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Procedia CIRP 75 (2018) 267–272

www.elsevier.com/locate/procedia

15th CIRP Conference on Computer Aided Tolerancing – CIRP CAT 2018

Tolerance analysis using a Computer Aided Tolerancing Software: ANATOLE 3D

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Abstract

In the aeronautic field, the required accuracy of finished parts is difficult to achieve with the best value for money. It is necessary to simulate the impact of manufacturing deviations in order to verify that the manufacturing process meets the requirements in spite of dispersions in each phase.
With support of research works from LURPA ENS Cachan University Paris-Sud and software engineering from DPS, Safran Aircraft Engines has developed a Manufacturing Computer Aided Tolerancing Software that aims to automatize the manufacturing specification transfer and optimize the manufacturing tolerances. This software uses input from the model based definition and from the tolerancing analysis performed by ANATOLE 3D (software edited by AIRBUS and DPS).

Keywords: 3D ISO manufacturing tolerancing, tolerance analysis, Computer Aided Tolerancing

1. Context

1.1. The tolerancing process

Typically, the engineering department defines parts' geometry and functional specifications. Engineers have to choose a manufacturing process to fulfill functional requirements. The manufacturing transfer consists in choosing the specifications to meet at each step then allocating the tolerances.

SAFRAN Aircraft Engines is eager to bring a new approach to the tolerancing process (Fig.1), which consists in expressing the production specifications directly with respect to the datum systems of the phases. The production specifications are used to set up each machined surface. This approach enables one to identify the mother specifications for tracking and adjusting each tool. The mother specifications are the most stringent productions specification, *ie.* the specifications it suffices to control to qualify the tool adjustment.

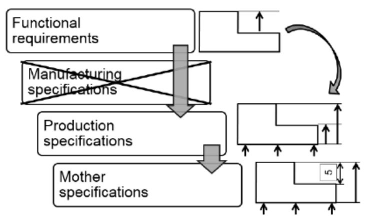


Fig. 1. The new approach to the tolerancing process [1].

1.2. State of the art

There are two main approaches for manufacturing tolerances' analysis.

10.1016/j.procir.2018.04.079

The first approach consists in carrying out operations in domains which model manufacturing deviations. The resultant of these domains gives an image of the actual finished part.

This resultant must meet the functional requirements. Thus, the Model of Manufactured Parts (MMP) proposed by Villeneuve and Vignat is the resultant of the deviations due to machining dispersions and to positioning dispersions [2, 3]. These deviations are expressed through the small-displacement torsor (SDT) [4]. More recently, Haghighi defined M-Maps, which model the resultant of the manufacturing defects determined by simulation [5].

The second approach consists in propagating the manufacturing deviations induced by each phase by means of calculations.

This is the type of approach which is used in the Δl method. This method, which was developed by Bourdet [6], enables one to express a functional or manufacturing requirement as an accumulation of manufacturing specifications through a one-dimensional calculation. This method was extended to 2D and 3D problems by Anselmetti [7]. 3D calculation methods based on SDT have been proposed by Ballot [8], Laifa [9] and Ayadi [10]. No CAT software for 3D manufacturing tolerancing is available on the market.

As a matter of fact, there is a need for a new manufacturing transfer software to address the market. This specific sotware, developed by Safran Aircraft Engines, will be relying on ANATOLE 3D, a Computer Aided Tolerancing software, initially developed by AIRBUS Group Innovations, and now maintained and improved by Digital Product Simulation. To process tolerances' computations, ANATOLE 3D implements the method of undetermined displacements [11] .

2. Assembly tolerancing with ANATOLE 3D

2.1. ANATOLE 3D main principles

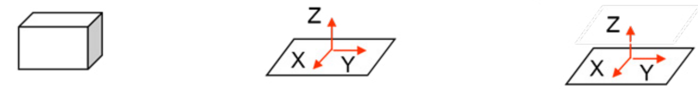
ANATOLE 3D is a tolerance analysis software developed in collaboration by DPS and AIRBUS (Innovation Works Department). ANATOLE 3D enables to calculate 3D stack chain, answering a need that hand-calculating can't. Fully integrated within CATIA V5, it uses the 3D MASTER Annotations on the parts of an assembly, but it is still usable if the Digital Mock Up (DMU) does not bear any CATIA V5 FTA Annotation. Its robust and effective solver, based on a generic statistical platform, OPENTurns[12] (Open source initiative for the Treatment of Uncertainties, Risk'N Statistics, issued from a joint development between Airbus and EDF), allows to get Worst Case Results and a Statistical Analysis. Furthermore, a sensitivity analysis allows to identify the contributors of the stack chain and to what extent they contribute. The associativity between the ANATOLE 3D study and the DMU, as well as the possibility of obtaining the sensitivity of each tolerance on the result make ANATOLE participate to the added value of the solution.

To perform an ANATOLE 3D study, kinematic links are created between the surfaces of the parts of an assembly, modelling the real kinematic of the assembly. According to their nature (planar, punctual…), these links will propagate the deviations of the surfaces according to different components, in rotation or translation. This modelling uses the small displacement torsor method.

This method uses a formal kinematics model of the assembly. There are three types of torsor:

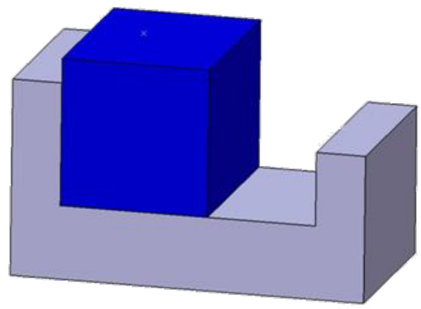
1. The Part torsor ($Tp_{A/R}$), which is the unknown of the problem.
2. The Surface torsor ($Tps_{i/A}$), which depends on invariant terms of the geometry.
3. The Link torsor ($Tl_{O1/O2}$) depending on link variation terms and on undetermined terms of link.

$$Tpp_{A/Rm} = \begin{bmatrix} Ptx_i & P_{RXi} \\ Pty_i & P_{RYi} \\ Ptz_i & P_{RZi} \end{bmatrix}_{Rm} \qquad Tps_{Plan/A} = \begin{bmatrix} \alpha & Otx \\ \beta & Oty \\ Orz & w \end{bmatrix} \qquad Tl_{O_1/O_2} = \begin{bmatrix} Crx_{O_2} & Ftx_{O_2} \\ Cry_{O_2} & Fty_{O_2} \\ Frz_{O_2} & Ctz_{O_2} \end{bmatrix}_{O_2}$$



The main interest in this model is that it enables geometrical deviations' propagation within an assembly.

Below is the example of a cube and its coping mechanism. A chosen modelling in ANATOLE 3D will be to link them with a planar joint on the cube's lower surfaceand a line curve joint on the cube's side surface .



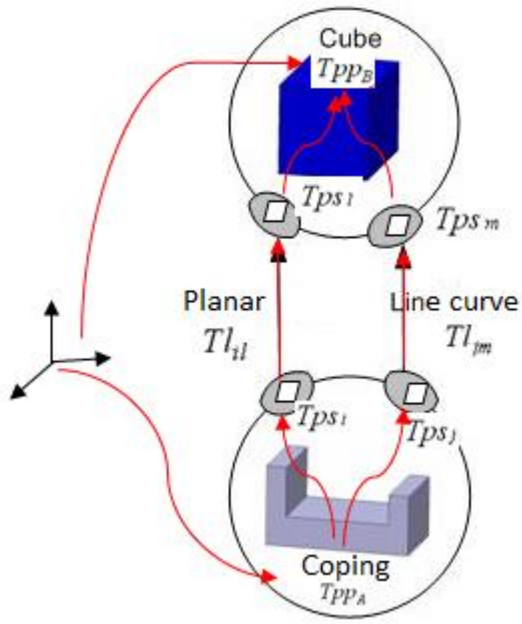


Fig. 2. Positioning links in an assembly.

Torsor chain expression: TpB/R = (TpA/R + Tps1/A) - (Tps2/B + TlO2/O1)

Singleness of a part movement expression: {Tp}/Ra =

$\{Tp/Ra\}^{(1)}$ /Ra = $\{Tp/Ra\}^{(2)}$ /Ra =….= $\{Tp/Ra\}^{(l)}$ /Ra where $\{Tp\}^{(i)}$ /Ra is the position variation of *p* part with respect to theoretical position and derived from the positioning link *i*.

Then, the global system to be resolved is the following:

$$\left.\begin{array}{l} Tpp_B = Tpp_A + Tps_i + Tl_{il} - Tps_l \\ Tpp_B = Tpp_A + Tps_j + Tl_{jm} - Tps_m \\ \ldots\ldots \\ Tpp_B = Tpp_A + Tps_k + Tl_{kn} - Tps_n \end{array}\right\} + \{TppBase\}/Ra = \{0\}$$

Then, for the formal resolution, the resolution is possible if only one part torsor is null.

Concerning the statistical analysis, ANATOLE 3D statistical module is based on generic statistical platform, OPENTurns[12].

This platform is the result of a large international community of research works on uncertainties management. Every type of statistical law is supported enabling short time quantile evaluation. Other software mainly use Monte Carlo draws for statistical analysis; however this method does not suit our caseas it requires a significant number of draws to provide an accurate result several thousand for a 99% confidence interval). Moreover, Monte Carlo's method is usually very time-consuming.

To perform a statistical analysis, it is needed to choose a statistical law among those already implemented in the tool (uniform, triangle, normal). This law will apply to the distribution of the capabilities of the model. Once the statistical law is chosen, it is necessary to choose a statistical criterion (either a percentage or a standard deviation) which will determine which are the limits of the statistical results. It is possible to change the criterion to measure its influence, the computation is made automatically.

To summarize:

- ANATOLE inputs are: the links created between the parts and the FTA Annotations.
- ANATOLE outputs are: the Worst Case results, Statistical Results and sensitivity analysis.

2.2. ANATOLE 3D GUI and processing

Here are described the main steps to create a model in ANATOLE 3D.

The assembly is composed of three parts, which all bear FTA Annotations.

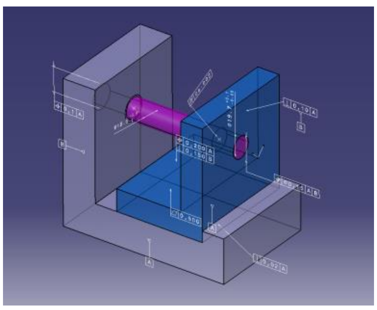


Fig. 3. Three-part assembly used for the example.

a) Kinematic links creation

To model the assembly, kinematic links have to be created between the surfaces of the different parts. To create a link, it is necessary to select two surfaces belonging to two different parts, then the software recognizes the nature of the surfaces and proposes to create the corresponding kinematic link. For instance, the first link proposed between the upper surface of the grey part and the lower surface of the blue one is a planar because it involves two planar surfaces. In the Definition of a kinematic link window, is given information about the link: surfaces and parts involved, nature of the link, application point and directions, and link's torsor components.

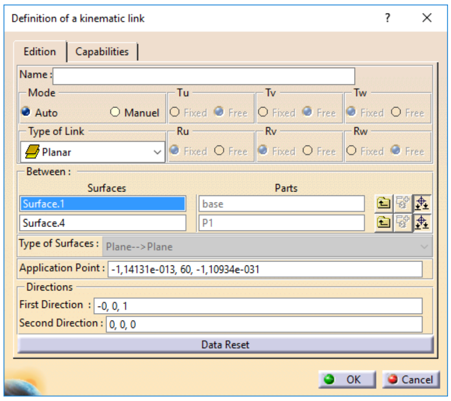


Fig. 4. Definition of a kinematic link window.

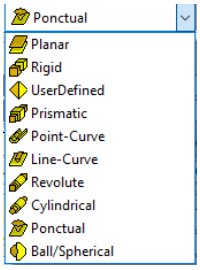


Fig. 5. Kinematic links existing in ANATOLE 3D

Every time a link is created, a feature (in yellow), is creating on the assembly to visualize. Below is the assembly after all links creation.

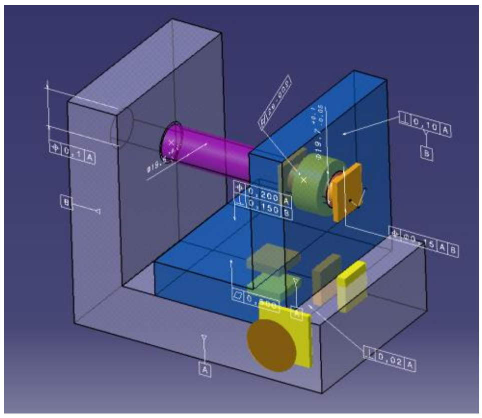


Fig. 6. Assembly with the ANATOLE 3D features.

b) Creating the geometrical requirements

Once the links have been created, geometrical requirements have to be created. In this example, the aim is to to calculate the position of the centre of the extremity of the purple axis toward the grey part. The requirement is created by selecting the two parts involved in it, a point and the directions of the study (directions which can just be picked on the geometry). That information is gathered in the geometrical requirement creation window as shown below:

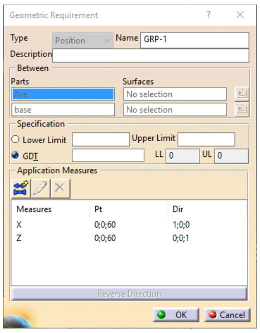


Fig. 7. Geometrical requirement creation window.

Once the requirements are created, a feature (in blue) is created to visualize.

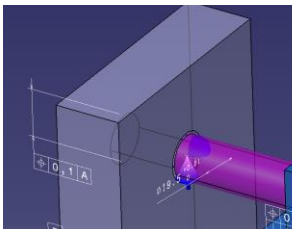


Fig. 8. ANATOLE 3D features to represent the geometrical requirement.

c) Overconstraints check

As explained earlier in this paper, it is necessary to have an isoconstraint system to perform the calculation. When many kinematic links are created, it is possible that some of them bloke the same degrees of freedom: in order to make the system isoconstraint, it will be necessary to release these components.

In ANATOLE 3D, overconstrained components are highlighted in red. The user has then to choose which one he wants to release.

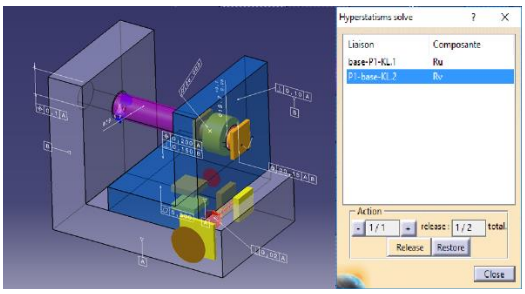


Fig. 9. Visualisation of the overconstraints.

d) The computation

Once the system is isoconstrained, it is possible to run the calculation.

In the project summary panel which is edited after the computation, are gathered different informations:

- The Worst Case min and max (WC Min, Max) for the geometrical requirements created, the statistical results min and max (it is possible to choose the statistical law).

Measures	LL	UL	WC Min	WC Max	Stat Min	Stat Max	OK/KO WC	OK/KO Stat
GRP-1								
X	0	0	-2,23	2,23	-0,68654	0,68654	KO	KO
Z	0	0	-2,41503	2,41503	-0,73065	0,73065	KO	KO
X_Modified geometry	0	0	-1,4271	1,4271	-0,364403	0,364303	KO	KO
Z_Modified geometry	0	0	-1,6121	1,6121	-0,422925	0,422925	KO	KO

Fig. 10. Result measures.

- The sensitivities of the links and their contribution, *ie* in what proportion the different links contribute to the result and according what direction.

Sensibility of Links						
Contributor	Component	Sensibility	S%	Contribution	C%	Sign
P1-base-KL2	Ru	100	29	0	0	-
Axe-P1-KL3	Ru	90	26	2,025	86	-
base-P1-KL1	Rv	60	17	0,1	4	+
Axe-P1-KL3	Tv	1	14	0,235	10	-
P1-base-KL4	Tw	1	14	0	0	-
Sensibility of Links_Modified geometry						
Contributor	Component	Sensibility	S%	Contribution	C%	Sign
P1-base-KL2	Ru	100	29	0	0	-
Axe-P1-KL3	Ru	84,39	25	1,22214	78	-
base-P1-KL1	Rv	60	17	0,1	4	+
Axe-P1-KL3	Tv	1	15	0,235	15	-
P1-base-KL4	Tw	1	15	0	0	+

Fig. 11. Sensibility of Links.

- The sensitivities of the tolerances, *ie* in what proportions the specifications on the surfaces contribute to the final result.

Sensibility of Tolerances		
Tolerance Annotation	WC Min	WC Max
Axis/Cylindricity.1/Val:0,02	-0,5	0,5
P1/Localisation.1/Val:0,15	-4,5	4,5
P1/Perpendicularity.1/Val:0,02	-1	1
base/Perpendicularity.1/Val:0,02	-1	1
base/Perpendicularity.3/Val:0,15	-0,5	0,5
Sensibility of Tolerances_Modified geometry		
Tolerance Annotation	**WC Min**	**WC Max**
Axis/Cylindricity.1/Val:0,02	-0,5	0,5
P1/Localisation.1/Val:0,15	-2,7	2,7
P1/Perpendicularity.1/Val:0,02	-1	1
base/Perpendicularity.1/Val:0,02	-1	1
base/Perpendicularity.3/Val:0,15	-0,5	0,5

Fig. 12. Sensibility of the tolerances.

The geometry of the model has been modified to show how it influences the results. The sensibility of the links and of the sensibility of the tolerances has been displayed, regarding the measure in the X direction. For example, in this case the panel allows to understand easily that the geometrical modifications impacts the final result trough the link called Axe-P1-KL3 and the specification "P1/Localisation.1/Val:0,15".

3. Tolerancing transfer software: TransTol3D

TransTol3D is the software, add-on to Anatole3D, in which the method allowing to get the synthesis of specifications and a choice of the values of optimized tolerances is automatized. This software is a specific development by DPS for SAFRAN AIRCRAFT ENGINES, which holds its intellectual property.

Here after is detailed how the software proceeds.

Several CATPART files are created: containing a void part, the final part and parts which represent the machined part at each operation. These models are called 'stage models'.

Moreover, the active surfaces in each operation, ie. the datum surfaces and the machined surfaces are identified (by a color codes).

TransTol3D creates the links between the datum surfaces and a virtual jig, and an ANATOLE 3D study is created to determine the manufacturing specifications.

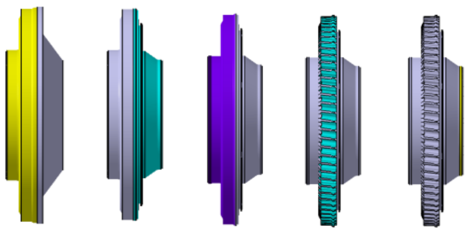


Fig. 13. Several Manufacturing intermediate models.

3.1. PITOL: Production and Intermediate Tolerancing

Given the fact that it is very difficult to develop the manufacturing specifications using the 3D methods, it has been suggested to delete this calculation step in the manufacturing transfer to directly transfer the functional requirements into production specifications [13].

Thus, if all production specifications of a phase are validated, the part is compliant after this phase; it is not necessary to check the intermediate specifications after the phase.

On the other hand, if a production specification is non-compliant, this requires a change or adjustment of the tool by therefore assessing the adjustment's value that needs to be done. The part is then potentially non-compliant, but not necessarily.

By way of derogation, the part is declared compliant if it complies with the intermediate specification after the phase. For that, it is also proposed to transfer the functional requirements in order to choose the intermediate specifications, by the way of considering the part at the end of each phase as a blank part capable of performing the finished part with the following phases.

In practice, two contexts make useful the intermediate tolerancing:

- If the part is supposed to be undeformable during production: in case of non-compliance on a production specification of a surface, it suffices to check the intermediate specifications containing this surface as a toleranced surface or as a datum surface.
- If the part is liable to deform during production: the intermediate manufacturing drawing contains all the intermediate specifications. This drawing is particularly useful in three cases: after a critical phase that can release internal constraints of the part (large roughing, heat treatment, welding ...), after a major production incident (shock during handling, collision in machining...) and for receiving a partially outsourced part.

In summary, the PITOL principle consists of directly transferring functional requirements to production specifications on one hand, and to intermediate specifications on the other hand.

To validate the PITOL method, the results have been compared to what it is obtained with the analysis line method.

3.2. DMITPOL: Deviation Model for PITOL

When the PITOL principle is applied, it is proposed to model the manufacturing deviations respecting the following rules [13]:

1. Associate a coordinate system with the datum system of each manufacturing phase.

2. Use the coordinate system of the first phase as a reference for all the calculations.

3. Express the manufacturing deviation of the surface with respect to the datum system of the phase where it is manufactured.

4. Determine the deviation between two phase coordinate systems by the unification of the deviations of the datums surfaces.

The coordinate system associated with each phase is in nominal position with respect to the datum system of the phase, which can be composed of setting-up surfaces, or of measured surfaces. This modeling associated with the PITOL principle is called DMPITOL, which stands for Deviation Model for Production and Intermediate TOLerancing.

PITOL and DMPITOL are used inside the TransTol3D software, that has been developed for SAFRAN Aircraft Engines, and rely on the method of undetermined displacements, used in the CAT software ANATOLE 3D.

4. Conclusion

Manufacturing transfer is the activity of determining the manufacturing specifications.

Safran Aircraft Engines has proposed a manufacturing transfer method that has been automated in a specific software TransTol3D, relying on the ANATOLE 3D CAT software.

The software inputs shall come from the digital environment of the company, to build a continuous and efficient process.

In order to address this issue, PITOL (Production and Intermediate TOLerancing) and DMPITOL (Deviation Model for PITOL) are recommended.

A manufacturing transfer method has been developed. It enables to efficiently realize specification synthesis, tolerance analysis and tolerance optimization. Then the method is automated into a software, so that it is useable in the industry context. In order to ease the use of the method by SAFRAN Aircraft Engines, some rules have been proposed which enable the calculation of manufacturing transfer for specific processes. Moreover, solutions are proposed to make the method suitable within the industrialization process.

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