PAYLOAD COMFORT – A Challenge for launcher's design

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Abstract

The "PAYLOAD COMFORT" is considered as a challenge for launcher's design. The reduction of vibration, acoustic and shock levels requires a constant attention for launcher. A continuous work has been performed on ARIANE 5 to maintain low level but the payload comfort is always an issue and improvements will be considered for new generation of launchers.

Among other events in flight, we point out the following major events limiting the payload comfort:

- Low frequency vibrations that occurs during the first phases of flight with two major load cases that are the blast wave at lift-off phase and the solid rocket booster thrust oscillations after 100 seconds which can generates significant dynamic environments. In order to reduce the impacts of these vibrations, an isolation device has been implemented between the boosters and the central core of the launcher, and a damping device has been installed on the cryogenic upper stage.
- Shock levels due to the fairing separation. A new separation system has been developed in order to reduce these shock levels.

The development of new versions of ARIANE launchers will be a new step in the dynamic environment control with challenging objectives to be reached. Therefore, it will be an opportunity to introduce new technologies and approaches, taking into account short, mid and long terms activities. The paper gives an overview of the main items, scoping on:

- Short term issues through a better mastering of the damping factors on launchers. Dedicated tools like a virtual testing method are being set-up to evaluate the damping brought by junctions, backed by flight analysis used for validation.
- Mid term issues through the introduction of dedicated hardware like Payload Isolation Device (PID) whose aim is to guarantee a friendly low frequency environment to the payloads.
- Long term issue through the introduction of Active Isolation Device (AID) and damping structures.

This problematic shall be efficiently treated through an international network involving laboratories, universities, research centres and industrial partners.

1. Introduction

The "PAYLOAD COMFORT" is a challenge for launchers' design, which has to be mastered. The reduction of vibration, acoustic and shock levels requires a constant attention, and a continuous work has been performed on ARIANE 5 to maintain low level of vibrations, but the payload comfort is always an issue and improvements will be considered for the next generation of launchers.

This paper describes the topics to be addressed at system level but also at technology level in order to master the vibrations on ARIANE launchers to control Payload Comfort: by the improvement of damping assumptions in current launcher dynamic predictions for short term applications, the development of a passive isolation device for midterm applications then the development of an active isolation device and of structural damping solutions for future launchers' design.

2 Dynamic environments on ARIANE 5

The dynamic environment is an important driver for launchers' design, as it is directly in relation with the payload qualification. Indeed, it is described in Launchers' User's Manual including the requirement concerning the Quasi-Static Loads (QSL) & Sine levels for the payloads which are as « Design Driver » for the satellite's structure and equipments.

The High Frequency (HF) environment is induced by shocks and acoustic and technical solutions have been developed. As an example, an improved fairing separation system called "HSS3" has been developed in order to reduce the shock levels "at emission" generated during the separation of the fairing. Also, other technical solutions as Tuned Mass Dampers (TMD) or Passive Isolation Devices (PID) are available in order to secure the reduction of shock near the payloads, when needed.

The Low Frequency (LF) environments are generated by some flight events, in particular the blast wave occurring at the lift-off phase and the solid rocket booster thrust oscillations (called ODP) occurring after 100 seconds of flight.

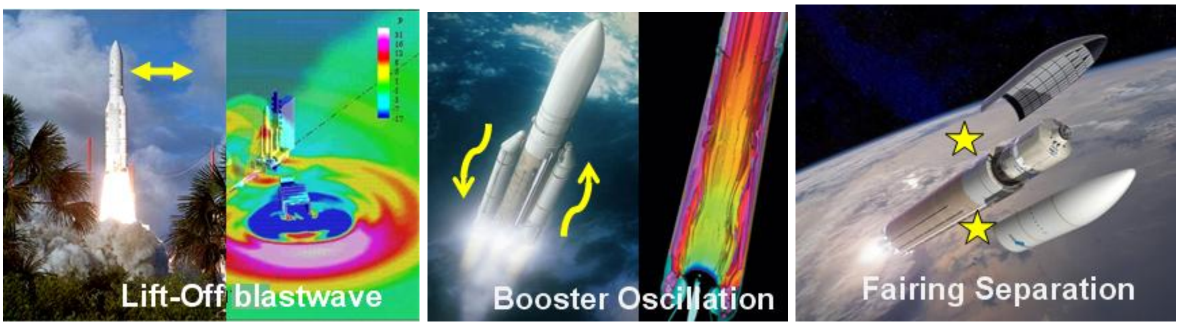


Figure 1: Main ARIANE 5 flight events

Since the first version of ARIANE 5, an elastomeric isolation device (called DIAS) has been implemented between the boosters and the central core of the launcher in order to reduce the impact of ODP on the central stages and the payloads. A complementary friction damping device (called SARO) has been developed for the ARIANE 5 Evolution Cryogenic A (A5E/CA) to be integrated between the two cryogenic tanks of the upper stage [2].

In the framework of the development of new versions of ARIANE launchers, a particular effort has been engaged in order to master the LF payload environment, especially concerning the ODP phenomenon. Several solutions hare being investigated , among them the architecture of the upper part, the stiffening of carrying structures, the integration of dampers or the soft-mounting of the payload with a PID. This last solution has been retained to improve the comfort of the lower payload on A5ME. Indeed, a PID is a simple way to tune the modal responses of the payloads in order to isolate them from the rest of the launcher. However, the design of a PID represents also a challenge to manage some antagonist constraints as longitudinal & lateral modes, first and second soft-mounted payload modes which are in general coupled to the global launcher modes.

3. State-of-the-art on "Payload Comfort"

3.1 State-of-the-art on Isolation

The most usual way to attenuate low frequency vibrations on vehicles is to implement an isolation device. The isolation device decouples dynamically the payload from the rest of the vehicle by its soft-mounting. Moreover, in order to reduce the excitability of the resulting suspension mode, a damping function is usually added. In the space world, the current technological solutions which are mature enough are Passive Isolation Devices (PID) such as those that have been developed in the USA by MOOG or Honeywell companies. Indeed, USA has already developed several PID in order to improve the payload comfort on launchers in the framework of an US Air Force program [4]:

- The "Softride" products developed by MOOG (CSA Engineering) are based on flexible metallic beams for the isolation function including viscoelastic constrained layers to ensure the damping function. The "Omniflex" concept isolates the payloads essentially in axial contrary to the improved concept "Multiflex" which isolate also in lateral. It has flown several times on US launchers. More recently, another kind of isolation device with a "C-ring" shape has been developed to be integrated between two stages of the launcher ARES in order to attenuate the impacts of the dynamic loads due to ODP. The MOOG products are adaptable to different classes of payload or launcher stages Mass, centring & Inertia (MCI). They are intrinsically stable because passive.

- The "ELVIS" concept developed by Honeywell is based on pneumatic & hydraulic devices to isolate axial and lateral vibrations with the particularity to remains stiff for the payload rocking modes to limit the payload lateral displacements avoiding any risks of shocks with the fairing. This last function is ensures by the "D-strut" technology based on antagonist pneumatic cavities (see figure below) which offer the advantage of an improved axial isolation of the payload. The pure lateral (shearing) motion is also isolated.

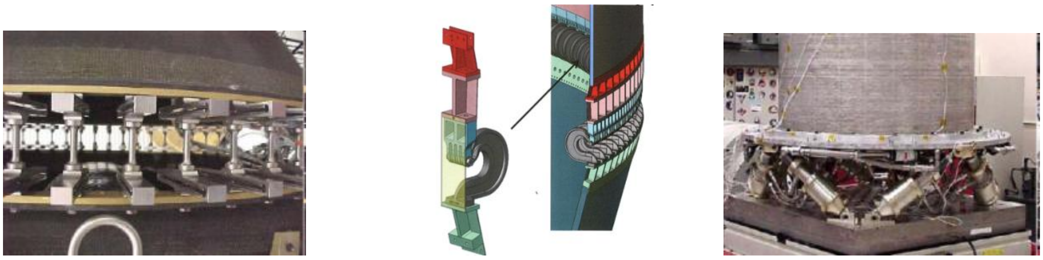


Figure 2: American Passive Isolation Devices (MOOG & Honeywell)

- No active isolation device has been developed yet to a sufficient maturity, so as to be integrated on a launcher. Indeed, the passive solutions are clearly preferred because it is easier to demonstrate their reliability and safety. However, some significant improvements of the payload dynamic environments could be offered by active or "semi-active" devices, minimizing also the system impacts.

3.2 State-of-the-art on material damping

Another way to attenuate low frequency vibrations on vehicles is to introduce damping in the carrying structures. The problem is to increase significantly the damping, especially at low frequencies, on structures which shall also be sufficiently rigid and light. Although many materials seems promising, they are not today mature enough to take place on a launcher. Moreover, there is still a need for selecting the most appropriate material and develop such applications.

Restricting to monolithic conventional materials, the graph hereunder shows that the polymers offers potentially excellent damping performance but with low rigidity, while metals are rigid but with very low damping properties.

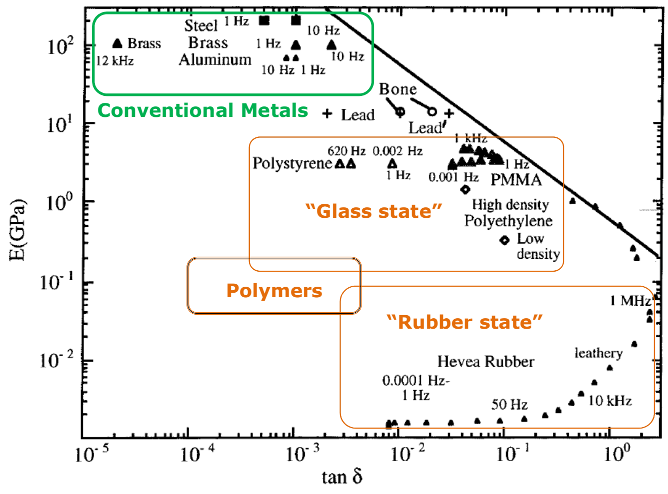


Figure 4: Material's structural damping

Nevertheless, this cartography illustrates also that the viscoelastic properties of polymers are complex and greatly influenced by the excitation frequency and also by other environmental parameters like temperature. At low frequencies, damping is mainly associated to relaxation phenomenon and can be improved by modifications of the composition and micro-structure. However, it is necessary to associate to the damping structure (polymer) a rigidifying structure (conventional materials), for example by sandwich structures reinforced with coatings or with loaded materials.

The short operational life of a launcher offers some flexibility compared to other kind of vehicles because of a lower impact of fatigue on structures. Moreover, the main dynamical loads occur during the 2 first minutes of flight which represents a very short duration. The next flight phases are more quiet and the major difficulty become the progressive increase of the thermal range, between cold and hot environment. This last point can be managed by adapted thermal comfort solutions like insulation or a thermal regulation if needed to master the mechanical characteristics during all the flight.

Based on this conditions and requirements, some solutions of combined rigid and damping materials have been proposed, like:

- Damping metallic materials used for acoustic absorption (but high density),
- Sandwich materials including damping cores and glues,
- Monolithic materials including elastomeric nanoparticles or stone particles,
- Functionalized materials (polymer/metallic trellis).

However, the efficiency of these solutions remains to be demonstrated, especially for the low frequency range and a maturation and development plan is necessary.

3.3 State-of-the-art on damping at junctions

A third way for improving damping is to take advantage of the damping generated at the launcher junctions. Indeed, a significant part of the damping is due to the junctions in the current structures. Also, some research studies have been engaged [1][5] in order to measure it then to be able to predict it, and a potential solution could be now to design junctions to increase the structural damping using validated tools and adequate materials.

4. Payload Comfort Road Map

The ARIANE launcher evolution roadmap give the schedule for technology maturation, in general, and in particular for a payload comfort road map :

- **ARIANE 5 ES/ECA for short term applications**: the return of experience from the current launchers enables a better understanding of payload comfort drivers and technologies. Some research studies have been performed about damping and isolation. New tools are now used in order to improve our knowledge on current launcher dynamic behaviour.

- **ARIANE 5 ME for mid term applications**: A "Payload Comfort" working group has been engaged in 2010 to propose technical solutions in order to guarantee a friendly payload environment on this new version of launcher. Then, it has been decided to develop a PID which is currently in progress in phase B.

- **ARIANE 6 for long term application**s: the next generation of launchers may offer the opportunity to introduce advanced technologies and devices for payload comfort, with the conditions that these new solutions are economically competitive, robust and sufficiently demonstrated. It is now possible to evaluate the efficiency of advanced concepts and materials through a comparison with the current structures (including the PID developed on A5ME) on a common representative demonstrator, taking into account the necessity of achieving in due time a sufficient maturity level TRL of 6 for a possible integration in ARIANE 6 development. The topics that can be taken into account are in particular:

    - Advanced alternative solutions for Passive Isolation Device (PID)
    - Advanced alternative solutions for Active Isolation Device (AID)
    - Semi-Active Isolation Device (SAID) to improve the performances of the PID by the mastering of the payload suspension modes
    - Advanced damping materials and structures.

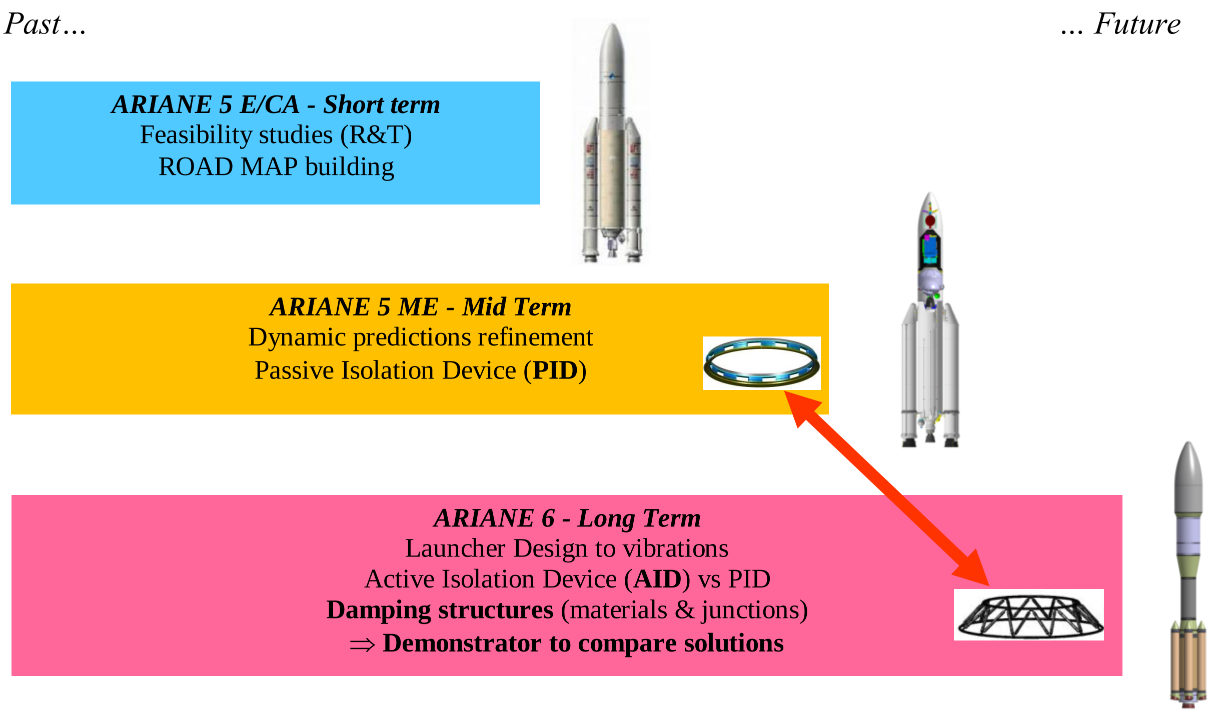


Figure 5: "Payload Comfort" roadmap

5. Payload Comfort advanced topics

The different advanced topics may be gathered in 4 different legs:

- **Leg 1: Launcher System studies** in order to improve the current dynamic environments assessments by a refinement of damping assumptions, to assess new payload qualification processes on ARIANE Launchers, to assess the integration of passive or active isolation devices on the launcher (IRL), to propose structural damping increase targets, to design new launchers like ARIANE 6 taking into account dynamic from the beginning.
- **Leg 2: Advanced Isolation Devices**, including both Passive Isolation Devices (PID) and Active Isolation Devices (AID) or Semi-Active ones (SAID) to be tested and compared on a common demonstrator.
- **Leg 3: Advanced Damping Solutions**, dealing with materials, junctions and design. This leg aims to prepare a prototype of damping payload adaptor to be tested on a common demonstrator.
- **Leg 4: On-ground demonstration,** that is the preparation of a full scale dynamic demonstrator constituted of an existing payload structural mock-up (STM) mounted on an existing adaptor (PAS) to be submitted to flight representative environment. A first test campaign has to be dedicated to evaluate the behavior of this reference configuration. In other test campaigns, PID solutions, then SAID, AID and damping solutions shall be tested in the same representative environment to be evaluated comparatively.

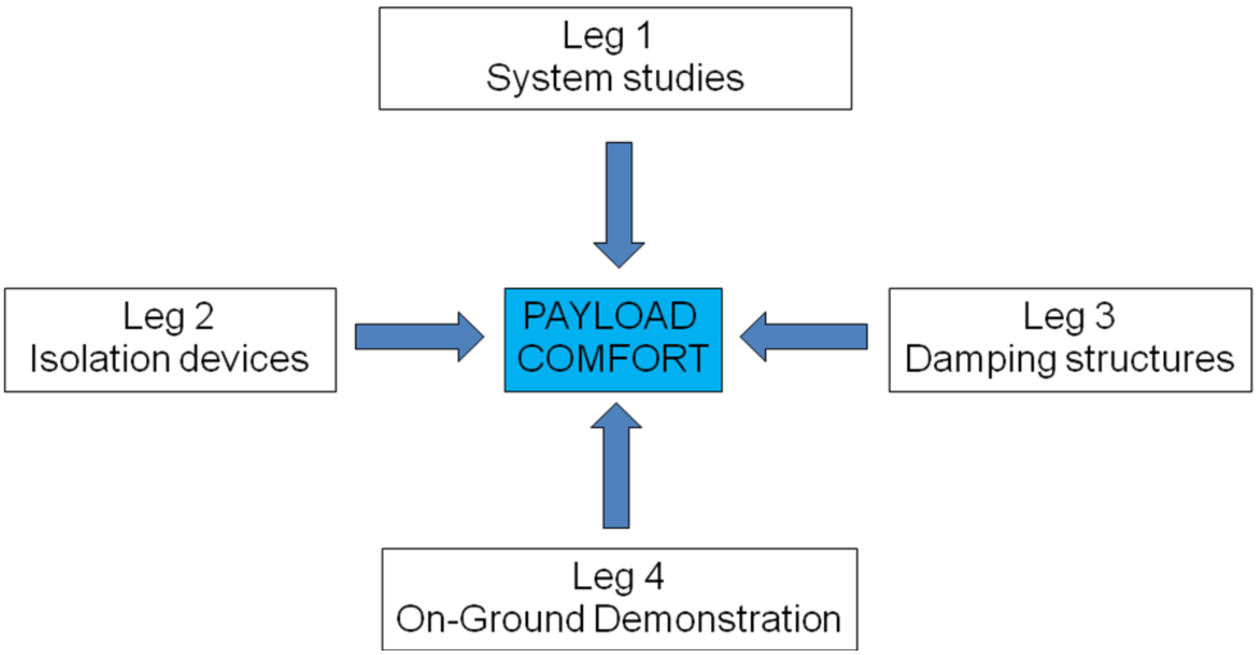


Figure 6: “Payload Comfort” advanced topics

5.1 Launcher system studies

Payload Comfort is the result of the global behaviour of a system: the launcher and the payload itself. To obtain a realistic status on this topic, it is therefore mandatory that launcher’s simulation, analysis, prediction tools and methods are available and validated.

Obviously, the integration on the launcher of add-on devices like a PID will increase the cost and the mass of the launcher and introduce supplementary risks to be managed at System levels like payload relative displacements and launcher controllability. So, the first step is to consolidate the current status.

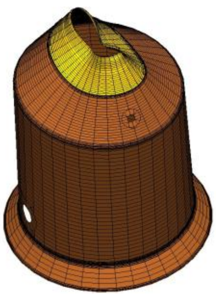
Previous dynamic mock-up ground tests and flight correlations have shown that the ASTRIUM predictions of the overall mass [M] and stiffness [K] matrices of the ARIANE launchers are very good. The damping [C] matrix requires - beyond the classical modal analysis approach - a more complete mathematical formulation leading to a full [C] matrix which couples the natural modes together. A first step developed at ASTRIUM is to consider a "structural damping approach" which leads naturally to a full coupled matrix [C]. The next step will have to take into account as much as possible the global system including several kinds of damping sources as large mass of fluids, lot of junctions, different kinds of equipments that can attenuate the launcher mode's energy. Besides, the structural damping properties of the materials used on ARIANE launcher's structures has to be taken into account. However, metallic materials (aluminium) or very rigid composite (high modulus) are used in order to obtain high rigidity and low mass but with very low levels of damping. Increasing the damping properties of structural materials and their assembly is today an objective.

For analysis of the "real" damping matrix [C], new innovative tools are today available:

- The "JOINTVIRT" software developed by LMT Cachan [1][5]: this tool permits to evaluate the damping generated at the main junctions of a launcher.
- The "COSMAD" software developed by INRIA [3]: this tool permits to evaluate the modal damping in operation, without the knowledge of the excitation. It can be used on ground tests or flight measurements. This tool has been validated for transient "hammer-like" excitations (ex: lift-off or stage separations) and "random-like" excitations (ex: Buffeting, engine noise). Its application to harmonic excitations is still to develop.

These methodologies are being used in order to identify damping effects in current ARIANE 5 analyses. These analyses will be completed by complementary experimental validations (JOINTVIRT) and/or ARIANE 5 measurement plan improvement (COSMAD). Today, interesting preliminary results have been obtained

- The structural damping of upper part structures deduced from flight measurements for example by the analysis of the upper payload separation involving SYLDA and PAS structures



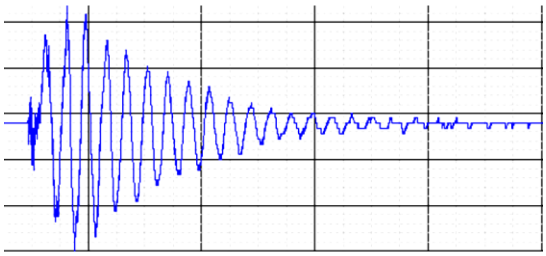
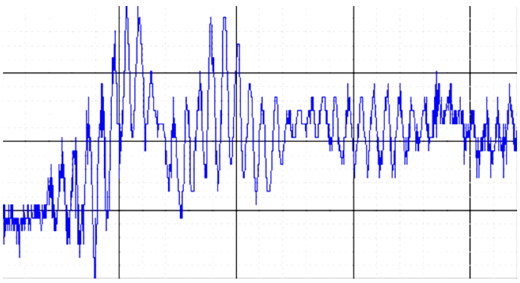


Figure 7: Payload Separation (model and flight response)

- The launcher overall modal damping deduced from flight measurements



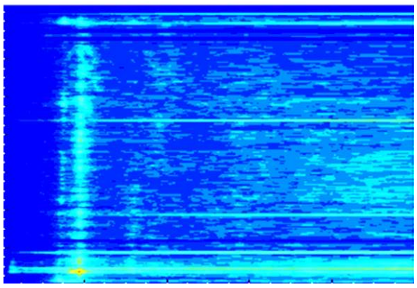


Figure 8: Launcher's flight response (time history and evolutive spectrum)

- Some junctions constitutes significant sources of damping, especially radial junctions but also potentially the conical junctions and the clamped-band of the payload which could represent a significant contributor of damping. One can see on the figure here-below that the junction’s damping increases with the dynamic load level which constitutes an important feature to reduce the dynamic responses at limit levels of excitation in launcher’s predictions.

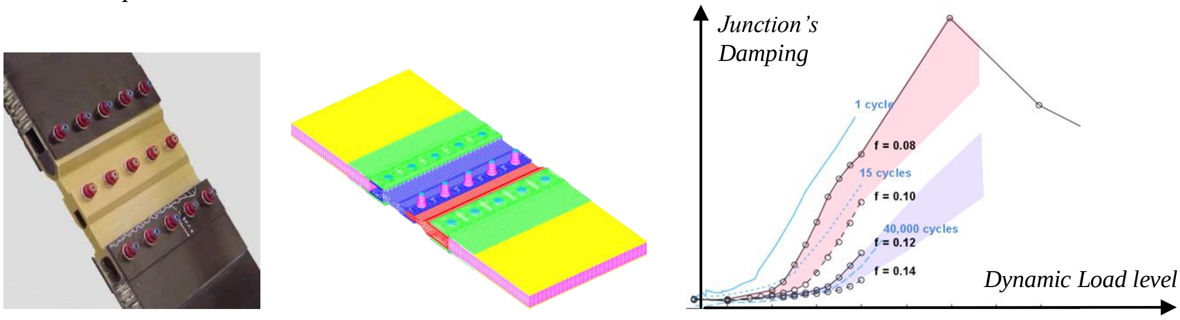


Figure 9: Launcher’s junction damping (modeling and experimental validation)

It is clear that for new launchers, it is very important to study the dynamic behaviour from the beginning of the development (phase A) in order to point out as soon as possible the risks and to propose possible solutions “Payload Comfort” solutions with regard to cost saving. It consists in computing the dynamic responses of the launcher and payload inside a parametrical loop taking into account all uncertainties (structures, excitations, payload domain, etc.). This new approach permits to envisage a reduction of dynamic loads with potential benefits for the payload (friendly environments) and for the launcher with potential mass and cost saving.

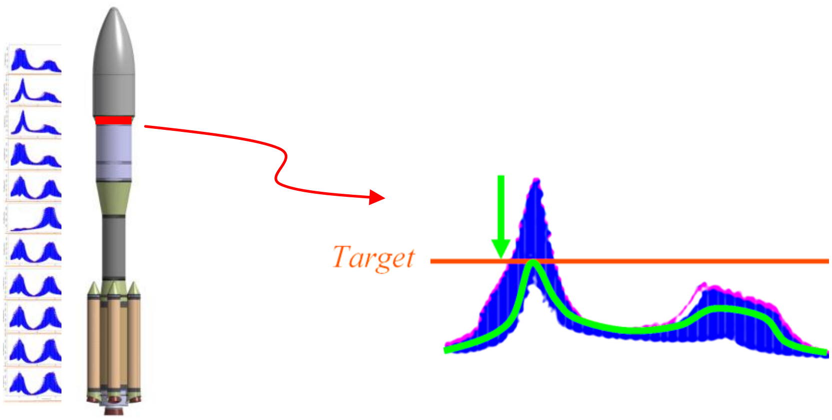


Figure 10: Evaluation and improvement of new launchers dynamic behaviour

5.2 Advanced Isolation devices

Advanced Isolation Devices include PID, and new SAID and AID. ARIANE 6 potential application offers the opportunity to increase their maturity at a same level of maturity around 6 and compare their efficiency on a same common flight-representative breadboard dynamic model including a full-scale payload and adaptor mock-up.

- A Passive Isolation Device (PID) consists in a soft-mounting of the payload in order to obtain a suspension frequency lower than the excitation frequencies. On the other hand, the PID shall generate sufficient damping on the suspension modes to avoid detrimental effects like launcher controllability. The advantage of passive system is the stability but the challenge is to manage a set of natural modes as axial and lateral modes (first modes and higher order). However, the PID has been pointed-out to be the most mature and secured one today. The reference PID is the one developed within the A5ME program and has been chosen after a trade-off phase A, with respect to several criteria.

Figure 11: Passive Isolation Device (PID) principle

- An Active Isolation Device (AID) is currently studied by ASTRIUM (BREMEN) in the frame of GSTP ESA (DLR). The principle is to compensate the vibration loads by controlled reaction loads in order to isolate the payload from incident vibrations. Different strategies of control are possible, semi-active or purely active. The maturity of the electrical device including energy harvesting and demonstration of its innocuousness to the launcher (essentially GNC stability) are planned to be assessed.

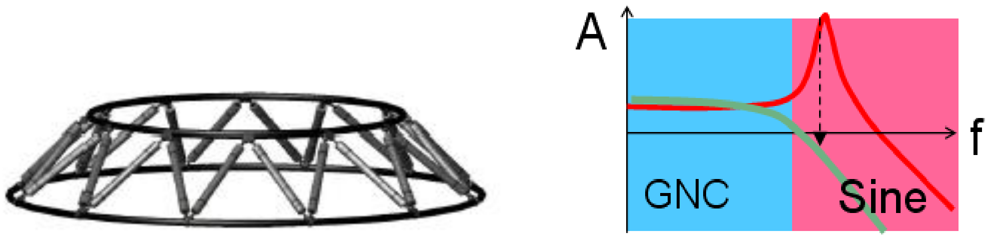


Figure 12: Active Isolation Device (AID) principle

The principle of a Semi-Active Isolation Device (SAID) is to generate reaction damping loads to vibration loads to attenuate essentially the suspension mode of the payload soft-mounted (like PID). This technology offers the advantages of the active without his drawbacks: SAID is intrinsically stable. One solution for midterm applications is to develop a semi-active damping device (set of struts) to be installed in parallel to the PID in order to increase the damping on the suspension modes in case of too high relative displacements which can occurs for example in case of strong gust. Several concepts of SAID have already been studied, using for instance magnet-rheological technology (ONERA/CNAM) or friction based technology (EADS).

5.3 Advanced Damping solutions

When taking into account the dynamic behaviour of a launcher at the very beginning of its design, it becomes possible to take advantage of all the damping possibilities, that is the materials, the junctions, the design of the structural parts.

Specific structures may be adapted, for instance payload carrying structures such as Payload Adaptor Fitting (PAF) or SYLDA. Advanced technological solutions may be introduced in their design to increase the damping of these launcher substructures, so as a prototype of "Damping PAF" made of improved materials & junctions might be tested on the same breadboard model as isolators including a payload simulator and a LVA

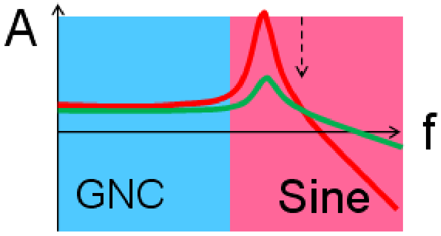


Figure 13: Structural Damping principle

- The Design itself of a structure is a key driver in order to improve the attenuation at low frequency by the maximization of the dissipation energy which depends on the shearing rate of the internal dynamic loads. New adaptor's architectures while using well matured materials and junctions could be analysed in order to maximize damping efficiency on the basis of launcher specifications. The efficiency of the damping structures studied shall be verified at launcher level by virtual testing to be sure of their final efficiency to meet the objectives of "Payload Comfort",

- The materials of a structure are also a key driver in order to improve the attenuation at low frequency. Many possible candidates of damping materials like resins, adhesives, honeycombs, foams, prepregs or elastomers can be identified and the more promising rigid and damping ones could be assessed and selected with respect to a set of requirements including the constraints of space environments and manufacturing feasibility. For these materials, the maturity is quite low today and elementary tests like DMA are the first step to achieve. But for the most promising ones they should be tested and included in the "damping PAF" prototype for full scale tests, and/or reduced scale mock-up. A French ANR project (called MATAMOR) in collaboration with French laboratories and companies has been initiated, but of course any new potential solution will deserve attention and characterization.

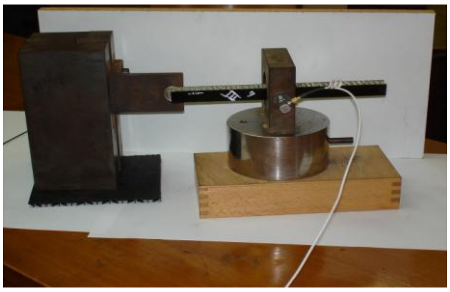


Figure 14: Structural Damping tests (samples & mock-up)

- The junctions of a structure constitute also a potential source of attenuation at low frequency, in particular, PAF interfaces, Clamped bands, conical and radial junctions like in the SYLDA. The virtual testing of junctions, screw tightening torques, viscoelastic layers are candidate for advanced damping junctions studies. In order to maximize the efficiency of this research on damping at junctions, a French ANR project (called ARIAN) in collaboration with French laboratories and companies has been initiated.

Figure 15: Junction's Damping improvement (conical and clamped-band)

5.4 On-ground demonstrations

In order to evaluate the efficiency of the attenuation solutions developed, they will be compared on the same full-scale demonstrator constituted of reference existing structures. The mock up shall include representative payload (P/L) and adaptor (PAF+LVA) excited by a shaker table delivering representative launcher dynamic environment as transient, random or harmonic excitations encountered in flight based on ARIANE 5. The test campaign should be divided in 3 kinds of sequences:

- Tests with the reference structures : Launch Vehicle Adaptor (LVA), Payload Attached Fitting (PAF) and Payload Mock-Up,
- Tests including the isolator devices at the LVA/PAF interface: PID, then AID and SAID,
- Tests including the damping PAF prototype.

The first sequence will permit to validate the tools used for the dynamic predictions. On the other hand, it will permit to have reference dynamic responses to evaluate the efficiency of the proposed attenuation devices by comparison "with" and "without".

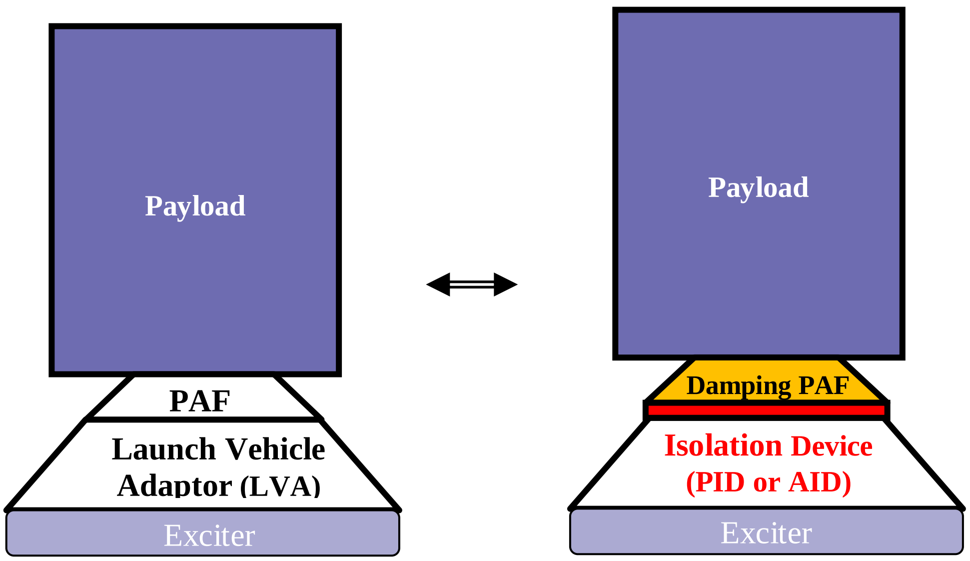


Figure 16: Payload Comfort Demonstrator (with and without attenuation devices)

6 Conclusion

The “PAYLOAD COMFORT” is considered as a challenge for Launchers’ design. The reduction of vibration, acoustic and shock levels requires a constant attention for launcher. A continuous work has been performed on ARIANE 5 to maintain low level of vibration, but the payload comfort is always an issue and improvements will be considered for the next generation of launchers.

The next ARIANE 6 launcher offers the opportunity to implement advanced technological solutions for payload comfort, like isolation devices and damping structures. Their maturity and economic efficiency have to be demonstrated in due time up to necessary TRL 6 through a full-scale demonstrator constituted of a realistic payload mounted on an adaptor submitted to flight representative vibrations. Once this knowledge demonstrated at the payload interface, it could be extrapolated at other junctions of the launcher, like inter-stages junctions for instance.

This problematic shall be efficiently treated through an international network involving laboratories, universities, research centres and industrial partners.

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