Tolerance synthesis: quantifier notion and virtual boundary

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Abstract
The purpose of functional tolerancing process is to define the geometrical specifications of parts ensuring functional requirements. For automotive and aircraft industries, the tolerance synthesis has become an important issue in product design process. Indeed, designers need methods and rules to determine the tolerances. To define rules, a mathematical formulation of tolerance synthesis is detailed. This mathematical formulation of tolerance synthesis simulates the influences of geometrical deviations on the geometrical behavior of the mechanism, and integrates the quantifier notion (existential quantifier ‘there exists’ and universal quantifier ‘for all’). It takes into account not only the influence of geometrical deviations but also the influence of the types of contacts on the geometrical behavior of the mechanism; these physical phenomena are modeled by convex hulls (compatibility hull, interface hull and functional hull) which are defined in parametric space. With this description by convex hulls, a mathematical expression of the admissible deviations of parts integrates the quantifier notion. This notion translates the concept that a functional requirement must be respected in at least one acceptable configuration of gaps (existential quantifier there exists), or that a functional requirement must be respected in all acceptable configurations of gaps (universal quantifier for all). With this approach, some rules are formalized to determine the modifier (maximum material condition or minimum material condition) function from the type of quantifier. These rules have been performed with success in French automotive industries.

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1. Introduction
The geometrical variations of parts involve a degradation of functional characteristics of mechanisms. Tolerance synthesis studies the influence of these geometrical variations of parts on the geometrical behavior of the mechanism and on the functional requirement. These geometrical variations must be limited by tolerances to ensure a certain level of quality.

For automotive and aircraft industries, the tolerance synthesis has become an important issue in product design process. Significant body of literature is related to tolerancing methods. Summaries of state of the art, the most recent developments, and the future trends in tolerancing research can found in Refs. [6,39] as well as in a number of survey papers such as Refs. [3,7,22,26,34,37].

Indeed, designers use rules to determine the tolerances; an example of rules [4]:

- for an assembly requirement or a minimal clearance requirement, the functional virtual boundary of a feature of size is the maximum material condition.
- for a maximum clearance requirement or maximum deviation requirement, the functional virtual boundary of a feature of size is the least material condition.

This article completes these rules and focuses on the quantifier notion for tolerance synthesis. This notion translates the concept that a functional requirement must be respected in at least one acceptable configuration of gaps (existential quantifier ‘there exists’), or that a functional requirement must be respected in all acceptable configurations of gaps (universal quantifier ‘for all’). A configuration is a particular relative position of parts of an assembly depending of gaps without interference between parts. This quantifier notion permits to formalize a mathematical
formulation of tolerance synthesis and to deduce some rules to determine the modifier (maximum material condition or least material condition) for all functional requirements and for all assembly process requirements:

If [considered feature = feature of size] and [contact = floating] and [requirement must be respected in at least one acceptable configuration of gaps (\(\exists\))] then the functional virtual boundary of this considered feature is the maximum material condition.

In the last decade, a significant amount of research has been devoted to the development of specification models [3, 23,25,37] with virtual boundary. Jayaraman and Srinivasan have proposed conditional tolerancing and virtual gauge methodologies to define the Virtual Boundary Requirement (VBR) \([17]\). More recently, Robinson proposes the application of an Maximum Material Part, Least Material Part (MMP–LMP) tolerancing principle, which is an extension of the Maximum Material Condition and Least Material Condition (MMC and LMC) modifiers \([24]\). For these approaches, we can notice that a geometrical specification is restricted to maximum material requirement or least material requirement. The quantifier notion completes these approaches and justifies the use of a specification with MMC and LMC modifiers.

Moreover, an amount of research has been devoted to the development of tolerance analysis \([2,13–15,18,19,28,29,33,35,41]\) and synthesis \([1,4,8,10,12,24]\). Usually, tolerance synthesis is determined from a specification model. Like that, some tolerance syntheses are developed from the tolerance zone approach by Fleming \([12]\) and Robinson \([24]\). Some others are based on variational geometry \([13,15,16]\), at last, some are based on vectorial tolerancing \([2,8,14,18,19,28,29,36]\). For example, in tolerance synthesis based on tolerance zone, inequalities expressing the fact that the tolerated features have to be in tolerance zones are introduced. The conditions on the features are known, the unknowns are the values of the tolerances of these conditions. In this article, a tolerance synthesis is elaborated without any a priori on a specification model. The conditions on the features are unknown, they are searched.

Section 1 provides an informal introduction to the quantifier notion. Mathematical formulation is developed in Section 2. In Section 4 an industrial application with some rules deduced of the mathematical formulation is detailed.

2. Quantifier notion for geometrical product requirement—expression and its effects

By using functional analysis method, designers define major functional requirements and technical requirements that allow to determine the geometrical product requirements which are geometrical constraints between product’s surfaces.

In this section, the quantifier notion is illustrated with a geometrical requirement of a simple mechanism which permits a linear movement (Fig. 1). The base 1 is in permanent connection with the shaft 3 by a cylindrical pair. The part 2 is in cylindrical pair with this shaft. A geometrical product requirement limits the orientation variation between surfaces 1b and 2c.

2.1. Quantifier notion for geometrical product requirement—expression

To express this geometrical product requirement, some designers define a condition on the functional characteristic between product surfaces: angle (PL1b, PL2c) \(\leq\) \(\delta\) (Fig. 2a). These product surfaces are substitute surfaces identified by an operation of association \([42]\). The functional characteristic defines the variation of the angle between two substitute surfaces in functional relation.

Indeed, a mechanism is a set of parts with joints. Most of joints have functional gap. These gaps induce displacements between parts. Each relative position defines a configuration of the joint. A configuration is a particular relative position of parts of an assembly depending of gaps without interference between parts. The product geometrical requirement limits the orientation variation between two surfaces of the mechanism, which are in functional relation. This requirement is a condition on the functional characteristic between these surfaces. As the mechanism includes a floating contact, the relative orientation of these surfaces depends on the configuration, which is not single (Fig. 2b). Therefore, the value of the functional characteristic depends on the configuration of the mechanism. There is an ambiguity in the expression of the requirement because the considered configuration is not described. In which configuration, the condition of the geometrical requirement...
must be checked. The expression of the geometrical product requirement is not univocal.

Hence, to define a univocal expression of the condition corresponding to a geometrical product requirement, this expression is completed by a quantifier ($\exists$ or $\forall$) [9]. The quantifier translates the concept that the condition must be respected in at least one configuration of the mechanism ($\exists$), or that the condition must be respected in all configurations of the mechanism ($\forall$).

- In the case of the quantifier $\exists$, if there exists one configuration of the mechanism such as the value of the functional characteristic is less than or equal to the tolerance, then the geometrical product requirement is respected.
- In the case of the quantifier $\forall$, if for all configurations of the mechanism, the value of the functional characteristic is less than or equal to the tolerance, then the geometrical product requirement is respected.

2.2. Quantifier notion for geometrical product requirement—its effects

If the geometrical product requirement must be respected in at least one configuration, these gaps enable a positioning adjustment of parts; they facilitate the respect of the geometrical product requirement. Therefore, if the geometrical product requirement is respected when the gaps are least, then for all admissible gap values there exists a configuration of the mechanism such as the geometrical product requirement is respected. To ensure a minimum gap, the virtual boundary is maximum material condition (Fig. 3a).

If the geometrical product requirement must be respected in all configurations, the gaps do not make easier the respect of the geometrical product requirement. Therefore, if for all configurations of the maximum gaps the geometrical product requirement is respected, then for all admissible gap values the geometrical product requirement is respected. To limit the maximum gap, the virtual boundary is least material condition (Fig. 3b).

The quantifier notion conditions the determination of the expression of geometrical specifications of parts (maximum material condition or least material condition). It allows to define a univocal expression of the geometrical product requirement, it reduces the correlation uncertainty [43], which is the non-correlation between the design intent and the actual specification [9]. In Section 3, the quantifier notion makes it possible to formalize a mathematical formulation of tolerance synthesis.

3. Mathematical formulation of tolerance synthesis

The best way to determine the optimal tolerances is to simulate the influences of deviations on the geometrical behavior of the mechanism. Usually, for mathematical formulation of tolerance synthesis, the geometrical behavior is described using different concepts as Variational geometry [16,25], Geometrical behavior law [2], Clearance space and deviation space [14,27,36], Gap space [41], Genetic algorithms [20] and kinematic models [11,28,38].

We principally need a detailed description of each variation...
to characterize the geometrical behavior [15]. Two main approaches can be distinguished: by tolerance zone around theoretic geometry [24] or by parameterization of deviations from theoretic geometry [2,8,14,35].

The approach used in this article is a parameterization of deviations from theoretic geometry, the real geometry of parts is apprehended by a variation of the nominal geometry. The substitute surfaces model these real surfaces (Fig. 4). This parameterization of variations is detailed in Section 3.1, it enables to define a variations parametric space, in which each coordinate system axis represents a parametric variable.

The mathematical formulation of tolerance synthesis takes into account not only the influence of geometrical deviations on the geometrical behavior of the mechanism and on the geometrical product requirements, but also the influence of the types of contacts on the geometrical behavior [10,29]; all these physical phenomena are modeled by convex hulls (compatibility hull, interface hull and functional hull; these convex hulls are detailed in Section 3.2) which are defined in the variations parametric space. A convex hull or a convex polytope may be defined as a finite set of points, or as the intersection of a set of half-spaces, or as a region of n-dimensional space enclosed by hyperplanes [5,40].

With this description by convex hulls, a mathematical expression of the admissible deviations of parts is detailed in Section 3.3.

3.1. Geometrical description by variations parametric space

Geometrical behavior model needs to be aware of the surface deviations of each part (situation deviations and intrinsic deviations) and relative displacements between parts according to gap (gaps and functional characteristics) [10]. Compared with the nominal model (Fig. 4a), each substitute surface has position variations, orientation variations and intrinsic variations [11,27]:

- The situation deviations define the orientation and position variations between a substitute surface and the nominal surface (Fig. 4c).
- The intrinsic deviations of substitute surface are specific to their type. They define the surface variations. For instance, the intrinsic variation of a substitute cylinder is radius variation between the substitute cylinder and the nominal cylinder (Fig. 4c).

and also two types of relative displacements between parts:

- The gaps define the orientation and position variations between two substitute surfaces in contact [10,14,35] (Fig. 4b). Three types of contact are distinguished:
  - floating contact (Fig. 5a) (the two surfaces in contact have a possible normal relative displacement),
  - slipping contact (Fig. 5b) (the contact is held by a mechanical action between the two surfaces, and the mechanical action prevents normal relative displacement but not tangential relative displacement),
  - fixed contact (Fig. 5c) (the contact is held by a mechanical action between the two surfaces, and the adherence produced by a mechanical action prevents any relative displacement during a normal use of the mechanism).
- The functional characteristics define the orientation and position variations between two substitute surfaces in functional relation (Fig. 4b).

The deviation of parts, the gaps between parts and the functional characteristics between parts are described by parameters. Thereafter, the geometrical behavior of parts will be defined in space such as each coordinate axis corresponds to a parameter that is the variations parametric space [27]. Four types of subspace corresponding to the four

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Fig. 4. Substitute and nominal models—variations description.

Fig. 5. Types of contact.
types of parameters are distinguished:

<table>
<thead>
<tr>
<th>Subspace name</th>
<th>Column vector</th>
<th>Designation</th>
</tr>
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<tbody>
<tr>
<td>Situation</td>
<td>( s )</td>
<td>Space of all situation deviations of parts</td>
</tr>
<tr>
<td>Intrinsic</td>
<td>( i )</td>
<td>Space of all intrinsic deviations of parts</td>
</tr>
<tr>
<td>Gap</td>
<td>( g )</td>
<td>Space of all gaps between parts</td>
</tr>
<tr>
<td>Functional characteristic</td>
<td>( fc )</td>
<td>Space of all functional characteristics between parts</td>
</tr>
</tbody>
</table>

‘Situation’ represents the space of all situation deviations. The symbol \( s \) always denotes a column vector in Situation space. Each component of the column vector \( s \) is a situation deviation parameter. Intrinsic space, Gap space and Functional characteristic space are defined in the same manner.

3.2. Geometrical behavior description by convex hulls

The tolerancing synthesis model is based on the expression of the geometrical behavior of the mechanism; various hulls modeling the geometrical behavior of the mechanism are defined:

- the relations between small displacements of surfaces of parts lead to the compatibility hull (\( D_{compatibility} \)). Composition relations of displacements in the various topological loops (Fig. 1) express the geometrical behavior of the mechanism. The composition relations define compatibility equations between the situation deviations and the gaps [2]. The set of compatibility equations, obtained by the application of composition relation to the various cycles, makes a system of linear equations. So that the system of linear equations admits a solution, it is necessary that compatibility equations are checked. These compatibility equations characterize some hyperplanes in the Situation × Gap × Functional characteristic space.

- the constraints of contacts between parts surfaces nominally in contact lead to the interface hull (\( D_{interface} \)).
  
  Interface constraints limit the geometrical behavior of the mechanism and characterize non-interference or association between substitute surfaces, which are nominally in contact [28]. These interface constraints limit the gaps between substitute surfaces [10,14,35]. These constraints define the interface hull in Gap × Intrinsic space. In the case of floating contact, the relative positions of substitute surfaces are constrained technologically by the non-interference, the interface constraints result in inequations defined in Gap × Intrinsic space [10]. In the case of slipping and fixed contact, the relative positions of substitute surfaces are constrained technologically in a given configuration by a mechanical action. An association models this type of contact; the interface constraints result in equations defined in Gap × Intrinsic space [10].

- the functional constraints between part surfaces in functional relation lead to the functional hull (\( D_{functional} \)). The functional requirement limits the orientation and the location between surfaces, which are in functional relation. This requirement is a condition on the relative displacements between these surfaces. This condition could be expressed by constraints, which are inequations [14,27]. These constraints define the functional hull in Functional characteristic × Intrinsic space.

3.3. Relations between convex hulls

The objective of this mathematical formulation is to define the necessary and optimal constraints on deviations of each part, i.e. the vectors \( s \) and \( i \) [8]. The previous geometrical behavior description and the quantifier expression enable to define the admissible deviations of parts such as the functional requirement is respected. These admissible deviations form a hull in situation and intrinsic spaces called specification hull. To define it, we formalized a textual relation and a mathematical relation between various hulls.

In the case of the quantifier \( \exists \), the specification hull is defined as:

‘the deviations are admissible’ is equivalent to ‘there exists an admissible gap configuration of the mechanism and a functional characteristic such as the geometrical behavior and the functional requirement are respected’.

The mathematical expression of this equivalence is:

\[
(s.i) \in D_{specification} \iff \exists g \in \text{Gap} : (s.g.i) \in D_{compatibility} \cap D_{interface}, \exists fc \in \text{Functional characteristic}, : (s.g.i.fc) \in D_{compatibility} \cap D_{interface} \cap D_{functional}
\]

In the case of the quantifier \( \forall \), the specification hull is defined as:

‘the deviations are admissible’ is equivalent to ‘for all admissible gap configurations of the mechanism, there exists a functional characteristic such as the geometrical behavior and the functional requirement are respected’.

The mathematical expression of this equivalence is:

\[
(s.i) \in D_{specification} \iff \forall g \in \text{Gap} : (s.g.i) \in D_{compatibility} \cap D_{interface}, \exists fc \in \text{Functional characteristic}, : (s.g.i.fc) \in D_{compatibility} \cap D_{interface} \cap D_{functional}
\]
This quantifier notion enables to formalize the relations between hulls (compatibility hull, interface hull and functional hull) and specification hull. These relations are a theoretical formulation of tolerance synthesis [10].

4. Industrial application

In order to determine quickly the tolerances of parts for complex product like aircraft or car body, we propose a method with a graphical tool (this graphical tool is based on assembly graphs) and some rules. In the following, the set of rules is enhanced, because it allows the determination of the modifier according to the type of the quantifier. This method has been used to tolerance a piston compressor (Fig. 6a).

4.1. Tolerancing method

The first stage of the method consists in understanding the structure of the mechanism to express the geometrical functional requirement and to represent it by graphs (Fig. 6). A joints graph (Fig. 6b) modelizes the structure of the mechanism; each vertex represents part and each edge between two vertexes represents a kinematic joint. For the needs of tolerancing, the kinematic joint must be decomposed into elementary joints between surfaces. The contact graph (Fig. 6c) is an extension of the joints graph; each vertex represents a part, each pole of a vertex represents a surface of the corresponding part and each edge between two poles represents an elementary joint. To represent the geometrical behavior of the mechanism by the contact graph, the type of contact is associated at each edge (Fig. 6c).

By using functional analysis method, designers define major functional requirements and technical requirements. Moreover the technical functional analysis allows determining the geometrical functional requirements, which limit the functional characteristics of the mechanism [21,31,32]. A rectangular vertex (Fig. 6) represents these geometrical functional requirements. In the case of the piston compressor, the considered functional requirement ensures a minimal axial clearance between the piston (part 12) and the connecting rod (part 11), (Fig. 6); it must be respected in all acceptable configurations of gaps.

The second stage of the method consists in the determination of the influences of the parts, the surfaces or the deviations on the considered functional requirement. The graph analysis method was developed by Ballu and Mathieu [4]. Indeed, the key deviations (corresponding to

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**Fig. 6. Industrial example (piston compressor).**
the deviations of surfaces on which the functional requirement is dependent) are determined by using graph simplification rules. Designers study the impact of the deviations and the gaps on the considered functional requirement to define the functional cycles [30] (Fig. 7). All edges participating to the functional cycles have an impact on the realization of the geometrical functional requirement.

The determination of the tolerances constitutes the last stage of the method. The tolerances corresponding to a requirement are related to all the key surfaces of the key parts and strictly to them and limit the key deviations and strictly them [4,31]. To determine the functional tolerances of each part, the following criteria is adopted [1,4]:

– the choice of the datum must be realized according to the type of contact.
– the hierarchy of the datum system must be defined according to the predominance of surfaces.
– the choice of the type of the specification must be realized according to the type of the key deviations.

At the end, the choice of the modifiers is not as obvious as that can appear [30]. To help designers, a set of rules is proposed, which allows the determination of the modifier according to the type of quantifier.

### 4.2. Rules for the quantifier

To define the necessary and optimal tolerances and strictly them, for the features of size (cylinder, two parallel planes), requirements (maximum material requirement, least material requirement) could be applied. To do so, designers determine the functional virtual boundary of each part for the considered functional requirement with the following rules:

– for an assembly requirement or a minimal clearance requirement, the functional virtual boundary of a feature of size is the maximum material condition.

In Section 1, it is shown that these rules are not universally correct. For a maximum deviation requirement, the functional virtual boundary depends on the type of the quantifier.

Therefore, the quantifiers condition the determination of the modifiers (maximum material condition or minimum material condition). In Sections 1 and 2, we present the quantifier notion and a mathematical formulation integrating this quantifier notion. As seen before, the quantifier notion allows determining the modifier. We formulate some rules deduced of the mathematical formulation (Table 1).

In the case of the piston compressor, we just consider the connecting rod (part 11). Surfaces on which the considered functional requirement depends, are the two parallel planes (surfaces c, c, and d, d') and the cylinder (surface e), (Fig. 8). The key deviations of these surfaces are angular and linear (due to the lever arm). Thus, the specified characteristic is a location (Fig. 9a). The previous criteria allow to choose the datum system of the location specification. To the choice of the modifier, the rules (Table 1) are applied.

For the datum system, the contacts of the surfaces are floating (Fig. 8); the considered functional requirement must be respected in all acceptable configurations of gaps, so the functional virtual boundary of the features of the datum

<table>
<thead>
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<th>Table 1</th>
<th>Rules to determine the modifier</th>
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<tr>
<td><strong>Rule 1</strong></td>
<td>If {considered feature = feature of size} and {contact = floating} and {requirement must be respected in at least one acceptable configuration of gaps (\exists)} then the functional virtual boundary of this considered feature is the maximum material condition</td>
</tr>
<tr>
<td><strong>Rule 2</strong></td>
<td>If {considered feature = feature of size} and {contact = floating} and {requirement must be respected in all acceptable configurations of gaps (\forall)} then the functional virtual boundary of this considered feature is the least material condition</td>
</tr>
<tr>
<td><strong>Rule 3</strong></td>
<td>If {considered feature = feature of size} and {relation = functional requirement} and {functional requirement = minimal clearance} then the functional virtual boundary of this considered feature is the maximum material condition</td>
</tr>
<tr>
<td><strong>Rule 4</strong></td>
<td>If {considered feature = feature of size} and {relation = functional requirement} and {functional requirement = maximum clearance} then the functional virtual boundary of this considered feature is the least material condition</td>
</tr>
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</table>
system is the least material condition (Rule 2 of Table 1), (Fig. 9). Indeed, the gaps between the connecting rod and crankshaft (part 7) do not facilitate the respect of the functional requirement. For all acceptable configurations of these maximum gaps, the functional requirement must be respected. These gaps are at their maximum, when each of the mating features is at its least material size.

The tolerated feature is a feature of size, which is directly constrained by the functional requirement (Fig. 8). The functional requirement ensures a minimal axial clearance between the piston and the connecting rod. Hence, the functional virtual boundary of the tolerated feature is the maximum material condition (Rule 3 of Table 1), (Fig. 9). Indeed, the minimum clearance between the piston and the connecting rod occurs when the feature (c, c’) is at its maximum material size.

These rules (Table 1) are deduced of the mathematical formulations of functional tolerance synthesis and assembly tolerance synthesis [10]. Therefore, these rules are universally correct, they do not depend on the context, they are consistent with the designer’s intent. They enable an automatic determination of the modifier (maximum material condition or least material condition). They enable only a conceptual tolerance synthesis, they do not enable quantification of the tolerances.

The best way to quantify the tolerances is to simulate the mechanism variations. Two main approaches can be distinguished: worse-case analysis [15] and statistical analysis [22]. Tolerance analyses (worse-case analysis) need to be aware of the definition of variational class of the mechanism relative to each virtual boundary of each part [18]. To define each virtual boundary of each part, these rules can be used. This conceptual tolerance synthesis completes various approaches of tolerance analysis, and they enable a simulation of the worst geometrical behavior [18,19,28,29,32,41] (Fig. 10).

5. Conclusion

This article presented a mathematical formulation of tolerance synthesis taking into account the geometrical behavior and the quantifier notion. To define the optimal tolerances of parts, the expression of the functional requirement is completed by a quantifier (∃ or ∀). This quantifier translates the concept that the functional requirement must be respected in at least one acceptable configuration of gaps (∃), or that the functional requirement must be respected in all acceptable configurations of gaps (∀). This quantifier notion enables to formalize a relation between n-hulls that modelize the geometrical behavior of the mechanism, and specification hull that limits the deviations of parts. This mathematical formulation is a formal expression of tolerance synthesis.
The quantifier conditions the determination of the modifier (maximum material condition or least material condition). Moreover, this quantifier notion points out the fact that the following rules are not universally correct:

- for an assembly requirement or a minimal clearance requirement, the functional virtual boundary of a feature of size is the maximum material condition.
- for a maximum clearance requirement or maximum deviation requirement, the functional virtual boundary of a feature of size is the least material condition.

For an industrial application of the quantifier notion, some rules allow to determine the MMC/LMC modifier for all functional requirements and for all assembly process requirements. For designers, these rules facilitate the determination of the functional virtual boundaries of parts; they have been performed with success in French automotive industry.

References


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