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Functional ISO specification of a blade: a tolerancing challenge

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Abstract

When talking about ISO tolerancing of a mechanical component it generally comes along with the hypothesis that the component is rigid. Our study deals with a turbine blade on which significant constraints are exerted during operation, causing deformation of its aerodynamic part. For that reason, ISO specification of rigid parts do not apply on the entire component. Therefore, this contribution is about the proposition of a tolerancing method that permits to perform ISO tolerancing of different parts of the component while taking into account the possible deformations. On the example of a turbine blade the developed approach based on existing methodologies is explained in detail containing tolerance writing and deformation analysis.

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Keywords: Functional analysis ; Model Based Definition; ISO tolerancing

1. Introduction

SAFRAN is not the only manufacturer in the design and manufacture of turbojet engines. Civil engines such as the LEAP of the international CFM consortium, which is 50% owned by Safran Aircraft Engines and 50% by General Electric, are the first proof of this. Engine components are often manufactured by industrial partners in France and abroad. They do not have the same means of production or control. Moreover, it is essential that all geometrical component definitions, control tools or production dimensioning documents can be outsourced. In order to avoid any interpretation of the definitions, it is essential to use unambiguous language of the geometrical definition of mechanical components. This language is now governed by ISO standards [1,2,3,4].

Several components of the turbojet engine are assembled under prestressing and undergo mechanical or thermal stresses in operating configuration. The geometry of these components therefore evolves according to the stresses exerted. The nominal geometry and dimensional limits are then defined by the functional conditions corresponding to the different operating phases. The difficulty is to define the ISO geometrical specifications on the geometry of the component in the free state that allow the respect of the requirements in its constrained state. An industrial example is first presented to illustrate the problem on a concrete case. The approaches available in the state of the art are then presented. In a third part, the proposed approach based on a combination of existing tolerancing methods and component stiffness analysis is proposed.

2. Industrial example

The industrial component illustrating the problem is a low-pressure turbine blade of an aircraft engine. This turbine blade is composed of three parts (see Fig. 1):

- an aerodynamic part,
- an upper part,
- a lower part.

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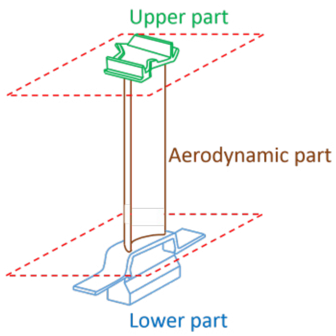


Fig. 1. Different parts of the turbine blade

In the operating configuration, the upper and lower parts are rigid and do not deform geometrically. The aerodynamic part of the turbine blade is deformed during assembly and then in operating configuration. The geometry of the turbine blade in the free state is therefore different from the geometry in the constrained state.

During assembly, the turbine blades are positioned by their lower part on a disc and stacked in a crown on the upper part. In order to assemble all the blades into a crown, they are deliberately deformed (see Fig 2) to be assembled under stress, thus ensuring that there is no gap and that the contact surfaces are maintained in operating configuration. This deformation results in a geometrically over-constrained positioning.

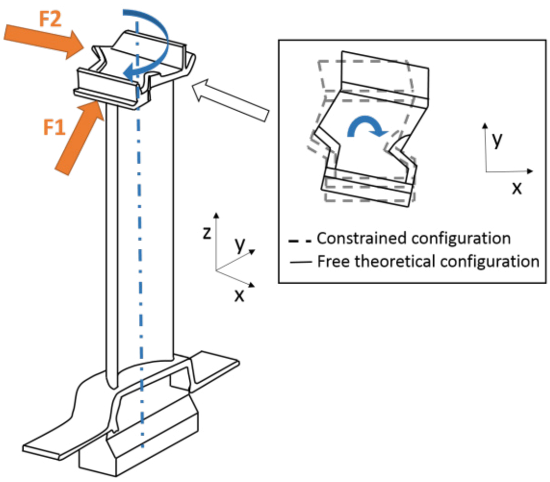


Fig. 2. Free theatrical configuration of the turbine blade

To ensure that the geometry of the turbine blade can be controlled in any production site, the geometrical definition of the component must be defined using ISO geometrical specifications in its free state.

3. State of the art; geometrical specification taking into account deformation effects

The following chapters give a brief overview on existing approach with regards to the approaches of ISO tolerancing and geometrical deformation management.

3.1. Sensitivity analysis

Sensitivity analysis consists in determining the influence of assembly parameters on key characteristics. Assembly parameters may represent fixture locators deviations or component geometry deviation from the nominal models. Sensitivity analysis is mainly performed when linear mechanical model can be used. In this case, the influence of each parameter can be determined by itself. The sensitivity matrix represents how the assembly geometry varies when a unit variation of a parameter is applied. This application is widely developed in the literature [5,6,7,8]. The parameter may represent a unit displacement at a given point or the amplitude of a deviation field for example.

Determination of sensitivity matrix is possible when the mechanical model of deformation is linear. In this case, sensibility is similar to the one obtained when dealing with rigid components. The only difference is that the locating scheme may be over constrained since the component complies on the mate joints. When dealing with non-rigid components, sensitivity integrates the relations between forces and displacements.

The calculation of the sensitivity matrix has to be available in tolerancing software since it is the basis for sensitivity analysis.

3.2. Free state and stressed state tolerancing

ISO standard [9] defines the rules for dimensioning and tolerancing of non-rigid components. This standard specifies dimensioning and tolerancing rules for non-rigid components that require the elements to be constrained when checking specified dimensions and tolerances.

The geometrical and dimensional tolerances followed by the symbol Ⓕ define the specifications to be checked in the free state when the other tolerances are defined by the conditions indicated in the associated note. This standard then leaves the choice of how to constrain the component. Numerically, components can be constrained by numerical simulation or physically by assembly tools.

Ascione and Polini [10] propose to evaluate the geometry of the component using a tool simulating its position in its use configuration. In this way, the deviations between the geometry of the assembled component and the nominal geometry are directly identified. These deviations take into account several factors:

- tightening sequence,
- assembly equipment,
- manufacturing process,
- measuring process.

Petitcuenot [11] proposes to define the geometry of a component by a free state and a constrained state by numerical simulation. The numerically constrained state corresponds to a defect filter that separates defects such as twisting and bending of the beam. This filtering is carried out by comparing component deviations with typical deformation models. These models represent defects that have no influence on the operation of the component. The assembly of all these models defines a technological modal base.

Filtering then allows more precise control of smaller defects such as holes or bumps that could disturb the airflow and thus alter the aerodynamic performance of the blade.

Radvar-Esfahlan [12], Sabri [13] or Thiébaut [14] propose an inspection method for non-rigid components based on simulation using finite element analysis. The component is first mounted on a tooling defining a geometrically equally constrained configuration. The only mechanical solicitations exerted on the component are the weight and forces exerted at the supporting points. This allows gravity deformations to be evaluated using finite element analysis for which positioning points are used as boundary conditions. Therefore, the actual geometrical deviations can be calculated by taking into account the rigid transformation of the model.

3.3. Geometrical specifications synthesis

Anselmetti [15,16] proposed the CLIC method to perform geometrical specifications synthesis based on knowledge of behavior, contacts and gaps within the mechanism. For each component of the mechanism, all contact elements are identified and indexed. Anselmetti constructs a position setting table for each component of the system Figure 3.

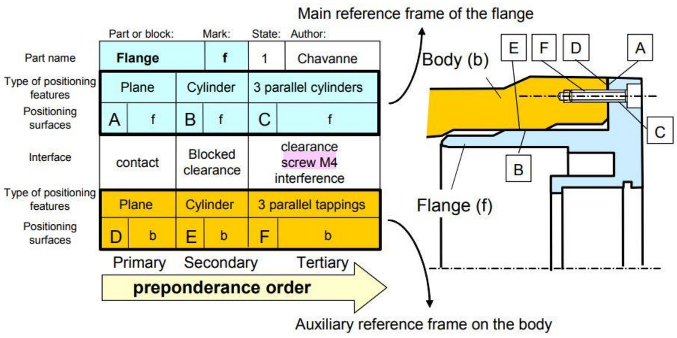


Fig. 3. Position setting table [15]

All junctions are ranked in the table. The two colors of the table identify two different components, line 2 defines the type of surfaces and line 3 identifies the surface. The rank is defined from left to right. Line 4 defines the type of contact between the surfaces of both components.

For each joint, the requirements for assemblability or assembly accuracy are defined. The geometrical data and indications provided by the positioning tables allow to deduce the geometrical requirements of each primary, secondary and tertiary link. Anselmetti then defines a standard tolerancing library to specify the surfaces of junctions in relation to the surface typology. The proposed specifications for the assembly shown in Figure 3 are shown in Figure 4.

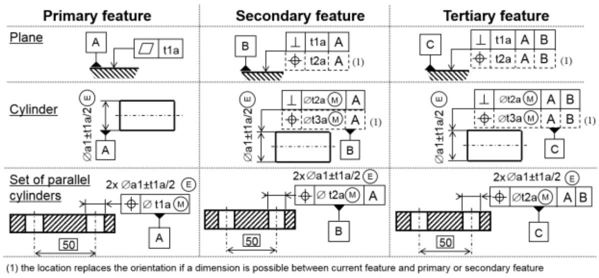


Fig. 4. Proposed geometrical specifications

CLIC method is suitable for the complete mechanical system. It is used to build datum systems and dimensioning of final surfaces when the complete assembly is defined.

3.4. Industrial issue

The low-pressure turbine blades are partly manufactured by companies outside Safran Aircraft Engines. The use of control assemblies, which reproduce the constrained state of the component, is not possible in industrial applications. Indeed, the use of such control assemblies requires replicating the positioning for each case. In order to respect the production rate, the companies do not have the possibility to create a constrained status of all components during their controls. The physically constrained configuration is therefore not applicable.

Definitions are often intended to be outsourced to other companies that have their own means and methods of control. The definition mus^{2} ^{2}t remain simple and unambiguous, allowing rapid production and inspection of components. It is difficult to impose digital processing on an external company, especially when more and more engines orders are placed and production lead times have to be reduced. As a result, approaches requiring the use of finite element calculation tools are not applicable.

Assemblies that include prestressed deformable components are complex. Conventional tolerancing methods for rigid components generally lead to very tight tolerances. In the following chapter we propose a tolerancing method of the rigid parts of a deformable component without constraining the displacements allowed by the deformable parts using ISO geometrical specifications.

This method is based on Anselmetti's proposed method for tolerancing rigid components and on a global analysis of the stiffness of the various parts of a slightly deformable component.

4. Proposed approach

As presented in section 2, the components to which the proposed approach applies are composed of rigid and deformable components. The proposed approach is to specify each rigid part using ISO geometrical specifications. The originality of the approach consists in defining some datum systems on several rigid parts, which allows the use of geometrical specifications that keep meaning even if the component is deformed. The proposed approach is illustrated on the component shown in the figure 5, which is called a specimen.

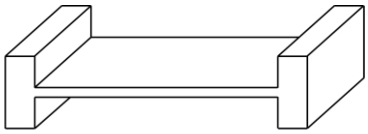


Fig. 5. Specimen

The parts 1 and 3 of the specimen shown in Figure 6 are rigid, part 2 is deformed in operating configuration. It therefore allows relative displacements between part 1 and part 3 during operation.

In this study, part 2 will show the relaxation of mobility between part 1 and 3.

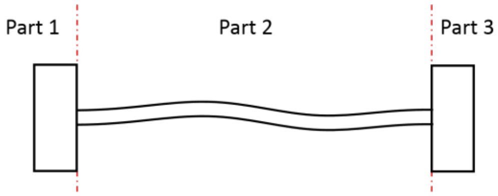


Fig. 6. Different parts of the specimen

The proposed approach consists of 4 steps that will be detailed in the following four subsections. These steps are:

- Analysis of positioning and mechanical solicitations on the component
- Analysis of component stiffness
- Association of mobility levels with rigid parts
- Building datum systems

4.1. Analysis of positioning and mechanical solicitations on the component

Figure 7 shows the position of the specimen in the constrained state. The detailed positioning is as follows:

- a planar joint represented by three point joints (1,2,3) on surface A
- a straight-line linear joint represented by two point joints (4,5) on the surface B
- a point joint (6) on the surface C
- a planar joint represented by three point joints (7,8,9) on the surface D

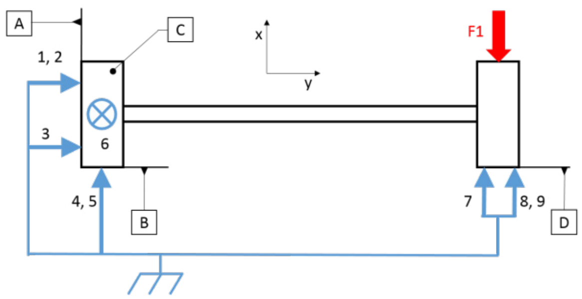


Fig. 7. Nominal position of the specimen

This positioning, which would be geometrically over-constrained for a rigid component, is made possible for the specimen by deformation of the part 2 due to force F1. The geometry in this nominal constrained state is the same as shown in the figure 5.

4.2. Analysis of component stiffness

Positioning of part 1 of the specimen is geometrically equally constrained via surfaces A, B and C. Part 3 of the specimen is kept in contact with plane D by the F1 effort and deformation of part 3. In the nominal operating configuration, the component is deliberately prestressed to eliminate any risk of gap in the links. This prestressing results in a geometry in the free state of the specimen that is different from that in the constrained state.

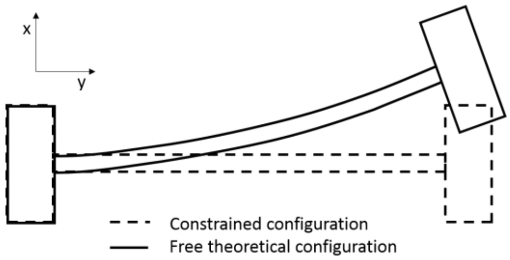


Fig. 8. Free state geometry of the specimen

The geometry of part 2 allows it to flex around the z-axis and twist around the y-axis. As a result, part 1 does not block the translation of part 3 following x nor the rotation around the y and z axes.

4.3. Association of mobility levels with rigid parts

The study of the rigidity of the part 2 makes it possible to determine the surfaces that suppress the degree of mobility of rigid parts.

Part 1 is directly positioned by six point joints (1,2,3,4,5,6) which define a geometrical iso-constrained positioning.

Part 3 degrees of freedom are suppressed by A, D and C surfaces. A (1,2,3) surface suppresses the translation y and rotation around x. D (7,8,9) suppresses the translation y and the rotations around x and z. Finally, C (6) suppresses the next translation z.

The result of this stiffness analysis is summarised in the table showing the association of the surfaces and the degrees of mobility removed.

Table 1. Suppression of degrees of mobility

Degrees of mobility	Part 1	Part 3
Tx	B	D
Ty	A	A
Tz	C	C
Rx	A	A
Ry	B	D
Rz	A	D

4.4. Building datum systems

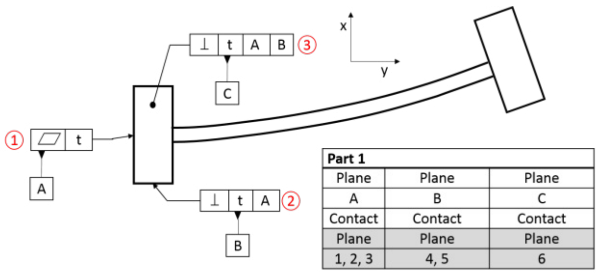
A datum system is associated with each rigid part. The datum systems are constructed using the positioning table defined by Anselmetti [15].

A specified datum system consists of an ordered list of two or three specified datums. The associated elements are obtained successively in the order defined by the geometrical specification. The relative orientation of the associated surfaces is theoretically exact but their relative position is variable.

This order defines the orientation constraints for the association operation: the primary specified datum imposes orientation constraints on the secondary and tertiary specified datums; the secondary specified datum imposes orientation constraints on the tertiary specified datum.

In the example of the specimen, part 1 is positioned by surfaces A, B and C. The table in Figure 9 shows the positioning table for part 1 defined by Anselmetti.

- surface A blocks three degrees of freedom.
- surface B blocks two degrees of freedom.
- surface C blocks the last degree of freedom.

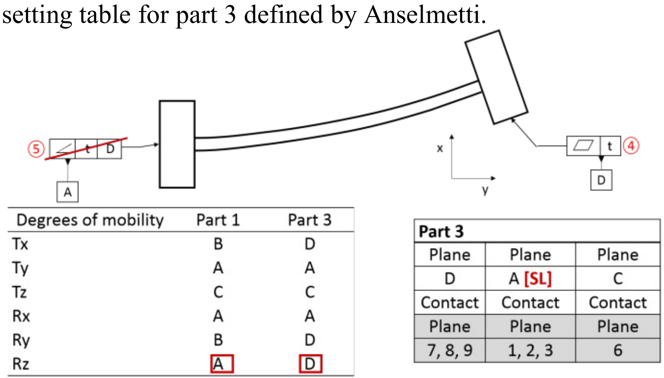


Part 1		
Plane	Plane	Plane
A	B	C
Contact	Contact	Contact
Plane	Plane	Plane
1, 2, 3	4, 5	6

Fig. 9. Datum system of part 1

Specifications 1,2,3 are determined using models for the tolerance of Anselmetti's positioning characteristics. The positioning is isostatic and the order of predominance of the surfaces is defined. The datum system then consists of the specified primary A, secondary B and tertiary C datums.

Part 3 is positioned by surfaces A, D and C. The table in Figure 10 without the red modifications represents the position setting table for part 3 defined by Anselmetti.



Degrees of mobility	Part 1	Part 3
Tx	B	D
Ty	A	A
Tz	C	C
Rx	A	A
Ry	B	D
Rz	A	D

Part 3		
Plane	Plane	Plane
D	A [SL]	C
Contact	Contact	Contact
Plane	Plane	Plane
7, 8, 9	1, 2, 3	6

Fig. 10. Datum system of part 3

Specifications 4,5,6 without red modifications are determined using models for the tolerance of Anselmetti's positioning characteristics. Table 1 defines the blocking of the rotation around z of part 3 by surface D. This makes it possible to simplify surface A as a line of A identified by secondary datum A[SL].

Specification 5 in Figure 10 orientates plane A with respect to D. This specification does not functionally represent the requirements of the component, part 3 moving with respect to part 1 following rotation around z, this specification is suppressed and a specification of the position of surface D with respect to surfaces A and B allows limiting the defect of rotation around z.

- surface D blocks three degrees of freedom
- surface A blocks two degrees of freedom
- surface C blocks the last degree.

The datum system consists of the specified primary D, secondary A and tertiary E datums.

Figure 11 shows specifications that meet the requirements.

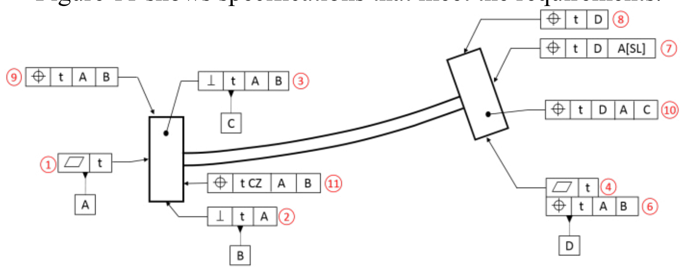


Fig. 11. Geometrical specifications on the specimen

Specifications 1,2,3,3,4,6 in Figure 11 are those defined by Anselmetti's CLIC method [15,16] in the models for the tolerance of positioning characteristics.

Specifications 8,9,10,11 are examples of functional requirements transcription. The same goes for specification 7, which fulfils a requirement limiting the translation defects x and rotation around z of part 3 with respect to part 1.

5. Conclusion

This paper focuses on the synthesis of geometrical specifications for components with rigid and deformable parts. The proposed method consists in modifying Anselmetti's geometrical specification synthesis method for rigid components by adapting it to the case of a component comprising rigid and deformable parts. A study of the rigidity of deformable parts is carried out to identify the degrees of freedom suppressed in these parts. A summary table summarizing the suppression of degrees of freedom is then proposed. The combined use of position tables and freedom suppression summary tables finally allows to specify the rigid parts of the component using ISO geometrical specifications.

The use of this method makes it possible to control the rigid parts of the deformable components without using a control assembly that reproduces the constrained state of the components.

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