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Tolerance Allocation and Analysis of Precision Aerospace Components

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Abstract: Tolerancing plays a vital role in design process. For aerospace components, any deviation beyond allowable limit can result in catastrophic failure.In this work, toleranceanalysis is performed to address axis misalignment due to tolerance stacking in flight vehicle components and allocation of optimal tolerances for minimum cost obtained using DFM analysis.

Keywords–Geometric Dimensioning &Tolerancing (GD&T), Tolerance Allocation,Tolerance Analysis (TA), Worst-case TA, Statistical TA,Design For Manufacture (DFM).

I. Introduction

Tolerance design is a subject of key importance to precision aerospace assemblies with a view for interchangeability.Tolerance analysis assists the designer to realize whether the assigned tolerances are accurate in fulfilling functional requirementsor there is need to modify them. Tolerance analysis is used in various fields and some researchers used traditional models while others have developed new models overcoming the drawbacks of the traditional ones.

Sangmun Shin et al. (2010) [1] proposed an integrated optimization schemeto determine both the optimalsettings of the process parameters and the optimal tolerance simultaneously by using the Lambert W function and verified with numerical examples.**NadeemShafi Khan (2011)[2]**presented a new 3D model for tolerance transfer in manufacturing process planning in that it is built upon the Coordinate Measuring Machine (CMM) readings using graph theoretic approach for the statistical tolerance analysis.**Mansuy et al. (2011) [3]** entailed a tolerancing process where functional conditions are decomposed into specifications based on standards/qualitative synthesis, and calculation of tolerances to minimize manufacturing cost expressed as a function of tolerances.**Kuo-Ming Cheng and Jhy-Cherng Tsai (2013) [4]** investigated a method for optimal statistical tolerance allocation with a reciprocal exponential cost–tolerance functionto minimize manufacturing cost subject to constraints on tolerance target and machining capabilities illustrating an example.**Shao-Gang Liu et al. (2013) [5]** focused on application ofanalytical methods to solve tolerance optimization model, including both manufacturing cost and quality loss withassembly tolerance constraint and process accuracy constraints.**LoïcAndolfattoet al. (2014) [6]** addressed assembly technique selection and allocation of geometrical tolerancesby solving a multi-objective optimization problem to minimize the cost associated with activity and geometric tolerance and the non-conformity associated with the assembly planon a case study.**Sahani et al. (2014) [7]** presented a methodology for systematic solution of tolerance stackup for angularityinvolving geometrical characteristicsusing graphical approach.

Substantial work was carried out by researchers for tolerance optimization with cost consideration using different methods.In the present work,allocation of appropriate tolerancesto the components/sections/shellsof the flight vehicle is carried out followed by tolerance analysis to deal with the issue of thrust axis misalignment that can arise due to stackup of geometric tolerances provided on the components, resulting in increase in body rates and consequentialrollingof the vehicle during operation of the flight, which is detrimental for achieving the flight mission. Tolerances are allocated in such a way to counter this effect and also to meet the functional requirements. Owing to tightening of tolerances, the analysis results are well within the limits, leaving a scope for relaxing them a little bit. As the cost of manufacturing the flight vehicles is high, it is considered to have an initial estimate of the cost by DFM analysis. As tighter tolerances can lead to higher cost, an attempt is made to optimize the tolerance values taking manufacturing cost as a criterion.

II. Material and Methodology

Much of the contribution for the tolerance stackup in the vehicleis attributed to the coaxiality tolerances and the perpendicularity tolerances provided on the interfacing features of mating components, resulting in angular and lateral shift of the longitudinal axis of the vehicle from one end to the other, causing angular shift of the geometric axis from its theoretically exact location. In order to estimate the possible axis shift, 3D CAD model of the flight vehicle components is made in Pro-E Wildfire 4.0, as shown in figure 1 and analyzed forangular variation/shift ofgeometric axis due to tolerance stacking from one end of the vehicle to the other,as shown schematically in figure 2,using CETOL 6σ Ver. 8.1 software.The maximum and minimum deviations areobtained for Worst-case and Statistical methods. The cost of manufacturing the components is estimated using DFM Concurrent Costing module Ver. 2.4 of DFMA BDI (Boothroyd and Dewhurst Inc.) software. Optimization of the tolerance values for the components of the flight vehicle for minimum total cost of manufacturing is performed using MATLAB 2015b toolbox. The objective of this work is

i. To find the maximum angular variation that might occur after assembly of all the components.

ii. To analyze if this variation is within design specifications and if it is not, then to modify the tolerances to restrict the variation.
iii. To find optimal tolerance values for minimum cost of manufacturing.

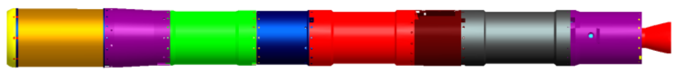


Figure 1 3D CAD Model of Flight Vehicle

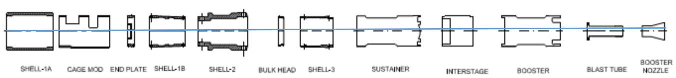


Figure 2 Schematic of Axis Misalignment

The CETol model is created by synchronizing the CETolAnalyzerand the 3D CAD modelallowing selection ofcontributing 3D features of componentsdirectly from Pro-E.Then the tolerances for the selected features are specified and the datums identified. The joints between one component and the other areprovided based on their relative location, orientation and Degrees of freedom. The assembly is checked for any under-constraints or over-constraints. The 'Measure' here is the angular shift between the geometric axes of the first component and the last component in the sequence of assembly,capturing the accumulated variation. The procedure used in CETol software is illustrated infigure 3 and the graph tree of the assembly along with the joints and the Measureare shown in figure 4.Results are provided in Sec. III.

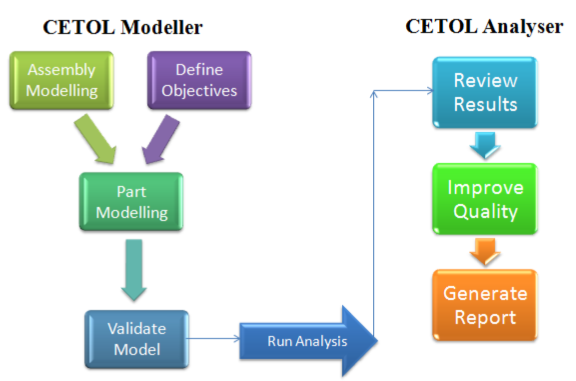


Figure 3CETol Procedure for Tolerance Analysis

The manufacturing cost is estimated by considering material cost, processing cost, rejects etc. using DFM module. The figure 5shows the GUI of the software and figure6 shows the bar chart ofvariousestimated costs involved in manufacturing for the first five components of the flight vehicle (the tool can provide comparison for five components at a time).

According to G Prabhaharanet al. [9], the cost equation is taken as,

$$C(t) = A + \frac{B}{t^2} \dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

where,

A: typical fixed cost (per part) in the manufacturing process,
B: cost of making a single part or component,
t: tolerance values provided on components.

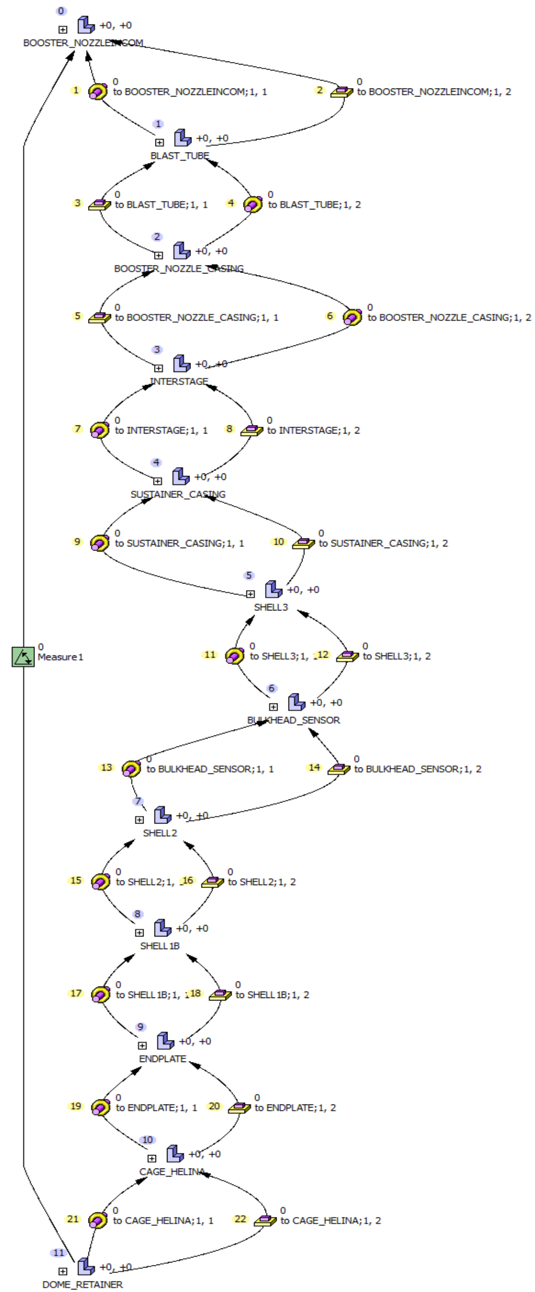


Figure 4 Graph tree showing assembly in CETol

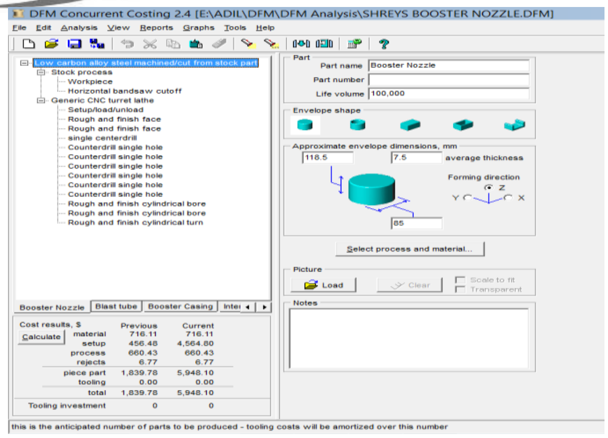


Figure 5GUI of DFM Concurrent Costing 2.4 Module

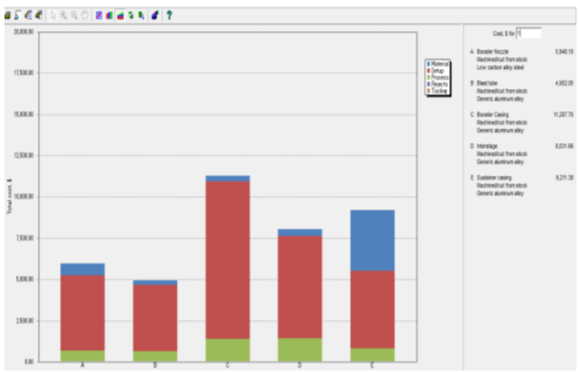


Figure 6Bar Chart for first five components

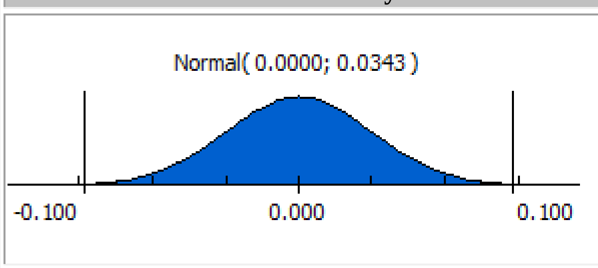
III. Results and Tables

The results of tolerance analysis using CETol software for Worst case and Statistical methods are shown in Table 1.

Table 1 Tolerance Analysis Results using CETol Software

Measurement Type:	ANGULAR	**Tolerance Type:**	SYMMETRIC

Derivative-Based Statistical Analysis

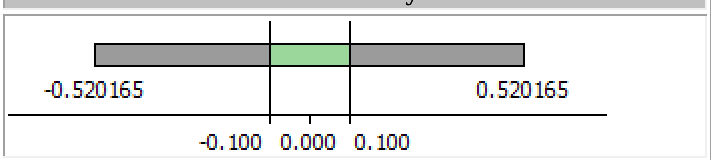


Sigma = 2.91
Percent Yield = 99.64%
DPMU = 3,561.51

Variable:	**Contribution: (>= 1%)**	**Sensitivity:**	**Parent Tolerance:**
ASM0001 / BLAST_TUBE;1 / BLAST_TUBE / Feature5 / to Feature1 / RX	13.90%	1.00000000 deg/deg	PER | 0.050 | Feature1 |
ASM0001 / BOOSTER_NOZZLEINCOM;1 / BOOSTER_NOZZLEINCOM / Feature3 / to Feature1 / RX	13.05%	1.00000000 deg/deg	PER | 0.050 | Feature1 |
ASM0001 / SUSTAINER_CASING;1 / SUSTAINER_CASING / Feature3 / to Feature1 / RZ	4.70%	0.92387953 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / INTERSTAGE;1 / INTERSTAGE / Feature2 / to Feature1 / RZ	4.64%	0.92387953 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / INTERSTAGE;1 / INTERSTAGE / Feature3 / to Feature1 / RZ	4.64%	0.92387953 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / BOOSTER_NOZZLE_CASING;1 / BOOSTER_NOZZLE_CASING / Feature4 / to Feature1 / RZ	4.64%	0.92387953 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / SUSTAINER_CASING;1 / SUSTAINER_CASING / Feature4 / to Feature1 / RZ	4.63%	0.92387953 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / BLAST_TUBE;1 / BLAST_TUBE / Feature3 / to Feature1 / RX	4.19%	1.00000000 deg/deg	PER | 0.050 | Feature1 |
ASM0001 / BOOSTER_NOZZLE_CASING;1 / BOOSTER_NOZZLE_CASING / Feature2 / to Feature1 / RZ	3.57%	0.92387953 deg/deg	PER | 0.050 | Feature1 |
ASM0001 / SHELL2;1 / SHELL2 / Feature3 / to Feature1 / RX	2.79%	-0.70710679 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / SHELL1B;1 / SHELL1B / Feature3 / to Feature1 / RX	2.79%	0.70710679 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / SHELL2;1 / SHELL2 / Feature4 / to Feature1 / RX	2.79%	-0.70710679 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / SHELL1B;1 / SHELL1B / Feature3 / to Feature1 / RZ	2.79%	-0.70710679 deg/deg	PER | 0.100 | Feature1 |

ASM0001 / SHELL2;1 / SHELL2 / Feature3 / to Feature1 / RZ	2.78%	-0.70710679 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / SHELL2;1 / SHELL2 / Feature4 / to Feature1 / RZ	2.78%	-0.70710679 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / CAGE;1 / CAGE / Feature4 / to Feature1 / RX	2.75%	0.70710679 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / CAGE;1 / CAGE / Feature4 / to Feature1 / RZ	2.75%	0.70710679 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / CAGE;1 / CAGE / Feature3 / to Feature1 / RX	2.62%	0.70710679 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / CAGE;1 / CAGE / Feature3 / to Feature1 / RZ	2.61%	0.70710679 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / SHELL1B;1 / SHELL1B / Feature4 / to Feature1 / RX	2.40%	0.70710679 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / DOME_RETAINER;1 / DOME_RETAINER / Feature2 / to Feature1 / RX	2.40%	0.70710679 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / DOME_RETAINER;1 / DOME_RETAINER / Feature2 / to Feature1 / RZ	2.40%	0.70710679 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / SHELL1B;1 / SHELL1B / Feature4 / to Feature1 / RZ	2.40%	-0.70710679 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / INTERSTAGE;1 / INTERSTAGE / Feature3 / to Feature1 / RX	1.03%	0.38268343 deg/deg	PER | 0.100 | Feature1 |

Derivative-Based Worst-Case Analysis



Variable:	**Contributi on:**	**Sensitivi ty:**	**Parent Toleran ce:**
ASM0001 / BLAST_TUBE;1 / BLAST_TUBE / Feature5 / to Feature1 / RX	11.15%	1.00000000 deg/deg	PER | 0.050 | Feature1 |
ASM0001 / BOOSTER_NOZZLEINCOM;1 / BOOSTER_NOZZLEINCOM / Feature3 / to Feature1 / RX	10.80%	1.00000000 deg/deg	PER | 0.050 | Feature1 |
ASM0001 / SUSTAINER_CASING;1 / SUSTAINER_CASING / Feature3 / to Feature1 / RZ	6.48%	0.92387953 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / INTERSTAGE;1 / INTERSTAGE / Feature2 / to Feature1 / RZ	6.44%	0.92387953 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / INTERSTAGE;1 / INTERSTAGE / Feature3 / to Feature1 / RZ	6.44%	0.92387953 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / BOOSTER_NOZZLE_CASING;1 / BOOSTER_NOZZLE_CASING / Feature4 / to Feature1 / RZ	6.44%	0.92387953 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / SUSTAINER_CASING;1 / SUSTAINER_CASING / Feature4 / to Feature1 / RZ	6.44%	0.92387953 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / BLAST_TUBE;1 / BLAST_TUBE / Feature3 / to Feature1 / RX	6.12%	1.00000000 deg/deg	PER | 0.050 | Feature1 |
ASM0001 / BOOSTER_NOZZLE_CASING;1 / BOOSTER_NOZZLE_CASING / Feature2 / to Feature1 / RZ	5.65%	0.92387953 deg/deg	PER | 0.050 | Feature1 |
ASM0001 / SHELL2;1 / SHELL2 / Feature3 / to Feature1 / RX	4.99%	-0.70710679 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / SHELL2;1 / SHELL2 / Feature4 / to Feature1 / RX	4.99%	-0.70710679 deg/deg	PER | 0.100 | Feature1 |

ASM0001 / SHELL1B;1 / SHELL1B / Feature3 / to Feature1 / RX	4.99%	0.707106 79 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / CAGE;1 / CAGE / Feature4 / to Feature1 / RX	4.96%	0.707106 79 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / CAGE;1 / CAGE / Feature3 / to Feature1 / RX	4.84%	0.707106 79 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / SHELL1B;1 / SHELL1B / Feature4 / to Feature1 / RX	4.64%	0.707106 79 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / DOME_RETAINER;1 / DOME_RETAINER / Feature2 / to Feature1 / RX	4.64%	0.707106 79 deg/deg	PER | 0.100 | Feature1 |

Variable:	**Angular Sensitivity: (Top 5 variables)**	
ASM0001 / BOOSTER_NOZZLEINCOM;1 / BOOSTER_NOZZLEINCOM / Feature3 / to Feature1 / RX	1.00000000	
ASM0001 / BLAST_TUBE;1 / BLAST_TUBE / Feature3 / to Feature1 / RX	1.00000000	
ASM0001 / BLAST_TUBE;1 / BLAST_TUBE / Feature5 / to Feature1 / RX	1.00000000	
ASM0001 / BOOSTER_NOZZLE_CASING;1 / BOOSTER_NOZZLE_CASING / Feature2 / to Feature1 / RZ	0.92387953	
ASM0001 / BOOSTER_NOZZLE_CASING;1 / BOOSTER_NOZZLE_CASING / Feature4 / to Feature1 / RZ	0.92387953	

The estimated cost of all the components in terms of A & B individually obtained using DFM Concurrent Costing 2.4 is given in Table 2.

Table 2 Cost estimated using DFM Concurrent Costing 2.4

Sl. No.	Component Nomenclature	Cost in INR	
		A	B
1	Booster Nozzle	5288	660
2	Blast tube	4306	646
3	Booster Casing	9906	1382
4	Interstage	6610	1423
5	Sustainer Casing	8400	812
6	Shell 3	7402	489
7	Bulkhead	5018	202
8	Shell 2	7705	676
9	Shell 1B	8483	689
10	End Plate	6301	275
11	Cage	9160	863
12	Dome Retainer	5100	220

Due to the stringent tolerances provided, the angular shift values obtained byCETol software are well within the design limits of ±1˚,indicating that there is a scope of relaxing them to reduce manufacturing costs. Hence, optimization is required to be performed to minimize the cost.

From the equation (1), the objective function to be minimized is the total cost of manufacturing subject to the constraints that the total permissible angular shift is limited to 0.7˚. The assumption here is that the machines used for manufacturing have accuracy to obtain minimum tolerance of 0.05 mm. Matlab toolbox is used for optimizing the cost function subjected to these constraints.Figure 7gives the optimal tolerance values for all the components obtained by optimization.

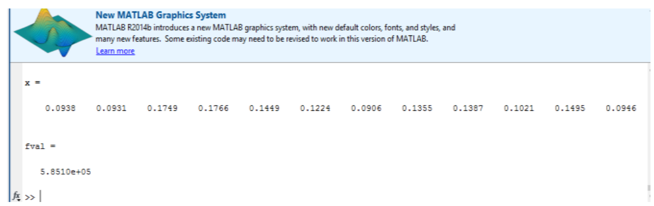


Figure 7Optimal tolerance values obtained from Matlab

In figure 7, the matrix ‘x’ gives the values of the tolerances for all the components in the order of their assembly sequence. The function ‘fval’ indicates the minimum cost of manufacturing for the optimal tolerance values subjected to constraints. For comparison purpose, the initial and the optimal tolerance values of the components are tabulated in table 3. The results also show a reduction in estimated cost of around 44%.

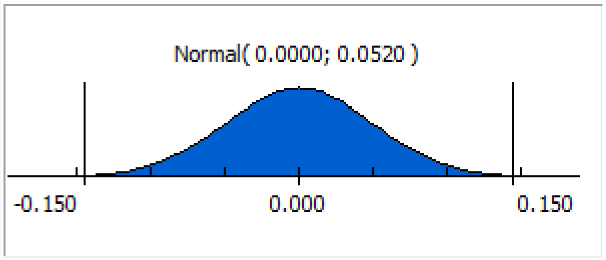
Table 3 Tolerance Values – Initial and Optimal

Sl. No.	Component Nomenclature	Tolerance values in mm	
		Initial	Optimal (rounded)
1	Booster Nozzle	0.05	0.09
2	Blast tube	0.05	0.09
3	Booster Casing	0.10	0.18
4	Interstage	0.10	0.18
5	Sustainer Casing	0.10	0.15
6	Shell 3	0.10	0.12
7	Bulkhead	0.10	0.09
8	Shell 2	0.10	0.14
9	Shell 1B	0.10	0.14
10	End Plate	0.10	0.10
11	Cage	0.10	0.15
12	Dome Retainer	0.10	0.10

Once again, the angular shift is estimated using CETOL tool with these optimaltolerance values, rounded to two decimals,and the results are provided in Table 4.The maximum angular shift estimated with the optimal tolerance values is ± 0.73˚, which is within the allowable limits.

Table 4 Tolerance Analysis Results withOptimal Tolerance Values using CETol Software

Measurement Type:	ANGULAR	**Tolerance Type:**	SYMMETRIC
Derivative-Based Statistical Analysis			



Sigma = 2.89
Percent Yield = 99.61%
DPMU = 3,892.84

Variable:	**Contribution: (>= 1%)**	**Sensitivity:**	**Parent Tolerance:**
ASM0001 / BOOSTER_NOZZLE_CASING;1 / BOOSTER_NOZZLE_CASING / Feature2 / to Feature1 / RZ	19.80%	0.92387953 deg/deg	PER | 0.1784 | Feature1 |
ASM0001 / BOOSTER_NOZZLEINCOM;1 / BOOSTER_NOZZLEINCOM / Feature3 / to Feature1 / RX	11.99%	1.00000000 deg/deg	PER | 0.0726 | Feature1 |
ASM0001 / BLAST_TUBE;1 / BLAST_TUBE / Feature5 / to Feature1 / RX	11.48%	1.00000000 deg/deg	PER | 0.0688 | Feature1 |
ASM0001 / CAGE;1 / CAGE / Feature4 / to Feature1 / RX	5.97%	0.70710679 deg/deg	PER | 0.2230 | Feature1 |
ASM0001 / CAGE;1 / CAGE / Feature4 / to Feature1 / RZ	5.96%	0.70710679 deg/deg	PER | 0.2230 | Feature1 |
ASM0001 / CAGE;1 / CAGE / Feature3 / to Feature1 / RX	5.68%	0.70710679 deg/deg	PER | 0.2230 | Feature1 |
ASM0001 / CAGE;1 / CAGE / Feature3 / to Feature1 / RZ	5.67%	0.70710679 deg/deg	PER | 0.2230 | Feature1 |
ASM0001 / BLAST_TUBE;1 / BLAST_TUBE / Feature3 / to Feature1 / RX	3.46%	1.00000000 deg/deg	PER | 0.0688 | Feature1 |
ASM0001 / BOOSTER_NOZZLE_CASING;1 / BOOSTER_NOZZLE_CASING / Feature2 / to Feature1 / RX	3.41%	0.38268343 deg/deg	PER | 0.1784 | Feature1 |
ASM0001 / INTERSTAGE;1 / INTERSTAGE / Feature2 / to Feature1 / RZ	2.59%	0.92387953 deg/deg	PER | 0.1131 | Feature1 |
ASM0001 / INTERSTAGE;1 / INTERSTAGE / Feature3 / to Feature1 / RZ	2.59%	0.92387953 deg/deg	PER | 0.1131 | Feature1 |
ASM0001 / SUSTAINER_CASING;1 / SUSTAINER_CASING / Feature3 / to Feature1 / RZ	2.11%	0.92387953 deg/deg	PER | 0.1015 | Feature1 |
ASM0001 / BOOSTER_NOZZLE_CASING;1 / BOOSTER_NOZZLE_CASING / Feature4 / to Feature1 / RZ	2.02%	0.92387953 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / SUSTAINER_CASING;1 / SUSTAINER_CASING / Feature4 / to Feature1 / RZ	2.02%	0.92387953 deg/deg	PER | 0.100 | Feature1 |
ASM0001 / SHELL2;1 / SHELL2 / Feature4 / to Feature1 / RX	1.84%	-0.70710679 deg/deg	PER | 0.1230 | Feature1 |
ASM0001 / SHELL2;1 / SHELL2 / Feature3 / to Feature1 / RX	1.84%	-0.70710679 deg/deg	PER | 0.1230 | Feature1 |
ASM0001 / SHELL2;1 / SHELL2 / Feature3 / to Feature1 / RZ	1.84%	-0.70710679 deg/deg	PER | 0.1230 | Feature1 |
ASM0001 / SHELL2;1 / SHELL2 / Feature4 / to Feature1 / RZ	1.84%	-0.70710679 deg/deg	PER | 0.1230 | Feature1 |
ASM0001 /	1.24%	0.707106	PER |

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<table>
<tr><td>DOME_RETAINER;1 / DOME_RETAINER / Feature2 / to Feature1 / RX</td><td></td><td>79 deg/deg</td><td>0.1088 | Feature1 |</td></tr>
<tr><td>ASM0001 / DOME_RETAINER;1 / DOME_RETAINER / Feature2 / to Feature1 / RZ</td><td>1.24%</td><td>0.707106 79 deg/deg</td><td>PER | 0.1088 | Feature1 |</td></tr>
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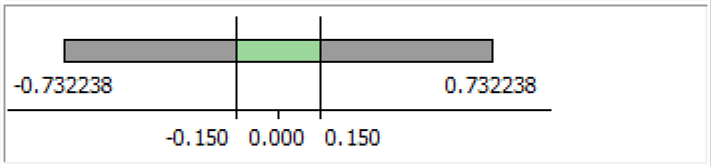
Derivative-Based Worst-Case Analysis



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<tr><th>Variable:</th><th>Contribution:</th><th>Sensitivity:</th><th>Parent Tolerance:</th></tr>
<tr><td>ASM0001 / BOOSTER_NOZZLE_CASING;1 / BOOSTER_NOZZLE_CASING / Feature2 / to Feature1 / RZ</td><td>14.31%</td><td>0.923879 53 deg/deg</td><td>PER | 0.1784 | Feature1 |</td></tr>
<tr><td>ASM0001 / BOOSTER_NOZZLEINCOM;1 / BOOSTER_NOZZLEINCOM / Feature3 / to Feature1 / RX</td><td>11.14%</td><td>1.000000 00 deg/deg</td><td>PER | 0.0726 | Feature1 |</td></tr>
<tr><td>ASM0001 / BLAST_TUBE;1 / BLAST_TUBE / Feature5 / to Feature1 / RX</td><td>10.90%</td><td>1.000000 00 deg/deg</td><td>PER | 0.0688 | Feature1 |</td></tr>
<tr><td>ASM0001 / CAGE;1 / CAGE/ Feature4 / to Feature1 / RX</td><td>7.86%</td><td>0.707106 79 deg/deg</td><td>PER | 0.2230 | Feature1 |</td></tr>
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<tr><td>ASM0001 / INTERSTAGE;1 / INTERSTAGE / Feature3 / to Feature1 / RZ</td><td>5.17%</td><td>0.923879 53 deg/deg</td><td>PER | 0.1131 | Feature1 |</td></tr>
<tr><td>ASM0001 / SUSTAINER_CASING;1 / SUSTAINER_CASING / Feature3 / to Feature1 / RZ</td><td>4.67%</td><td>0.923879 53 deg/deg</td><td>PER | 0.1015 | Feature1 |</td></tr>
<tr><td>ASM0001 / BOOSTER_NOZZLE_CASING;1 / BOOSTER_NOZZLE_CASING / Feature4 / to Feature1 / RZ</td><td>4.57%</td><td>0.923879 53 deg/deg</td><td>PER | 0.100 | Feature1 |</td></tr>
<tr><td>ASM0001 / SUSTAINER_CASING;1 / SUSTAINER_CASING / Feature4 / to Feature1 / RZ</td><td>4.57%</td><td>0.923879 53 deg/deg</td><td>PER | 0.100 | Feature1 |</td></tr>
<tr><td>ASM0001 / SHELL2;1 / SHELL2 / Feature3 / to Feature1 / RX</td><td>4.36%</td><td>-0.707106 79 deg/deg</td><td>PER | 0.1230 | Feature1 |</td></tr>
<tr><td>ASM0001 / SHELL2;1 / SHELL2 / Feature4 / to Feature1 / RX</td><td>4.36%</td><td>-0.707106 79 deg/deg</td><td>PER | 0.1230 | Feature1 |</td></tr>
<tr><td>ASM0001 / DOME_RETAINER;1 / DOME_RETAINER / Feature2 / to Feature1 / RX</td><td>3.58%</td><td>0.707106 79 deg/deg</td><td>PER | 0.1088 | Feature1 |</td></tr>
<tr><td>ASM0001 / SHELL1B;1 / SHELL1B / Feature3 / to Feature1 / RX</td><td>3.55%</td><td>0.707106 79 deg/deg</td><td>PER | 0.100 | Feature1 |</td></tr>
<tr><td>ASM0001 / SHELL1B;1 / SHELL1B / Feature4 / to Feature1 / RX</td><td>2.12%</td><td>0.707106 79 deg/deg</td><td>PER | 0.0645 | Feature1 |</td></tr>
</table>

Variable:	Angular Sensitivity: (Top 5 variables)	
ASM0001 / BOOSTER_NOZZLEINCOM;1 / BOOSTER_NOZZLEINCOM / Feature3 / to Feature1 / RX	1.00000000	
ASM0001 / BLAST_TUBE;1 / BLAST_TUBE / Feature3 / to	1.00000000	

Feature1 / RX		
ASM0001 / BLAST_TUBE;1 / BLAST_TUBE / Feature5 / to Feature1 / RX	1.00000000	
ASM0001 / BOOSTER_NOZZLE_CASING;1 / BOOSTER_NOZZLE_CASING / Feature2 / to Feature1 / RZ	0.92387953	
ASM0001 / BOOSTER_NOZZLE_CASING;1 / BOOSTER_NOZZLE_CASING / Feature4 / to Feature1 / RZ	0.92387953	

IV. Conclusion

The flight vehicle assembly is analyzed for total angular shift due to the geometric tolerances on the components by performing tolerance analysis. Optimal tolerance values are obtained for minimum estimated manufacturing cost. Tolerance analysis results obtained using the optimum tolerance values indicate that the angular shift is within allowable limits.

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