Measurement plan definition on Ariane V launcher

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Abstract

This paper deals with the dynamic behavior of Ariane 5 launcher during the flight. The studies performed for the production of Ariane 5, concerning the dynamic levels analyses, consist of a flight prediction and a measurements post flight analysis based on several sensors placed on the launcher. Studies are carried out to make the best use of flight data to improve the models representativeness. This paper concerns the definition of sensors (number, placement, orientation, etc.) allowing an efficient identification of the modal characteristics of the launcher. A robust design approach has been tested in order to take into account the modeling errors. The result is sub-optimal with respect to a theoretical approach without any error, but it is supposed to be robust to modeling discrepancies. A second algorithm is also proposed to assess the values of certain parameters (for instance the stiffness of certain components), taking into account flights measurements. A simple case has been treated to validate the feasibility. The sensor placement step has been performed for a booster ground test that should occur before the end of 2006.

Acronyms

CPC	**C**orps de **P**ropulseur **C**hargé (part of EAP)
DIAS	**DI**spositif **AS**souplisseur
EAP	**E**tage d'**A**ccélération à **P**oudre (boosters)
EfI	**Ef**fective **I**ndependence sensor placement methodology
EPC	**E**tage **P**rincipal **C**ryotechnique
ESC-A	**E**tage **S**upérieur **C**ryotechnique version **A**
I/F	**I**nter**F**ace
HM7b	Ariane 5 upper stage engine (ESC-A)
KE	**K**inetic **E**nergy
MPS	**M**oteur à **P**ropergol **S**olide
OdP	**O**scillations **d**e **P**ression (pressure oscillations)
PSD	**P**ower **S**pectral **D**ensity
wrt	**w**ith **r**espect **t**o

1 - Introduction

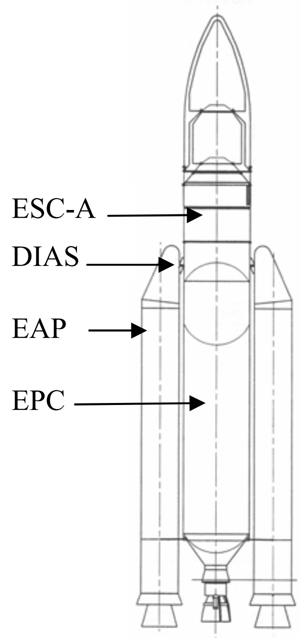
In-flight system identification is an essential aspect of Ariane 5 launcher development and production. Ground tests are generally not fully representative of the actual behavior during flight taking into account of all the interactions ; one important problem is to anticipate the impact of the links between the stages (not only the local stiffness but also the damping brought by these components).

This paper presents recent researches concerning the sensor placement process that has been defined in order to fulfill some precise objectives. Various types of measurement are performed on the launcher, including local strain assessment, acceleration or vibration. The study is here restricted to structural dynamic analysis.

Sensor placement algorithms have been studied for long. An interesting one is the EfI methodology (see reference [2]). The idea is to minimize the effect of measurement errors, using the Fisher information matrix. Other methods have been tested and compared to EfI, such as KE method for which sensors locations contain the largest kinetic energy ; EfI reveals to be more efficient.

In this paper, we tried to take into account the uncertainties of the model used to implement the sensor placement, in order to gain confidence in tests that are difficult and costly for space applications.

Ariane 5 launcher definition.



The launcher (A5E/CA version) is composed of a lower part including the EAP (solid propulsion boosters) and the EPC (central cryogenic stage) and of the upper part mainly composed of the ESC-A (upper cryogenic stage), the fairing and the payloads.
The EAP is divided in several sub-systems. The MPS is the propulsive part of the booster ; the CPC includes the MPS and some equipment.
The DIAS is the sub-system that ensures the link between the EAP and the EPC. The function of this device is to transmit the boosters thrust to the central core. A secondary function is to filter structural dynamic energy coming from the EAP towards the central core and in particular to the payloads that may be sensitive to such excitations.
The flight duration (boosted phase) is about 1 500 sec. The EAP flight phase lasts about 140 s. The EPC engine (Vulcain) is ignited a few seconds before lift-off and has a time functioning of 530 s. Finally, the upper stage engine is ignited after EPC jettison and lasts 940 s.
The EAP phase is the most severe one in terms of dynamic excitations. These excitations are of many kinds : external (acoustic phenomenon, wind, etc.) and internal (engine noise, separation shocks, etc.).

The development of Ariane 5 launcher is based on general specifications dealing with the main sizing aspects including :

- general loads (static loads),
- dynamic environment of the launcher.

Concerning mechanical aspects, the sizing of the launcher was initially carried out using simulation tools. The objective was to quantify static and dynamic loads at the level of several interfaces defined on the launcher (for example between the lower and upper stages of the launcher). As ground tests are limited and partly representative, it is necessary to validate the specification with the help of flight measurements. Sensors are placed close to the above-mentioned interfaces, so that the loads levels can be checked taking into account the real behavior of the launcher during flight. A sensor definition plan has been made.

One can see that the interest of flight measurements is linked to several needs :

- validate the dynamic levels specified for each stage or equipment and for the payloads,
- give data in order to enhance the models that are used for recurrent dynamic analysis.

Concerning the studies of dynamic behavior, system level analyses of the launcher are made through « coupled load analysis » which take into account the interactions between the payload and the rest of the launcher. The representativeness of the models is determinant to have accurate previsions. The flight is divided into several load cases such as lift-off, EAP jettison, EPC shut-off, HM7b ignition, etc. The most critical flight phase is the atmospheric phase including lift-off (as mentioned above), lasting about 140 sec, at the end of which the EAP are jettisoned. Before separation, some sources of excitation appear inside the boosters due to perturbations of gas flow in the MPS. This excitation is characterized by pressure oscillations (Δp) applied to the internal surface of the MPS and finally create dynamic responses of the whole booster. These dynamic oscillations initiated in the boosters induce structural dynamic responses on all the structures of the launcher, including the payload, which is the feared impact.
The methods developed and detailed below for this particular load case can be applied to some other ones, such as lift-off which is another sensitive phase for the launcher.

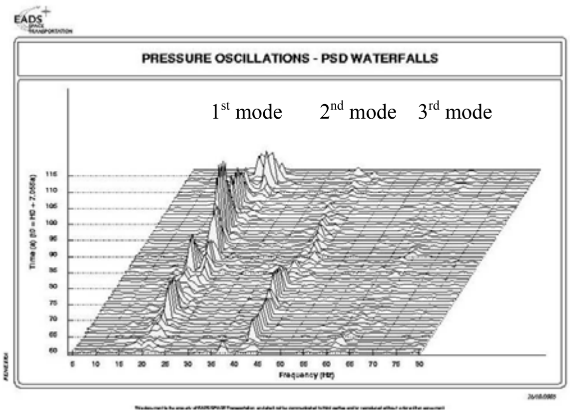
Some difficulties are related to sensor setting that will not be discussed here. The main parameters that have to be defined are :

- the sampling frequency, this will depend on the frequency of the phenomenons that have to be measured,
- the range of measured values, in order to avoid saturations. The quantification has been settled to 256 bytes,
- operational constraints. Practically, a sensor cannot be located anywhere on the launcher. Some particular positions have been adapted (close to the engines and nozzles, inside cryogenic tanks, etc.).

Post-flight measurement analysis is undertaken after each flight in order to check the specifications. Now that a sufficient number of flights have been analyzed, statistics have been established and taken into account in renewed editions of the specifications. The upgrading of the Ariane 5 is managed through a program called ARTA (of which some tests are studied below).

2 – General description of OdP load case

Pressure oscillations (OdP) that appear during the EAP firing are due to a complex coupling between combustion and internal aerodynamics in the boosters combustion channels. Experience shows that this oscillatory behavior begins at one characteristic instant of combustion, starting from second half of the firing (ie 60 seconds for Ariane 5 EAP phase) and ending at the end of EAP phase.
These oscillations are characterized by several “acoustic” modes, called so because they are due to reflection of pressure waves on the extreme end surfaces of the booster cavity. The first and second acoustic modes appear respectively at about 20 Hz and 40 Hz. The levels of the following modes are less important and not studied thoroughly. These frequencies figures are linked to the geometry of the booster and gas properties.



Δp assessment vs frequency

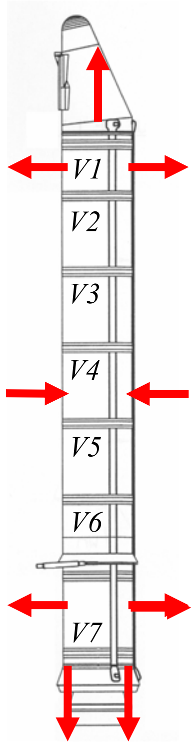
This excitation is characterized by a significant dispersion concerning the levels and frequency ranges. From one flight to another, the Δp levels may differ noticeably.

In this paper, the study is focused on the second acoustic mode, which can be coupled with the first EAP structural mode whose frequency appears to be close to 40 Hz at the end of EAP flight phase. This coupling may lead to high dynamic levels if the associated damping is low.

For this acoustic mode, the distribution of Δp is in phase at the extremities of the combustion chamber. As they are applied to opposite surfaces, the resultant deformation of the 2nd acoustic mode is a "breathing mode". The EAP alternatively lengthens and shortens. Lateral expansion of the EAP is also one of the effects of this excitation.

For the modelization used for dynamic analyses of this load case, the Δp is supposed to have a sinus shape in function of the longitudinal coordinate. That means that the Δp is equal to zero roughly at 0.25 and 0.75 times the length of the EAP.

As shown on the diagram above, the Δp associated to the second mode is low in comparison with the Δp of the first mode. Even so, due to potential couplings, the effects on the launcher may be significant. In fact, couplings between the 1st longitudinal mode of the EAP and the excitation are seen for each flight whereas couplings with other structures (located on the central core, such as the payloads in particular) are less frequent.

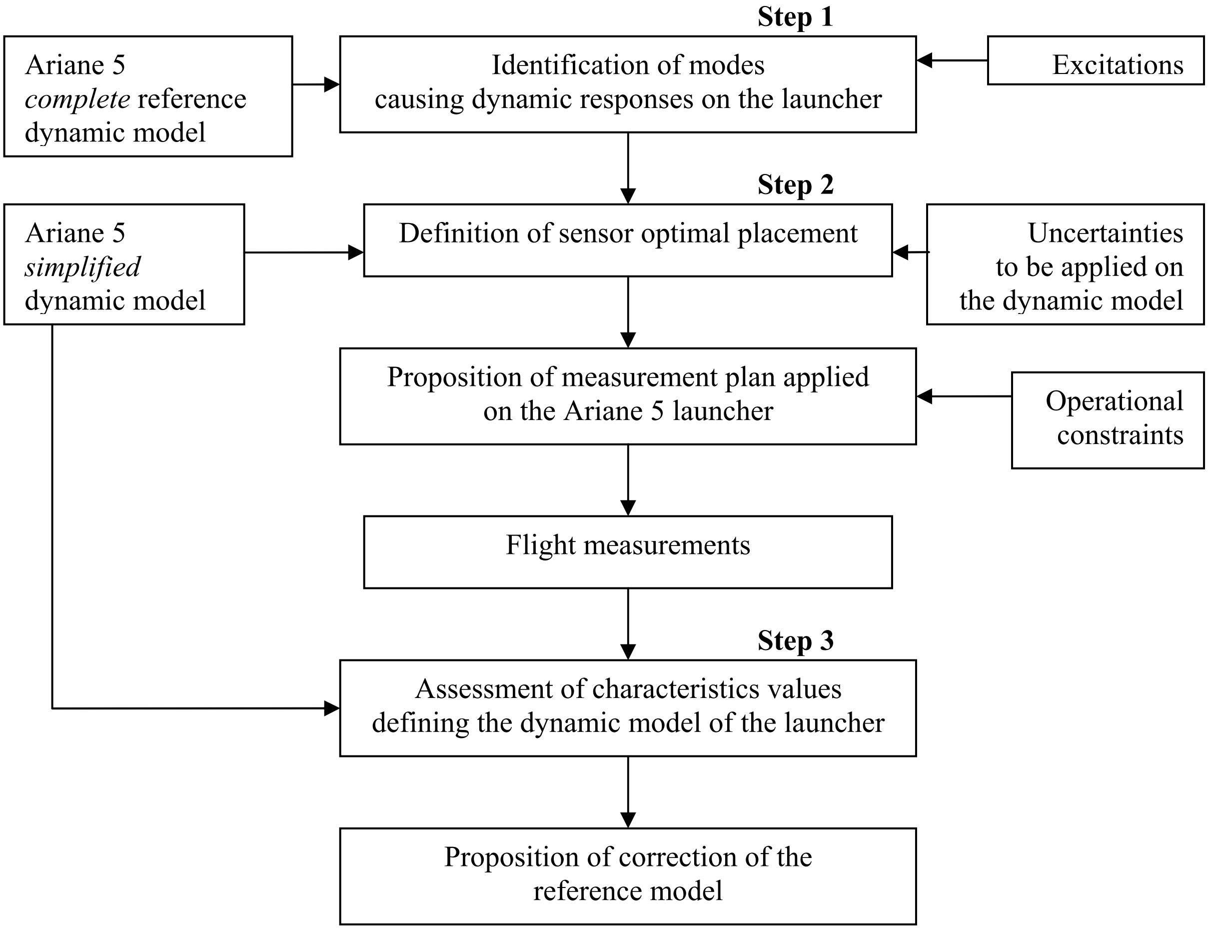


As shown above, the EAP is subdivided into several cylinders (V1 to V7) to meet production constraints. For the second acoustic mode, the Δp are mostly applied on V1, V7 and V4. The Δp is supposed to be close to zero at V5-V6 and V2-V3 I/F levels.

3 – General logic of sensor placement

As described above, the choice of sensors must be fit into a general logic corresponding to objectives at system or stage level. The subject that is studied here is the enhancement of the knowledge of the launcher characteristics. The final goal is to propose some modifications of the reference model, in order to improve the accuracy of dynamic response assessments.

The process consists of the following steps, which require preliminary analyses to obtain satisfactory results :
Step 1 – identification of important structural modes,
Step 2 – sensor placement,
Step 3 – calculation of some characteristic parameters, deduced from measurements.



The Ariane 5 complete dynamic model (present reference model) is composed of several about 200 000 degrees of freedom. The computation time of the modal base associated to one flight time is too long to be repeated several hundred times as it should be to define the optimal placement of sensors, as it is set out hereunder. The use of a simplified model of the launcher is imposed by the necessary high number of computations. Three models have been developed during Ariane 5 development : the complete one that is regularly updated and tends to be more and more detailed, an intermediate one (about six hundred degrees of freedom) and a very simple one (five nodes) that has been used to test the methods and set the first sensor placement. A simple model is inevitably restricted to one focused problem ; this is the case for the simpler one that is used only to check the behavior of the interaction between the EAP and the central core during the tail-off phase of EAP flight.

The dynamic model of the launcher is composed of many sub-systems and links. Each characteristic (thickness, stiffness, Young modulus, condensation rules, etc.) has an impact on the modal definition of the structure (frequencies, modal shapes, etc.). Obviously, even if ground tests are performed to quantify these figures, some uncertainties remain. The sensor placement algorithm that has been used is designed to take into account errors on the model characteristics.

This process has been tested for two application cases :

- for the launcher in flight condition, during the OdP phase. A simplified approach has been tested to validate the feasibility to restore stiffnesses of two components (see § 4.1 below),
- for EAP firing ground tests foreseen at the end of 2006, steps 1 and 2 have been implemented (see § 4.2).

Step 2 algorithm

The problem here is to optimize the choice of sensors, taking into account uncertainties on the parameters **u** (such as masses, geometry or stiffnesses) defining the dynamic system (**u** is a vector). In reference [1] this is presented as « *Info-gap robustness analysis* ». As for all optimization problems, a performance index P(**s**) has to be defined (**s** is a vector defining the set of sensors : placement and direction of measurement). The chosen figure of merit is here the observability of a selection of modes (see below). The idea is to exchange a reduction of observability of a chosen set of modes for an increase of robustness with respect to uncertainties.

The robustness is defined by a single scalar parameter α ($0 \leq \alpha \leq 1$) that sets the bounds of the range for each component of **u**, by the means of percentages ($\mathbf{u}^*$ being the nominal value of **u**) :

$$R(\alpha,\mathbf{u}^*) = \{ \mathbf{u} \,/\, | u_i - u_i^* | \leq \alpha.u_i^* \}, \text{ for } i = 1,n \quad (1)$$

where $R(\alpha,\mathbf{u}^*)$ is the realizable parameter sets consistent with the uncertainty α, u_i are the components of **u** (u_i^* are the components of $\mathbf{u}^*$).

First, the optimal nominal placement of sensors **s** must be determined, considering nominal values of the n components of **u** (ie $\alpha = 0$). This leads to a performance P_{nom}. The solution for the sensors optimal placement, which maximizes the robustness α, is based on a scalar β that quantifies the reduction of performance ($0 < \beta \leq 1$) :

$$\text{Max} (\alpha^*(\mathbf{s},\beta)), \text{ Max wrt } \mathbf{s} \quad (2)$$

where $\alpha^*(\mathbf{s},\beta)$ is defined by :

$$\alpha^*(\mathbf{s},\beta) = \text{Max} (\alpha \,/\, \text{Min} (P(\mathbf{s}) \geq \beta.P_{nom} , \text{ with } \mathbf{u} \text{ within } R(\alpha,\mathbf{u}^*))), \text{ Max wrt } \alpha \text{ and Min wrt } \mathbf{u} \quad (3)$$

The solution of the optimization problem (2) is difficult. A simplified solution has been searched in order to have a reasonable time of computation ; in particular, for a given set of sensors, the equation (3) is solved with the help of Monte-Carlo method (see Step 2 below). The resulting algorithm has been implemented (the goal is to find the maximum value of α) :

Step 0	Selection of the modes that will be treated by the algorithm
	Set the initial value of α : $\alpha = -\Delta\alpha$
Step 1	Incrementation of α ($\alpha = \alpha + \Delta\alpha$)
Step 2	Generation of N eigenbases, with a uniform dispersion of **u** consistent with (1)
Step 3	Computation of the performance index, for each potential sensor position
Step 4	Determination of the set of sensors related to the solution of equation (2)
	If the performance index P(**s**) is greater than $\beta.P_{nom}$ then go to Step 1

The determination of optimal sensors (step 3) is a good indicator of the robustness of the computed placement. If the choice of sensors evolves noticeably in function of α, it means that the selected modes are difficult to measure. The stability of the choice of sensors with respect to robustness parameter α is linked to an acceptable adequacy between the number of sensors and the modes that are studied.
The chosen criterion is here the sum of modal displacements, for all the selected modes. This figure of merit quantifies qualitatively the observability of the modes. An eigenmode may be considered observable if at least one sensor gives significant level of response. Other criteria can be defined, such as distinguishability.

Step 3 algorithm

The goal is here to assess the values of certain parameters defining the dynamic model of the launcher (some components of the vector **u** defined in step 2 for which uncertainties exist), taking into account the flight measurements. As the resolution of this problem may require a large number of eigenbasis computations, here again a simplified model should be used. Finally, this analysis shall give some indications to correct the reference model that is utilized for development and production studies of Ariane 5 launcher. Our methodology is based on classical control theory approach.

The problem is to determine the formulations of mass matrix M(**u**) and stiffness matrix K(**u**) that minimize an error function based on measurements :

$$\text{Min}\ (\ L(\mathbf{x},\mathbf{p},\mathbf{u})\ )\quad (4)$$

where :
x(t) is the state vector of the dynamic system (positions of the nodes), $\mathbf{x} \in R^n$
p(t) is the Lagrangian parameter linked to the state equation of **x** $\mathbf{p} \in R^n$
u is the vector defining the uncertain parameters $\mathbf{u} \in R^k$

The state equation of x is : $M(\mathbf{u}).d^2\mathbf{x}(t)/dt^2 + K(\mathbf{u}).\mathbf{x}(t) - \mathbf{F}(t) = 0$ (5)
with **F**(t) being the external force vector applied to the system $\mathbf{F} \in R^n$

The function to be minimized is J(**u**). This function J(**u**) quantifies the difference between the measured accelerations and the computed ones with the state equation (5) :

$$J(\mathbf{u}) = 1/2\ \Sigma_{j=1,m} \int_{[0\,;\,T]} \{\ d_j^{model}(t) - d_j(t)\ \}^2\ dt\quad (6)$$

where :
$d_j(t)$ is the displacement (at the node j), deduced from the accelerations utilizing temporal integrations over the interval [0 ; t]. The choice of the number and of the locations of nodes (the number of sensors parameters is $m \leq n$) is the object of step 2. The results obtained here may be used to refine the definition of sensors.

The resulting Lagrangian function, considering the function to be minimized and the state equation is :

$$L(\mathbf{x},\mathbf{p},\mathbf{u}) = J(\mathbf{u}) + \int_{[0\,;\,T]} \mathbf{p}(t).(\ M(\mathbf{u}).d^2\mathbf{x}(t)/dt^2 + K(\mathbf{u}).\mathbf{x}(t) - \mathbf{F}(t)\ )\ dt\quad (7)$$

The computation of partial derivatives of L(**x**,**p**,**u**) gives the means to calculate the optimal value of **u** minimizing the function J(**u**). One difficulty is the integration of the adjoint state **p**(t), which is set by final conditions ; this means reverse integration process.

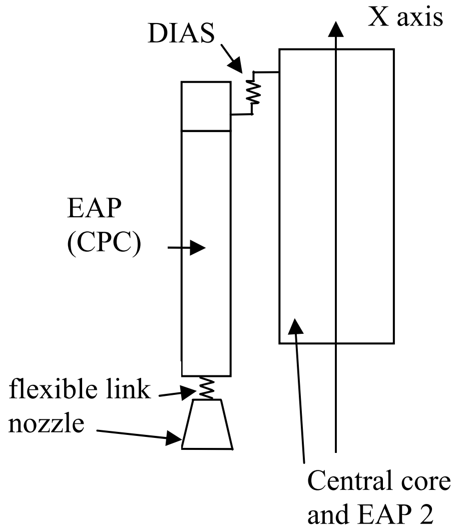
4 – Optimal placement of sensors, application

4.1 – Flight exploitation

The procedure has been applied to a simplified model of the launcher representative of the behavior at the end of EAP flight (around 95 s after lift-off) with respect to the interactions between the EAP and the central core. The link between the two stages is made with a dedicated device whose function is to reduce the transfer of the structural dynamic energy created inside the EAP (pressure oscillations phenomenon) towards the central core (and especially to the payloads). The chosen solution was to filter these dynamic levels with the help of a low stiffness structure called DIAS (Dispositif Assouplisseur) made out of several layers of metallic and rubber shearing plates. As a result, the actual value of the stiffness is not precisely known. Moreover, this stiffness is function of the frequency of the excitation and ground tests are difficult to implement for the frequency range of the 2^{nd} acoustic mode. Flight exploitation may be an interesting means to better assess the stiffness of the DIAS.
Furthermore, the flexible material that links the nozzle to the EAP has an impact on the results. The nozzle is designed to be orientated in order to ensure the attitude control of the launcher. For the EAP, this device introduces a component with a low stiffness. Here again, the value of the dynamic stiffness of this device is not well quantified.

The application of the algorithm defined in chapter 3 is implemented here to have a better assessment of the stiffness value of the DIAS and of the nozzle link for the frequency range associated to the second acoustic mode of EAP pressure oscillation excitation.

The model of the launcher is relevant with respect to the impact of the DIAS and the flexible link between the nozzle and the EAP. The central core and the second EAP are gathered in one single body ; this is justified by the difference in mass between one EAP (about 84 tons at this time of flight) and the total mass of the rest of the launcher (275 tons). Lateral behavior of each component is not simulated in this model.
The model is reduced to five nodes (one for the nozzle, two for the EAP and two for the central body). This allows multiple simulations without restriction due to computation time. For both steps 2 and 3, it is necessary to compute a large number of modal basis. This aspect may be a drawback if the precision needed requires a more detailed model.



Step 1 : Identification of important modes
The computation of the eigenbasis shows the expected behavior of the model with respect to the real one in flight. Apart from the rigid body mode, the results obtained are consistent with what is seen in flight and give the following eigenvalues and eigenvectors :

- The first mode (**4 Hz**) is related to the DIAS, with quasi-rigid behaviors of EAP (including the nozzle) and of central core. In flight, this mode is close to 3 Hz, but what is searched here is the dynamic stiffness of the DIAS for the second acoustic mode frequency range (around 40 Hz). The objective of the step 3 is to correct the value of DIAS stiffness, taking into account the measurements.
- The second mode (**26 Hz**) is linked to the central core deformation. Of course, the actual modes of the central core are much more complex.
- The third mode (**37 Hz**) is linked to the EAP deformation (longitudinal lengthening), which is the important mode that may cause high responses on the EAP and consequently on the central core.

One can notice from the computed deformation amplitudes, based on this simplified model, that the participation of the nozzle in this mode is relatively important, that is why the restitution of the stiffness of the flexible interface between the nozzle and the CPC (Corps de Propulseur Chargé, that is EAP tank) is made along with the one of the DIAS.

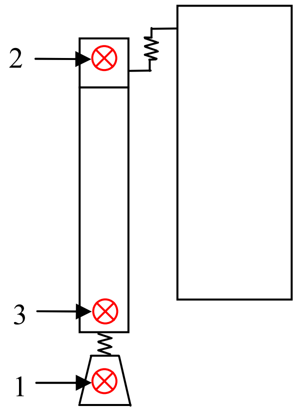
The frequency of this mode, considering the EAP alone without the nozzle, is close to 42 Hz, which means that the nozzle (and the link with the central core) has an impact of about 10 %. The impact of the nozzle on this mode has been confirmed with the reference model of the launcher (complete model) during development studies.

One can consider this model sufficiently representative of the behavior of the launcher in flight, for what is searched to be simulated.

Step 2 : Definition of sensor optimal placement

The algorithm defined in chapter 3 has been applied to this simple case. Potential positions have been defined on each component, using interpolations to compute the displacements outside of the nodes. The optimal positions obtained with the assumptions mentioned above are the following :

The optimal placement of sensors shows that the nozzle is the best location to measure the modes. The two extremities of the EAP (without the nozzle) are the following best locations. This sensor placement is linked to the measurement of *all* the modes of the system (four modes for this application). One can see that the resulting positioning is well adapted to the measurement of the longitudinal mode of the EAP.



For this implementation, the effect of uncertainties has been taken into account, following the step 2 algorithm described in chapter 3. The assumption was that the definition parameters (masses of the components, stiffnesses of the DIAS and the nozzle link, longitudinal stiffnesses of the bodies) are dispersed with a uniform probability law (all variables are supposed to be independent). The placement is compliant with these uncertainties. The algorithm gives an assessment of the derivative of the criterion with respect to the dispersion of parameters : **0.35 % / %**, which means that for an uncertainty of ± 10 % (assuming uniform probability law) of the parameter values (eg EAP mass or DIAS stiffness), the observability of the modes is globally reduced by 3.5 %.

This derivative is certainly different for another case. Nevertheless, if this order of magnitude is respected, this means that the defined placement is robust and the choice of three sensors should be correct.

Step 3 : Assessment of characteristic parameters

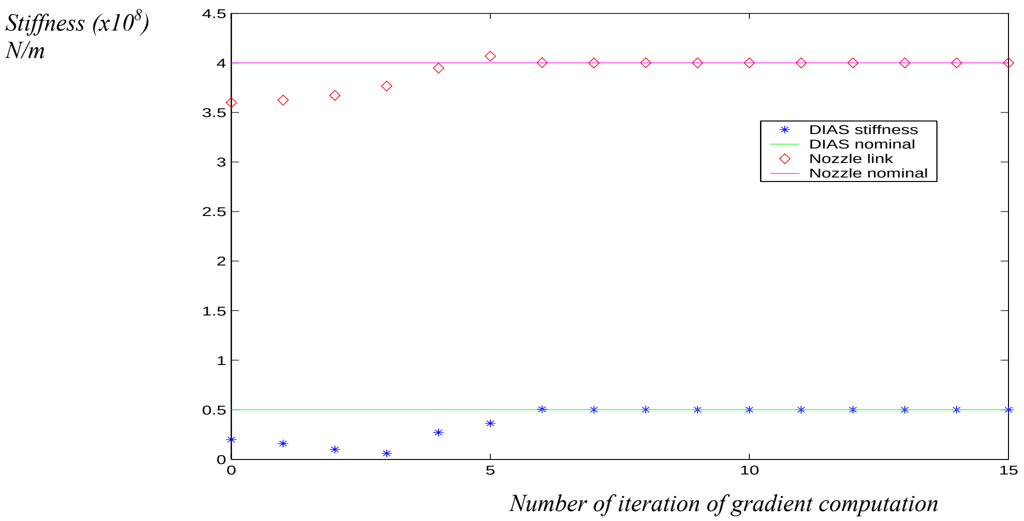
The algorithm defined in chapter 3 has been tested, using a synthetic set of measurements. The objective is here to show the results obtained with a very simple case. Utilizing flight measurements is planned for future studies, with adaptation of the algorithm.

The parameters defining the system are the following ones (vector **u**), the model is the one described above (5 nodes model) :

- mass & stiffness of the central core (275 tons / 7.5 10^8 N/m)
- mass & stiffness of the EAP (84 tons / 6 10^8 N/m)
- mass of the nozzle & stiffness of the link (6 tons / 4 10^8 N/m)
- stiffness of the DIAS (0.5 10^8 N/m)

These values are indicative. The underlined values are uncertain and shall be corrected using measurements data. The values given above are supposed to be the real ones and will be restored with the help of the step 3 algorithm. The initial values of nozzle link and DIAS stiffnesses are respectively 3.6 10^8 and 0.2 10^8. These values are close to the aimed ones.

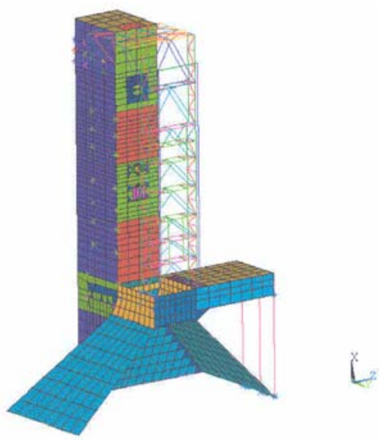
The system has been excited in compliance with the second acoustic mode features, that is on the lower and upper ends of the EAP. The algorithm restored precisely the real values, as shown below :



For this application, less than 10 iterations were necessary to obtain the aimed results. This process will be tested for more complex conditions, using real (filtered) measurements.

4.2 – EAP ground test application

The test bench has been modeled taking into account recent modifications concerning other utilizations. The size of the complete model (including the EAP) is about 9 000 nodes. The EAP is linked to the bench as it would be with the launcher during flight. However, one important difference concerns the upper link which is made without the DIAS. A modified front skirt is used in order to measure the thrust level of the EAP (which is in fact one of the main objectives of the test).
The step 2 has been implemented on this system in order to define the measurement plan. The corresponding time of flight is close to 120 seconds after EAP ignition.



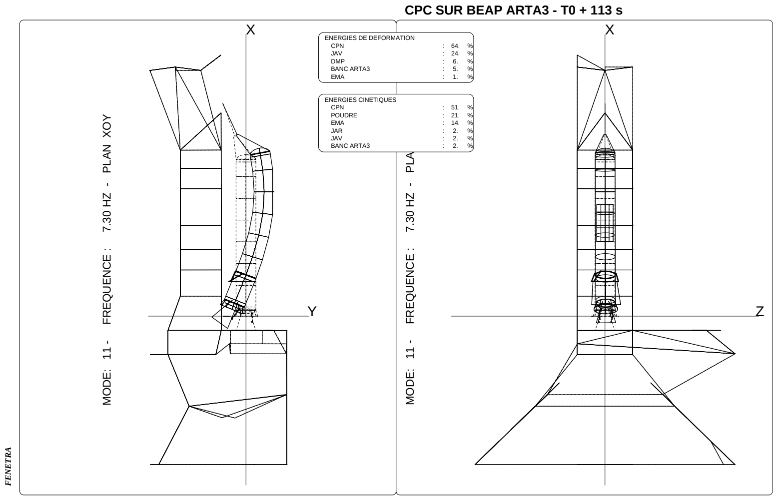
Ground tests are performed on the MPS in order to test slight modifications of the booster. These tests are performed under a program called ARTA (Accompagnement de Recherche et de Technologie Ariane 5). A test has been carried out on November 4th 2004 (« ARTA3 » test) and a test is foreseen before the end of 2006 (« ARTA4 » test).

The choice of the interesting modes is driven by the following potential influences that may be critical for Ariane 5 launcher :

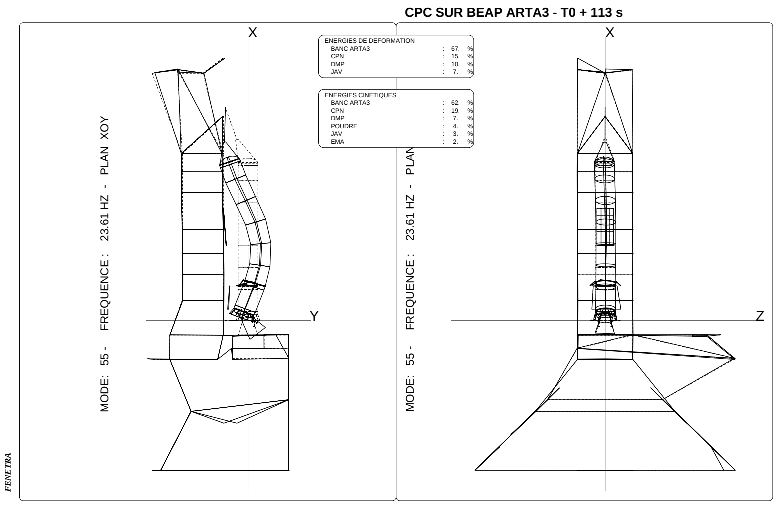
- the first lateral mode of the EAP that has an impact on the lateral behavior of the launcher and finally on the attitude control, this mode is linked to the DIAS characteristics,
- lateral modes of the EAP may be coupled with other structures on the central core,
- in the same way, the longitudinal mode of the EAP may be coupled with the central core and potentially with the payloads.

The selection of modes has been made taking into account the difficulties encountered in flight. Certain modes are excited during some flight phases and may induce high dynamic responses, on the payloads in particular. Three modes have been chosen.

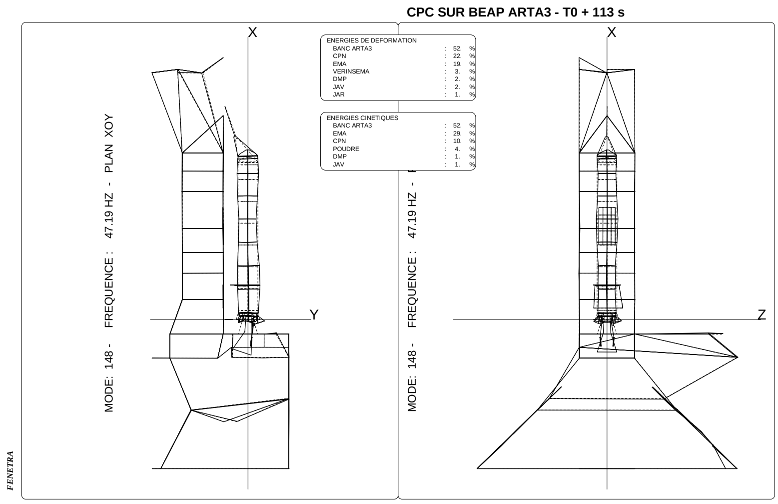
The first selected one (Mode 11) is involved in the low frequency range of modes that may have potential impact on the stability of the attitude control loop of the launcher. The second one (Mode 55) may be excited by the first acoustic mode at the end of EAP flight. Similarly, the third one (Mode 148) may be excited by the second acoustic mode. Those couplings can endanger the dynamic behavior during the flight.



Mode 11



Mode 55

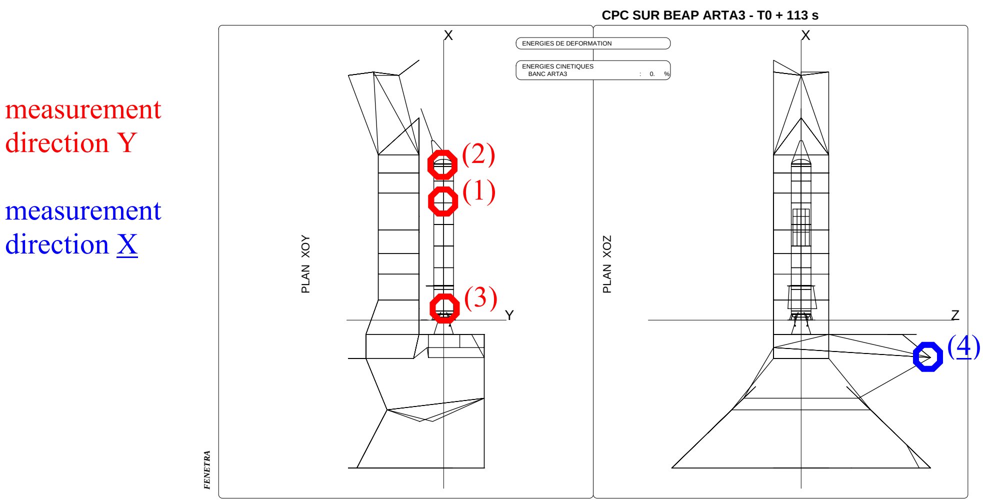


Mode 148

The optimal placement of sensors has been determined using the step 2 algorithm described in chapter 3. Three cases have been tested, corresponding to the optimal definition linked to the three modes mentioned above (number 11, 55, 148).

Results

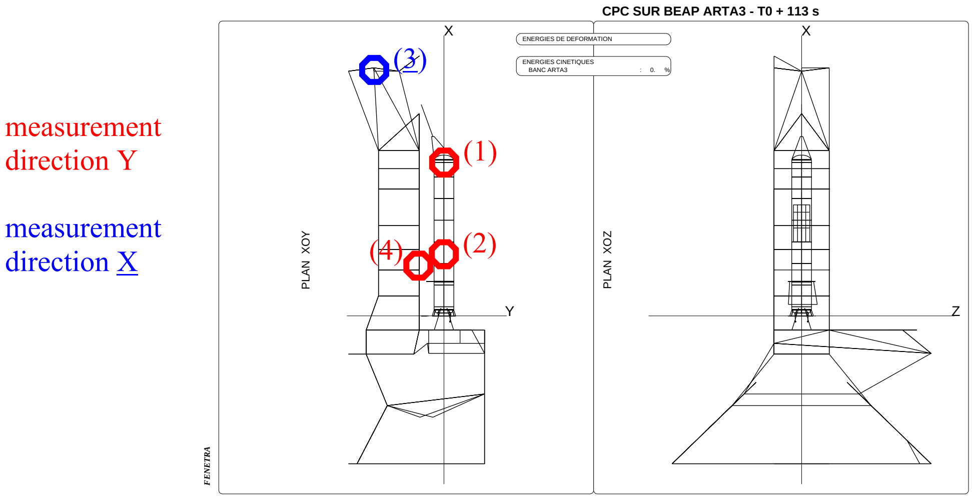
The obtained results give precise locations considering the whole structure including the bench and the EAP.



Optimal placement for **Mode 11**

The optimal sensors (for which the observability is maximized) for mode 11 are sorted as follows :

sensor	direction of measurement	location	criterion
(1)	Y	V2 / V3 I/F	$0.120\ 10^{-3}$
(2)	Y	Upper V1	$0.090\ 10^{-3}$
(3)	Y X	Lower V7	$0.090\ 10^{-3}$ $0.070\ 10^{-3}$
(4)	X	Bench	$0.003\ 10^{-3}$

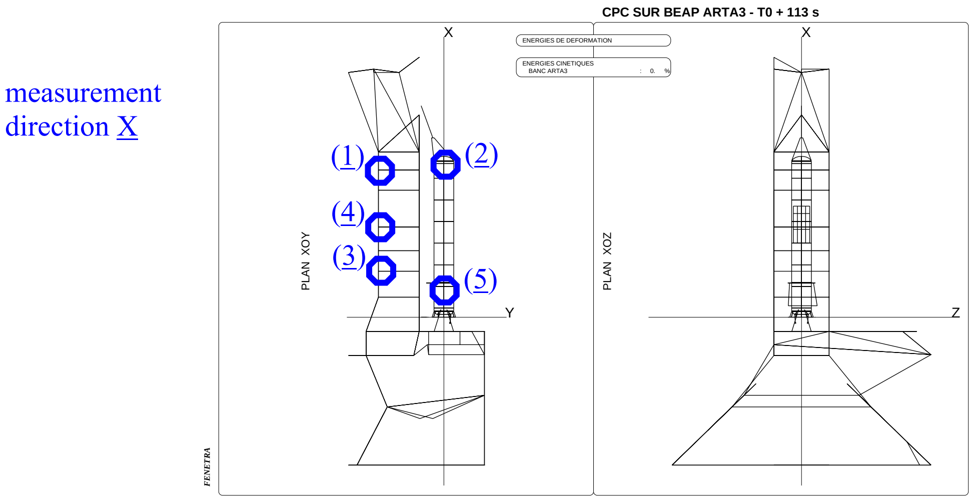


Optimal placement for **Mode 55**

The optimal sensors (for which the observability is maximized) for mode 55 are sorted as follows :

sensor	direction of measurement	location	criterion
(1)	Y	Upper V1	$0.036\ 10^{-3}$
(2)	Y	V5	$0.024\ 10^{-3}$
(3)	X	Bench	$0.016\ 10^{-3}$
(4)	Y	Bench	$0.011\ 10^{-3}$

For the mode 148, the JAR structure (lower part of the EAP) has been withdrawn from the selection because the associated deformations are mostly caused by local modal behaviors.



Optimal placement for **Mode 148**

The optimal sensors (for which the observability is maximized) for mode 148 are sorted as follows :

sensor	direction of measurement	location	criterion
(1)	X	Bench	$0.016\ 10^{-3}$
(2)	X	Upper V1	$0.012\ 10^{-3}$
(3)	X	Bench	$0.012\ 10^{-3}$
(4)	X	Bench	$0.008\ 10^{-3}$
(5)	X	Upper V7	$0.007\ 10^{-3}$

It appears that the couplings between the EAP and the bench are more significant than those linked to the lateral modes.

Comparatively, the criterion associated to the mode 11 is significantly higher than the ones of the following modes (close to one order of magnitude). This is a general behavior of modal decomposition ; the modal deformations are lower as the frequency increases. If the algorithm is used with a criterion based on the sum of the modal deformations for several selected modes, the risk is to hide the impact of high frequency modes. One solution would be to weight some mode by factors in order to level the contributors.

These placements have been implemented taking into account of the uncertainties, following the step 2 algorithm. For this application, it appears that the proposed placement is robust to uncertainties. One can see that the optimal placement for the mode 148 (longitudinal lengthening of the EAP) leads to the conclusion that the deformations due to this mode can be seen also on the bench, which was not obvious.

5 – Conclusion

A sensor placement process is proposed in this paper, corresponding to development and production needs of Ariane 5 launcher. Several algorithms have been defined. The tests performed showed interesting results that will be enhanced in the future.

The sensor placement is one of the important steps ; a robust approach (with respect to uncertainties on the main parameters defining the launcher) has been defined and tested on a very simple case. Prospects are envisioned to apply it to several load cases of Ariane 5 dynamic studies. This algorithm has been applied to an EAP ground test that will take place shortly.

Assessing the value of certain parameters (the stiffness of the DIAS has been mentioned above as one representative example) would constitute a valuable gain in launcher knowledge. The methodology presented here may be used to have a complementary approach to ground tests.

References

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