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Opera suspicionată (OS)	Opera autentică (OA)
Suspicious work	Authentic work

OS	I.Cristea, M.Gherghel, C.Axinte, Simplification of tolerance analysis, In: Modelling and Optimization in the Machines Building Field (MOCM), 9, Vol. I, 2003, p.43-46.
OA	W.J.Lee, T.C.Woo, Tolerancing: its distribution, analysis, and synthesis, Department of Industrial and Operations Engineering, Technical Report No. 86-30, The University of Michigan Ann Arbor, Michigan, December 1986, Disponibil la: http :// deepblue . lib . umich . edu / bitstream / 2027 . 42 / 6228 / 5 / bam0402.0001 . 001 . pdf

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SIMPLIFICATION OF TOLERANCE ANALYSIS

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Abstract: Tolerance, representing a permissible variation of a dimension in an engineering drawing, is synthesised by considering assembly stack-up conditions based on manufacturing cost minimisation. Tolerance (stack-up) analysis, as an inner loop in the overall algorithm for tolerance synthesis, is performed by approximating the volume under the multivariable probability density function constrained by non-linear stack-up conditions whit a convex politop. This approximation makes use of the notion of reliability index in structural safety.

Keyword: tolerance analysis, called tolerance, tolerance distribution

. Introduction

Dimensions in engineering drawings specify ideal geometry for size, location, and form. Since dimensions are ubject to variability inherent in the manufacturing process, some variations, such as ±0,001, from the nominal value re allowed. The permissible amount, in this example 0.002, is called tolerance.

As a design variable, tolerance should be as near zero as possible. But, because of practical considerations uch as an increase in cost, tolerance as a manufacturing variable is often larger than ideal. While larger tolerances re less costly to realise, they are usually associated with poor performance. This trade-off between specification and ealisation illustrates the traditional conflict between design and manufacturing.

As a design-manufacturing variable, tolerance has more than a local effect in the decision process. Parts are 'in-spec" if they are functionally equivalent and interchangeable in assembly. Even though individual tolerances are 'in-spec" if bly. Even though individual tolerances are in-spec, the sum of the individual tolerances in a assembly may not be.

In practice, a designer starts whit some initial values for tolerances. If the result of analysis turns out to be 'out-of-spec", the designer reassign some of the tolerances and iterates the analysis procedure. The process of leciding while tolerances are to be changed and by how much is referred to as tolerance distribution. When performed manually, tolerance distribution is often guided by experience. without a rigorous procedure, it is difficult o ensure than local changes in tolerances reflect global criteria such as functionality and cost. Distributing tolerances uch than the result of tolerance analysis is reflected is referred to as tolerance synthesis. This paper presents the development of such a procedure.

Tolerances synthesis is formulated here as an optimisation problem by treating cost minimisation as the objective function and the stack-up conditions as the constraints. Probabilistic concepts are used. Since olerance implies randomness, a random variable and is standards deviation are associated with a dimension and its olerance. Such a probabilistic approach enables the partial satisfaction of the stack-up conditions.

By permitting a small fraction of the assemblies, say 0,3 percent, to be out-of-spec, an increase in olerances may be obtained and in turn a reduction in cost may be achieved. This probabilistic approach is considered to be advantageous over the deterministic approach. Since the deterministic approach [3,4] handles only the percent in-spec case, the resulting tolerances may be more conservative than necessary.

2. Simplification of Tolerance Analysis

Tolerance analysis is to compute the yield P(**Rr**) from a set of tolerances (standard deviations) that constitute the multivariate normal p.d.f. Ø (X;V) in equation (1). The integration is to be taken in the reliable regi **Rr** bounded by m+2n functions. As an inner loop in the overall algorithm for tolerance synthesis (shown in Fig.1 tolerance analysis demands speed and accuracy.

$$P(\mathbf{R}_R) = \int_{X \in \mathbf{R}_r} Ø(X;V)\,dX \qquad (1)$$

For speed, a two-step approximation of **Rr**, illustrated in Fig.2, is taken: first as a convex polytope and then as an inscribed hypersphere. While the computational advantage of replacing m+2n functions by m+2n hyperplanes and subsequently by a single radius may be obvious, the locations at which linear approximation is to be taken may not be. For accuracy, the consideration of preserving the probabilistically denseset area should be taken as illustrated by the column of figures on the right of Fig. 2. Now, suppose **Rr** has been suitably transformed such that the dimensions z_i are independent and that they follow the standard normal distribution. Refer to Fig.3 and consider two expansion points for linearization, Z_1 and Z_2, with distances d1 and d2, respectively. Because of normality, the densest area is in the vicinity of the origin. Further more, the density decreases exponentially in distance squared, i.e., (1/2 π) (e - e) . It becomes clear then, by choosing the point **Z** closest to the origin both speed and accuracy can be achieved.

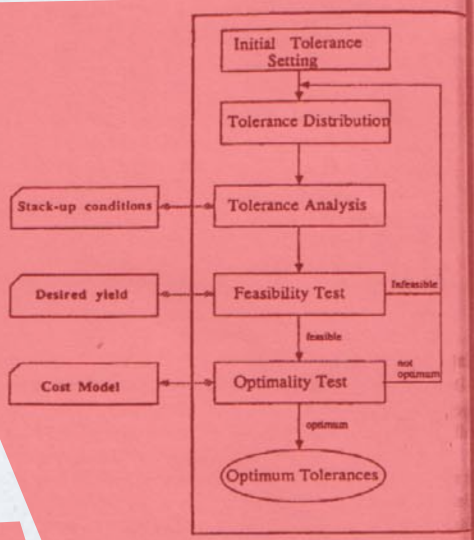

Fig. 1 Basic scheme of tolerance sintesis

The reliability index β is defined as the minimum distance from the origin to a limit-state surface formed by a design function in an independent standardized coordinate system, called the *standard system*. (The transformation from the dependent vector space to the standard system **Z** is explained in the Appendix.) The point **Z** on the limit state surface with the minimum distance to the origin is referred to as the *design point*. Linearization at the design point is performed by finding the tangent hyperplane in the standard system. The design function G(**Z**) is thus linearized by the tangent hyperplane L(**Z**) at **Z** such that **Rf** is approximated by **Rf**. The remainder of this section is devoted to the relations between P(**Rr**) and β .

Consider the simple case of only one design function. Because of the rotational symmetry in the standard system the probability of covering one side of the tangent hyperplane can be computed from the univariate normal distribution. Hence, the approximated yield P(**Rr**) only involves looking up the standard normal distribution table.

Lemma 1: In the case of a single design function, P(**Rr**) can be approximated by

$$P(\mathbf{R}_R) \approx \Phi(\beta). \qquad (2)$$

Note that, for a linear design function, $P(P_R) = \Phi(\beta)$. The accuracy of (2) depends on the curvature of the design function. As long as the radius of curvature at the design point is large compared to the reliability index, (2) has been shown to be quite accurate in most practical cases.

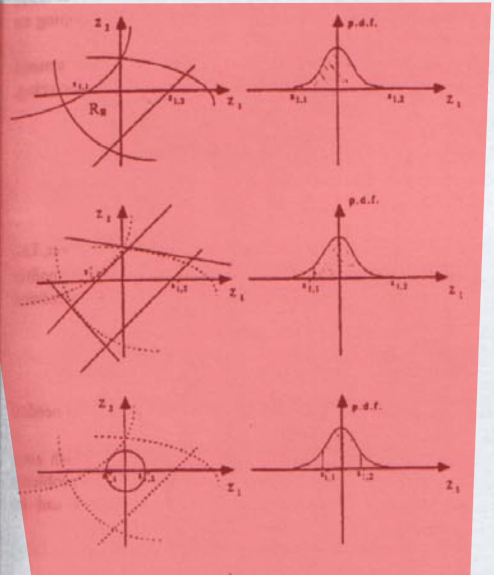

Fig.2 Approximate of R_R

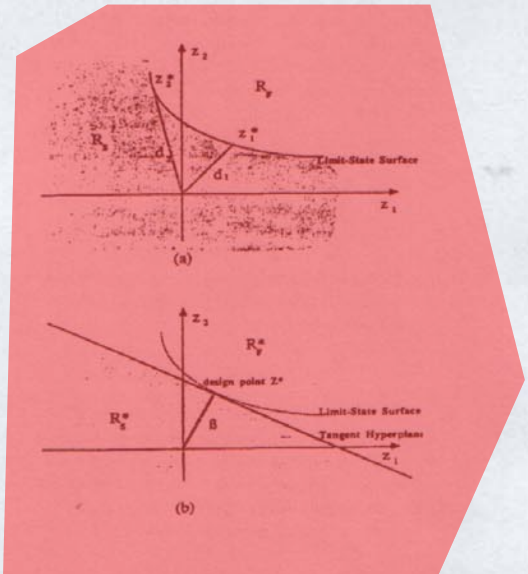

Fig. 3 Reliability index as distance

Now, consider the general case of multiple design functions. The approximated reliable region **Rr** after the linearization is always convex and P(**Rr**) can be obtained by the following lemma:

Lemma 2 : The yield P(RR) is approximated after the linearization by:

$$P(\mathbf{R}_R) \approx P(\mathbf{R}_R) = \int_{-\infty} \int_{-\infty} \varphi(0;CM)\, d_{z1} \ldots d_{zm+2n} \qquad (3)$$

where the correlation matrix of z_j's , denoted by CM, is the correlation matrix of the safety margins Mj.

Bounds are useful since equation cannot be evaluated for a general CM.

Lemma 3: The probability of covering the convex polytope **Rr** is bounded by:

$$x^2((\min_{j=1}^{m+2n} \beta_j)^2) \le P(Rr) \le \min_{j=1}^{m+2n} \{\Phi(\beta j)\} \qquad (4)$$

The lower bound is based on the observation that the hypersphare with a radius of the minimum of βj always lies inside **Rr** (and **Rr**) and the probability covered by this n-dimensional hypersphere is $x^2((\min_{j=1}^{m+2n} \beta j)^2)$. The upper bound of (4) holds the probability of the intersection is less than or equal to its component probability.

Summary and discussion

This paper presents a novel procedure for tolerance synthesis by distributing tolerances so as to satisfy the stack-up conditions. As a global criterion, cost minimisation is used. Probabilistic concept for tolerance analysis and synthesis are introduced. In terms of dimensions and tolerances, areas of interest to manufacturing and to design are defined as tolerance region and safe region, respectively. The intersection of the two regions, i.e., the reliable region, R_R, is investigated in detail.

Tolerance analyses for computing $P(R_R)$ is expedited through an approximation of R_R with convex polytope R_R^*. bounds of $P(R_R^*)$ is examined by using the reliability index β. For the upper and lower bounds, the probabilistic optimisation problem for tolerance synthesis is converted into two NLP_S. then, effort is devoted to developing an algorithm, which is an iterative method of ensuring convergence.

This iterative method demonstrates the potential for automatic tolerance synthesis, especially for the general non-linear case. The concept in this paper contribute to the understanding of parameters in design, manufacturing and assembly by investigating:

(a) the relation between tolerance and nominal dimension;
(b) the relation between tolerance and desired yield;
(c) the relation between tolerance and stack-up conditions ;
(d) the relation between tolerance and manufacturing cost.

The cost due to rework is implicitly assumed to be included in the manufacturing cost of the dimension, i.e. in $C_i(\sigma_i)$ of equation (10)[7]. As tolerance becomes smaller, the corresponding rework cost increases. Another possibility of analysing rework cost is to separate it from manufacturing cost. Then, the total cost can be represented in the following form:

$$\sum_{i=1}^{n} C_i(\sigma_i) + C_{RW}(p_1,.....p_n)\{1 - P(R_R)\}$$

where $C_{RW}(.)$ denotes the cost due to rework and p_i is the zero-one variable for dimension x_i such that if x_i is needed to rework then $p_i=1$ and otherwise $p_i=0$. the challenge is I obtaining the values of p_i, $1 \le i \le n$.

Another interesting area of tolerances is to analyse and synthesise the discrete tolerances, in which each tolerance is treated as a discrete variable and associated with a specifies manufacturing process. For these problems due to discrete tolerances, the basic scheme of this paper (i.e., the concept of the reliability index and its monotonicity with respect to tolerances) is expected to be used.

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