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Technical paper

Tolerance design optimization on cost–quality trade-off using the Shapley value method

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ABSTRACT

Part tolerance design is important in the manufacturing process of many complex products because it directly affects manufacturing cost and product quality. It is significant to develop a reasonable tolerance scheme considering the demands of cost and quality to reduce the production risk and provide a guide for supplier management. Traditionally, some kinds of cost objective functions or variation propagation models are often applied in part tolerance design. Moreover, designers usually solve the tolerance design problem by constructing a single-objective model, dealing with several single-objective problems, or establishing a comprehensive evaluating function combining several optimization objectives with different weights. These approaches may not adequately consider the interdependent and the interactional relations of various demands and balance them. This paper presents a kind of tolerance design approach at the early design stage of automotive parts based on the Shapley value method (SVM) of coalitional game theory considering the demands of manufacturing cost and product quality. First the part tolerance design problem is defined. The measuring data in regular production is collected instead of working on specific objective functions or design models. Then how the SVM is adopted to solve the tolerance design problem is discussed. Lastly, a tolerance design example of a vehicle front lamp demonstrates the application and the performance of the proposed method.

1. Introduction

Part tolerance is a crucial factor in the manufacturing process of many complex products like automobiles, airplanes, and ships, because it directly affects manufacturing cost and product quality. Tight tolerances can ensure good part quality, but simultaneously impose a high investment stress on the company. In contrast, loose tolerances may cause a series of problems such as part interference, assembly quality deficiency, and frequent fixture adjustment [1]. Moreover, different part suppliers have different capabilities, and there exists a conflict between the part quality demand from manufacturers and the cost planning of suppliers. Consequently, it is significant to develop a reasonable tolerance scheme considering the demands of cost and quality to reduce the production risk and provide a guide for supplier management.

Fig. 1 shows the flowchart of tolerance design for automotive parts. At the early design stage, designers first establish a primary tolerance scheme for every assembly component after the identification of the product performance characteristic and the production investment planning. Once the initial tolerance schemes are identified, more specific tolerances of manufactured parts at the detailed design stage will be designed accordingly. Then the rationality of the tolerances is verified through trial production. It is noticed that a tolerance scheme without adequately considering the cost and the quality demand at the early design stage will undoubtedly add workload to the later tolerance verification process such that it will reduce development efficiency and increase costs. Therefore, under the condition of lack of specific design information, an appropriate theoretic model that can describe the interaction and the conflict between manufacturing cost and product quality is significant for the early design stage in automotive manufacturing. In this research, a tolerance design method with game theory is proposed considering the cost and the quality demand at the early design stage of automotive production to reduce the production risk. The derived tolerance and the corresponding cost scheme can also be regarded as a guide for tolerance design of specific part features at the detailed design stage and helpful for supplier management.

In the past few decades, the problem of part tolerance design has often been solved through the approach of tolerance allocation. A great deal of work has been done in this field. Chase et al. [1] presented exhaustive search, univariate search and sequential

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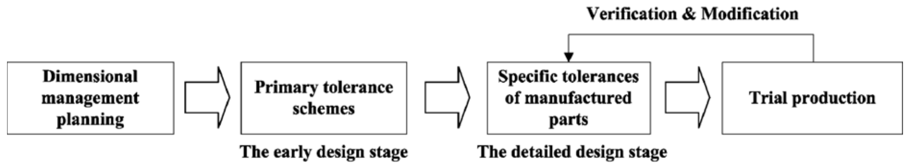

Fig. 1. Flowchart of tolerance design for automotive parts.

quadratic programming to solve the tolerance allocation problem. Kopardkar and Anand [2] proposed a neural network-based approach to predict individual part tolerances for the tolerance allocation problem considering machines' capabilities and mean shifts. Ji et al. [3] established the tolerance allocation model based on the machinability of the parts using second-order fuzzy comprehensive evaluation. Chou and Chang [4] presented a model of optimal tolerance allocation considering both tolerance cost and the present worth of quality loss such that the total assembly cost/loss is minimized. Ding et al. [5] proposed a method for process-oriented tolerance synthesis of rigid multistation assembly systems, where process tolerances were allocated by solving a nonlinear constrained optimization problem. Tseng and Huang [6] proposed a multi-plant tolerance allocation model and used a mathematical programming model to distribute the components to the suitable plants to achieve objective of minimizing multi-plant manufacturing costs. Li et al. [7] solved the tolerance allocation problem by establishing the quality-driven and the cost-driven models respectively in the multistation compliant assembly. It can be noticed that some kinds of cost objective functions or variation propagation models are often applied in traditional tolerance design. The researchers need to investigate specific structure and process information of the part and design relevant parameters and principles in order to establish these functions or models. On the other hand, designers usually adopt the single-objective optimization with some kinds of constraints, deal with several single-objective problems simultaneously, or establish a comprehensive evaluating function to solve tolerance allocation problems. A lump model combining several optimization objectives with different weights may not be desirable as it is difficult to evaluate the importance of each optimization objective and the interaction and the conflict of various demands may not be adequately considered.

Tolerance design on the cost–quality trade-off is essentially a multi-objective optimization problem. The concept of Pareto-optimal solutions has been found to be useful in this context [8,9]. The game theory approach for generating the best compromise (Pareto-optimal) solution is proposed in the present work. Game theory is a mathematical tool developed to study decision-making in conflict situations. It aims to abstract essential elements of competitive situations, put them in mathematical models, and use these models to find an optimal trade-off among the conflicting multiple objective functions [10]. There are mainly two game theories representing different types of interactions among optimization objectives (or players in game theory terminology): non-cooperative and cooperative.

Mcdonnell et al. [11] and Xie et al. [12] demonstrated the application of non-cooperative game theory in engineering fields. The non-cooperative analysis seeks to find a stable solution (referred to as Nash equilibrium) where no player may improve his payoff by choosing some other strategies as long as other players maintain their resource choices. However, it is noticed that the solution process of a non-cooperative game is often tedious and difficult; in some cases, the solution may not converge and is not necessarily Pareto efficient. On the other hand, a cooperative model assumes that each player is a member of a team and is willing to compromise his own profit to improve the whole situation. Resources will be allocated such that all players are as well off as possible, and an improvement in the profit for one player does not result in an unacceptable loss for another one. The bargaining game method and the coalitional game method are two typical branches in this field. The bargaining method seeks to yield an arbitration solution maximizing some kind of distance between the equilibrium point and a status-quo point [13,14]. The coalitional game aims to analyze the behavior of groups of players (coalitions) and their inner relations so as to get a stable profit allocation scheme that no players or coalitions want to break away. Da Silva et al. [15] used the Shapley value method (SVM) of coalitional game theory to solve the problem of congestion cost allocation in the competitive electricity markets. Lima et al. [16] discussed several coalitional game solutions including the Core, the Shapley value and the Kernel for the allocation of the cost of losses to generators and demands in transmission systems. On the problem of part tolerance design in this research, the key point is to combine tolerance design characteristics with relevant game components, and thus transform the tolerance design problem into the appropriate game model.

In this paper, a kind of tolerance design approach at the early design stage of automotive parts is proposed based on the SVM of coalitional game theory. Instead of constructing specific objective functions of cost and quality, we just collect necessary measuring data in previous regular production and establish a game model considering the conflict between the cost and the quality demand by transforming part and product information into relevant game components. Then the game model is solved by the SVM. The final optimization scheme, which is identified from the Pareto-optimal set, is a kind of payoff allocation among players making everyone's profit not worse than that from one's own efforts. It is a fair and stable trade-off that has adequately considered the interdependent and the interactional relations among all the players' payoffs and can be considered as one kind of importance evaluation of each player based on their contribution to the whole coalition [10,17,18]. The computational procedure is demonstrated through a design example of a vehicle front lamp assembly.

2. Problem definition

There are various approaches that can be used to evaluate the cost and the quality level of parts and products in production, and different companies may adopt different measures. Fig. 2 shows the common cost, quality evaluation approaches of parts and products in the automotive manufacturing process. Suppliers usually provide parts periodically in the regular production stage of automotive products. There are always all kinds of part inspection reports and relevant cost information recorded by the suppliers for each batch of parts. In general, the variation of measuring points or the process capability index can be used to represent the part quality level. The obtain-cost (usually including price of bargain and cost of trade) or risk-cost can be used to represent the part cost level. Further, manufacturers also evaluate the cost and the quality level of automotive products with all kinds of measures after the general assembly process in the manufacturing factory. For instance, assembly cost and rework cost are often calculated to estimate the product cost level in