UNDERSTANDING TOLERANCE BUILD UP IN MECHANICAL PARTS AND ASSEMBLIES – AND DEALING WITH THEM - HISTORICAL AND MBD APPROACHES

WHITE PAPER

e2 Engineering experiences

Acceleration | Value | Technology

1. Abstract

For any product to be assembled in mass production, it is important that any component in the assembly fit with rest of the components regardless of the batch or source of production and meet the assembly and functional needs.

Variation is a law of nature and no component maintains the exact dimensions or features from one part to the next.

Tolerance analysis systematically attempts to predict this variation and attempts to build robustness in the component and assembly design by properly accounting for this variation.

This paper looks at the basics and types of variation, and how they add up to the total tolerance that a design needs to account for.

It also highlights the traditional methods of tolerance analysis and their drawbacks.

Finally, a new approach and tools for solid model-based analysis will be provided.

2. Variation

Variation is part of nature. No process repeats exactly over the course of time

- The variation can be in the time it takes to complete a task such as
  - o Driving to work from home

- Errors in completing a task such as
  - o Bags misplaced by airlines

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- Dimensions and features within a part in a production process

3. Types of Variations

Natural or random variation such as the time that it takes to get to work
- Normal variation in the wind speed and direction
- Slight variation in the exact path to work (driving on the far or near side of a bend in the road)
- Effect of other vehicles on the road (being stuck behind a slow-moving vehicle)
- Number of green and red lights at intersections
- Error in reading the elapsed time
    - Rounding off minutes in the departure and arrival time

Special Causes
    - Accident on the road
    - Snow or ice
    - Car trouble, driving slower because of low pressure in one of the tires

Dimensional Variations

In an ideal world, all the dimensions in all the parts within an assembly would be exactly nominal and the assemblies would fit perfectly all the time. See Figure 1. The nominal dimension is X.0. Every single part is exactly X.0.
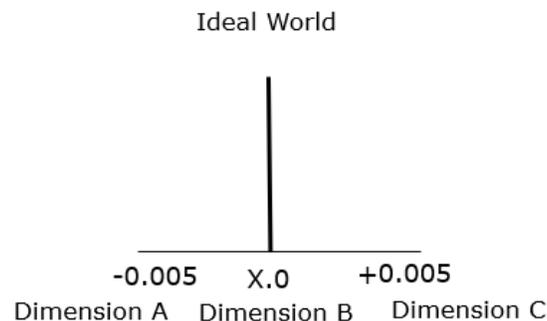

Figure 1

Figure 2 shows real world distributions. Mean represents the average of all dimensions, mode represents the one that occurs most of the time and median is the dimension that has 50% of the dimensions smaller than it and 50% larger than it. Figure 3 shows a bimodal

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distribution. This may be due parts coming from two different cavities in the same mold or two different machines or two different manufacturers. Ideally, the mean, mode and median dimensions should be coincident and the same as the designed nominal dimension.
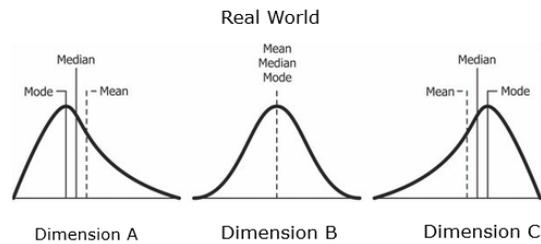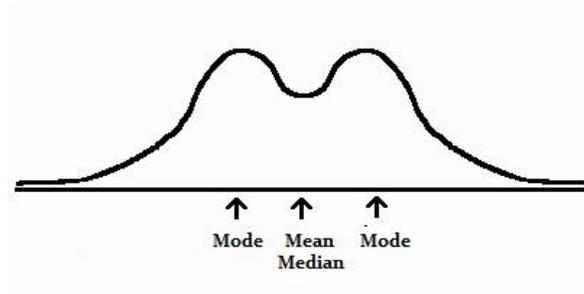

Figure 2

Figure 3

Make Up of the Total Tolerance
The following discussion lists the main causes of variation that make up the total tolerance.

Constant Factors

Initial Error

Tooling

Wrong initial dimensions in a metal stamping:

The distance between two piercing pins in a stamping die is 1.005 inches instead of 1.000 inches. The distance between the centers of the holes will be .005 inch longer – always!

Wrong spring back compensation in the die (See figure 4). The included angle therefore becomes 95 degree instead of 90 degrees. Dimension A (the center distance between the holes) will be A + y * tan 5 deg instead of the intended A - always!
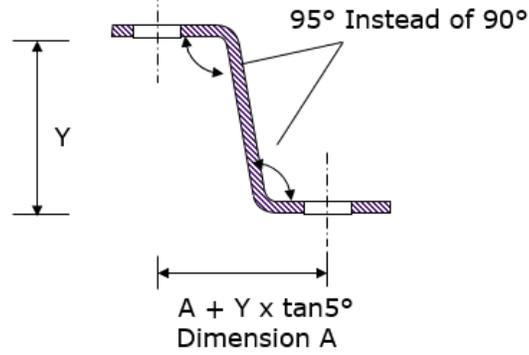
Figure 4

Wrong shrinkage factor – in a plastic part:

Wrong shrinkage is used for the resin - .008 inch/inch instead of .006 inch/inch. A 10-inch-long dimension will be .002 * 10 = .02 inch longer – always!

Tool Dependent Tolerance – Regardless of Age

Plastic Parts

These can be dimensions across parting lines. The mold may not close exactly the same every shot, especially if a piece of flash is caught between the halves. Dimension B may be B+.00x/-.000.

Dimensions created by moving parts
within one half of the tool may have the same kind of variation (see Figure 6). The lifter may not always be exactly at the same location relative to the inside surface or the snap every shot. Therefore, the snap dimension may be X -.000/+ .00x
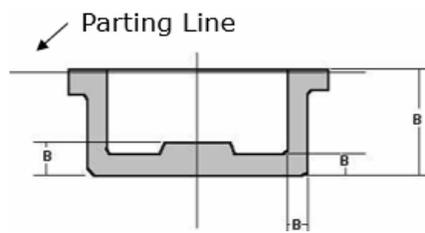

Figure 5
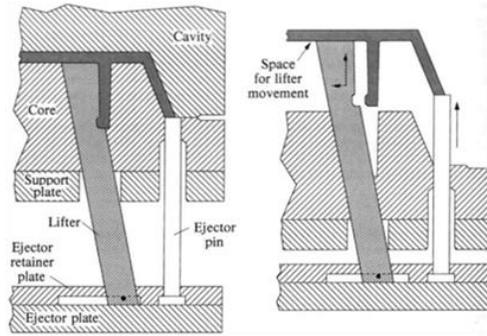
Figure 6[1]

Metal Stampings and Machining

The bottoming out of the punch may be too much or too little causing a deviation from the nominal angle and the related dimensions of the part. See Figure 7.
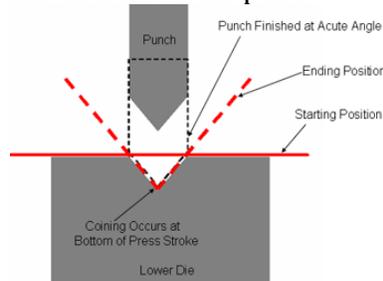

Figure 7[2]

The progression in a stamping die may vary from stroke to stroke due to the very minor clearance in diameter between the pilot hole and the pilot pins. See Figure 8.
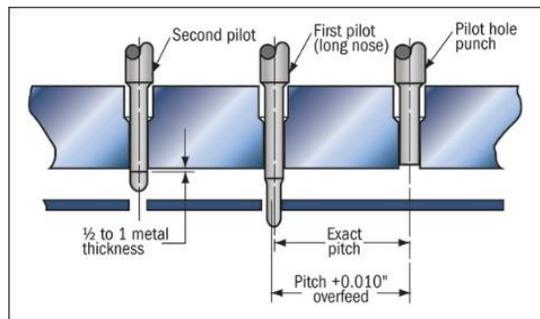

Figure 8[3]

Holding jigs and fixture may not always hold the part in the exact place due to slop or metal shavings. The dimensions of the machined features will therefore vary from part to part. See Figure 9.
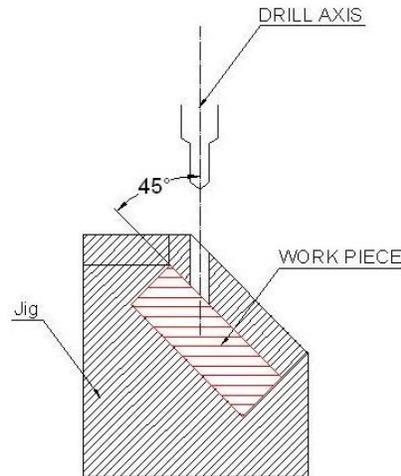
Figure 9[4]

Set Up

Almost all processes will have some variation in dimensions from setup to setup.

In the case of molded parts there may be variation in the pressure, temperature and time settings (more details later).

In the case of stampings, the down stroke depth may vary from setup to setup.

In the case of machining, the part placement, cutting tools and depth of cutting tools may vary.

Material Related

The dimensions will vary due to difference in the material properties from lot to lot.

Plastics

Shrinkage

Resins do not have the exact shrinkage from lot to lot.

Directional Shrinkage

The directional shrinkage can vary both from lot to lot and within a lot – as an example the density of glass concentration can vary from part to part and lot to lot resulting in variations in shrinkage and therefore the dimensions.
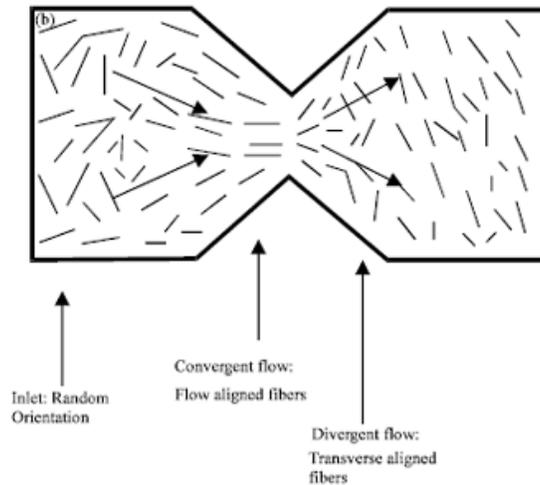
Figure 10[5]

Metals

Temper, Spring Back - the temper and therefore the spring back may vary slightly from lot to lot.

Temper, Distortion - parts that are heat treated or annealed after forming or machining may show uneven distortion such as in Beryllium Copper alloys during the post stamping heat treatment.

Material Thickness - the thickness variation in the metal strip may cause variations in spring back causing shifts both in angles and feature dimensions.

Design

Examples
Plastics

The most important rule in plastic parts is uniform wall thickness. Non-uniform wall thickness results in nonuniform and unexpected dimensional shrinkage leading to variations in dimensions and feature. Let us take a minute to understand why this happens by looking at Figure 11 and 12. Figure 11 shows a part that has half the thickness on the left as compared to the right. Figure 12 is an infra-red image of the temperature profile of the part as it comes out of the mold. The right has a lot more heat content and has a temperature of 238 deg F. The left with less heat content has a temperature of 118 deg F. The right continues to shrink for a lot longer time than the left. This uneven shrinkage causes distortion as seen in the bottom view and dimensional variation as seen in the arrows on the left and right.
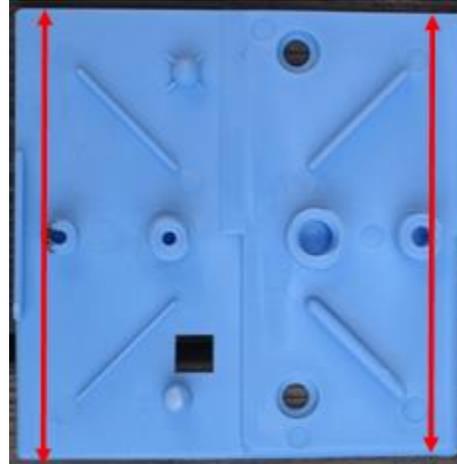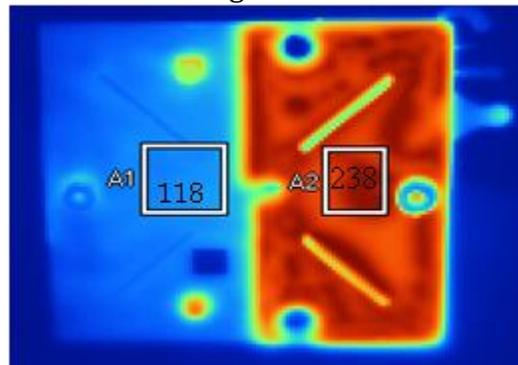
Figure 11

Figure 12[6,7]

Thin to Thick Flow – Hesitation

This is another example of unpredictable behavior in plastics. Figure 13 shows a thin area shown by the rectangle area surrounded by a thicker area. The thick area fills first. In the meantime, the plastic has cooled down and has a difficult time filling the thin area. This causes differential shrinkage in different areas in addition to other adverse effects.

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Figure 13[6]

Process Related Tolerance in Plastics – A Detailed look

Plastics are unique in the fact that even slight difference in processing conditions can have severe effects on the dimensional variations.

Here is quick summary of these processing conditions:

- Pressure, Temperature, Time, Humidity
  - Pressure
    - Injection Pressure
    - Holding Pressure
    - Back Pressure
- Temperature
  - Melt temperature
  - Coolant temperature and flow rate
  - Mold temperature
  - Drying temperature
- Time
  - Injection Time
  - Gate Freeze Time
  - Hold Time
  - Decompression
  - Drying Time
- Humidity
  - Dew point of drying air

Measurement Error:

Bad parts can pass for good and good parts can be rejected due to measurement errors. This can occur even with the best equipment and personnel.

These errors fall into two classes.

Reproducibility

- Two operators or two setups coming up with different readings

Repeatability

- Same operator or setup coming up with different readings.

4. Overall Tolerance

The overall tolerance, therefore, is the addition of all of the above
Or
TTotal = TMaterial + TDesign + TTooling + TSetup + TProcessing+ TMeasurement

5. Tolerance Stack Up Analysis, Importance and Benefits

Tolerance Analysis is auniversal term including two subcategories: methods used to determine the meaning of individual tolerance specifications and the process of determining the cumulative variation possible between two or more features. The second part of the definition is commonly called a tolerance stack up. Tolerance Stack Up Analysis provides a numerical answer to a tolerance accumulation question.

Typical questions include:
- Will these two surfaces touch in their worst-case? If so, how much will they interfere?
- Will the pin fit within the hole?
- How can we know if the worst-case assembly will satisfy its dimensional objectives?

Using vectors, create a "closed" loop diagram from the starting surface to the ending surface. Do not include gaps when selecting the path for the dimension loop. Each vector in the loop diagram represents a dimension.

Use an arrow to show the direction of each "vector" in the dimension loop. Identify each vector as positive (+), or negative (–), using the following convention.

For horizontal dimensions:
Use a + sign for dimensions followed from left to right.
Use a – sign for dimensions followed from right to left.
For vertical dimensions:
Use a + sign for dimensions followed from bottom to top.
Use a – sign for dimensions followed from top to bottom.
Assign a variable name to each dimension in the loop. (For example, the first dimension is assigned the variable name Hole 1, the second, Hole 2.)
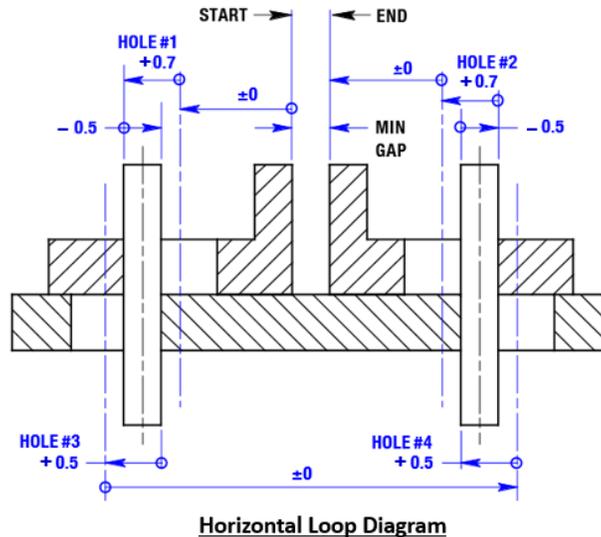
Figure 14

6. Methods of Tolerance Stack Up Analysis

To perform tolerance stack up analysis, there are two methods which are very common in the industry:
1. Worst Case
2. Root Sum Square (RSS)

Worst Case Method

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 simultaneously. The accumulated tolerance can be written as (ΔY)

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, the probability that all individual tolerances occur at their worst-case limits is low. However, this method can be used in designing fixtures and used for collision avoidance by robot's analysis.

Root Sum Square (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 may be overly optimistic and sometimes the number of rejections in the assembly is more than predicted. Total tolerance of assembly can be given as-

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

Where,
n = Number of constituent dimensions in the dimension chain
δi = Tolerance associated with the ith 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 the loop is sufficiently large

Let's implement these methods one by one by taking an example.

Calculations

- Worst Case Method

A worst-case tolerance analysis method is simple arithmetic (that's right... just addition and subtraction), so let's start there.

Say, we have an assembly of four thick plates like below:

Tolerance Stackup
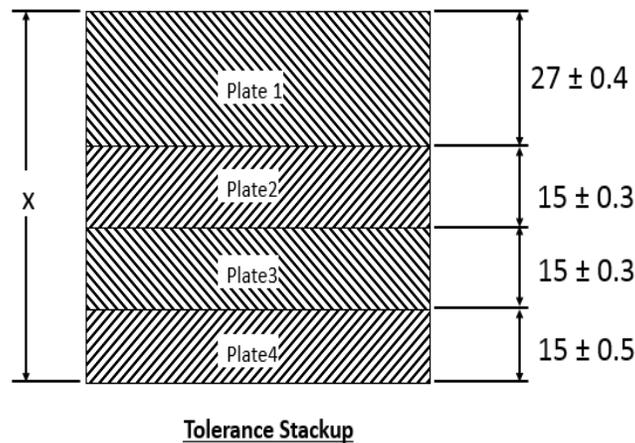
Figure 15

The thickness and tolerance of the four plates are shown in the above figure. We have to find out the dimension "X" and its tolerance value. Proceed as below:
- Calculate the lower specification limit (LSL)size for each of the plates like below:
  For Plate 1:
  LSL= 27-0.4 = 26.6
  For Plate 2:
  LSL= 15-0.3 = 14.7
  For Plate 3:
  LSL= 15-0.3 = 14.7
  For Plate 4:
  LSL= 15-0.5 = 14.5
- Sum up the LSL thickness values of all the plates, and you will get the LSL thickness of the whole assembly as below:
  TL = 26.6 +14.7 + 14.7 + 14.5 = 70.5
  (TL = Total LSL thickness values)
- Calculate the upper specification limit (USL)size for each of the plates like below:
  For Plate 1:
  USL= 27+0.4 = 27.4

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For Plate 2:
USL= 15+0.3 = 15.3
For Plate 3:
USL= 15+0.3 = 15.3
For Plate 4:
USL= 15+0.5 = 15.5

- Sum up the USL thickness values of all the plates, you will get the USL of the whole assembly as below:
  TU = 27.4 + 15.3 + 15.3 + 15.5 = 73.5
  (TU = Total USL thickness values)

- Tolerance of the whole assembly can obtained as:
  (TU – TL) / 2 = (73.5-70.5)/2 = 1.5

- Sum up the nominal thickness dimensions of all the plates to get the nominal thickness value of the whole assembly, like below:
  TN = 27 + 15 + 15 + 15 = 72

  (TN = Total Nominal)

So, by the worst-case method we got the overall dimension (X) of the assembly as:
$X = 72 \pm 1.5$

Assembly tolerance stack-up analysis is used for calculating the tolerance value of the overall assembly (or a gap in the assembly) from the tolerance values of the individual components. The worst-case method of the stack up analysis is the simplest.

- **RSS (Root Sum Square)**

1D RSS:

$$\sigma_{ASM} = \left(\sum_{i=1}^{n} \sigma_i^2 \right)^{\frac{1}{2}}$$

Distribution 1 + Distribution 2 = Stackup Distribution

σ_i = Standard deviation of the "ith" dimension

The root sum square (RSS) method works on a statistical approach. It assumes that all of the components have normal statistical distribution.
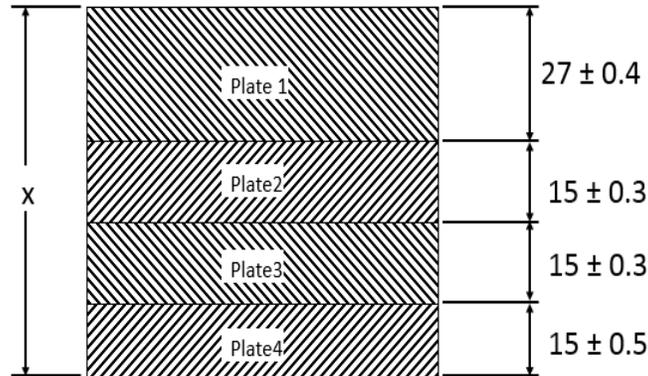
Tolerance Stackup

The aim of the assembly tolerance stacks up analysis is to find out the overall thickness (X) of the assembly with tolerance. We have the thickness and the tolerance values of all the plates (plate 1, 2, 3 and 4).

- Calculate the nominal thickness of the whole assembly as below:
  X = 15 + 15 + 15 + 27 = 72

- Find the Standard Deviation (σ) of each of the component tolerance as below:
  σ plate 1 = 0.4/3 = 0.133
  σ plate 2 = 0.3/3 = 0.1
  σ plate 3 = 0.3/3 = 0.1
  σ plate 4 = 0.5/3 = 0.167

- Find out the standard deviation of the tolerance zone of the assembly as shown below:
  σassembly = √ [(σplate1)^2 + (σplate 2)^2 + (σplate3)^2 + (σplate4)^2] = 0.256

- Find out the tolerance zone of the assembly like below:
  T = σassembly * 3 = 0.256*3 = 0.768

  So, the thickness dimension (X) with the tolerance zone of the assembly will be:
  X = 72 ± 0.768

The root sum square or RSS or statistical tolerance stack up method is useful for tolerance stack up analysis of an assembly having multiple components.

Traditional Methods of Tolerance Stack Analysis

Tolerance Stack Up Analysis has traditionally been performed manually either on paper/whiteboard or on spreadsheets. Sometimes the analysis is not even performed and left to the designers' experience and intuition.

The most commonly used tool is the spreadsheet and needs creation of templates according to assembly requirement. These templates manage all the product requirements based on all the dimensions and tolerances. The user manually inputs these dimensions and tolerances into the spreadsheet template reading from 2D drawings. With the updates in model, spreadsheets must be updated manually. This complete process requires specialized skills and an in-depth knowledge of tolerance analysis and Geometric Dimensioning and Tolerancing (GD&T) concepts. Also, it is tedious, time consuming and error prone due to manual intervention.

7. Tolerance Stack Up Analysis: A Model Based Definition (MBD) Oriented Approach

Most of the companies today are moving towards an MBD environment by having Product Manufacturing Information on the model itself with a few specific details on drawings. MBD environment doesn't mean no paper drawings at all rather it defines model as the controlling element for design with few specifically required information on drawings. Information like dimensional tolerances, GD&T on the model surfaces, material to be used etc. is stored in model itself. It does maintain the associativity of model with this information. For example, GD&T information defined to a specific surface or tolerances are linked to the features.
Hence, MBD comes with every information required to automate a Tolerance Stack-Up Analysis which is a tedious and time-consuming task companies struggles with.

8. How Geometric Stackup^{TM} leverages MBD

Geometric Stackup provides a simple solution to perform tolerance stack-up analysis on complex assemblies that contain complete PMI (Product and Manufacturing Information) such as dimensional tolerances and GD&T with unprecedented ease, speed and accuracy – reducing tolerance stack up calculation time from hours to minutes. It enables users to perform Tolerance Stack Up Analysis directly on the 3D models capturing tolerances directly from the model if provided during design or from the standard databases like ISO 2768, ASME or industry specific tolerances defined within the software.

Geometric Stackup supports Worst case and Statistical analysis for the calculation. Worst-case analysis evaluates the maximum of dimensions and tolerances to calculate the maximum and minimum distance between two features or parts. Statistical tolerance stack-ups evaluate the maximum and minimum values based on mathematical calculation combined with some method for establishing likelihood of obtaining the maximum and minimum values, such as Root Sum Square (RSS)/Root Mean Square (RMS) available up to 6 sigma deviation. It allows the user to incorporate GD&T and Assembly shift for performing precise Tolerance Stack-Up Analysis.

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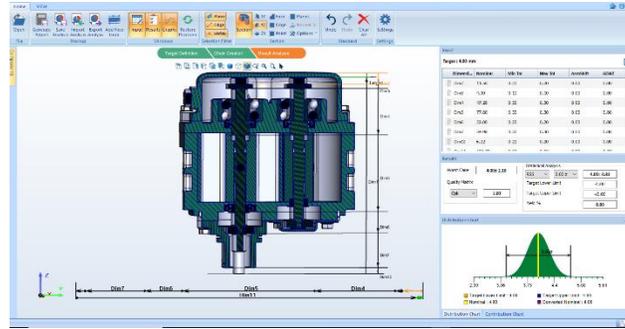
Geometric Stackup
Figure 17

To achieve the desired results, the user can look at the contribution of all the dimensions towards tolerances and edit the dimensions causing more variation to achieve the maximum yield. The figure 18 and 19 shows how a user simulated the tolerances in Dim 11 to achieve the maximum yield.
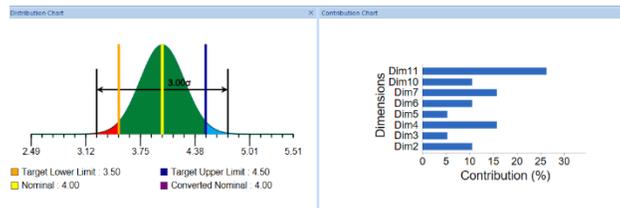
Figure 18
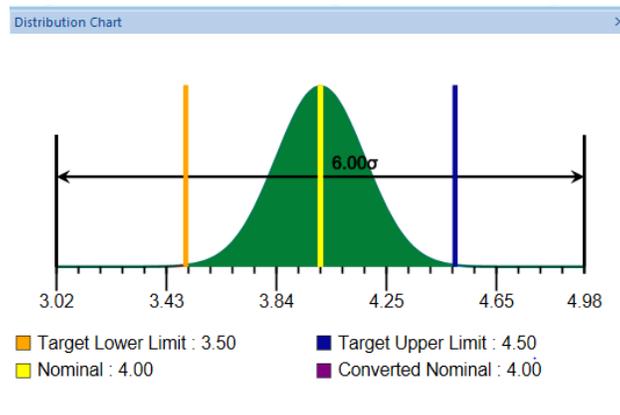
Figure 19

It is also important to understand the relationship of the cost to adjusting the tolerances. Tightening the tolerances may result in an unjustifiable increase of the manufacturing cost

It clearly shows the benefit of using Geometric Stackup over the traditional spreadsheets to perform Tolerance Stack Up Analysis. Interacting directly with 3D model while performing the analysis also helps the designer understand the design more thoroughly.

9. Conclusion

From rivets and bolts, to seats and engines, an Airbus 380 is made up of about four million individual parts produced by 1,500 companies from 30 countries around the world. All these components must fit exactly right in every plane, every time. If they do not, the results can be catastrophic!

While most engineers are not designing a 380, they ARE dealing with a very competitive pressure cooker like environment of breakneck speed, efficiency, robustness and cost.

Components for an assembly are being produced all over the globe and assembled in multiple locations.

If that is not enough, these components are also being designed in various locations by engineers who do not have the same level of skill or discipline.

This requires that the tolerance analysis on these components need to have reproducibility, repeatability, accuracy, speed, and optimization that leads to the most robust, speedy and cost-effective design.

This leads to a two-step process.

One, have a thorough understanding of why the variation occurs in the first place.

Two, use standardized tools and the solid model of the assembly which every engineer around the world shares to conduct the complex tolerance analysis and optimization.

Geometric Stackup is THE answer to the latter.

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10.   Authors

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Vikram is a Fellow of the Society of Plastics Engineers and past Chairman of its Product Design and Development Division. He retired as the Director of Mechanical Engineering Services at Motorola Solutions in Holtsville, NY where he set up and headed an international group of professionals, state of the part simulation capabilities and training programs that were key contributors to improving the robustness of Motorola products. He has over 40 years of experience in product design, development, manufacturing and management, especially in plastics.

He is a sought after trainer and has trained thousands of engineers and suppliers in the proper design and manufacturing of plastic parts and assemblies in the US, China, Taiwan, Canada and India. He is a certified Six Sigma Black Belt and has led or mentored numerous projects resulting millions of dollars in savings. He holds or has pending over 21 US and International patents.

He is the author of "Robust Plastic Product Design - A Holistic Approach", Hanser Publications, Germany

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11. References

(1) Courtesy http://www.gotstogo.com/misc/engineering_info/snap_design.htm

(2) http://www.thefabricator.com/article/stamping/die-basics-101-part-xv

(3)http://www.metalformingmagazine.com/magazine/article.asp?iid=95&aid=7871

(4) http://www.brighthubengineering.com/machine-design/47444-jigs-vs-fixtures/#imgn_0

(5) http://scialert.net

(6) Robust Plastic Product Design: A Holistic Approach, Hanser Publications -Vikram Bhargava

(7) Photo Courtesy John Bozelli

(8) http://www.brighthubengineering.com/machine-design/56403-assembly-tolerance-stack-up-analysis-using-the-rss-method/

(9) https://www.tolerancestackup.com

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