assembly joints.

#### 5.2.1 Generation of geometric tolerance items based on design requirements

The geometric tolerance item is determined by the structure type of surface and its constraint type. The commonly used surfaces in engineering are mainly planes and cylinders, while the constraint types between surfaces mainly include distance requirements, orientation requirements, position requirements, and shape requirements. Based on the above surface types and constraint types, the specifications for generating
geometric tolerance items based on the design requirements can be obtained as shown in Table 3.

### 5.2.2 Generation of geometric tolerance items based on assembly joint attribute

According to attribute information such as the surface type, constraint requirements, and priority order that compose the assembly joints, the generation specification of geometric tolerance items based on assembly joint attribute can be constructed.

For the meta-assembly joints (as MJ in Table 4) that constitute the composite assembly joint:

1. When the meta-assembly joint is the primary assembly joint, the geometric tolerance items of the mating surface are self-reference tolerances such as profile tolerance or shape tolerance.
2. When the meta-assembly joint is the secondary assembly joint, the mating surface of the primary assembly joint is used as the datum. And the geometric tolerance items are cross-reference tolerances, that is, direction tolerance, position tolerance, or profile tolerance. Specific tolerance items can be derived according to the surface type and design requirements, as shown in Table 3.
3. When the meta-assembly joint is the third assembly joint, the mating surface of the primary assembly joint is the first datum, and the mating surface of the secondary assembly joint is the second datum. The geometric tolerance items are cross-reference tolerances, that is, direction tolerance, position tolerance, or profile tolerance. Specific tolerance items can be derived according to the surface type and design requirements, as shown in Table 3.

For the composite assembly joints (as J1~J6 in Table 4):

4. Firstly, the position constraints should be considered. The geometric tolerance items of the mating surfaces are same, when the position constraint between the meta-assembly joints is consistent with the type of mating constraints between the mating surfaces. And when the two constraints are inconsistent, the position constraints between the meta-assembly joints should be guaranteed first and then the constraints between the mating surfaces.
5. On the basis of (4), the geometric tolerance items are selected for the meta-assembly joints that constitute the composite assembly joints according to (1), (2), and (3).

For example, for the composite assembly joint “\( J_1 MJ_1 \rightarrow \text{fit} MJ_2 \)” in Table 4, the position constraint type between the meta-assembly joint MJ1 and MJ2 and the mating constraint type between the two mating surfaces forming MJ1 and MJ2 are all plane fit. So the geometric tolerance items are all flatness. On the other hand, for the composite assembly joint “\( J_2 = MJ_1 \rightarrow \text{parallel} MJ_2 \)” in Table 4, the position constraint type between the meta-assembly joints MJ1 and MJ2 is parallel, and the mating constraint type between the two mating surfaces forming MJ1 and MJ2 is fit. Therefore, priority is given to ensure that the position constraints between the meta-assembly joints are parallel. When the meta-assembly joint is used as the primary assembly joint, the surface profile not only ensures the shape of surface, but also restricts the position between the surfaces. So the surface profile can be selected. When the meta-assembly joint is used as the secondary assembly joint or the third assembly joint, the cross-reference tolerance is selected according to the position relationship between the surfaces.

### 5.2.3 Datum transfer based on assembly joint

With the decomposition of the initial functional requirements, the geometric tolerance items gradually decomposed to the part and the surface. In this process, the datum also gradually
Table 3 Specification for geometric tolerance generation based on design requirements

| Constraint types           | Surface types                        | Design requirements | Geometric tolerance specification |
|---------------------------|--------------------------------------|---------------------|-----------------------------------|
|                           | plane-plane                          |                     |                                   |
|                           | distance requirements                |                     |                                   |
|                           | cylinder-cylinder                    |                     |                                   |
|                           | plane-cylinder                       |                     |                                   |
| parallel                  | plane-plane                          |                     |                                   |
|                           | cylinder-cylinder                    |                     |                                   |
| orientation requirements  | plane-plane                          |                     |                                   |
|                           | inclined cylinder-cylinder           |                     |                                   |
|                           | plane-cylinder                       |                     |                                   |
| vertical                  | plane-plane                          |                     |                                   |
|                           | cylinder-cylinder                    |                     |                                   |
| position requirements     | coaxial cylinder-cylinder            |                     |                                   |
|                           | symmetrical plane-plane              |                     |                                   |
migrates from the product-level to the part-level and the geometric feature surface-level with the decomposition of the assembly joints. During this process, two specifications should be followed:

**Specification 1:** When the initial datum is one of the mating surfaces, the datum will be transferred to another mating surface with the decomposition of the assembly joint, as shown in Fig. 7a. When the types of the two mating surfaces are the same, and the transferred datum and the initial measured element belong to the same part, the geometric tolerance items of the measured element relative to the datums are consistent with the initial tolerance items; when the types of the two mating surfaces are inconsistent, that is, the type of the datums changes after the transfer, the geometric tolerance items of the measured element relative to the datums are selected according to Table 3. At the same time, in order to ensure the accuracy of geometric tolerance transmission, the datum is added with shape and position constraints, and its geometric tolerance items need to be determined according to Table 4.

As shown in Fig. 7b, the surface F1,1 is referenced to the F2,1 with positional requirements, according to structural transformation of the initial functional requirements. The surfaces F2,1 and F1,2 cooperate with each other to form the primary assembly joint, and the surfaces F2,2 and F1,3 form the secondary assembly joint. With the transmission of geometric tolerances, the datum migrates from F2,1 to F1,2 inside the assembly joint. According to the above specifications, the initial measured element F1,1 still maintains the position tolerance requirements relative to the new datum F1,2. To ensure the accuracy of tolerance transmission, according to Table 4, the geometric tolerance items of the mating surfaces F1,2 and F2,1, which constitute the primary assembly joint, are flatness; the geometric tolerance items of the mating surfaces F1,3 and F2,2, which constitute the primary assembly joint, are perpendicularity.

**Specification 2:** When the initial datum is not mating surface, the orientation and position requirements of the initial measured element relative to the initial datum are converted into the following three geometric tolerance requirements:

1. The orientation and position requirements of the initial measured element relative to the new datum in the same part where the initial measured element is located.
2. The shape and position requirements of the mating surfaces.
3. The orientation and position requirements of the mating surface relative to the initial datum in the part where the initial datum is located.

As shown in Fig. 8, the initial design requirement is the position requirement of the measured element F1,1 relative to the datum F2,3, where the initial datum F2,3 does not form an assembly joint. With the transmission of geometric tolerances items, the initial geometric tolerances items will be decomposed. In P1 where the measured element is located, F1,1 should have position requirements relative to the new datum F1,2; In the part P2, the mating surface F2,1 constituting the primary assembly joint is relative to the initial datum F2,3 to ensure the position requirement. In the primary assembly joint formed by the mating surfaces F2,1 and F1,2, and the secondary assembly joint formed by F2,2 and F1,3, the flatness and perpendicularity tolerance items are generated according to Table 4. In the part P2 where the initial datum F2,3 is
Table 4 Specification for geometric tolerance generation of assembly joint

| Joint Type | Surface | Primary Joint | Secondary Joint | Third Joint |
|------------|---------|---------------|-----------------|------------|
| $MJ = \text{plane}$ | ![Diagram](image1) | ![Diagram](image2) | ![Diagram](image3) | ![Diagram](image4) |
| $MJ = \text{cylinder}$ | ![Diagram](image5) | ![Diagram](image6) | ![Diagram](image7) | ![Diagram](image8) |
| $J_1 = MJ_1 \rightarrow MJ_2$ | ![Diagram](image9) | ![Diagram](image10) | ![Diagram](image11) | ![Diagram](image12) |
| $J_2 = MJ_1 \rightarrow MJ_2$ | ![Diagram](image13) | ![Diagram](image14) | ![Diagram](image15) | ![Diagram](image16) |
| $J_3 = MJ_1 \rightarrow MJ_2$ | ![Diagram](image17) | ![Diagram](image18) | ![Diagram](image19) | ![Diagram](image20) |
| $J_4 = MJ_1 \rightarrow MJ_2$ | ![Diagram](image21) | ![Diagram](image22) | ![Diagram](image23) | ![Diagram](image24) |
located, the mating feature surface $F_{2,1}$ where the primary assembly joint is located should have a direction position requirement relative to the initial datum $F_{2,3}$.

6 The transfer process of geometric tolerance items based on assembly joints

The top-down transfer process of geometric tolerance items is shown in Fig. 9. Starting with the initial design requirements, the initial geometric tolerance items are transferred from the product-level to the part-level, finally to the geometric feature surface-level along the transfer paths of part-level and geometric feature surface-level, within the constraints of functional requirements and structural correlations. The process mainly includes the following 6 steps:

1. Determination of initial geometric tolerance item

According to the design requirements and structural constraints of the product, the initial geometric tolerance items are determined (refer to Table 3).

2. Accomplish the structural transformation of functional requirements

Parts and surfaces are analyzed from the aspect of functional requirements, and function correlations are extracted, based on which the transformation model of functional requirements is constructed, and structural transformation of functional requirements is realized.

3. Determine the order of assembly joints

According to the mating surface composition of the assembly joints and the type of constraint correlation, the degree of freedoms analysis is performed to determine the order of the assembly joints.

4. Construct the transfer path of geometric tolerance items

1. Construct the transfer path of part-level

The transfer path of part-level geometric tolerance items is generated, with parts related to functional or structural associations as nodes, along the sequence of upper parts pointing to lower parts. Finally, the paths are ordered.

2. Construct the transfer path of geometric feature surface-level

Based on the functional requirements and structural constraints of the mating surfaces, as well as the shape and position constraints between the general structural surfaces, the transfer paths of geometric feature surface-level are generated and ordered.

5. Transfer of geometric tolerance items based on structural constraints

1. Selection of geometric tolerance items based on structural constraints

Based on the shape and position constraints between the functional elements and the structural constraints between the surfaces, the geometric tolerance items of the start part are selected.
According to the position of the datum, the datums are transferred between assembly joints and the general structure surface, respectively. The position tolerance is added to the parts where the datums are located, and the shape tolerance is added to the mating surface to ensure the mating accuracy.

(3) Path-based geometric tolerance items transfer

The geometric surface where the initial design requirements are located is used as the start surface, and the geometric tolerance items are transferred in the direction of the geometric tolerance transfer path. The geometric tolerance items are transferred sequentially to the related surfaces until the surface is the geometric surface corresponding to the initial design requirements in the end part.

7 Example

The transmission parts and connection parts in the crankshaft-piston mechanism are taken as examples to verify the top-down transfer method of geometric tolerance items. The crankshaft-piston mechanism converts the reciprocating motion of the piston into the rotational motion of the crankshaft and at the same time converts the pressure on the piston into the torque output of the crankshaft, so as to drive the load. The mechanism is mainly composed of piston, connecting rod group and crankshaft, as shown in Fig. 10.

Among them, the piston pin P2, the retaining ring P3, the bolt P6, and the nut P10 are standard parts. So there is no need to analyze them for geometric tolerances.

The allocation process of the mechanism’s geometric tolerance items is as follows:

(1) According to the functional requirements and structural constraints of the crankshaft-piston mechanism, the initial geometric tolerance items are determined.

In order to avoid piston pulling, abnormal wear of the main bearing, increased oil consumption and other defects, improve service life, the parallelism error among the piston pin hole, connecting rod journal, crankshaft, and other parts should be effectively controlled. Therefore, the initial design requirement of the crankshaft-piston mechanism is that the pin hole axis l1, the rod journal axis l2, and the crankshaft journal axis l3 remain parallel (refer to Table 3); the initial geometric tolerance items of related parts can be determined, as shown in Fig. 11.

(2) Structural transformation of functional requirements
According to the functional requirements and structural constraints, the functional surface of each part in the crank-piston mechanism is extracted, as shown in Fig. 12.

Based on the function decomposition, the mechanism includes two main functions: transmission and connection. Among them, the transmission function is mainly realized by the parts P1, P2, P5, P9, and P11. The connection function is undertaken by the parts P6, P5, P9, and P10. Take transmission function and connection function as examples. Firstly, the transmission and the connection function requirements are transformed into the position relationship between the surfaces, and the shape and position constraints are established, based on which the structural transformation of functional requirements is realized. The transformation model of crankshaft-piston mechanism’s functional requirements is shown in Fig. 13.

(3) Determine the order of assembly joints

The mating surface composition of all assembly joints between the transmission parts and the connection parts and their constraint types are analyzed. And the order of multiple assembly joints between the two associated parts is judged according to the related rules, as shown in Table 5.

(4) Construct the transfer path of geometric tolerance items

(1) Construct the transfer path of part-level

According to the initial design requirements and structural constraints between the parts, the piston P1 and the crankshaft P11 can be set as the start part and the end part, respectively, and other transmission parts are the intermediate nodes. The transfer path of part-level geometric tolerance items based on the transmission function, named path I, is constructed. Similarly, transfer paths II and III based on the connection function can be established. Since part P6 and P10 in path III are standard parts, path III can be ignored.

\[
P_1 \rightarrow P_2 \rightarrow P_5 \rightarrow P_{11} \quad \text{(11)}
\]

\[
P_6 \rightarrow P_5 \rightarrow P_9 \rightarrow P_{10} \quad \text{(12)}
\]

\[
P_6 \rightarrow P_{10} \quad \text{(13)}
\]

(2) Construct the transfer path of extended part-level

In the part-level paths I and II, the related information of mating surface pairs are added to obtain the transfer paths of extended part-level named path a and path b.

\[
\begin{align*}
P_1 \xrightarrow{F_{1,1}} & P_2 \xrightarrow{F_{2,1}} P_5 \xrightarrow{F_{5,1}} P_{11} \\
P_6 \xrightarrow{F_{6,1}} & P_{10} \xrightarrow{F_{10,1}} P_1
\end{align*}
\]
Construct the transfer path of geometric feature surface-
level.

The extended part-level path $a$ and $b$ are further represented
graphically. The position constraint between the general struc-
ture surfaces in the part is added, based on which the graphical

\[
\begin{align*}
  b & \xrightarrow{F_{6,1}} P_6 \xrightarrow{F_{5,2}} P_5 \xrightarrow{F_{5,4}} F_{5,3} \xrightarrow{F_{5,5}} P_3 \xrightarrow{F_{10,1}} P_{10} \\
  F_{6,1} & \xrightarrow{F_{6,3}} F_{5,3} \xrightarrow{F_{5,2}} P_9 \xrightarrow{F_{9,1}} F_{9,2} \xrightarrow{F_{9,3}} P_{10} \\
  \end{align*}
\] 

(15)
representation of the geometric feature surface-level is obtained. As shown in Fig. 14a, in order to ensure transmission accuracy, the axis of hole \( F_{5,1} \) needs to be parallel to the axis of hole \( F_{5,5} \); therefore, the position constraint “parallel” is added between general structural planes \( F_{5,1} \) and \( F_{5,5} \). As shown in Fig. 14b, since the two meta-assembly joints composing the composite assembly joint \( J_{5,6} \) should be vertical according to the design requirement, “vertical” constraint should be added between the general structural surfaces \( F_{5,3} \) and \( F_{5,2} \). Similarly, “vertical” constraints should be added between the surfaces \( F_{9,2} \) and \( F_{9,3} \).

Based on the abovementioned result, the surfaces are sequentially connected according to the initial transfer direction, and the continuous transfer paths of geometric feature surface-level i, ii, and iii are obtained:

![Fig. 14](a) geometric feature surface-level transfer path based on path a (b) geometric feature surface-level transfer path based on path b
Table 6

| Initial Surface | F1,1 | F5,3 | F5,2 |
|-----------------|------|------|------|
| Tolerance Item  |     |      |      |

The order of the meta-assembly joints that constitute the composite assembly joints is analyzed to rank multiple geometric feature surface-level paths generated under the same functional requirement. The part-level path b includes two composite assembly joints J5,6 (f2) and J5,9 (f2). According to the principle of primary assembly joint, the mating surfaces F6,2 and F5,3 which constitute the primary assembly joint have priority over F6,1 and F5,2, and the mating faces F5,4 and F9,1 which constitute the primary assembly joint have priority over F9,2, F5,2. So the path ii through the surface F5,3, F5,4, and F9,1 with F6,2 as the start surface has a high priority.

(5) Transfer of geometric tolerance items based on structural constraints

(1) Selection of initial tolerance items in the path

Firstly, the geometric tolerance items are determined for the initial surface (non-standard parts) of each geometric feature surface-level transfer path. When the initial surface is a mating surface, the geometric tolerance items can be selected according to the function requirements, surface types, and the order of assembly joints by referring to Table 3 and Table 4. When the initial surface is a general structural surface, the geometric tolerance items can be selected according to its functional requirements, surface types, the shape, and position constraints by referring to Table 3.

In this example, the mating surface F1,1 is the initial surface of the transfer path i, the primary assembly joint J11,21 is formed by F1,1 and F2,1, and the design requirement is that the two cylinders F1,1 and F2,1 are coaxial. Therefore, the mating surfaces F1,1 and F2,1 must have cylindricity tolerance requirements, referring to Table 4; similarly, the geometric tolerance item of the initial surface F5,3 of path ii is cylindricity. The mating surface F5,2 is the initial surface of the path iii, which forms the secondary assembly joint J52,61 with F6,1. And the design requirement is that F5,2 and F6,1 fit together, so the geometric tolerance item is “perpendicularity” with the mating surface F5,3 as the datum. The geometric tolerance items corresponding to the initial surface in each transfer path of geometric feature surface-level are shown in Table 6.

\[ F_{6,2} \rightarrow \text{coaxial} \rightarrow F_{5,3} \rightarrow \text{vertical} \rightarrow F_{5,4} \rightarrow \text{fix} \rightarrow F_{9,1} \]  
\[ F_{6,1} \rightarrow \text{fix} \rightarrow F_{5,2} \rightarrow \text{vertical} \rightarrow F_{5,3} \rightarrow \text{coaxial} \rightarrow F_{9,2} \rightarrow \text{vertical} \rightarrow F_{9,3} \rightarrow \text{fix} \rightarrow F_{10,1} \]  

Fig. 15  Transfer of datums under the initial design requirement

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according to the shape and position constraints between the surfaces (see Table 3). When two adjacent surfaces in the path are the general structural surfaces of the same part, the geometric tolerance items are transferred according to their shape and position constraints (see Table 3). In this process, if the mating surface belongs to a standard part, it is only taken as the transfer node, and no tolerance item is assigned to it.

The transfer path of geometric feature surface-level of the crankshaft-piston mechanism is shown as follows:

\[
\begin{align*}
F_{1,1} & \rightarrow F_{2,1} \rightarrow F_{3,1} (\varphi) \rightarrow F_{4,1} (\varphi) \rightarrow F_{5,1} (\varphi) \\
F_{6,2} & \rightarrow F_{5,3} (\varphi) \rightarrow F_{5,4} (\varphi) \rightarrow F_{9,1} (\varphi)
\end{align*}
\]

F\_{2,1}, F\_{6,2}, F\_{6,1}, and F\_{10,1} in the above path are all surfaces of standard parts, so only the correlations characteristics of them are analyzed without considering their geometric tolerance items.

(6) Summary of geometric tolerance items

According to the above rules and specifications, the geometric tolerance items of each part in crankshaft-piston mechanism can be obtained, as shown in Fig. 16.

8 Conclusion

In order to solve the mapping of function, structure, and geometric tolerance and realize the top-down analysis of geometric tolerance, a transfer method of geometric tolerance items based on assembly joints is proposed. The method has the following characters:

(1) The top-down transfer process of geometric tolerance items at part-level and geometric feature surface-level is defined, which is helpful to realize the synchronous design of geometric tolerance and product structure.

(2) The structural transformation model of functional requirements is established to realize the unified expression of geometric tolerance semantics; the assembly joint is regarded as the basis of geometric tolerance items. By defining the structural information such as joint type, mating surface type, constraint type, and DOF constraint, the functional requirements and structural constraints between parts and surfaces are fully expressed; the generation and transfer rules of tolerance items based on assembly joints are established, which lays a foundation for the selection of tolerance items.

(3) Based on the functional requirements and structural constraints, the transfer paths of geometric tolerance items at part-level and geometric feature surface-level are established; on this basis, the functional requirements are transformed into geometric tolerance items of the initial surface in the transfer path; the tolerance items between the same type of mating surfaces are copied along the path; the tolerance items between different types of mating surfaces and general structural surfaces are transformed; at the same time, with the transfer of datum, the transfer of tolerance items is completed. The establishment of transfer paths improves the efficiency of tolerance design and facilitates the automation and standardization of geometric tolerance design process.

Potential future studies related to this work are as follows: Firstly, the geometric tolerance analysis of complex surface has not been involved. How to take the complex surface as the basic mating surface of assembly joint and study the
mechanism of tolerance transformation will be the content of further study; in addition, some atypical parts have the ambiguity of functional requirements analysis. How to accurately extract and analyze functional semantics and ensure the objectivity of structural transformation of functional requirements is also an important content to be studied in the future.

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