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A Review on Geometrical Tolerance Applications in The Automotive Industry

(Satu Ulasan terhadap Aplikasi Toleransi Geometri dalam Industri Automotif)

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ABSTRACT

This paper presents some of the earlier studies pertaining of analytical methods for tolerance, its effect and applications in the automotive industry. In today's automotive and aerospace industries, the tolerance process is crucial in the design phase and product development. In the design process, issues such as matches and limits, geometric and tolerance dimensions (GD&T) should be considered by designers to assist manufacturers and installation operators to reduce the cause of failure of critical parts. The impact of failure can destroy some critical parts and reduce the system performance. It is also noted that automotive suppliers for part and components face problems related to the quality due to miscommunication related to tolerance. Quality improvements with various methods have been made by automotive suppliers for part and components to remain competitive and building long-term relationships with automotive manufacturers. Automotive parts suppliers are required to contribute towards improving the overall quality of the car. While empirical studies show that statistical concepts are essential for good and important quality management in tackling the manufacturing process, there is insufficient emphasis on the use of tolerance in quality practices among these suppliers. The impact on manufacturing costs and the methods used will be reviewed as a benchmark for further research to optimize and improve the component reliability. As a result, it can be ascertained that extensive researches have been carried out worldwide focusing on tolerance optimization method for mechanical components in the automotive industry.

Keywords: Geometrical dimensioning and tolerance; fit and limit; product development

ABSTRAK

Kertas kerja ini membentangkan beberapa kajian yang terdahulu berkaitan dengan kaedah analisis untuk toleransi, kesannya dan penggunaannya di dalam industri automotif. Dalam industri automotif dan aeroangkasa hari ini, proses toleransi adalah penting dalam fasa reka bentuk dan pembangunan produk. Dalam proses reka bentuk, isu-isu seperti padanan dan had, dimensi geometri dan toleran (GD&T) perlu dipertimbangkan oleh pereka untuk membantu pengilang dan pengendali pemasangan untuk mengurangkan punca kegagalan terhadap bahagian yang kritikal. Impak terhadap kegagalan boleh memusnahkan bahagian kritikal dan menurunkan prestasi sistem. Didapati juga pembekal peralatan dan komponen automotif menghadapi masalah berkaitan dengan kualiti disebabkan oleh masalah komunikasi berkaitan toleransi. Penambahbaikan kualiti dengan pelbagai kaedah telah dilakukan oleh pembekal alatan dan komponen automotif untuk kekal kompetatif dan untuk membina hubungan jangka panjang dengan pengilang otomotif. Pembekal bahagian automotif diminta untuk menyumbang ke arah meningkatkan kualiti keseluruhan kereta. Walaupun kajian empirikal menunjukkan bahawa konsep statistik penting untuk pengurusan kualiti yang baik dan penting dalam menangani proses pembuatan, terdapat penekanan yang tidak mencukupi mengenai penggunaan tolerasi dalam amalan kualiti di kalangan pembekal ini. Kesan kepada kos pembuatan dan kaedah yang digunakan akan dikaji semula sebagai penanda aras untuk kajian lanjut untuk mengoptimumkan dan meningkatkan kebolehpercayaan komponen. Sebagai keputusan, didapati terdapat penyelidikan yang meluas dilakukan di serata dunia menumpukan kepada kaedah pengoptimum toleransi untuk komponen mekanikal dalam industri automotif.

Kata kunci: Geometri dimensi dan toleransi; padanan dan had; pembangunan produk

INTRODUCTION

In the design process, geometric dimensioning and tolerancing (GD&T) contains information regarding the specifications to manufacture components. Geometrical product specification using International Organization for Standardization (ISO, 2004) standards have been evolved and improved American Society of Mechanical Engineers (ASME) Y14.5-2009 standards which resulted of enhancing GD&T language. ASME and ISO have developed standards for defining, representing, and presenting the information of GD&T in order to facilitate that exchange and its' interpretation (Frechette et al. 2011). In the automotive industry, the tolerance processes are major activities especially in design and product development phase (Dantan et al. 2005; 2008). Generally, the dimensioning and tolerance is a precise mathematical expression which has been used to specify the acceptable variation in manufacturing or assembly process (Saravanan et al. 2014; ASME Y14.5M-2009). Product specifications are associated with tolerances, which represent the acceptable limits for measured parts.

In today's worldwide growth demands of automotive production capacities, the competitiveness of the automotive company has been stimulated. In the automotive industry, quality is reflected by the customer's satisfaction of the products and services offered. Therefore, each department and activity in the automotive industry must have the same culture in order to satisfy the internal customers in producing parts and components with high quality (Sanches et al. 2008; Norhamizah & Baba 2008). Critical conditions at the functional and aesthetic quality for a product will come from the relations between each one component in the assembled products. Process in the product development (PD) can be seen as an assembled form for the product geometry. Based on several reasons, the original form can be divided, because safety precaution, aesthetical values and ability to manufacture for the automobile body (Dagman et al. 2006). Modifications of the geometry and design can be done without a huge increase in production cost and it can change at the PD stage. It can overcome production problems related to the shape of the geometry by a slight change in the original design.

For instance, vibration of the rotating parts such as bearings and drive shafts due to the unbalance and misalignment has always been a major problem in automotive components. These high value of vibrations may destroy critical parts at the system such as bearings, gears and coupling. (Askarian et al. 2007). The other problem is the deviations between the ideal computer-aided design (CD) geometry and the actual parts manufactured. In order to ensure the component meet its intended function well and can be assembled properly, tolerances are assigned.

Two main measuring directions used for evaluating variations in the automotive industry are the gap and flush which are defined as the distance perpendicular between two parts and the axis between their normal surfaces (Dagman et al. 2006). These visualizations can be used to specify the tolerable gap and flush for all points simultaneously (Stoll et al. 2008). The tolerances definition was originated from the manufacturing specification requirements of each part. For instance, in the case of a piston compressor, functional requirements considered to ensure that the minimum axial clearance between the connecting rod and the piston should be allowed in all acceptable gaps. Sensitivity analysis is performed to identify tolerances that affect each gap, as defined in Equation (1). The weights for each tolerance will be calculated by evaluating the measurement variance σ^2_{TOT}, after all tolerances are applied to the assembly components with the same measurement variance σ^2_{TOT-Ti} (Polini 2011).

$$C_t = \frac{\sigma^2_{TOT} - \sigma^2_{TOT-Ti}}{\sigma^2_{TOT}} [\%] \tag{1}$$

Dantan et al. (2008) proposed a model with a unified description of geometrical specifications based on current engineering practices which allows for a complete and coherent tolerance process for developments in the fields of tolerance and metrology. Chase and Parkinson (1991) emphasized that tolerance process must be considered during detail design phase, hence the need for analysis of existing approaches which deal with tolerance synthesis in design. This paper aims to identify and provide an extensive literature review of the effect of geometrical tolerance specifically in the automotive industry.

TOLERANCE APPLICATION IN THE AUTOMOTIVE INDUSTRY

In many industries, GD&T data was created and stored as an integral part of models to drive downstream activities including engineering, analysis, production, and inspection. Software applications associated with these activities must be able to exchange and interpret GD&T information correctly to achieve the goal. Tolerance analysis is used to predict the effects of manufacturing variations of finished components and to ensure design tolerances in manufacturing data can be used to define the variation specifications (Pawar et al. 2011). Low tolerances are more preferred by designers with suitable fit limit, function and performance, on the other hand, manufacturing engineers prefer open tolerances to meet their production schedule (Saravanan et al. 2014).

Functional tolerance process is always used to define the geometrical specifications for ensuring components to work as its desired purpose (Dantan et al. 2005). For example, variation at split-line from assembling processes caused by component dimensional changes and assembly variations can influence the output variation. The design variation on component and manufacturing process can influence the split-lines and give negative impressions to components and user interpretation. Quality characteristics are important in car components. Visual Quality Appearance (VQA) can be defined as the visual impression of a product to the customer. The VQA is affected by tolerance variation in the design, visual and geometrical sensitivity (Dagman et al. 2006). For example, Figure 1 shows a scenario where the gap has been expanded and narrowed respectively as a whole by applying the same gap value at each of the points.

The manufacturing process involves many activities including design, analysis, fabrication, cost, change management, supply chain management and after sales service (Hoffmann et al. 2011). Components and model inter-changeability for mass production can be accomplished by a set of tolerance limit when the given part is fitted to function during the assembly process. Any component must be designed

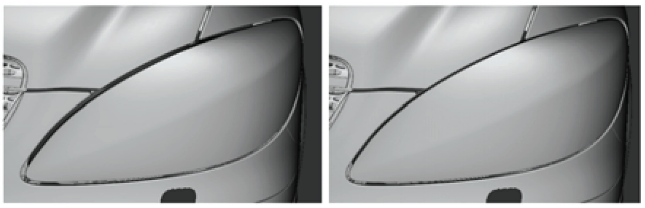

FIGURE 1. Different visualization of gap sizes generated by the prototype (Stoll et al. 2008)

and manufactured in the tolerance zones and fit limit referring to its function and component size. Interchangeability with any other size is assumed as a correct design to allow a precise specification of nominal size in tolerance zones. The determination of tolerances for complex components such as aircraft, car bodies, graphic tools and some rules have been developed to further enhance the ability of the transformer to determine according to the appropriate limit type (Dantan et al. 2005). According to Guzman and Hammett (2003), most of automotive companies do not have formal tolerance adjustment as their strategies. The publications of tolerance applications in automotive industries are shown in Table 1. The publications list is reviewed and derived from online journal which are related to tolerance applications in the automotive industry. From the table, it can be observed that the tolerance applications have been used to improve the quality and accuracy of the product whereby higher degree of precision will increase the manufacturing cost of components. On the other hand, Concurrent Engineering (CE) has emerged as the rule which leads the way for design and manufacturing in tolerance analysis. This method is the best way to solve installation problems so that lower costs with high quality are obtained. Polini (2011a) claimed that the CE has been used for communications with the aim of reducing repetition and product removal times. Meanwhile, conformance testing (CT) in the automotive industry has been successfully implemented for specified requirements associated with product, process and services. This can been found in Frechette et al. (2011) which proposed a new strategy for the CT in measurement. Successful implementation of a standard using software application has several benefits for users.

TABLE 1. Tolerance application in automotive industries

Resource	Part
Dantan et al. (2005)	Industrial example (piston compressor).
Dantan et al. (2005)	Key deviations and contacts of the connecting rod.
Dantan et al. (2005)	Worst configurations of the functional virtual boundaries of the connecting rod
Dantan et al. (2005)	Geometrical specification of the connecting rod.
ASME Y14.5M-2009	Schematic diagram showing the gear hub/shaft, the overall dimensions, and defining coordinate system
Marguet et al. (2001)	Aircraft skin's jig with tooling hole system
Marguet et al. (2001)	Winch arm mounted on the helicopter
Dantan et al. (2008)	Position between the two cylinders.
Saravanan et al. (2014)	Piston and block analysis
Wyk (1999)	Assembly Variation for Outer Release of the Side Door Latch
Kumar et al. (2009)	Schematic of an automobile body structure assembly
Trument et al. (2006)	Tolerance Reverse Engineering of mounting bracket of a car break assembly
Polini (2011)	Automotive seat (i) and seat track A (ii) including section view (iii). Symmetric track
Pawar et al. (2011)	A motor assembly drawing (Jeang 1999), Crank, shaft
Chethan et al. (2013)	Automotive Body Assembly process
Chang et al. (2009)	Analyzing the tolerances in disk cam mechanisms with a flat faced follower
Ding et al. (2000)	Allocating tolerance based on product design characteristic for each component
Udupa et al. (2013)	Design and Tolerance Stack up Analysis of Car Side Door Latch

TOLERANCING METHOD FOR THE AUTOMOTIVE INDUSTRY

Tolerance design values in each axis must be small designated by key parameters. Translational movements translate along an axis while rotational movements for rotations around an axis. Platform-based engineering (PBE) requires a strong foundation in model-based engineering (MBE). The basic forms of PBE and MBE appear in the automotive industry by using this method in manufacturing, where a set of products is designed and certain sets of members are obtained by selecting certain parameters and constraints (Hoffman 2011).

The design process is performed and integrated by using CAD systems, which generate 3D information of product models and achieve a fully graphic creation that has several advantages of modeling systems such as dimensions, geometric shapes, locations, orientation and kinematic adjustments. Automotive front suspension and mounting brackets of the braking system assembly are examples of inverse designs that use coordinate measurement machines (CMM) and laser scanners equipped with high accuracy CAD modeling

These methods is used to obtain surface roughness and dimension tolerances for automotive components with various casting and machining features and are validated against actual and existing drawings for the same components (Jamshidi et al. 2006). Tolerance analysis is a method of predicting and analyzing assembly variation for tolerance of individual components and assembly operations (Chethan et al. 2013). As Guzman and Hammett (2003) stated that the methodology of tolerance revisions and adjustments is a key step for validation process of a new vehicle. Actual variation levels and subsequent process monitoring demands observed in production can predict over 90% of the variations. North American OEM was involved to develop and be adopted as a standard practice for dimensional evaluation and revision of sheet metal components.

Dantan et al. (2005) proposed a mathematical formulation of tolerance synthesis in order to define the rules by taking into geometrical behavior and simulate influences of geometric deviations on geometric behavior of the mechanism and integration quantification. Mathematical basis for the inter component changeability came with existence of the development and standardization of GD&T.

For example, the GeoSpelling model allows for completed and coherent tolerance (Dantan et al. 2008). By using the model, all the classic activities such as specification, analysis, synthesis, and verification of tolerance can be implemented. Geometric features which are created from the model of a non-ideal surface of the part by different operations can define specification condition for characteristics as shown in Figure 2.

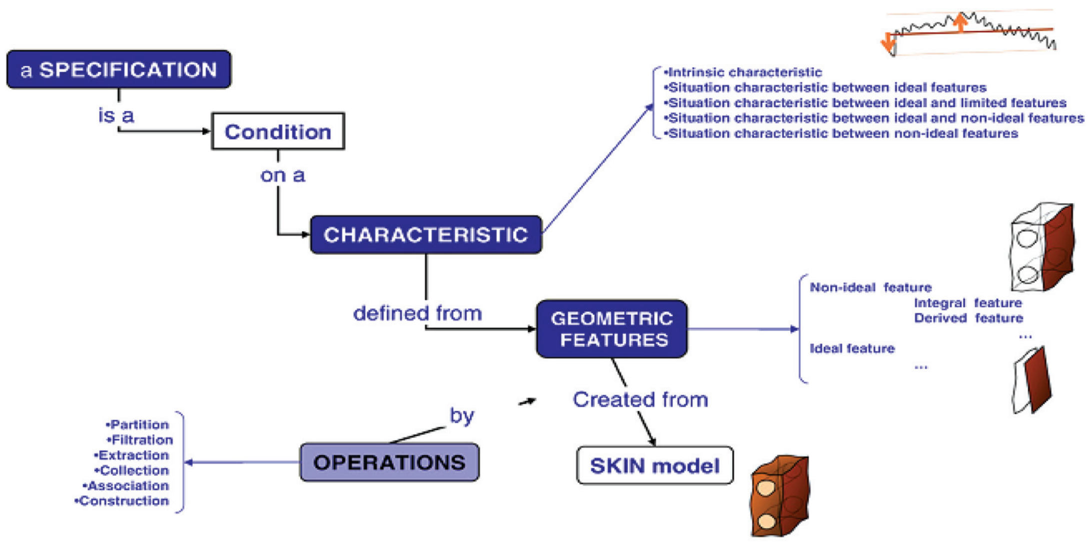

FIGURE 2. GeoSpelling basic concept (Dantan et al. 2008)

Moreover, the technical functional analysis allows determination of the geometrical functional requirements, which were limited to the functional characteristics of the mechanism (Marguet et al. 2001; Soderberg et al. 2002). Functional tolerance process was proposed to define the geometrical specifications of components to ensure the validation of its functional requirements. Product geometrical requirements of a component was developed to ensure it meets the level of quality defined. Therefore, it is essential for the designers to have specific rules and methods to determine the tolerances.

Component geometry features will be defined in each coordinate axis in accordance with parameters such as parametric variations. Section deviations, gaps and functional features between sections are illustrated by parameters. A synthesis of research papers on analysis Wyk (1999) notes that the multi-dimensional tolerance analysis is an approach where the result is valid as long as the tolerance is not too large compared to the curvature on the surface of the space. In addition, this method is a systematic procedure for modeling and analyzing variations in design and installation (Chase 1999). In general, complicated problems are easier to solve by using this method as it helps to divide the problem into easier pieces to be evaluated.

EFFECTS OF TOLERANCE AND COST TO THE AUTOMOTIVE MANUFACTURING

In line with the technology and performance requirements by the automotive industry, the design stage has attracted attention which relates to the design tolerance for high precision in order to manufacture at a lower cost and increase precision of assemblies. The product development process has two critical phases. Concept design and start-up study finds that more than 75% of the cost of a product is due to the decision made during this stage (Dantan et al 2008; Feng et al. 2000; Allen et al. 2013). Results and information generated during this phase has a major impact on the success of the design phase, so these phases can determine the rules that enable information management, manufacturing assessment, preliminary planning of the process and cost estimates of products (Feng et al. 2000; Desrochers & Laperriere 2001). According to Kumar et al. (2009), the accuracy cost

TABLE 2. Analysis method for tolerance in automotive

Resource	Analysis method
Pawar et al. (2011)	Tolerance Synthesis
ASME Y14.5M-2009	Analytical approach
ASME Y14.5M-2009	Standstill analysis
ASME Y14.5M-2009	Spinning analysis
ASME Y14.5M-2009	Combined spinning and thermal analysis
ASME Y14.5M-2009	Spinning analysis using post-failure measurements
Dantan et al. (2008)	Tolerance analysis
Soderberg et al. (2001)	Genetic Algorithms
Saravanan et al. (2014)	CFD (Computational Fluid Dynamics)
Saravanan et al. (2014)	FEA (Finite Element Analysis)
Royand et al. (1999)	Monte Carlo simulation
Feng et al. (2000)	Tear Down and Component Analysis
Pawar et al. (2011)	Neural Network
Chethan et al. (2013)	Six sigma
Lanzetta et al. (2010)	Genetic Algorithms
Mazur et al. (2011)	Statistical tolerance analysis
Majeske et al. (2003)	A Case Study Using DOE
Singh et al. (2006)	Tolerance analysis
Nuraini et al. (2008)	Application of Monte Carlo Simulation for Free Piston Engine Cylinder Block Design

of a component dimensions depends on the process and resources required for the production of the dimension within its tolerance limits. It means that more precise tolerance allowances between the assembled parts can lead to lower costs and the possibility to reduce the total rejection and re-work on components for each installation

The analysis of tolerance research area in the automotive industry is shown Table 3. In this paper, the aim is to obtain the research gap for future research in the automotive industry such as optimization of tolerance for longevity and efficiency in rotational mechanical components in the automotive industry. The reduction of cost has always been the main objective of manufacturing activities. If the redesign is needed because of unforeseen tolerance problems, which cannot be traced before actual rallies, business costs will be high especially when considering that 40-60% of cost production is estimated as a result of the installation process (Polini 2011a; Delchambre 1996). The total cost defined as the cost of manufacturing and quality loss expressed is expressed by the following equation (Polini 2011b; Jayaprakash et. al. 2010),

$$TC_i = \sum_{j=1}^{q} k_j [(U_{ij} - T_j)^2 = \sigma_{ij}^2] = \sum_{k=1}^{m} C_M(t_{ik}) \qquad (2)$$

where,

m is the number of components of the installation dimension q in the finished product,

k_j is the cost coefficient of the j-th resultant dimension for quadratic loss function,

U_{ij} is the j-th resultant dimension from the i-th experimental results,

σ_{ij} is the j-th resultant variance of statistical data from the i-th experimental results,

T_j is the design nominal value for the j-th assembly dimension,

t_{ik} is the tolerance generated during the i-th experiment for the kth component, and $C_M(t_{ik})$ the manufacturing cost for the tolerance t_{ik}.

TABLE 3. Literature analysis for tolerance research area in automotive industries

Resource	Research Area			
	Cost Effect	GD&T	Fit, Limit & Tolerance	Quality
ISO 2004	x			x
ASME Y14.5M-2009			x	
Marguet et al. (2001)		x		
Dantan et al. (2008)		x		
Soderberg et al. (2002)		x		
Soderberg et al. (2001)		x		
Wyk (1999)		x		
Royand et al. (1999)	x			
Feng et al. (2000)		x		x
Kumar et al. (2009)	x	x		x
Trument et al. (2006)	x	x		
Polini (2011)			x	
Pawar et al. (2011)	x	x		
Chethan et al. (2013)	x			x
Norhamizah et al. (2008)				x
Huang et al. (2006)	x	x	x	
Li et al. (2006)	x			x
Roy et al (1999)		x		
Rui et al. (2010)		x		
Talib et al. (2012)				x
Wu et al. (1988)	x	x	x	

Tolerance applications are widely used in the research or case studies related to the automotive industry, such as for vehicle body parts or moving parts. Process tolerances at individual sheet metal forming operations are well understood and the industry has adopted geometric tolerances and dimensions using some standards, using the combinational theory and applications of tolerance stacks and allocation of tolerances of individual operations are not mature. In many case studies that related to automotive industry, several methods to acquire the capability in terms of function components, thermal effects and the capacity of the components has been used. GD&T is a universally accepted graphic language to improve communication, product design, and quality. The advantages of using GD&T in engineering design and product development are to erase problems using symbols and received data universally, using datum and datum systems to define dimension requirements regarding interfaces, defining dimensions and receipts related to functional relationships and use tolerance dimensions as a requirement using a method that reduces accumulation of tolerance. Tolerance analysis can provide information that can be used to control hardware and assembly. Due to this, the tolerance assembly requirements have to certain limit value for critical components, resulting in reduced manufacturing cost and high product reliability.

Improving manufacturability using design for manufacturing shows that interchanges between costing with robustness and between quality and robustness were identified. Quantified under the assumptions that changing fixture layouts does not increase costs and the considered system cost depends only on allocated product and process tolerances. As Manufacturers need to take into account the environment, they tend to research to produce their products in such a way as to minimize environmental hazards, while at the same time maintaining their costs (Hammond et al. 1998)

Tolerance affects the cost of manufacturing in the automotive industry; therefore, the dimensional tolerances must be defined to ensure the functioning parts. Tolerances are important in automotive industry because it will boost the economy by expanding the activities which are directly involved in the manufacturing of automotive. Furthermore, the benefits can contribute to other sectors such as transportation equipment, aerospace, marine and service sectors. Tolerance in the automotive industry must be controlled from the product design process until the assembly stage. Supplier or vendor must communicate about tolerance and have same knowledge about tolerance.

CONCLUSIONS

This paper presents a review of the impact and contribution of tolerance towards the automotive industry and presents scenarios of the competitiveness of automotive parts or product quality issues in the automotive manufacturing industry. Tolerance is known as the acceptable range of the deviation for a given dimension. Since most of automotive component uses the variable material, the parts must be manufactured to achieve certain standards and need the precision necessary to meet specified tolerances. This paper presents some of the earlier studies pertaining to analytical methods for tolerance, tolerance effect and tolerance applications in the automotive industry. GD&T needs to be considered from the design stage to reduce the cause of failure in the critical part of the next process because it can reduce performance system.

From the literature, it can be concluded that the factors that are affected by tolerance are: (i) Manufacturing time, (2) Reworking (iii) Quality of products. Therefore, future research should take into account the effect of tolerance in terms of product performance, product life time, efficiency and any parts and assemblies that are be developed in rotating mechanical products. Tolerance is an important part of being considered in automotive manufacturing which includes design, engineering capabilities, and full-scale manufacturing operations.

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REFERENCES

Allen, D. E., Kramadibrata, A. R., Powell, R. J & Singh, A. K. 2013. Default risk in the European automotive industry. *International Review of Business Research Papers* 9(1): 22- 37.

Askarian, A. & Hashemi, S. M. R. 2007. Effect of axial force, unbalance and coupling misalignment on vibration of a rotor gas Turbine. *14 International Congress on Sound & Vibration*, ICSV14, Cairns Australia.

ASME Y14.5M-2009. Dimensioning and tolerancing. *The American Society of Mechanical Engineers*, New York, USA.

Chang, W. T. & Wu, L. L. 2009. A computerized approach for tolerance analysis of disk cam mechanisms with a flat-faced follower. *Transactions of the Canadian Society for Mechanical Engineering* 33(3): 459-485.

Chase, K.W. & Parkinson, A. R. 1991. A survey of research in the application of tolerance analysis to the design of mechanical assemblies. *Research in Engineering Design* 3: 23-37.

Chase, K.W. 1999. Multi-dimensional tolerance analysis (automated method). In *Dimensioning and Tolerancing Handbook*, edited by Paul Drake Jr. McGraw-Hill.

Dagman, R., Soderberg, R. & Lindkvist, L. 2006. Form division in automotive body design linking design and manufacturability. *International Design Conference*, Design 2006, Dubrovnik Croatia.

Dantan, J.Y., Mathieu, L., Ballu, A. & Martin, P. 2005. Tolerance synthesis: quantifier notion and virtual boundary. *Computer-Aided Design* 37: 231-240.

Dantan, J.Y., Ballu, A. & Mathieu, L. 2008. Geometrical product specifications - model for product life cycle. *Computer-Aided Design* 40: 493-501.

Desrochers, A. & Laperriere, L. 2001. Framework proposal for a modular approach of tolerancing. *Proc. of the 7th CIRP International Seminar on Computer Aided Tolerancing*, 93-102.

Ding, Y., Jin, J., Ceglarek, D. & Shi, J. 2000. Process-oriented tolerance synthesis for multistage manufacturing system. *American Society of Mechanical Engineers, Manufacturing Engineering Division* 11: 15-22.

Feng, S.C. &. Song, E.Y. 2000. Information modeling of conceptual design integrated with process planning. *In: Proc. of ASME DETC/DFM.*

Frechette, S., Jones, T. &. Fischer, B., 2011. A strategy for testing product conformance to geometric dimensioning & tolerancing standards: technical notes. *Procedia Engineering 12th CIRP Conference on Computer Aided Tolerancing.*

Guzman, L.G. & Hammett, P.C. 2003. A tolerance adjustment process for dimensional validation of stamping parts and welded assemblies. *Office for the Study of Automotive Transportation Research Institute*, The University of Michigan, SAE -01-2871.

Hammond, R., Amezquita, T. & Bras, B.A. 1998. Issues in the automotive parts remanufacturing industry: discussion of results from surveys performed among remanufacturers. *International Journal of Engineering Design and Automation,* Special Issue on Environmentally Conscious Design and Manufacturing 4(1): 27-46.

Hoffmann, C.M., Vadim, S. & Vijay, S. 2011. Geometric interoperability for resilient manufacturing. *Department of Computer Science Technical Reports*, *Purdue University*, Paper 1746.

Huang, M.F. & Zhong, Y.R. 2006. Concurrent process tolerancing based on manufacturing cost and quality loss. *Manufacturing the Future*.

ISO, International organization for standardization ISO/IEC guide 2. 2004. standardization and related activities general vocabulary, *International Organization for Standardization*, Geneva, Switzerland.

Jamshidi, J., Mileham, A. R. & Owen, G. W. 2006. Dimensional tolerance approximation for reverse engineering applications. *International Design Conference-Design*, Dubrovnik – Croatia.

Jayaprakash, G., Sivakumar, K. & Thilak, M. 2010. Parametric tolerance analysis of mechanical assembly by developing direct constraint model in CAD and cost competent tolerance synthesis. *Intelligent Control and Automation* 1: 1-14.

Kumar, R.S., Alagumurthi, N. & Ramesh, R. 2009. Optimization of design tolerance and asymmetric quality loss cost using pattern search algorithm. *International Journal of Physical Sciences* 4 (11): 629-637.

Lanzetta, M. & Rossi, A. 2010. Roundness evaluation by genetic algorithms. *Department of Mechanical, Nuclear and Production Engineering University of Pisa*, Via Diotisalvi 1, 56122 Pisa, Italy.

Li, Z., Kokkolaras, M., Izquierdo, L. E., Hu, S. J. & Papalambros, P. Y. 2006. Multiobjective optimization for integrated tolerance allocation and fixture layout design in multistation assembly. *Proceedings of IDETC/CIE 2006 ASME 2006 International Design Engineering Technical Conferences & Computers and Information in Engineering*, Philadelphia, Pennsylvania, USA.

Norhamizah, S. & Baba, M.D. 2008. A case study on the implementation of quality control circle in the production line of a manufacturing company, *Jurnal Kejuruteraan* 2: 1-10.

Majeske, K. D. & Hammett, P. C. 2003. Predicting assembly dimensions with functional build: a case study using DOE. *Journal of Manufacturing Processes* 5(1): 54-65.

Marguet, B. & Mathieu, L. 2001. Method for geometric variation management from key characteristics to specifications. *CIRP Seminar on Computer Aided Tolerancing*, France.

Mazur, M., Leary, M., Huang, S., Baxter, T. & Subic. A. 2011. Benchmarking study of automotive seat rack sensitivity to manufacturing variation. *International Conference on Engineering Design*, Technical University Of Denmark.

Pawar, S.Y., Chavan, H. A. & Chavan, S. P. 2011. Tolerance stack up analysis and simulation using visualization VSA. *International Journal of Advanced Engineering Technology* 2(1): 169-175.

Polini, W. 2011a. To carry out tolerance analysis of an aeronautic assembly involving free form surfaces in composite material. *Advances in Composite Materials - Ecodesign and Analysis*: 195-221.

Polini, W. 2011b. Geometric tolerance analysis, *Springer*.

Roy, U. & Li, B. 1999. Representation and interpretation of geometric tolerances for polyhedral objects. *Computer Aided Design* 31(4): 273-85.

Rui, W., Thimm, G. L. & Sheng, M. Y. 2010. Review: geometric and dimensional tolerance modeling for sheet metal forming and integration with CAPP. *International Jurnal Advance Manufacturing Technology* 51(9): 871-889.

Sanches Jr, L. M., Filho, M. S. & Batalha, G. F. 2008. Automotive body-in-white dimensional stability through pre-control application in the subassembly process. *Journal of Achievements in Materials and Manufacturing Engineering* 31: 705-711.

Saravanan, A., Balamurugan, C. & Karthik, A. 2014. Evolutionary optimization of geometric tolerances for compliant assemblies with contact interactions. *ARPN Journal of Engineering and Applied Sciences* 9(4): 419-427.

Nuraini, A. A., Ahmad Kamal Ariffin, M. I., Mohd Jailani M. N. & Nordin, J. 2008. Application of Monte Carlo simulation for free piston engine cylinder block design, *Jurnal Kejuruteraan* 20: 83-93.

Singh, P.K., Jain, S.C. &. Jain, P.K. 2006. Concurrent optimal adjustment of nominal dimensions and selection of tolerances considering alternative machines. *Computer-Aided Design* 38: 1074-1087.

Soderberg, R. & Lindkvist, L. 2002. Geometrical coupling analysis in assembly design. *Second International Conference on Axiomatic Design*, ICAD 024, Cambridge, USA.

Soderberg, R. & Lindkvist, L. 2001. Automated seam variation and stability analysis for automotive body design. *CIRP Seminar on Computer Aided Tolerancing*, France.

Stoll, T. & Paetzold, K. 2008. Gap and flush visualization of virtual non ideal prototypes. *International Design Conference*, *Design* 2008 Dubrovnik Croatia.

Talib, M. A., Munisamy, S. & Ahmed, S. 2012. Automotive parts manufacturing industry: unraveling the efficacious quality framework. *Interdisciplinary Journal Of Contemporary Research In Business* 4(3): 217-226.

Truman, C.E. &. Booker, J.D. 2006. Analysis of a shrink-fit failure on a gear hub/shaft assembly. *Engineering Failure Analysis,* 14: 557-572.

Udupa, N., Hegde, R. & Kumar, G. R. 2013. Design and tolerance stack up analysis of car side door latch. *International Journal of Research In Mechanical Engineering & Technology* 3(2): 192-197.

Wu, Z., Elmaraghy, W. H. & Elmaraghy, H. A. 1988. Evaluation of cost-tolerance algorithms for design tolerance analysis and synthesis. *ASME Manufacturing Review* 1(3): 168-179.

Wyk, D. V. 1999. Multi-dimensional tolerance analysis (manual method). In Dimensioning and Tolerancing Handbook, edited by Paul Drake Jr. McGraw-Hill.

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