GEOMETRICAL TOLERANCE STACK UP TECHNIQUES

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Abstract: *Tolerance design has become a very sensitive and important issue in product and process development because of increasing demand for quality products and the growing requirements for automation in manufacturing. This chapter presents tolerance stack up analysis of dimensional and geometrical tolerances. The stack up of tolerances is important for functionality of the mechanical assembly as well as optimizing the cost of the system. Many industries are aware of the importance of geometrical dimensioning & Tolerancing (GDT) of their product design. Conventional methods of tolerance stack up analysis are tedious and time consuming. Stack up of geometrical tolerances is usually difficult as it involves application of numerous rules & conditions. This chapter introduces the various approaches viz. Generic Capsule, Quickie and Catena methods, used towards tolerance stack up analysis for geometrical tolerances. Automation of stack up of geometrical tolerances can be used for tolerance allocation on the components as well as their assemblies considering the functionality of the system. Stack of geometrical tolerances has been performed for individual components as well as assembly of these components.*

Key words: *GDT, Tolerance stack up, Generic Capsule, Quickie, Catena Method.*

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This Publication has to be referred as: Sahani, A[jai] K[umar]; Jain, P[ramod] K[umar] & Sharma S[atish], C. (2013) Geometrical Tolerance Stack Up Techniques, Chapter 52 in DAAAM International Scientific Book 2013, pp. 857-872, B. Katalinic & Z. Tekic (Eds.), Published by DAAAM International, ISBN 978-3-901509-94-0, ISSN 1726-9687, Vienna, Austria
DOI: 10.2507/daaam.scibook.2013.52

1. Introduction

The technology has undergone major changes over the centuries to meet the changing requirement of the society. During World War II, the United States manufactured and shipped spare parts overseas for the war effort. Many of these parts were made to specifications but would not assemble. The military recognized that producing parts that do not properly fit or function is a serious problem since lives depend on equipment that functions properly. After the war, a committee representing government, industry, and education spent considerable time and effort investigating this defective parts problem; this group needed to find a way to insure that parts would properly fit and function every time. The result was the development of GDT.

Features toleranced with GDT reflect the actual relationship between mating parts. Drawings with properly applied geometric tolerancing provide the best opportunity for uniform interpretation and cost-effective assembly. GDT was created to insure the proper assembly of mating parts, to improve quality, and to reduce cost. Before designers can properly apply geometric tolerancing, they must carefully consider the fit and function of each feature of every part. Properly applied geometric tolerancing insures that every part will assemble every time. Geometric tolerancing allows the designers to specify the maximum available tolerance and consequently design the most economical parts.

There are 14 different types of geometric tolerances, mainly divided into three types for individual features, for related features, or for both individual and related features. It is shown in Table 1and symbols of these types of tolerances are shown in Figure 1.

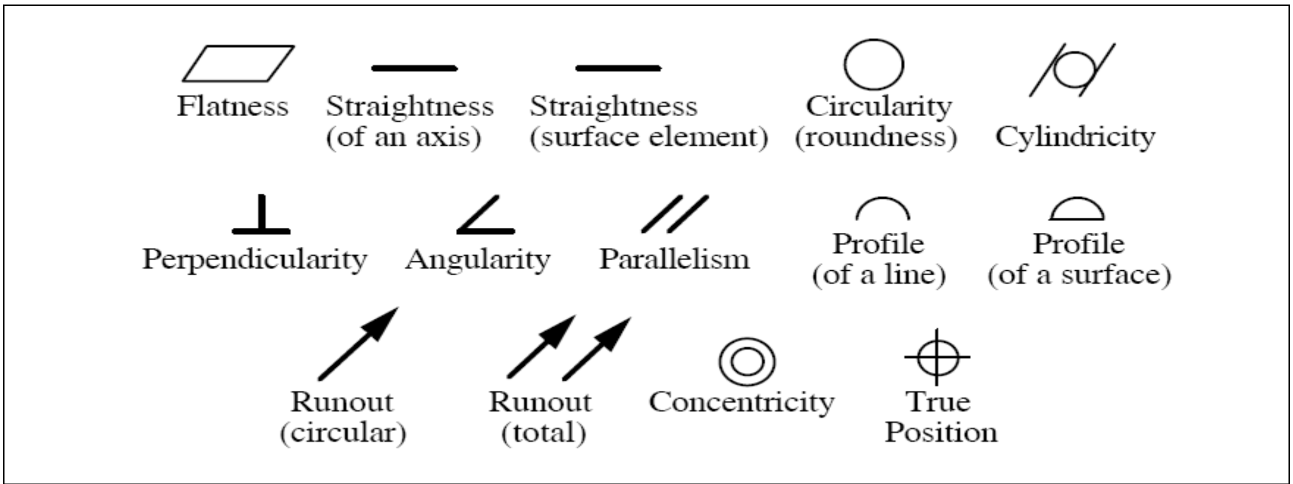

Fig. 1. Symbols for geometric feature control [ANSI Y 14.5M-1982]

The purpose of stack up analysis is to establish the dimensional relationships within a part or assembly. It enables part tolerance to be optimized while maintaining functionality and maximum part interchangeability and allowing minimum manufacturing cost to be achieved. One of the most important reasons for using stack analysis is that problems can be discovered and solved on paper rather than in the prototype or production, and thus evaluation and modification can be done at the early stage of design.

	Type of Tolerance	Characteristic
For Individual Features	Form	Straightness
		Flatness
		Circularity
		Cylindricity
For Individual or Related Features	Profile	Profile of a Line
		Profile of a Surface
For Related Features	Orientation	Angularity
		Perpendicularity
		Parallelism
	Location	Position
		Symmetry
		Concentricity
	Runout	Circular Runout
		Total Runout

Tab. 1. Types of Geometric Tolerances

This chapter introduces different graphical approaches like the Catena, Quickie and Generic Capsule methods to perform assembly tolerance stack analysis for various geometrical tolerances. There are many methods to calculate the cumulative effect of tolerance stack ups at specific points of a mechanical assembly with known individual tolerances (both type and value). The worst case and root sum square methods of tolerance stack up are commonly used methods. The worst case approach is applicable when the number of constituent dimensions in assembly is very small, the volume of production is very small and 100 per cent acceptance is required. The weakness of the method is that its predictions become too conservative, because as the number of components in the assembly increases then the chances of all the individual tolerances occurring at their worst case limits reduce. The Root Sum Square Approach is applicable when the number of constituent dimensions in assembly is sufficiently large; the volume of production is very high and finite rejection of the product assembly is acceptable.

2. Overview of Tolerancing

Engineering, as a science and a philosophy, has gone through a series of changes that explain and justify the need for a new system for managing dimensioning and tolerancing activities. The evolution of a system to control the dimensional variation of manufactured products closely follows the growth of the quality control movement. During the 1960s and 1970s, the trend in engineering education in the United States shifted away from a design-oriented curriculum toward a more theoretical and mathematical approach. Concurrent with this change in educational philosophy was the practice of issuing contracts between customers and suppliers that increased the physical separation of engineering personnel from the manufacturing process. These two changes, education and contracts, encouraged the development of several different product design philosophies. The philosophies include engineering driven design, process driven design, and inspection driven design.

2.1 Engineering Driven Design

An engineering driven design is based on the premise that the engineering designer can specify any tolerance values deemed necessary to ensure the perceived functional requirements of a product. Traditionally, the design engineer assigns dimensional tolerances on component parts just before the drawings are released. These tolerance values are based on past experience, best guess, anticipated manufacturing capability or build-test-fix methods during product development. When the tolerances are determined, there is usually little or no communication between the engineering and the manufacturing or inspection departments. This method is sometimes called the “over-the-wall” approach to engineering design because once the drawings are released to production, the manufacturing and inspection personnel must live with whatever dimensional tolerance values are specified.

2.2 Process Driven Design

A process driven design establishes the dimensional tolerances that are placed on a drawing based entirely on the capability of the manufacturing process, not on the requirements of the fit and function between mating parts. When the manufactured parts are inspected and meet the tolerance requirements of the drawings, they are accepted as good parts. However, they may or may not assemble properly. This condition occurs because the inspection process is only able to verify the tolerance specifications for the manufacturing process rather than the requirement for design fit and function for mating parts.

2.3 Inspection Driven Design

An inspection driven design derives dimensional tolerances from the expected measurement technique and equipment that will be used to inspect the manufactured parts. Inspection driven design does not use the functional limits as the assigned values for the tolerances that are placed on the drawing. The functional limits of a dimensional tolerance are the limits that a feature has to be within for the part to assemble and perform correctly. One inspection driven design method assigns tolerances based on the measurement uncertainty of the measurement system that will be used to inspect finished parts.

3. Previous Research

A lot of work has been done in the field of conventional tolerancing. Conventional tolerancing methods do a good job for dimensioning and tolerancing size features and are still used in good capacity today, but conventional tolerancing do not cater precisely for form, profile, runout, location and orientation features. Geometric Dimensioning and Tolerancing is used extensively for location, profile, runout, form and orientation features. The stack of geometrical tolerances has been done by Ngoi *et al*. In his research, a generic approach has been presented which is simple and systematic process of tolerance stack analysis. The model is constructed, representing the given and the unknown dimensions. The proposed method uses, as the name implies, a generic capsule, which takes into account all the related aspects of the axis and surface type of tolerance. Ngoi *et al*. presented an elegant approach by using the 'Quickie' technique towards tolerance stack analysis for GDT. The proposed approach has the potential to significantly reduce the amount of work required and computerization is proving to be promising. The 'Quickie' GDT method is applicable to all geometric characteristics. However, due to different treatments in various families of geometric characteristics, the 'Quickie' GDT approach analysed runout and concentricity tolerances. Ngoi *et al.* presented a straightforward, easy-to-use graphical approach known as the "Catena" method for tolerance stack analysis, involving geometric characteristics in form control – flatness, straightness, circularity and cylindricity. No complicated mathematical formulae are required in deriving the solution. Ngoi *et al.* suggested Nexus method for stack up of position tolerance involving bonus and shift tolerances. The method constructs graphical representations of features termed Nexus cells. The cells contain all geometric information of the features in numerical values. After each feature is represented by a Nexus cell, the cells are linked up to form the Nexus model for the part. Once the model is completed, it can be used to evaluate GDT problems associated with the part. The method is also applicable for assembly. The "Noded graph" model by Ngoi *et al.* is constructed, representing the given and the unknown dimensions. Links are then established, using the model, which help to formulate the stack path of interest into a linear equation. The equation is used to complete the tolerance stack analysis module. Swift *et al.* introduced a knowledge-based statistical approach to tolerance allocation, where a systematic analysis for estimating process capability levels at the design stage is used in conjunction with statistical methods for the optimization of tolerances in assembly stacks. The method takes into account failure severity through linkage with failure mode and effects analysis (FMEA) for the setting of realistic capability targets. Ngoi *et al.* presented a simple graphical method to represent the process links between surface planes, and leads to ease in performing the validity of a process plan. The approach used the linear optimisation software, LINDO, to solve the respectively linear working dimension and manufacturing tolerance equations. Ngoi *et al.* presented a simplified approach of model construction directly from the process plan. With the model constructed, the relevant process links between any two surfaces can be easily determined. Unlike other methods, it does not require transcribing the link information into constraint equations. The formation of the constraint equations is made easier by direct read-out from the model. He JR described an extension of a model which determines an optimum set of dimensions and tolerances for machining processes at minimum manufacturing cost. This optimisation minimizes the cost of scrap, which is a function of manufacturing tolerances, as the objective function. Requirements of design sizes, geometrical tolerances (both form and position) and machining allowances are expressed mathematically as constraints for the optimization. Singh *et al.* reviewed different methods of tolerances allocation and found mean shift models. The combination of the basic approaches can appropriately be considered more useful because of simplicity of application and improved precision over the plain basic. Numerical integration and experimental design methods are relatively less complicated, and are useful especially when it is difficult to express the assembly response function analytically or when computation of the partial derivatives is difficult. Singh *et al.* reviewed tolerance synthesis approaches for tolerance stack-up i.e. the worst-case and the root sum square approaches, or a combination of the aforementioned basic approaches, viz. the Spotts criteria and the Greenwood and Chase criteria, used in an estimation of the tolerance build-up. There is a need to have properly estimated mean-shift factors to get precise results. Zhang and Wang used the exponential cost-tolerance model for the various machining processes for the allocation of design and machining tolerances based on the least manufacturing cost criterion using simulated annealing as the optimization method. Ahluwalia *et al.* developed a computer aided tolerance control (CATC) system based on the tolerance chart technique. The selection of manufacturing processes and sequence of processes affects process tolerance stacking. The system can be used for computer aided process planning (CAPP) and for CAD/CAM integration. Chase *et al.* described a procedure for tolerance specification based on quantitative estimates of the cost of tolerances, which permits the selection of component tolerances in mechanical assemblies for minimum cost of production. Chase *et al.* described several algorithms for performing tolerance allocation automatically, based on optimization techniques. A cost vs. tolerance function is used to drive the optimization to the minimum overall cost. The methods provide a rational basis for assigning tolerances to dimensions. Sahani *et al.* compared different methods for stack up of geometrical tolerances.

4. Methods for Tolerance Stack Up

In this section, methods have been presented, that can calculate the cumulative effect of tolerance stack ups at specific points of a mechanical assembly. It is assumed that individual tolerances are known (both type and value). The different methods are as follows:

4.1 Worst Case Analysis

This method, also known as linear stack-up, is the most basic method for predicting the effect of individual tolerances on the whole assembly. In this method, tolerance analysis is done by assuming that all the individual tolerances occur at their worst limits or dimensions simultaneously. The accumulated tolerance (ΔY) can be written as

$$\Delta Y = \sum_{i=1}^{n} \delta i \qquad \textbf{(1)}$$

Where,

n = Number of constituent dimensions in the dimension chain

δi = Tolerance associated with dimension.

This approach is applicable when

(a) The volume of production is very small
(b) 100 per cent acceptance is required
(c) The number of constituent dimensions in assembly is very small

The weakness of the method is that its predictions become too conservative, because as the number of the parts in the assembly increases then the chances of all the individual tolerances occurring at their worst case limits reduce. This method can be used in designing fixtures and also used for collision avoidance by robots.

4.2 Statistical Tolerance Analysis

This method assumes a probability distribution function (pdf) for the variation of tolerances and then uses this function to predict the assembly variability in the system. A standard procedure for tolerance analysis is to determine the first four moments of this function and use these to choose a distribution that describes the system variability. The main techniques for statistical tolerance analysis are described below.

4.2.1 Root Sum Squares Method (RSS)

It is the most general form, assuming a Normal or Gaussian distribution for component variations. This case is very popular and frequently used in mechanical assemblies because of its simplicity. It has been found that it is very optimistic and many times the number of rejections in the assembly is more than predicted. Total tolerance of assembly can given as

$$\Delta Y = \sqrt{\sum_{i=1}^{n} \delta_i^2} \qquad (2)$$

Where,

n = Number of constituent dimensions in the dimension chain
δi = Tolerance associated with dimension.

This approach is applicable when

(a) The volume of production is very high
(b) Finite rejection of the product assembly is acceptable
(c) The number of constituent dimensions in assembly is sufficiently large

4.2.2 Estimated Mean Shift Model

It is a slight modification of the RSS analysis. In RSS we assume that the variation of each component dimension is symmetrically distributed about the mean or nominal dimension, which in real processes, is shifted due to setup errors or drifts due to time- varying parameters such as tool wear. In this method the mean is shifted to accommodate the variations.

$$\Delta Y = \sum_{i=1}^{n} \alpha i \delta i + z/3 \sqrt{\sum_{i=1}^{n} (1-\alpha_i^2)\delta_i^2} \quad (3)$$

Where,

αi = mean shift factor associated with the manufacturing process for dimension Xi

Z = 3.00, corresponding to 99.73 percent yield this value is most commonly used in an analytical treatment

4.2.3 Taguchi's Method

The general idea of Taguchi's method is to use fractional factorial or orthogonal array experiments to estimate the assembly variations due to the component variations. This means that the modified Taguchi method is a product Gaussian Quadrature method that gives correct values of the moments up to the fifth moment for linear functions. This method is similar to the Quadrature method.

4.2.4 Reliability Index Method

This method calculates the yield or the probability of successful assembly based on the Hasofer-Lind reliability index. Given the moments of the component parameters, each of these random variables is transformed into a standard normal random variable.

4.2.5 Motorola Six Sigma Model

It is a modification for the RSS method, developed by the Motorola Corp, where a process capability index is assumed. The process capability index is six times the variance of the process. It is a modification of the estimated mean shift model that assumes that the mean of a process shifts due to process variations due to tool wear. In order to achieve high quality in a complex product comprised of many components and processes, each component and process must be produced at significantly higher quality levels in order for the composite result to meet final quality standards.

4.3 Monte Carlo Simulation

Monte Carlo Simulation is a powerful tool for tolerance analysis of mechanical assemblies. It can be used for both nonlinear assembly functions and non-normal distributions. It is based on the use of a random number generator to simulate the effects of manufacturing variations on assemblies as shown in Figure 2.

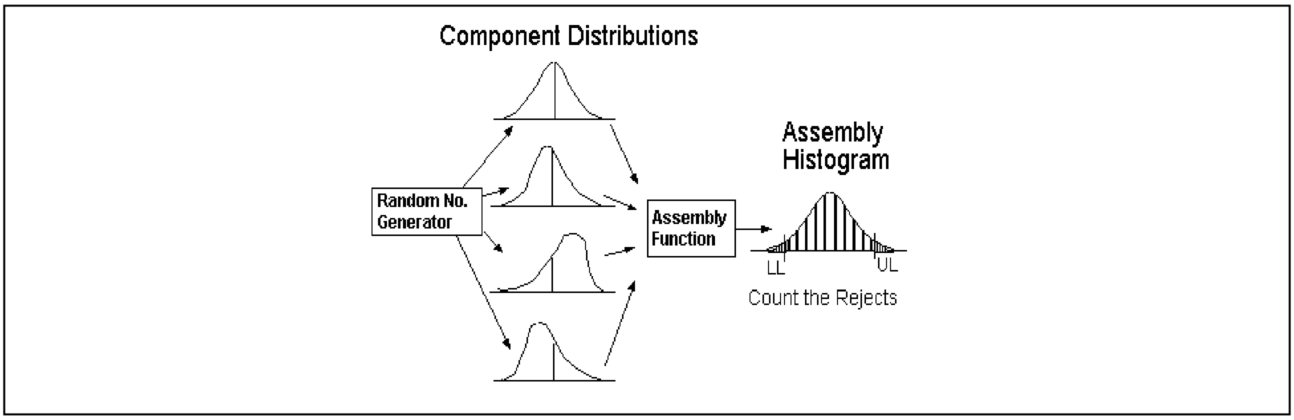

Fig. 2. Monte Carlo distribution

5. Methodology

A case is taken up for the tolerances stack up of an assembly by proposed methods. The assembly consists of two components: I and C section as shown in Figure 3a. The drawings of both the components are shown in the Figure 3b and Figure 3c.In this case, extremum of X is to be calculated.

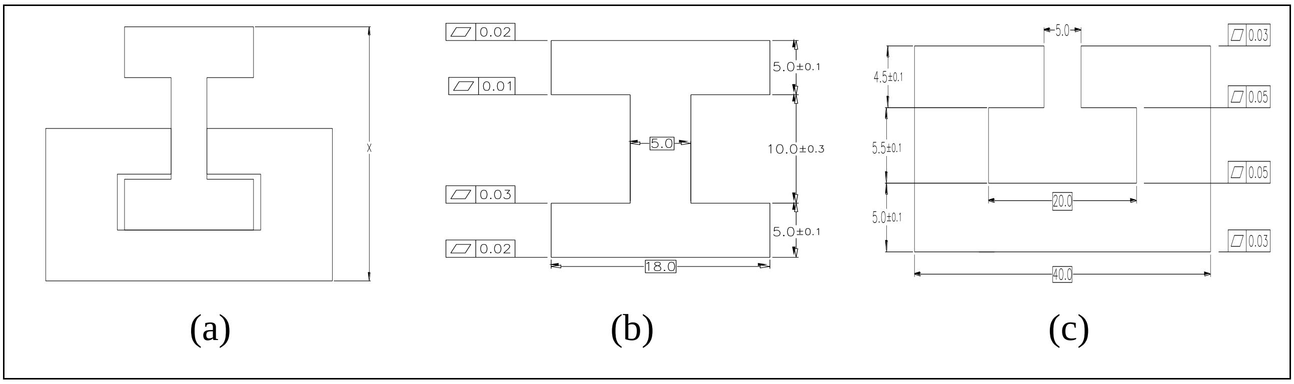

Fig. 3. (a)Assembly of I & C section; (b) I section; (c) C section

5.1 Generic Capsule

In this method, the steps to be followed are labelling, modeling, formulation and evaluation. Firstly, the surfaces dimensioned are labeled as shown in Figure 4. Here, surfaces with bilateral flatness tolerance specifications are labelled twice. Those labels that have an asterisk (*) suffixed to the alphabets represent the virtual surface created by the presence of the geometrical tolerance. Those surfaces that do not have the asterisk represent the basic surfaces i.e. surfaces that are separated apart by basic dimensions. The part number for the I is 1 while the part number for the C is 2.

Having completed the labelling phase, the graphical model can then be constructed as shown in Figure 5. In the case of an assembly, the graphical model is constructed part by part. The two part models are then linked together by dashed line that represent surface contact.

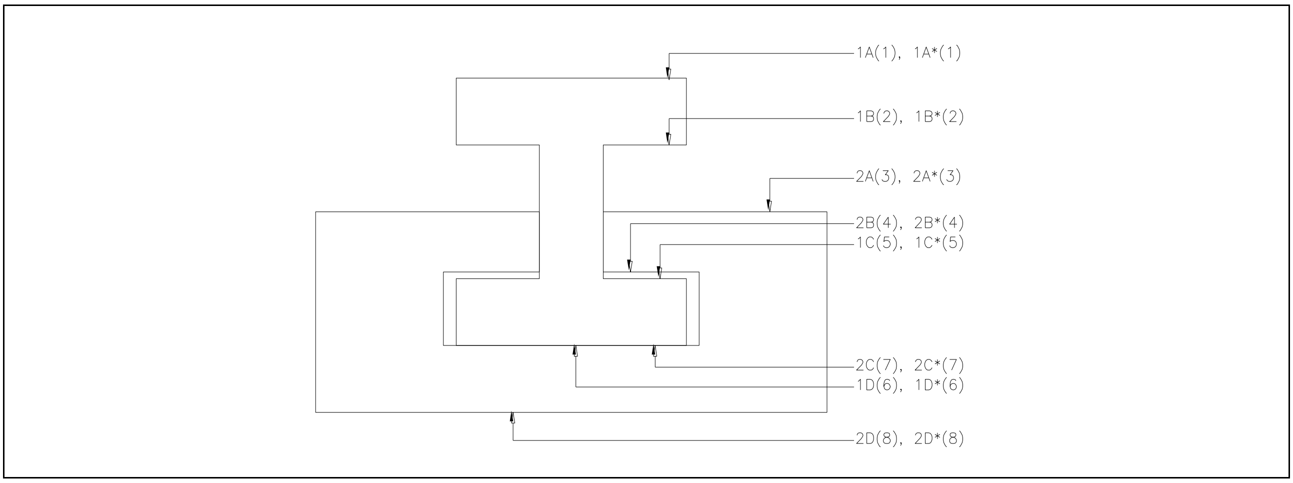

Fig. 4. Labelling of assembly

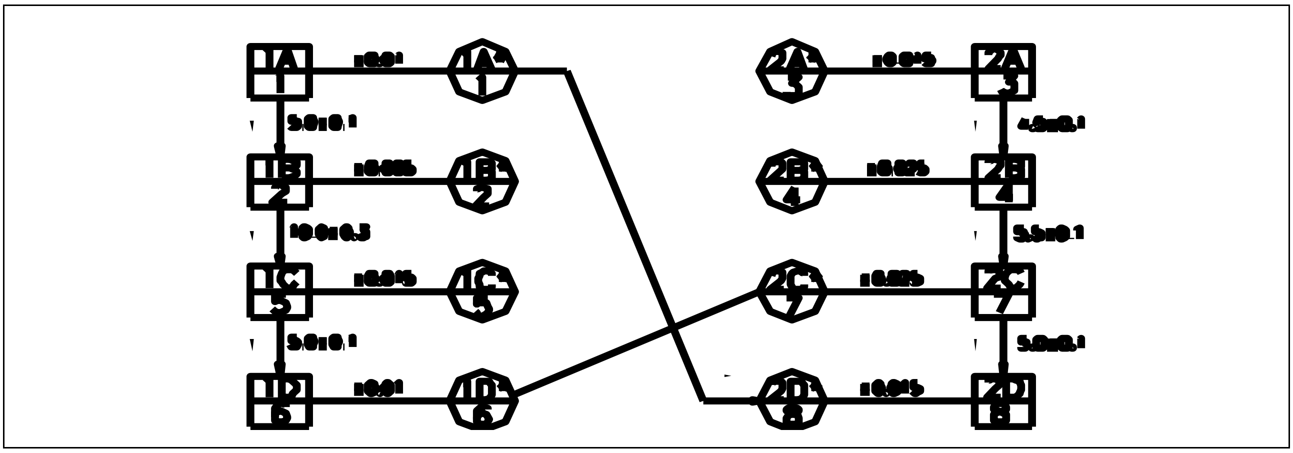

Fig. 5. Graphical Model

Upon the completion of the model, the stack path is identified which passes through the dashed line that connects between 1D* and 2C* . The expression derived from the stack path is

1A*2D* + 2D*2D – 2C2D + 2C2C* + 2C*1D* + 1D*1D – 1C1D – 1B1C – 1A1B + 1A1A* = 0

Upon substitution and simplification,

$$X = 25.0 \pm 0.66$$
$$X_{max} = 25.66$$
$$X_{min} = 24.34$$

5.2 The Quickie Method

The surfaces are numbered in sequence from top to bottom. Referring to Figure 6, the ‘Quickie’ GDT graphical model is developed and shown in Figure 7.

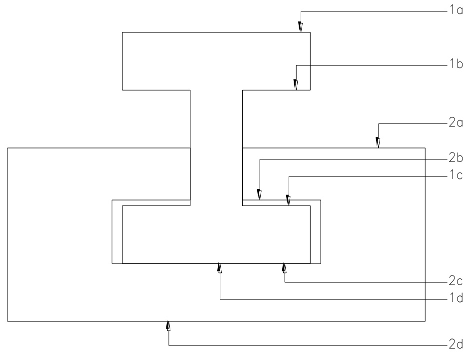

Fig. 6. Surface numbered from top to bottom of assembly

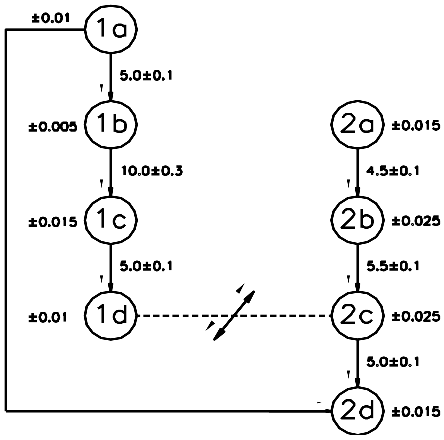

Fig. 7. Quickie GDT model for assembly

Path	Dimension	Tolerance
1a1b	+5.0	±0.110
1b1c	+10.0	±0.300
1c1d	+5.0	±0.100
1d2c	0	±0.010
2c2d	+5.0	±0.140
1a2d	+25.0	±0.66

Tab. 2. Tabulation for assembly

The results in a closed loop being formed and the data are tabulated in Table 2. From Table 2, X_{max}= 25.0 + 0.66 = 25.66 and X_{min} = 25.0-0.66 = 24.34 respectively.

5.3 The Catena Method

The “Catena” methodconsists of establishing a closed-loop stack path between a pair of nodes and summing up the values in the closed-loop using the vector principle to obtain the solution.

The surfaces of each part are labelled from top to bottom(Figure 8). The assignment of identity is dependent on the availability of dimensions between any two surfaces. All tolerances available in the assembly are converted to the bilateral form.

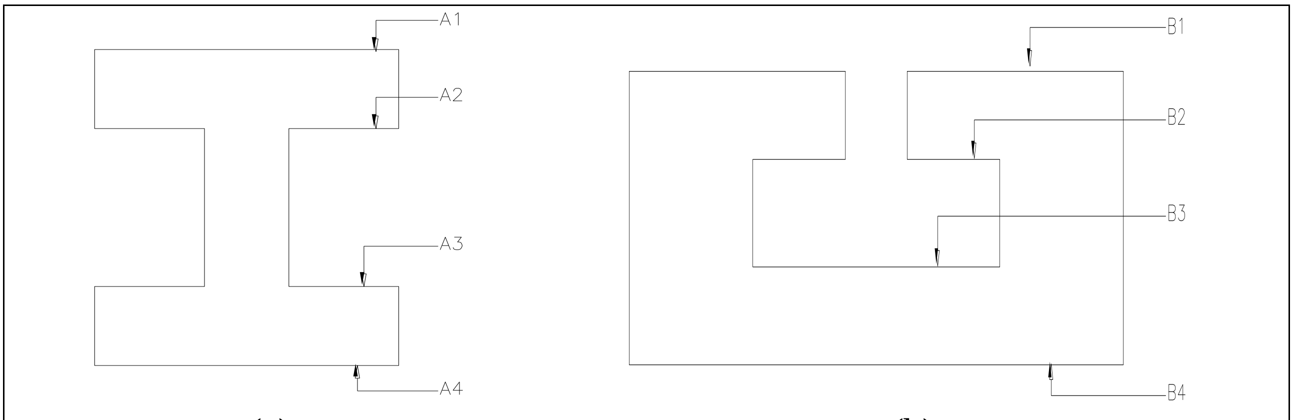

Fig. 8. (a)Labelling for I section; (b) Labelling for C section

With this information, a nodal representation for a surface of a part can be constructed. Surface B4 of the "C Section" part in Figure 9 is used as an example, and the nodal representation is shown in Figure 10. The surface node consists of three portions. The semi-circular portions identify the part and its surface. The upper-right portion is catered for in the "Offset" case, whereas the bottom-right portion is catered for in the "Adjacent" case. The geometric tolerances for offset and adjacent cases used in the stack calculation are (±GT) and (-GT/2±GT/2) respectively. The Catena Model is shown in Figure 10.

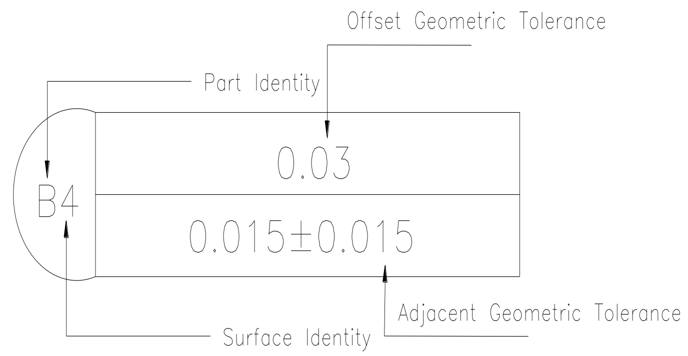

Fig. 9. Nodal representation of surface

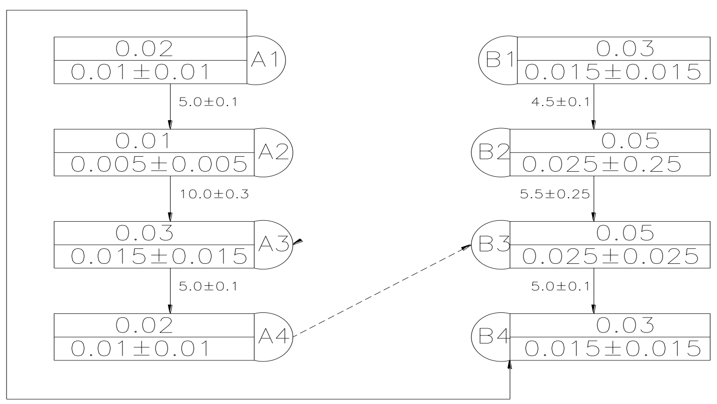

Fig. 10. Nodal representation of surfaces in assembly

Upon the completion of the Catena model, the stack path is identified which should pass through the dashed line that connects between B3 and A4. The closed loop path will be A1-B4-B3-A4-A3-A2-A1 and the expression derived is

$$X \pm 0.015 - (5.0 \pm 0.1) \pm 0.025 \pm 0.01 - (5.0 \pm 0.1) - (10.0 \pm 0.3) - (5.0 \pm 0.1) \pm 0.01 = 0$$

$$X = 25.0 \pm 0.66$$

$$X_{max} = 25.66$$

$$X_{min} = 24.34$$

5.4 Conventional Method

The extremum of X are calculated as

X= Flatness at 2D+2C2D+ Flatness at 2C+ Flatness at 1D+1C1D +1B1C+1A1B+ Flatness at 1A

$$= (\pm 0.015) + (5.0 \pm 0.1) + (\pm 0.025) + (\pm 0.01) + (5.0 \pm 0.1) + (10.0 \pm 0.3) + (5.0 \pm 0.1) + (\pm 0.01)$$

$$= 25.0 \pm 0.66$$

So,

$$X_{max} = 25.66$$

$$X_{min} = 24.34$$

However, it is difficult to computerise the conventional method for tolerance stack up. So, this method is not useful for large assemblies where as graphical approach techniques provide an opportunity to handle large assemblies by writing a computer program.

6. Logic for Computation

For calculation of distances between one surface to another, a system has been developed (Figure 11) for the orientation based geometrical tolerance. While running the system, it asks for which type tolerance you want to cater for. After key in the proper tolerance type, it asks the number of components. For each component, we have to give the input that includes number of surfaces, the distance between one surface to another. While providing the distances, it also asks for the dimensional tolerance. Once the above step is completed, the input required is the reference surface and the parallelism on each surface. After inputting all these details, the geometrical tolerances are divided by 2 because of bilateral in nature. Same types of input should be provided for all other components. After that the system asks whether you want to carry out the assembly of these components. If the answer is no, then the output is displayed in form of resultant matrix which provide the distance between one surface to another of same component. The stack up of tolerances has been done by both technique i.e. worst case and root sum square approach. Hence for each component, there are four matrices i.e. maximum and minimum values by both WC and RSS approach.

If the selection of whether you want to carry out the assembly is yes, then it asks how many components you want to assemble. The number of the components being assembled is keyed in. Then it asks the component numbers of top and bottom followed by the mating surface. Now, automatically the bottom component of previous assembly is taken as top component for next mating assembly, it asks for the bottom one and so on. The resultant matrix is generated of the order of total number of surfaces. The order of resultant matrix is nxn, where n is the total number of surfaces in the assembly. Now Results of assembly can be shown in form of matrix $\mathbf{R}$ given below

$$\mathbf{R} = Assem(i, j) \qquad\qquad i, j = 1, \cdots, n$$

7. Conclusion

This chapter presents efficient and effective graphical methods for evaluating tolerance stack up problems. These methods are simple, straightforward and easy to apply. The user does not need to remember the numerous rules regarding tolerance stack up analysis. The models constructed are graphical replica of the geometrical relationship between the features and parts in the assembly. Using these models, the stack up can be done. These stacks up will assist the designers in evaluating the relative effect of individual tolerances and making necessary changes in early stage of design. The systematic tolerance analysis algorithm is suitable for both manual calculation and computer programming.

An automatic system has been developed. The developed system is capable of calculating the unknown distance for the components as well as their assemblies with n number of components having m number of surfaces. This system can be used for orientation geometrical tolerances i.e. parallelism, perpendicularity and angularity. This system is based on WC and RSS approaches. The system helps the designer to reallocate the tolerances in very complex mechanical assemblies without affecting the functionality as well as manufacturability. The process of manufacturing can be decided based on reallocated tolerances. The manufacturing process of individual component is decided so as to minimize the overall cost of the system. However the system has a limitation of catering for only one type of tolerance at a time. To date, no single tolerancing software is able fully to automate such analysis. Tolerancing software can be developed using the computational methodologies of these methods to evaluate geometric tolerance stack problems. Further these accumulated tolerances can be distributed on different components for optimization of cost.

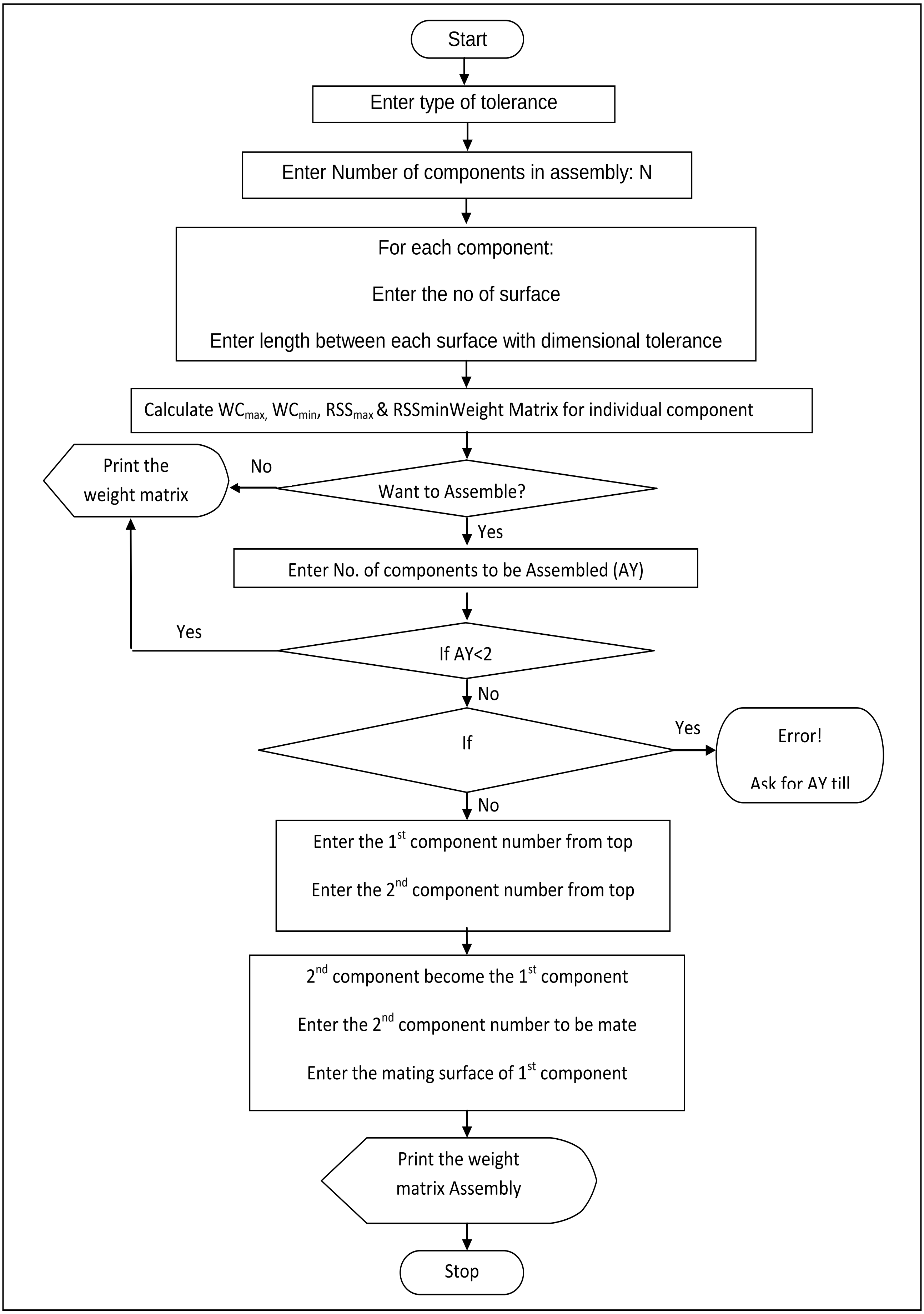

Fig. 11. Flow chart for tolerance stack up program

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