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Review on Techniques of Tolerance Design in Mechanical Engineering

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Abstract – Tolerance design has become a very sensitive and important issue in product and process development because of increasing demand for a key element in industry for improving product quality and the growing requirements for automation in manufacturing. Tolerance decisions can profoundly impact the quality and cost of product. It is an interactive process between design and manufacturing decision making. Designers want tight tolerances to assure product performance; manufacturers prefer loose tolerances to reduce cost. There is a critical need for a quantitative design tool for specifying tolerances. The investigation and comparative analysis of recent studies related to the design requirements in mechanical engineering and manufacturing capabilities together in a common model, where the effects of tolerance specifications on both design and manufacturing requirements can be evaluated quantitatively. In this paper, we presented the systematic review of tolerance design involves repeated computation following two alternate steps: (a) tolerance analysis and (b) tolerance synthesis. Significant amount of literature is related to tolerance methods. Summaries of state of the art, the most recent developments, and the outcome of this paper claims the various research gaps identified from literature review.

Keywords - Tolerance Analysis, Tolerance Design, Tolerance Synthesis

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1. INTRODUCTION

Routing Tolerance plays a vital role in any industrial product. Designer has to be very careful while dealing with tolerance. It is highly demanded to sell a product at low cost with higher accuracy. So it can perform efficiently. To fulfil such requirements it is advised to know about tolerance.

1.1 Role of tolerance

Manufacturing planner is focused on operation based tolerance allocation to minimize manufacturing cost. Quality assurance verifies that the manufactured part comply with design specifications or not. So designer has to define drawings in such manner that both these requirements can be satisfied.

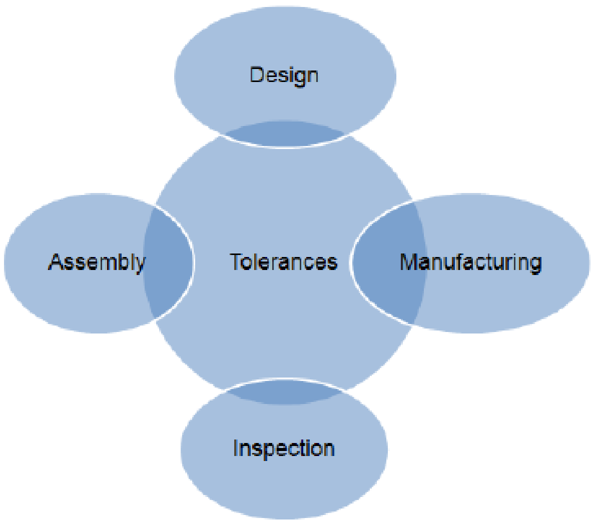

Figure 1: Role of Tolerance at Various Stage of Product

As shown in above figure.1, tolerance plays vital role in these 4 stages. For the designing and inspection purpose, requirement of tolerance is less while for manufacturing and assembly, requirement of tolerance is higher. It is also recommended to determine the kind of tolerance required at various stages of product. For the design and assembly, tight tolerance is required while in manufacturing and inspection, lesser tolerance is required.

Tolerance design is usually carried out on detailed geometric entities after structure design process [1]. If accuracy problems occur during tolerance design, designer has to return to the structure design to modify. Due to lack of consideration of tolerance in the early stage, design process can hardly be successful in one time which leads to inevitably increasing cost and time. In order to achieve efficient optimization between structure and tolerance, concurrent design is necessary. Nowadays, few works have comprehensively considered the tolerance design in the conceptual structure design stage. Narahari Y [2] has proposed a method called DFT (design for tolerance) with a function-assembly-behavior model. Based the model, he has given detailed design activities at successive stages along with methods and best practices for tolerance analysis and synthesis. Roy U [3] has proposed a design synthesis process for evolution of a product, which forms a mapping from functional requirements to artifact in multiple stage of design evolution. Dantan JY [4] has put forward a methodology called ITP (Integrated Tolerancing Process) to ensure tolerance traceability. He has built relationships between tolerance and function (or decomposed sub-function). Mantripragad [5] has put forward a top-down tolerance design method that supports assembly model, based on which assembly order and assembly tolerance are studied. Most of those literatures have clearly pointed out the existing problems and demonstrated the importance of the tolerance design in the early stage. Some problem-solving related theories have been developed, yet, specific practical resolution scheme is still needed to be exploited. Review of deterministic methods in tolerance synthesis Two models for calculating a tolerance stackup (accumulation) have been widely used? (a) the worst case (WC) model (sometimes called a sure-fit model, or the arithmetic law model), and (b) the root sum square (RSS) model (sometimes called a statistical-fit model, or the variance law model). The WC model assumes that all the component dimensional tolerances occur at their worst limit at the same time. It is used by product designers to ensure that all machining tolerances or assemblies meet the specified tolerance stackup or assembly limit. When the number of component tolerances in machining or the number of parts in an assembly increases, the component tolerances must be reduced in order to meet the tolerance stackup or assembly limit, which results in a high manufacturing cost. In this paper, tolerance synthesis with the WC model is referred to as deterministic tolerance synthesis. Section II presents a literature reviews on techniques of tolerance design in mechanical engineering. Section III presents the comparative study and research gaps. Finally, Section IV presents the conclusion.

2. LITERATURE REVIEW

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.

Dr. Dinesh Shringi et al [6], analysis of new non-traditional tolerance stack up conditions is performed in this paper. A comparative cost analysis of different stack up models is solved by the combined simulated annealing and pattern search algorithm is determined in this paper. After explaining tolerance stack-up condition, 5 different models for stack-up analysis are explained along with equations like worst case, root-sum-square(RSS), modified RSS, spott's model, estimated mean shift(EMS). It is concluded that among all these models, worst case gives tighter tolerances which increase the manufacturing cost. To overcome this problem RSS model is introduced in which normal distribution parameter is included. But after getting the final value by RSS model it is divided by 3. Now the reason of being divided is not clearly mentioned here. To make this model more convenient, modified RSS model is introduced in which correction factor in introduced. Now value for the correction factor is different from the various research personnel. To overcome this trouble one new model is established as spott's model in which mean is taken of worst case and RSS. By considering a shaft bearing example, a cost comparison is made between all these models in which it determined that by using RSS cost is lesser than all other methods.

Mathieu Mansuy et al [7], performed a new calculation method for worst case tolerance analysis and synthesis in stack type assemblies. As name suggest new approach is considered for the stack assemblies without clearance and with clearance. It is concluded that there are so many factors that affect the stack-up analysis which assembly having clearance. It is also concluded that any kind of complex assembly can be converted into a single chain assembly with the help of this research work and can make relationship between functional condition and geometric tolerance by considering worst case. To make an assembly in a single chain influence coefficient is used which direct the chain and decide whether to make summation or subtraction of tolerances. Among all these influence coefficients which have the higher value is considered as reference.

Prof. Suyash Y. Pawar et al [8], tolerance stack up analysis and simulation using visualization vsa is performed in this paper. This paper represents how the manual methods for tolerance stack up analysis and simulation are different and less efficient than tolerance stack up analysis and synthesis using visualization vsa. From this paper it is concluded that tolerance stack-up analysis performed manually is not so efficient and realistic as in worst case, it is considered that all the tolerance are at their worst case simultaneously while in statistical tolerance analysis, assumption is made that tolerances are individual and have normal distribution. Therefore, RSS is used but in actual they are not perfectly correlated in machining. Also such kind of tolerance analysis is performed in one direction which does not represent perfect idea about 3 dimensional tolerances. But when tolerance stack up analysis is performed with visualization vsa, it distributes the tolerance in the descending order. Due to it, for the worst case higher tolerance is achieved than the RSS model as the size of component increase which leads to manufacturing cost down.

Luc Laperriere et al [9], tolerance analysis and synthesis using jacobian transforms is performed in this paper. Also mathematical relationship is established between small possible displacement of function element and functional requirement. This is expressed set of matrix form with a jacobian matrix. And it gives desired analysis relationship. It is concluded a relationship is established between functional requirement and functional element by using jacobian matrix. Here one tolerance chain is identified and then one nominal expression is derived which represents relative position and orientation between functional element in a pair and then converted in 4*4 homogeneous transforms. The position and orientation of functional elements are degraded using 3 orthogonal translations and 3 orthogonal rotations with each pair of functional element. This relationship is provided with jacobian matrix between each pair of both functional elements. Then to achieve the final result pseudo inversion of jacobian matrix is performed and desired functional requirement is obtained.

Paul Beaucaire et al [10], statistical tolerance analysis of over constrained mechanisms with gaps using system reliability method is performed in this paper. From the paper, it is to calculate the probability of defects for over constrained mechanisms having gaps. For that probabilistic approach is used and it is very useful. In this research paper the values of functional characteristics are based on gaps. They are not based on part deviations as in other methods. Here random variables are used as deterministic variables. It is clearly explained that assembly with gaps is easier but functionality with gaps is complex. To overcome functionality issues, structural reliability domain is used. For that several contact points while making assembly are treated separately. They are dependent events. Here defect probability is calculated at designing phase with the help of FORM system method. Normally functional requirement is dependent on part deviation. So it will be the first step to reduce uncontrolled variable in the probability formulation. To calculate defects in part, two methods are appropriate meanwhile Lee and Woo approach is not so accurate and Monte-Carlo consumes more time.

Fangcai Wu et al [11], improved algorithm for tolerance allocation based on Monte-Carlo simulation and discrete optimization is performed in this paper. In this paper nonlinearly constrained tolerance allocation problems are considered and to handle them Monte-Carlo technique is used and to improve it genetic algorithm is used. From the paper, it is concluded that optimal ratio is achieved between the sum of the manufacturing costs and the probability of the respect of geometrical requirements and assembly requirements. For the real time application, traditional optimization algorithm is so complex that it is impossible to solve it as, function F is not available in analytic form. To implement Monte-Carlo simulation, geometric behavior should be defined. For that equation is to be developed in which part deviations, gaps and functional requirements are constrained.

Jinn-Tsong Tsai et al [12], an evolutionary approach for tolerance design is performed in this paper. Worst case tolerance design problems are solved with the help of sliding-level orthogonal differential evolution algorithm with a two level orthogonal array. For that two examples are considered, one is of 10 variables in which linear, non-linear, quadratic and polynomial forms are contained and second is of speed reducer design in which 7 variables and multiple non-linear engineering constraints are contained. From this paper, it is concluded that with the help of SLODEA2OA, effect of parameter variations and computation time is reduced. With the help of it, the obtained solution is within specified tolerance which makes vertex analysis result easier.

Somvir arya et al [13], application of Monte-Carlo technique for analysis of tolerance and allocation of reciprocating compressor assembly is performed in this paper. From this paper, It is concluded that normal distribution is considered for Monte-Carlo simulation. Skewed distribution is negative for all part dimensions and for all modules dimensions and the value of it is 0.3. Rejection rate is 0.21 which shows that the finally only 1% rejection rate is allowed.

3. COMPARATIVE ANALYSIS

Paper Title	Year	Techniques	Highlights	References
A Survey of Research in the Application of Tolerance Analysis to the Design of Mechanical Assemblies	1991	Analysis Tool Market Share Engineering Design Nonlinear Effect	New models for tolerance accumulation in mechanical assemblies, including the Motorola Six Sigma model. Algorithms for allocating the specified assembly tolerance among the components of an assembly. The development of 2-D and 3-D tolerance analysis models. Methods which account for non-Normal statistical distributions and nonlinear effects. Several strategies for improving designs through the application of modern analytical tools.	[18]
Review of statistical approaches to tolerance analysis.	1995	Tolerances, solid modelling, statistical methods	solid modelling systems and to the geometric tolerancing standard	[15]
Tolerance Allocation Methods for Designers	1999	tolerances, solid modelling, statistical methods	Centering the Mean of the Assembly Distribution 2 Upper or Lower Limit Justification of the Mean 3 Reducing the Spread of the Distribution	[19]
Important issues in tolerance design of mechanical assemblies. Part 2: tolerance synthesis	2009	tolerance design, mechanical assemblies	The allocation of assembly tolerance among the individual dimensions.	[20]
Parametric Tolerance Analysis of Mechanical Assembly by Developing Direct Constraint Model in CAD and Cost Competent Tolerance Synthesis	2010	Tolerance Analysis, Tolerance Synthesis, CAD Integration, Optimization, Neural Network.	It deals development of direct constraint model in CAD, which is in-tegrated to an optimal tolerance design problem. A back-propagation (BP) network is applied to fit the cost-tolerance relationship. An optimization method based on Differential Evolution (DE) is then used to locate the combination of controllable factors (tolerances) to optimize the output response (manufacturing cost plus quality loss) using the equations stemming from the trained network.	[17]
A Concurrent Design Method for Functional Tolerance and Structure based on the Principle of Decomposition and Reconstitution.	2013	growth design, concurrent design, functional requirement, tolerance design	The concurrent design methodology for functional tolerance using the principle of decomposition and reconstitution using growth design based on functional surfaces. A concurrent design methodology is given, including growth design-supported structure-tolerance design process, assembly information model and TTRS-based tolerance representation model. A recursive design method for function to structure mapping is proposed.	[16]
Integration of tolerances in the mechanical product process: Assembly with defects modelling	2013	CAD model, assembly mating constraints, dimensional tolerance, geometrical tolerance, realistic assemblies.	The DMU improvement requires the tolerance integration in CAD model. A developed model allows obtaining the components with defects according to dimensional and Geometrical tolerances specified in the nominal model. In CAD model, the assembly of the components with dimensional and geometrical defects requires the updating of the assembly mating constraints. This paper presents a method to redefine the mates of the realistic assemblies.	[21]

On the basis of the methods and examples discussed in the previous sections, the following observations can be made:

The integer programming approach can be easily applied to 1D deterministic tolerance synthesis problems. In the case of nonlinearity of the tolerance stack up constraint or the cost function with respect to component tolerances, or both, the IP approach cannot be used.

Table 1 Comparison of IP, DOE, and TM approaches

Approach	Deterministic synthesis			Application to probabilistic synthesis	
	Objective (Cost)	Constraint	Optimality	Simulation	Objective (Variation)
IP	Linear	Linear	Yes	No	Linear
DOE	Linear Nonlinear	Linear Nonlinear	Yes (full) No (functional)	Yes	Linear Nonlinear
TM	Linear Nonlinear	Linear Nonlinear	No	Yes	Linear Nonlinear

The DOE approach can be applied to small scale and large scale tolerance synthesis problems. However, for large scale problems, it is time consuming to create the tables and calculate the tolerance stack up and response if no standard software is available. The DOE approach can be used for both linear and nonlinear cases, since it does not require any linearity assumptions for the response and constraints.

The Taguchi method does not appear to be superior to the DOE approach, even in solving deterministic problems where the interaction between factors is not considered. First, the set of orthogonal arrays available in the literature is limited. Sometimes, a tailoring (reduction) is required so that the existing orthogonal arrays can be used. The final solution is sensitive to the tailoring. Second, the Taguchi method finds solutions of lower quality than the DOE approach, even for small size problems without tailoring. This is because the orthogonal arrays are constructed heuristically. However, the algorithm used to reduce the number of runs in the DOE approach is robust and efficient". It can be applied to construct any required array. The Taguchi method constructs orthogonal arrays be providing limited tables, while the DOE approach constructs orthogonal array by providing general, efficient, and robust algorithms.

Table 2 Comparison of the tolerance analysis methods

criteria \ method	Tolerance Charts	Parametric-Linearized	Parametric-Nonlinear (CATs like VisVSA4.0, Mech. Adv., New version CETOL)	Kinematic CATs (old versions CETOL)	ASU T-Maps (evolving)
dimensionality	1-D	mainly 2-D	2-D constraints + 3-D history	3-D	3-D
Analysis Type	worst-case only	worst-case + statistical	worst-case + statistical	worst-case + statistical	worst-case + statistical
Scope (Tolerance types)	dim. & geometric	dim. & some geometric	dim. & most geometric	dim. & some geometric	dim. & all geometric
Bonus/Shift Tolerances	yes	no	yes	no	yes
Datum Precedence	yes	no	indirect	no	yes
Tolerance Zone Interaction	N/A	no	yes	no	yes
Directly Based on 3D Tol. Zones	projected zone	no	point based*	point based*	yes
Analysis Level	part and assembly	part and some assemblies	part and assembly	good for assembly	part and assembly
Ease of Use & Learning	easy	moderate	difficult	difficult	moderate
Compatibility with CAD	yes	yes	no	no	yes
Accuracy of Results (Sensitivity to User Expertise, Repeatability)	good	moderate	poor	moderate	good

* The model and variation scheme depend a lot on the user-defined points (control points, end point of vectors, etc.)

4. RESEARCH GAPS

From the above literature review, certain criteria are identified for the purpose of comparison and evaluation of a tolerance design method for mechanical engineering. Further, it is observed that there is a need for a method that can do real world optimal tolerance design suitable for mechanical assemblies. As per the progress of research in this domain, we listed the research problems.

- Most of the approaches developed for the tolerance allocation use manufacturing cost only and very few have considered quality cost also.
- Assemblies involving interrelated dimension chains (more than one assembly response functions with some common dimensions) should be handled without any trouble.
- Tolerance design not to direct relation between the deviation of product specification and the machining tolerances.
- Tolerance design method no considers concurrently the product design tolerances and process design tolerances.
- The tolerance allocation methods have not considered positional tolerance. Moreover, the methods which are used to convert geometrical tolerances into linear tolerances have also not been attempted.
- Most of the recent works considered the only GA for optimization of tolerance allocation for mechanical assemblies. Very few researchers concentrated on the optimization of tolerance allocation of mechanical assemblies utilizing other evolutionary algorithms. No study attempted to identify the

percentage contribution of tolerances on the total cost. Moreover, no systematic study was there to compare the performance analysis of various evolutionary algorithms.

5. CONCLUSION

This paper presents the reviews on techniques of tolerance design in mechanical engineering. The literature related to Taguchi, RSS methods for bottom to top tolerance stack up analysis are described. In this paper we studded the comparative study and analysis of the elliptic particle settling analysis cold, hot, and isothermal particle sedimentation. We presented the investigation and comparative analysis of recent studies. The outcome of this paper claims the various research gaps identified from the literature review.

REFERENCES

1. Fang H.F. & Wu Z.T. (1995). A research of concurrent design in computer aided design tolerance and process tolerance. China Mechanical Engineering; 06: pp. 25-7.

2. Narahari Y., Sudarsan R., Lyons K.W., Duffey M.R., Sriram R.D. (1999). Design for tolerance of electro-mechanical assemblies: an integrated approach. IEEE Transactions on Robotics and Automation; 15: pp. 1062-79.

3. Roy U., Pramanik N., Sudarsan R., Sriram R.D., Lyons K.W. (2001). Functionto- form mapping: model, representation and applications in design synthesis. Computer-Aided Design; 33: pp. 699-719.

4. Dantan J.Y., Anwer N., Mathieu L. (2003). Integrated tolerancIng process for conceptual desIgn. CIRP Annals Manufacturing Technology; 52: pp. 135-8.

5. Mantripragada R. & Whitney D.E. (1998). The datum flow chain: a systematic approach to assembly design and modelling research in engineering design. Research in Engineering Design 1998;10:150-165

6. Dinesh Shringi, Kamlesh Purohit (2013). Analysis of New Non Traditional Tolerance Stack Up Conditions, International Journal of Engineering Research and Applications (IJERA), Vol. 3, Issue 2, March -April 2013, pp. 1419-1424.

7. Mathieu Mansuy, Max Giordano, Pascal Hernandez (2011). A new calculation method for the worst case tolerance analysis and synthesis in stack-type assemblies, International Journal of Science, M. Mansuy et. al./Computer-Aided Design 43, pp. 1118–1125

8. Suyash Y. Pawar, Harshal A. Chavan, Santosh P. Chavan (2011). TOLERANCE STACK UP ANALYSIS AND SIMULATION USING VISUALIZATION VSA, International Journal of Advanced Engineering Technology, IJAET/Vol.II/ Issue I/January-March 2011/169-175

9. Luc Laperriere, Hoda A. EIMaraghy Z. (2000). Tolerance Analysis and Synthesis Using Jacobian Transforms, Annals of the CIRP Vol. 49/1/2000/359-362

10. Paul Beaucairea, Nicolas Gaytona, Emmanuel Duca, Jean-Yves Dantanb (2013). Statistical tolerance analysis of over-constrained mechanisms with gaps using system reliability methods, Computer-Aided Design 45, pp. 1547–1555

11. Fangcai Wu, Jean-Yves Dantan, Alain Etienne, Ali Siadat, Patrick Martin (2009). Improved algorithm for tolerance allocation based on Monte Carlo simulation and discrete optimization, international journal of Computers & Industrial Engineering 56, pp. 1402–1413

12. Jinn-Tsong Tsai (2012). An evolutionary approach for worst-case tolerance design, Engineering Applications of Artificial Intelligence 25, pp. 917–925.

13. Nadeem Shafi Khan (2011). Generalized Statistical Tolerance Analysis and Three Dimensional Model for Manufacturing Tolerance Transfer in Manufacturing Process Planning, ARIZONA STATE UNIVERSITY, May 2011.

14. Taguchi G. (1989). 'Quality engineering in production systems', McGraw-Hill, New York.

15. Nigam, S. D., & Turner, J. U. (1995). Review of statistical approaches to tolerance analysis. Computer-Aided Design, 27(1), pp. 6–15. DOI:10.1016/0010-4485(95)90748-5

16. Zhang, H., Cao, Y., Wei, Y. & Yang, J. (2013). A Concurrent Design Method for Functional Tolerance and Structure based on the Principle of Decomposition and Reconstitution. Procedia CIRP, 10, pp. 194–202. DOI:10.1016/j.procir.2013.08.031

17. Govindarajalu Jayaprakash, Karuppan Sivakumar, Manoharan Thilak (2010). "Parametric Tolerance Analysis of

Mechanical Assembly by Developing Direct Constraint Model in CAD and Cost Competent Tolerance Synthesis" Intelligent Control and Automation, 1, pp. 1-14.

18. Kenneth W. Chase, Alan R. Parkinson (1991). "A Survey of Research in the Application of Tolerance Analysis to the Design of Mechanical Assemblies" April 5, 1991.

19. Kenneth W. (1999). Chase Department of Mechanical Engineering Brigham Young University "Tolerance Allocation Methods for Designers".

20. P. K. Singh, P. K. Jain, and S. C. Jain (2009). "Important issues in tolerance design of mechanical assemblies. Part 2: tolerance synthesis" on 21 April 2009.

21. M. Tlija, B. Louhichi & A. Benamara (2013). "Integration of tolerances in the mechanical product process: Assembly with defects modelling", Bordeaux.

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