ARIANE 5 NEW UPPER COMPOSITE INCLUDING A NON LINEAR DAMPER: PREDICTION OF THE DYNAMIC BEHAVIOUR AND VALIDATION DURING ON-GROUND TESTS & FLIGHTS

V. Le Gallo, T. Romeuf
EADS SPACE Transportation, Les Mureaux Centre, France

Due to the foreseen evolution of the satellites market, the increase of ARIANE 5 performance became a necessity. To reach 10t performance, the new cryotechnic upper stage (ESC-A) has been developed by the reuse of ARIANE 4 third stage well-known components which enabled a fast development.

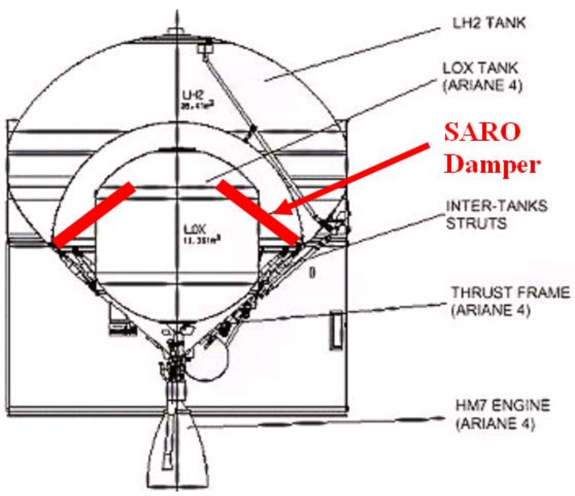

Fig. 1. ARIANE 5 Upper cryogenic stage “ESC-A”

According to the conclusions of the CNES and EADS Space Transportation dynamic working group, the dynamic loads on the payloads and on the launcher had to be especially checked. After a feasibility phase, a non-linear damping device (friction pad system), called SARO, was designed to keep the vibration levels low. This system must allow a static displacement due to thermal deformations of the cryotechnic tanks and provide a high damping with small dynamic displacement. The SARO force threshold was defined as an optimum with respect of the payloads dynamic environment.

The logic of qualification of the launcher has taken into account this specific hardware by the elaboration of a specific methodology including the development of a dedicated non-linear prediction tool and its validation by two kinds of full-scale tests :

- “MD tests” : dynamic tests on a complete mock-up of the overall upper stage including the SARO device with simple conditions (sine excitations at room temperature),

- "MINI-MD tests": dynamic tests on a simplified configuration made up of by a double resonator including one SARO, representative of flight conditions aspects (main modes, complex excitations, cryogenic temperature).

Logic of development

Early in the development of the ESC-A stage, the dynamic environment was considered as a key point. A dynamic integrated task force was created gathering dynamic specialists from CNES (the Program Director) and EADS ST, the Industrial Architect of ARIANE family and the Stage Contractor at that time. One of the task force conclusions in order to keep the payload accelerations low was to implement a local damper [R2] [R5], called SARO, for LOX Tank Damping System. In fact, due to the difference of diameters between ARIANE 4 (2.6 m) and ARIANE 5 (5.4 m), the new stage ESC-A generated low frequency motions of heavy structures such as the LOX tank filled with 12 tons of fluid.

The task force defined the location, the type and the characteristics of the hardware. Based on preliminary tests, the solution proposed by the Stage Contractor, a friction damper was accepted by CNES and EADS Space Transportation [R1]. The feasibility and the efficiency of the damper were one key point of the new stage development.

Taking into account the implementation of such a non-linear damper on the new stage, the Industrial Architect had to develop and to validate by tests a logic and new methodologies, for the A5E/CA qualification phase and the coupled load analysis. As usual during a launcher development, the classical "modal survey test" fulfilled all the dynamic linear objectives. For non linear aspect, the SARO efficiency had to be confirmed and the industrial Architect methodologies had to be validated :

- first, on the upper composite point of view including two pressurized tanks and in-flight structures,
- then, at cryogenic temperature for the damper, with the flight excitation profiles.

SARO damper definition

The most efficient system identified was the one with four struts located between the upper part of the LOX tank and the lower inner part of the LH2 tank. At the beginning, SARO dynamic characteristics were roughly defined for a linear damper but any other technology dissipating the same energy per cycle for the considered load case could be studied. The main constraints of this device were to be efficient for very low levels of dynamic displacements (less than a millimeter) and also to allow important quasi-static displacements (few centimeters during the filling and the pressurization of both tanks) under cryogenic conditions. From a theoretical point of view, several technologies could fulfill the requirements such as hydraulic, hydrodynamic, rubber and friction concepts. From a technological point of view, solutions were not all equivalent so tests have been performed especially at flight temperature. After tests in thermal and dynamic environments, the friction pad seemed to be the simplest and the most efficient solution.

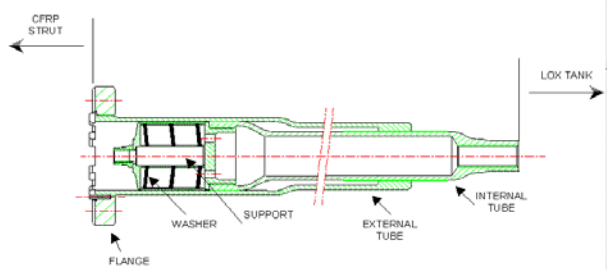

Fig. 2. SARO device

EADS-ST had developed special tools to take into account the non-linear behavior of the damper. The optimized set of damper characteristics was obtained minimizing payloads accelerations onto the launcher :

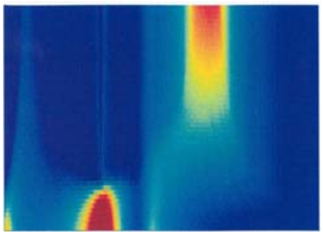

Fig. 3. SARO optimization (parametric study)

The stiffness and the force threshold were the object of a requirement to the Stage. Specified value of the friction force had to be reached with a tolerance of 20%. Methodology of prediction

The methodology of prediction developed for the qualification of the launcher A5E/CA is based on a coupling between linear finite element model without SARO (overall launcher including fluid-structures coupling) and a MATLAB® non-linear element for the SARO behavior. For the test prediction, the damper characteristics were extracted from test results (friction force FF and stiffness Ks).

"MD tests" : Upper stage ground sine tests

During the ARIANE 5 development, three modal survey tests [R3] [R4] were performed for each main structure of the launcher. The new Upper Composite test plan included :

- static tests to validate flexibility matrix,
- clamped dynamic tests for EAP-EPC flight studies,
- free-free dynamic tests for ESC-A flight studies.

IABG GmbH at Ottobrunn (Germany) performed the modal survey test, during four months, under EADS Space Transportation responsibility.

The upper composite configuration was constituted of :

- ESC-A stage clamped on the ground,
- Dual payload carrier structure (SYLDA),
- Upper and lower payload adapters (ACU),
- Nose fairing mass dummy ,
- Upper (6.5 tons) and lower (4.5 tons) payload dummies.

The test article was in clamped condition at room temperature. The total weight was 30 tons and the height was 17 m. The eigen modes were identified by 410 transducers (acceleration, displacement, force and load), for sine excitations delivered by 13 exciters. Comparing the computed EAP flight modes and test modes in terms of eigenfrequencies, mode shapes and strain energies, thirty target modes were defined, up to 100 Hz.

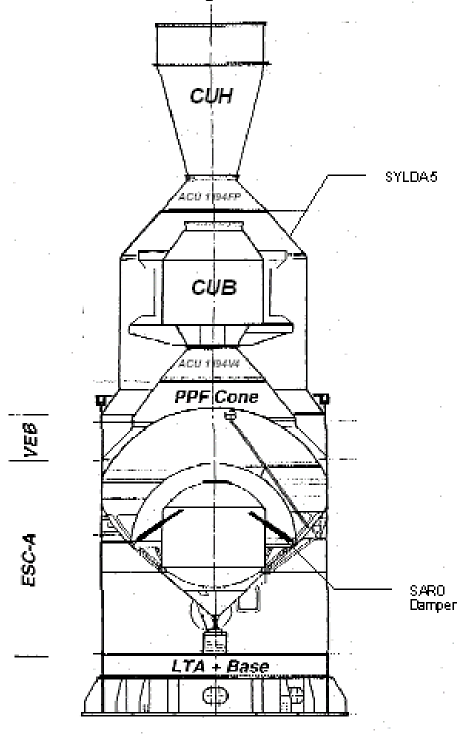

Fig. 4. "MD" tests configuration

The modes for which dampers were specified were especially worth to investigate. In non-linear domain, target modes were classified in two groups:

- Modes for which the non-linear behavior was a main objective of this test like "damper modes" or LOX tank bending motion,
- Modes for which the test prediction identified a non-linear behavior in the test configuration like the second bending mode of the upper payload or LOX tank longitudinal mode.

The limit between linear and non-linear domains was defined by the damper force threshold :

- below the damper threshold FF, the test article was considered as a linear structure and classical linear methodologies could be applied.
- above the damper threshold FF, the non-linear domain was reached and the non-linear approach was requested.

Therefore the main test objectives were split:

in the linear domain :

  - validation of FE models,
  - modal characterization especially damping,
  - validation of the linear approach.

- in the non-linear domain :
  - confirmation of damper efficiency, validation of the tools used for the qualification of the launcher.

Linear domain

For low frequency modes (< 45 Hz) in the linear domain, the differences between the Finite Element (FE) eigenmodes and the experimental ones were excellent :

Frequency = 2 to 5%
Generalized mass = 10 to 20 %
MAC (Mode shapes) = 0,6 to 1,0

Notice that the MAC was greater than 0,9 for the main SARO target modes. Obviously, these modes were validated, first, in the linear domain. For these target modes, the correlation between test and prediction was very good and consequently the validation of the FE models was established.

Non -linear domain

After the linear test, all the non-linear target modes were well known but the excitation levels had to be increased in order to reach the non-linear domain. Red lines were defined mode by mode according to the safety margins and the test prediction. The non-linear domain was reached as soon as one damper slides. So during the tests, the relative displacement transducers were checked in real time.

The damper efficiency notion can be defined in both harmonic and time-domain approaches. The FFT of damper force versus damper relative displacement showed uneven components of the excitation frequency and therefore uneven components in the response of the test article.

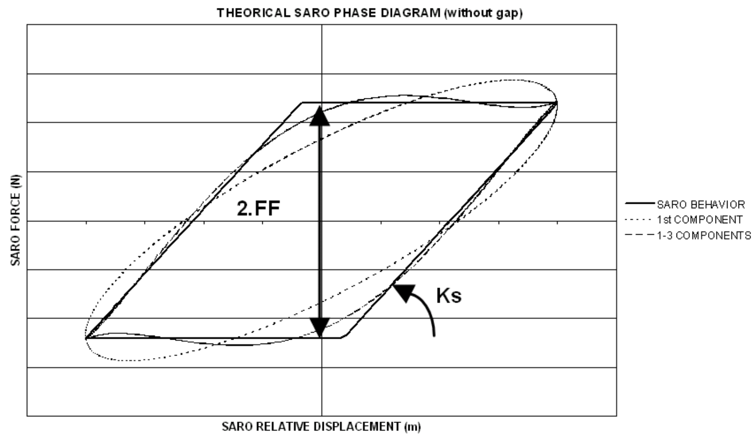

Fig. 5. SARO phase diagram (& harmonics)

Two approaches were considered :

- an harmonic approach, only taking into account the excitation of the first harmonic component of the response,
- a time-domain approach using the complete response.

The friction pad was a local damper and the modal damping approach had to be confirmed by test. So different ways were used to define the damper efficiency :

- Global criterion : damping ratio between non-linear and linear results
- Local criterion : mean value of damper efficiency for main transducers.

Both criterions were computed and compared for each excitation level. The results on both harmonic and time–domain approaches confirm the main hypothesis of ESC-A stage development: the SARO friction damper provided damping at system point of view. The local efficiencies depend on the test article location and the two damping definitions are consistent in the harmonic approach.

Prediction tool validation

Generally, on the main accelerations, the prediction results are above the test response, with a maximum discrepancy of 30%. The harmonic approach, less time consuming and the time domain approaches provided similar results.

"Mini-MD tests" : SARO non linear tests

The test article is a double resonator system including one SARO, two heavy masses (4,6 and 1,4 tons) and two exciters providing forces up to 20 KN, random up to 2000 Hz. 41 transducers (acceleration, displacement, force and load, temperature) were implemented. The dynamic characteristics were defined according to main frequencies of the ESC-A stage in EAP flight configuration with and without damper stiffness.

The objectives of these tests were :

- to confirm and characterize the damper efficiency in flight conditions :
  - damper temperature (-160°C),
  - dynamic excitation (multi-sine, random and sine, EAP flight phase life profile),
  - dynamic environment (eigenmodes)
- to validate the assumptions of a constant phase diagram of the SARO,
- to check the cumulative effect of combined excitations,
- to validate tools and methodologies used for coupled load analysis.

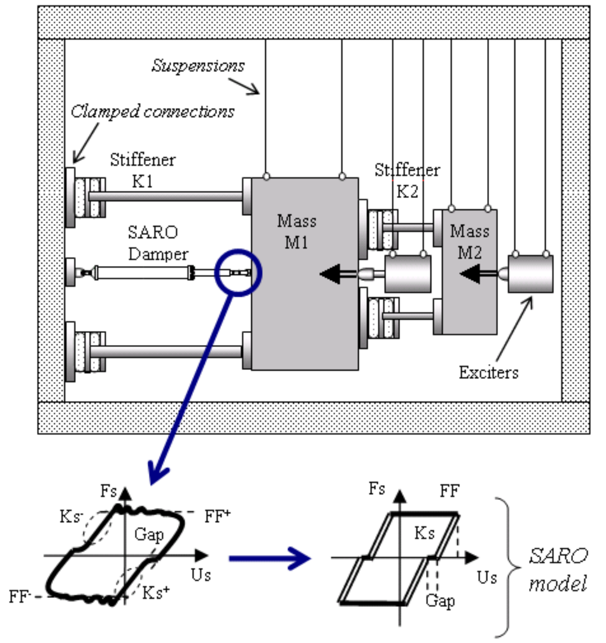

Fig. 6. "MINI-MD" SARO tests

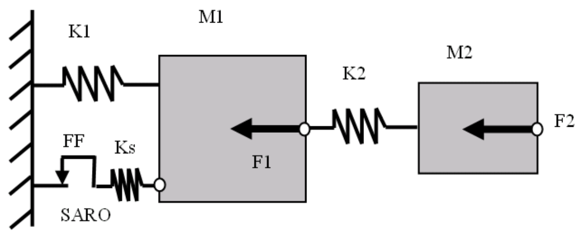

Fig. 7. "MINI-MD" model

One of the original features of this MINI-MD test was to represent the complete life profile of the SARO from the lift-off up to the boosters separation, using prescribed excitations issued from A5 measurements and A5E/CA flight prediction results :

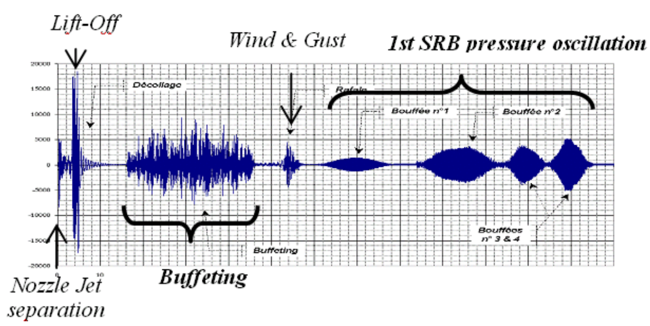

Fig. 8. SARO life profile (exciter 2)

Test results

Results from MINI-MD test campaign confirmed :

- the good stability of the SARO characteristics in flight conditions,
- the good quality of the prediction results with discrepancies generally lower than 15%,
- the improvement of the new concept of SARO "Tulip", greatly more stable than the previous "Baseline" one used on the first A5E/CA flight in 2002. So, this new concept has been chosen for next flights,
- the SARO efficiency to significantly reduce the vibrations generated by the 1st EAP acoustic mode associated to pressure oscillations (attenuation factor up to factor 4), but also for the Buffeting case (attenuation factor that can reach 2).

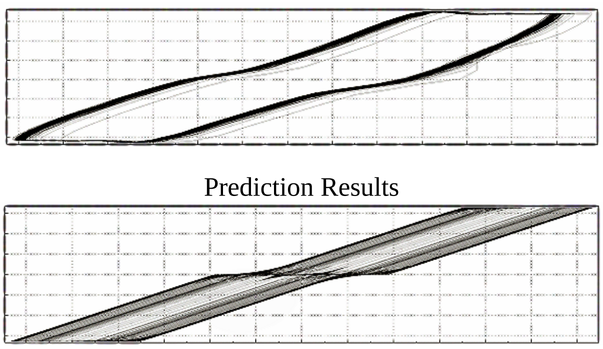

Fig. 9. Sine tests results (SARO phase diagram)

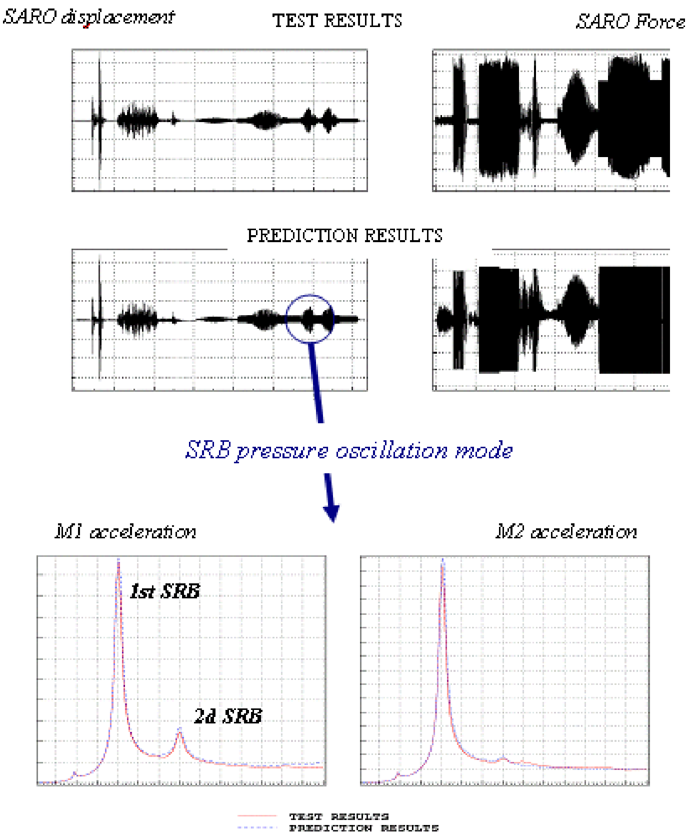

Fig. 10. SARO life profile results

Post-flight analysis

Ultimately, it has been shown, in flight conditions, that the SARO system has a good behaviour, particularly the new "Tulip" concept, used during the last successful flight 521 and which is indeed a very stable system.

The SARO friction force has been measured with a good accuracy in flight conditions and met the specified value:

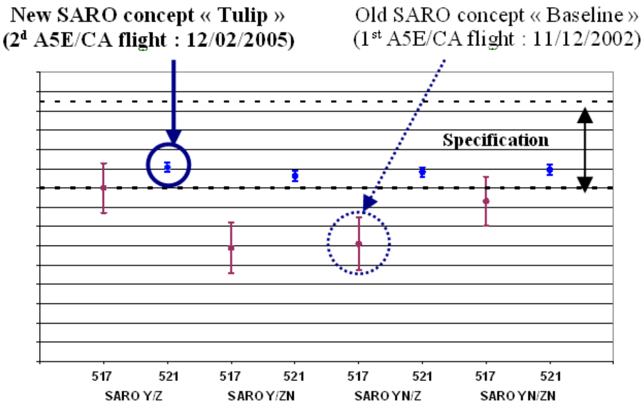

Fig. 11. Mean SARO friction forces in flight

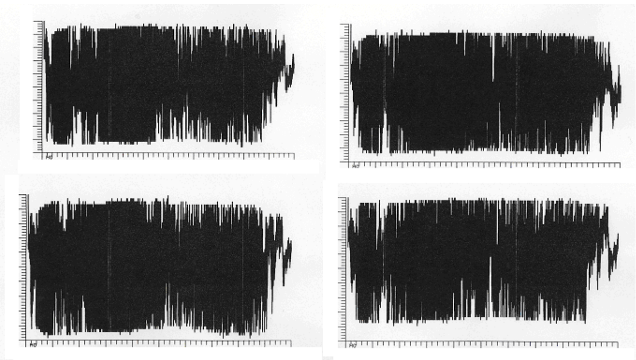

Fig. 12. SARO friction forces time-histories in flight

The measured SARO relative displacements during the flight were compared to the one issued from the qualification loop of the launcher, for all the main load cases. It shows the good agreement between predictions and reality. Flight analyses confirm that the SARO can play a significant role in the damping of launcher and payloads vibrations for the 1st EAP acoustic mode associated to pressure oscillations (for which it has been developed) but also for other load cases, namely the Buffeting phase, as previously seen in mini-MD tests conclusions.

Conclusion

Since 1999, the European space community was deeply involved in the development and the qualification of a new configuration of ARIANE 5. The ARIANE 4 third stage provided a propulsion bay consistent with this short-time schedule. A CNES-EADS Space Transportation integrated task force was created early during the stage development. It was helpful to find a solution and to define the new stage specifications. To keep the dynamic levels low, a friction damper was developed and has demonstrated its efficiency during two tests at system level. Thus validated, the logic and methodologies defined by EADS Space Transportation enable to be confident in flight predictions of the new version of ARIANE 5. It is now confirmed by means of the two first flights of this launcher. After four modal survey tests EAP, EPC, Upper Composites including EPS and ESC-A, EADS under CNES contract demonstrated the high level of management for system-level tests and for development of coupled load analysis methodologies. The European Space Agency and ARIANESPACE own a launcher able to reach 10 tons in GTO dual configuration.

Acknowledgements

The authors wish to thank the representatives of CNES, French Space Agency, EADS-ST GmbH and IABG GmbH involved in the ESC-A development and qualification.

Terminology

A5	:	ARIANE 5
A5E/CA	:	ARIANE 5 Evolution with ESC-A
CNES	:	Centre National d'Etudes Spatiales (French Space Agency)
EADS-ST	:	European Aeronautic Defense and Space – Space Transportation Company
EAP	:	Solid Rocket Boosters
EPC	:	Principal Cryotechnic Stage
EPS	:	Storable Propellants Stage
ESC-A	:	Cryotechnic Upper Stage
FE	:	Finite Element (model)

FF	:	Friction Force
FFT	:	Fast Fourier Transform
LH2	:	Liquid Hydrogen (tank)
LOX	:	Liquid OXygen (tank)
MAC	:	Modal Assurance Criteria
MD	:	Dynamic Mock-up
SARO	:	Oxygen Tank Damping System

References

[R1] E. Hornung, R. Jakel, H. Oery, E. Costes. "Damping devices for optimising the dynamic behavior of ARIANE's new cryogenic upper stage ESC-A". 51st IAC, Rio de Janeiro, 2000.

[R2] A. Rittweger, J. Albus, E. Hornung, H. Öry, P. Mourey, "Passive damping devices for aerospace structures". 50th IAC. Amsterdam, 1999.

[R3] D. Barthe, J. P. Leriche, P. Metz, D. Langlais, O. Monnot. "ARIANE 5 System Dynamic tests. Preparation and exploitation from Industrial Architect". Spacecraft and Structures and mechanical testing. Paris, 1994.

[R4] J. P. Leriche, O. Quemeras, S. Dillinger, A. Grillenbeck, P. Mourey. "Updating ARIANE 5 booster models using the modal survey and real firing test data". First European conference on launcher technology. Toulouse, 1999.

[R5] P. Mourey, C. Gratien, R. Jakel, Y. Lefebvre. " Optimization of the new upper stage (cryogenic) of ARIANE 5 on a dynamic point of view". First European conference on launcher technology. Toulouse, 1999.