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Geometric Tolerance Applications and Analysis Method in Rotational Mechanical Components

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Abstract: This paper focus a review on geometrical tolerance application and effects in rotational mechanical components. In today's rapid competition on pump and turbomachinery industry the geometrical tolerancing process plays a significant role in high rotational speed of shaft. The imbalance force and misalignment of the shaft during rotating is the cause of the system's vibration. Therefore, Geometrical Dimensioning and Tolerance (GD&T) has been considered as an essential requirement to be fulfilled by rotating machinery manufacturers and assembly worker. The impact and the level of damage to critical parts of the machine were reviewed as a benchmark for further study to reduce the problem and improve the life time component. As a result, there are extensive researches such as optimisation of tolerance for mechanical components in rotating machinery.

Keywords : Geometrical Dimensioning and Tolerance (GD&T), Rotational Component, Geometric tolerances, Unbalanced Rotors, Shaft Misalignment.

I. INTRODUCTION

Today, the shaft with critical rotation speed and is capable of operating in a very long time is very widely used and well-suited in the industry especially involving pump and turbo engine machinery. It has been reported that when the rotation speed of the shaft is too high if any defects, geometric deviations and materials used for the system are inadequate it can lead to dangerous conditions and cause severe damage [1]. Failure due to such deflection can be avoided by adhering to the safety line and permitted limits. In the system it is necessary to avoid the use of rotation speeds close to this critical speed because fast moving parts are always excited by the applied load and if the frequency used is equal to one of the natural frequencies of moving parts known as resonance phenomena. Unbalance and misalignment of the shaft will cause vibrations in the system and can destroy important components of the rotating system [2]. So these factors need to be considered and studied when designing a rotating system. The relationship between manufacturing accuracy and the impact of rotating shaft on dynamic geometry.

Tolerance design, assembly process and component deformation are issues that need to be addressed in meet the geometry requirements of the rotating system [3]. Rotation accuracy improves the system's ability to operate better. Studies to produce rotation accuracy and investigate tolerance analysis methods are important to improve capabilities so that the system can operate better. The present system design still requires bearing components to assist the mechanism in the rotation system. Gradually Geometric tolerances (GT) have been introduced for functional and technical to purposes more efficient method for determining geometrical variations in mechanical component [4]. GT functions to describe the geometric properties for different types of tolerance in design [5].

According to GB / T 1182-2008 GD&T has been classified into five different types and there are fourteen tolerances characteristics that have their own function [1, 6, 7]. Figure 1 shows the variation of geometric characteristic control that affects the function and application in different ways. All geometric tolerances are determined by the standard set of symbols in the drawing. GD&T is part of the design process and was developed with the purpose of providing information on design as well as assisting downstream activities in manufacturing process. Software applications related to these activities are used with the aim of properly converting and interpreting geometric tolerances (GT) information based on ASME and ISO standards [8]. According to ASME Y14.5M-2009 GD&T is the exact mathematical language used to determine acceptable variations for parts or assemblies. Today, the process of producing 3D digital product models using computer aided design (CAD).

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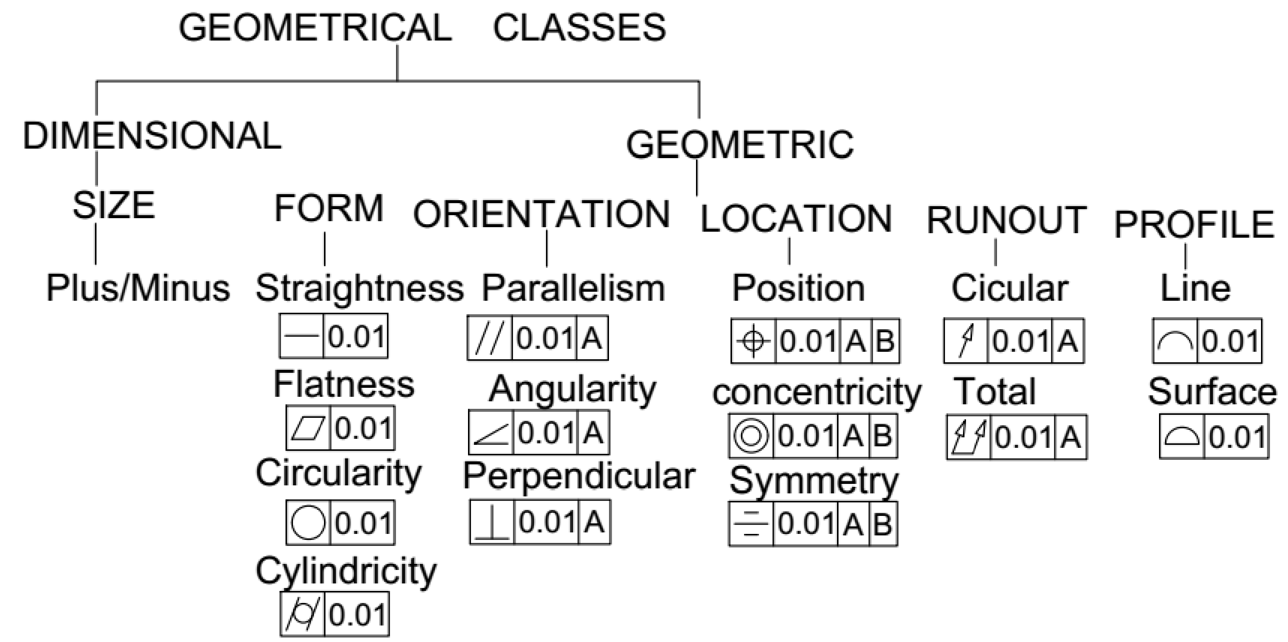

Figure 1: Standard ASME Y14.5M-2009 tolerance classes/symbols using GDT

II. PROBLEM IN ROTATING MACHINERY

Rotating systems are widely used in many engineering fields and therefore rotation accuracy is a major issue in the design of the system. In the manufacture of components a random variation of nominal geometry will result from imperfections in the manufacturing process causing these variations to spread and accumulate rapidly as these components are installed and the system operates [9].

The vibrations in the system can be generated when the geometrical defects in the system element may be due to weakness during the installation process and the effects of wear and tear. The resulting defects may be due to the merged surface which may result in component alignment and loss of component balance [10]. Unwanted vibrations in the system cause significant noise, component wear, high heat and component fatigue [11]. Vibration of the rotating parts such as bearing and drive shaft due to the unbalance and misalignment has always been a major problem in automotive components. In aircraft tolerance analysis, the modeling is extremely important. For the tolerance analysis, distribution, synthesis, evaluation and inspection are based on a previous model. There are no systematic, complete or quick ways to express these aspects of tolerance for a unified model during the aircraft manufacturing tolerance expression [12].

An imbalance is a common problem in the rotating system because the main axis of rotation inertia is not equal to its geometric axis. Larger centrifugal imbalances occur due to higher system speeds and when the components rotate to higher power leads to higher operating speeds. The centrifugal force imbalance is expressed as equation (1) follows by Askarian & Hashemi, 2007:

$$F_x = m_e r\Omega^2 \cos\Omega t \ , \ F_y = m_e r\Omega^2 \sin\Omega t \quad (1)$$

Where;

m_e = unbalance mass

r =unbalance radius and

Ω= rotational speed

Misalignment is an error that can cause damage and failure of the rotating system. Misalignment of the rotating will cause the force and vibration that make the system more difficult to accommodate operations perform and causes more than 70% of the rotating system damage caused by vibration problems. It is practically perfect alignment is difficult to produce because there are many factors such as heat growth, uneven load in the system and improper foundation that interfere with alignment [13]. Misalignment is a situation in which the shaft and other components are not in the same center during rotation resulting in incorrect angular alignment that influences the response force and results in an unstable moment in connectivity that will affect the system [1]. Modern high-performance machines cannot operate continuously or close to critical speeds. Applications in high-speed rotation systems are recommended to reduce 15% of operating speed from critical speeds system [14]. It is important to establish the accuracy so that the components are in a straight line to avoid the presence of an outside alignment as shown in figure 2 or angular misalignment as shown in figure 3. The shaft misalignments can exist in many directions and therefore a three-dimensional space is needed to address the problem which can be divided into vertical and horizontal planes to find out how many offsets and angles exist in each of these planes simultaneously. Imbalance these conditions need to be applied in the coupling location as there is a dangerous vibration system [15].

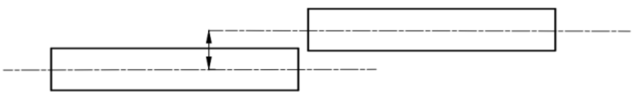

Figure 2: Parallel offset

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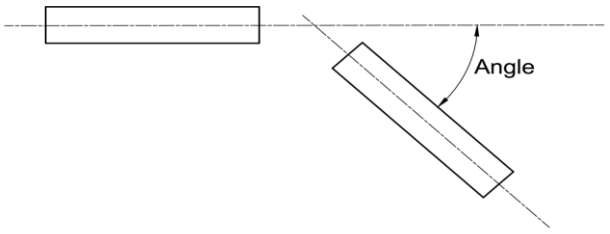

Figure 3: Angular offset

In the automotive industry there are two main measurement directions for assessing variations in the relationship where the gap is a horizontal or straight space between the surfaces of parts and the flush is a space due to the uneven surface height between the parts. Figure 4 shows the gradient and direction of flush variation for critical product dimensions where in the flush direction and the gradient there are roots in three areas which are component variations in installation and concept strength [16].

Figure 4: The gap and flush measuring directions

Maintenance problems have resulted in low availability of rotating equipments in refineries, forcing to depend heavily on importation of finished petroleum products and requiring the investigation of its existing maintenance management practices [17]. Variation problems occur throughout the entire system of rotating systems and variations will increase with the system speed. Dynamic properties for rotating shaft have the effect of varying unbalanced stiffness and bending stiffness [3].

A. Application of Tolerance in Rotating Machinery

ASME has developed and improved to use the GD&T languages by publishing ASME Y14.5-2009 standards. Improvement of this standard by taking into account the design requirements and use of modern methods and equipment. It has been found that GD&T standards are still dependent on methods for interpreting data and are still in the process of developing semantic models. It has been found that GD&T standards are still dependent on methods for interpreting data and are still in the process of developing semantic models [8]. GD&T analysis focuses on developing models that involve tolerance with mathematical representations to estimate and evaluate the effects of design, manufacture and installation [18]. The Dimensioning and Tolerance (D&T) methodology uses these principles with the aim of providing planning for a logical analysis of the design. Flexible rotors are widely used in industrial areas with long and thin geometrical shaft designs to save space. Dimensional measurement errors have a direct impact on GT values for components [11]. Based on the mechanical change process the impact of measurement error can be eliminated using dynamic error method, spectral analysis and separation method. However, geometrical deviation is a consideration in modeling simulations for tolerance as the most prominent representation scheme concludes geometric distortion abstraction [19]. Most models for the collection of tolerances only consider translational defects and rotational parts. Tolerance is the main evaluation in the design process that consists of analyzing and predicting the effect of geometric tolerance on product function and quality.

Aircraft assembly simulation is a new technology used in the manufacture of modern aircrafts. One could visually simulate the methods on the computer, resolve product feasibility, accessibility and verify the reasonableness of the assembly process design. Assembly of products for aircraft components is a complex process that requires high accuracy and manufacturing for aircraft components requires careful installation tolerance design to ensure installation accuracy and improve installation design efficiency and to reduce production costs. Technology for tolerance analysis will help improve the quality and efficiency of aircraft installation [12]. The real geometry of the part is obtained by the representation of small geometry displacements against variations in nominal dimension or geometry using a small displacement torsor or homogeneous matrix [20].

III. APPLICATION OF GEOMETRIC CHARACTERISTIC IN ROTATING PART

In making variations there may be circular characteristics that may occur due to imperfect rotation, imperfect cuts, insufficient lubrication, poor machine parts and chuck jaw deviation. Roundness with poor geometry of the outer surface can cause vibrations during rotation and may cause vibration and irregular sound. Roundness is an object such as a circle or cylinder with tolerance evaluated by reference to ideal geometric properties [21]. Rotation accuracy depends on the centrifugal force and variations in cylinder geometry which affect the stability of the system [3]. In the measurement and analysis of rotating system vibrations, it is possible to detect and locate important errors such as mass imbalance, alignment, rubbing and cracking of the crack [22]. Geometric characteristic (GC) error assessment is an important element in producing accurate manufacturing of mechanical components.

GT errors are generally evaluated using Limit state method **(**LSM). It is found that some methods are not suitable for geometrical tolerance analysis because they are very difficult to use in practices such as worst on worst (WOW) that often produce pessimistic results or Root-sum-square (RSS) only yields results for average mean variations [7]. The conventional way knowing the order of tolerance for assembly is by reference to relevant engineering experience. Figure 5 shows the hole and pin assembly for the two base and plate sections using positioning for geometric samples represented by control point variation model (CPVM) and analyzed using Monte Carlo simulation (MCS) method [23]. CPVM models can represent and determine assembly surfaces, datum planes, emission and assembly disorders. In this case the assembly capacity rate was simulated using the MCS [23, 24]. Run-out measurement shows the speed of behavior due to two factors namely the amount of geometric and rotor axis rotation error. Measurement data used as geometric information in the finite element (FE) model. Simple measurement using only one sensor can't distinguish these basic components from each other [24]. Table 1 shows previous research on the application of tolerance.

From the table obtained there are various studies on tolerance. Previous studies have included the use of tolerance to improve the quality, cost, develope of standart and the impact of tolerance on the performance system.

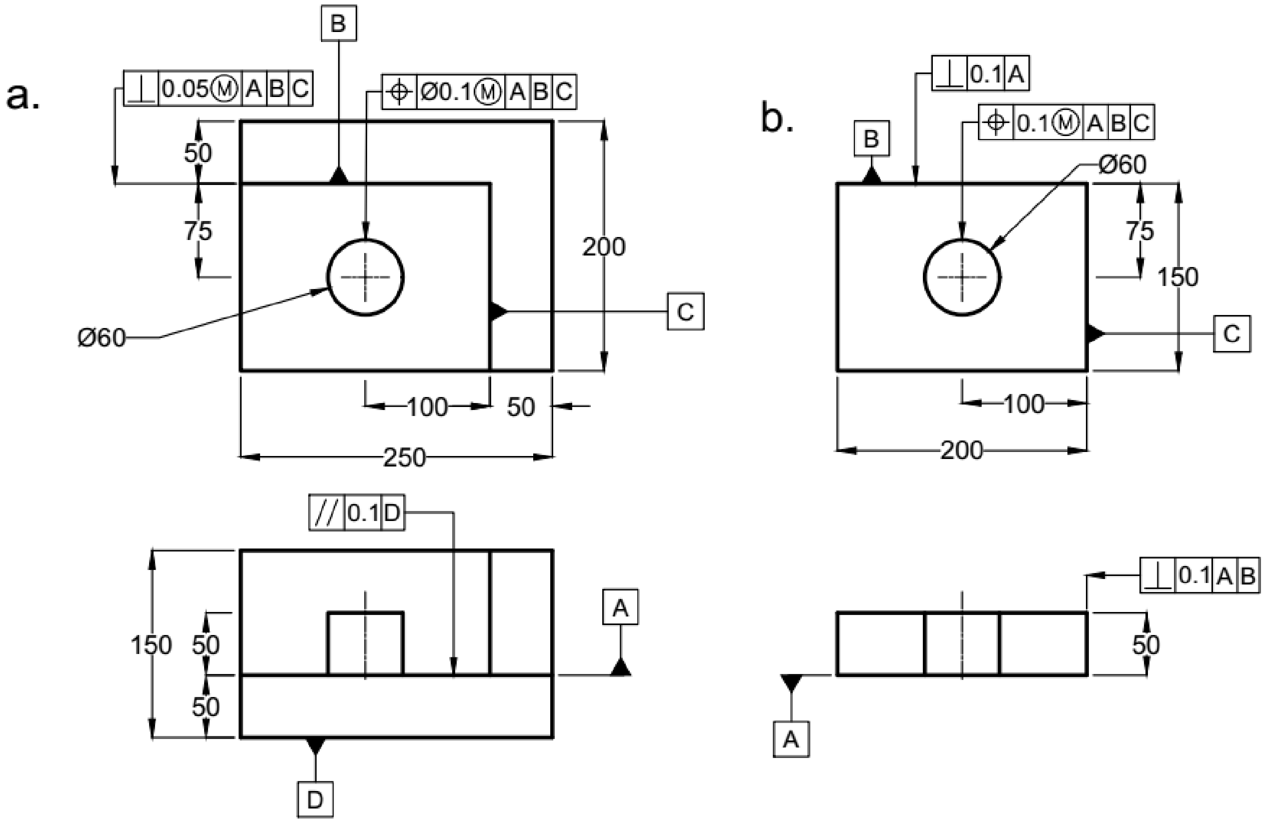

Figure 5: The example control point variation models (a) Base part (b) Plate part

Table 1: previous research about tolerance

Authors	Key research area	Research scope	Method
Dantan et al., 2005 [25]	Tolerance synthesis	Rules & regulations for determining the tolerance required by designers	Mathematical synthesis of tolerance synthesis to simulate geometric mechanisms and integrate quantification responses
Saravanan et al., 2014 [26]	Geometric tolerances	Suggest alternate methods to overcome the effects of predictions	• Simulations using finite element analysis (FEA) for interaction relations in assemblies • Solve assembly, machining and tolerance zones using GA method
Dantan et al., 2008 [20]	Geometrical specifications	• Complete model for tolerance process • Proposal to rebuild standards in the field of tolerance and metrology to ISO	Model GeoSpelling
Ansarifard & Jaamialahmadi , 2014 [1]	Geometric tolerances	Effect of geometric tolerance on rotation shaft with natural frequency	MATLAB 2013
Frechette et al., 2013[8]	Geometric dimensioning & tolerancing	Presents strategies for testing compliance with GD&T ISO and ASME standards	The strategy is test architecture, test requirements, test cases and coverage analysis

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Louhichi et al., 2015 [27]	Geometric dimensioning & tolerancing	Suggests a new approach for integrating tolerance in CAD models to determine part defects	• Implementing objective function assembly (OFA) • Provide assembly results closer to the actual assembly in mechanical systems
Toulorge et al., 2016 [28]	Geometrical accuracy	Present a method for generating a valid high accuracy network with optimized geometry accuracy	• Taylor expansions of the curves • Measure with standard Hausdorff distances between geometric and mesh model
Huang & Zhong, 2006 [29]	Tolerance based manufacturing	Models for interpretation geometrical tolerances	Concurrent integrated chains for geometric dimensional and tolerance (GD&T)
Guo et al., 2013 [4]	Tolerance analysis	• Review the accuracy of rotations related to design tolerance, installation process and section deformation •Tolerance representation and tolerance analysis	Based on small displacement torsor (SDT) model
Grandjean et al., 2013 [5]	Form errors	Focus on mechanical joints surface is made up of two plane surfaces	Mobility precision domain is defined for a particular sliding assembly
Yan et al., 2015 [7]	Tolerance analysis	Penyelidikan mengenai analisis toleransi perhimpunan dengan memberi tumpuan terhadap toleransi dimensi	Monte-Carlo simulation
Hussain et al., 2012 [9]	1. Tolerance analysis	➢ Methods for controlling the dispersion of assembly variations using relative orientation techniques	➢ Present mathematical modeling methods for predicting distribution of variation statistics present in complete assemblies
	2. Geometric dimensional case study	➢ The method of assembling axi-symmetric rigid structure of components is not to produce straight line	➢ Two-dimensional structure assembly study using Monte Carlo simulation method
	3. Tolerance representation	➢ A literature review in the field of assembly modeling to focus on the representation of related tolerances.	➢ Method uses: • Offset • Parametric space model • Algebraic • Vectorial tolerance Homogenous Transformation Matrix
Rogers, 2009 [11]	Tolerance allocation	• Develops a tolerance for mass and center of gravity against discrete components to produce a balanced system • Developing the transfer function and variables. • Proposed method of tolerance allocation	Multi-Dimensional Variation Analysis • Sensitivity Analysis • Statistical Simulation • Model Comparison
Islam, 2009 [18]	Dimensioning and tolerance	• The relationship required to obtain the dimension and tolerance values represented in the matrix • Individual dimension and tolerance values are determined using a comprehensive solution strategy	Interactive and appropriate methodology used in Concurrent Engineering (CE) environments

Wu, 2015 [24]	Assembly tolerance analysis	Investigate the effect of geometric errors caused by datum for tolerance	• Tolerance analysis for installations based on actual machine models • Monte Carlo simulation
Schleich et al., 2014 [30]	Tolerance analysis approaches	Comparative study of tolerance analysis using CAT simulation and tolerance based on skin model	Review the weaknesses of existing tools for skin model concepts
Barkallah et al., 2012 [31]	Manufacturing tolerance	Study the planning milling process for determine the appropriate tolerance to manufacturing.	• Statistical Tool • Experimental result and the simulation result are compared
Davidson & Shah, 2010 [32]	GDT tolerance classes	Representing GDT Tolerance classes	T-Map mathematical models
Humienny et al., 2003 [33]	Dimensioning and tolerance	The parts of the assembly are defined by the dimension and tolerance vector (VDT) for specification and validation	Stackup of location and orientation vectors for experiment-based shaft sleeve–plate installation using coordinate measuring machines
Mansuy et al., 2013) [34]	Tri-dimensional tolerance analysis	General methods of tolerance analysis for mechanical systems mounted with parallel links	• Mathematical toola • Monte Carlo
Davidson & Shah, 2004 [35]	3D tolerance analysis	Generate a geometric model of mathematical tolerance	New model methods for representing each tolerance zones as hypothesized points, maps and combines for assembly of parts
Loose et al., 2009 [36]	Integrating GD&T	Developed variation propagation models	• Developed a method for translating GD&T characteristic • Follow standard ANSI Y14.5
Frechette et al., 2013 [8]	Geometric dimensioning & tolerancing standards	Presents strategies for testing compliance with ISO and ASME standards	• Create 3D digital product using GD&T information • Use architectural tests, requirements tests, case tests and coverage analysis
Manolache, 2002 [37]	circularity problem	Presents a method for obtaining circularity deviation when real circular geometric features are inspected using coordinate metrology	Method is based on genetic algorithms for computing the geometrical ideal feature which the best approximate the measured set of points according with standardized association criteria
Jeang, 1998 [38]	Tolerance chart	Introducing a mathematical model to balance the tolerance chart during machining	State the variability of the process in the quadratic loss function which represents the difference between the measurement of the part and the target value
Dantan et al., 2012 [39]	Tolerance analysis.	Analysis using mathematic model	Methods Tolerance analysis using mathematic models
Kenneth, 1999 [40]	Tolerance analysis	Systematic procedures for modeling and analyzing variations in product assemblies	Direct Linearization method (DLM) for mechanical assembly analysis of tolerance
Chen et al., 2014 [41]	Three dimensional tolerance analysis	Uses four main methods for 3D tolerance analysis	The methods used are: Tolerance-map (T-Map), Matrix model, Unified Jacobian-Torsor model Direct linearization method (DLM)

Schleicha & Wartzack, 2016 [42]	Comparison of tolerance analysis	Comparison between quantitative and tolerance analysis based on skin model	Three tolerance analysis techniques are used namely the order of tolerance, vector loops and tolerance analysis based on SDT
Homri et al., 2017 [43]	Tolerance analysis	Presents a new model for analyzing shape defects in installation simulations	Developing a metric capital method decomposition (MMD) to model various types of defects in mechanisms
Venkaiah & Shunmugam, 2007 [44]	Circularity error	• Presents Circularity evaluation • Evaluating circular errors by referring to limacons for eccentric properties in component determination and radius penetration in measurements	Geometry calculations based on algorithms for minimum and maximum of limosons
Karnik et al., 2005 [45]	Geometric algorithms	Describes the underlying systems and algorithms for performing geometric capture analysis to determine whether a new rotation component is available.	• Analyze the feasibility of detention using a bonded cylinder • Analyze feasibility of detention by ignoring off-axis features • Analyze other parts of the database for feasibility retention by including off-axis features
Chiabert et al., 1998 [46]	Geometric dimensioning and tolerance	• Focus on GD&T approaches for design and inspection activities • GD&T approach for design for assembly (DFA)	Comparing simple GD&T descriptions to the more traditional ones.
Cheng Lin (2009) [47]	Geometric dimensioning and tolerancing	Presents a formula for calculating GD&T position	Comparison of other approaches to the rules of tolerance used for all three material conditions namely maximum material MMC, LMC) and RFS
Sahani et al., 2014 [48]	Tolerance stack up analysis	Presents a methodology for the solution of systematic tolerance to problems involving geometric properties	Present angle tolerance for illustrative methodology using two approaches: WC)and RSS
Anselmetti & Louati, 2005 [49]	Manufacturing tolerancing	Tolerance with ISO standards for analyzing these tiered specifications and for generating manufacturing specifications with ISO standards	Graphic representation methods for component characteristics, plan processes and functional requirements in accordance with ISO standards including datum reference framework
Mao et al., 2009 [50]	Geometrical product specification	Develop method for assessing the uncertainty of cylinder errors	Methods of optimization algorithms namely particle swarm (PSO) and uncertainty theory
Nigam & Turner, 1995 [51]	Tolerance analysis	Technical studies apply statistical methods for mechanical assembly tolerance analysis.	Method applied to solid modeling systems and geometric tolerance standards
Salomons et al., 1996) [52]	Tolerance analysis	Use the optimization equation to find the maximum or minimum value for the installation	Methods for the analysis of tolerances for feature-based back-support systems (FROOM) as part of the functional tolerance module.
Feng & Yang, 1995[53]	Dimension and tolerance	Introducing a model of dimensionality and tolerance data to develop the basics of ISO	Model dimensions and product tolerance using tolerance software applications.

Ashr54]af et al., 1997 [54]	Geometric tolerances	Approaches to the geometry of synthesis tolerance in the design process	• Manufacturing process to minimize production costs • Optimizing the magnitude of geometric tolerance using GA
Kandikjan et al., 2001 [55]	Dimensioning and tolerance	Presents a computational model to validate dimension schemes and tolerance specifications in accordance with dimension and tolerance practices	Validation uses dimension and tolerance graphs to represent datum reference frames
Scholz, 1995 [56]	Tolerance stack analysis	Explain the various methods of absorption tolerance without going beyond the theory and derivation details behind	The methods used are worst case, arithmetic tolerance and simple statistical tolerance
Shahtaheri et al., 2017 [57]	Dimensional and geometric tolerance	Approaches to redesign and site improvement taking into account various dimensions and geometry	• Methodology for developing tolerance in modular construction with the proposal of an integrated structure analysis framework. • Methods for dimensions and geometry with the aim of reducing redundancy and reducing project costs
Merkley, 1998 [58]	Tolerance analysis	Predicting assembly force, pressure and deformation in assembly of parts using assembly tolerance and finite element analysis	Linearized constraint based solutions i. Closed-form solution of the Pin orientation ii. Linear variations of the Pin or Hole Problem iii. Linear variations of the tab or slot problem v. Limitations of the direct linearization method • Results are validated using Monte Carlo simulation.
Dionne et al., 2010 [59]	Geometrical and dimensional tolerances	• GD&T analysis to determine kinematic bracelets that influence functional requirements and tolerance for relative position between two topological elements • Solution procedures to verify whether functional requirements will affect current tolerance	• Use the process of interpretation of geometry and dimensional tolerance • Presents the process of tolerance analysis using C ++ library implementation for geometry interpretation and dimensional tolerance
Jaballi et al., 2011 [60]	Tolerancing synthesis	Synthesis tolerance for tolerance identified after transfer	Rational methods of algorithms for synthesis of 3D manufacturing tolerances (R3DMTSyn) for developing surface technology-related rules and related topologies (TTRS)
Yan et al., 2016 [61]	Statistical tolerance analysis	Produces methods for statistical tolerance analysis	Uses homogeneous transformation matrix for Newton-Raphson assembly and iterative procedure to solve assembly constraint equation
Yang et al., 2013[62]	Statistical tolerancing	Comparison of the model of tolerance analysis for 3D functionality using statistical tolerance approach based on set point variations	The methods presented are MGRE feature points, geometric surface feature points and discrete geometric surface points and then the tolerances with installation characteristics were analyzed using a homogeneous transform matrix

A. Analysis Method of GD&T in Rotating Machine.

Since the GD&T is very significant in most rotating machinery, a critical analysis is needed to find out the case and reaction.Run-out characteristics are the sum of geometric errors and rotational axis rotation effects [3]. Investigating the impact between dimensional accuracy and dynamic geometry for rotating cylinders was performed using Fourier transform (FFT) analysis.

Variation in cylinder wall thickness were measured using FE model to analyze behavior. Vibration spectrum analysis has been a common tool for detecting misalignment. In-depth studies of dynamic and vibrational forces have been very helpful in understanding and diagnosing features, mismatches, and vibrational spectrum analysis have become a common tool for misalignment detection.

Coordinate measuring machine (CMM) is used as a procedure for assessing the geometry tolerance of cylinders and data is presented based on minimum zone criteria [63].

The mathematical model is a method for analysis of product tolerance, computing the composition of the tolerance amount, deviation and the cross-domain release domain for the kinematic chain in parallel to validate the domain entry [22]. Methods based on mathematical tolerance are effective for tolerance analysis [20]. GeoSpelling is an ISO-recommended model for building standards in the field of tolerance and metrology to explain geometry specifications. Some situations of varying degrees of tolerance are shown only through the transformation of 3D models into 2D models. Model-based engineering (MBE) uses 3D models with several criteria in determining the geometry and specifications of products known as Products and manufacturing information (PMI) by ASME Y14.5M, 2009). Unnatural designs of tolerances such as interco-ordination dimensional chains are expressed by means of calculations that show variations in tolerances in only three dimensions [12]. MCS is a simple and widely used method of statistical tolerance analysis because it considers probabilistic behavior for the manufacturing process. This method produces a large sample of accurate predictions that require intensive computation [9]. The most common procedure is to use a random generator for a set of dimensions in assembly for component distribution. The installation function is a sample that uses a set of dimensions in production by estimating the parameters for installation. Previous studies on geometric tolerance to installation quality have been found to have significant effects in some cases and to give effect to rigid bodies [7].

IV. GENETIC ALGORITHMS FOR ROUNDNESS EVALUATION

The GA method is widely used in research for implicit parallel search to solve complex or non-linear optimization problems. This method is easy to implement and useful as an optimization tool as it quickly focuses on local optics that are very close to or in line with the optimal solution. Many solutions can be processed at the same time by obeying elite and random rules. GA can make a unified assessment for a central candidate that is an individual of the population (chromosome). The enclosed area is the search space for the central candidate that is the initial population selected during the data acquisition algorithm [21]. From the studies conducted Genetic algorithms (GA) is more difficult compared to partical swams optimization (PSO) in principle for the same process. PSO based algorithms have been developed to evaluate cylinder damage based on error assessment and error relaxation [64]. The definitions of timeliness and boredom have been set by ISO in detail for PSO algorithms with the aim of solving optimization problems.

A. Computer Aided Tolerance CAT) method for Tolerance Analysis.

There are various software suitable for tolerance analysis such as CATIA 3D FTA, CETOL 6 Sigma, Vi VSA and eM-TolMate which have different functions, capabilities and applications [20]. Tolerance analysis takes into account parts deformation, displacement and rotation components that can be calculated using computer aided engineering (CAE) software such as ANSYS, Romax [4]. Quality and efficiency of aircraft installation can be improved by using a tolerance analysis technology approach.It has also become the key technology to shorten the manufacturing cycle. Current commonly used tolerance design software days include, eM-Quality and CETOL 6 sigma. In order to ensure the accuracy in aircraft assembly, a complete combination of simulation and tolerance analysis software simulation are used during the assembly simulation analysis. Assembly simulation software usually DELMIA, 3DCS with VSA [12]. A three-dimensional computer aided tolerance (CAT) parametric model for sensitivity analysis was developed based on the Catia V5 and 3DCS. Using visual basic (VB) and visual basic algoritma (VBA) scripts is more helpful in the analysis of tolerance that can be achieved with high automation [16]. CAT methods developed to support current tolerance activities in the design process to control the derivation of geometry requirements, specifications, synthesis and analysis [30].

B. Geometric Tolerance Analysis for Rotating Shaft at Natural Frequency

Vibration spectral analysis is a commonly used method for detecting misalignment detections in studies of dynamic and vibrational forces to understand and diagnose fault lines. The 3-D linear elasticity relation is used to calculate the axial force generated by rotation taking into account the axisymmetric parameters of the shaft whose diameter is smaller than the shaft length. The principle of the D'Alembert equation used to study the equilibrium rotation of the shaft is from the radial direction as in equation (2) below [1]:

$$\frac{\partial}{\partial r}\left(r\sigma_r\right)-\sigma_\theta=-\rho\, r^2\Omega^2 \qquad (2)$$

Where,
Σr= Radial stresses
$\sigma\theta$ = Circumferential stresses
ρ = Shaft density
Ω = Constant shaft speed

There are various causes of variations in mechanical assemblies such as dimensions, geometry characteristics and variations in kinematic adjustment during installation due to natural changes in the manufacturing and installation process. The feature of GT is the dimensional tolerance where the nominal value is zero and is coupled with the corresponding surface relation value. The impact of GT features on each joint will result in variations in rotation or rotation whose direction will be determined by the type of kinematic joints and geometric characteristics [7]. The increasing complexity of mechanical systems requires an increasing cost for their development, production and exploitation.

At the same time, demands for energy and environmental efficiency, reliability, service life and load capacity are growing [30].

C. Tolerance Analysis in Mechanisms Motion System

Tolerance is a fundamental requirement in the design process that consists of predictive tolerance analysis to know the effect of geometric tolerance on product function and quality.

Tolerance analysis methods need to be classified into one, two or three dimensions because they require the representation of geometric deviations from the mathematical model for representations based on vector tolerance, surface technology and topology. The small displacement torsor (SDT) and the tolerance map are used to determine the domain deviations that occur (Schleich et al., 2014). Dynamic implementation during operation is difficult or impossible to measure as well as inaccurate values when rotating the shaft slowly [12].

D. Simulation for Higher Pair Contact and Tolerance Analysis

This analysis aims to simulate the relationship between the surface of two rigid bodies and the local point relationship at all times [65, 66]. Study process to developed the installation function and assessing ability to predict installation dimensions for production using design of experimental (DOE) and tolerance analysis [65]. Two variables will affect the construction of durability by the method of attachment for the reading of the constructive functional dimension. Quarterly assemblies in production were randomly selected to allow comparisons between assemblies to construct the functions produced using the standard production process [66]. The trend of the researches listed in Table 2, show the method used in GDT analysis for rotational component. Various methods and approach used in the study and analysis related to geometrical tolerance analysis in mechanical rotational component. Various studies relating to geometrical tolerance show that geometrical tolerance is essential to improve product quality, product reliability, long life product and manufacturing cost.

Table 2: Tolerance analysis method using for rotational machine

Approach	Authors	Method	Key Purpose	Advantages	Disadvantages
Dynamic behaviour	Keskiniva et al., 1995 [67]	Run-Out Measurements	Measures behavior with flexible roll deflection due to imbalance as a function of running speed	Focus on the effect of rotating shaft	Not suitable for another shape
Analyse material structure	Fowler et al., 1997 [68]	Ultrasonic Measurement	Analyze material structure	Can determine the thickness or structure of components	Can know the thickness used
Analysis for cross-sections	Bathe et al., 1976 [69]	FE Analysis (Cross-section model)	Measured wall thickness distribution	Tolerance studies of variation in shaft wall thickness are allowed from inner wall roundness	Does not have end supported and the inner surface profile
Outer surface of the cylinder	Forsberg et al., 2006 [70]	FE Analysis Cylinder Model	Measured wall thickness variation	Modelled as for perfect cylinder geometry	Mesh coordinates based on Lagrange interpolation
Misalignment experiments	Nakhaeinejad et al., 2009 [71]	SpectraQuest's Machinery Fault Simulator™	Experiment for common mechanical fault	Comprehensive test for rotating machinery	Does not appear in the medium angular misalignments
Numerical model	Yang et al., 2011 [72]	3D-NRRO tolerance analysis for parallel deviation in rotating machinery	Examine the accuracy of high-precision bearings with three-dimensional values for rotating systems	Can investigate the relationship between internal movement and elastic defect theory.	Only cylinders shape

Sampling of individual points	Shawky et al., 1996 [63]	CMM Data	Evaluating geometric tolerances	Automated tools with software for post-processing and complex surface measurement	Uses manual instruments
Demonstrated that a dependent dimension in assembly	Humienny et al., 2003 [33]	Vectorial Tolerancing	Mathematical model approach to the representation of geometric tolerance	Unique specification and validation for dimension functions analyzed in assemblies	Tolerance analysis capabilities and synthesis systems
Analysis of rotating mechanism	Schleich & Wartzack, 2015 [19]	Approaches to the analysis of tolerance using rotating mechanisms	Tolerance analysis for rotating mechanisms based on the shape of higher kinematic models	Focus on simulation models for section assembly and relationship evaluation	Divided into pre, during and post processing stages
Hypothetical Euclidean pointspace	Davidson et al., 2010[35]	Tolerance maps	Mathematical approaches for the representation of geometric tolerances	The combination of tolerance on a feature built from an inspired trail and described in coordinates	T-Map incorporates size tolerance into one or more features
Statistical tolerance Analysis	Polini et al., 2011[73]	Monte-Carlo Simulation	Statistical tolerance analysis	The random value of each section and the response function are calculated for each set of section	Uses sample of response function values
Thermal boundary conditions	Truman et al., 2006[74]	Combined spinning and thermal analysis	Analysis heat impact on thermal boundary	Analyze the effect of internal heat and thermal conditions on the boundary	Shaft devices for temperatures from 30^0 C to 60^0 C
Rotating machinery	Swanson et al., 2005[75]	Rotating Dynamics – Cylindrical Modes	Consider what happens to the first mode of our rotor once it is spinning	Can consider what happens to the first mode of our rotor once it is spinning	Rotating machinery has to rotate to do useful work,
Statistical moments	Driot et al., 1996[76]	Taguchi's method	Simple estimates of statistical moments with the functions of various random variables	Estimates in a simple way the functions of a statistical moment	Improve accuracy quickly for sample counts
Tolerance analysis software	Chen et al., 2014 [41]	CETOL 6 Sigma From ` Sigmetrix	Tolerance analysis using the latest CAT system	Ability to achieve design with specified specifications	Requires more complex software

Modeling the tolerances	Ansarifard et al., 2014 [1]	MATLAB 2013 software	Presents the effect of geometric tolerance on rotating shaft with natural frequency	The deviation modeling is done with a set of points that deviates from a random number	Must write the code

V. CONCLUSION AND SUGGESTIONS

This review provides GT applications and analysis in rotational mechanical component. GT is the acceptable geometry range between component manufacturing accuracy and the effect of dynamic geometry on rotating cylinders. Geometrical tolerance is a very important issue to ensure product life extension and prevent critical parts system being destroyed. Various approaches and modeling have been applied to enhance the capabilities of components with geometric tolerance. Implementation of the acquired methods to achieve optimum capacity for component performance. Optimal performance can be achieved by using the appropriate methods or tools. Mathematical models are an important element to develop because they represent the properties or characteristics of products such as function, configuration, performance and even the life cycle of components. The method of smart algorithms that has been developed can solve the problem of optimizing geometric tolerances that work to improve the accuracy of the algorithm and its effectiveness obtained by comparing it with other optimization algorithms. Software applications for geometrical tolerance analysis can assist in system engineering, information systems and software engineering to visualize systems planning, manufacturing, testing and moving systems. Strategic planning of tolerance-related research can also develop product enhancements to ensure achievable performance and to provide greater engineering applications for rotating components such as automotive equipment and machinery equipment.

Geometric optimization of tolerance in shaft rotation can improve system reliability as well to improve rotation system performance, rotational accuracy and adherence to safety lines to prevent failure due to deflection above permitted tolerances. GT must be considered as it has a direct impact on rotation accuracy. It can be concluded that the evaluation of geometric tolerance in design can improve the system life cycle and should also be avoided using rotation speeds close to critical speed

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