PROBABILISTIC APPROACH AND INERTIAL TOLERANCING FOR H/C RAMP-UP IN PRODUCTION

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Abstract

The functional Geometrical Tolerance Management is a top-down approach leading to systems specification at each level of the Aircraft assembly, and following the 3 main phases of the Helicopter lifecycle: Design phase, Development phase and Serial life.

During Serial life, we shall provide optimized methods and tools matching with quality and production objectives (OTD, OQM, ramp-up) and viewing results format. Since the tolerances are represented by a network, we have defined a format for injecting the results at a given level as input data to the next level. Due to the nature and interconnections of this network, the volume of data to be processed can be significant. So we have implemented an appropriate numerical technique to deal with a continuous influx of measurement data.

The objective is to purpose a comprehensible representation of the re-evaluated risks at each stage of the process, i.e.: Initial risks related to the current helicopter definition, Re-evaluated risks related to an aircraft serial number completed with each new measurement of characteristics for this aircraft, Re-evaluated risks related to the observed variability of the product / process at assembly level.

Our new industrial model leads to change our approach from a curative model to another model applied to QN process with root cause identification and manufacturing process monitoring allowing deploying preventive and corrective action plan. Behind that our objective is to avoid recurring QN and to switch to a Risk management model by several lever deployments.

When a functional geometrical target is too much tight, its cascade of tolerances is at the feasibility limit of production. In this case, Geometrical Tolerancing method loses its benefits.

The aim of this paper focus on our process deployment based on the last A/C development in Airbus Helicopters, presenting the first results, the advantages and drawback for Industrialization & serial phase based on the antitorque brackets integration. The antitorque bracket is the master element of the junction between Main Gear Box and fuselage.

The antitorque bracket has tight tolerances due to the stress way and its functional geometrical tolerance cascade. Its manufacture is at the limit of production means. The production of antitorque bracket generates many QN. Each part is going to generate recurring cost and added time of production. To solve this problem, we have chosen to understand what phenomena are in cause and manage non-quality risk with the application of inertial Tolerancing approach.

In function of the level of nonconformity calculated, an action plan is defined.

1. INTRODUCTION

1.1. Functional geometrical Tolerance management

The Functional geometrical Tolerancing management is based on a System Engineering philosophy, and inspired from Airbus way of managing interfaces between systems such as airframe work-packages, electrical, mechanical, air conditioning systems of the aircraft, etc.

The Functional geometrical Tolerance management is leaded by a process, based on end to end philosophy. This process defines the way of managing geometrical specifications concerning the aircraft during its complete lifecycle. Indeed, geometry is one of the key parameter to achieve aircraft performance gathering a set of generic and specific functions such as Aerodynamic performance, Aesthetic aspects, Handling capacity, Modularity and Maintenance capacity (Interchangeability), Tightness, Etc.

The geometry of an aircraft is the result of many manufacturing operations performed by many stakeholders, each one being responsible for distinct tasks. As a result, geometrical management is centred on Frontier and Interface management,

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following the sharing of responsibilities of vehicle systems and integrators.

- Phase 1: Design phase/ Definition of specification: convergence of design/manufacturing processes in regard to geometrical systems specifications at top level of the H/C. Those are technical loops until have the best compromise between design principle and assembly process.

- Phase 2: Development phase / Convergence of specification: Optimization of Design principle and manufacturing process until obtain all geometrical specification.

- Phase 3: Serial life / Check of specification: Monitoring strategy deployed through the appropriate quality plan to demonstrate continuous conformity of the products.

This approach is lead to a cascade of geometrical specification in line with the product cascade, where Frontier specification becomes an input data for system design and manufacturing engineering.

Insofar as geometry management requires a transversal approach with the contributions of many stakeholders and skills, there is a need of a process assuring the robustness of design against A/C performance criteria.

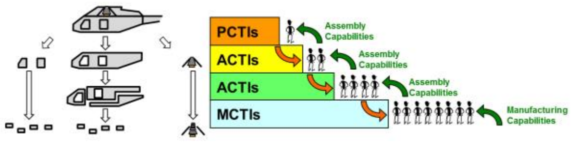
The main stakes of strengthening our mastery of geometrical specification are:
- Ensure customer satisfaction (On Target Quality/Parts interchangeability);
- Master product integrity with a focus on contractual commitments with suppliers;
- Manage interactions between product design and assembly process;
- Reduce tailoring/rework rate and assembly lead time;
- Ease production offsets.

The Functional geometrical Tolerance management process is currently deployed in Airbus Helicopters.

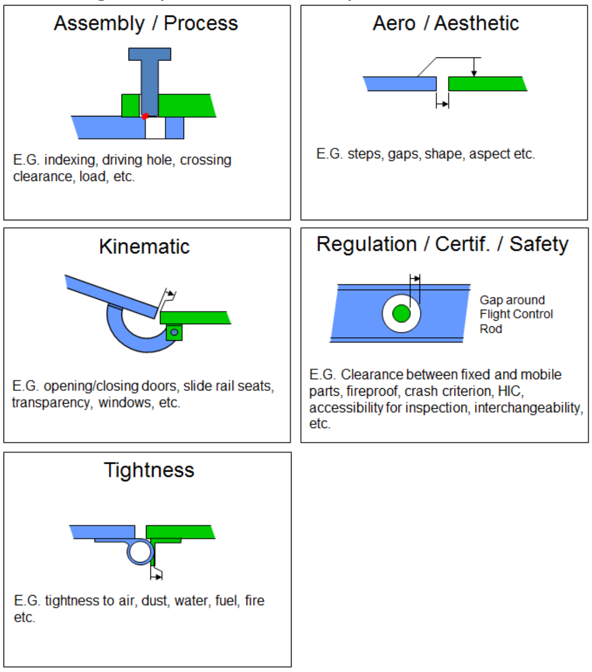
1.2. Description

The functional geometrical Tolerance management process consists in cascading A/C requirements through design and manufacturing breakdown in order to validate technical and industrial choices done at each step of the development.

This is a top-down approach leading to systems specification at each level of the Aircraft assembly (vehicle, airframe & systems, sub-systems, parts) and following the 3 main phases of the Helicopter lifecycle: Design phase, development phase (MAP) and Serial life.

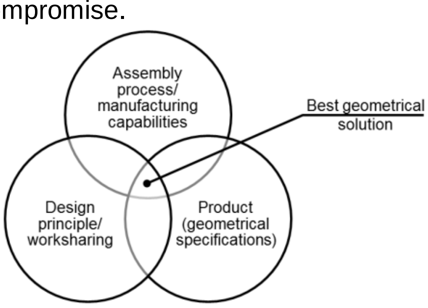


The starting point of the functional geometrical Tolerance management activity is to define the list of geometrical performance requirements of the A/C (Aesthetic / Aerodynamic / Interchangeability / Servicing Requirements / etc.).



The Functional geometrical Tolerance management is a transversal activity concerning design, production and quality people. It deals with tolerance requirements to fulfil at each step of assembly of the aircraft. These requirements are identified in accordance with defined product cascade of the A/C and according to functional analysis of each installation.

All along the development, this approach brings to influence manufacturing technologies, design principles and assembly sequences to define the best compromise.



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Each level of specification is officialised to guaranty the robustness and tractability of requirement break-down through A/C geometrical specification.

2. SCOPE

2.1. Starting point

“Each time, when we design an assembly of two elements with multiple fixations, the cascaded tolerances are too tight. The manufacturing doesn’t/can’t respect tolerances, BUT, at the end, we have no problem of assembly.” What is the reason of this gap between the theory and the practice?

When the target value of functional geometrical specification is too much tight, its cascade of tolerances is at the feasibility limit of production. In this case, geometrical Tolerancing method loses its benefits and generates a level of Non-conformity too excessive and not acceptable by their generated costs.

The aim of this paper is to present new approaches which allow increasing tolerance specification of parts and managing risks of non-assembly.

2.2. Root cause: type of calculation

The choice of calculation is one of root cause identified:

Arithmetical calculation or Worst case calculation gives tolerances too accurate, as consequence to increase the price of part, but it only the guaranty to have zero reject at assembly level. This calculation is applied for all type of production.

$$IT_{SPEC} = \sum IT_{CASCADE}$$

Statistical calculation increase the tolerance values of the cascade but increase the cost of the part by the implicit constraint: apply Statistical Process Control (SPC), know and maintain the capability of the manufacturing process (Cp and Cpk). This calculation is applied for medium and big-sized production. There are two types of calculation known:

- Quadratic calculation:

$$IT_{SPEC} = \sqrt{\sum (IT_{CASCADE})^2}$$

$$with\ Cpk \geq 1mini$$

- Quadratic calculation with Bender coefficient (security coefficient). The bad knowledge of its production doesn’t allow being sure about 6σ production. The production is evaluated as 4σ. For this reason, a security coefficient of 1.5 (4σ/6σ) is applied.

$$IT_{SPEC} = 1{,}5 \times \sqrt{\sum (IT_{CASCADE})^2}$$

$$with\ Cpk \geq 1mini$$

And a third calculation defines and uses by Airbus:

- ASCR Calculation (Airbus Safety Coefficient Result) which takes into account the disproportion between stacks and the number of stacks.

$$IT_{SPEC} = 1{,}6 \times f \times \sqrt{(IT_{CASCADE})^2}$$

$$f = -0{,}0056 \times \left(C_{1st\ STACK} - \left(\frac{100}{N}\right)\right) + 1.04$$

$$with\ Cpk \geq 1mini$$

$C_{1st\ STACK}$: $Contribution\ of\ the\ first\ stack$ (%)
N: $Number\ of\ stack\ with\ a\ contribution\ superior\ to\ 1\%\ of\ the\ Worst\ Case\ calculation$

2.3. Root cause: Evaluation of the target value of final geometric specification

The definition of the target value is only theoretical and under estimate compared to the practice.

The target value is cascaded in each element of the assembly. The target value is fixed by the skill concerned by the geometry:

- Stress-value max of deformation;
- Aerodynamics-maximum admissible gap & step;
- Manufacturing Process-Max gap to apply liquid shim;
- Assembly process-fit of fixation;
- Perceived quality-Maximum and minimum gap;
- Safety-Maximum misalignment of door stops;
- Etc.

For the function assembly, the chain of dimensions is performed with the technical assumption each part is rigid. Therefore, the cascade doesn’t take into account the deformation at the fixation or the deformation of parts.

The assembly doesn’t take into account all particularities of design principle: Adjustment of part floatability into fixations, temperature, stress of assembly…

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Therefore, the result of this remark is than the good calculation of tolerance is:

- For arithmetical calculation:

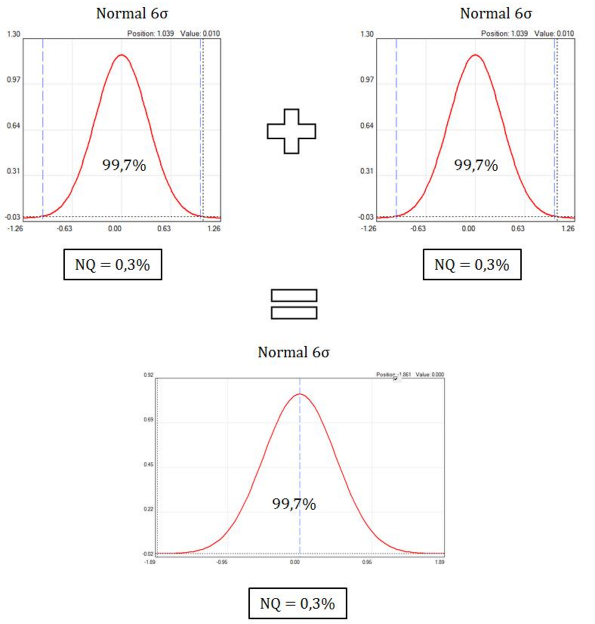
$$IT_{SPEC} = \sum IT_{CASCADE} - \sum IT_{OTHER\ PHENOMENA}$$

- For quadratic calculation:

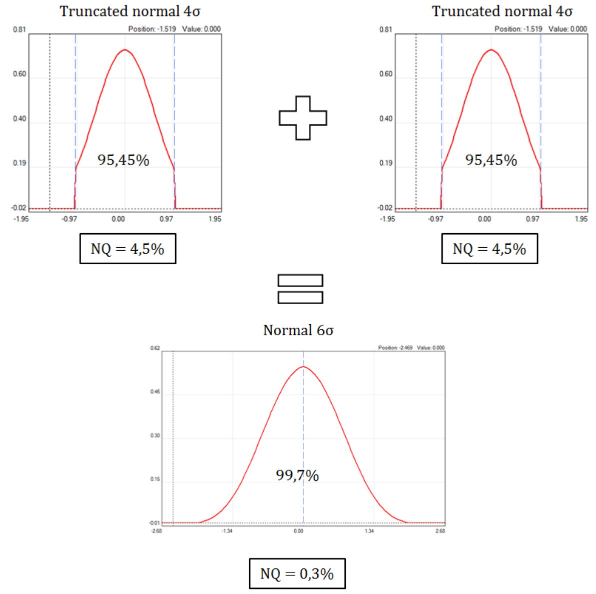
$$IT_{SPEC} = \sqrt{\sum (IT_{CASCADE})^2} - \sum IT_{OTHER\ PHENOMENA}$$

2.4. Financial aspect

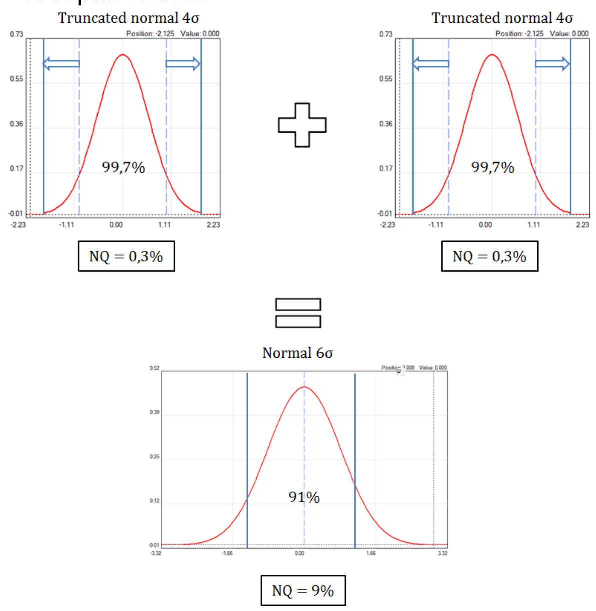
- *Theory:* If the production respects the rule of the statistic production, it's possible to evaluate the cost of the non-quality if we know the cost of parts and the cost of the action of assembly or repair:



- *Practice:* The production throws parts which are out of specification and its production is only capable to have 4σ or less. Therefore, the cost of non-quality is more expensive than the prediction:



- *New approach:* the aim is to increase the tolerance specifications of parts to have less reject parts and more assembly risk, if the cost of part production is more expensive than the assembly or repair action:



The next curve, which shows the relation of the non-quality cost and the price of parts and assembly, allows defining when it's necessary to use this new approach:

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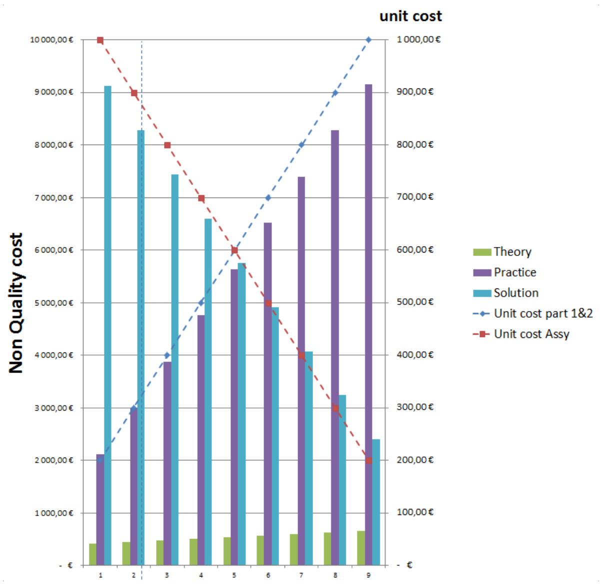


3. PHENOMENA OF FLOATABILITY

To increase the tolerance cascade on elementary part, we have decide to perform chains of dimensions which take into account the floatability and adjustment as benefits considering our type of production – Medium series.

Adjustment gaps, floatability in fixations are often used as a stack of defect and not as a benefit.

The Tolerancing method has shown its benefit for serial production, when manufacturing want to assemble faster and produce more: the technical assumption of this requirement/specification is to not have time to adjust parts between them.

Adjust part can be a better financial solution.

- Without adjustment:

$$IT_{SPEC} = \sum IT_{DEFECT} + \sum ADJ$$

- With adjustment:

$$IT_{SPEC} = \sum IT_{DEFECT} - \sum ADJ$$

$$\rightarrow IT_{SPEC} + \sum ADJ = \sum IT_{DEFECT}$$

$$\rightarrow \boldsymbol{Target\ Value} = \boldsymbol{IT_{SPEC}} + \sum \boldsymbol{ADJ}$$

ADJ: *Adjustment value*

3.1. Conditions of the studied case

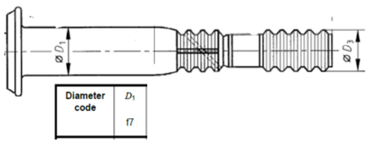
The method should be applied only when the next requirements are validated:

- Assembly geometrical specification is tight
- The assembly geometrical requirements is priority than other requirements
- There are several fixations (more than 2)
- There are no pilot holes (floatability available)
- The chain of dimensions is basic and composed by only two stacks. The airbus statistical common rules cannot be applied because we are under the number of stacks.

3.2. Definition of the Final geometrical specification

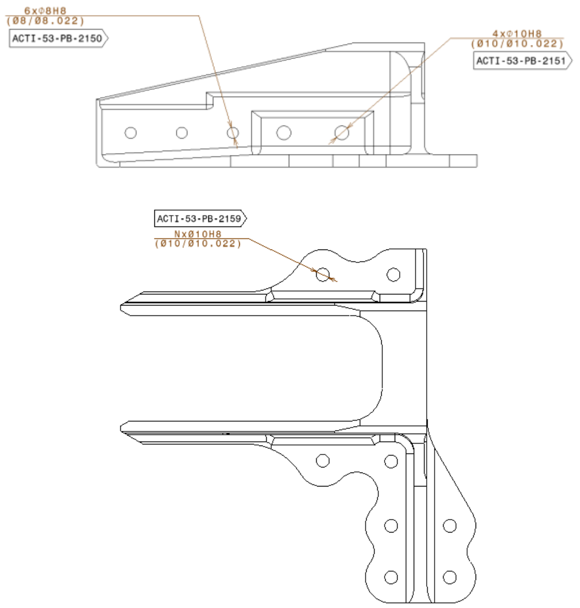
The geometric assembly requirement is defined by the clearance between fastener and holes. The value is the minimum clearance between parts and fastener because only this range is always available.

3.2.1 Fixation

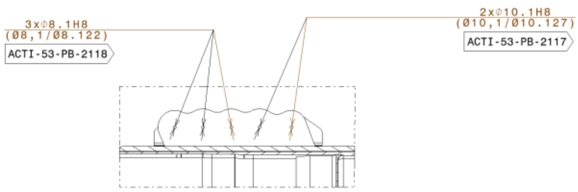


Ø8f7: Ø7,971/Ø7,987
Ø10f7: Ø9,972/Ø9,987

3.2.2 Antitorque bracket



3.2.3 Airframe



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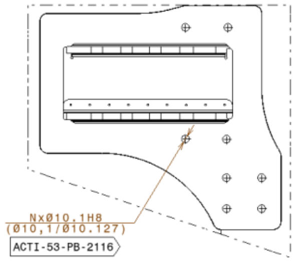
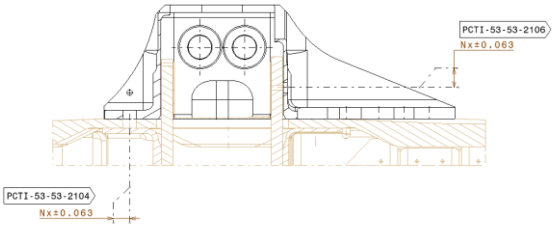


3.2.4 Calculation

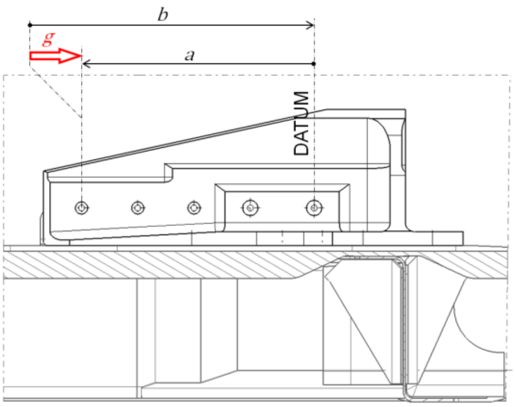
min. floatability - airframe/fixation = Ø10,1-Ø9,987 = 0,113 and Ø8,1-Ø7,987=0,113
min. floatability - bracket/fixation = Ø10-Ø9,987 = 0,013 and Ø8-Ø7,987 = 0,013
min. Global floatability = 0,126 (±0,063mm)

3.2.5 Definition on drawing



3.3. Evaluation: 0 risk = Arithmetical approach (worst case)

The production of each geometrical requirement which participate to the chain of dimensions has a normal distribution. All parts which are out of specification are rejected. All assembly can be performed quickly without problem.

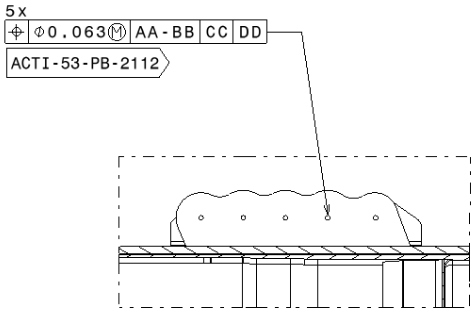


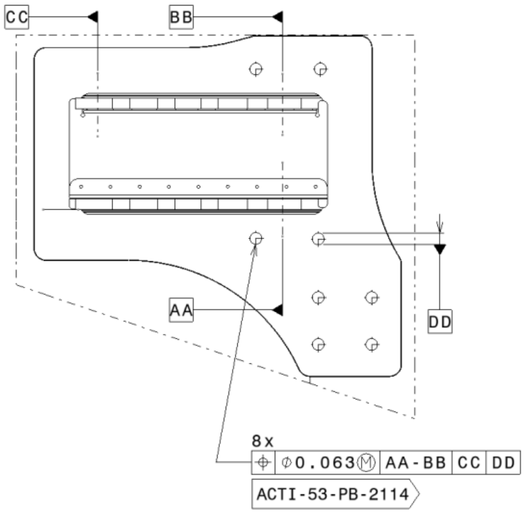
$$IT_g = IT_a + IT_b$$

$$\rightarrow IT_a = IT_b = \frac{0{,}126}{2} = 0{,}063mm$$

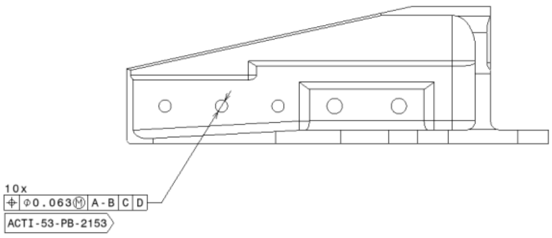
The cascade on drawing is the following:

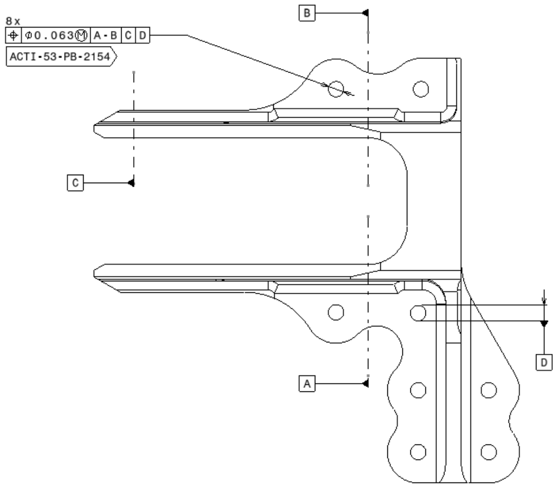
- For the airframe





- For the bracket





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If we consider the floatability at the datum:

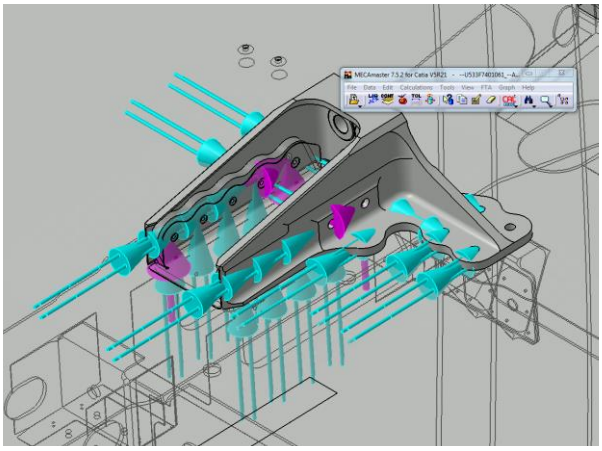
$$IT_g = IT_a + IT_b - floatability$$

$$\rightarrow IT_a = IT_b = \frac{0{,}126 + 0.063}{2} = 0{,}0945mm$$

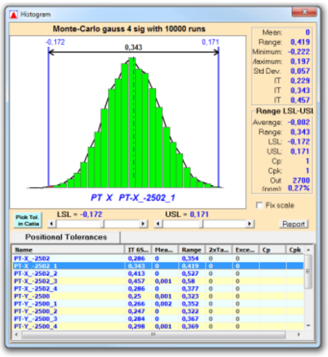
It's possible only if we have one hole. But, more there are holes, less adjustment is available and the new problem is to find how to use correctly the floatability with the number of hole.

3.4. With risk management = Inertial Tolerancing approach (Statistical)

To evaluate the assembly system, we use the software MECAmaster to modelize the 3D chains of dimensions which take into account the floatability of holes.



First, we perform a "Monte Carlo" simulation (10000 runs) in probabilistic with all defect at 0. Then, we perform another "Monte Carlo" simulation in 4σ with the floatability equal to 0.



The aim is to find if there is a case of floatability existing which allows to assemble a case of defect out of specification.

The 4σ calculation allows introducing a safety coefficient at the result. Instead of asking an Indicator of process Capability (Cpk) superior or equal to 1.33, the tolerance specification should fulfil a Cpk ≥ 1.

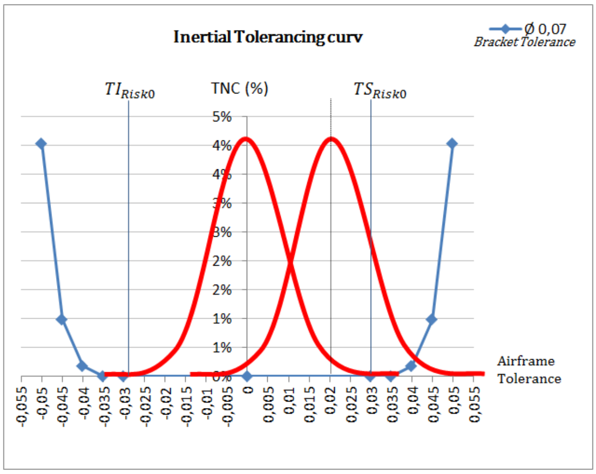
The result is the rate of non-compliance (TNC) by combination of tolerance specification on parts.

TNC	0,063					
bracket / airframe	Ø 0,05	Ø 0,06	Ø 0,07	Ø 0,08	Ø 0,09	Ø 0,1
Ø 0,06	0%	0%	0%	0%	0%	1%
Ø 0,07	0%	0%	0%	0%	1%	4%
Ø 0,08	0%	0%	0%	1%	3%	9%
Ø 0,09	0%	0%	1%	3%	8%	18%
Ø 0,1	0%	1%	4%	10%	19%	53%

After economic study, all partnership of the design decide to write a tolerance of Ø0,07 for the bracket and Ø0,1 on airframe.

That's means 4% of assemblies aren't going to be possible. And to have no more 4% of TNC, the process of drilling holes of the airframe should have a Cpk≥1 and a centering acceptable μ≤0,02. And, the process of drilling holes of the bracket should have a Cpk≥1 and an acceptable centering μ≤0,0035.

For this choice of risk, we have this inertial curve for the production of airframe hole.



3.5. Definition on drawing set

To inform manufacturer, the symbol ST and "Cpk≥1 ; μ≤X.XX" should be added near the specification (e.g. ISO18391:2016) A note should be added to link "ST" symbol at a Technical Note where the choice of acceptable TNC has been done and signed by all partnership of the design:

NOTE

ST EACH INDIVIDUAL PART SHOULD FULFILL THE TOLERANCE SPECIFIED AND THE BATCH OF PARTS SHOULD FULFILL THE TWO ADDED SPECIFICATIONS: CAPABILITY OF PROCESS Cpk AND CENTERING μ
TOLERANCE VALUE IS JUSTIFIED IN THE TECHNICAL NOTE UXXXAXXXE01

The cascade on drawing is the following:

- For the airframe

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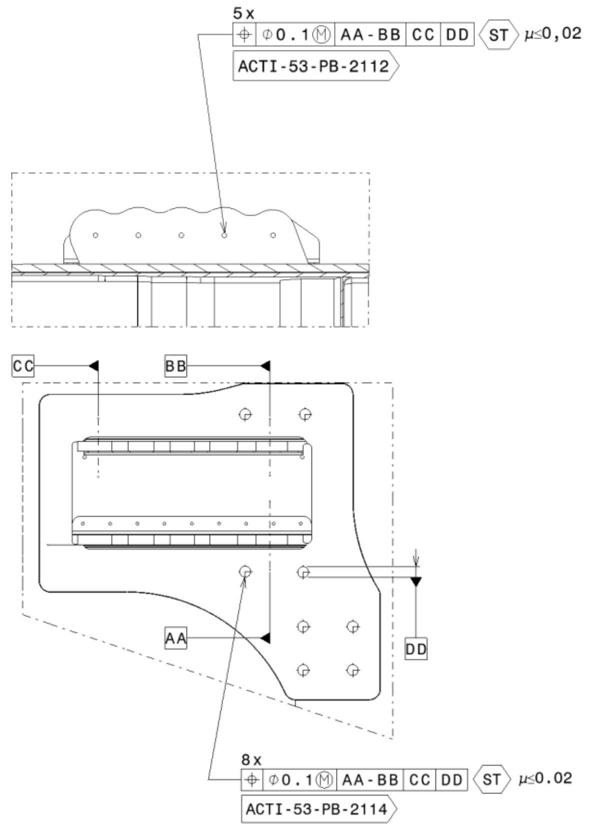
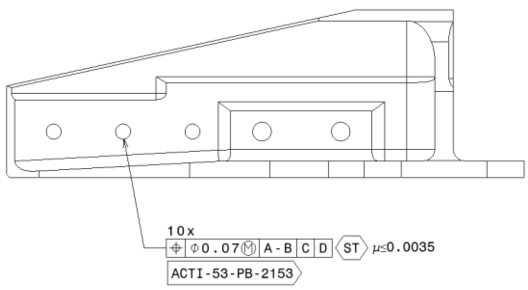
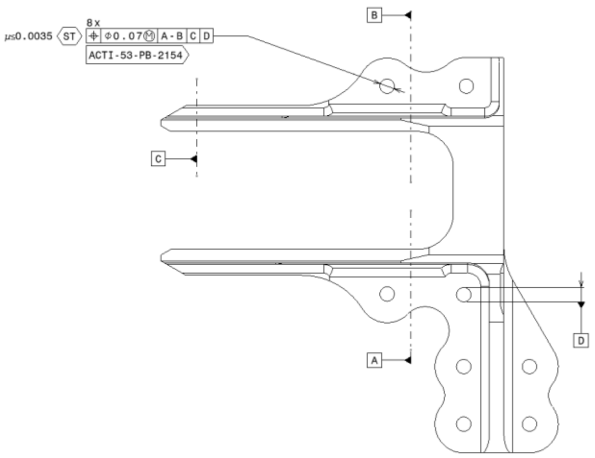


- For the bracket





This new approach is difficult to enforce and thus, it is not possible to apply at each geometrical specification.

4. PHENOMENA OF DEFORMATION

4.1. Type of Deformation

There are two different approaches to take into account the deformation:

- The deformation of parts is added to IT calculated to define the nominal of design principle.

$$N = \frac{IT_{SPEC}}{2} + D$$

$$D: Deformation$$

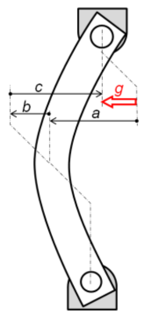
e.g. In flight, a galley moves to 10mm. The result of the chain of dimensions of the assembly is equal to ±5mm. To have no contact between the structure and the galley, the nominal should be design at 15mm.

- The deformation is an acceptable specification to increase the interval of tolerance of the final geometrical requirement.

$$IT_{SPEC} = IT_{CALCULATED} - D$$

$$\rightarrow \underbrace{IT_{SPEC} + D}_{New\ IT_{SPEC}} = IT_{CALCULATED}$$

e.g. A rod is attached by its two extremities on two airframe brackets. The fit of each fixation is $H7g6$ ($\approx \pm 0.015$). g should be inferior to this fit. With the two manufacturing and assembly tolerance of rod and airframe bracket, it's impossible. If it's agreed to put a constraint of 1mm into the rod, it's now possible to perform this assembly.



$a = \pm 0.4$ *(rod tolerance)*
$b \approx \pm 0.015$ *(fit of fixation)*
$c = \pm 0.5$ *(airframe tolerance-grey parts)*

$$g = (\pm 0.4 + \pm 0.5 + \pm 0.015) - 1 = -0.085$$

$$\rightarrow g < \pm 0.015$$

The disadvantage of this method is to know the deformation of your elements. To know and be sure of the deformation value, it should be calculated and measured. To do that, the measure should be performing with two steps: Measure in the "Free State" and Measure on a control tooling representative of the part set position.

4.2. Assembly process

The chain of dimension is based on the design principle and the assembly process. If two parts

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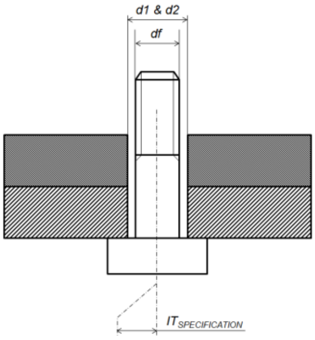
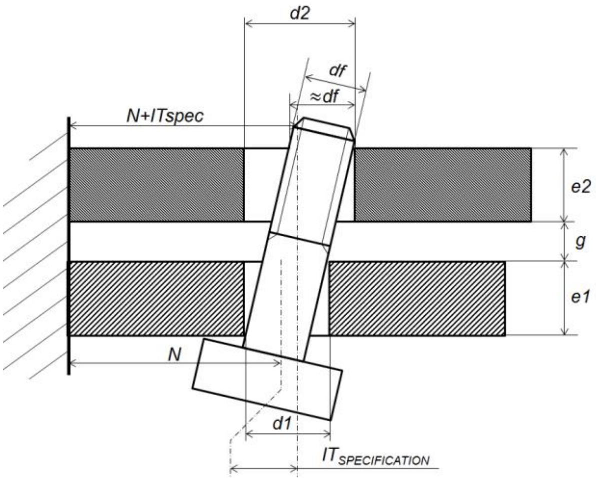
are in contact, the target value of the geometrical requirement is lower than if these two parts are not in contact:



$$IT_{SPEC} = d1_{MINI} + d2_{MINI} - 2 \times df$$



$$\frac{IT_{SPECIFICATION}}{d1_{MINI} - df} = \frac{e1_{MAXI} + g + e2_{MAXI}}{e1_{MAXI}}$$

$$\rightarrow IT_{SPEC} = \frac{(e1_{MAXI} + g + e2_{MAXI}) \times (d1_{MINI} - df)}{e1_{MAXI}}$$

N: Nominal value of the position of hole

The disadvantage of this solution is to mask the constraint into the parts of the assembly. But, this method explains lot of cases, where the calculation shows the impossibility to assemble and where the assembly is perform without problem.

In the case of the antitorque bracket, with a gap between parts of 0.1mm and a thickness of 9mm, the new IT_{SPEC} is equal to 0,253mm.

$$\rightarrow IT_{SPEC} = \frac{(9 + 0.1 + 9) \times (0.126)}{9}$$

The stress calculation give authorized interference between parts of 0,102mm with these same technical assumptions:

$$IT_{SPEC} = \sum IT_{CASCADE} - \sum IT_{DEFORMATION}$$

$$\rightarrow \pm 0.063 = \sum IT_{CASCADE} - 0{,}102$$

$$\rightarrow 0{,}228 = \sum IT_{CASCADE} \; (< 0{,}253)$$

5. APPLICATION

The adding of these new parameters allows to get closer of the reality and to be less conservative with the production requirements. On the other hand, it increases the risk at the assembly step. The application of this new method should be performed at the bottom-up stage of the functional Tolerancing process. The cost of the part and the criticality of the part should be taken into account to enforce this new approach.

For our antitorque bracket, the cost of fabrication of 2546€ (compared to the cost of the time of assembly) and the high criticality of this part, justify to improve the Tolerancing evaluation.

if we increase the floatability to a limit of acceptable deformation in holes:

$$IT_{SPEC} = \pm 0{,}063 \; \rightarrow \pm 0{,}114$$

With the application of floatability risk matrix, the tolerance cascade can be increase significantly from ±0.063 (Cpk>1, μ=0): to ±0.14 (Cpk>1, μ<0.04):

TNC bracket / airframe	Ø 0,1	Ø 0,11	Ø 0,12	Ø 0,13	Ø 0,14	Ø 0,15	Ø 0,16	Ø 0,17	Ø 0,18
Ø 0,1	0%	0%	0%	0%	0%	0%	0%	0%	0%
Ø 0,11	0%	0%	0%	0%	0%	0%	0%	0%	0%
Ø 0,12	0%	0%	0%	0%	0%	0%	0%	0%	0%
Ø 0,13	0%	0%	0%	0%	0%	0%	0%	0%	0%
Ø 0,14	0%	0%	0%	0%	0%	1%	2%	4%	7%
Ø 0,15	0%	0%	0%	0%	1%	2%	4%	7%	11%
Ø 0,16	0%	0%	0%	0%	2%	4%	6%	11%	16%
Ø 0,17	0%	0%	0%	0%	4%	7%	11%	16%	23%
Ø 0,18	0%	0%	0%	0%	7%	11%	16%	23%	52%

In our case, the antitorque brackets are produced by batch of 10 parts. If the assembly don't work, the associated action plan is to test another bracket. In this case, we should define two types of brackets drawings, one for the Final Assembly line and the most precise one for in services customer deliveries.

6. CONCLUSION

The experience with Tolerancing management shows that the first "top-down" and "bottom-up" approach give a result which can be far of the reality.

A "worst case" cascade gives a result which guaranty 100% of assembly but it is not representative of our manufacturing process. The analysis of the production and the application of statistical method give another result which is more accurate and get closer of the reality. We had stated that other parameters can improve our cascade: as take into account fixation floatability and adjustments of as-

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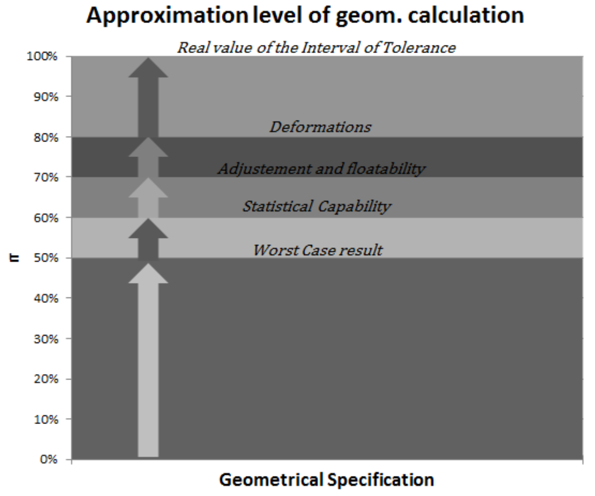
semblies or as take into account masked deformations.



The application of this method is difficult and parameters of production are very important, that's why it's not possible to perform all the study with that. The cost of part, the cost of the assembly and the criticality should be taken into account.

We know our new approach get closer reality. Therefore, it is very interesting to apply it. But, we know we always stay conservative because we certainly neglect some parameters: for example, the maximum floatability is calculated with the maximum diameter of the fixation and minimum diameter of hole, but in reality this floatability is bigger than that.

We study now with all the measure on H/C, the convergence with our new technical assumptions.

7. NOTATION

IT: Interval of Tolerance
H/C: Helicopter
Cpk: Process capability indices

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