CHAPTER 1

INTRODUCTION

1.1 BASICS OF TOLERANCE DESIGN

The three basic aspects of tolerance design are as follows.

1.1.1 Critical link between Design and Manufacturing

In the fiercely competitive global economy of today, product success is awarded to the company that can guarantee quality at low cost. With such demands, tolerance analysis and the control of manufacturing variation has received increased recognition. It has been realized that the arbitrary selection of the tolerances on engineering drawings is no longer acceptable, as the effects of tolerance assignment are far-reaching. Not only the tolerances and variations affect the ability to assemble the final product, but also the production cost, process selection, tooling, set-up cost, required operation skills, inspection and gauging, and scrap and rework. The variations constrained or bounded by the tolerance also directly affect product performance and robustness of design. And poorly performing products will eventually lose out in the market place.

Both engineering design and manufacturing personnel are concerned about the effects of tolerances. Engineers often assign tight tolerances to assure desirable fit and functioning of their designs. Manufacturers prefer loose tolerances to make parts at ease and at low cost. Therefore, tolerance
specification has become a critical link between engineering design and manufacturing (Figure 1.1), a common meeting ground where competing requirements may be resolved.

Figure 1.1 Tolerance Design – critical link between design and manufacturing

There is a critical need for specifying tolerances. Statistical methods offer powerful analytical tools for predicting the effects of manufacturing variations on design performance and production cost. There are, however, many factors to be considered. Statistical tolerance analysis is a complex problem that must be carefully formulated to assure validity, and then carefully interpreted to accurately determine the overall effect of tolerance assignment on the entire manufacturing enterprise.
1.1.2 Sources of Variation

In order to analyze the effects of the accumulation of component variations on assembled products or mechanical assemblies, all potential sources of variation in an assembly must be included. A comprehensive procedure is presented by which an engineer can systematically create a model for estimating assembly variations for a broad range of product types and applications.

There are four main sources of variation in a mechanical assembly:

- Dimensional variation of individual components
- Geometric feature variation
- Variation due to small kinematic adjustments among components which occur at assembly line
- Variation due to deformation of individual parts of assembly.

The first two are the result of natural variations in manufacturing processes, third is from assembly process and procedures and the fourth variation is due to inertia and temperature effects.

Figure 1.2 shows dimensional variations on a component. Such variations are inevitable due to fluctuations of machining conditions, such as tool wear, fixture errors, set up errors, material property variations, temperature, worker skill, etc. The designer usually specifies limits for each dimension. If the manufactured dimension falls within the specified limits, it is considered acceptable. Since this variation will affect the performance of the assembled product, it must be carefully controlled.
Figure 1.2 Example of dimensional variation.

Figure 1.3 shows geometric variations on a component. They provide additional tolerance constraints on shape, orientation, and location of produced components. It may be used to limit the flatness of a surface, or the perpendicularity of one surface on a part relative to established datums. In an assembly, geometric feature variations will accumulate and propagate similar to dimensional variations. Although, smaller than dimensional variations, they may be significant in some cases, resulting from rigid body effects. A complete tolerance model of mechanical assemblies should therefore include geometric feature tolerances.

Figure 1.3 Example of geometric variation
Kinematic variations are small adjustments between mating parts which occur at assembly time in response to the dimensional variations and geometric feature variations of the components in an assembly. For example, if the roller in the clutch assembly is produced undersized, as shown in Figure 1.4, the points of contact with the hub and ring will change, causing kinematic variables b and $\Phi_1$.

Usually, limiting values of kinematic variations are not marked on the mechanical drawing, but critical performance variables, such as a clearance or a location, may appear as assembly specifications. The task for the designer is to assign tolerances to each component in the assembly so that each assembly specification is met. It is the kinematic variations which result in implicit assembly functions. Current tolerance analysis practices fail to account for this significant variation source.

Figure 1.4 Example of kinematic variation

1.1.3 Variation due to deformation of individual parts of assembly

Traditional tolerance design is based on assumption that all the parts of the assembly are rigid. The parts of the assembly will undergo deformation due to inertia effect like gravity, angular velocity and environmental
conditions like change in operating temperature. The deformation of the various components is not negligible and they play an important role in tolerance design of assembly. Variations due to deformation of parts will accumulate and propagate along with the assembly process. Such accumulated variations would affect the final quality of the assembly. The variation due to deformation affects functional requirements of the assembly, which results in rework or wastage. It is thus an important task to predict the dimensional variations of a final assembly during the design and process planning stage.

In a comprehensive assembly tolerance analysis model, all four variations should be included. If any of the four, is overlooked or ignored, it can result in significant error. Only when a complete model is constructed, can the designer accurately estimate the key characteristics of the assembly. Key characteristics are key features that must be satisfied for the assembly to meet its design intent.

The objective of this work is to generalize the procedure by which for all the four variation sources may be included, particular interest is the assembly kinematics employed to set up the kinematic assembly constraints and effect of variation due to deformation of parts on key characteristics of the assembly. Once a comprehensive assembly tolerance analysis model is developed, optimization of the same is done to predict and evaluate assembly variations.

1.2 OUTLINE OF THE THESIS

The goal of this research work is to develop a procedure that can do real world tolerance design suitable for any mechanical assembly. They are as follows;
• To develop a comprehensive assembly tolerance model in which all variations are included.

• To develop a tolerance design capable of addressing assumptions made in conventional methods furnished in the literature.

• To develop a procedure for tolerance design of assembly considering deformation of parts due to inertia effects like gravity and angular velocity.

• To develop a procedure for robust design of assembly considering deformation of parts due to environmental conditions like change in operating temperature.

• To generate a global optimal tolerance design.

• To develop a tolerance design procedure capable of eradicating source of errors in conventional methods shown in the literature.

1.2.1 Case study I : Optimal Tolerance Design of Mechanical Assembly Considering Inertia Effect

The inertia effect like gravity, velocity etc, results in deformation (change in length) of a component. The amount of deformation produced by the gravity effect is directly proportional to density of the material. In this study, the deformation due to gravity effect is determined using finite element analysis and they are suitably incorporated in the tolerance stack up equation of tolerance design, thereby loosening tolerance requirement of critical components.
The piston-cylinder assembly (Mao et al 2009) is the application example for the proposed tolerance design. Figure 1.5 shows the graphic representation of the assembly along with dimensions.

![Figure 1.5 Piston – cylinder assembly](image)

**Table 1.1 Piston – cylinder assembly characteristics**

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Assembly type</th>
<th>Variables</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimization of Total manufacturing cost considering Inertia effect</td>
<td>Piston Cylinder assembly</td>
<td>Nominal and tolerance value for non critical dimensions</td>
<td>Statistical</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Simulated Annealing algorithm (Mao et al 2009)/ NSGA II and finite element simulation</td>
</tr>
</tbody>
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1.2.2 Case study II: Optimal Tolerance Design of Mechanical Assembly Considering Temperature Effect

Thermal expansion plays an important role in many applications. In a situation where a precise design compensation, slack, dimension or tolerance is required for the product to function properly, thermal impact must be taken into consideration during the design process, particularly when a complicated product with multiple components and various materials operates under a wide range of temperature. In addition to thermal effect, gravity effect also results in deformation (change in length) of a component. In this study, the deformation due to thermal impact and gravity effect was determined using finite element analysis and is suitably incorporated in the tolerance stack up equation of tolerance design, thereby loosening tolerance requirement of critical components.

![Figure 1.6 Gear box assembly](image)

**Figure 1.6 Gear box assembly**

The gearbox assembly is the application example for the proposed tolerance design. Figure 1.6 shows the graphic representation of the classic Bjorke gearbox assembly along with dimensions.
Table 1.2 Gear box assembly characteristics

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Assembly type</th>
<th>Variables</th>
<th>Constraints</th>
<th>Conventional Techniques used/ Improvements made (Proposed Techniques)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimization of Total manufacturing cost considering Inertia and Thermal effect</td>
<td>Gear Box assembly</td>
<td>Nominal and tolerance value for non critical dimensions</td>
<td>Worst-case</td>
<td>Response surface methodology (Jeang et al 2002)/ NSGA II and finite element simulation</td>
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1.2.3 Case study III : Parametric Tolerance Design of Mechanical Assembly Considering Inertia and Temperature Effect

In this work, a cost – tolerance model based on neural network methods is proposed in order to provide product designers and process planners with an accurate basis for estimating the manufacturing cost. Then tolerance allocation among the assembly components is carried out to ensure that the functionality and design quality are satisfied considering the effects of dimensional and geometric tolerances of various components of the assembly by developing a parametric CAD model. In addition, deformations of various components of mechanical assembly due to inertia and temperature effects are determined and the same are integrated with tolerance design. The benefits of integrating the results of finite element simulation in the early stages of tolerance design are discussed.
The proposed method is explained with an application example of motor assembly (Jeang et al 1999) as shown in Figure 1.7, which consists of an x – base, crank, shaft and motor base.

**Table 1.3 Motor assembly characteristics**

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Assembly type</th>
<th>Variables</th>
<th>Constraint equation</th>
<th>Conventional Techniques used/ Improvements made (Proposed Techniques)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimization of Total manufacturing cost</td>
<td>Motor assembly</td>
<td>Nominal and tolerance value (DGTs) for non critical dimensions</td>
<td>Parametric CAD model</td>
<td>Response surface methodology (Jeang et al 1999)/ Neural network, NSGA II and finite element simulation</td>
</tr>
</tbody>
</table>

1.3 **ORGANIZATION OF THE THESIS**

This thesis is organized as follows: Literature review is given in chapter 2. Chapter 3 has information regarding finite element simulation,
neural network and intelligent optimization techniques. 3. Details of the case study I – Optimal tolerance design of mechanical assembly considering inertia effect, case study II - Optimal tolerance design of mechanical assembly considering temperature effect and case study III – Parametric tolerance design of mechanical assembly considering inertia and temperature effect, are given in chapters 4, 5 and 6 respectively. The conclusion and scope for future work are presented in the last chapter.