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Statistical tolerance analysis of over-constrained mechanisms with gaps using system reliability methods☆

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HIGHLIGHTS

- Gaps cannot be considered as random variables.
- The tolerance analysis issue is formulated thanks to the quantifier notion.
- Two defect probabilities are defined: functionality defect probability and assembly defect probability.
- Defect probabilities are computed using a system reliability method: FORM system.

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ABSTRACT

One of the aims of statistical tolerance analysis is to evaluate a predicted quality level at the design stage. One method consists of computing the defect probability P_D expressed in parts per million (ppm). It represents the probability that a functional requirement will not be satisfied in mass production. This paper focuses on the statistical tolerance analysis of over-constrained mechanisms containing gaps. In this case, the values of the functional characteristics depend on the gap situations and are not explicitly formulated with respect to part deviations. To compute P_D, an innovative methodology using system reliability methods is presented. This new approach is compared with an existing one based on an optimization algorithm and Monte Carlo simulations. The whole approach is illustrated using two industrial mechanisms: one inspired by a producer of coaxial connectors and one prismatic pair. Its major advantage is to considerably reduce computation time.

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1. Introduction

In very competitive industrial fields such as the automotive industry, more and more interest is being paid to the quality level of manufactured mechanisms. It is very important to avoid warranty returns and manage the rate of out-of-tolerance products in production, which can lead to assembly line stoppages and/or wastage of out-of-tolerance mechanisms. The quality level of a mechanism can be evaluated by the number of faulty parts in production or by the number of warranty returns per year. However, these two methods of product quality evaluation remain *a posteriori*. Tolerance analysis is a more interesting way to evaluate a predicted quality level at the design stage. Scholtz [1] proposes a detailed review of classical methods whose goal is to predict functional characteristic variations based on component tolerances. Moreover, statistical tolerance analysis enables the definition of the probability that the functional requirement will be respected or not, as does the well-known RSS (Root Sum of Squares) method.

Advanced statistical tolerance analysis methods allow the defect probability of an existing design to be computed, knowing the dimension tolerances and functional requirements. These are called probabilistic approaches and this paper focuses mainly on them. Various assumptions about the statistical distributions of component dimensions can be made, based on their tolerances and capability levels. For example, the APTA (Advanced Probability-based Tolerance Analysis of products) method proposed by Gayton et al. [2] enables random mean deviations and standard deviations of components' statistical distributions to be considered during the whole manufacturing phase. Defect probability, noted P_D in the following, is expressed in ppm (parts per million). It represents the probability that a functional requirement will not be satisfied in mass production. In a mechanism comprising several parts, P_D is usually computed based on a classic analytical chain of dimensions. Nigam and Turner [3] list most of classic methods which enable P_D to be computed. In addition, several methods from the structural reliability field can be used [4].

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Nomenclature

P_D	Defect probability of the mechanism
P_{Da}	Assembly defect probability of the mechanism
P_{Df}	Functionality defect probability of the mechanism
Φ_n	n-dimensional multivariate normal cumulative distribution function
$\mathbf{D}$	Vector of part deviations
D_i	i-th part deviation
$\mathbf{P}$	Vector of part positions
P_i	i-th part position
m_i	i-th assembly constraint
N_m	Number of assembly constraints
g_i	i-th non-interference constraint
N_c	Number of non-interference constraints
Ω	Non-interference domain
$\tilde{f}$	Linearized function
N_s	Number of contact point situations
$\hat{\mathbf{P}}_i$	$\mathbf{P}$ coordinates relative to the i-th contact point situation
L_i	Performance function associated with the i-th contact point situation
N_{ds}	Number of dominant contact point situations

In some over-constrained mechanisms, gaps are present, allowing part displacements. Thus, depending on the gap situations, different dimension chains are required to control one functional characteristic. The formulation and computation of P_D for such mechanisms are not straightforward, and classic methods which deal with chains of dimensions cannot be used. Over-constrained mechanisms can be faulty because they cannot be assembled, or because they are not functional. Thus, two defect probabilities are defined: the assembly defect probability P_{Da} and the functionality defect probability P_{Df}.

The present paper focuses mainly on the functional requirement issue, because of its greater complexity compared to that of assembly. Nevertheless, the assembly issue is mentioned in the sections concerned. Section 2 is devoted to presenting existing methods capable of dealing with these issues and details one in particular. It has already been used [5] and is based on an optimization algorithm and Monte Carlo (MC) simulations. Only MC simulations are required to compute P_{Da}. This methodology is very precise in general but requires a large number of runs (optimization runs for the functionality issue). The main contribution of this article is an innovative methodology detailed in Section 3 and inspired by the work of Ballu et al. [6]. It greatly decreases the computational effort. Both assembly and functionality defects are expressed as dependent event intersections. P_{Df} and P_{Da} are then computed thanks to system reliability methods, using the n-dimensional multivariate normal cumulative distribution function Φ_n. Both approaches are compared for two industrial mechanisms: one inspired by a coaxial connector supplier (Fig. 1) and one prismatic joint (Fig. 2). The results are given and commented in Sections 4 and 5. The proposed method can be adapted to other over-constrained mechanisms featuring gaps.

2. Existing approaches to tolerance analysis for mechanisms containing gaps

2.1. Short bibliography review

In the literature, gaps are often neglected, mainly because only iso-constrained mechanisms are studied. In over-constrained mechanisms, they have to be taken into account [6–8]. To study

Fig. 1. Industrial coaxial connector.

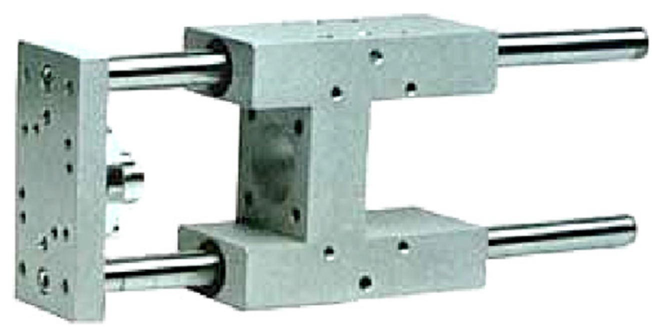

Fig. 2. Industrial prismatic joint.

such mechanisms, all mobilities between parts, arising from the presence of gaps, have to be considered. For this purpose, a new formulation of the tolerance analysis issue based on the quantifier notion was developed by Dantan and Qureshi [9] and Qureshi et al. [5]:

- The mathematical expression of tolerance analysis for the assembly requirement is: *For all* acceptable deviations (deviations which are inside tolerances), *there exists* a gap situation such that the assembly requirements are verified.
- The mathematical expression of tolerance analysis for the functional requirement is: *For all* acceptable deviations (deviations which are within tolerances), and *for all* admissible gap situations, the functional requirements are verified.

The quantifiers ∀ "*for all*" and ∃ "*there exists*" provide an unambiguous expression of the condition corresponding to a geometrical product requirement. This opens a wide area for research in tolerance analysis and in particular enables a mathematical formulation of P_{Df} and P_{Da}. These two defect probabilities are dependent but are treated separately in the following.

2.2. Geometric model

In the manufacturing phase, several deviations appear due to manufacturing processes. These are called manufacturing deviations. Many imperfections types are identified in a geometrically

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