CHAPTER 2

LITERATURE REVIEW

This chapter reviews the current state of knowledge in the area of tolerance design relevant to this thesis. The first section introduces previous works in the area of concurrent tolerance design. The second section reviews previous works that deal with optimization techniques for tolerance design. The third section reviews previous works that deal with tolerance design using finite element simulation. The fourth section reviews previous works that deal with application of neural network in tolerance design. The last section summarizes the issues that require further investigation and form the basis for the central topic of this thesis.

2.1 CONCURRENT TOLERANCE DESIGN

Tolerance is a bridge between design, manufacturing, and quality engineers, and it also plays a key role in concurrent engineering. Ideally, one can imagine that the smart technique for tolerance synthesis takes into account the coupling between design, manufacturing, and quality, for the sake of achieving a minimal total cost and reducing lead-time. However, in existing work on tolerance synthesis, this has not been the case.

Conventionally, tolerance synthesis is carried out in two stages: design and process planning. However, design engineers allocating design tolerances are often unaware of manufacturing processes and their production capabilities. Furthermore, manufacturing engineers who allocate processes
must typically work within the tolerance limits set by design engineers; otherwise it requires cycling through the design/process-planning loop and results in longer lead times. But in accepting tolerances set by design engineers, the process planners also limit the range within which they can set process tolerances. This, in turn, leads to tight process tolerances and high manufacturing cost.

One well-used method for measuring quality is quality loss as introduced by Taguchi (1989). Performance degradation can be measured as a deviation from some target value, and asserted that the degradation can be related to a loss in value to the consumer called a quality loss. Taguchi emphasized that the level of a product’s quality is not the same as there are number of defective products; rather, it refers to the magnitude of societal losses. Even if a product is well within its specifications, it has a quality loss if its quality characteristic value is not at the ideal performance target. This loss is defined in monetary terms so that it can be compared to the product’s manufacturing cost.

Tight tolerances are preferred to ensure product performance, which degrades as parts deviate from nominal values. However, tight tolerances imply high manufacturing cost, so loose tolerances are preferred from a manufacturing perspective. This conflicting relation between the effect of tolerances on quality loss and on manufacturing cost makes it very difficult to establish near-optimal tolerance specifications.

Unfortunately, all existing methods for tolerance synthesis either fail to consider quality loss (e.g. methods of tolerance synthesis for manufacturing) or are not concurrent engineering methods (e.g, quality-based methods). The concurrent tolerance design may be based on any one or more objective functions given below:
1. Minimum manufacturing cost

2. Minimum quality loss

2.1.1 Minimizing Manufacturing Cost

In order to lower manufacturing cost, tolerances are assigned based on the particular sequencing of machining processes. Optimal tolerance allocation over multiple process alternatives has been treated by various researchers. Ostwald and Huang (1977) first formulated a technique for optimal tolerance allocation choosing one of possible many process alternatives. A similar model is that of Lee and Woo (1989), in which tolerances are treated as process-specific, but this model uses a simplified stack-up condition and a more efficient branch and bound algorithm. Chase et al (1990) presented three methods: exhaustive search, univariate search and sequential quadratic programming to solve the models originally proposed by Ostwald and Huang. Nagarwala et al (1994) proposed a new slope-based method that took into account process selection. Zhang and Wang (1993) reported an analytical model for simultaneously allocating design and machining tolerances based on a criterion of least manufacturing cost. In their model, tolerance allocation is formulated as a nonlinear optimization problem based on cost-tolerance relationships. A simulated annealing algorithm is used to solve the optimization problem. Al-Ansary and Deiab (1997) solved the same model using genetic algorithms; they found that genetic algorithms performed better than simulated annealing algorithms for solving nonlinear programming problems. The models of Singh, Jain and Jain (2003, 2004, 2005, 2006, 2008), Prabhakaran et al (2004), Noorul Haq et al (2005), Jean-Yves Dantan et al (2008), Isabel Gonzalez et al (2009) and Siva Kumar et al (2009) are more practical than those previously mentioned because they allow single dimensions to be produced by multiple processes and because the cost-tolerance function is treated as continuous rather than discrete. Also the
models allow tolerances to be loosened—compared to the other models—they have been considered quite successful. However, they fail to consider product quality, which degrades when tolerances are loosened.

2.1.2 Minimizing Quality Loss

All costs incurred during a product life cycle can be divided into two main categories: manufacturing cost, which occurs before the product reaches the customer; and quality loss, which occurs after the product is sold. A loose tolerance (low manufacturing cost) indicates that the variability of product quality characteristics will be great (high quality loss). On the other hand, a tight tolerance (high manufacturing cost) indicates that the variability of product quality characteristics will be small (little quality loss). Hence, there is a need to adjust design tolerance between quality loss and manufacturing cost in order to reach an economic balance during product tolerance design.

Examples of quality loss analysis are provided in a few studies. Taguchi (1989) proposed that quality loss should be treated as a cost along with manufacturing cost. This quality loss measure represents the loss to the society that occurs when a product deviates from the optimum set of design. Kapur et al (1990) presented a general optimization model in terms of costs associated with variances of the components and losses associated with the variability from the quality characteristic target. Cook and DeVor (1991) proposed a means of computing the quality loss function from their S-model. The model of Vasseur et al (1993) allocates tolerances based on profit maximization. Soderberg (1993) developed a quality loss function based on component lifetime. Jeang (1995) developed a few general mathematical models to determine product tolerances minimizing the combined manufacturing costs and quality losses (but not considering alternative manufacturing processes selection), using quadratic and geometrical decay

2.2 OPTIMIZATION TECHNIQUES FOR TOLERANCE DESIGN

The tolerance design problem becomes more complex in the presence of alternative processes (or machines) for manufacture of each dimension. This is because the manufacturing cost–tolerance characteristics differ from process to process, and from machine to machine. In such a tolerance design problem, in addition to the set of tolerances for each dimension, an optimal process (or machine) combination is also obtained. Formulation of this advanced tolerance design problem as a multivariable non-linear optimization problem results in a combinatorial and multi-modal solution space. The problem becomes more pronounced with interrelated constraints, resulting either from interrelated dimension chains (multiple dimension chains with a few dimensions shared by two or more of them), or stock removal considerations in case of multi-operation manufactured components. In such cases the constraints mutually influence one another because of the variables (tolerances) in common. Each dimension (or manufacturing operation) can be assigned only one value to the associated tolerance. In assigning a value to a tolerance common to more than one constraint, all the relevant constraints should be regarded simultaneously.
Optimal solution of this complicated problem has been a challenge and an interesting topic of research for decades. The conventional techniques like iteration method (Yuan Mao Huang et al 2006), sequential quadratic programming (Rao et al 2005 and Chiang kao et al 2000) adaptive branch and bound method (Deng and Deng 2002), heuristic method (Huang et al 2005) and nonlinear integer programming method (Wang and Liang 2005) are not applicable to this problem for getting exact global solution in a closed form. Other non-linear programming approaches can be applied, but they suffer from their own weaknesses and in general fail to yield a global or near-global solution. However, any conventional non-linear optimization method can be attracted by local minima.

To overcome the drawbacks of conventional optimization approaches, intelligent optimization techniques like GA (Prabhakaran et al 2004, Noorul Haq et al 2005), NSGA-II, DE, MODE and MOPSO (Babak Forouraghi, 2008) can be used. The advantages of intelligent optimization techniques are i. They are population-based searches, so global optimal solution is possible. ii. They do not need any auxiliary information like gradients, derivatives, etc. iii. They can solve complex and multimodal problems for global optimality. iv. They are problem independent, i.e. suitable for solving all types of problems.

So this work proposes an intelligent optimization techniques namely Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) to do optimal tolerance design. In the last 20 years, genetic algorithms (GAs) have been applied in plethora of fields namely control, system identification, robotics, planning and scheduling, image processing, pattern recognition and speech recognition (Al-Ansary and Deiab 1997, Forouraghi 2002, Singh, Jain and Jain (2003, 2004, 2005, 2006), Prabhakaran et al 2004, Noorul Haq et al
2.3 TOLERANCE DESIGN USING FINITE ELEMENT SIMULATION

When designers are performing tolerance design, they generally assume that the parts for assembly are not geometrically perfect with regard to their nominal geometry. It is also assumed that they have no flexibility. The assumption that parts and therefore mechanisms are rigid, forces us to solve hyperstaticity by increasing precision, as well as to add manufacturing constraints. Thus, the price will increase, in this case, an iso-static solution can be used, or clearance can be increased, which makes good geometrical defects. Today, part sizes are optimized as much as possible. Therefore, the sizes of parts are decreasing. Thus, the flexibility of parts increases. Moreover, the elastic displacements are not negligible or comparable to dimension tolerances of many parts. It is also observed that elastic displacements of parts and joints are of same nature. Therefore, it is necessary to build models where elastic displacements and joints are mixed with tolerancing.

In general, the component variation is recognized as a major problem in elastic assembly processes. A number of methods and tools have been developed to simulate the assembly processes and to analyze the assembly variation. Currently, the variation analysis of non-rigid assemblies has attracted many researchers. Liu and Hu (1997) considered the compliant nature of sheet metal parts and proposed an influence coefficients method to analyze the effect of component variation and assembly spring-back on the assembly variation by applying linear mechanics and statics. The influence coefficients method was a key technique to get the component stiffness matrix. Camelio et al (2001) successfully extended this approach to model the

2.4 TOLERANCE DESIGN USING NEURAL NETWORK

The primary objective of tolerance design is to distribute assembly tolerances between components. Applications of tolerance design require mathematical modeling of cost-tolerance relationships. The trade-off between specification and realization illustrates the traditional conflict between design and manufacturing. Distinct operations have different cost-tolerance relationships. In order to make a reliable trade-off between design tolerances and costs, it is necessary to obtain the cost-tolerance relationships. Most
researchers agree that there is an inverse relationship between tolerance and cost (Zhang et al 1993). Numerous cost-tolerance functions for various machining operations, which include turning, milling, drilling, grinding, casting, etc., are given in the literature (Al-Ansary et al 1997, Chase et al 1990, Dong et al 1994, Lee et al 1989 and Lee et al 1993). They include exponential, reciprocal squared, reciprocal power, reciprocal, discrete, polynomial, B-spline and hybrid form, etc., functions. These functions are established by regression analysis using empirical data from the real manufacturing. Tolerance synthesis is more complicated in an assembly due to the fact that a manufacturing process for an assembly consists of placing various components and subassemblies jointly to establish a finished product with an expected functionality. Once the cost-tolerance relationships have been generated, mathematical models for tolerance synthesis can be built to obtain the optimal tolerance design. In real manufacturing environments, the cost-tolerance relationship exits. However, it is quite difficult to obtain the parameters of cost-tolerance functions. Using traditional methods of regression analysis, one must make assumptions about the form of the regression equation or its parameters, which may not be valid in practice. Regression analysis may be inclined to generate numerous tables of results. These results are frequently difficult for design engineers to interpret without a statistics background. In addition, the previously developed forms of cost-tolerance relationships may not be suitable for considering quality loss. Quality loss is the cost incurred in a product life that occurs after the product is sold. The quality loss is also ideal function for establishing practical manufacturing tolerances.

Neural network approach though regarded as a statistical method, it is used to learn feature hidden within design experiment. Chen and Chan (1993) presented a procedure that included a neural network and a fine tuning algorithm to optimize the tolerance allocations for achieving minimum cost.

2.5 SUMMARY

A review of previous research studies in the area of concurrent tolerance design and applications of various optimization techniques, finite element simulation and neural network in tolerance design is presented in this chapter. Major conclusions of this review are summarized as follows:

- The volume of literature in research on concurrent tolerance design is large. However, they are based on an assumption that all the parts of assembly have no flexibility. The assumption that various parts of an assembly are rigid results in increase of precision and also increases manufacturing constraints.

- Conventional non-linear optimization techniques have been used by a few researchers in tolerance design. However, usage of conventional technique, in general will fail to yield a global or near global solution as they will be attracted by local minima.

- Intelligent optimization techniques have been used by a few researchers in tolerance design. However, none have considered
the inherent flexibility of all parts of the assembly and their effect.

- Finite element simulation has been used by a few researchers in tolerance design to determine the effect of deformation of sheet metal parts in the assembly. However, usage of finite element simulation to consider the effect of deformation of all parts of the assembly due to inertia and change in operating temperature, is absent in the literature.

- A couple of efforts in the literature addressed the usage of neural network to develop cost-tolerance function of tolerance design. However, neural network models have to be used in conjunction with intelligent optimization technique, which is absent in the literature.

- An integrated tolerance design approach, considering the effect of deformation of all parts of the assembly due to inertia and change in operating temperature, using finite element simulation and intelligent optimization technique is absent in the literature.

To overcome limitations of the existing works and advance the knowledge base of tolerance design, this study aims at establishing an integrated tolerance design approach to investigate the effect of deformation of all parts of the assembly using finite element simulation and intelligent optimization technique. By using finite element simulation, the dimensional variations of final assembly can be predicted during the design and process planning stage itself thereby minimizing its effect on final quality of the assembly. Intelligent optimization technique is used to optimize tolerance design process where the objective is to minimize total manufacturing cost. The deformation has been included in the functional constraint equation in order to ensure that the optimal tolerance values obtained as end product of optimization satisfies functional requirements.