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Development of Low-shock Separation Systems for Payload Fairings

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Abstract

Payload Fairings (PLF) protect the payload from aerodynamic and acoustic pressure, heat, and environmental influences during on-ground operations and the initial stages of flight. Once the launch vehicle has passed the dense atmosphere and the aerodynamic loads become negligible, the payload fairing is jettisoned to maximize the overall payload capacity of the launcher. Fairing separation systems traditionally rely on pyrotechnic solutions for both the horizontal and vertical separation planes. While such pyrotechnic separation systems are very reliable and compact owing to their high energy-to-mass ratio, they are typically associated with high cost and shock loads transferred to the adjacent structure, which limits the payload comfort and can often be a design driver for the structure.

For the past years, Beyond Gravity (formerly RUAG Space) has been developing a novel low-shock separation and jettison system for future PLFs, which is based on discrete mechanical latches for the vertical and horizontal separation in combination with a hinge-guided rotational jettisoning of the fairing halves. The absence of pyrotechnics allows for significantly reducing the shock loads generated during separation, enabling satellite providers to increase the performance and capabilities of their payloads. Further advantages of this system include increased design freedom for the fairing structure as well as modularity, enabling scaling to different launch vehicle sizes at a lower development effort.

This paper presents the main outcomes of the low-shock separation system development – mainly carried out in the frame of ESA's Future Launchers Preparatory Programme (FLPP) – and builds on previous work performed by Beyond Gravity on low-shock separation systems [2] – [4]. An overview of the development approach is given and key technical results from the development and qualification phase are shown, including global PLF design and analysis to assess the overall system performance under flight conditions. Furthermore, the developed latch-based solution is compared against a system architecture using an integrated clamp band for the horizontal separation, and an outlook is given on Beyond Gravity's future plans of transferring the developed technology to Europe's next generation medium launch vehicles.

1. Introduction

Beyond Gravity is a leading European supplier for launcher and spacecraft subsystems with more than 40 years of experience in the development and manufacturing of payload fairings. The payload fairing protects the payload against aerothermal and acoustic loads during flight and is separated once the launcher has passed the dense atmosphere, so as to maximize its overall payload capacity. For this purpose, payload fairings require a separation system enabling on-command jettisoning of the fairing segments. The fairing separation systems currently used in the European medium and large launch vehicles rely on pyrotechnic solutions, which – despite their high reliability and extensive flight heritage – emit relatively high shock loads to the adjacent structures, thereby limiting the payload comfort. Motivated by the improvement potential of the heritage pyrotechnic separation systems, Beyond Gravity is developing a new family of pyro-free low-shock separation systems for the next generation of launch vehicles, aiming to add value to their customers and reduce the development effort and cost in an increasingly competitive market – while maintaining 100% mission success reliability [4].

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2. Fairing Separation Systems

2.1 State of the Art

The separation systems currently in use are based on pyrotechnic cords, which are embedded in metallic profiles along the horizontal and vertical split lines of the PLF. When activated, the explosive energy provided by those cords fractures the profiles, thereby separating the fairing halves from each other and the launch vehicle. For the jettisoning, the kinetic energy required to achieve sufficient clearance from the launch vehicle and payload is provided by the Vertical Separation System (VSS), which rapidly accelerates both fairing halves outwards in a primarily translational (but unguided) movement. Figure 1 illustrates the two heritage separation architectures employed in Beyond Gravity's payload fairings. For the Large Launch Vehicles (LLV, e.g. Ariane 5/6), the horizontal separation is initially realized via a frangible joint. The entire PLF is then slightly lifted by preloaded spring packages before the vertical separation and jettisoning occurs via a pyrotechnic thrust rail. The payload fairings of the Medium Launch Vehicles (MLV, e.g. Vega/Vega-C) separate and jettison in the same manner, the only difference being that a tension belt is used in the Horizontal Separation System (HSS) instead of a frangible joint.

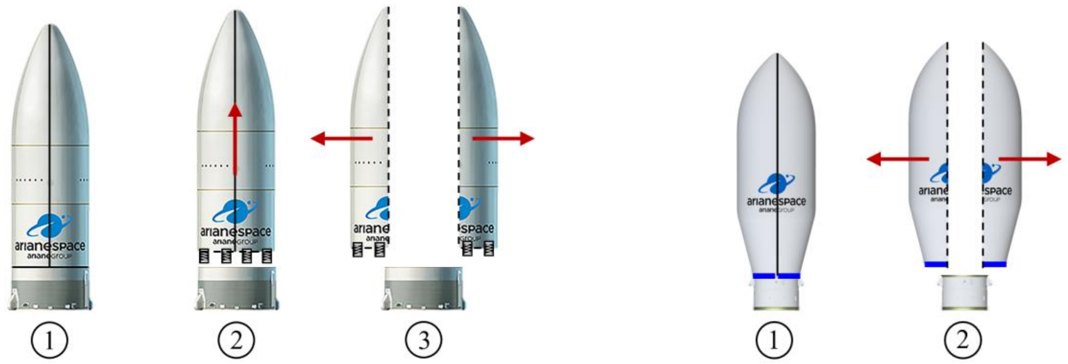

Figure 1: Beyond Gravity's heritage separation architectures for LLV (left) and MLV (right) PLFs

2.2 Potential for Improvement

The main advantages of separation systems relying on continuous frangible profiles are the compact and lightweight design (owing to high energy-to-mass ratio), high reliability, and a continuous load transfer with low peak fluxes. As mentioned previously, pyrotechnic separation systems furthermore do not require a dedicated jettison system, as the separation impulse is provided as part of the vertical separation. However, there are some inherent downsides associated with pyrotechnic systems:

- High shock: pyrotechnic systems emit high shock loads, which limit the payload comfort and require a stronger/stiffer (= heavier) load-carrying structure of the satellite. The high shock loads furthermore limit satellite providers to install sensitive instruments (e.g. optics).
- High cost: pyrotechnic systems are expensive in the total cost of ownership; contributors are not only component cost, but also increased regulatory, safety, logistics, and handling complexity for pyrotechnics, as well as excessive acceptance and qualification testing requiring large vacuum chambers.
- Design impact: due to the high shock loads, pyrotechnic systems require special choice of material and layup in the fairing structure to ensure sufficient clearance of the half shells from the payload during the unguided post-separation phase. This tailoring of the fairing modal dynamics during jettisoning increases the design complexity and is not necessarily in favor of the structural performance against flight loads.
- Non-reusable: pyrotechnic systems lead to a destructive severance of the HSS and VSS profiles, making them non-reusable.
- Supply chain risk: the market for pyrotechnic systems is dominated by few suppliers, bringing additional risk to the end customers.

2.3 Moving towards Low-shock Separation Systems (LSSS)

Motivated by the improvement potential associated with state-of-the-art pyrotechnic separation systems, Beyond Gravity is developing a novel separation and jettison system, which adopts a hinge-guided rotational jettisoning in

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combination with modular mechanical separation systems scalable to different PLF sizes (c.f. Figure 2). Some of the envisaged benefits of this new separation architecture include:

- Low shock: the system generates lower shock output compared to pyrotechnic systems, which enables satellite providers to reduce the payload structural mass and increase its capabilities (e.g. more sensitive instruments).
- No pyrotechnics: in addition to reduced shock loads, the absence of pyrotechnics significantly facilitates regulatory aspects, handling, logistic, safety, etc. as well as qualification and acceptance of the system.
- Modularity and scalability: the system is built around modular and discrete mechanical separation systems, enabling scaling to different PLF sizes at comparatively low development effort.
- Reusability: as compared to pyrotechnic systems, the severance of the fairing half shells occurs in a fully non-destructive way, making the system suitable for reusable fairings.
- Increased design freedom for PLF: the low shock loads combined with the guided rotational jettisoning do not require any special tailoring of the fairing dynamic behavior, which allows for maximizing the performance of the PLF structure against flight loads (thereby permitting to reduce structural mass).
- Testing and qualification: the novel separation architecture offers the possibility to conduct full-scale qualification and acceptance testing on ground and without the need for large vacuum chambers.
- Better control of the jettison event enabled by the guided rotational jettisoning.

All of the abovementioned benefits will yield a reduction in both the recurring and non-recurring costs compared to pyrotechnic systems and improve Beyond Gravity’s competitiveness and time to market. However, as pyrotechnic solutions are unmatched in terms of the performance-to-weight ratio and realize both the separation and jettisoning with the same system, changing to mechanical separation systems will come at a mass penalty for the PLF.

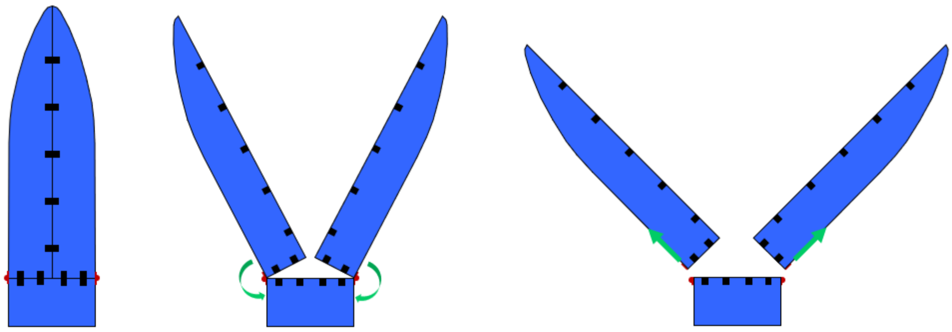

Figure 2: Low-shock separation and jettison architecture

3. Low-shock Separation System Development

3.1 Development Approach

Figure 3 shows Beyond Gravity’s development approach for the low-shock separation and jettison system along with the status of the subsystem selection. As part of FLPP technology development, a study was initiated in 2014 aiming at the design, development and verification of a new Separation and Jettison System (SJS) for future payload fairings. Initially, a screening and trade-off phase was conducted to identify the most promising SJS architectures. The focus was firstly put on the development of a rotational jettison system based on Hinge and Actuator (H&A) mechanisms. This technology was led to a maturity level representative of TRL5, after a full-scale functional test for a Medium Launch Vehicle (MLV) fairing. Subsequent developments then focused on the Low-shock Separation System (LSSS). Between 2017 and 2020, Beyond Gravity internally developed and qualified low-shock separation and jettison systems for payload fairings of Small Launch Vehicles (SLV) as part of its commercial FlexLine™ program [1]. This program adopted the rotational jettisoning approach for its SLV PLF and developed a new separation system based on discrete latch mechanisms. Building on this proven commercial design, which underwent extensive subcomponent as well as full-scale testing, upscaled variants with full ECSS-compliance were developed in the frame of FLPP for MLV and LLV class PLFs. The development was accompanied by various qualification and confidence test campaigns on subsystem level, which demonstrated full functionality and high repeatability under representative environmental conditions and loads. In addition to a system architecture fully relying on latches in both the VSS and HSS, a system variant using an integrated clamp band in the HSS was also developed and evaluated. This paper mainly focuses on the latches-based system architecture but also presents the main outcomes of the clamp band development.

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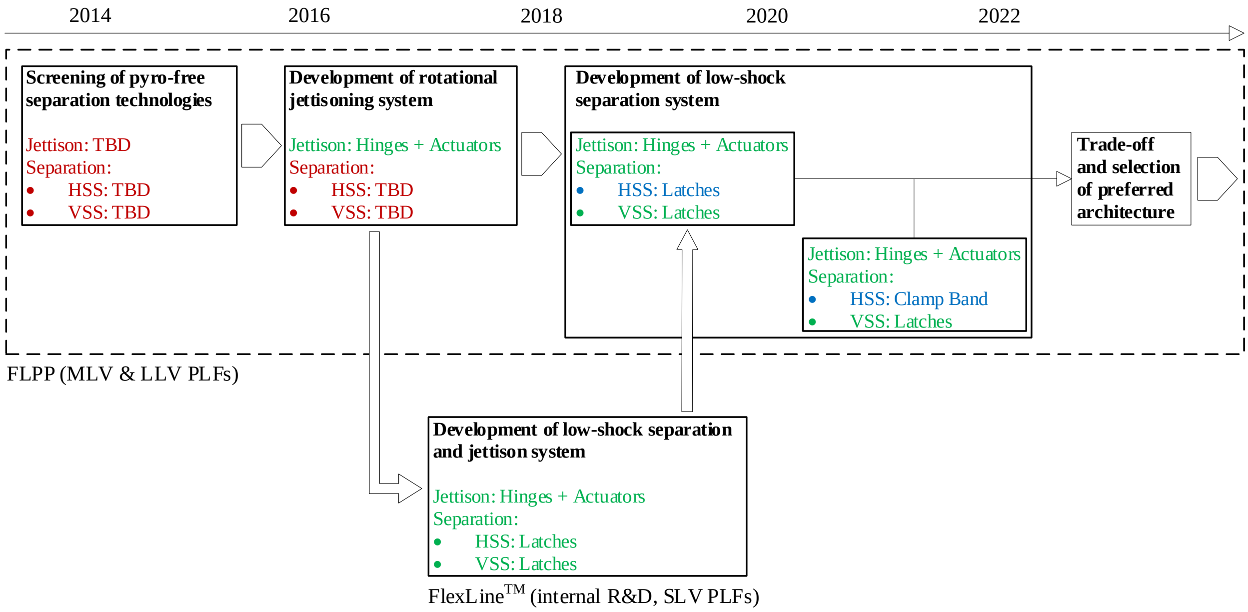

Figure 3: Development approach for Beyond Gravity's low-shock separation and jettison system

3.2 System Description

The developed low-shock separation and jettison system is comprised of a separation system at the horizontal and vertical split plane, whose main function is to provide load transfer and to sever the fairing half shells from each other and the launch vehicle upon the separation command. The rotational jettison system then imparts the separation impulse and ensures controlled movement of the separating fairing halves with sufficient clearance to the payload and the launcher. The following technical solutions are adopted for the two systems – a graphical illustration of the full-scale system for a MLV class PLF is shown in Figure 4.

1) The separation system is comprised of discrete latch mechanisms distributed along the horizontal and vertical split planes, which ensure discretized load transfer and release upon activation by an internally guided pneumatic system. Beyond Gravity uses a proprietary design for the latches and activation system, which has been developed and successfully qualified as separation system in payload fairings and interstage adapters for commercial SLVs within Beyond Gravity's FlexLine™ program [1].
2) The rotational jettison system consists of hinges located at the base of each fairing half in combination with gas spring actuators located inside the PLF, which induce the rotation of the half shells about the hinges once the latch mechanisms of the HSS and VSS disengage. Once a certain rotation angle is reached, the half shells are jettisoned by springs integrated in the hinges.

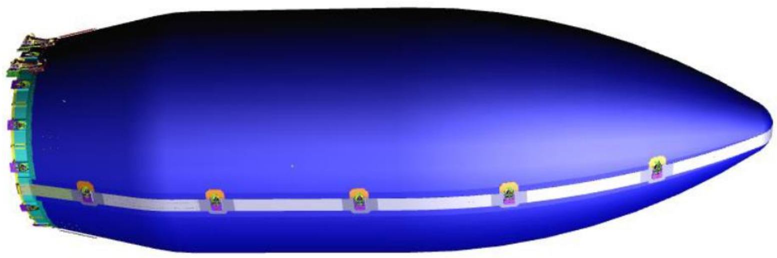

Figure 4: 3D model of the studied MLV PLF (Ø2.6m) with hinges (top left), actuators (internal), and mechanical latches in the HSS and VSS

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3.3 Analysis

As part of the low-shock separation system development within FLPP, global design and analyses were performed for a Ø2.6m MLV PLF, as previously reported in [4]. From a structural point of view, one of the main concerns associated with discrete separation systems (as opposed to continuous frangible profiles) is the discretized load transfer, which is expected to yield higher stress concentrations in the fairing structure. Finite Element Analysis (FEA) performed for representative flight and separation loads confirmed the appearance of such load concentrations in the PLF structure (c.f. Figure 5), but proved overall positive margins of safety (MoS) across the full load envelope and compliance of the design for stress, buckling, and displacements – all without the need for adding local reinforcements to the baseline fairing design.

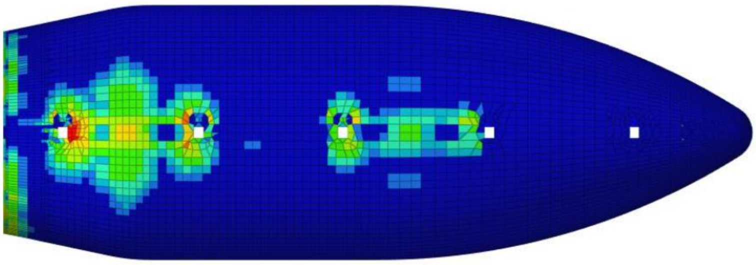

Figure 5: Face sheet laminate MoS (red +0.7 … blue >10)

Besides the aforementioned stress peaking, another key aspect of release systems based on discrete connections is the gapping in between the attachment points, as such gapping can lead to the intrusion of hot gas into the payload compartment during flight. Prevention of such leaks is therefore a standard requirement for payload fairings [4]. Figure 6 and Figure 7 depict the gapping distribution between the latches for a MLV PLF configuration with 2 x 5 VSS latches and 14 HSS latches, respectively. The resulting gaps are acceptable but not negligible from a structural point of view, especially in certain regions along the VSS split line. Such gapping must therefore be covered by appropriate sealing solutions at the vertical and horizontal interfaces, which are capable of accommodating the relative displacements without leaking hot gas into the payload bay. As the gapping is affected by the number and spacing between the latches as well as the stiffness of the fairing structure, there is typically an optimum configuration yielding minimum fairing mass at acceptable gapping.

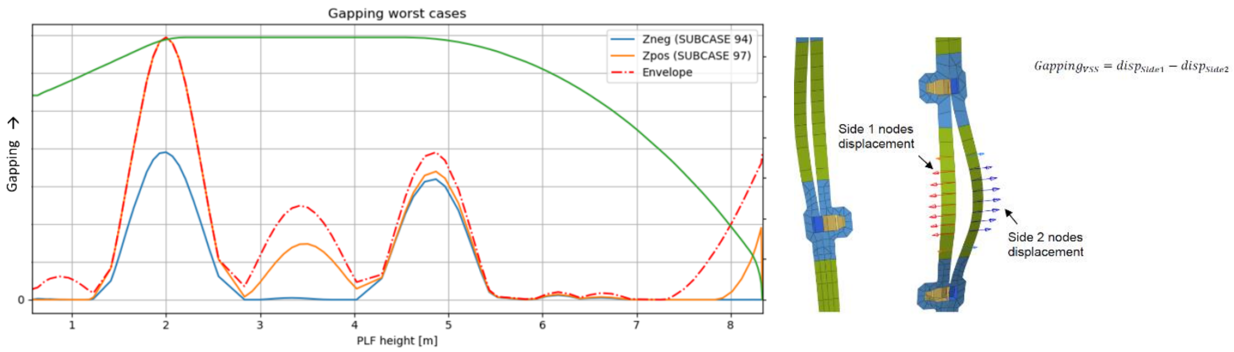

Figure 6: MLV VSS gapping between latch locations (fairing outer contour in green)

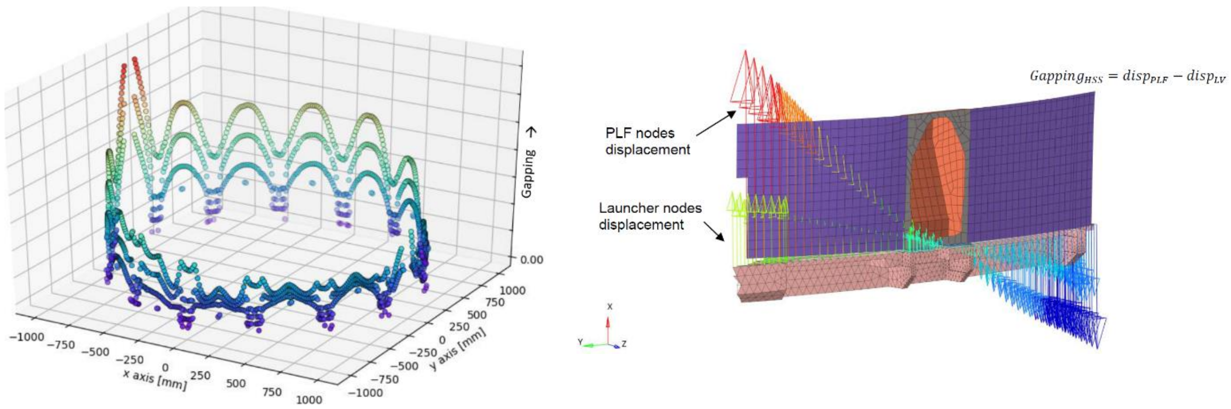

Figure 7: MLV HSS gapping between latch locations

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3.4 Testing

The separation system development was accompanied by various qualification and confidence test campaigns aiming to verify functionality of the system under relevant environments and loads, including vibrations, hot & cold conditions, thermal cycling, static loads (latch and structure level), latch release under external loads, etc. Both breadboard testing was performed for iterative design improvements and qualification of key components on subsystem level (c.f. Figure 8), as well as subassembly and full-scale testing to verify functionality of the global system. Within FLPP, the latch mechanisms for MLV class PLFs were developed and qualified up to TRL5 based on breadboard validation tests in relevant environments, ensuring ECSS compliance. The development of the Hinge & Actuator system was led to a full-scale demonstration test for a representative MLV PLF half shell (Figure 9 left), rendering it also TRL5. As part of Beyond Gravity's commercial FlexLine^{TM} program, the functionality of the entire low-shock separation and jettison system for SLV PLFs was demonstrated based on full-scale separation tests (Figure 9 right).

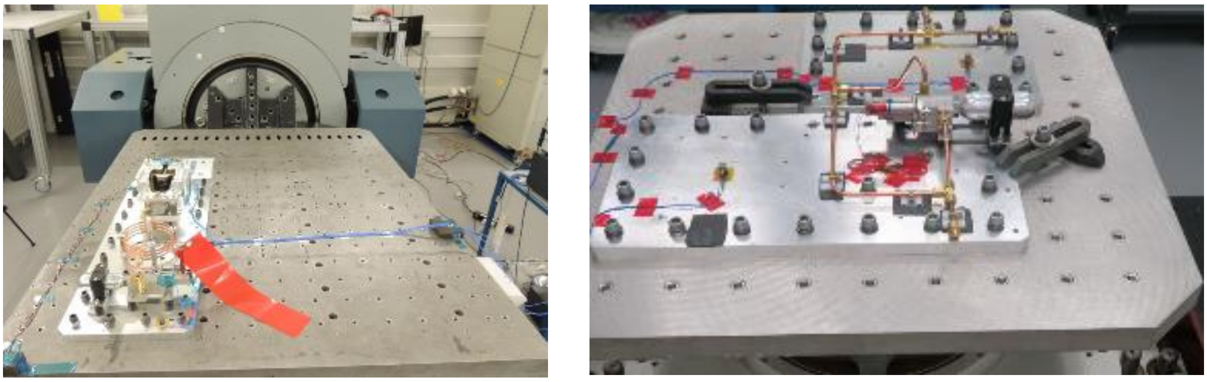

Figure 8: Subcomponent testing under relevant environmental conditions

Figure 9: Full-scale testing; left: demonstration test of hinged jettison system for a Ø2.6m MLV PLF; right: demonstration test of the full separation and jettison system for a Ø1.5m SLV PLF

3.4.1 Synchronization

To prevent excessive load concentrations at and gapping between the discrete latch connections without unnecessarily increasing the structural stiffness/mass of the fairing, the number of latches required to keep both parameters at an acceptable level increases with the fairing size. Therefore, proper control and synchronization of the individual latch releases become increasingly important to achieve the desired separation and jettison performance. The timing between individual latch releases has been extensively characterized based on numerous tests involving multiple latches and flight-representative arrangements of the activation system.

For the commercial SLV PLF, both analyses and full-scale separation tests confirmed that the fairing reliably separates even under dispersed cases with non-synchronous release of the latches. For the MLV PLF, successful separation against non-synchronous latch release was verified by analysis. For this purpose, the individual synchronization budgets of the separation system components (activator, distribution system, latch) were initially characterized based

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on subsystem tests. Table 1 shows that the individual subcomponent contributions are in the single-digit millisecond regime, with slightly higher delays present when multiple activators are used for redundancy. Dynamic separation analysis against dispersed cases, which considered the cumulative synchronization budget (up to 225ms) as delay between the latch releases, confirmed positive jettison clearance between the PLF and the payload/launch vehicle and overall low sensitivity of the system to such delays. It could thus be verified that the impact of latch release timing on the jettisoning is measurable but has minor impact on the remaining clearance of the fairing half shells from the launch vehicle and payload, owing to the hinge-guided rotational jettisoning approach [4].

Table 1: Synchronization budget of LSSS components for MLV PLF configuration

Activator repeatability	±2ms
Latch repeatability	±3ms
Synchronization between activators	±13ms
Travel time per meter of pneumatic line	<5ms
Sum (for 8m group with central activator)	**≤±38ms**
Minimum available budget	**≥225ms**

4 Scalability to Large Launch Vehicles (LLV)

One of the key advantages of the developed latch-based separation system is its modularity, enabling scaling to different launch vehicle sizes at comparatively low development effort. Besides Small and Medium Launch Vehicles, this scalability has also been assessed for Large Launch Vehicles (LLV), by designing, modelling and analysing a representative LLV PLF (Ariane 6, Ø5.4m) with hinge-based jettison system and latches in the HSS and VSS (c.f. Figure 10). As mentioned previously, the number of latches required in the HSS and VSS increases with the fairing size to prevent excessive stress concentrations at and gapping between the discrete connections. As for the MLV PLF configuration, the expected gapping for LLV class PLFs was characterized based on structural analyses against flight loads and evaluation of the resulting displacements at the horizontal and vertical split planes. The maximum gapping magnitudes for the studied LLV PLF are shown in Figure 11 for the VSS and HSS, respectively, and are also to be accommodated by appropriate sealing solutions. When scaling the system from the MLV to the LLV PLF configuration, the number of latches required to keep the gapping magnitudes at a comparable level increases from 2 x 5 VSS latches and 14 HSS latches for the MLV PLF to 2 x 9 VSS latches and 18 HSS latches for the LLV PLF.

Regarding the behavior during jettisoning, the payload fairings of the European LLVs are generally more compliant than the MLV PLF previously investigated, where the inversed conical section at the rear end (so called “boat tail”) provides a stiffening effect to the half shells as they are jettisoned. In fact, such bending compliance is promoted on purpose in Beyond Gravity’s heritage PLF designs, which require large elastic deflections of the jettisoned half shells to ensure sufficient clearance from the payload. This leads to conflicting requirements on jettison clearance vs. structural efficiency and might necessitate a fairing structure that is heavier than needed to sustain the flight loads. Here, the hinged jettison approach adopted in the low-shock separation system will enable to remove such design constraints. Through extensive separation analyses, it was shown that a high stiffness is conducive to the jettison quality when using a hinged rotation approach [3]. This will allow for maximizing the overall structural performance of the fairing and reducing its structural mass as compared to the heritage pyrotechnic separation systems.

Overall, the use of latch-based separation systems in LLV PLFs was shown to be feasible from a technical point of view. However, as mechanical solutions cannot reach the performance-to-weight ratio of pyrotechnic systems, and considering the higher number of latches required in LLV PLFs to prevent excessive stress peaking and gapping, changing to latch-based separation systems in LLVs was shown to have a considerable mass impact, not only for the fairing itself but also for the remaining mass on the launcher. Therefore, in a first step, Beyond Gravity considers the developed low-shock separation system better suited for payload fairings of Small and Medium Launch Vehicles, where the mass penalty of the separation system can be compensated by an increased efficiency of the fairing structure.

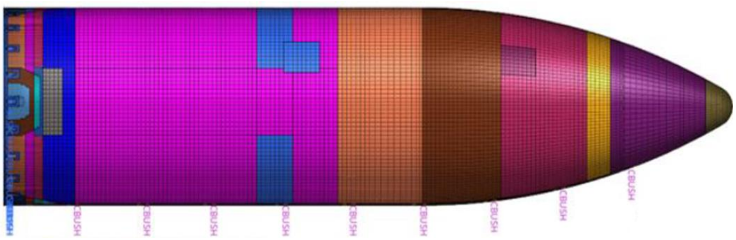

Figure 10: Model of LLV class PLF (Ø5.4m) with hinge-based jettison system and latches in the HSS & VSS.

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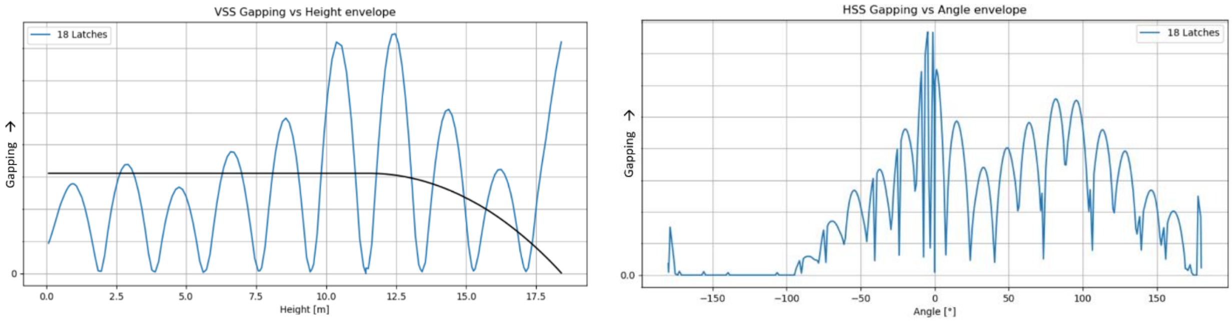

Figure 11: Gapping between VSS (left) and HSS (right) latches for the LLV PLF (fairing outline shown in black)

5 Comparison Latches vs. Clamp Band in the HSS

In addition to the separation system architecture fully relying on latches in both the HSS and VSS (c.f. Figure *4*), a system variant using an integrated clamp band in the HSS and latches in the VSS has been investigated and compared against the latches-only solution. The basic design intent of using a clamp band is to limit the load concentrations in the launch vehicle forward structure caused by the discretize load transfer of the latches, and to increase reliability by reducing the number of mechanisms to activate. The separation system design with integrated clamp band in the HSS and latches in the VSS was advanced to a design maturity level representative of TRL4, including sizing and global model concept design for both the MLV and LLV class PLF, and verification by analysis (static and separation) for the MLV configuration. Figure 12 shows a 3D model of the clamp band-based separation system on the investigated MLV PLF.

A trade-off between the two release system architectures was performed, combining both technical (mass, performance) and programmatic (RC/NRC, development, scalability, sourcing) criteria. Though the integrated clamp band was shown to be the technically superior solution with higher performance at slightly lower mass, the programmatic aspects are in favor of the latches-based solution with advantages mainly in cost, development, and scalability. Beyond Gravity therefore decided to continue the development activities for the latches-based HSS solution, keeping the integrated clamp band for potential future structures with an extreme bias on performance over cost and programmatic aspects.

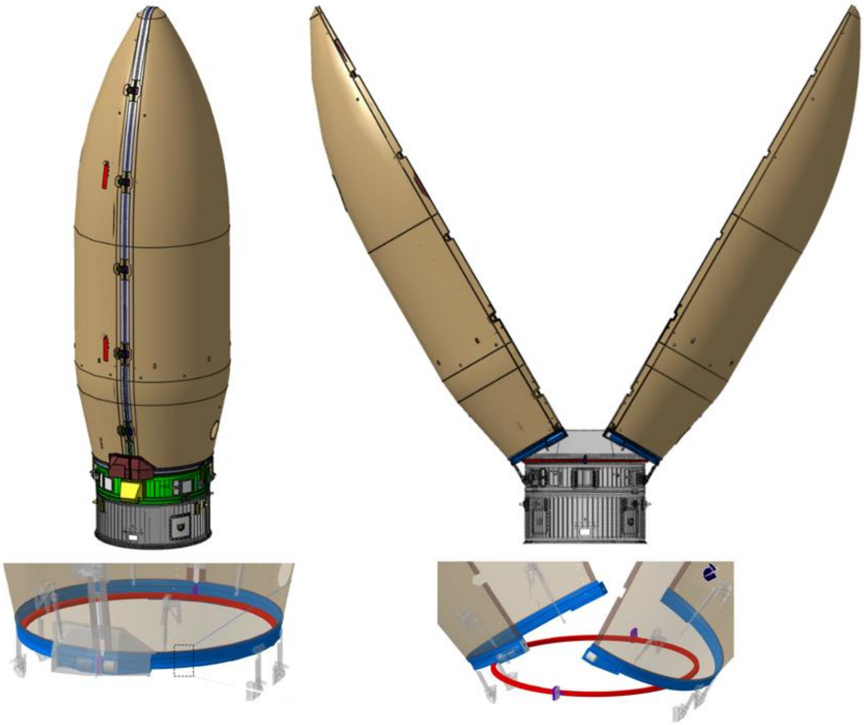

Figure 12: 3D model of MLV PLF with integrated clamp band in the HSS and latches in the VSS

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6 Outlook: Next-generation European MLVs

The previous studies on low-shock separation systems performed in the frame of FLPP were tailored primarily to two fairing configurations: a Ø2.6m MLV class PLF with boat tail (representative of a Vega fairing) and a Ø5.4m LLV class PLF without boat tail (representative of an Ariane fairing). Though the developments and trade-offs performed throughout the program have mitigated – in the short term – the interest of the latch-based separation system for the LLV PLF configuration, it was well proven for the MLV PLF configuration. However, the Ø2.6m MLV fairing configuration considered in previous phases is no longer deemed in line with the evolution of the European MLV market. For this reason, future development efforts are focused on maturing the low-shock separation and jettison system for a target PLF that is compatible with the next-generation of European MLVs. This expected upcoming development phase, also to be performed in the frame of FLPP, will thus consolidate the current SJS design and scale it to the selected target MLV PLF configuration, including a detailed design and analysis of the full system (hinges, actuators, separation system). Furthermore, subsystem confidence tests are planned to further mature the technology and demonstrate the capability of the overall solution to sustain representative loading and functionality of the simultaneous horizontal and vertical releases.

7 Conclusions

In the frame of internal developments and ESA’s Future Launcher Preparatory Programme (FLPP), Beyond Gravity has significantly advanced the design, development and verification of a new separation and jettison system (SJS) for future payload fairings. The possibility of implementing a rotational jettison strategy with pyro-free low-shock separation systems was proven feasible for commercial small launchers and ESA’s medium and large launch vehicles by the studies, analyses, and tests performed. The chosen SJS configuration, which combines a gas spring actuated rotational jettisoning with discrete mechanical latches for the horizontal and vertical separation, is successfully de-risked in its key aspects (stress, deformation, separation behavior) and qualified to high technology maturity based on extensive analyses and testing, indicating the full reliability of the approach and a high degree of repeatability. Future efforts are focused on maturing the technology for the transfer into Europe’s next generation medium launch vehicles.

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