TESTING PHILOSOPHY FOR ARIANE 5 STRUCTURES QUALIFICATION THROUGH RECENT EXAMPLES

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ABSTRACT

The Ariane5 structures qualification methodology has recently been improved especially in the frame of low frequency dynamic environments encountered during Ariane flights. For example, the 3D dynamic behaviour of the launcher taking into account all possible load cases at a given moment during flight, obliged us to modify our dynamic dimensioning rules so as to combine excitations coming from different launcher's axes: lateral and longitudinal. Therefore, standard monoaxial sine tests are no more considered as "direct qualifying tests".

On top of that, more and more non linear systems are integrated in the launcher's stages. The objective is either to reduce the dynamic stresses locally (i.e. by using dampers or mechanical filters in order to prevent high amplification factors) or, to optimise the dynamic behaviour at the "system" launcher level (i.e.: the liquid oxygen tank friction damper system of Ariane new upper stage which has been developed in order to reduce the dynamic levels on the spacecrafts). The dynamic models have been improved consequently. And the dynamic tests, at different levels (several and single stages levels, elementary level), are necessary to validate these dynamic models including nonlinear elements.

This paper presents, through some examples, the testing philosophy for Ariane5 structures qualification. It will show the necessary links between tests and theoretical models approaches. Vibration environments will mainly be covered. Nevertheless, acoustic and static testing philosophy for qualification will also be briefly mentioned. For these later cases, the mathematical models are necessary to justify the test configuration by providing correction factors so as to cover the different effects: adjacent structures, loading conditions, thermal gradients, temperatures, pressure…

At the very end of the qualification process, the first flight results must validate the methodology. For that, the flight measurement plan is particularly improved for the qualification flight. An important effort is made to verify the most critical flight phases (i.e.: microphones outside and inside the stages for lift-off phase, unsteady pressure transducers on the rear part of the launcher for atmospheric "buffeting" phase…). A quick view of a typical first flight measurement plan will be finally shown.

1. INTRODUCTION

The purpose of this paper is to recall the testing philosophy for Ariane 5 structures and to show the relationship between models and tests in the frame of qualification towards environments.

One must distinguish the primary structures which are main structures sustaining the general loads of the launcher (thrust frames, skirts, structural tanks, fairing…), and the secondary structures which include equipments and their supports, lines, engine or stage components such as valves, compensators, pumps…

The dimensioning rules and qualification process depend on the type of structure, primary or secondary, which must be analysed. But in both cases, models and tests are most of the time necessary. Models are necessary to compute the maximum stresses and the minimum margin of safety in all locations. This cannot be obtained directly by test due to the usually limited number of sensors on the specimen. Tests are necessary to validate the model at dedicated locations and to demonstrate that the structure is able to withstand the dimensioning loads with the required margins. At the end, both approaches are complementary and permit to justify the dimensioning of a structure.

Sometimes, one can avoid a test when the analysed structure can be assessed by heritage. This situation can appear in case of small changes or in case of similarity for main structures and for secondary structures (ribs thickness evolution on a skirt, similar kind of support as already used somewhere else on the launcher…).

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2. DIMENSIONING AND QUALIFICATION OF PRIMARY STRUCTURES.

The central point of the dimensioning rules is the identification of the dimensioning load cases. It is necessary to list, for all areas and associated materials and technologies, the potential failure modes (leakage or gapping, rupture, plastification, buckling…). All the load contributions must be identified: thermal, pressure, general and local mechanical loads. The combination rules must correctly be established. On Ariane 's programs, the loading conditions (input data, adjacent structures and boundary conditions) are given and justified by the industrial architect. These loading conditions are part of the specifications for the contractor in charge of the structure: they cover all possible launcher configurations (single or dual launch, eventually different feeling rates for tanks, short or long fairing…). They are justified by "system" launcher activities; the objective is to remain as close as possible to flight conditions and avoid useless additional margins.

For a given main structure and its associated adjacent structures, a finite element model is developed. The mechanical loads are directly applied on it and the main structures are naturally equilibrated through the boundary conditions specified. The thermal map applied on the mesh comes out from a thermal model which can be the same as the one used for the verification of equipments thermal qualification. The thermal model uses as input, radiative and convective fluxes in addition with interface temperatures with adjacent structures. At the end, the computed thermal map should provide dimensioning stress contribution. Figure 1 summarizes the methodology for the dimensioning selection cases and for the computation of MOS (margin of safety).

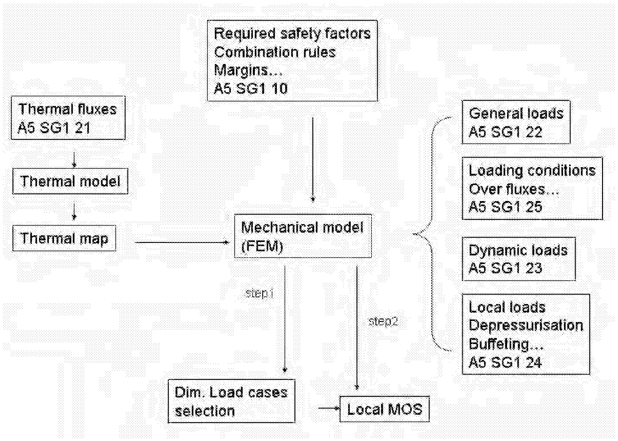


Figure 1 : dimensioning process

The step 1 of figure1 corresponds to the selection of the dimensioning load cases using a limited number of criteria: maximum or minimum main adjacent structures interface fluxes and deformations, and sometimes local stresses on area of the analysed structure. On step 2, the margin of safety are calculated everywhere with the above dimensioning load cases.

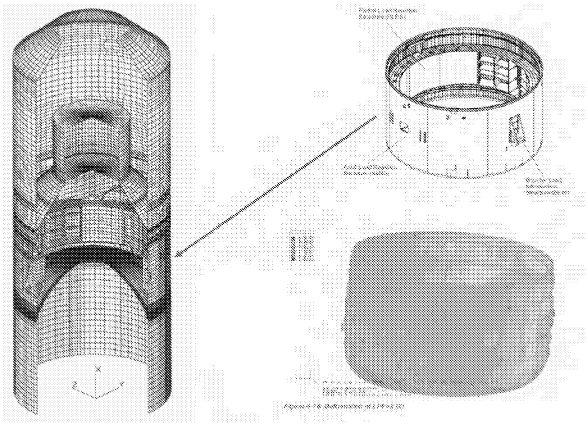


Figure 2: example of FEM used for dimensioning: the upper skirt of main cryogenic stage of Ariane5

Figure 2 gives an example of finite element model developed for the dimensioning of Ariane5 main body front skirt. The original model of the skirt shown with the adjacent structures on the left side of figure 2 has recently been improved for thermo-mechanical buckling analyses (see deformations on fig2 with the refined mesh).

The industrial responsible of the structure to be validated, must propose a testing configuration: structures and loading conditions (mechanical and thermal if needed). The proposed test configuration is justified by using mechanical and thermal numerical models in order to cover the following points:

- The structure thicknesses and the adjacent structures that will be tested don't correspond to the requirement indicated in the dimensioning rules.
- The tested loading conditions (mechanical and thermal) may be simplified compared with the real dimensioning load cases conditions.

Therefore, the industrial will propose computed correction factors which will modify the safety factors originally required. The final margins will be given by test results taking into account these additional factors. Additional correction factors may also be used for the material characteristics of the specimen to be tested. They can be justified by tests on samples which will represent the stage test specimen. The way to compute the corrected safety margin Jc is summarised below:

Relationship between qualification loads and limit loads: P qual= P lim * Jc

with Jc= (Kt + (Kadj * Kmin * J)) / (Kσ * Ko)
J: required safety factor (failure mode)

where Kt, Kadj, Kmin, Ko, Kσ are correction factors covering effects respectively of thermal gradients, adjacent structures and surfluxes, thicknesses, temperatures, material characteristics. These factors will cover the differences between test conditions and dimensioning conditions.

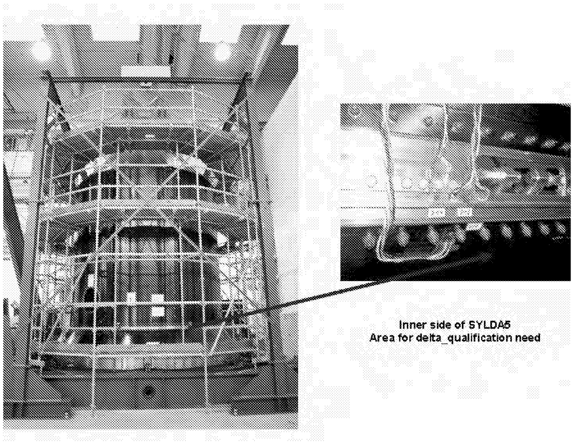


Figure 3: test performed on the upper carrying structure of Ariane5 (SYLDA)

Figure 3 illustrates a static test campaign perform on the Ariane5 SYLDA. The objective was the static qualification of the structure due to a modification of the intermediate ring connection to the lower cone which is pointed out in the picture. Stiffness and strength tests were performed. As an example, the corrected safety factor was about 1.4 instead of 1.25 in the area of the separation system of SYLDA5 (rupture or buckling criteria for metallic parts).

3. DIMENSIONING AND QUALIFICATION OF SECONDARY STRUCTURES.

In the following, we will focus on the low frequency dynamic aspect. The other contributions (acoustic, thermal, static, imposed deformations or prestresses, pressure…) will generate additional stresses that will be combined with dynamic loads. Acoustic qualification will be briefly discussed at the end.

3.1. General rule for low frequency dynamic load assessment, models and tests.

The general rule is illustrated through figure 4.

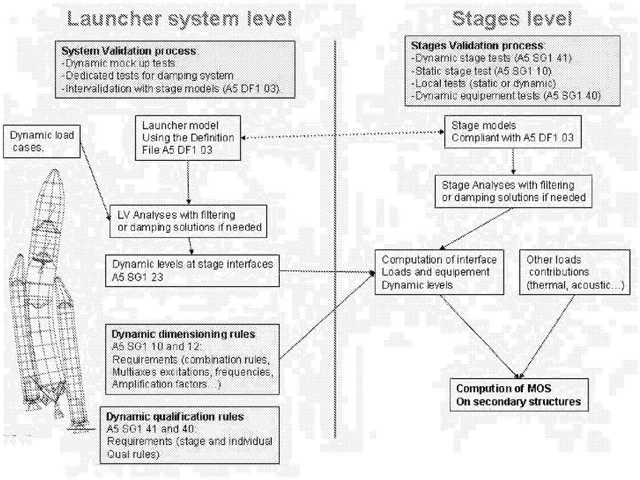


Figure 4 general rule for dynamic qualification

One of the major difficulties raised during a launcher development is to specify the more precisely as possible the foreseen flight limit dynamic environments on all the structures. When looking at flight data (see figure 5), one can see that the dynamic loads are mainly transient: side loads at engine ignition, lift off, gust, stage separations, thrust tail-off …

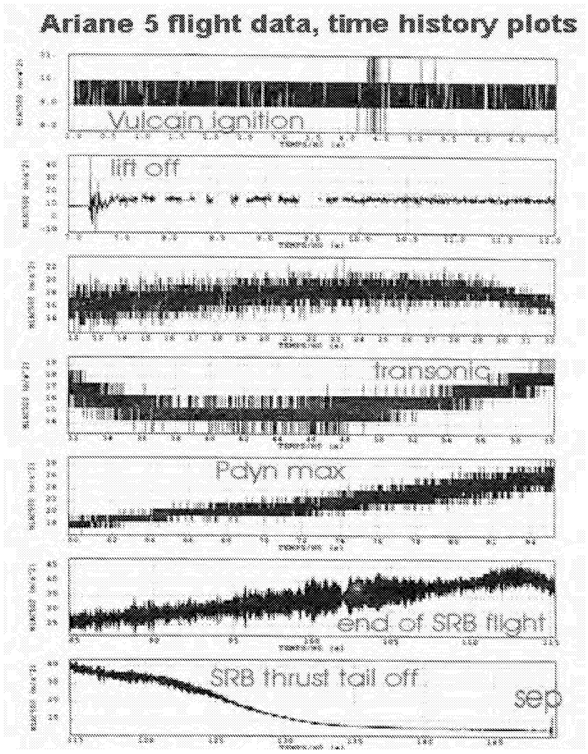


Figure 5: typical flight data, acceleration versus time, SRB flight phase.

Nevertheless, one quasi-harmonic phenomenon occurs during Ariane5 flight: the oscillations of pressure inside SRB (Solid Rocket Booster) combustion chamber. This latter case, in association with the dynamic characteristic of the booster itself, will strongly excitate the eigenmodes of the launcher. The pressure oscillation corresponding to the first acoustic mode of Ariane 5 boosters (eigen-frequency alround 21Hz) will appear at frequency which can vary from 18Hz until 25Hz depending on the flight instant in relation with the unsteady internal aerodynamic flow (see figure 6).

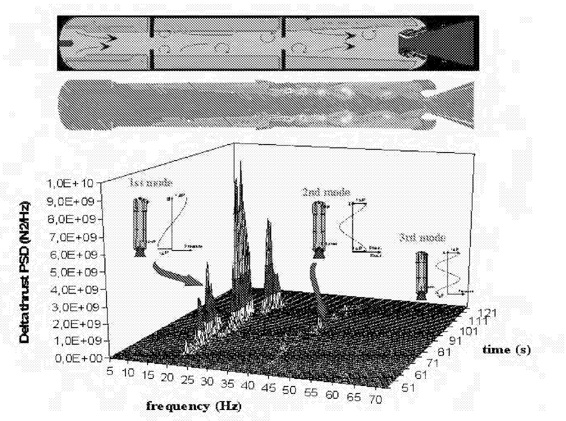


Figure 6 : pressure oscillations flight results.

Finally, the low frequency dynamic environment for the launcher's structures is described as sine equivalent environments. Only translation sine levels are specified at main stage interfaces (see figure 7).

This type of specification is justified by system analyses and sometimes flight data. It is to be noticed that for a new launcher system, uncertainties oblige us to keep system margins that could be cancelled after the completion of several instrumented flights, if needed. This also justifies the enveloping finally chosen harmonic excitation.

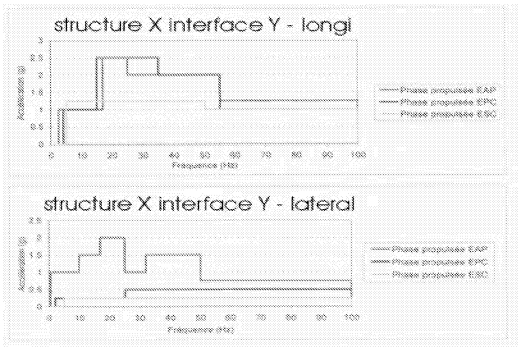


Figure 7: example of sine loads specified at main stage interfaces.

The sine interface limit levels must be applied at main interfaces of each structure in order to evaluate the dynamic responses of secondary structures. A recent evolution of our rules implies to combine, for each possible frequency, the effect of X, Y and Z interfaces excitations. In addition, changes were introduced in the methodology to treat the case of structure multiple interfaces.

In a generic manner, the different axes of dynamic excitations are combined with a linear superposition, frequency by frequency, through a modulus summation. This provides a conservative methodology without any consideration about phasing between X, Y and Z excitations.

The way to apply sine levels at different interfaces (case of multiple structure interfaces) , is treated case by case taking into account the specificities of the structure to be analysed. Dynamic system studies will justify the number of main interfaces to consider (figure8 for the new upper stage of Ariane5).

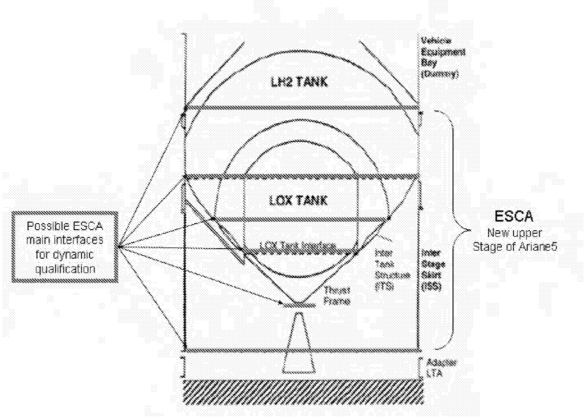


Figure 8: example of possible main interfaces for dynamic loading conditions on the ESCA.

Unfortunately, technical problems are often encountered when applying these rules, for example:

- The specification is given as imposed space average accelerations (limit values) at stage main interfaces, but sometimes the interface deformations, which are often observed, can affect the dynamic behaviour of the stage. In that case, a feedback is necessary between Industrial Architect and the Industrial in charge of the structure: either a change in the main interfaces is decided or an artificial modification of the levels is proposed.

- The specification is given as enveloping sine equivalent levels (cf fig7). Therefore, anti-resonances due to global clamped eigenmodes are skipped. Applying high dynamic levels at the corresponding eigen frequencies will provide unrealistic dynamic responses. This problem is generally solved using a notching criterion. As an example, the enveloping sine equivalent levels must not induce higher loads than the already specified general dimensioning loads. At the end, the acceptability of the notching has to be justified by the launcher system analyses.

Lot of works performed with dynamic models are necessary at each level: system and stage. These models have to be validated by tests which will participate to the qualification. But, most of the time, the stage dynamic tests are no more considered as directly qualifying tests. In the general logic shown in figure4, the consistency between the Architect Industrial model and the stages models is fundamental. The large system dynamic mock up tests bring an important validation step in the qualification process of the launcher system.

3.2 Validation of dynamic models, non linearities.

Dynamic models are used:

1- For the justification of equipments and components lay-out for each structure. The dimensioning of the secondary structures must be in agreement with the main requirements: high eigen-frequencies and low dynamic amplifications of supported equipments.

2- For global launcher system studies which justify the interface sine levels, the control loop stability, the POGO stability (possible interaction between hydraulic, propulsive and mechanical systems), the general loads dynamic contribution, the margins for kinematics purpose (separation of stages, lift off…).

The validation of models for point 1 objectives is provided by the industrial responsible of the structure with stage dynamic tests and sometimes local dynamic tests. Figure 9 shows tests performed on the new upper stage of Ariane5 by EADS in IABG facilities.

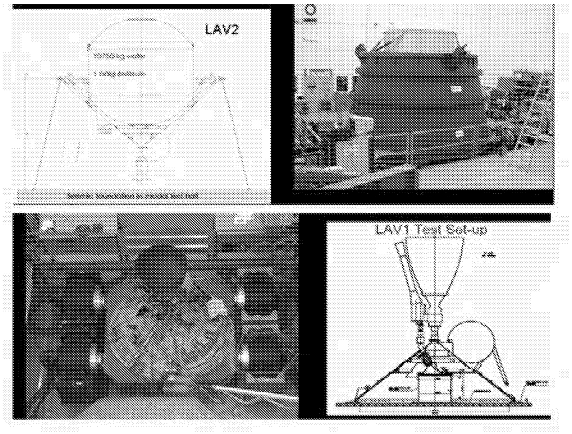


Figure 9: dynamic ESCA tests for model validation

For the dynamic model of the ESCA thrust frame (BMA), different type of tests were performed:

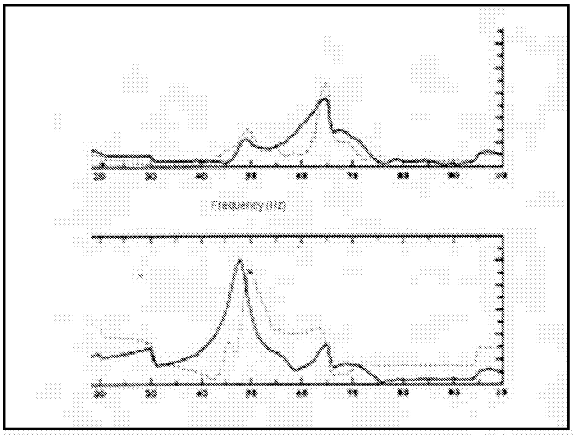
- modal test for global mode identification

- vibration test on BMA alone called LAV1: the larger BMA interface is clamped on the shaker table. This configuration was proposed as a simple configuration for model correlation. It also permitted to provide early dimensioning dynamic levels for accommodated equipments.

- Vibration test on BMA plus LOX tank of ESCA stage (LAV2): a specific adapter was developed in order to introduce an imposed motion at main BMA interface keeping its local flexibilities (breathing / ovalisation motions were allowed).

So the validation of the BMA dynamic model shall be pronounced based upon the correlations made between above test results and predictions. In addition, a complete dynamic stage test (including LH2 tank and the main skirts of ESCA) and dedicated local dynamic tests (lines and other components) were performed.

The validation of models must be agreed according to the defined criteria. Eigen-frequencies and dynamic amplifications shall be correctly assessed (i.e. +/- 5% or 10% on frequencies respectively for global or local eigen-modes; +/- 10% or 20% on amplification factors respectively for global or local eigen-modes). The criteria can be adjusted depending on the final objective of the numerical analyses: if the model is used to compute interface loads, big differences between test and prediction can be accepted at a frequency that will give low dynamic loads. For this latter situation, it is recommended to instrument the test specimen not only with accelerometers but also with strain gauges. This will help to bring some robustness on the output loads of dynamic model. Of course, intermediate criteria can be proposed such as correlation between test and model on generalised mass, effective parameters, MAC indicators (which is based upon eigenmodes orthogonality properties).



Measured Modes			Analytical Modes		
No.	Freq. [Hz]	Item/Shape	No.	Freq. [Hz]	MAC [%]
1	33.1		36	34.5	84
2	35.5		148	35.7	92
3	39.9		40	39.4	18
4	41.2		41	40.2	26
5	43.7		45	41.5	51
6	46.5		56	46.4	58
7	49.7		73	53.2	16
8	54.8		79	54.0	16
9	57.8		149	56.3	40
10	59.1		151	59.7	52

Figures 10 and 11: example of a comparison between model and test results on responses and modal criteria.

It is to be noted that dynamic tests sometimes need to be corrected (effect of adjacent structures, perturbation of test facilities…). Dynamic models can be used to reduce these effects. For this type of difficulties, it's recommended to foresee a high number of sensors on adjacent structures and on the shaker table. Sometimes, during a modal test, the ground on which the specimen is clamped will not react as an infinite stiff boundary condition. It will pertubate the dynamic behaviour of the structure. Therefore, sensors on ground will be useful and the validation of the dynamic model will be easier.

The validation of point 2 objectives is provided by both the industrial architect and the industrials in charge of the structures. The launcher dynamic model is made of different structural models representative of global modes. Some models are provided by industrials after dynamic reductions (i.e. vehicle equipment bay, front skirts…); others are made by the Architect (i.e.: fairing, ESCA new upper stage…). In this latter case it generally means that two models may exist for a same structure. Of course, the Architect model is not as detailed as the industrial one. The models used by Industrial Architect are compliant with the definition indicated in the general document A5DF 1-03 (see fig4) which must be approved by the industrials. This definition file also includes static numerical tests to be checked by all parties. Sometimes, eigen-modes of big mass equipments are also mentioned. The validation is finally obtained after tests completion (static and dynamic):

- Main stiffnesses are verified during static tests of each structure; interface stiffnesses between structures are part of big system mock up tests.

- Eigen modes of big mass equipments are verified during stage or local dynamic tests

<u>Particular cases of non-linear elements</u>

The reduction of dynamic environment becomes more and more an early goal to consider in the launcher programs. One of the reasons is to insure moderate dynamic levels on spacecrafts. Two different types of solution are proposed:

- Either to adapt the architecture of the launcher in order to prevent high dynamic levels. For example, on the ESCA, the longitudinal eigenmode of LOX tank suspension must be above 16.5Hz (the tank plays a role of dynamic absorber then the spacecraft longitudinal levels decrease).

- Or to introduce damping or filtering systems.

This second situation can be preferred when a problem of dynamic environment is encountered late in the development process (i.e.: filtering device between SRB and main body towards booster's thrust fluctuations: DIAS). But sometimes, such systems are proposed because no solution appeared to be available when working at architecture level of stages. Two pairs of SARO (LOX tank damper system of ESCA,[1]) have been introduced between LH2 and LOX tanks of ESCA in order to increase the apparent damping of LOX tank first lateral eigen-mode. The system is a friction damper; its implementation is shown on figure 12.

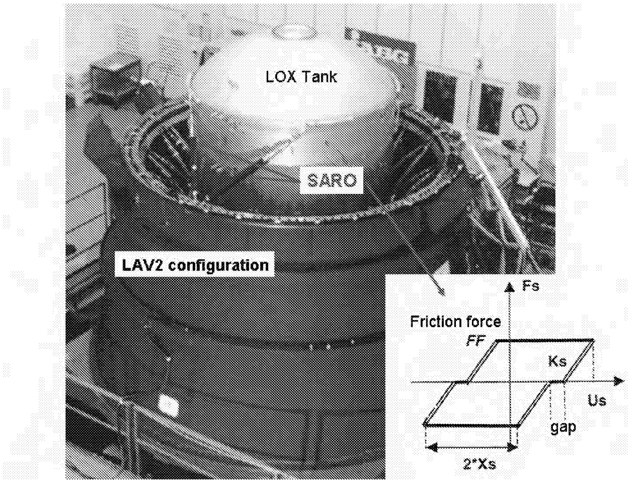


Figure 12: SARO implementation, view on LAV2 configuration.

Most of the damping and filtering systems are non-linear components which can be idealised with equivalent linear elements in general system launcher studies. This was not the case for the SARO: the Industrial Architect had to adapt its simulation tools in order to restitute correctly the induced dynamic behaviour.

During the new Ariane5 upper stage dynamic mock up test, the characterisation of the SARO behaviour and its consequences was a major objective. This exercise raised lot of question marks: concerning the influence of gapping at the SARO extremities, the effect of sweeping excitation frequency, the effect of simultaneous frequencies of excitation. The discrepancies on the friction force were found to be more important than foreseen. The impact of this latter point had to be analysed with the model. For the other points and in order to improve the model validation, it was decided to complete the previous exercise with a simplified configuration where the dynamic behaviour of the launcher is reduced to a two degree of freedom system: one for the ESCA LOX tank lateral mode and one for a spacecraft plus adaptor eigenmode. This mini dynamic mock-up test (called miniMD) took place at EADS Bordeaux (see figure 13 for a scheme of the test configuration).

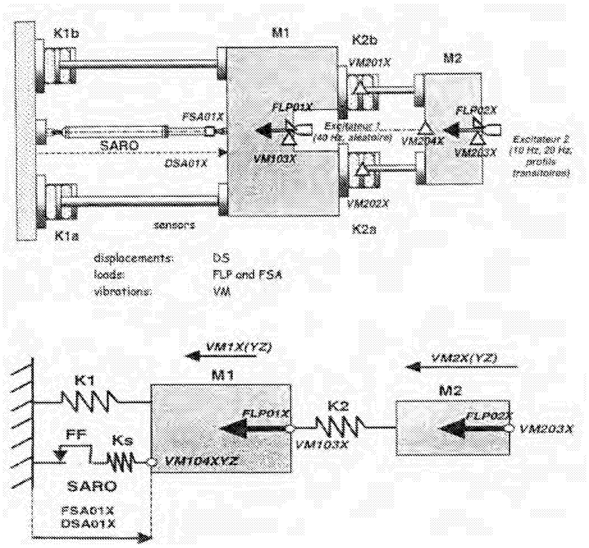


Figure 13: SARO miniMD, scheme of the test configuration and associated model.

The objective of these SARO MiniMD tests was to validate the behaviour of SARO (hardware and numerical model) with regard to sine environnement at different single or simultaneous frequencies, and with regard to transient and random environments. Despite some small differences with the prediction, the validation was pronounced. And at the end of the test campaign, a flight type environment was simulated with a good agreement between test and prediction on the displacement and SARO loads (see figure 14).

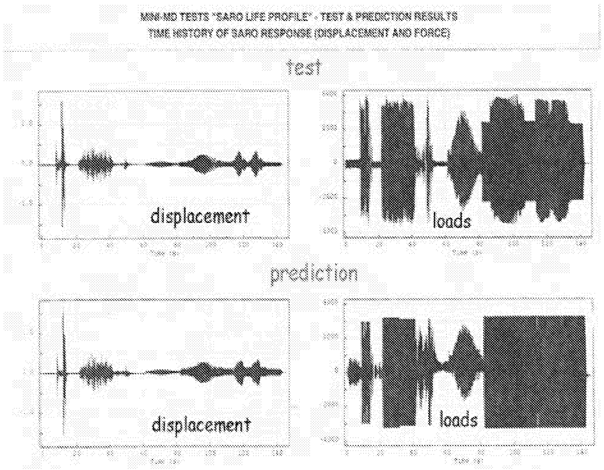


Figure 14: SARO miniMD, comparison between test and prediction with flight type of input.

3.3 Parametric instability: application on Ariane5's ESCA Lox tank

Preliminary remark: this particular phenomenon is not affecting only secondary structures but also primary structures that will be submitted to a risk of buckling under dynamic loads.

During the stage vibration test of ESCA, high amplification factors at the Lox tank equator were measured around 40Hz when exciting the structure in longitudinal axis. A deep notch was necessary to avoid over-stressing the Lox tank. This phenomenon was demonstrated by EADS to be in relation with a risk of parametric instability of the tank submitted to high dynamic loads. It is the result of the following observations:

- Coincidence of two types of eigenmodes around 40hz:
  - A Lox tank bulkhead mode that will provide high excitation input for the second type of mode.
  - The breathing eigen-mode which depends on the delta-pressure of the tank (pressure during test was much lower compared to flight, providing a more critical situation in test).
- Very low modal damping in relation with the above mentioned breathing mode.
- High axial excitation of the stage around 40 Hz demonstrated by system dynamic studies for the second SRB acoustic mode thrust fluctuations.

Figure 15 recalls the Mathieu equations which have to be solved and the stability diagram including to test and flight configurations curves. In an early step, the dynamic model was used in order to justify the risk of instability. The previous test results permitted to evaluate the dampings of the involved eigen modes.

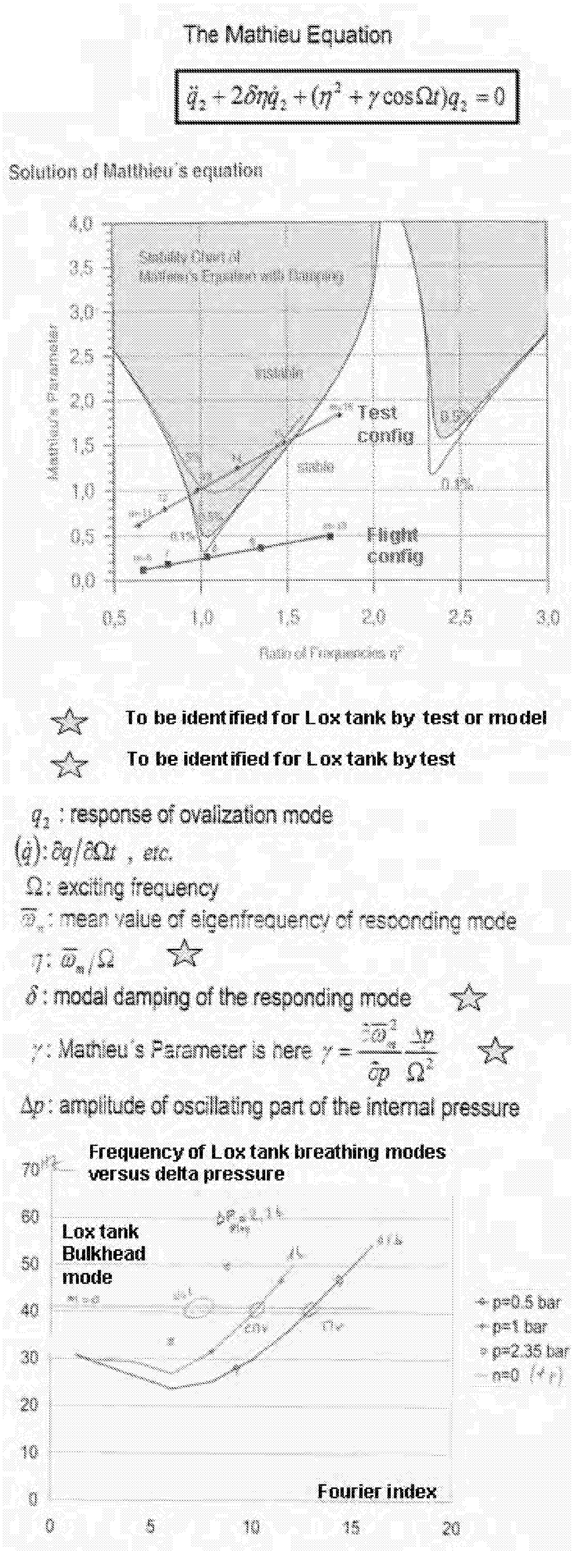


Figure 15: parametric instability equations, case of ESCA Lox tank first evaluation.

The assessment of the risk is closely linked to the longitudinal dynamic input level at the interface between the thrust frame (BMA) and the Lox tank. Dynamic test were performed with the following objectives:

- Validate the dynamic behaviour predicted with flight delta pressure in the tank.

- Justify the damping assumption of the two types of modes involved (especially the breathing modes which need a high number of sensors at tank equator).

- With the requested minimum input sine level in the 40Hz frequency range, demonstrate a margin between the critical breathing modal damping and the real modal damping. Of course, no parametric instability should occur during test.

The tests (see figure16) were made of sweep sine around the frequency corresponding to a possible coupling between the two types of modes, with different delta-pressure of the tank, increasing progressively the dynamic levels. It was agreed that a direct verification could be given when applying the required limit level plus 3dB.

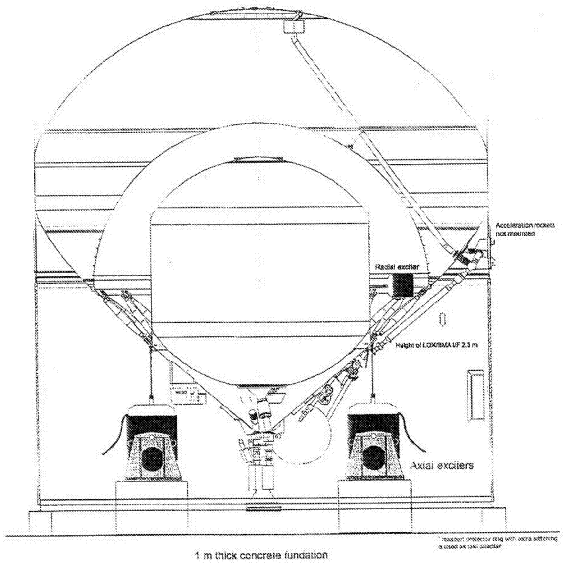


Figure 16: test configuration ESCA LOX tank assessment towards the parametric instability risk.

At the end, the performed tests associated with the mathematical model confirmed the stability status and allowed us to avoid either a structural modification of the tank or the implementation of damping system. A margin of two was finally demonstrated with regard to flight 517 conditions.

3.4 General rule for acoustic qualification

This paragraph recalls briefly how acoustic qualification is performed on Ariane5. The acoustic pressure field around the launcher and inside inter-stages is specified in a general document applicable to each structure of the launcher. The sound pressure levels (SPL) are described as equivalent diffuse acoustic field in each frequency octave band (see figure 17). These acoustic limit loads were justified taking into account test bench results on SRB, Vulcain engine and launcher reduced scale acoustic test (FAUGA ONERA facility). For most of the stages, a test in acoustic chamber is requested. It is asked to demonstrate qualification margins of 2dB on top of limit levels. Nevertheless, and as for static and dynamic environments, the test configuration must be justified with regard to:

- Adjacent structures or acoustic shields

- Representativity of the stage itself (i.e.: absence of nozzle, equipments…)

- Fluid representativity (i.e.: possible high concentration of helium during lift-off)

A vibro-acoustic model is generally proposed; it will permit to assess the differences between test and flight configurations, and will provide correction factors to be applied on power spectral density of measured accelerations.

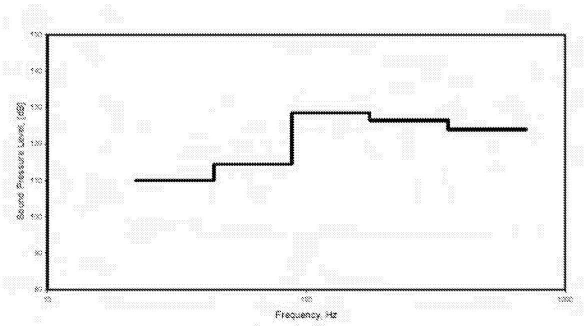


Figure 17: example of acoustic SPL specified on Ariane5, interstage with Helium.

A comparison has to be made between equipments random qualification levels and corrected measured levels at the corresponding locations. In case where the individual qualification levels are not sufficient, a change in the lay-out or a delta-qualification may be needed. The absence of equipment's eigenmodes in the frequency of interest can be used as an acceptable argument to avoid a delta-qualification.

With regard to induced acoustic loads, the industrial in charge on the structure to be analysed must justify if this contribution is negligible or not. If direct acoustic field is generally not dimensioning for structures, induced random loads have to be evaluated and superimposed with the other load types.

4. IMPORTANCE OF FLIGHT MEASUREMENTS PLAN FOR FINAL VALIDATION.

At the very end of the qualification process, the flight results validate the methodology expressed in the previous paragraphs. The first launcher's flight is usually associated to a technological telemetry corresponding to an increased acquisition capability (bandwidth, channels number) compared with the operational telemetry used for recurrent flights. Apart from functional measurements, hundreds of sensors are installed on an Ariane5: accelerometers, microphones, steady or unsteady states pressure sensors, strain gauges…

They permit to confirm the foreseen environments:

- Sensors are dedicated to the assessment of flight load conditions:
    - pressure inside the combustion chambers of engines and boosters will allow deriving the thrust fluctuations.
    - external pressure oscillations on the rear part of the main body (mainly the nozzle extension) will validate the buffeting loading condition of this area (see figure 19 for instrumentation and levels measured on flight 511).
- Sensors are dedicated to the direct verification of specified inputs:
    - external and internal acoustic levels (see figure 18 for instrumentation of internal microphones on the upper part of flights 501/502/503)
    - main stage interface sine equivalent levels.
    - interface loads (i.e. attachment struts between SRB and main body, payloads interface…).
- Sensors will allow a comparison at equipment or component levels between flight and ground tests.

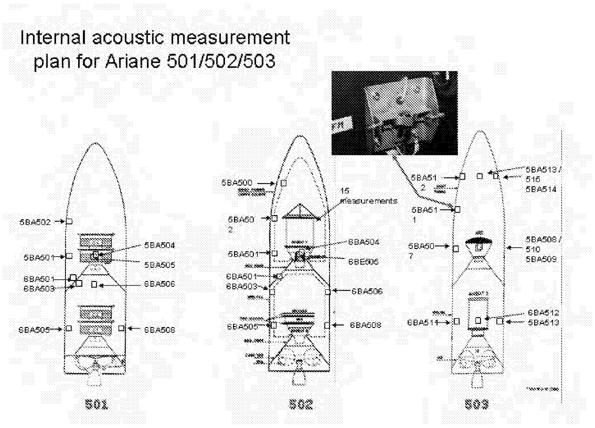


Figure 18: illustration of flight measurements during qualification flights for acoustic.

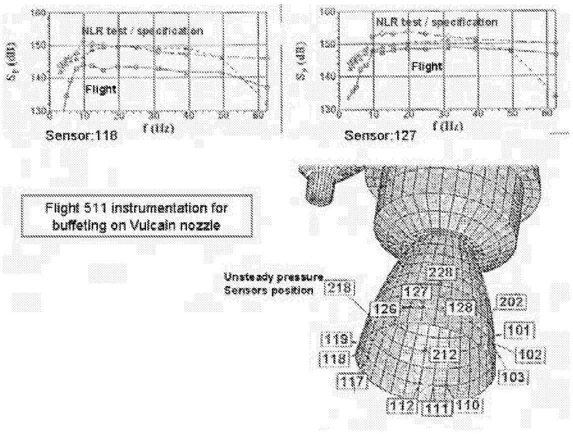


Figure 19: unsteady pressure measurement on the rear part of Ariane5 launcher, flight 511.

The exploitation of flight data are made in two major steps:

- The level 0, just after the flight, gives a rapid statement about the validation of environments. Anomalies can be raised for non-foreseen events, or for measured levels higher than specified or foreseen. Depending on their critical character, these anomalies should be treated before the next flight.

- The level 1, which must be decided before the first flight, will provide a synthetic view on environments for several flights, allowing to adjust the load cases and the models. This type of activity is important for the new version of launchers, in order to specify the environment the most precisely as possible. Level 1 can also conclude for a need of delta-qualification on the launcher in operation.

5. CONCLUSION

This paper gives a brief synthesis of the general Ariane's rules for the verification of dimensioning. For both primary and secondary structures, models and tests are complementary. The test configuration must be justified compared to the dimensioning configuration; the model will provide correction factors in order to cover the differences. On an other hand, test will allow to validate the models and will demonstrate the margins.

The dynamic environment of Ariane obliged us to adapt our dimensioning rules methodology, and the stage dynamic tests can hardly be considered as "directly" qualifying tests. Such tests are mainly used to compare and update the dynamic models which will deliver:

- The sine loads on supported equipments taking into account worst case of excitation axes combination. The resulting sine dynamic contribution has to be combined with acoustic, thermal and pressure effects. The dimensioning of the support will be justified either by elementary tests or by file provided sufficient margins are available.

- The sine levels on equipments taking into account worst case of excitation axes combination. These levels should justify the sine qualification of the equipments.

The dynamic models integrate more and more non-linear components for which dedicated tests may be necessary. An example with a friction damper (SARO) is shown in this paper. In addition, dynamic loads can create a risk of parametric instability for tanks. The example of the new upper stage of Ariane5 is briefly described. The stability validation is based on the use of specific tests and mathematical models.

In addition, this paper recalls the importance of flight measurements for the validation of the environments and the associated proposed qualification methodology.

REFERENCES

1. P.Mourey, E.Louaas, *Implementation of a friction damper in the new cryogenic upper stage of Ariane5,* Spacecraft and Launcher dynamics environments workshop, El Segundo, California, USA, 2001.