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DEVELOPMENT OF EVALUATION METHOD FOR GEOMETRICAL TOLERANCE VALUE OF POSITIONAL CHARACTERISTIC IN ROTATIONAL SHAFT

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Abstract

Various factors influence the accuracy of a rotation systems that needs to be considered during design, installation, and deformation of the components. High-speed rotation systems require rotational accuracy that is typically associated with geometric tolerances (GT). Improper GT value disrupts the system and can cause damage to components involved with the system. This paper develops a method for evaluating GT values for determining positional characteristics of a rotating equipment such as turbines, pumps, generators, blowers, and gearboxes. The GT value to consider is located at the midline of the shaft and positioning became one of the most important features in a rotating system. This paper also presents a method to determine the optimal value of GT easily and more efficient A mathematical model for obtaining GT values based on the possible positions for the construction of tolerance zones using offset methods and algebraic methods has been established. Both of these methods are related to each other to obtain optimal GT values. An optimization analysis with genetic algorithm (GA) by using the obtained geometrical mathematical models. Evaluation of the obtained GT values using the square tolerance zone, round tolerance zone, statistical analysis, finite element analysis (FEA), and reliability calculation have been carried out. Based on the calculations and simulations can aid to determine the suitability of the obtained GT values and to predict the effects of the rotating system. Referring to the GD&T standard of ASME Y14.5-2009, this study can produce GT values and coefficient values for each shaft measurement from 1 mm to 500 mm diameter that needs to be considered in the design, manufacture, and installation process and can prevent damages to critical parts of the rotating system.

Keywords: Geometrical tolerance, Least material limit, Mathematical model, Maximum material limit, Position characteristic, Rotating shafts.

1. Introduction

Geometric dimension and tolerance (GD&T) are a universally accepted graphical language for improving communication in product design and quality by ASME Y14.5 in 2009. The NSF Design, National NSF Supervisor and Research has established ASME Y14.5 and ISO 1101 to ensure effective communication with international standards [1, 2]. Geometric tolerance languages use a set of well-defined symbols, rules, definitions, and conventions to enable the smooth communication. The types of geometric tolerances are categorized into five main groups: form, location, orientation, profile, and runout as well as combining 14 features and symbols of geometric tolerance [3, 4].

GD&T is a factor that needs to be considered for rotation accuracy as it has a direct impact on the performance rotation of the shaft [5-7]. When high-speed rotations of rotating equipment, all defects and geometrical deviations of the system will cause faster propagation of defects that are due to factors of the unbalanced rotor and incorrect alignment. The definition of concentricity and positional has been determined by the International Standard Organization [8]. Within GD&T, locations are tolerance types and have geometric characteristics such as position, concentricity, and symmetry. The actual size feature is shown by a drawing called a datum frame that has certain features and meanings [9]. Evaluation of location errors, such as concentricity and position, is important for rotating component accuracy and to investigate tolerance analysis for improving rotational performances. To analyse tolerance errors, it is important to know the appropriate algorithm for extracting the characteristics of the measured data.

In this study, a method to determine the optimal GT value has been proposed. The mathematical model fits the standard and provides installation for two dimensions. Mathematical formulations for tolerance synthesis are simulated to determine the effect of deviations in geometrical mechanisms. The mathematical formulations used are the offset and the algebraic method respectively, in which both methods are related for obtaining the GT value. Both methods search the appropriate GT range values to be used. In mass production, it is difficult to maintain precise dimensions or geometrical perfection of mechanical components. However, GD&T allows multiple imperfections in size and shape to be employed for installation as long as it is within the tolerance range allowed. The method for analysing existing tolerance based on conventions has been compiled from engineering practices where it does not use mathematical principles [10].

The process of inspection on the resulting components involves measuring dimensions for compliance with product specifications as they are related to tolerance, which represents acceptable limits in the design process. The quality of part manufacture is determined by the design and tolerance of the manufacturing, which affects the geometric characteristics and functions of the finished parts [11].

Geometric deviation representation is still a major issue in tolerance simulation modeling, because. Calculation of the effects of irregularities on system Behavior and the application of analytical techniques provided as the three main issues of tolerance analysis [12, 13]. The three main issues in tolerance analysis are to establish mathematical models for the expression and representation of geometric deviations, geometric specifications, and geometric requirements, to model the effects of these geometric deviations on system installation and Behavior, and to provide solution techniques for models this, such as the worst-case or statistical evaluation [14]. In product design and manufacture, it is difficult to understand the effects of variations in dimensions and geometry [10]. The most frequently used model in GD&T analysis is to represent a zone of tolerance for a plane or line as a hypothesis point of space and coordinates for the assembly. This model relates to all assembly reference frames that use the level of freedom globally and includes the implementation of tolerance analysis systems.

A new method to obtain optimal GT value in a rotating system can improve manufacturability using design for manufacturing. It shows that interchanges between costing with robustness and quality [6]. The cost of accuracy is determined by material and GD&T such as shape and, size, the complexity of the shape, and the process of production [15]. Dimensional and geometric inspections in design of tolerance play an important role in the control and evaluation of quality in the product development process as they will impact the function requirements and manufacturing costs. In manufacturing, reasonable installation tolerance design ensures increased installation accuracy whereby by improving installation design efficiency, cause in reduction of manufacturing costs, and increasement in the installation success rate. Assembly tolerance analysis technology has helped in improving the quality and efficiency of assembly [16].

2. Methods

In this study, the shaft becomes an analytical specimen because it interacts with other components in the system. Geometric position is taken into consideration as these features have a serious impact on the system. The position of the rotation diameter will be analysed to determine the appropriate GT value. Regardless of the size of the diameter and design of the shaft, the GT value for the position properties must be within the appropriate limits for the rotating shaft to maximize the life of the system [17]. GT values are obtained by developing mathematical modal using the offset method and the algebraic method. GT value assessment is carried out by various methods to ensure that the GT value obtained is following the system.

2.1. Identify specification shaft

The shaft has a round cross-section and is used to transmit force. Shaft design involves the determination of pressure at a critical point. The rotating shaft is in a state of a variable load while operating [18]. Shaft designs usually focus on the critical area, the size to meet the strength requirements, and the overall size to meet the requirements of the elements to be supported [19]. The specifications and design of shaft are very important in the transmission sequence of a rotating system.

Shaft diameter is a major factor in determining the position of shaft rotation center. Therefore, the position of the deformation must be prudently considered during the design process. Thus, the shaft diameter can be obtained by external and material properties. The shaft transmission is under significant pressure due to bending moments and torsion because temporary effects or loads can also cause load failure [20]. The centrifugal force will directly affect the shape of the shaft circle depending on its rotational speed [21]. The shaft dimensions need to be obtained refer to the shaft basic system under normal running condition. Based on dimensional value and tolerance, a suitable GT value for the shaft can be determined.

The shaft design dimensions as shown in Fig. 1. In this study, the shaft specifications along with the least material condition (LMC) and maximum material condition (MMC) are decided and then developed by the probability of shaft position to precisely determine the GT linear relationship between input deviation and output performance. This model is useful in tolerance analysis represented by input deviation at specific locations of the GT values.

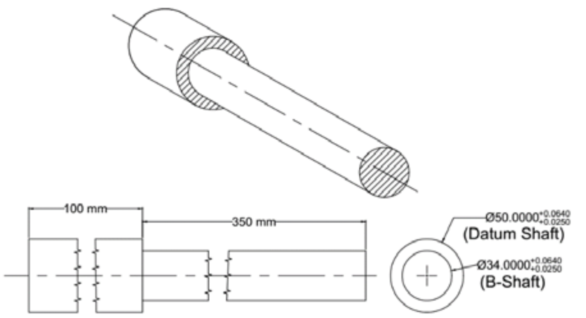


Fig. 1. Dimension of shaft design.

This analysis is a typical and relatively complex representation of GD&T in product manufacturing, i.e., 2D position tolerance along with measurement tolerance [22]. Using a set of infinite estimation points on the properties of parts, each point is recorded through the coordinates into a coordinate system by directly assessing the accuracy of dimensions and geometry. Then the division's analysis model will be obtained mathematically. The mathematical formula describes the process of changing the input characteristics on a shaft. Table 1 shows the design specification of shaft with and without GT value and the design specification shaft is shown in Fig. 2.

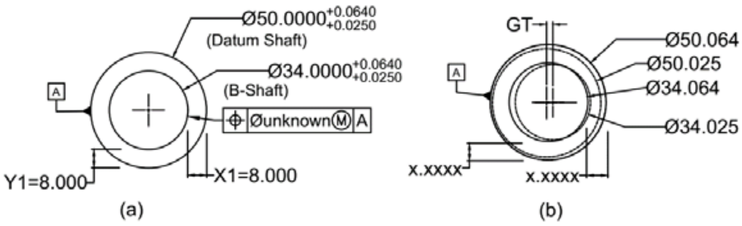


Fig. 2. Design specification shaft without GT value (a) Shaft Dimension with fit limit tolerance (b) Shaft possibility illustrated.

Table 1. Specification data shaft without GT value.

Limit Size (mm)		Basic size Shaft (mm) (Diameter)	Lower Limit (mm)	Upper Limit (mm)	Geometrical Tolerance (mm)	X-Position (mm)	Y-Position (mm)
0.064	0.025	50.000	50.025	50.064	Unknown	8	8
0.064	0.025	34.000	34.025	34.064			

2.2. Framework to determine the GT value

The importance of GD & T in product design must be well understood by the industry as it simplifies engineering drawings and directly integrates customer needs into product specifications and process control [23]. GD&T is known as a mathematical language used to determine the variation of acceptable product parts according to specified specifications [1, 7, 24]. This research proposes a framework for obtaining the GT values required in the process product design and rotating system installation. The existence of this framework can help to obtain the appropriate GT value for the rotating components in the industry. Figure 3 shows a framework as a guide for determining GT values.

The presence of tolerance depends on the specifications' precondition and is considered if in a permitted position. Total tolerance represents the combination of manufacturing tolerance and measurement of uncertainty for providing a suggestion of assurance. In this study, a basic size of shaft diameter of 34 mm and 50 mm is used to determine possible position of the shaft. Mathematical models are constructed to obtain GT values which will be evaluated by using four analysis methods are square tolerance zone, circular tolerance zone, statistical and finite element analysis (FEA), respectively. The method was developed to obtain the GT value for each diameter size by considering the overall LMC and MMC as the largest and smallest for each shaft size.

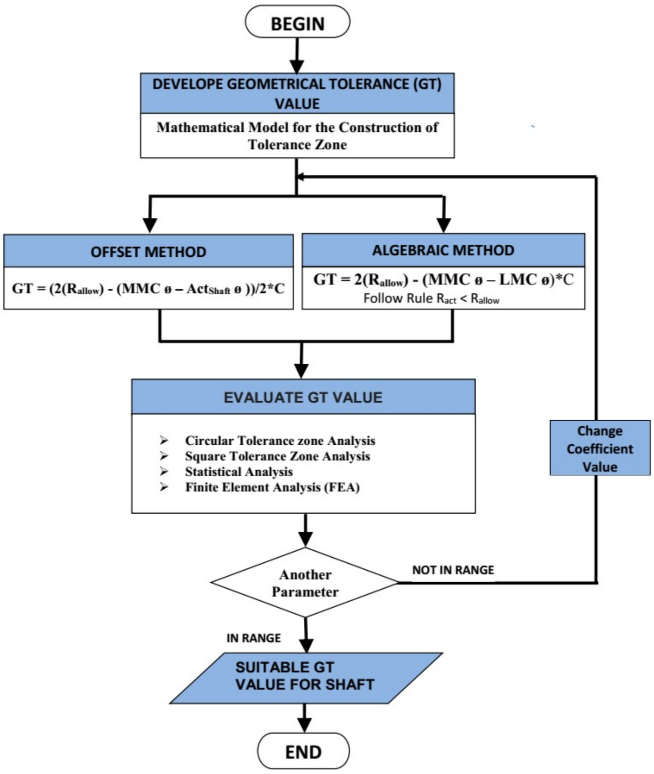


Fig. 3. Framework for determine GT value.

2.2.1. Mathematical model

Mathematical formulation is a method of obtaining GT values by the process of modifying input values or shaft characteristics for finding solutions of concentricity and position problems. The tolerance analysis approach should determine the mathematical formulation that can consider all the characteristics of the Behavioral model on shaft dimensional changes [25]. The center position is represented by the delta-x and delta-y coordinate pairs.

By find the offset value and position of the GT coordinate, the search space must include possible position and central concentric solutions. The center of rotation is the focus and the position that should be estimated is selected as the allowed values of the delta-x and delta-y coordinate points.

In engineering design, an optimum tolerance is defined as the task of tolerance of mechanical assembly components in terms of not only the function but also the minimum manufacturing cost [26]. ASME Y14.5M-2009 has systematically presented rules and formulas for tolerance analysis involving a wide range of geometric and dimensional tolerances [1]. Any relevant tolerance features must be taken for analysis where position distance will be expressed as the base without tolerance and included in each coordination calculation for center line of rotation. The presence of bonus tolerance and or the tolerance of the transition depends on the product specifications. This, bonus tolerance and transitional tolerance will exist and should be considered.

2.2.2. GT value by using offset method

The offset model proposed is one of the earliest methods for establishing a tolerance zone [27-30]. Shaft possibility location is defined as the variation allowed by the characteristic of the potential shaft position analysis. The positions typically utilize MMC or LMC and they are a very convenient in terms of control for axes, points, or planes in order to determine how many features vary from a given exact location. MMC and LMC have been utilized to control maximum and minimum shaft size and position the location to maintain function control. Usually when determining the exact position, a datum is referred to as Delta-x and delta-y coordinates.

Figures 4(a)-(d) show the shaft possibility position in different condition; in which (a) shows both shaft diameter are LMC; (b) shows that both shaft diameter are MMC; (c) shows that the datum of shaft diameter is LMC, and B shaft diameter is MMC and (d) shows that the datum of shaft diameter is MMC and B shaft diameter is LMC.

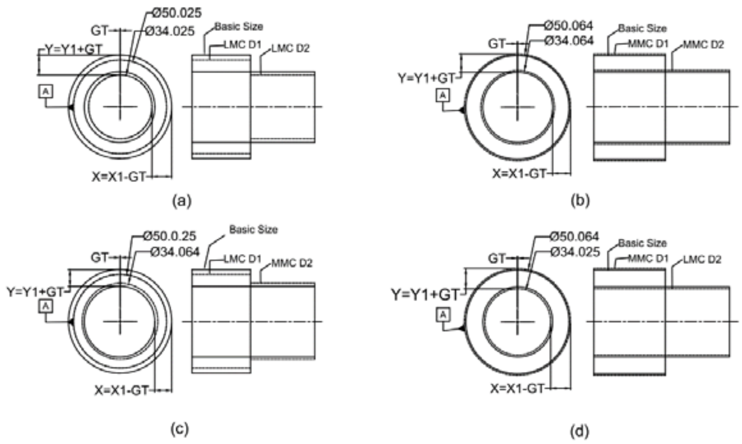


Fig. 4. Shaft possibility position.

The following equations shows the mathematical expression of the *GT* values by using offset method.

$$R_{allow} = [(MMC\ ø - Act_{Shaft}\ ø\ ) + GT\ /2] \quad (1)$$

where, $Act_{Shaft}\ ø$ represents the actual shaft diameter which can be determined by the following equation,

$$Act_{Shaft}\ ø = (LMC\ ø + Tolerance\ range/2) \quad (2)$$

where, *Tolerance range* can be determined by adding the absolute value of lower and upper limit as follows,

$$Tolerance\ range = |\ Lower\ limit\ | + |\ Upper\ limit\ | \quad (3)$$

Therefore, the allowance *R* is calculated as,

$$R_{allow} = (MMC\ ø - LMC\ ø)/2 \quad (4)$$

So, the GT value can be determined as,

$$GT = (2(R_{allow}) - (MMC\ ø - Act_{Shaft}\ ø\ ))/2 * C \quad (5)$$

where *C* is a coefficient of shaft diameter size

2.2.3. GT value by using algebraic method

Turner's theory of space M-space on form tolerance is limited to single-feature tolerance assuming zones derived from various controls, such as size and shape of tolerance [27, 31]. Zone construction as suggested with a model of variation for tolerance developed using algebraic constraints [27-32]. Overcoming limitations in parametric models have suggested an algebraic interpretation method for tolerance [28, 33, 34]. Variable models for tolerance were developed using algebraic constraints by proposing a method that describes semantic tolerance of geometry in the form of algebra [28-35]. The resulting variations will have a simultaneous effect on the size and shape of the tolerance as shown in Fig. 5.

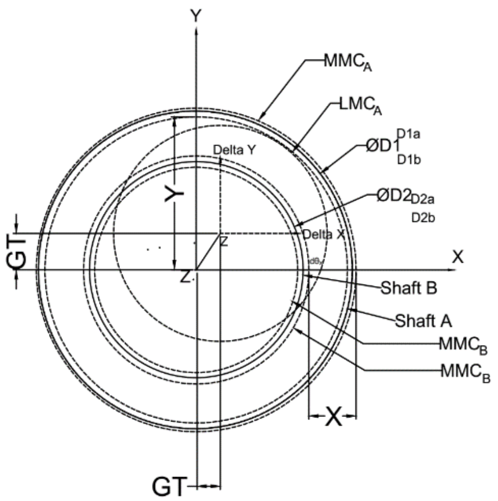


Fig. 5. Schematic representation of a transform for position characteristic.

The variable model for tolerance was developed using algebraic constraints for the x-position and the y-position of the variable defined as inequality. The tolerance zone is obtained by balancing the dimensions with least material condition (LMC) and maximum material condition (MMC) values that influence GT values. Delta-Y is a position error in the y direction and delta-X is a position error in the X direction that occurs due to the shaft dimension change. The schematic representation of the transformation of the position characteristic produces an algebraic equation for determining the GT value as a below:

where, *position – X1* represents the position difference for shaft radius in x-direction which can be determined by the following equation,

Position - X1 = (Shaft A – Shaft B) / 2 (6)

where, *position – Y1* represents the position difference for shaft radius in y-direction which can be determined by the following equation,

Position - Y1 = (Shaft A – Shaft B) / 2 (7)

where, *Tolerance range* can be determined by adding the absolute value of *upper limit* and *lower limit* as follows,

Tolerance Range = (Delta 1a – Delta 1b)/2 (8)

where, *position – X* represents the position difference for shaft radius in x-direction with GT Value which can be determined by the following equation,

Position - X= ((Shaft A – Shaft B) / 2) – GT (9)

where, *position – Y* represents the position difference for shaft radius in y-direction with GT Value which can be determined by the following equation,

Position - Y= ((Shaft A – Shaft B) / 2) + GT (10)

where, *Delta – X* represents the value difference in direction x which can be determined by the following equation,

Delta X = X– X1 (11)

where, *Delta – Y* represents the value difference in direction y which can be determined by the following equation,

Delta Y = Y -Y1 (12)

where, MMC_A represents the value upper limit for shaft A which can be determined by the following equation,

MMC_A = D1 + Delta 1a (13)

where, LMC_A represents the value lower limit for shaft A which can be determined by the following equation,

LMC_A = D1 + Delta 1b (14)

where, MMC_B represents the value upper limit for shaft B which can be determined by the following equation,

MMC_B = D2 + Delta 2a (15)

where, LMC_B represents the value lower limit for shaft B which can be determined by the following equation,

$$LMC_B = D2 + Delta\ 2b \tag{16}$$

The following equations shows the mathematical expression of the GT values by using algebraic method

where, R_{act} represents the actual shaft radius which can be consider the value by following equation,

$$R_{act} = (MMC_A - LMC_A)/2 \tag{17}$$

$$R_{act} = \text{Bonus tolerance}/2 \tag{18}$$

Calculate R_{Act} using by following equation

$$Act\ tol = \text{sqrt}\{(R_{act})^2 + (R_{act})^2\} \tag{19}$$

Follow the rule, Take the R_{allow} value greater than the R_{act} value

$$R_{act} < R_{allow} \tag{20}$$

$$GT = \text{Tol tol - Bonus tol} \tag{21}$$

$$\text{Allow tol} = R_{allow} = \text{Tol tol}/2 \tag{22}$$

$$GT = 2R_{allow} - \text{Bonus tol} \tag{23}$$

So, the GT value can be determined as,

$$GT = 2R_{allow} - (MMC_B - LMC_B)^* \text{ Coefficient} \tag{24}$$

where C is a coefficient of shaft diameter size

2.3. Evaluation GT value

Evaluation of GT values aims to analyse the effects of acceptable variation on mechanism Behavior. The main importance is to assess the level of product quality during its design stage [36]. An ideal GT value is a set of coordinates related to a mathematical model in which the effects of position and concentration on the center of mass are analysed.

Coordinates use a limited set of points representing the position of the center line of rotation of a section, each point being recorded through its coordinates into the coordinate system. Therefore, it is not possible to directly assess the accuracy of dimensions and geometry using mathematically obtained parts analysis models. This model is formed by ideal geometric features called substitute elements. Static problems are difficult to find in the best solution by improving methods to solve dynamic problems can optimize system performance with as many values as possible and continuous variables have an infinite amount of value.

2.3.1. Square tolerance zone analysis

In this paper, the GT values were evaluate using square tolerance zone analysis which consist of analysis of location faults and the coordinates received if the location is within the allowable square tolerance zone. According to ASME Y14.5M-2009, the application-related analysis such as measurement, radius and actual radius allowed for this shaft means that the coordinates received are only located within the permissible square tolerance zone as follows $R_{act} < R_{allow}$.

2.3.2. Circular tolerance zone analysis

By adopting the circular tolerance zone analysis, it can determine shaft status whether it can be accepted or rejected. This tolerance analysis method gives a bonus tolerance to assess the value of GT values to ensure the value of the system using the following Eq. (25),

where, *Actual tolerance* can be determined by radius actual value as follows,

Actual tolerance = R_{act} = sqrt{(Delta-X)^2 + (Delta –Y)^2} (25)

2.3.3. Statistical analysis

Statistical analysis is used for geometric tolerance models with the aim of predicting the magnitude of variation. The resulting statistical distribution can be used to estimate percentages and find out the specifications and quality levels for design and installation. In statistical analysis for the tolerance of each dimension shaft is seen as a random variable distributed based on probabilistic model derived from measured data or based on empirical linear model. Statistical analysis is a more practical and economical way to see the impact on GT values if the bar dimensions change [28, 37]. Analytical expressions are defined for LMC and MMC functions that determine their position along the x-axis and the y-axis. The formulas for methods involving location in GD&T are described widely in ASME Y14.5M-2009 [1].

However, to perform the statistical analysis of the reproduction of variations of shaft dimensions and to evaluate the optimization results obtained. Shaft dimension variations are generated as random variables that are normally distributed. The purpose of developing a probabilistic model is to obtain the optimum GT value for the shaft and to have a positive impact on the system. Any relationship of any kind can exist between the response of the assembly and the constituent part of the dimension or tolerance. Statistical methods are used to estimate the magnitude of variation in shaft rotation and to predict the effect of manufacturing variation. All kinematic system errors are statistically random variables. The dispersion of statistics is carried out statistically by the distribution algorithm. This method is used for nominal shaft dimensions from 1 mm to 500 mm. The change in value is derived from the measured data for each shaft dimension. The relationship between shaft variable values can be expressed as follows:

Since the allowed *radius must be larger than actual radius* which can be determined by the following equation,

$R_{act} < R_{allow}$ (20)

where, Act tol can be determined by actual tolerance which can be determined by the following equation

Act tol = $Ract$ = sqrt{(Delta-X)^2 + (Delta –Y)^2} (25)

where, R_{allow} can be determined by allowed radius which can be determined by the following equation

R_{allow} = [(MMC ø – $\text{Act}_{\text{Shaft}}$ ø) + GT /2] (1)

Allow tol = R_{allow} = Tol tol/2 22)

where, *Tol tol* can be determined by total value of tolerance can be determined by the following equation

$$\text{Tol tol} = \text{Bonus tol} + \text{GT} \tag{26}$$

where, *Bonus tol* can be determined by bonusl of tolerance value can be determined by the following equation

$$\text{Bonus tol} = MMC\ ø - Act_{Shaft}\ ø \tag{27}$$

2.3.4. FEA analysis

The value of GT obtained is analysed the effect of vibration frequency to see the effect caused by GT value. Rotational round capital analysis using component solid models for frequency analysis in which it combines rigid systems and flexible rotor dynamics obtained from FEA simulation [38, 39].

This paper aims to extract the geometric information of the spin section to determine position defect and shape in component tolerance zone [40]. Figure 6 shows the shaft design model for the respective FEA analysis. The related tolerance analysis involves process planning to improve the quality and reduce the cost of product relevant which will impact all stages of the life cycle and ensure system reliability [41-43]. The problem of relative position of the shaft without perfect geometry is improved by the problem of the relative position between the centres of rotation shaft [44, 45].

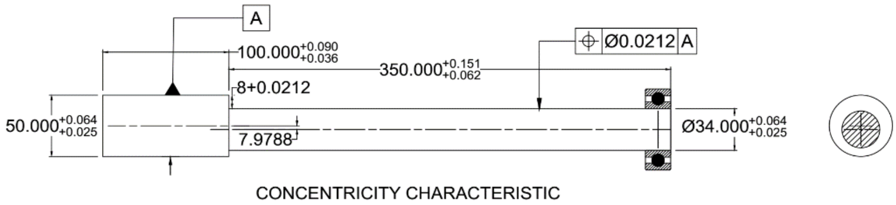


Fig. 6. Shaft design model for the FEA analysis.

3. Results and Discussion

3.1. GT value using algebraic method

Algebraic models are used to determine the error size of the shaft center position and the orientation of the tolerance zone by considering the parametric model zone.

Limitations of shape tolerance zones and maximum variations of features used in parametric and algebraic model domains must meet definitions in design standards where feature variations are always within the limits and boundaries of the tolerance zones obtained by balancing nominal features [46-48].

The tolerance limit that determines the zone is derived from the variable. An algebraic model used for 2D surfaces in which the producer zone has two translations of x and y-axes. The algebraic equation used can determine the boundary of the tolerance and the value of GT along the axis of the shaft.

GT values are derived from algebraic methods for critical functional requirements and product changes to facilitate the design and manufacturing process to achieve the required standard accuracy. The geometric tolerance symbols used refer to ASME Y14.5M-2009 and do not specifically specify the method of production or inspection required.

Calculation of the tolerance range must refer to the base rods of the shaft system for lower and upper limit values. From the mathematical model of computing GT values using the algebraic method obtained 0.0212 mm @ 21.2 microns as shown in Eq. (24). From the equation, the Ract, Act tol and the GT obtained is 0.0195 mm, 0.0276 mm and 0.0212 mm, respectively.

3.2. GT value using offset method

The offset model adopts a standard tolerance formula by understanding the Shaft Possibility position used to extract error size, position offset, and tolerance zone offset by considering the variation of the shaft diameter with the same features. The tolerance limit is the maximum boundary for both material surfaces. Individual tolerances for components are derived from boundary conditions using the offset method equations because the boundary requirements balance sufficient representation for component function requirements that require tolerance specifications for each different size.

Real feature data needs to be customized for real-time data extraction for parameters that represent real properties. MMC that limit the maximum fluctuation beyond nominal conditions and LMC that limit the minimum fluctuation under nominal conditions. Consider the cylindrical shape of the 2D representation of the shaft where MMC and LMC will be determined from the table shaft basis system. All parts have a single tolerance value [27]. Balancing method for predicting the mathematical model of GT values obtained from circle tolerance zone analysis. The MMC and LMC sections of various densities will be defined as the zone of tolerance as defined as the conditional tolerance zone.

The given parameters will produce an equation consisting of the parameter space determined by the shaft diameter (D1, D2), which is the nominal size condition. Concentricity and positions refer to the shaft possible position of the axis in terms of the axial point of the position received exactly as shown in Table 2. Tolerances in the 2-dimensional tolerance zone surrounding the accepted position will usually refer to the datum with the delta-x and delta-y coordinates when stated actual position. The point corresponds to the position tolerance where the most frequently placed location with two data will be the exact reference position. From the mathematical model of computing GT values using the offset method obtained 0.0209 mm @ 20.9 microns as shown in Eq. (5).

3.3. Evaluation of GT value

The purpose of tolerance analysis is to evaluate the GT value result to ensure the value suitable the system. The evaluated GT values are derived from two mathematical model methods namely the algebraic method that produces GT values of 0.0212 mm @ 212 micron and offset methods that produce GT values of 0.0209 mm @ 209 micron.

The largest GT value used to evaluate the GT value is 0.0212 mm @ 212 micron. According to the dimensions and tolerances of ASME Y14.5M-2009 (Application Analysis & Measurement) the actual radius and radius allowed for the shaft are stated as follows $Ract < Rallow$. The GT values obtained should be assessed using square tolerance zones, round tolerance zones, statistics and finite element analysis.

3.3.1. Square tolerance zone analysis

The GT value calculate from mathematical model is 0.0212 mm is later evaluated by using square tolerance zone analysis. The results obtained are shown in Table 2 and Fig. 7, which shows the detailed coordinates using square tolerance zone. According to the location error analysis, only coordinates A and B is accepted because their locations were inside the permissible range of square tolerance zone since. All coordinates C and D will be rejected because their location is outside the permitted square tolerance zone, but the rejection value is small.

Table 2. Shaft possibility position coordinates for GT value 0.0212.

Condition	Datum Shaft (A)	Shaft-B	X- Pos	Y- Pos	X1- Pos	Y1- Pos	Delta -x	Delta -y
(A) Both Shaft Diameter Are LMC	50.025	34.025	7.9788	8.0212	8	8	-0.0212	0.0212
(B) Both Shaft Diameter Are MMC	50.064	34.064	7.9788	8.0212	8	8	-0.0212	0.0212
(C.) Datum Shaft Diameter Are LMC and B shaft Diameter MMC	50.025	34.064	7.9593	8.0017	8	8	-0.0407	0.0017
(D) Datum Shaft Diameter Are MMC and B shaft Diameter LMC	50.064	34.025	7.9983	8.0407	8	8	-0.0017	0.0407

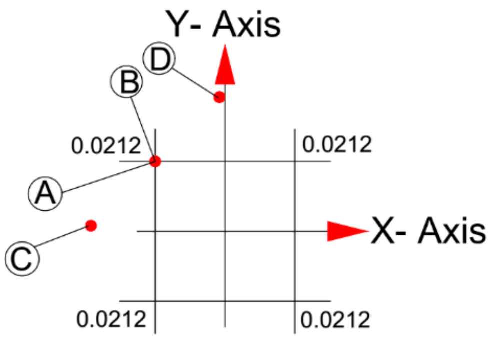


Fig. 7. Square tolerance zone analysis.

3.3.2. Circular tolerance zone analysis

The GT value calculated from mathematical model is 0.0212 mm is also to be evaluated using circular tolerance zone analysis, and its result were obtained as shown in Table 2 and Fig. 8. Circular tolerance zone can determine the status of the shaft above whether they can be rejected or accepted. Circular tolerance zone must calculate the actual radius obtained Ract 0.02998 mm@29.98 micron. Coordinates A and B can be accepted because it within in actual radius. The coordinates of C and D are rejected because the location is outside the actual radius.

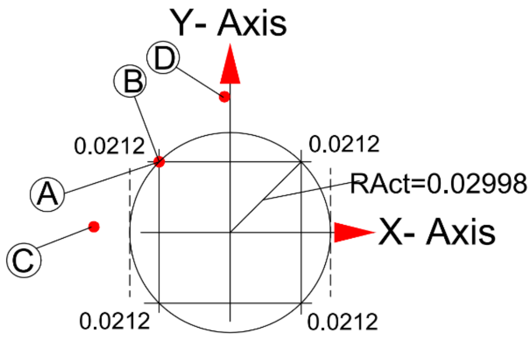


Fig. 8. Circular tolerance zone analysis.

It is assumed that the dimension must be referred as shaft possibility position. In this condition geometrical tolerance LMC and MMC must in consideration. It is obtained that the LMC datum shaft and LMC the actual shaft value is getting easier to get $R_{act} < R_{allow}$ for Shaft. In mathematical terms, then, the value allowable radius must high then actual radius satisfy.

3.3.3. Evaluation of GT value using statistical analysis

Statistical analysis uses equations to determine the value of the tolerance zone based on dimensional changes i.e. maximum material limit and minimum material limit shaft determined in the standards and relevant parameters. Simulations were also performed to analyse the effects of dimension variations, shaft performance and measurement error for each shaft size. Applications that use statistical tolerance analysis can show variations on central tendencies and the likelihood of errors being improved. Each analysis must comply with $R_{act} < R_{allow}$ if it does not comply and is considered to be a failure and the GT value is considered to be exceeded as shown in Table 3 and Fig. 9 shows the optimum condition for GT value 0.012 mm and both shaft diameter is LMC.

Coefficient and GT values were derived from statistical analysis by developing a statistical program for statistics. Table 4 shows coefficient and GT value by shaft size from 1 mm diameter to 500 mm diameter. From the data obtained each shaft size has different coefficient and GT values.

Table 3. $R_{act} < R_{allow}$ with GT value 0.0212.

Condition	Datum Shaft (A)	Shaft- B	Act. Tol = R_{act}	Bonus Tol	Tot. Tol	Allow Tol = R_{allow}
(A) Both Shaft Diameter Are LMC	50.025	34.025	0.0300	0.039	0.060	0.0301
(B) Both Shaft Diameter Are MMC	50.064	34.064	0.0300	0.000	0.021	0.0106
(C.) Datum Shaft Diameter Are LMC and B shaft Diameter MMC	50.025	34.064	0.0408	0.000	0.021	0.0106
(D) Datum Shaft Diameter Are MMC and B shaft Diameter LMC	50.064	34.025	0.0408	0.039	0.060	0.0301

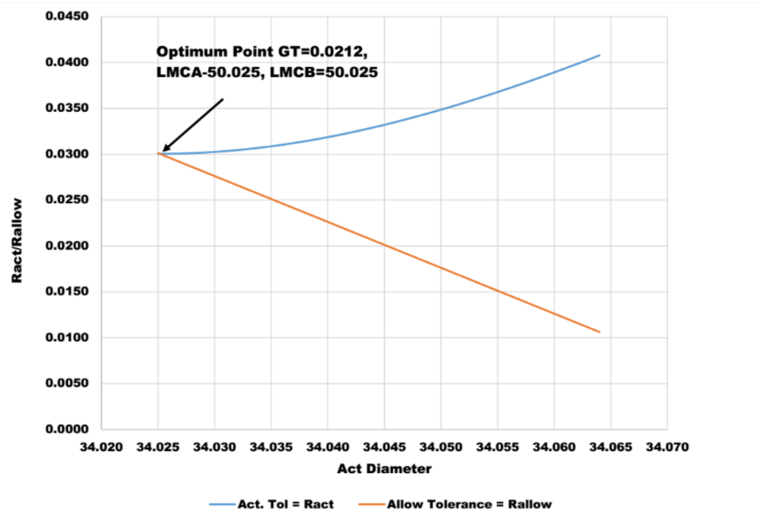


Fig. 9. Optimum for value GT and shaft size.

Figure 10 shows the GT values and acceptable ranges using the algebraic method. This value is used for rotating shaft assessments to determine system suitability. Using algebra models can also realize ANSI and ASME standards for size and position. The calculations performed are oriented with varying shaft dimensions. This intersection exceeds the limit specified by the design intent as shown in the R_{act} < R_{allow} equation.

Table 4. Coefficient and GT value by shaft size.

BASIC SIZE SHAFT (A) (mm)		BASIC SIZE SHAFT (B) (mm)		Algebraic Method, GT = 2*Rallow* - (MMCB – LMCB) * C				Offset Method, GT = (2(*Rallow*) - (MMC ø – ActShaft ø))/2 * C			
				Coefficient, C		GT value		Coefficient, C		GT value	
Over	**T0**	**Over**	**T0**	**Over**	**T0**	**Over**	**T0**	**Over**	**T0**	**Over**	**T0**
1	3	1	3	1.20	1.27	0.0072	0.0076	1.10	1.17	0.0071	0.0076
3	6	3	6	0.63	1.28	0.0073	0.0097	0.75	1.03	0.0071	0.0098
6	10	6	10	0.72	1.28	0.0096	0.0120	0.80	1.01	0.0096	0.0121
10	18	10	18	0.72	1.30	0.0118	0.0148	0.80	1.00	0.0118	0.0147
18	30	18	30	0.72	1.30	0.0143	0.0180	0.79	0.98	0.0144	0.0179
30	40	30	40	0.78	1.30	0.0175	0.0213	0.79	0.96	0.0176	0.0214
40	50	40	50	1.28	1.30	0.0210	0.0213	0.94	0.96	0.0209	0.0214
50	65	50	65	0.8	1.30	0.0210	0.0250	0.79	0.95	0.0209	0.0252
65	80	65	80	1.29	1.30	0.0248	0.0250	0.94	0.95	0.0249	0.0252
80	100	80	100	0.81	1.30	0.0248	0.0293	0.79	0.93	0.0249	0.0293
100	120	100	120	1.28	1.31	0.0289	0.0296	0.92	0.93	0.0290	0.0293
120	140	120	140	0.82	1.31	0.0289	0.0344	0.78	0.92	0.0291	0.0343
140	160	140	160	1.29	1.31	0.0339	0.0344	0.91	0.92	0.0339	0.0343
160	180	160	180	1.29	1.31	0.0339	0.0344	0.91	0.92	0.0339	0.0343
180	200	180	200	0.87	1.31	0.0340	0.0393	0.79	0.91	0.0340	0.0391
200	225	200	225	1.28	1.31	0.0384	0.0393	0.91	0.90	0.0387	0.0391
225	250	225	250	1.28	1.31	0.0384	0.0393	0.91	0.9	0.0387	0.0391
250	280	250	280	0.91	1.31	0.0389	0.0442	0.81	0.91	0.0391	0.0439
280	315	280	315	1.31	1.31	0.0442	0.0442	0.90	0.91	0.0434	0.0439
315	355	315	355	0.98	1.31	0.0442	0.0486	0.82	0.91	0.0437	0.0485
355	400	355	400	1.30	1.31	0.0482	0.0486	0.90	0.91	0.0479	0.0485
400	450	400	450	1.00	1.31	0.0484	0.0529	0.83	0.91	0.0483	0.053
450	500	450	500	1.31	1.31	0.0529	0.0529	0.91	0.91	0.0530	0.053

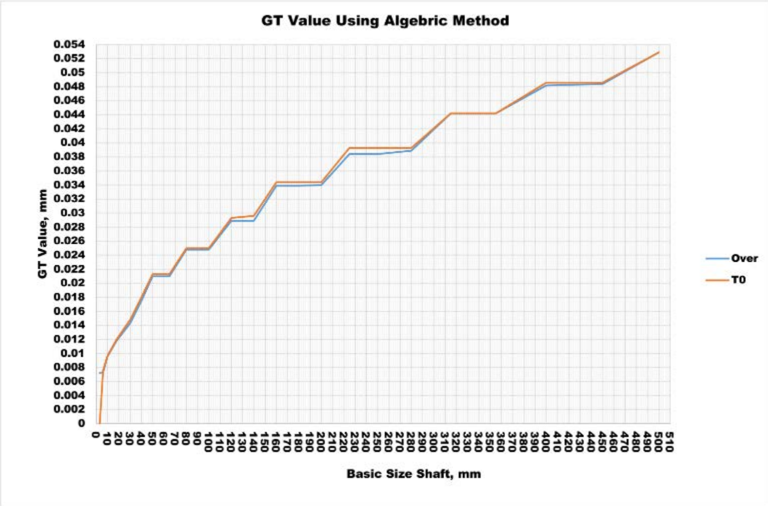


Fig. 10. GT value using algebraic method.

Figure 11 shows the GT values and acceptable ranges using the offset method. However, the error may not be significant if the feature width ratio is comparable, and the tolerance zone width is small. Proper positioning has measurement characteristics and can control location and orientation. Unusual variation calculated based on precise feature level.

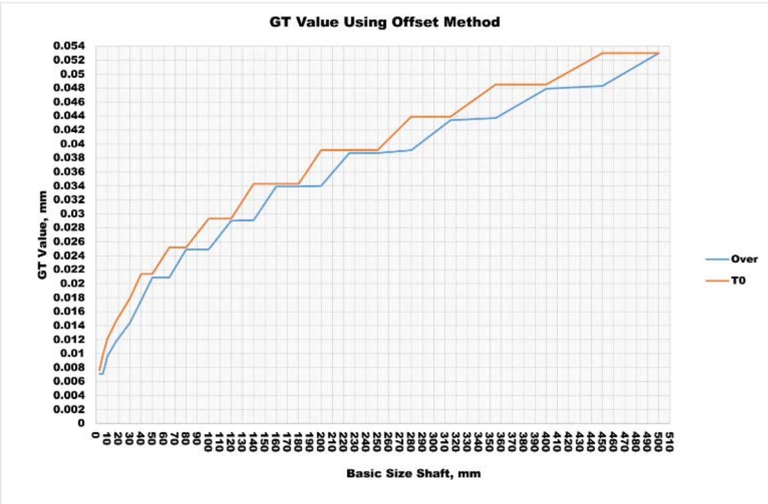


Fig. 11. GT value using offset method.

Figure 12 and Table 5 show the GT values and acceptable ranges. This range is obtained by taking the lowest and highest values in the algebraic method and offset method. By combining the two methods can produce a higher range but still within acceptable range. GT values need to be obtained within a certain range to provide flexibility in product manufacturing. In manufacturing it is difficult to produce precise dimensions in large production therefore the range for dimensions can help meet the specifications of a product.

Table 5. GT value range.

Basic size shaft (mm)		GT value range (mm)	
Over	T0	Over	T0
1	3	0.0071	0.0076
3	6	0.0071	0.0098
6	10	0.0096	0.0121
10	18	0.0118	0.0148
18	30	0.0143	0.0180
30	40	0.0175	0.0214
40	50	0.0209	0.0214
50	65	0.0209	0.0252
65	80	0.0248	0.0252
80	100	0.0248	0.0293
100	120	0.0289	0.0296
120	140	0.0289	0.0344
140	160	0.0339	0.0344
160	180	0.0339	0.0344
180	200	0.0340	0.0393
200	225	0.0384	0.0393
225	250	0.0384	0.0393
250	280	0.0389	0.0442
280	315	0.0434	0.0442
315	355	0.0437	0.0486
355	400	0.0479	0.0486
400	450	0.0483	0.053
450	500	0.0529	0.053

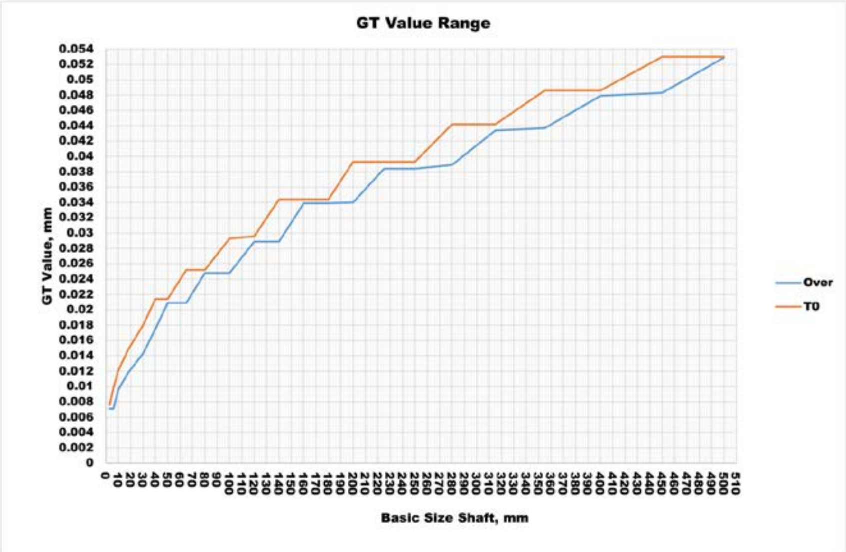


Fig. 12. GT value range.

3.3.4. Evaluate GT value using FEA analysis

Shaft is a study specimen because it will interact with other components in the system. Therefore the shaft rotation centreline which is the GT value is studied to determine the effect on other related components in the system. If the condition of the shaft is in an imperfect state it will have an effect on other components.

FEA application to determine the effect of GT value on the shaft system by modeling the relationship between two contact surfaces that may have small gaps or effects that occur on individual nodes. Results from FEA analysis found only blue and green in ball bearing and no red colour. It is found that maximum stress and pressure on the bearing are only at that level as a result shown in Fig. 13, Table 6. Figure 14 shows the result at maximum point for contact opening at surface nodes analysis.

The results show that the GT value used indicates a contact value is 5.042E-01 and is still safe for the system. From the data and formulation obtained will be simulated using the FEA software to evaluate the value of GT. This simulation is conducted to find out the effect of GT value on product performance. Changing the shaft depends on centrifugal force and centrifugal force on dynamic geometry is rotating speed function. Therefore, the amplitude of the outer surface can be quite high from the operating speed. The relation between the manufacturing accuracy and its effect on the dynamic geometry of a rotating cylinder is investigate. An analysis of the geometric characteristics of vibration and force is a method used to diagnose the effect of misalignment in the rotating component. Excessive vibration will cause damage to components such as coupling and bearings.

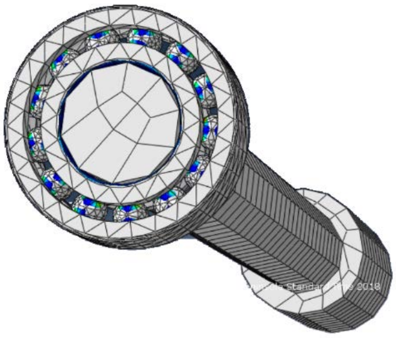
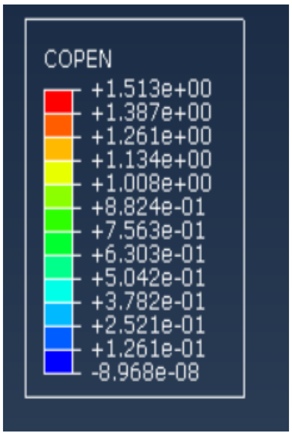


Fig. 13. Contact opening at surface nodes analysis.

Table 6. Result contact opening at surface nodes analysis.



Frame No	**Contact Opening at Surface nodes**
1	-8.968E-08
2	1.261E-01
3	2.521E-01
4	3.782E-01
5	5.042E-01
6	6.303E-01
7	7.563E-01
8	8.824E-01
9	1.008E+00
10	1.134E+00
11	1.261E+00
12	1.387E+00
13	1.513E+00

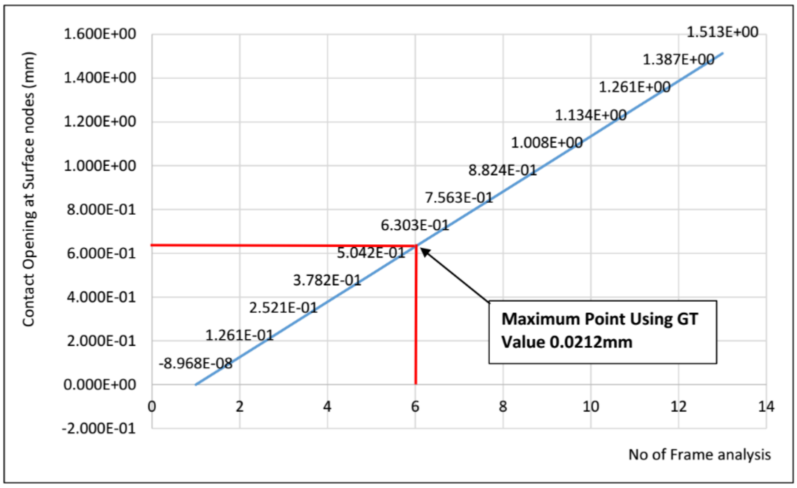


Fig. 14. Maximum point for contact opening at surface nodes analysis.

4. Conclusions

In the manufacturing and installation process there are several dimensions that interact with other dimensions and have an effect on the installation function. In today's highly competitive industrial environment, design efficiency and product quality as well as lower production costs are required. Designers and manufacturers should consider GT values for critical features in the design and installation of rotating shaft systems.

A study to determine the more optimal GT values as a guide in the design and installation process to reduce errors. Integration with designer and manufacturing activities is essential to meeting objectives. Tolerance is known as an acceptable deviation distance from a certain dimension. The relationship between manufacturing accuracy and its influence on the dynamic geometry of a rotating cylinder is investigated. The analysis is done by considering the imbalances and imbalances in the rotor system. In terms of efficiency and ability to find the optimal solution, a smaller GT value is better for the system but difficult to obtain a small GT value in the manufacturing and installation process. This study has developed a mathematical model to facilitate the acquisition and optimization of GT values for shaft rotation systems. The correct GT value should be considered regardless of the shape of the shaft because the center of the shaft rotation point is a geometric fault on the component which will cause the collection and distribution of the geometric error on the rotating component. Good GT value achieves good system performance and can control the spread of damage to improve system quality and achieve key system features.

By considering the relative position of the shaft to the LMC and MMC this method is formed by the relationship between the delta-x and delta-y coordinates to determine the basic position and variation of the control coordinate variables for geometric elements. Tolerance analysis was performed to predict the influence of dimensional variation on the system with the GT value obtained where the larger the shaft size, the greater the GT value obtained. From the development of the formulation model, the shaft function optimization is produced to predict the reliability caused by the GT effect and as a guide for the manufacturing and installation process to reduce errors. The rotational accuracy of the component depends on the GT value on the center axis of the rotating shaft and reduces the vibration effect of the shaft. From this study can produce a table to refer to the GT value from 1 mm diameter to 500 mm for position characteristics in the shaft rotation system. This table will more easily help designers, makers and installers to determine GT values by meeting the *Ract* <*Rallow* equation.

Nomenclatures

$A_{ctshaft}$	Actual Shaft Size
Delta 1a	Upper Limit Shaft A
Delta 1b	Lower Limit Shaft B
Delta 2a	Upper Limit Shaft A
Delta 2b	Lower Limit Shaft B
LMC_B	Lowest Material Condition for Shaft B
LMC_A	Lowest Material Condition for Shaft A
MMC_A	Maximum Material Condition for Shaft A
MMC_B	Maximum Material Condition for Shaft B
R_{allow}	Allowable Radius
Ract	Actual Radius

Greek Symbols

ø	Diameter of shaft

Abbreviations

ASME	American Society of Mechanical Engineers
ISO	International Organization for Standardization
FEA	Finite Element Analysis
GD &T	Geometrical Dimensioning & Tolerance
GT	Geometrical Tolerance

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