PRACTICAL EXAMPLE OF A THERMO-ELASTIC CLASSIFICATION SYSTEM

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ABSTRACT

Future space missions require ever increasing levels of pointing accuracy to accomplish their missions successfully. As the requirements of these missions become ever more stringent, it is of utmost importance to characterize and predict precisely the thermo-elastic behaviour of these instruments and spacecrafts. Over the last few years, ATG Europe B.V., Thales Alenia Space France and Italia, and OHB System AG have presented multiple times their work on different aspects of TE analysis [1-2,5 -7]. Since 2021, a consortium of these core partners has worked on the TEV (Thermo-Elastic Verification) project under ESA contract [3]. A significant contribution of this project is the definition of a classification system, which consists in an efficient integrated workflow that allows the engineer to quantify the contribution of different deformation mechanisms and features to the overall deformation of the instrument. Such method is supported by an integrated analysis toolset that allows the engineers to perform efficiently complete multidisciplinary loops (e.g., full STOP iterations).

The main target of such methodology is providing knowledge on the design parts and features with the biggest contribution on the final thermo-elastic performance. This therefore points the engineer directly to the specific parts or features whose modelling and design shall be paid special attention.

This paper will show a practical example of such methodology. Results and example models are based on the aforementioned Thermo-elastic Verification activity [3].

1. INTRODUCTION AND CONTEXT

Thermo-elastic verification deals with prediction of stresses and deformations due to thermal loading of a structure. In most cases, the thermo-elastic deformations during operational phases may cause degradation of the performances of the instruments on the spacecraft. This article presents a practical application of the thermo-elastic classification method developed in the context of the ESA funded project "European Methods for Thermo-Elastic Verification", in collaboration with key companies in the European Space sector. Such project aims at establishing Europe wide accepted and validated methods for thermo-elastic verification.

The classification process is one of the steps of the thermo-elastic verification approach proposed in the guidelines generated as output of the project [4]. The objective of the proposed approach is to verify, avoiding unnecessary efforts, that the response of the performance parameters of a structure remains within specification during a mission, while having a robust repeated process that minimizes the total effort. Nevertheless, in order to do so, it is fundamental to understand the contribution of certain features to the structure's response under the applicable thermal environment. For the sake of clarity, here are some definitions of the terms established as thermo-elastic terminology, for further information please refer to [4]:

- Feature: The term feature is used to describe any potential aspect in the mathematical model, physical model or design, which may affect the magnitude of the TE (Thermo-Elastic) responses. Some features can be quantified, but others cannot. Material properties, mesh density or the representation of a certain part are examples of features.
- Performance parameter: Output supporting the verification of the compliance to a TE performance requirement. It can be either a direct TE ouput, or some form of derived magnitude obtained by post-processing a direct TE output.

The thermo-elastic verification process allows the engineers to identify the criticalities of various features of a structure for the TE performance using thermal and structural models. The four main steps of the process are:

1. Identification: establishing which performance parameters are relevant for the problem, and which thermo-mechanical deformation mechanisms may critically affect these performance parameters.
2. Modelling: best practices to capture all relevant thermo-mechanical deformation mechanisms and establish mathematical adequacy of the modelling.
3. Classification: establish which thermal cases, thermal features, mechanical features, and thermo-mechanical features of the design are critical for ensuring positive margins on these performance parameters.
4. Final performance compliance verification: once a model is deemed fit for purpose the formal verification against requirements can be performed.

This article focuses on showing an example of the application of the third step, classification.

2. THE CLASSIFICATION PROCESS

The classification process consists in performing different numerical methods as described in [4] to determine whether the models are considered sufficient to meet the verification needs of the project or further refinement of certain areas is required.

The different analysis and numerical methods are applied to the models (usually thermal and structural) that were developed in the modelling step. The classification is then performed in the three fields of interest, the thermo-mechanical, the thermal and the structural.

The three metrics driving the decision to state either a need for refinement of some features or the compliance of the model as “fit for purpose” are:

1. The overall margin of each performance parameter. Margin here refers to the difference between the calculated value and the applicable requirement taken as reference. Such margin is calculated with an initial TE analysis of all the relevant thermal scenarios with the model generated in the modelling step.
2. The relative contribution of the different features to the performance parameters, meaning the impact of each feature on the calculated values of the performance parameters. Such metric is estimated based on a double logic: first, the magnitude of the performance responses variations is compared to the overall margins; second, the relative contribution of the different features to such responses’ variation is analysed to determine which features have a higher contribution.
3. The uncertainties associated with the performance parameter responses caused by the uncertainties of the different features. The assessment of this metric is applicable to the thermal and structural models and will be applied in the so called thermal and structural model impact assessment. Note that the uncertainty can be defined through different means [4] and account also for missing features/parts. Therefore, uncertainties will in many cases be based on qualitative assessments rather than quantitative values. Uncertainties assessment is therefore likely to improve with experience, with the application of the process to multiple projects.

It is important to remark that this assessment is performed separately for each relevant thermal case and performance parameter. Nominally, the combination of the outputs of each metric and for each thermal case give the engineers an overview of the need to further update the model or not. However, such process can be lengthy, and in some cases, performing the complete process might not be needed. Then, by considering the three metrics as a whole, the classification process can be tailored to the specific application: For example, a simple equipment with high initial margins may not need a complete and extensive numerical classification. On the other hand, complex systems with very stringent performance requirements may need to follow the full process.

The outcome of the classification process will determine where improvement of the model is needed, or whether the current models can be considered adequate or fit for purpose. In this document this model improvement is referred to as “refinement”.

3. EXAMPLE PROBLEM

The example provided in this article is the PLATO DMBB (Demonstrator model Breadboard). It is a cut-out of the PLATO optical bench assembly consisting of 4 camera departments instead of 26. It was used by OHB in a thermo-elastic campaign [5]. It has also become one of the practical examples of reference within the thermo-elastic verification methods project [4].

In Figure 3-1 an overview of the design elements of the PLATO DMBB are shown. The DMBB is primarily made of CFRP and Titanium. The titanium parts serve primarily as interface elements whereas the main structural support/stiffness is provided by the CFRP parts. The CFRP panels are bolted together in combination with Aluminium inserts or CFRP cleats.

Both the Titanium and CFRP parts serve a thermal insulator. In addition, the CFRP also has a very low CTE.

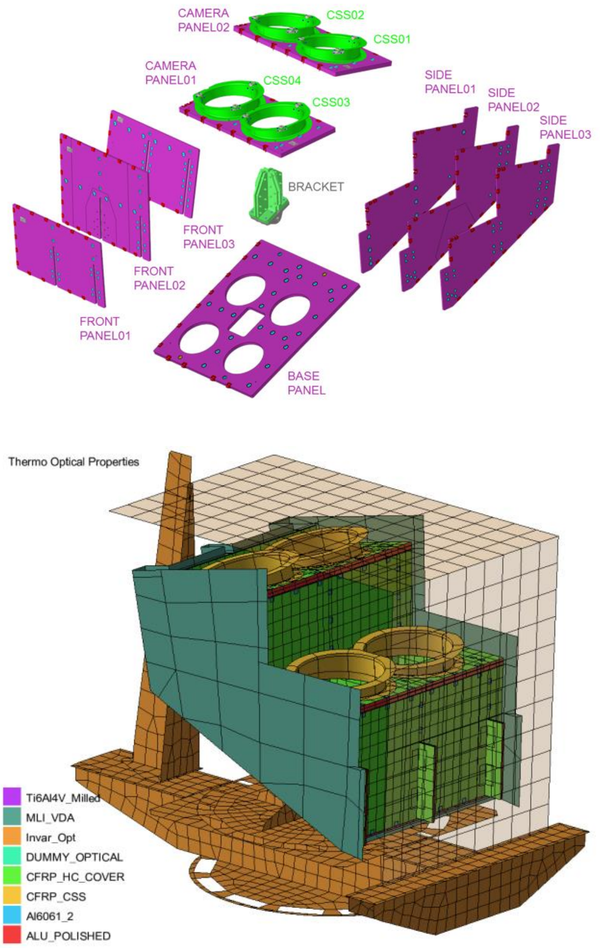

Figure 3-1: PLATO DMBB design elements overview

This example is considered of great interest due to the existence of previous TE studies and of testing data. However, also due to the existence of previous studies and a TE test, it has some particularities. For instance, the thermal scenarios considered in this example are limited to the test phases highlighted below (see Figure 3-2):

Because the test setup of the PLATO DMBB was specifically designed to measure the relative rotations of the camera mountings (CSS), the (fictitious) performance parameters for this example are the LoS (Line of Sight) of the 4 CSS's in-plane, for both the x and y direction (see Figure 3-1), with respect to the CSS1:

- Stability in the sinusoidal, transient part of the test
- Absolute deviation, in the "max. gradients" as marked in Figure 3-2.

Other possible performance parameters such as strength are not considered for this example.

4. APPLICATION OF THE CLASSIFICATION PROCESS

For the numerical classification of the PLATO DMBB three separate steps are carried out:

- Thermo-mechanical classification
- Structural model impact assessment
- Thermal model impact assessment

As stated above, the performance parameter considered are the relative rotations of the CSSs 2, 3 and 4 with respect to CSS1. Table 4-1 shows the results of the initial calculations of the thermal cases considered in this example. As it can be observed, the largest distortions correspond to the relative rotations of CSS4 relative to CSS1. For the sake of simplicity, in this article the results will focus only on this performance parameter, but the same assessment shall be performed for all the performance parameters.

To start the classification process, the three metrics are calculated or estimated for each performance parameter and thermal case. The logic applied to the estimations is:

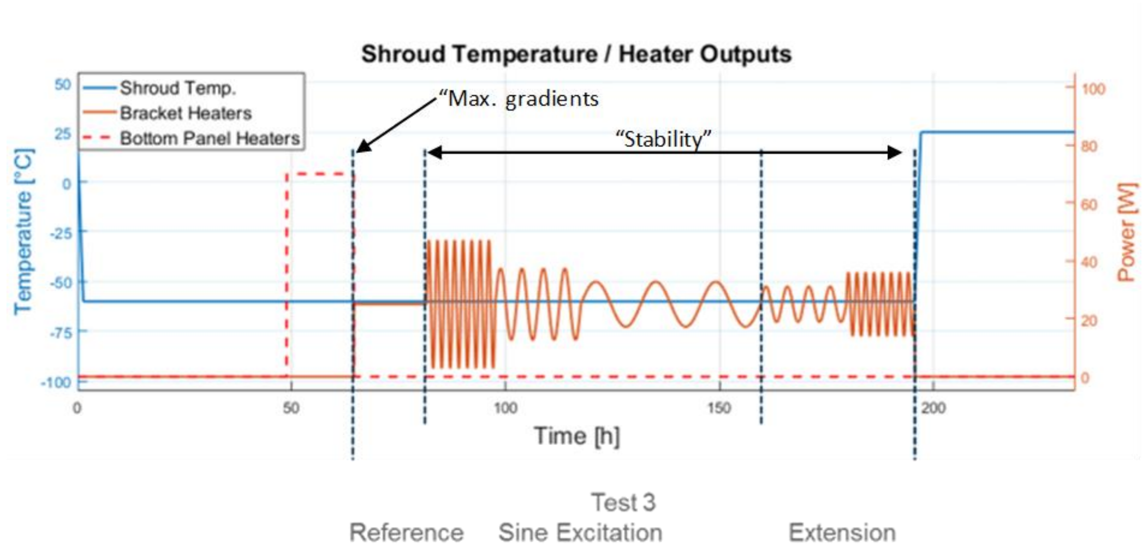

Figure 3-2: Schematic overview of the PLATO DMBB test phases

- Metric 1: The overall margin of the performance parameter is quantitatively unknown due to the lack of explicit requirements. Therefore, this metric is qualitatively defined as small and positive in this example (i.e. overall margin: medium).
- Metric 2: Regarding the relative contribution to the performance parameter's response, considering the lack of overall margin in this example, the contribution of the different features has been qualitatively classified as Low, Mid, or High, depending on the relative magnitude with respect to the contribution of the other features.
- Metric 3: The uncertainty covers the implicit uncertainty of each feature. For instance, the fact that bolts have been modelled as springs, but the exact level of representativeness is not known.

Table 4-1: Results of the initial TE analysis for the "Stability" and "Max. Gradient" phases of the test

Transient	Rotation axis	Max. peak to peak variation in "Stability" phase [µrads]	Distortion in "max. gradient" phase [µrads]
CSS2	R1	24.22	-66.8
	R2	4.30	-54.2
CSS3	R1	5.92	7.1
	R2	11.61	-47.1
CSS4	R1	23.44	-73.3
	R2	14.67	-82.9

Since in this example there are no overall margins of the performance parameters, the need for refinement has been assessed qualitatively, only based on the contribution and uncertainty of each feature. Thus, the need for refinement stated in this exercise may not be applicable, since the margins could already be large enough.

In the following subsections, the three classification steps defined above are developed. Given the interest and complexity of the here called thermo-mechanical classification methods (especially its specialised versions), this article focuses on that part of the process and its logic.

5. THERMO-MECHANICAL CLASSIFICATION METHOD

For the thermo-mechanical classification different features of the structure are identified and grouped together (in groups of nodes). Then, the importance of the different regions of the model can be assessed by analysing the contribution of different features (here the regions) of the model to the total performance parameter response. However, unlike a thermal or structural model impact assessment, the thermo-mechanical classification normally does not provide a readily interpretable answer. The results might be driven by underlying thermal or structural model, or by the regions in which the model was grouped. Therefore, the conclusions here extracted may need to be verified using dedicated sensitivity analysis on the thermal and/or structural models.

The basic principle of this methodology relies on linear super-position as expressed with the equation (1):

$$\{\boldsymbol{u}\}_{group\ n} = \begin{bmatrix} TE \\ Transfer \\ Matrix \end{bmatrix} \begin{bmatrix} \{\boldsymbol{0}\}_{group\ 1} \\ \dots \\ \{\boldsymbol{\Delta T_{TN}}\}_{group\ n} \\ \dots \\ \{\boldsymbol{0}\}_{group\ N} \end{bmatrix} \qquad (1)$$

The basic idea of this approach already exists for a long time. For instance, in [8] Airbus DS presents a process that follows a similar logic, using unitary temperature increase methodologies to highlight the main thermal and mechanical contributors to the stability. In this paper an extended version, showing even more insight into the TE contributors is explained and used.

5.1. Steady state "Max Gradient" results

This method consists in applying the real temperature field (as opposed to unitary temperature fields) of one of the thermal scenarios to the T-nodes belonging to one of the groups the model is divided into. By doing so, it is possible to analyse the contribution of each of the groups to the performance parameter response. This provides high value information regarding which features have the biggest contribution under the thermal environments.

Figure 5-1 is an example of the kind of results that can be obtained through the application of the here presented classification methods. It is a plot which displays much information, trying to show in an easy-to-read manner multiple levels of information on the responses of the performance parameters. For instance, Figure 5-1 shows the contributions of different T-node groups and physical phenomena in a nested fashion. This is possible because by application of the principle of linear superposition, it is possible to decompose the thermal loads in a manner that allows to calculate the contribution to the performance parameter response due to different phenomena (see [5][6] for further details). The logic behind it is the following:

On a first level, the empty yellow bars represent the total performance parameter response caused by the group defined in the X axis label. In this example, the constituent contributions to the total

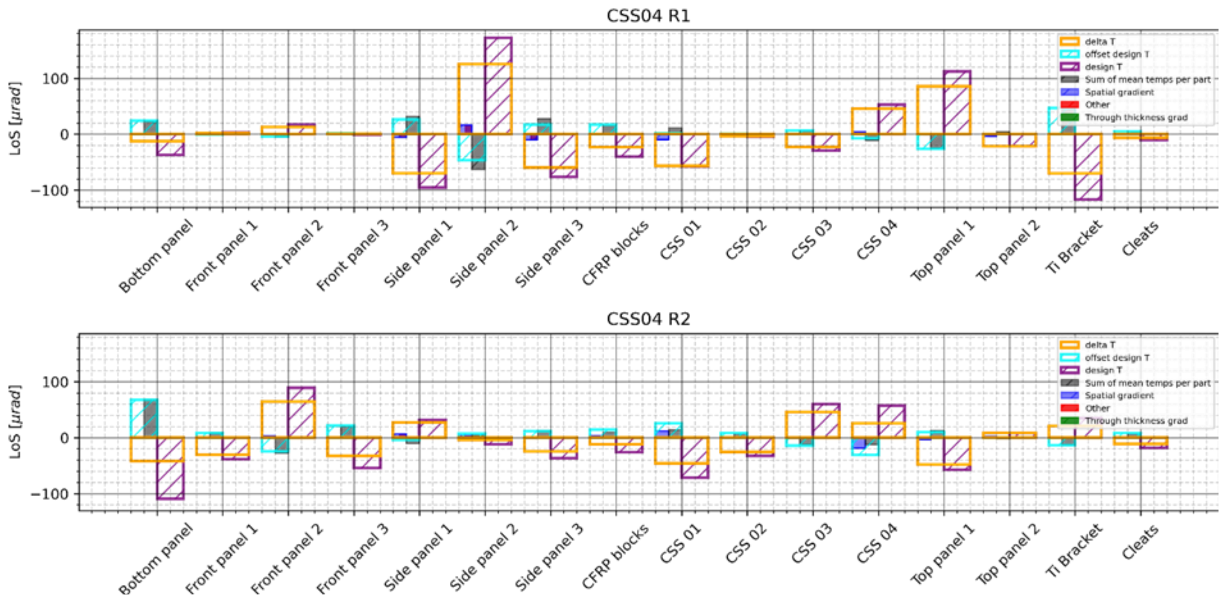

Figure 5-1: Contributions to the total performance parameter response “Relative rotation CSS4 w.r.t CSS1” in the thermal scenarios “Max. Gradient” of the different groups the model is divided into and the type of thermal loads.

performance parameter response have been presented with it. The contributors are, on a first level of distinction, the contributions of the design temperature field and the temperature offset relative to the design temperature.

$$\{\boldsymbol{u}\} = \sum_{n=1}^{N} \{\boldsymbol{u}\}_{design\ offset,\ \ group\ n} + \sum_{n=1}^{N} \{\boldsymbol{u}\}_{design,\ \ group\ n} \tag{2}$$

Then, the contribution to the performance parameter response due to the offset w.r.t the design temperature field is further analysed, dividing it into the contributions due to the mean temperature and due to the spatial gradients.

$$\{\boldsymbol{u}\}_{design\ offset} = \sum_{n=1}^{N} \{\boldsymbol{u}\}_{\mu_{spatial},\ \ group\ \ n} + \sum_{n=1}^{N} \{\boldsymbol{u}\}_{spatial\ variations,\ \ group\ n} \tag{3}$$

Finally, the contribution to the performance parameter response due to the spatial gradients is divided into the contributions due to the through thickness gradients and other possible gradients.

$$\{\boldsymbol{u}\}_{spatial\ variations} = \sum_{n=1}^{N} \{\boldsymbol{u}\}_{diff.\ grad.,\ \ group\ n} + \sum_{n=1}^{N} \{\boldsymbol{u}\}_{center\ temperature,\ \ group\ n} \tag{4}$$

Therefore, each of the coloured bars plotted inside the first one displays the contribution of a specific physical phenomenon to the total response.

These individual contributors to total response of the performance parameter follow from variations of equation (1). They are provided below in a generalized sense. However, if the contribution is computed over only a subset of the types of thermal loads (e.g. on *offset design T* instead of *Delta T*) then the temperature vector ΔT_{TN} will need to be adjusted accordingly.

The specialised classification methods applied in this example, together with a brief description of their logic are summarized below:

- For some applications it makes sense removing the static component of the performance parameter responses caused by the difference between the reference temperature and the design operating temperature. This allows to focus on the variations of the responses relative to a constant temperature (stability analysis).

$$\{\boldsymbol{u}\}_{\boldsymbol{design\ offset,\ \ group\ n}} = \begin{bmatrix} TE \\ Transfer \\ Matrix \end{bmatrix} \begin{bmatrix} \{\boldsymbol{0}\}_{group\ 1} \\ \cdots \\ \{\boldsymbol{\Delta T_{TN}} - \boldsymbol{\Delta T}_{design}\}_{group\ n} \\ \cdots \\ \{\boldsymbol{0}\}_{group\ N} \end{bmatrix} \tag{5}$$

$$\{\boldsymbol{u}\}_{\boldsymbol{design},\ \boldsymbol{group\ n}} = \begin{bmatrix} TE \\ Transfer \\ Matrix \end{bmatrix} \begin{bmatrix} \{\mathbf{0}\}_{group\ 1} \\ \dots \\ \{\boldsymbol{\Delta T}_{design}\}_{group\ n} \\ \dots \\ \{\mathbf{0}\}_{group\ N} \end{bmatrix} \quad (6)$$

With

$$\boldsymbol{\Delta T_{design}} = \boldsymbol{T_{design}} - \boldsymbol{T_{ref}} \quad (7)$$

Being the total performance parameter response defined as the sum:

$$\{\boldsymbol{u}\} = \sum_{n=1}^{N} \{\boldsymbol{u}\}_{design\ offset,\ group\ n} + \sum_{n=1}^{N} \{\boldsymbol{u}\}_{design,\ group\ n} \quad (8)$$

- Effects due to spatial temperature gradients: In this case, the mean spatial temperature of the offset temperature field w.r.t to the design temperature of each group is computed and subtracted from the T-Nodes temperatures as follows:

$$\{\boldsymbol{u}\}_{spatial\ variations,\ group\ n} = \begin{bmatrix} TE \\ Transfer \\ Matrix \end{bmatrix} \begin{bmatrix} \{\mathbf{0}\}_{group\ 1} \\ \dots \\ \{\boldsymbol{\Delta T_{TN}} - \Delta T_{\mu_{spatial,\ group\ n}}\}_{group\ n} \\ \dots \\ \{\mathbf{0}\}_{group\ N} \end{bmatrix} \quad (9)$$

Where $\mu_{spatial}$ represents the spatial average. The contribution of the T-node group mean temperature can be calculated as computed similarly:

$$\{\boldsymbol{u}\}_{\mu_{spatial},\ group\ n} = \begin{bmatrix} TE \\ Transfer \\ Matrix \end{bmatrix} \begin{bmatrix} \{\mathbf{0}\}_{group\ 1} \\ \dots \\ \{\boldsymbol{\Delta} T_{\mu_{spatial\ \ group\ n}}\}_{group\ n} \\ \dots \\ \{\mathbf{0}\}_{group\ N} \end{bmatrix} \quad (10)$$

Being the total performance parameter response the sum of the individual contributions:

$$\{\boldsymbol{u}\} = \sum_{n=1}^{N} \{\boldsymbol{u}\}_{\mu_{spatial},\ group\ n} + \sum_{n=1}^{N} \{\boldsymbol{u}\}_{spatial\ variations,\ group\ n} \quad (11)$$

- Effects due to differential bending (through thickness temperature gradients): Following a similar approach it is possible calculating the contribution caused by the through thickness gradients. This method provides useful output only for parts in which such temperature gradients are well and unambiguously defined. For this method, it might be needed to divide a T-Node group into two sub-groups, one with the nodes corresponding to the top panel and another one with the nodes of the bottom panel.

$$\{\boldsymbol{u}\}_{diff.\ grad.,\ group\ n} = \begin{bmatrix} TE \\ Transfer \\ Matrix \end{bmatrix} \begin{bmatrix} \{\mathbf{0}\}_{group\ 1} \\ \dots \\ \left\{\Delta \boldsymbol{T_{TN\ (Top)}} - \frac{\Delta \boldsymbol{T_{TN(Bot)}} + \Delta \boldsymbol{T_{TN\ (Top)}}}{2}\right\}_{group\ n\ (Top)} \\ \left\{\Delta \boldsymbol{T_{TN(Bot)}} - \frac{\Delta \boldsymbol{T_{TN\ (Bot)}} + \Delta \boldsymbol{T_{TN\ (Top)}}}{2}\right\}_{group\ n\ (Bot)} \\ \{\mathbf{0}\}_{group\ N} \end{bmatrix} \quad (12)$$

$$\{\boldsymbol{u}\}_{center\ temperature,\ group\ n} = \begin{bmatrix} TE \\ Transfer \\ Matrix \end{bmatrix} \begin{bmatrix} \{\mathbf{0}\}_{group\ 1} \\ \dots \\ \left\{\frac{\boldsymbol{\Delta T_{TN(Bot)}} + \boldsymbol{\Delta T_{TN\ (Top)}}}{2}\right\}_{group\ n\ (Top)} \\ \left\{\frac{\boldsymbol{\Delta T_{TN\ (Bot)}} + \Delta \boldsymbol{T_{TN\ (Top)}}}{2}\right\}_{group\ n\ (Bot)} \\ \{\mathbf{0}\}_{group\ N} \end{bmatrix} \quad (13)$$

Being the total performance parameter response defined as the sum:

$$\{\boldsymbol{u}\} = \sum_{n=1}^{N} \{\boldsymbol{u}\}_{diff.\ grad.,\ group\ n} + \sum_{n=1}^{N} \{\boldsymbol{u}\}_{center\ temperature,\ group\ n} \quad (14)$$

- In addition, a similar methodology can sometimes be applied to highlight the effect of CTE mismatches in the design. Given that the base structure is made of low CTE CFRP, this method was not applied on the PLATO DMBB and is excluded from this paper.

The application of such a methodology (which results were shown in Figure 5-1) allows some preliminary conclusions to be extracted for this example:

- Absolute temperature levels are the drivers of the performance parameter response. The contribution of spatial gradients is reduced.
  - Practically there is no contribution due to the through thickness temperature gradients.
  - The contribution of the spatial gradients is negligible compared to the absolute temperature levels.
- The contribution of the side panels, front panels and CSS seems to balance each other to a large extent.

These conclusions can be combined with the other metrics as is shown in Table 5-1. In this table, the overall margin of performance parameter follows directly from a tradition margin computation and is shared by all features of the model (as it is a global property for each individual performance parameter). The contribution from a feature follows directly from the numerical process described in the preceding section. Finally, the uncertainty is based on a qualitative assessment based on all available information, taking into account the amount of detail that is put into the model, typically uncertainty from similar items and/or materials properties etc.

By combining these three metrics it is then decided whether any of the features require further refinement. In this context refinement refers to the process of systematically increasing the confidence in the model predictive capability through the reduction of uncertainty. Examples of refinement in the context of this document are model correlation by testing, Sub-Models/ Local modelling studies, detailed modelling, mesh convergence studies.

It can be observed that in this first step the model has been found fit for purpose. These preliminary conclusions shall be consolidated through thermal and structural impact assessments (see also sections 6 and 7). As briefly described in previous section, the concise knowledge on where the features are impacting the thermo-elastic responses cannot be obtained only through the thermo-mechanical classification methods.

Table 5-1: Thermo-mechanical classification table for the PLATO DMBB after the “Max. Gradient” thermal case assessment

CSS4, Stability rel. rot.	**Overall Margin of performance parameter**	**Contribution from feature**	**Uncertainty of feature**	**Need for refinement**
Bottom panel	Mid	High	Low	No
Front panels		Mid	Low	No
Side panels		High	Low	No
CFRP blocks		High	Low	No
CSSs		Mid	Mid	No
Top panel		Mid	Low	No
Ti Bracket		High	Low	No
Cleats		Low	Low	No

5.2. Transient results

In similar manner than for the case of the “Max. Gradient” stationary thermal case, different thermo-mechanical classification methods are applied to the sinusoidal phase of the test. The analysis focuses on both the peak-to-peak stability and the full transient evolution, where the peak-to-peak stability represents the difference between the maximum positive and minimum negative states of the performance parameter response.

The same kind of analysis per physical phenomena and group can be reproduced when assessing the transient evolution of the performance parameter response. Furthermore, the response can be divided into a time mean distortion averaged over time and the fluctuations relative to such mean value as follows:

$$\{\boldsymbol{u}\}_{temporal\ variations,\ \ group\ n} = \begin{bmatrix} TE \\ Transfer \\ Matrix \end{bmatrix} \begin{bmatrix} \{\boldsymbol{0}\}_{group\ 1} \\ \cdots \\ \left\{\boldsymbol{\Delta T_{TN}} - \boldsymbol{\Delta T}_{\mu_{temporal}}\right\}_{group\ n} \\ \cdots \\ \{\boldsymbol{0}\}_{group\ N} \end{bmatrix} \quad (15)$$

$$\{\boldsymbol{u}\}_{\mu_{temporal},\ group\ n} = \begin{bmatrix} TE \\ Transfer \\ Matrix \end{bmatrix} \begin{bmatrix} \{\boldsymbol{0}\}_{group\ 1} \\ \dots \\ \{\boldsymbol{\Delta T}_{\mu_{temporal}}\}_{group\ n} \\ \dots \\ \{\boldsymbol{0}\}_{group\ N} \end{bmatrix} \quad (16)$$

Where the subscript $\mu_{temporal}$ represents the temporal mean. Then, the total distortions are again defined by the summation over all T-node groups of the individual contributors.

$$\{\boldsymbol{u}\} = \sum_{n=1}^{N} \{\boldsymbol{u}\}_{\mu_{temporal},\ group\ n} + \sum_{n=1}^{N} \{\boldsymbol{u}\}_{temporal\ variations,\ group\ n} \quad (17)$$

Figure 5-2 shows the results of applying similar classification methods than Figure 5-1 to the temperature field resulting from the peak-to-peak calculation on the sinusoidal phase of the test. Nevertheless, in this case no differentiation has been made between the contributions of the design temperature field and offset.

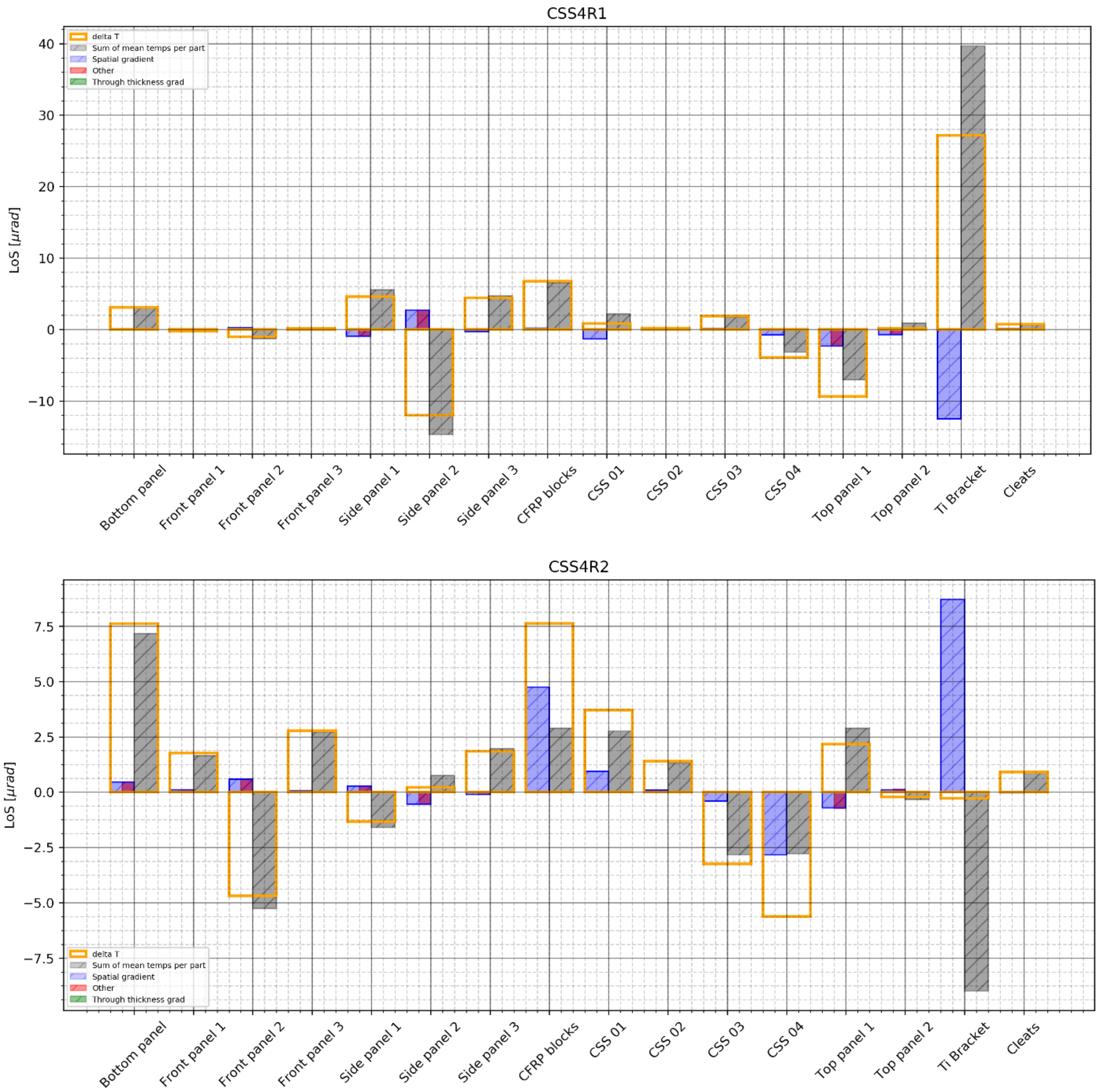

Figure 5-2: Contributions to the peak-to-peak total performance parameter response "Relative rotation CSS4 w.r.t. CSS1" in the thermal scenario "Stability" of the different groups the model is divided into and the type of thermal loads.

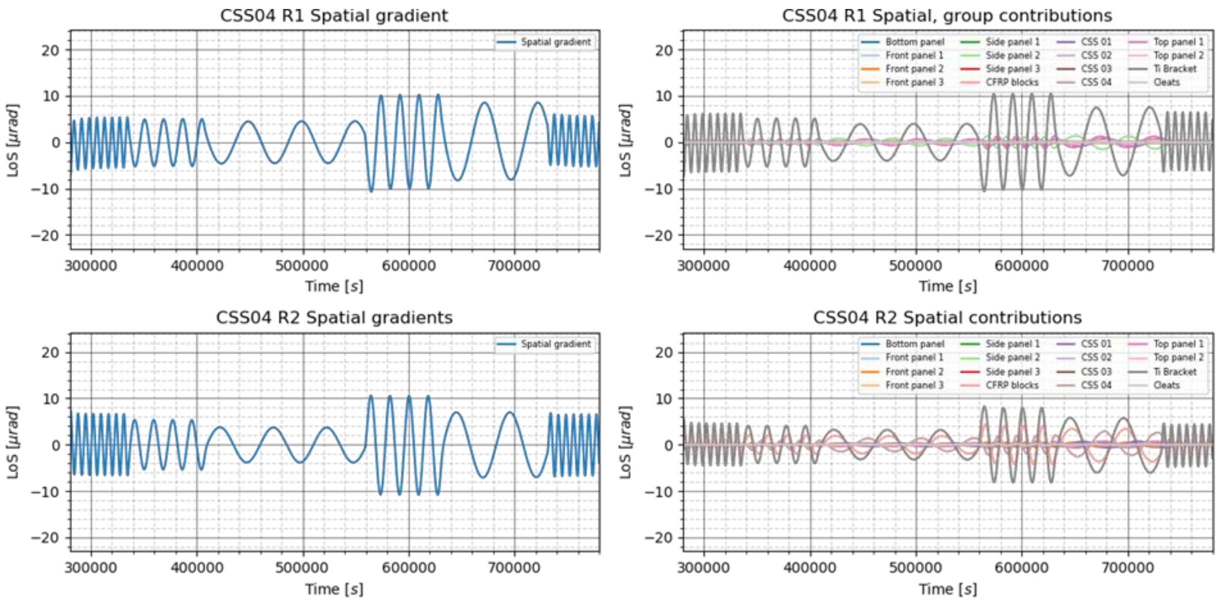

Figure 5-3: Transient evolution of the contribution to the performance parameter response "CSS4 relative rotation w.r.t CSS1" due to the in-plane temperature gradients. On top the rotations around X axis, and on bottom the rotations around Y axis. On the left, the total performance parameter response due to the in-plane temperature gradients. On the right, the sub-contribution caused by each of the groups.

Table 5-2: Thermo-mechanical classification table for the PLATO DMBB after the "Stability" thermal case transient assessment.

CSS4, Absolute rel. rot.	Overall Margin of performance parameter	Contribution from feature	Uncertainty	Need for refinement
Bottom panel	Mid	High	Mid	Yes
Front panels		Mid	Low	No
Side panels		Mid	Low	No
CFRP blocks		High	High	Yes
CSSs		Mid	High	Yes
Top panel		Mid	Mid	No
Ti Bracket		High	High	Yes
Cleats		Low	Mid	No

From this analysis the following observations can be made:

- Spatial temperature gradients have a more significant contribution in the transient phases.
- The Ti brackets have significantly increased their contribution. Now it is driving the CSS4 relative distortions around the X axis.

Figure 5-3 shows the transient evolution of the contribution of each of the groups to the performance parameter response due to the in-plane temperature gradients. On top, the rotations around X axis, and on the bottom, the rotations around Y axis.

Considering all the insights gained through the execution of the thermo-mechanical classification methods to the "Stability" thermal case, Table 5-2 shows the classification. The logic of this table is similar to what was previously discussed in the context of Table 5-1.

It is relevant to note that in this case it was observed that some features such as the bottom panel, CFRP blocks, CSSs and the Ti brackets required some refinement. It must be remarked that for this exercise the margins have been assumed to be small and positive, and therefore higher margins could imply that there was no need for refinement.

Ultimately the need for refinement is dictated by the envelope of both Table 5-2 and Table 5-1. In this case, the transient stability analysis dictate that some parts of the model will need to be refined in this fictitious example.

6. THERMAL MODEL IMPACT ASSESSMENT

As a continuation of this process, once the thermo-mechanical classification process identifies some features that need refinement, a thermal model impact assessment process shall be executed to assess the thermal contribution of those features.

The features that need to be assessed follow from the identification step and are typically the features that are either:

- small (e.g. individual joints);
- cannot be captured by the thermo-mechanical classification (e.g. orbital fluxes)
- features that were implicitly represented by other features in the thermo-mechanical classification for which a need for refinement has been identified.

In this case, the process is based on a sensitivity study on the selected features. Table 6-1 shows the features and variables analysed in the sensitivity study, together with the magnitude of their variations considered.

Table 6-1: PLATO DMBB model features and their variations considered in the thermal model impact assessment.

Model features	Attribute	Variations x, 1/x
Interface Conductivity	Conductivity	1.5
Thermal Capacitance	Capacitance	1.15
Conductivity Invar	Conductivity	1.1
Conductivity TI Bracket	Conductivity	1.1
MLI performance	-	1.5
Conductivity Composites	Conductivity	1.4
CFRP eps	Emissivity	0.83/0.77
MLI eps	Emissivity	0.07/0.03
CFRP CSS eps	Emissivity	0.864/0.804
Alu polished eps	Emissivity	0.07/0.03
TI eps	Emissivity	0.19/0.15

The features selected on this table contain both features that may directly have an uncertainty associated to them as well as features that envelope other features. This concept is explained in more detail for the structural model impact assessment in section 7, where this concept of enveloping is more intuitive.

The sensitivity analysis is then performed for both the “Max. Gradient” and “Stability” thermal cases, and performing the same assessments described in the thermo-mechanical classification section. Below some observations per thermal case:

- In the “Stability” thermal case it was observed that the selected thermal features have small contribution, especially in the rotations around Y axis. It was also observed that the sensitivity was mostly driven by the conductivity of the composites and thermal capacitance. These points out to the relevance of the thermal mesh size in this model.
- In the “Max. Gradient” thermal case it was observed that the results are driven by the composite conductivity. Moreover, it was also observed that the rest of features have negligible contributions.

These conclusions can be summarized in a table similar to Table 5-1 and Table 5-2. For brevity, these results are not explicitly shown in this paper.

7. STRUCTURAL MODEL IMPACT ASSESSMENT

As a continuation of this process, once the thermo-mechanical classification process highlights features requiring some refinement, a structural model impact assessment that studies those features shall be performed. In this example, the impact assessment is based on sensitivity analyses on the features that potentially need refinement. The general idea is similar to the thermal model impact assessment discussed previously.

Table 7-1 summarizes the variables selected for the sensitivity study. It shall be remarked that the magnitudes of the variations were selected as an illustrative example. It is acknowledged that such magnitudes shall be defined by industry and are subject to be updated based on experience. In many cases, realistic ranges for the variables may not be readily available (as is the case in this example). For those cases it is recommended to use order of magnitude ranges, and first classify the contributions. After combining the results in a table similar to Table 5-1 and Table 5-2 it can then be decided whether additional effort needs to be spent on refining the ranges.

In addition, it is again recalled that the features selected in Table 7-1 contain both features that may directly have an uncertainty associated to them as well as features that envelope other features. For instance:

- A CTE may capture the direct uncertainty in its properties as well as for instance any temperature dependent behaviour that is not included in the model. Only if the contribution is found to be large in the refinement step, may this temperature dependent behaviour be modelled explicitly.
- The spring stiffness may simplify a complex

joint (e.g. a bolt through a potted insert) into a single variable. Only if this stiffness is found to have a great contribution may the bolt, glue and insert be modelled separately.

Table 7-1: PLATO DMBB model features and their variations included in the structural model impact assessment.

Model features	**Parameters from features to be varied**	**Variations x, 1/x**
Inserts and bolts Stiffness	E	10
Inserts and bolts alpha	CTE	1.1
Adhesives	E	10
Interfaces Springs	K1,K2,K3,K4,K5,K6	10,10,10,10,10,10
Camera cylinders	CTE	1.1
Side panels	E	1.1
Camera panels	E	1.1
Camera flange rings	CTE	1.1
Cleats stiffness	E	10
Cleats alpha	CTE	1.1
Lug	CTE	1.1

The sensitivity analysis is then performed for both the “Max. Gradient” and “Stability” thermal cases, and performing the same assessments described in the thermo-mechanical classification section. For the “Stability” case transient calculations only a sub selection of time stamps was analysed, interpolating then the results. This was done to reduce the FE computation times since the thermo-elastic transfer matrix (see [4]) used for the thermo-mechanical classification method and the thermal model impact assessment cannot be used. Below some observations per thermal case:

- In the “Stability” thermal case it was observed that the interfaces’ stiffness, and the CTE of the interfaces, the cleats and the lugs have a significant contribution. It was also observed that these parameters have a higher contribution than the variables studied in the thermal model impact assessment. This puts the relevance of modelling appropriately the stiffness in the spotlight.
- In the “Max. Gradient” thermal case it was observed that the performance parameter responses are driven by the uncertainty in the stiffness.

These results clearly show the need to investigate in more detail the representativeness of the structural links stiffness. Furthermore, it is interesting to note that the conclusions obtained through the sensitivity analyses on both thermal cases are not entirely equal, making evident the need to perform the structural model impact assessment in all the relevant thermal load cases.

As before, these conclusions can be summarized in a table similar to Table 5-1 and Table 5-2. For brevity, these results are again not explicitly shown in this paper.

8. CONCLUSION

This paper presented a brief excerpt on parts of the numerical classification process also further detailed in [4]. By effectively combining and extending on existing processes, it is possible differentiating the contribution of different (physical or mathematical) features of the model. Especial attention is given to the special variations of the thermo-mechanical classification methods, that allow the engineers to effectively assess the contribution to the performance parameter responses due to spatial temperature gradients, through thickness temperature gradients, etc., without requiring model updates. This is considered a significant improvement, since in the past such a study has typically required time and effort demanding processes. For instance, the common way to analyse the contribution of spatial temperature gradients was based on lengthy and computationally demanding mesh convergence studies. By considering the three metrics of:

- The overall margin
- The relative contribution of the different features
- The uncertainties of the associated features

one can redistribute the efforts where they are needed the most.

In this paper, the main focus was on the methods for contribution assessment, also called thermo-mechanical classification methods. It must be remarked that the overall margin metric is very application dependent. Furthermore, uncertainties are expected to be often assessed in a qualitative manner, being mostly based on prior experience, similar parts/materials, etc.
As stated in the beginning of these conclusions, this paper presents a limited set of results of the application of this methodology to the PLATO DMBB in the framework of [4]. During the execution of this initiative, further and more detailed studies with this methodology have been performed. It was concluded that this methodology can be applied in practice, not being therefore limited to an academic exercise. However, the overall effort required can be significant if no dedicated numerical tools are

available to implement this process.

9. REFERENCES

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