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MODAL IDENTIFICATION AND MODEL UPDATING OF PLEIADES

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Abstract

This paper presents all the updating activities performed on the finite element model of PLEIADES. The model updating is usually limited to a correction of modal data, by changing the most sensitive physical design parameters. In this paper, the modelization errors are localized and corrected thanks to a residual energy criteria: the Constitutive Relation Error (CRE). This method was originally developed by the LMT Cachan, and then implemented by the FEMTO Institute (Besançon, FRANCE) for application in an industrial context.

The updating of PLEIADES is based on a modal approach: The experimental modes are identified using the Real Time Modal Vibration Identification (RTMVI) method. First, the model of the payload is updated with respect to a subsystem test performed on the instrument. Next, the model is condensed and included in the satellite model. The final step is to update the entire model using tests at satellite level. Primodal, a structural analysis tool developed by TOPMODAL (Toulouse, FRANCE) is used for correlation and updating.

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Notation

CRE	Constitutive Relation Error
FEM	Finite Element Model
PFM	ProtoFlight Model
FRF	Frequency Response Function
MAC	Modal Assurance Criterion
RFR	Resonance Frequency Research
RTMVI	Real Time Modal Vibration Identification
SVD	Singular Value Decomposition

Presentation of the context

Pleiades

Picard is a constellation of 2 satellites for Earth observation. It is both a civil and military mission. The structure includes a high resolution instrument under Thales Alenia Space responsibility, and a platform which was under ASTRIUM responsibility. The mass of the entire satellite is around 900 kg.

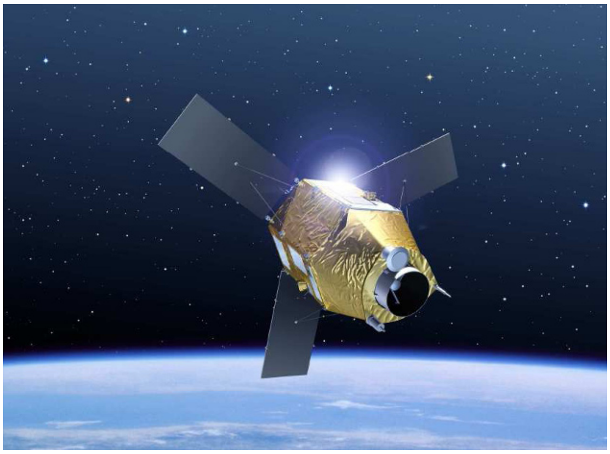

Fig. 1. Artistic View of Pleiades

Methodology and goals of model updating

The goal of model updating is to deliver a correlated model to the launcher authority. This model shall be representative in terms of modal behavior, to predict coupling between satellite and launcher modes.

This updating methodology is only based on a modal approach. The goal is to improve the MAC between prediction and test results and the difference between analytical and experimental eigenfrequencies. The final model may not be representative in term of stress if some properties have been changed significantly (as the Young's modulus).

2 updating methods have been used in parallel:

- the first one is based on the MAC and eigen-frequencies. The updating is directly based on the optimization of the difference between the model and the test results. The choice of updating parameters depends on their sensitivity with respect to frequencies or modal shapes. It is essential to have a good initial matching between analytical and experimental modes.

- the second one is based on the CRE. This method allows locating errors in the model, which gives a accurate indicator for the choice of updating parameters. This method depends on the instrumentation, and may not be accurate if the location and number of the sensors is not sufficient to have a good visibility of the model.

Tests used for the correlation

The tests used to update the instrument model have been performed in the beginning of 2008 on a PFM to qualify the payload. 132 sensors were used to measure the acceleration at different points of the structure. RFR are used to update the model.

For the entire satellite, tests on a PFM have been performed at the end of 2008. A total of 141 sensors located on the Bus were used to update the model.

Context of the study

This study is the following step of a collaboration between TOPMODAL, the FEMTO-ST institute and the CNES. The CRE (Contitutive Equation Error) has been implemented in the structural analysis tool, PRIMODAL, developed by TOPMODAL. This methodology was used for several years by the FEMTO institute through another tool, AESOP. Some previous study proved that the methodology is appropriate to large structure. The finite element model of PICARD has recently been updated successfully with AESOP.

This work on Pleiades was carried out by Pierre-Alain REBOUL during his internship in CNES. The goal was to validate this new implementation in PRIMODAL.

Modal identification

The CRE needs the experimental eigenvalues and eigenvectors. As no modal survey test has been performed, these modal parameters have to be identified from sine-sweep base excitation vibration tests. FRF are obtained by normalizing the responses by the acceleration measured on pilot sensors.

Identification has been performed with the RTMVI method. It assimilates each mode to a single dof system. This method is particularly efficient when modes are uncoupled, which is the case on almost all spacecraft structures. An improvement has been added to Primodal to take into account coupling between modes.

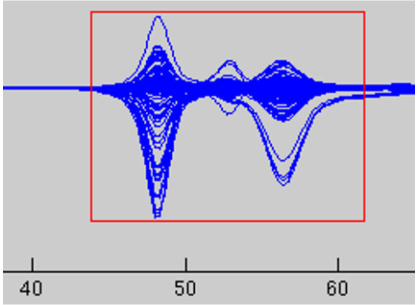

Fig. 2. Modal Identification with RTMVI in presence of 3 coupled modes

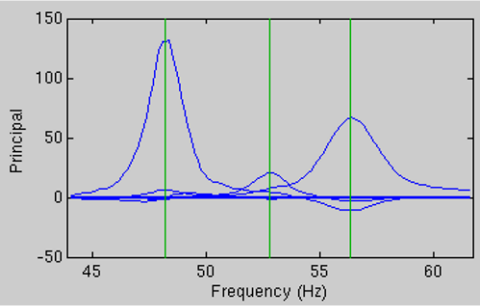

Fig. 3. SVD representation in presence of 3 coupled modes

The SVD tool has been added to PRIMODAL. It allows separating quickly independent components from a set of sensors responses, and assessing if a peak corresponds to a mode.

From this representation in Fig. 3, we can see that there are 3 independent components, and therefore 3 modes to be identified in this frequency range.

Theoretical approach of the CRE

$[\mathrm{M}]$	Mass matrix (n*n)
$[\mathrm{K}]$	Stiffness matrix (n*n)
$[\mathrm{K}_{\mathrm{elm}}]$	Stiffness matrix of one element (i*i)
$[\mathrm{K}_{\mathrm{red}}]$	Stiffness matrix reduced on the sensor nodes (c*c)
$\mathrm{U}_{\mathrm{exp}}$	Modal shape from identification (1*c)
λ_{exp}	Eigenvalue from identification (1*1)
Π	Projection of the sensors nodes (n*c)
U,V,W	Virtual fields of displacement (1*n)
U_{elm},V_{elm}	Displacement of dof link to the considered element (1*i)

Supposing that only stiffness errors are taking into account, the fields U and V are calculated by minimizing the following term:

$$(U-V)^t[K](U-V)+(\Pi U-U_{\mathrm{exp}})^t[K_{red}](\Pi U-U_{\mathrm{exp}}) \quad (2)$$

Respecting the condition:

$$[K]V=\lambda_{\mathrm{exp}}[M]U \quad (3)$$

We can combine the 2 terms by adding a factor comprised between 0 and 1. If we are confident of tests results, we can weight the second term, which represent the difference between the extended field U and the experimental acceleration measured on the dof sensors.

The localization criterion is defined for each element. It has the dimension of deformation energy, and can be calculated for a zone of the model by summing the error of elements belonging to this zone.

$$e_{elm}=(U_{elm}-V_{elm})^t[K_{elm}](U_{elm}-V_{elm}) \quad (4)$$

The error used for updating is calculated on the entire model:

$$e=(U-V)^t K(U-V)+(\Pi U-U_{\mathrm{exp}})^t K_{red}(\Pi U-U_{\mathrm{exp}}) \quad (5)$$

To update the model, the residual energy *e* has to be minimized.

This formula of CRE does not permit to localize mass error. But it is often sufficient, because the mass of the structure is generally well known. If we wish to localize mass error, we have to modify the formula (2). The field U, V and W are calculated by minimizing the following term:

$$\lambda \| U - V \|_K^2 + (1-\lambda) \| U - W \|_M^2 + \frac{\alpha}{1-\alpha} \| \Pi U - U_{\exp} \|_{Kred}^2 \quad (6)$$

Respecting the condition:

$$[K] V = \lambda_{\exp} [M] W \quad (7)$$

With λ and α comprised between 0 and 1.

The equivalent of the formula (4) for mass error is calculated with the following equation:

$$e_{elm} = (U_{elm} - W_{elm})^t [M_{elm}] (U_{elm} - W_{elm}) \quad (8)$$

The error used for updating is calculated on the entire model with the formula (6).

One advantage of this method is that analytical and experimental modes do not need to be paired.

The minimization of the CRE does not guarantee that the eigenfrequencies converge. It is generally the case when the model has a good visibility i.e. when the sensors allow locating a zone of the model when it is erroneous. If a zone has a low visibility, we may locate it even if no error is present. A modification of this zone could decrease the CRE without improving the eigenfrequencies. In this case, another updating method shall be used.

The quality of a model updating is generally judged by comparing analytical and experimental eigen- frequencies. Usual updating methods are based on parameter sensibility. One advantage of the CRE is that only erroneous parameters are modified

Updating of the Pleiades instrument

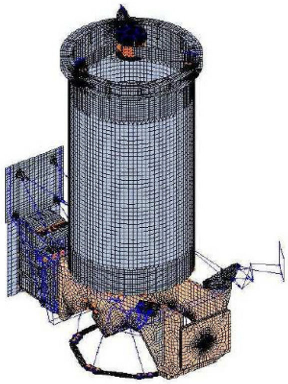

Fig. 4 : FEM of the Pleiades instrument

Comparison before model updating

The first step is to calculate the MAC and the differences between eigenfrequencies.

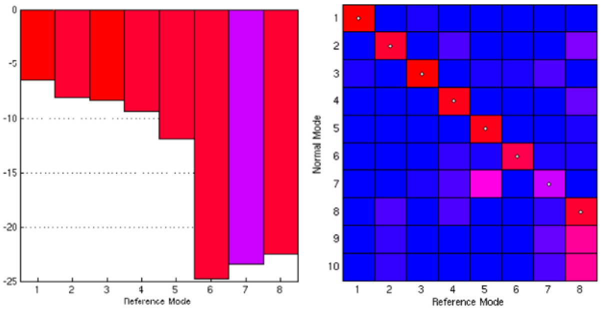

Fig. 5. MAC and eigenfrequency errors before model updating

The MAC is presented Fig. 5. Vertically (resp. horizontally), analytical (resp. experimental) modes are presented. The diagonal is clearly identified, which confirms that analytical and experimental modes can be paired. The first method of updating, based on MAC and eigenfrequencies, will be favoured.

The eigenfrequencies which indicate that the model is too stiff can be improved. A computation of the CRE confirms that the errors in the model come from stiffness.

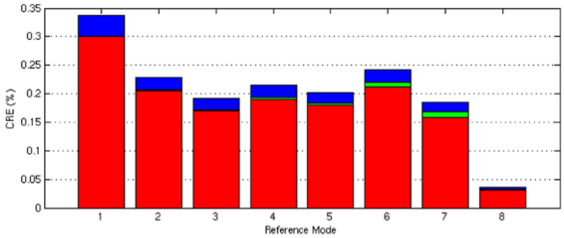

Fig. 6 In red, stiffness errors. In green, mass errors, in blue, errors from tests measurements.

Updating procedure

For the instrument, the choice of updating parameters is based on sensitivity. As we want to improve eigenfrequencies, parameters must have an influence on the modes. The first method of updating is favoured.

However, to be sure that the modification of the model is robust, the MAC and the CRE are observed at each step of the updating procedure. The improvement of the MAC is essential to keep an accurate representativity of the modal shapes. The improvement of the CRE provides confidence in the modification of the model, and ensures that parameters which have been modified were really erroneous.

The parameters modified in the instrument model are:

- thickness of structural plate
- Young's modulus of materials which constitute junction items

For large properties, the coefficient applied on these parameters is never higher than 1.3. But for junction items, this coefficient has been sometimes increased until 3.

Final comparison

The 2 following figures shows the improvements on the model.

- blue: before updating
- purple: after updating

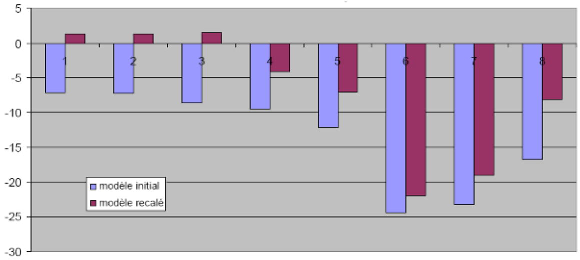

Fig. 7: Eigenfrequency errors before and after updating

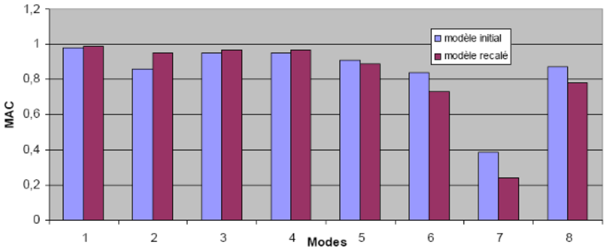

Fig. 8: MAC before and after updating

Frequencies have improved without degrading the MAC (the 3 last modes have a low effective mass). The global value of CRE is decreased from 1.98 to 1.76.

As a conclusion, we can say that the initial model was already well correlated. The improvement concerns only the eigenfrequencies. A model is generally stiffer in reality, thus providing margins during the preliminary design phases. As tests have been performed on the Flight model, the model to be delivered to the launcher authority shall be as predictive as possible, and there is no need to keep these margins.

Updating of the satellite Pleiades

Once the model of the instrument was updated, it has been condensed and included in the satellite model. This allows reducing the size of the model. Since the instrument has already been updated, only the model of the Bus structure will be modified.

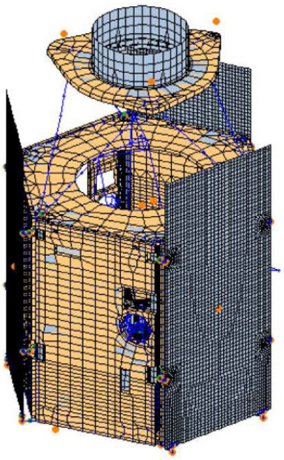

Fig. 9 : FEM of the satellite Pleiades

The instrument is located inside the platform.

Comparison before model updating

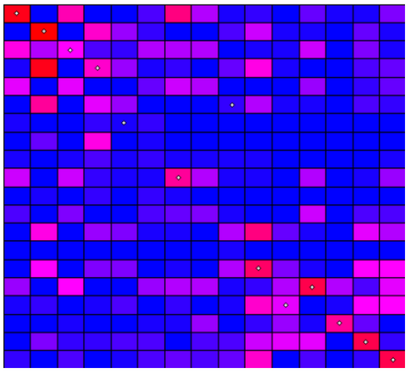

Fig. 10 : MAC before model updating

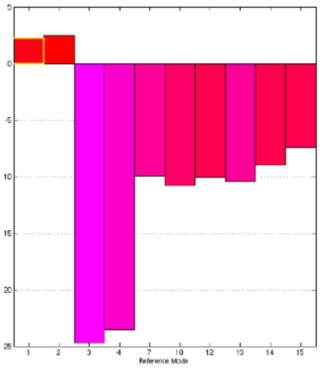

Fig. 11: Eigenfrequency errors before model updating

The diagonal is less identifiable as before. It is more difficult to pair analytical and experimental modes. In consequence, the CRE method is favoured. All 15 first modes are taking into account, even if the pairing is difficult.

From the MAC, we can observe that the distinguishability between some modes is weak. It is due to the fact that no sensors are located on the instrument during satellite test. The 4 first modes concern both the platform and the instrument, in phase or in opposition.

The model is stiffer than the real structure, except for the 2 first modes, because they mainly concern the instrument, which has already been updated.

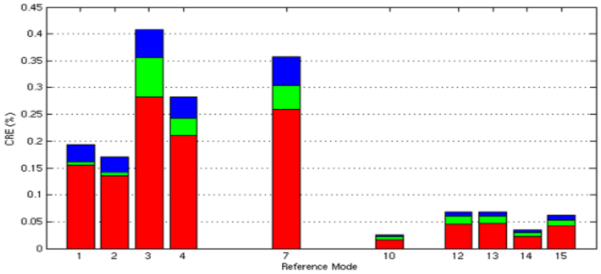

Fig. 12 : In red, stiffness errors. In green, mass errors, in blue, errors from tests measurements.

We can observe here that the mass and test error has a non negligible contribution. Only the 10 modes where the error is visible (for which the effective mass is significant) are taken into account in the following updating procedure.

Updating procedure

Updating parameters have been chosen through the CRE localization. It concerns mainly junction element (bar properties, thickness of small shell…).

The CRE has been minimized, by keeping an eye on the evolution of eigenfrequencies.

Final comparison

The 2 following figures shows the improvements on the model.

- blue: before updating
- purple: after updating

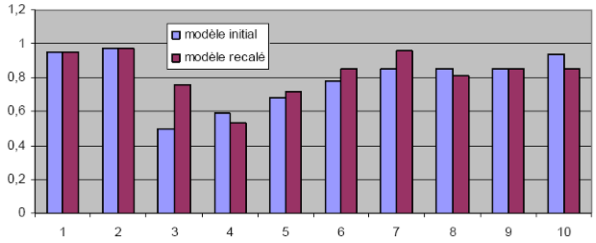

Fig. 13: MAC before and after updating

Globally, the MAC has improved (except for some modes). But for the third and fourth modes, the MAC is not satisfactory enough. It is certainly due to the lack of sensors on the instrument during satellite test. The CRE is highly dependant to the instrumentation, and is limited if the visibility of the model is not good enough.

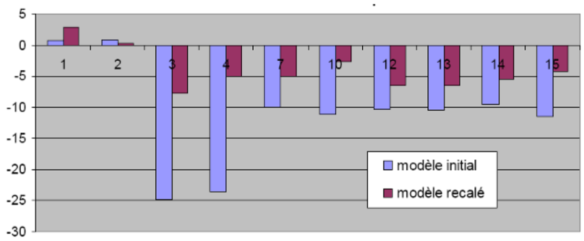

Fig. 14: Eigenfrequency errors before and after updating

The eigenfrequencies have improved, without degrading the 2 first modes.

Conclusion

The initial model was already well correlated in terms of MAC, but a difference between analytical and experimental eigenfrequencies remained. The purpose of this updating is to deliver to the launcher authority a model as predictive as possible. There is non need to keep a margin on frequencies. The main goal of this study was to reduce the eigenfrequency errors.

The results are satisfactory, the improvement in terms of eigenfrequencies is significant. The difficulty is to satisfy simultaneously different criteria: eigenfrequencies, MAC and CRE. Primodal is an efficient tool which allows evaluating clearly the influence of each parameter on all these criteria. It is far from an automatic procedure, Primodal gives numerous indicators which help the user to choose the correct parameters, and the appropriate methodology.

However some limitations can be mentioned:

- In the instrument updating step, the error localization was deficient, because localized parameters have a low influence on eigenfrequencies. Other more sensitive parameters have been chosen to change the modes
- The CRE was limited during the second step of the model updating, due to the lack of sensors on the instrument.

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