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Quality design method using process capability index based on Monte-Carlo method and real-coded genetic algorithm

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ABSTRACT

Variability in the performance and quality of products is an important issue in production engineering. Quality variability in mechanical production is due to irregularity of parts dimensions caused by machining errors. The dimensions of each part are usually managed by conventional tolerance at the design stage. Tight tolerance values result in reduced performance variation along with an increase in the manufacturing cost. Therefore tolerancing, which is a downstream process in mechanical design, is important in a detailed design process. Although quality is usually controlled in the manufacturing stage, not only production strategy but also management strategy will change in a positive direction and manufacturing cost is also reduced if the quality is also controlled at the design stage. This is because the design stage is an upstream process in manufacturing. This paper focuses on quality control in the design stage, and proposes a novel design method of process capability, which can statistically control parts dimensions based on product performance. The method consists of a numerical method and a real-coded genetic algorithm. A case study was analysed to evaluate the effectiveness of the proposed method. The result showed that the proposed method suitably allocates the STI for each part so that the product satisfies the required product performance.

1. Introduction

Actual dimensions of machined parts do not match the nominal dimensions specified at the design stage due to machining errors. Mechanical products consist of machined parts, and the product's performance depends on the functional dimension resulting from stack-up of the parts. Due to variability in the performance and quality of products, the dimensions of each part should be managed by conventional tolerance at the design stage. Tight tolerance values result in reduced performance variation along with increased manufacturing costs. Therefore, tolerancing, which is a downstream process in mechanical design, is an important factor in a detailed design process. Tolerancing methods are generally classified as worst-case or statistical. The worst-case method is traditionally used and involves easy calculations; stack-up of parts' variations is modelled as the sum of the limit of the variation of each part. Although this method perfectly guarantees the interchangeability of parts, the specified tolerances tend to be tight. However, the statistical method allows the tolerances to be relaxed considering statistical distributions of the parts dimensions. The method is based on statistical rules to ensure its compatibility in mass production. Various studies have focused on statistical methods.

For example, Skowronski and Turner (1997) examined Monte-Carlo variance reduction techniques, importance sampling, and correlation. They also proposed a method for using them in statistical tolerance synthesis. Zhang et al. (1998) proposed PCI (process capability index) based tolerance as a predetermined statistical tolerance zone. This tolerancing method can be used as an interface between design specification and statistical process control. Choi et al. (1999) applied a complex search method to ensure optimal allocation when tolerance limits were used and when Taguchi's quadratic loss function was defined. Li (2000) studied the relationship between unbalanced tolerance design and quality loss function. The study concluded that the optimal setting of the process mean, which minimizes the expected quality loss was obtained with respect to the asymmetrical ratio. Gao and Huang (2003) proposed an optimal tolerance balancing method for a nonlinear model. The method was based on process capability and validated through tests. Pillet (2003) detailed inertial tolerancing and compared it with traditional tolerancing methods. Pillet et al. (2005, 2015) proposed weighted inertia tolerance to obtain the best possible compromise between statistical and worst case tolerancing methods. The tolerance principle involved calculating the allowable range of the mean square deviation in relation to the target. Judic (2016) proposed a semi-quadratic method known as "Process Tolerancing" and compared it with "Inertial Tolerancing." Van Hoecke (2016) defined a tool risk

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caused by Gaussian hypothesis in statistical tolerancing, and related it to process capability indices.

Although designers use the statistical method that considers a condition of product performance and manufacturing cost, the conditions are rounded to the conventional tolerances as a scalar value. The intention of the designer can be reflected onto actual products if more detailed information is added to the tolerances on the design drawing. Consequently, the design drawing allows designers to design a product with additional value. Fortunately, the statistical tolerance index (STI), which is a useful tolerance specification for mass production, has been standardized in ASME Y14.5. The STI has a limited process capability index. When the STI is specified in design drawings, manufacturing processes must satisfy the limitation of the STI under statistical process control. Although the STI may result an additional manufacturing cost, it is a beneficial trade-off.

Because a product generally consists of several parts, there are two main problems when applying the STI to an actual design process: tolerance stack-up and tolerance allocation; these are the same as in conventional tolerancing. Before reasonably allocating the STI into parts' dimensions, the STI stack-up problem should be solved. Previous research has shown that the STI stack-up problem is known to be complex and difficult even if a product consists of only two parts. Srinivasan (1999) proved that a solution to the problem was generally represented by the Minkowski sum on the hyperplane of the mean and square of standard deviation. They provided an algebraic solution for the problem under the condition in which only limits of *Cpk* and *Cc* were specified. Based on their study, Otsuka and Nagata (2015) derived a more general algebraic solution for the problem and clarified its applicability condition. In addition, a numerical method using the Monte-Carlo simulation has been developed to obtain the approximate solution for the STI stack-up problem, because the problem is difficult to solve algebraically. Otsuka and Nagata (2017) also proposed a design method of target dimensions and *Cpm* indices based on product performance and cost.

This paper proposes the simultaneous design method of the target dimensions and four process capability indices, *Cp*, *Cpk*, *Cc*, and *Cpm*. The allocation method consists of the numerical method for the STI stack-up problem and a real-coded genetic algorithm using the UNDX crossover process (Kita et al., 2002; Ono et al., 2000). A case study was analysed to evaluate the effectiveness of the proposed method. The result shows that the proposed method suitably allocates the STI for each part so that the product satisfies certain conditions.

2. Statistical tolerance index (STI)

STI is a specification that uses a process capability index as an additional indicator for a manufacturing process with a conventional tolerance. STIs can be specified by adding "ST" into a hexagon. Fig. 1 (a) shows a design drawing in which conventional tolerances are specified. Fig. 1 (b) shows a design drawing in which conventional tolerances and STIs are specified. The specified dimensions, tolerances, and STIs in Fig. 1 are for illustrative purposes only. STI is applicable to both dimension and geometrical tolerances, so that STI can limit the distribution parameters of dimensional or geometrical errors of machined parts lot-by-lot. The STI is a useful tool to control performance and quality for mass produced products. However, it is not commonly used in current design processes due to its complexity.

2.1. Process capability index (PCI)

Machining processes in mass production must be controlled lot-by-lot to prevent machining errors. Process capability indices (PCIs) are non-dimensional parameters that have been used for a long time to evaluate the machining process quantitatively; they are defined as follows,

$$C_p = \frac{U-L}{6\sigma} \tag{1}$$

$$C_{pk} = \min\left(\frac{\mu-L}{3\sigma}, \frac{U-\mu}{3\sigma}\right) \tag{2}$$

$$C_c = \max\left(\frac{\tau-\mu}{\tau-L}, \frac{\mu-\tau}{U-\tau}\right) \tag{3}$$

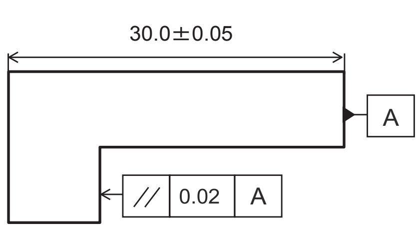
$$C_{pm} = \frac{U-L}{6\sqrt{\sigma^2+(\mu-\tau)^2}} \tag{4}$$

where L, U, μ, σ and τ are the lower limit of size, upper limit of size, process mean, process standard deviation and target dimension, respectively. T is the tolerance defined by the difference of U and L. When PCIs are limited within certain specified values such as $Cp \geq p$, $Cpk \geq k$, $Cc \leq c$, and $Cpm \geq m$ where p, k, c, and m are design parameters, the process must be controlled to maintain its capability within each parameter range. As the PCIs are defined by the process mean and/or standard deviation, the process is assumed to be controlled under statistical process control. When several STIs are simultaneously specified on a dimension, the allowable range of the mean and standard deviation tends to be complex. A population parameter zone (PPZ) is usually used to visually represent the area.

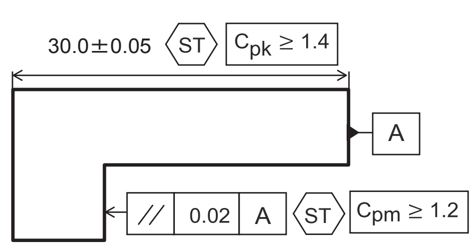
2.2. Population parameter zone

The PPZ represents an allowable range on the μ - σ plane when STIs are specified. Fig. 2 shows examples of PPZ when multiple STIs are specified.

The horizontal axis is the mean value and the vertical axis is the standard deviation value. The shaded area is the allowable range of the mean and the standard deviation. The solid boundary of the range is the allowable limit. When STIs are specified for each part dimension, the dimension has a corresponding PPZ. During the design process, designers need to decide suitable values and types of STI for each part dimension based on the required function, product performance, and cost of the final product. The decision process is equivalent to tolerance allocation. The STI stack-up problem must be solved before discussing the STI allocation problem, because the allocation problem is an inverse of the stack-up problem.



(a) conventional tolerance



(b) statistical tolerance index

Fig. 1. Example design drawings.