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# Framework for the Monitoring of Functional Requirements Along the Product Life Cycle

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**ABSTRACT.** This paper presents a framework for the calculation of functional requirements at several stages of the product life cycle. It uses the TTRS/MGRE concept for the determination of dimension chains. The geometry of the assembly is represented using a parametric model constituted of points and vectors. Finally, it also integrates the calculation of part deformation due to changing operating conditions thanks to existing techniques such as finite elements.

**RÉSUMÉ.** Ce papier présente le cadre de développement d'une méthode pour le calcul d'une exigence fonctionnelle donnée à plusieurs étapes du cycle de vie du produit. Cette méthode utilise les concepts de SATT et EGRM pour déterminer les chaînes de cotes. La géométrie est représentée grâce à un modèle paramétrique constitué de points et de vecteurs. Enfin, le calcul des déformations mécaniques dues au changement des conditions d'utilisation sera intégré par l'utilisation de techniques existantes comme les éléments finis.

**KEYWORDS:** Functional requirements, PLM, Life Cycle, Part deformation, TTRS

**MOTS-CLÉS :** Exigences fonctionnelles, PLM, Cycle de vie, Déformations, SATT

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## 1. Introduction

In most cases, a mechanical product is subjected to thermo-mechanical loads which vary along its life cycle. These variations are inducing elastic deformations which in turn can influence the value of the functional requirements. Generally the useful value of a functional requirement is the one taken under operating conditions. However, the great majority of products are designed and represented in Computer Aided Design (CAD) systems at the assembly stage of their life cycle. This means in fact that the values of the functional requirements are not necessarily calculated under operating conditions.

A typical application that illustrates best the above idea would be that of a jet engine for which the functional requirements varies during its own lifecycle. Indeed, the clearance between the rotor blades and engine housing (or stator) of the turbine will be quite different at assembly and in operation due to the high temperature and rotation velocity to which the rotor is subjected in service.

Therefore, a comprehensive design process would have to integrate the possibility for the designer to specify the product at the desired stage of the product life cycle. This paper proposes a framework for the calculation and the representation of a functional requirement along the product life cycle. To effectively help the designer in this way, the proposal approach integrates part deformation (as calculated from the stress analysis) into the tolerancing process.

## 2. Literature review

### 2.1. *Analysis and synthesis of tolerance zones*

In the field of tolerancing, a lot of work has been done to analyse or synthesise tolerances [Ghie et al.2007, Laperrière et al.2002] at a given phase (usually the assembly, or the design phase) of the product life cycle. Optimization of tolerances has also been carried out by several authors [Chase and Greenwood1988, Hu and Peng2007]. Some of them are optimizing tolerance in order to maximize mechanism robustness [Parkinson2000] or to minimize its cost [Singh et al.2006]. Others are considering both issues in their optimization process [Anselmetti2006].

### 2.2. *Tolerancing deformable parts*

Here are presented prior researches which have caught the authors' attention. Firstly, Samper [Samper and Giordano1998, Samper and Giordano2003] presents an approach which considers the influence of both part deformation and fit of joint into the analysis or synthesis of tolerance zones. Secondly, Cid [Cid et al.2005] developed a model which permits the evaluation of clearances under loads using a clearance torsor introduced in [Cid et al.2004]. This study investigates the case of the clearance between a

vehicle door and its frame. The representation of parts considers 3D surfaces instead of 3D volumes. Finally, Pierre [Pierre et al.2008, Pierre et al.2009] has investigated part of the jet engine particular issue mentioned in the introduction.

### **2.3. Configuration management in PLM systems**

In the field of Product Life-cycle Management (PLM), some researchers have introduced interesting concepts like Zina [Zina et al.2006] who defined the concept of "context" which could be used to define loads and environment in the proposal approach. Alternatively Eynard [Eynard et al.2004] presents an object oriented approach to help the designing team with the transmission of both design and calculation data such as geometry, use cases, loads, etc.

## **3. Product structure**

In order to properly represent tolerance analysis or synthesis along the life cycle, this framework proposes the use of a specific representation for each physical state (life-cycle stage) of the product. These representations could be expressed through several views of the assembly and different representations of the parts themselves in Computer Aided Design (CAD) systems.

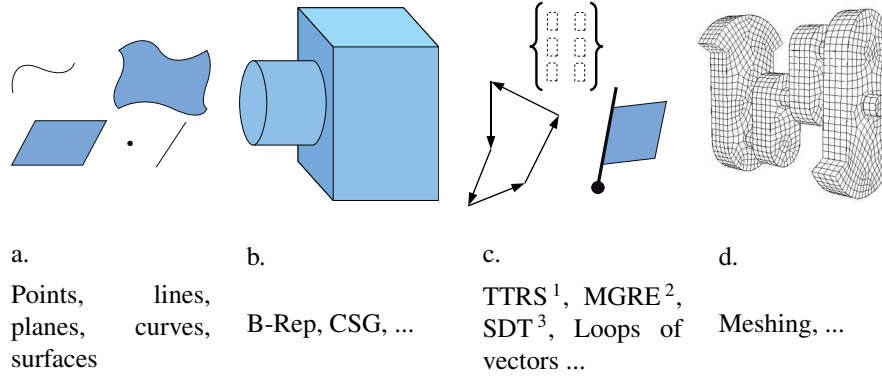
### **3.1. Assembly representations**

During the design phase, different design tasks must be completed and each one uses specific tools which are in turn based on one or several representations and theories. In the perspective of the proposed framework, all the models related to geometric modeling, tolerance analysis and simulation of part deformation need to be integrated. Some of these representations are presented in figure 1.

As it is the base of product design, the nominal CAD model will occupy a central place in the proposed framework. This model translates customer's expectations (in terms of functionalities) into the geometry of a virtual product. The approach also includes the creation of an upper level of geometric representation for functional requirements such as a skeleton representing ideal functional elements such as datums, interfaces, gauges, ... These elements compose a parametric model which is used to generate the final nominal geometry. The nominal geometry (or the parametric model) is in turn exploited for other designing tasks such as tolerancing or stress analysis.

Moreover, this study integrates Finite Elements Analysis (FEA) for the calculation of part deformations due to thermo-mechanical loads. Since it remains possible

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1. Technologically and Topologically Related Surfaces
  2. Minimum Geometric Reference Element
  3. Small Displacement Torsor



**Figure 1.** Models used for the representation of the mechanism

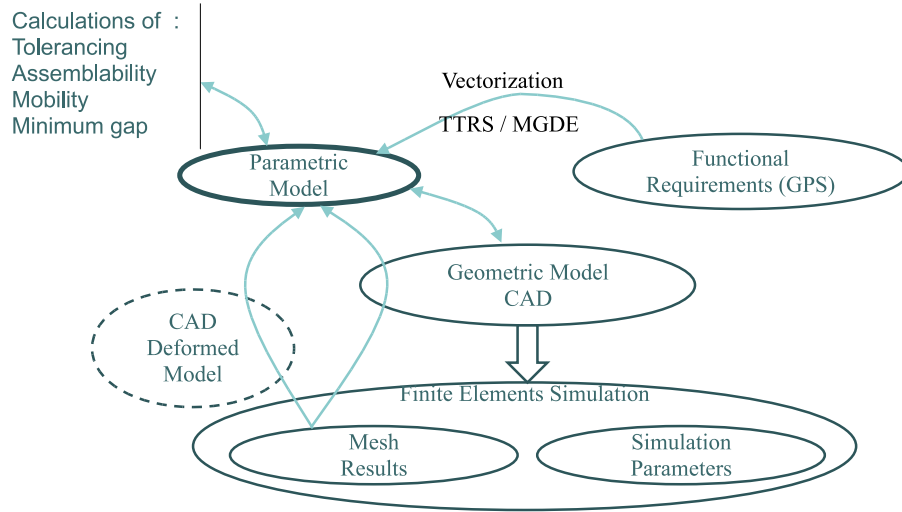
to obtain (or to develop) a Finite Element code for each physics involved along the product life cycle, this method can provide the designer with part deformation related to the changing environment in which the product evolves during its life-cycle. In this model, parts and assemblies are represented by discrete meshes.

Hence, the proposed framework includes several models to deal with functional requirement issues. As already explained in a previous paper [Mandil et al.2009] this framework will take functional requirements into account considering the evolution of their mean value along the product life cycle. However, it remains necessary to include tolerance zones in the model as they provide the designer with intervals for the potential value of a requirement (due to machining uncertainties). The analysis or synthesis of these intervals will be done using techniques presented in section 2. In order to monitor the evolution of the value of a given functional requirement, the framework proposes the use of TTRS<sup>1</sup> and MGRE<sup>2</sup> to build a vector loop linking the tolerance zones mentioned above. The evolution of the product along its own life-cycle will be characterized thanks to the evolution of the length and orientation of the vectors involved in the loop. The TTRS Model is based on a binary and recursive association of two functional surfaces (or group of surfaces). Globally, the goal of this association is to link each functional surface to another. The result of the association process on all the functional surfaces of a part or a mechanism is generally represented as a hierarchy tree. Additionally, this approach uses the concept of MGRE to obtain a mathematical representation of a given TTRS. The hierarchy tree is constructed by going through independent cycles in the kinematic graph. This theory is detailed in [Desrochers1991, Clement et al.1997, Desrochers2003].

### 3.2. Links and data exchange

In accordance with the previous subsection, and in order to properly represent assemblies, several models or views of the product will be needed. Since all of these

models represent the same product, the data contained in each model has to remain consistent with the others. Therefore communication is required between models. Figure 2 shows how these models are organized as a comprehensive set of data. Among



**Figure 2.** Links and data exchange between models

the four models presented in figure 2, the parametric model supports the core of the proposed approach because the calculation of the functional requirements are made on this model. Hence, the following paragraphs will outline how this model communicates with the three others. Considering that this framework uses finite elements tools as they are, the link between the CAD model and the finite elements tools will not be detailed here.

First of all, the functional requirements will be expressed as acceptable zones, datums, interfaces, gauges, etc. which will furthermore be represented in the parametric model using points and vectors and the TTRS / MGRE approach [Desrochers1991].

Secondly, the parameters defined in the parametric model can naturally be used in the CAD software to generate the corresponding geometry. Conversely, it still remains possible to measure the geometric features of the CAD model to determine the values of some parameters.

Thirdly, after the calculation of mechanical strains through finite elements techniques, the results have to be integrated into the parametric model. To this end, the authors propose to measure a deformed B-Rep model [Louhichi2008] and extract updated coordinates for the vectors defining the parametric model. For measurement purposes, the use of techniques inspired from metrology might prove to be helpful to determine MGRE coordinates on the deformed B-Rep model.

#### 4. Product requirements across the product lifecycle

The product life-cycle defines several use cases of the product which occur under different circumstances. In a typical scenario, the product works sequentially under various conditions. As these conditions induce dimensional variations (due to variations of the thermomechanical loads applied to the mechanism), it becomes useful to obtain a representation of the product at each relevant moment of its life-cycle in order to evaluate the functional requirement under each of those conditions.

Hence, this approach proposes the use of a specific mock-up for each relevant state of the product. Those mock-ups can be viewed as different configurations of the product and managed with existing PLM<sup>1</sup> techniques or tools.

Moreover, since the environment is not a design variable in itself, the specifications for a given requirement under two different states have to be compatible. To ensure such a compatibility, it might be useful for the designer establish priorities between the use cases of the product. Hence, strong requirement will be expressed for high priority states whereas slack specifications will correspond to low priority ones. For the jet engine example mentioned in the introduction (section 1) a strong requirement such as a minimum and maximum gap (with close values) should be expressed at the state where the engine is running at maximum power whereas a slack requirement of non-interference might be enough to ensure assemblability. In this case, the requirement in service has a greater priority than the same one at the assembly stage.

Finally, one can notice that there exists some redundancies in the information contained in the models representing the product at several states. For example, information such as joint topology or contact surfaces are supposed to be the same under all product states. It then appears interesting to consider the use of a structure to organize the data as a compact model.

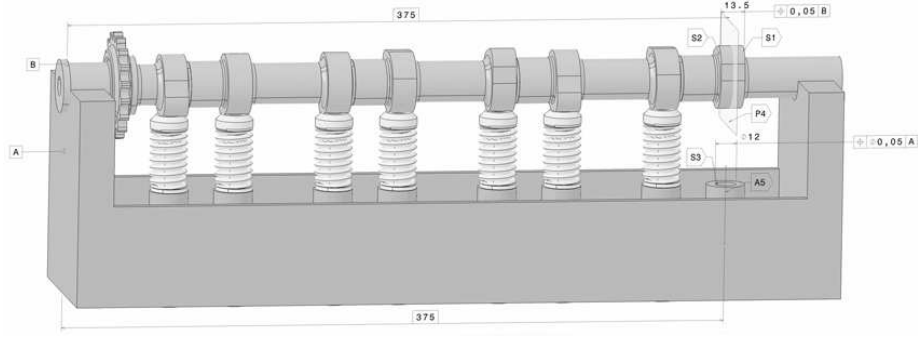
#### 5. Application case

In this section, the presented framework will be illustrated on a simplified camshaft and cylinder head mechanism presented in figure 3<sup>2</sup>. Each step of the proposal methodology will be treated manually with the following hypothesis.

The functional requirement under scrutiny will be the alignment of the valve support hole (noted S3 in figure 3) with the corresponding cam. In this scenario, the parts dimensions are supposed to be known after the assembly state of the life cycle, and the designer is concerned with the value of the misalignment in service due to the thermal expansion of the two parts. The cam which is the farthest from the shoulder of the camshaft bearing has been chosen in order to tackle the most unfavorable case in terms of thermal expansion. The value of thermal expansion misalignment must remain in-

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1. Product Life-cycle Management  
2. Enlargement in Annex I



**Figure 3.** Cylinder head and camshaft assembly

ferior to 0.2 mm under operating conditions. In our example, part deformation will not be calculated using a finite elements analysis, but rather employing a theoretical formulation.

### 5.1. Hypothesis

All usefull dimension values are presented in figure 3. The temperature at the assembly stage of the life cycle is 20°C. The cylinder head is made of aluminium and the camshaft of steel. Typical values of thermal expansion coefficients are presented in table 1. In service, the cylinder head is subjected to a temperature of 90°C whereas the camshaft temperature is 80°C.

| Material  | Notation   | Value                       |
|-----------|------------|-----------------------------|
| Aluminium | $\alpha_a$ | $2.38 \cdot 10^{-5} K^{-1}$ |
| Steel     | $\alpha_s$ | $1.20 \cdot 10^{-5} K^{-1}$ |

**Table 1.** Typical values of thermal expansion coefficient

In order to keep calculations simple, the authors have considered the restrictive but reasonable hypothesis of a one dimensional thermal expansion of the two parts along the cam shaft axis. The dimensions after thermal expansion will be computed thanks to the equation 1 where  $S_f$  and  $S_i$  stand for final and initial stage of the assembly life cycle,  $T$  for temperature and  $L$  for length. One can note that temperature and length depend on the life cycle stage.

$$L(S_f) - L(S_i) = \alpha \cdot L(S_i) \cdot (T(S_f) - T(S_i)) \quad [1]$$



## 5.2. Parameterization of the model

The first step in obtaining the parameterization vectors is to associate a TTRS to each pair of functional surfaces. Secondly, one has to build the TTRS tree for each part using the association rules described in [Desrochers1991, Clement et al.1997, Desrochers2003]. The construction of the TTRS tree induces the choice of an associated MGRE for each TTRS. Finally the vectors are deduced from both the TTRS tree and their associated MGRE.

For the construction of the TTRS tree representing the camshaft as shown in figure 4a, one must first denote that all the surfaces involved are planar. Consequently surfaces are associated as planar TTRS and their corresponding MGRE are matching theoretical planes. More specifically the example features three planar surfaces : B, S1 and S2. In the TTRS tree construction process, S1 and S2 have been associated first. As these two planes are parallel, the TTRS resulting from this association (P4) is also a planar TTRS parallel to its children surfaces. Accordingly, the associated MGRE is the median plane of S1 and S2 bears the name P4. Secondly, surface B is associated with P4, and the resulting TTRS (called CS in figure 4) is also planar and parallel to B and P4. The TTRS CS carries the distance between shoulder B and MGRE P4. Finally, the associated vector in the parametric model is normal to B and its norm is equal to the distance between B and P4 ; it is noted  $\overrightarrow{V_{CS}}$ .

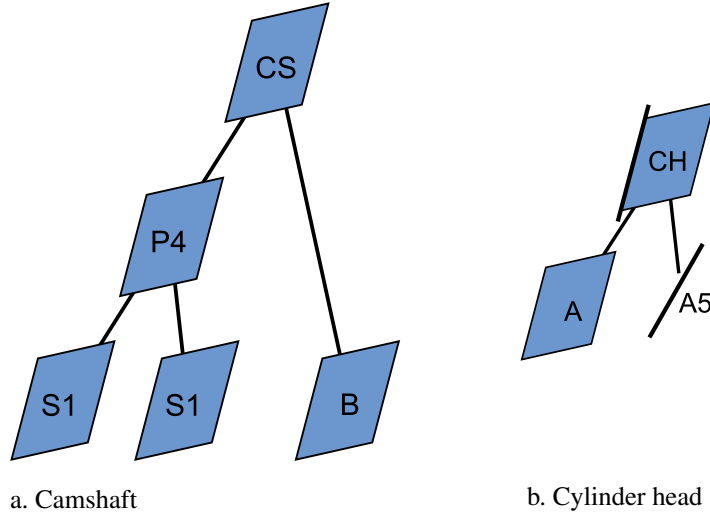
The same method is used to build the TTRS tree of the Cylinder head (figure 4b). This part has two functional surfaces, plane A and Cylinder S3. Cylinder S3 is represented by its axis or MGRE as the A5 line. Plane A and A5 are associated as TTRS CH. As the A5 line is parallel to plane A, the resulting TTRS is prismatic. This TTRS obviously carries the distance between plane A and A5. Therefore, the associated vector in the parametric model is normal to plane A and its norm is equal to the distance between plane A and line A5 ; it is noted  $\overrightarrow{V_{CH}}$ .

This parameterization allows the designer to characterize the alignment default between the cam and the valve support hole using to the norm :  $\|\overrightarrow{V_{CS}} - \overrightarrow{V_{CH}}\|$

## 5.3. Calculations

Thanks to the hypothesis in section 5.1 and the dimensions specified in figure 3, it becomes possible to calculate with equation 1, the norm of  $\overrightarrow{V_{CS}}$  and  $\overrightarrow{V_{CH}}$  under their service temperatures. The results are presented in table 2. They show that during the assembly stage of the life cycle to operating conditions the cam and the valve support hole are subjected to unacceptable misalignment. Indeed this default is greater than 0.2 mm.

As mentionned in section 4, the designer must establish priorities between the several stages of the life cycle. In this case, it appear obvious that the respect of functional requirement under operating conditions is more important than at assembly. Therefore it becomes interesting to compute what dimensions must be specified at 20°C in or-

**Figure 4.** TTRS tree of the parts

| Vector                        | Final temperature | Norm at 20°C | Norm at final temperature |
|-------------------------------|-------------------|--------------|---------------------------|
| $\vec{V}_{CS}$                | 80°C              | 375 mm       | 375.270 mm                |
| $\vec{V}_{CH}$                | 90°C              | 375 mm       | 375.625 mm                |
| $\vec{V}_{CS} - \vec{V}_{CH}$ |                   | 0 mm         | 0.355 mm                  |

**Table 2.** Final norm of parameterization vectors

der to have the cam and the valve support hole aligned under operating conditions. To compute these dimensions, the same approach was used as that described earlier. Hypothesis and results are presented in table 3.

| Vector                        | Initial temperature | Norm at initial temperature | Norm at 20°C |
|-------------------------------|---------------------|-----------------------------|--------------|
| $\vec{V}_{CS}$                | 80°C                | 375.625 mm                  | 375,355 mm   |
| $\vec{V}_{CH}$                | 90°C                | 375.625 mm                  | 375 mm       |
| $\vec{V}_{CS} - \vec{V}_{CH}$ |                     | 0 mm                        | 0.355 mm     |

**Table 3.** Updated norm of parameterization vectors at 20°C

These results (in table 3) show that there is no misalignment anymore under operating condition. However the 0.235 mm wide misalignment default is now detectable at assembly state (at 20°C). This misalignment default has to be added to the default calculated during the analysis of the functional requirement along the corresponding dimension chain (which has not been carried out in this study). If the accumulation of these two sources of misalignment produces a non acceptable default at assembly stage, then the complete system has to be redesigned altogether. In order to reduce

the misalignment due to thermal expansion, one solution would be to place the shaft shoulder in the middle of the camshaft itself, therefore distributing the thermal expansion on both sides.

## 6. Conclusion and perspectives

This paper has presented a framework for the representation and calculation of functional requirement values along the product life cycle. The proposed framework is based on existing concepts used in the field of tolerancing such as TTRS and MGRE for the definition of dimension chains and the study of functional requirements. It also uses existing tools like finite elements for the calculation of part deformation. It finally proposes the original idea of representing, with distinct configuration, each state of the product during its life cycle. To this end, a point and vector based model originating from the TTRS/MGRE representation is build. The advantage of this approach stems from the use of high level management tools such as TTRS and MGRE for geometries and tolerance zones representation. The future development of this approach will include the integration of 3D dimension chains and the automation of the method. The authors also envision the integration of this framework with PLM tools for the management of configurations, and the use of an object oriented formalism to represent parts and mechanisms and organize the data contained at the different levels of product modelisation.

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**Annex I : Enlargement of figure 3**

