Reusable Structures for CALLISTO

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Abstract

In order to make access to space more affordable for both scientific and commercial activities the German Aerospace Center (DLR), the Japanese Aerospace Exploration Agency (JAXA), and the French National Centre for Space Studies (CNES) joined in a trilateral agreement to develop and demonstrate the technologies that will be needed for future reusable launch vehicles. In the joined project CALLISTO (Cooperative Action Leading to Launcher Innovation in Stage Toss back Operations) a demonstrator for a reusable vertical take-off, vertical landing rocket, acting as first stage, is developed and built. As long-term objective this project aims at paving the way to develop a rocket that can be fully reused, and the joint efforts of the three agencies will culminate in a demonstrator that will perform its first flights from the Kourou Space Center, in French Guyana. Having regard to the aspect of reusable structures, the development of design represents a special challenge since the components have to withstand a variety of complex manoeuvres for multiple times. Additionally, this technical complexity leads to limitations in size and mass which must be observed during the design process. The structures have to be studied very individually to meet all the requirements for reaching optimal performance during ascent, return and landing. This paper focuses on the design solutions for CALLISTO's fairing, the aerodynamic surfaces and the approach & landing system with respect to their specific sizing load case during the mission. The challenging concept of deployable aerodynamic surfaces is especially highlighted as the deployment causes a significant transformation of the vehicles outer shape and consequently has direct impact on the trajectory. This also applies to the stowable landing gear that has been one main design challenge in the frame of CALLISTO.

1. Introduction

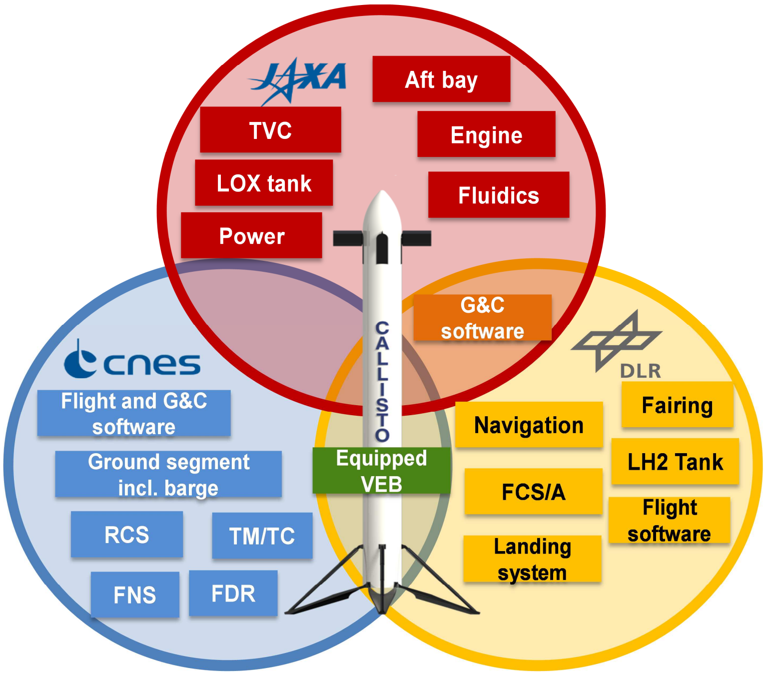
During the last years the interest in reusable space systems has reached its peak. International effort and success in this field arouse European interest to develop launch vehicles that allow full recovery of all components. The advantage of reusable systems is a long-term decrease of launch costs but also a re-increase of Europe's independency and operational flexibility for launches.

To further enhance the level of knowledge in this area DLR, CNES and JAXA are jointly working together on CALLISTO, a reduced scale vertical take-off and vertical landing (VTVL) first stage demonstrator. CALLISTO's main objective is to demonstrate the capability of a full recovery under conditions representative for an operational launchers first stage during the next years [1], [2], [3]. The information gathered during CALLISTO's flights will be applicable for future operational launch systems and thus will help to advance the complex subject of reusability in Europe and in Japan. On scientific level the gathered data will improve the understanding of foldable structures and the material behaviour of components that will go through multiple load cycles, defined by explicit tests and flights [4]. The data will also be useful to detect possible failures at an early mission state, to make reliable forecasts of damage propagation and, by that, to simplify the Maintenance, Repair and Overhaul (MRO) operations in between the flights.

2. Project Organization & Mission

For CALLISTO DLR, CNES and JAXA share equal level of responsibility and commitment taking advantage of the know-how and experience of each partner. The sharing of responsibility that has been developed is depicted in Figure 1. Since CNES is leading system design, its main responsibility at hardware level is the ground segment located in Kourou including several landing zones and amongst other a landing surface on open sea. CNES is also responsible for the telecommunication and telemetry system. On the vehicle, CNES will provide the Flight Neutralization System (FNS), the Reaction Control System (RCS), the Flight Data Recorder (FDR), a flight software and a Guidance and Control (G&C) software. DLR will also develop a flight and G&C software together with JAXA, differing from CNES software by the algorithm. Both variants will have the opportunity to be used for flight tests in Kourou. The Vehicle Equipment Bay (VEB) structure will be designed and provided by DLR which is also responsible for several other main load carrying components as the fairing, the insulated LH2 tank and the landing system. All equipment within the landing leg system and LH2 tank domains are also under DLR responsibility. In addition DLR will provide the Aerodynamic Flight Control System (FCS/A), the navigation function of CALLISTO, all related sensors (GNSS, radar altimeter, etc.) and an on board computer. Finally, DLR is responsible for landing dynamic simulations and flight aero-sciences. JAXA, the third partner, is the provider of one of the main components of CALLISTO: a reusable, re-ignitable and deep throttleable LOx/LH2 engine with about 40 kN thrust. JAXA is designing and manufacturing: the Thrust Vector Control (TVC) system, the power system and the aft-bay module. The whole fluidics system: feedlines and pressurization system and LOx tank are also under JAXA responsibility. Integration of CALLISTO will take place mainly in Japan and will be followed by hot firing tests in Noshiro test center before the vehicle will be transferred to French Guiana.

The main goal of CALLISTO is to gather data (both economic and technical) relevant to an operational reusable rocket first stage. The vehicle that will be built for this purpose will be about 13 m in length and 1.1 m in diameter; an aspect ratio comparable with the one of an operational launch vehicle. The demonstrator approach which is followed should allow achieving the aforementioned main goal of CALLISTO in a relatively short time. However, it implies that the product flight models will have to be built quickly without numerous intermediate steps.



FCS/A: Aerodyn. Flight Control System
FDR: Flight Data Recorder
FNS: Flight Neutralization System
G&C: Guidance & Control
RCS: Reaction Control System
TVC: Thrust Vector Control
TM/TC: Telemetry/Telecommand
VEB: Vehicle Equipment Bay

Figure 1: Sharing of the main tasks within CALLISTO project between CNES, JAXA and DLR

Therefore, most tests will be performed with the flight model and not with dedicated engineering models or mockups. The number of cycles, both mechanical and thermal, for which CALLISTO products have to be designed, is relatively high compared to traditional launch vehicle products. Most tests having an impact on the design of the DLR product flight models are summarized in Figure 2.

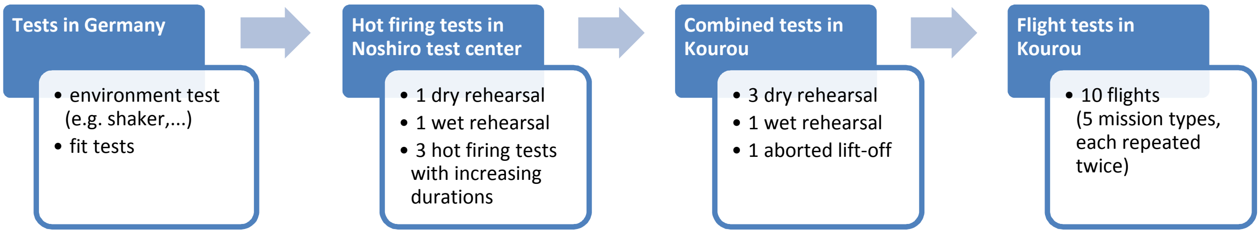


Figure 2: Test plan overview

Depending on the products, not all tests will have a sizeable impact on their design. In addition load cycles are very different from one test to the other. Even flight tests will be characterized by different load cycles. The mission to be achieved by CALLISTO to complete the test program, as displayed in Figure 3, will finalize the test series being the most energetic mission type. Prior to this mission, 4 mission types with lower energy level will be performed with each of the flight software to get stepwise closer to the final mission. For the first flights, low altitude and low velocity vertical hops with the landing legs already deployed are intended to be performed. For each new mission type, the altitude, the speed, the number of manoeuver (engine re-ignition, change of attitude, etc.) will be increased. As a consequence a relatively complex sizing process has to be applied to CALLISTO products and in particular load carrying structures.

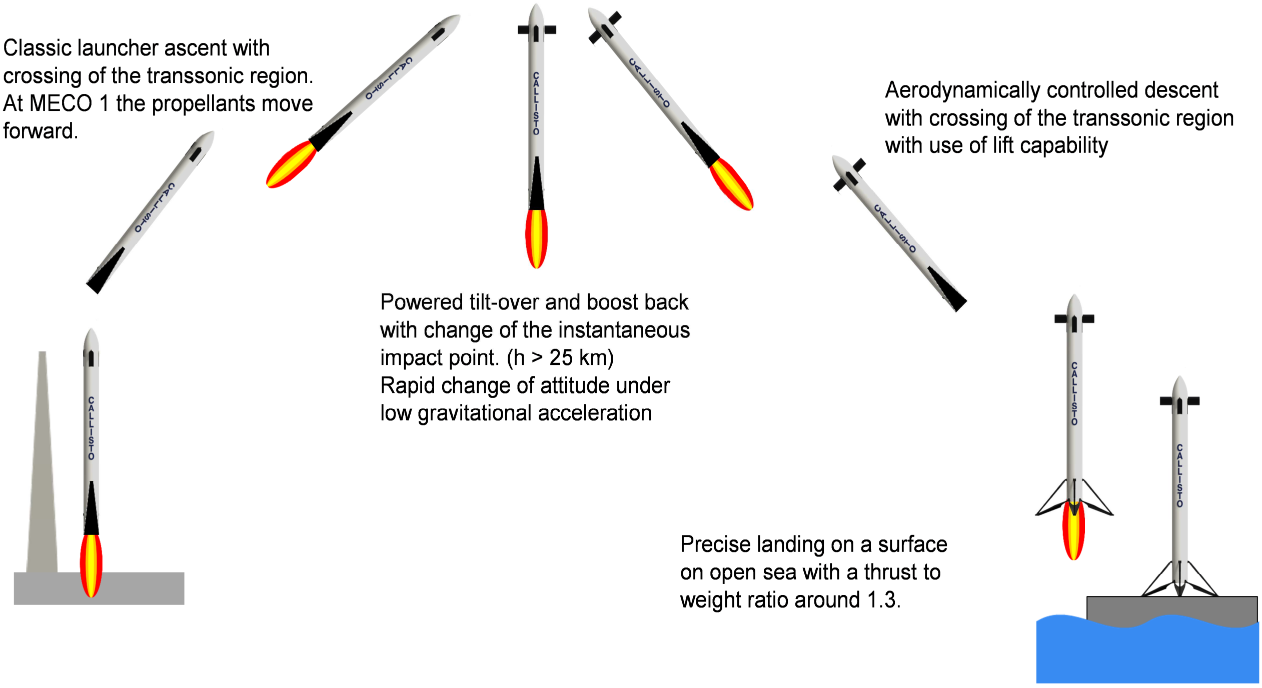


Figure 3: Overview of CALLISTO demonstration mission main phases

3. Structures & Reusability

CALLISTO's objective of a successful vehicle recovery and reuse directly induces challenging conditions for its structures as they have to withstand a variety of complex tests and manoeuvres for multiple times. The series of hot firing tests, combined tests and different flight tests results in a maximum number of 20 load cycles implying demanding conditions for the affected products. Additionally, the structures have to be compliant with limitations in mass budget for optimal performance while being robust enough for the mission's scenarios. Design and material properties of the vehicles components have to be studied very individually to meet all of these requirements.

Searching for an optimal flight performance during all flight phases leads to the development of foldable and stowable components as a major key technology. An active transformation of the vehicles outer shape during flight enables different flight configurations and thus providing the capability to react on specific load cases of each phase. Apart from this advantage, deployable structure design demands special attention because of the technical complexity and limited experience in the frame of reusability. For CALLISTO the structures considered as foldable are the aerodynamic surfaces of the FCS/A and the landing legs. In the following section the main design difficulties and the design procedure of these two structures will be highlighted. Moreover, and although that it is a solid structure, the fairing will be described. The fairings position changes significantly during the flight from being the vehicles top into being the bottom base so it has to be designed with respect to these different conditions.

3.1 Fairing

As one of CALLISTO's load carrying structures the fairing is exposed to non-negligible thermomechanical loads. Its function is to protect the front of the demonstrator from aerodynamic flow, particularly necessary during the ascent flight phase. Consequently, sizing loads occur in this phase induced by maximum static pressure conditions of the stagnation point at the nose tip [5]. At this point local air velocity becomes zero and the kinetic energy converts into pressure and thermal energy producing highest thermomechanical loads considerable for the design process.

Additionally, the design of the fairing shall consider the creation of beneficial aerodynamic conditions for each flight phase: During ascent the aerodynamic drag has to be minimized by shape and dimensions; during descent the fairing changes from being the vehicles top into being the vehicles base area and the drag budget has ideally to be maximized to support deceleration. A compromise is given by the fairing's ogive shape with dimensions resulting from aerodynamic calculations [6]. At the bottom towards VEB it offers enough space to house particular items; at the top the slim nose section avoids high drag values during ascent. The ratio of nose radius to base radius in combination with a total length of 1.3 m offers advantageous geometrical conditions and assists the air streamlines to follow the body's shape without high drag generation.

The fairing assembly is illustrated in Figure 4 and is comprised of a Carbon Fiber Reinforced Plastics (CFRP) main body, a separate nose cone and an aluminium mounting flange. The structure has to be instrumented for flight data acquisition.

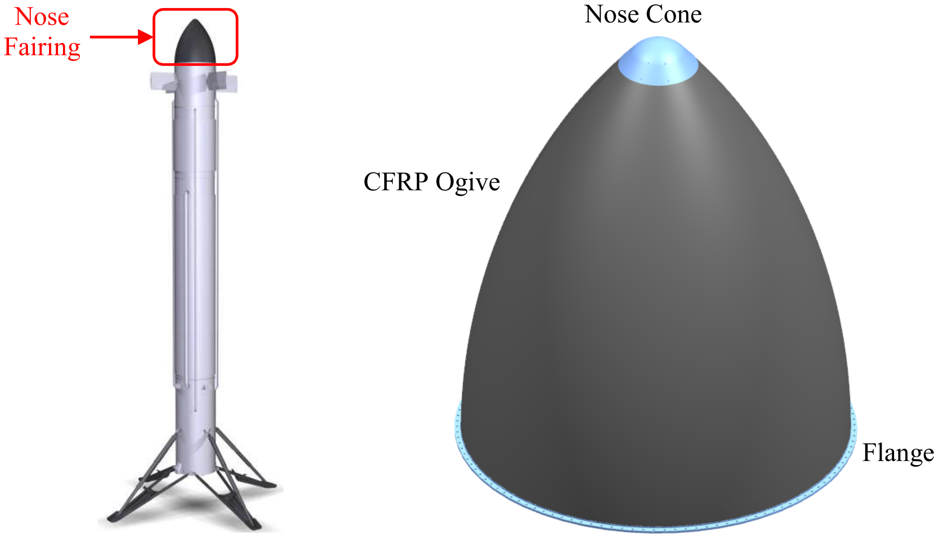


Figure 4: Assembly of CALLISTO's fairing

CFRP is selected for the main body due to robust mechanical properties and low weight. Compared to alternative material like aluminium, the density of CFRP is about 60% lower. For a large-sized structure as the fairing it has a noticeable impact on the mass. Using aluminium with the intention to achieve same mass range like CFRP would result in low material thicknesses causing problems of buckling and structure failure. Additionally, CFRP provides the opportunity of a modified layer and fiber alignment to achieve highest stiffness in load direction and thereby offers a wide scope of design options.

The fairing's nose cone is made of polyether ether ketone (PEEK). PEEK is an organic thermoplastic polymer with high mechanical and chemical resistance at high temperatures that are beneficial properties for the stagnation point area. Compared to classic CFRP material its maximum operating temperature is approximately two times higher. Moreover, the Global Navigation Satellite System (GNSS) antenna is accommodated in the nose cone implying the requirement of an organic material for radio-frequency (RF) transparency. Regarding MRO and reusability aspects the separate nose part simplifies operations on the antenna or the cone in between the flights.

In sum the most important aspect of the fairing's sizing is to find good compromise between mechanical properties and mass for vehicle performance support. For design optimization, simulations have been performed with the software ANSYS [7]. The module ANSYS Composite PrePost (ACP) is used to model the CFRP structure with precise definition of layered composite structures including material properties, assembly and orientation data of the layers. The ACP model is depicted in Figure 5, illustrating the model's elements and the orientation of one CFRP layer (green lines). With this model static-structural FEM simulations are performed based on the ascents maximum load case and failure criteria are analysed to optimize fiber directions, stiffness and weight. The right picture of Figure 5 represents the inverse safety factor of the most critical failure mode for each element. The maximum value of 0.69 is equivalent to the safety factor of 1.45.

First aerothermal calculations predict that thermal loading is a negligible load case for the fairing. Detailed thermal simulations are planned for validation of first estimations.

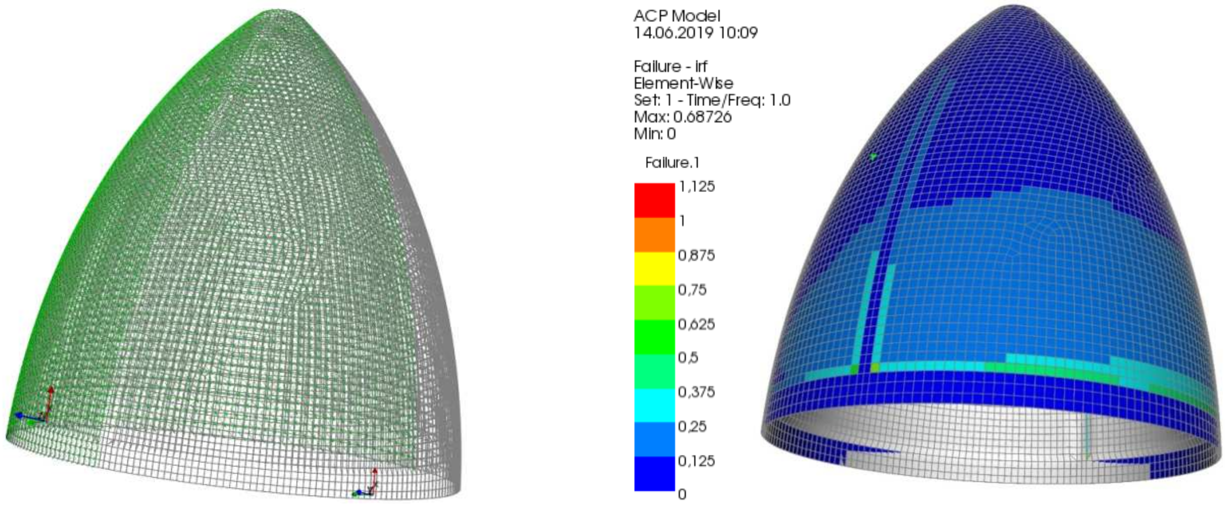


Figure 5: ACP fairing model (left) and resulting inverse safety factor of the maximum load case (right)

3.2 Deployable Aerosurfaces for FCS/A

As mentioned, one important key technology is the implementation of four foldable aerodynamic surfaces that are part of the FCS/A. Its purpose is to generate the aerodynamic forces for vehicle stability and controllability during entry while producing only minimum aerodynamic drag during ascent. To simultaneously meet these needs the aerodynamic surfaces are developed as foldable structures. The illustration of the system in Figure 6 shows the folded configuration for launch and ascent plus the deployed configuration for entry and landing.

Besides of the aerodynamic surfaces the FCS/A consists of four units each having:

- An actuator (geared electromotor) capable to deliver the needed hinge moment at a given rate for aerosurface rotation and deflection (not depicted in the figure).
- A bearing component taking the aerodynamic forces and bending moments during flight and transmitting them to VEB structure.
- A spring-based deployment mechanism including a Latch, Lock and Release Mechanism (LLRM) to keep the surfaces folded during ascent and to initiate the unfolding.
- A full system instrumentation especially for actuator control and flight data collection.

The control surfaces are of a conventional planar type with a quasi-diamond profile and sharp leading edges. This shape is the current reference resulting from aerodynamic drag and stability calculations and relying on existing knowledge and expertise of classical fins in the field of aerodynamics and manufacturing procedures.

The material selected for the control surfaces is aluminium. The LLRM contact point at the tip and the interface to the deployment mechanism (see Figure 6) would weaken inter-laminar fiber strength if CFRP structure is alternatively used. Compared to the fairing the surfaces have smaller dimensions and the lower density of CFRP would not have major influence on mass. In addition aluminium provides a high heat conductivity leading to a better distribution of the thermal loads which result from entry and deceleration effects. Due to these facts low increase in mass is accepted by the use of aluminium to guarantee functionality during relevant flight phases. Next design iteration will include precise thermal environment analysis for detailed sizing and material options.

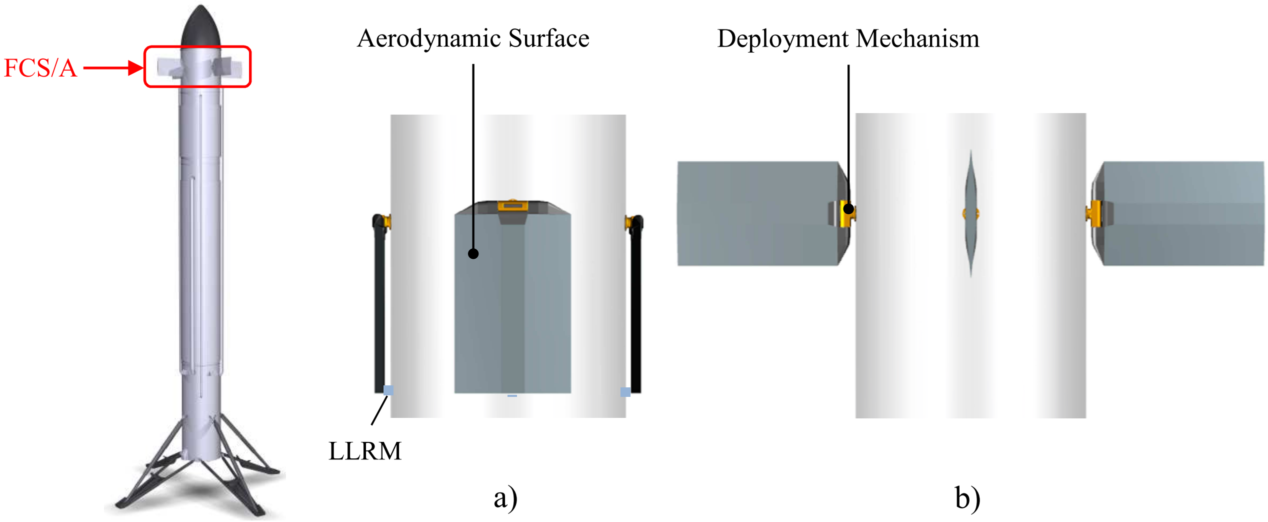
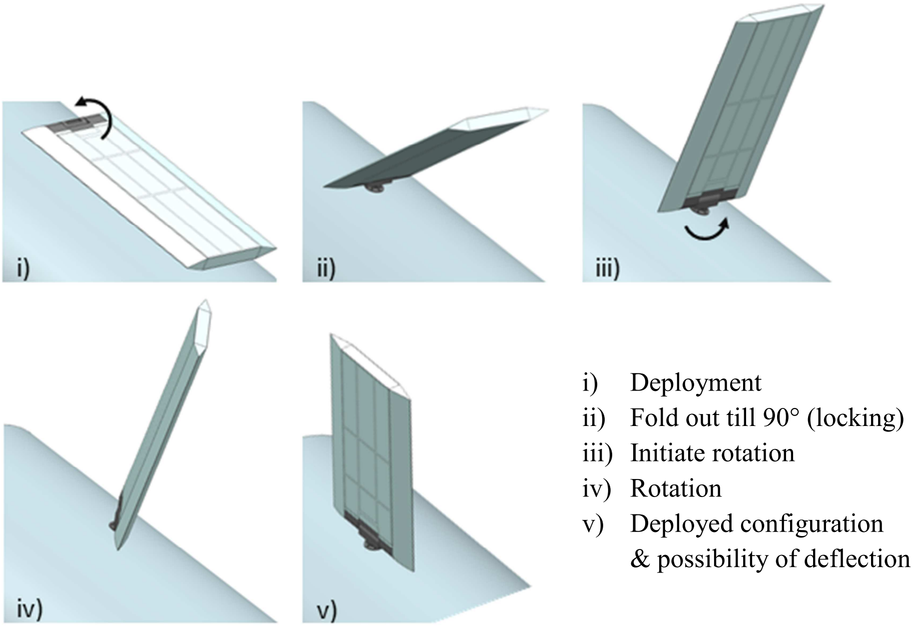


Figure 6: FCS/A on CALLISTO with aerodynamic control surfaces a) folded and b) unfolded

The deployment mechanism must ensure FCS/A functional performance for all relevant flight and ground phases while resisting the static and dynamic load environment. Design development is led by following critical scenarios: deployment under dynamic pressure conditions during flight, resistance of occurring loads during entry and folding/unfolding under conditions for ground handling, testing and MRO. The reacting forces on the VEB shall be minimized by the design concept. Additionally, the mechanism has to be assembled of interchangeable components to simplify MRO operations.

The unfolding will be performed at a trajectory point of minimum dynamic pressure reducing the drag that the mechanism and aerosurfaces have to overcome and reducing the loads that are transmitted to the VEB. The scheme of the unfolding sequence is illustrated in Figure 7. The deployment by the spring mechanism takes place in i) – iii) and stops at 90° by an integrated locking device within the deployment structure. In iv) and v) the actuator system (integrated inside the vehicles body, not depicted here) rotates the surface and offers the possibility of fin deflection during flight. Dedicated kinematic tests will be performed to guarantee functionality for multiple time deployment.



i) Deployment
ii) Fold out till 90° (locking)
iii) Initiate rotation
iv) Rotation
v) Deployed configuration
& possibility of deflection

Figure 7: Schematic illustration of the fin unfolding sequence (dimensions can differ from current baseline)

Based on the high energy flight mission of Figure 3, the critical mechanical load case is the maximum dynamic pressure during re-entry flight phase. A FEM analyses have been set-up to validate the sizing approach and to optimize stiffness and weight. Static-mechanical simulations of the maximum pressure load case have been performed with ANSYS workbench to predict material behaviour of the structural components. In Figure 8, the von Mises stress distribution of the hinge connection between actuator and aerosurface is illustrated. The values of 535 MPa at the flange and 683 MPa at the body's edge are resulting based on titanium material as the simulations showed that the required strength is very high. Aluminium is not used due to its specific strength values that are approximately three times lower than titanium strength. The singularities at the corner radius on the top (red zones) are negligible effects resulting from disadvantageous mesh resolution at sharp-edged areas and idealised contact between curved faces. Optimization of the radius can be performed in order to decrease the singularity effects.

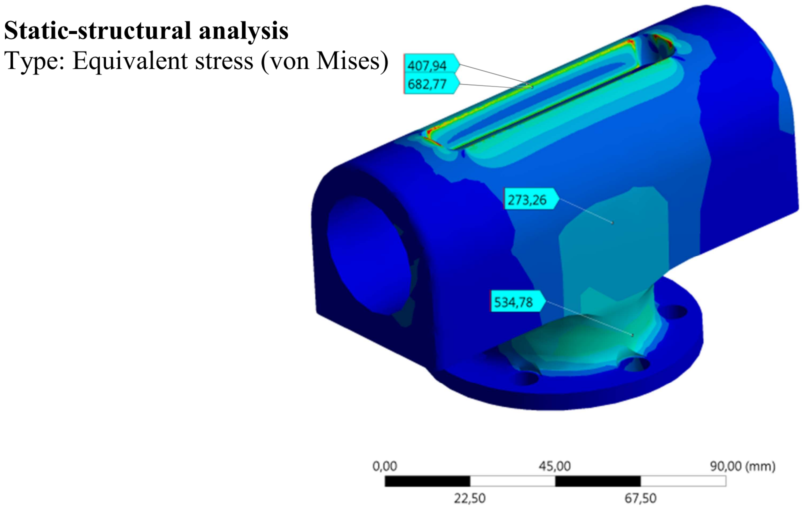


Figure 8: Equivalent stress (von Mises) of the deployment mechanism hinge resulting from maximum pressure loads during entry

The technology of the FCS/A is still in its iterative development phase confined by the outputs of aerodynamic calculations for the best shape, design of deployment and control mechanism, volume, mass and load limitations. Finding a compromise for a functional concept within the bounds of the requirements is the big challenge of this technology and also the reason why simulation results cannot be presented in detail for this state of the project.

The entire FCS/A shall be reusable after defined post-flight MRO operations. To return the aerodynamic surfaces to flight readiness they have to be folded back and the LLRM has to be re-set for launch after necessary visual inspection of all components.

3.3 Approach & Landing System

To provide the capability of a vertical landing on predefined landing zones under given boundary conditions the development of an Approach & Landing System (ALS) is essential. The ALS enables the vehicle to stand autonomously after landing and, for lower energy tests, also at launch. Regarding the high-energetic mission the purpose during touchdown is to absorb residual kinetic energy to limit the mechanical load transfer to the vehicle body, to provide static and dynamic stability and to maintain adequate ground clearance between engine nozzle and ground. During other flight phases the ALS shall avoid producing additional drag. Therefore, the leg structure is folded and locked against the vehicle body to least affect the aerodynamic flow before the deployment is initiated by a pneumatic system.

The entire ALS consists of four assemblies divided in following sub-components: the leg structure including attachments to the vehicle, the pneumatic system, the landing gear controller and the instrumentation.

The landing leg structure, illustrated in Figure 9, is comprised of a telescopic primary structure and a secondary structure both made of CFRP, favourable for these large components due to mass saving reasons. They are interlinked by a metallic footpad.

- Telescopic primary structure: consists of three CFRP hollow struts which glide in each other. It is the stowable part of the landing device that mainly performs the deployment initiated by the pneumatic system. During touchdown the primary structure transfers the mechanical main loads to the vehicle and limits them by plastic deformation of energy absorbing components.

- Secondary structure: consists of two identical hollow CFRP struts. Together with the primary structure it absorbs the landing loads transferring minimum to the vehicle itself. Further it provides an aerodynamic cover for the primary structure. In folded configuration the cover shall minimize the impact to the aerodynamic flow; in deployed configuration the cover shall provide a shield effect against the engine stream that thermally affect the primary structure due to ground effects during approach. As a result of this thermal load case a Thermal Protection System (TPS) is required for the secondary structure sized and designed for the entire test plan & missions profile.
- Footpad: The only contact area between leg and ground. The used material is titanium since it is the focal point of force introduction at landing and has to withstand high mechanical loads.

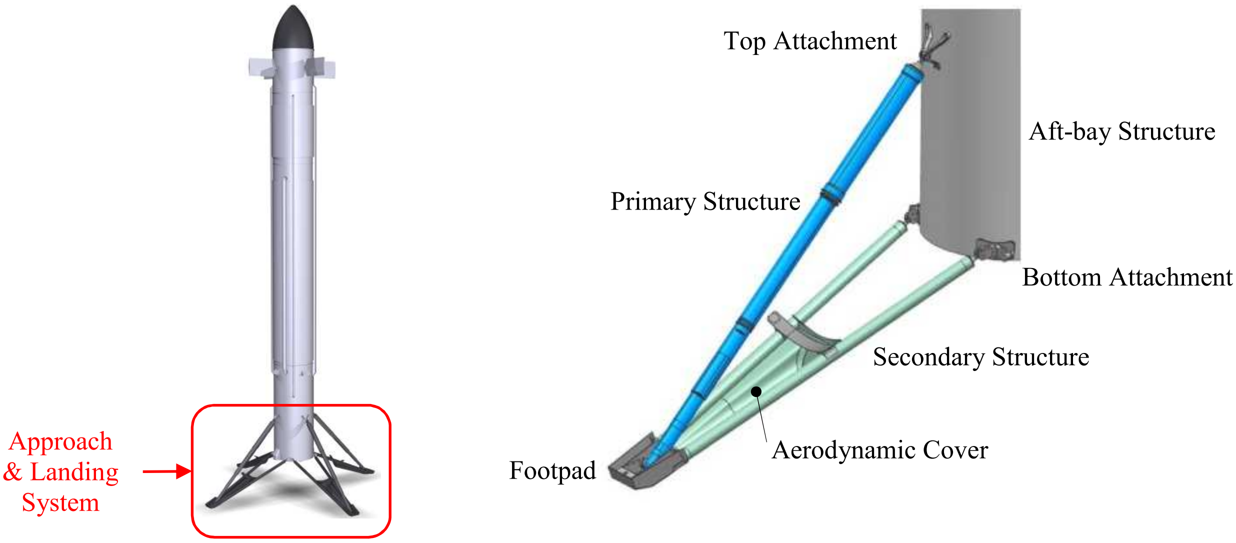


Figure 9: Position of the ALS and landing leg assembly

Geometrical boundaries for the main dimensions of the leg structure in folded and unfolded conditions are given by kinematic analysis and system requirements.

Deployment system / pneumatic system

The deployment of the landing legs is done by pressurizing the telescopic primary struts. The struts themselves are built up out of 3 segments which glide in each other. See Figure 10.

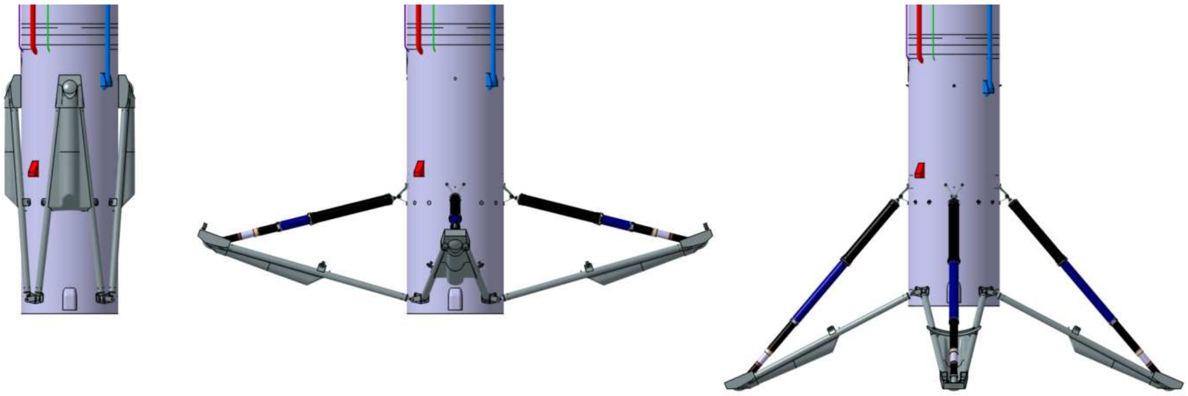


Figure 10: Primary structure of the ALS during deployment sequence

The working fluid is Helium that comes from pressure tanks which are also used for pressurizing the fuel tanks. At the desired time resp. height a dedicated Landing Gear Controller (LGC) gives an electronic command to open the LLRM and the isolation valve. The gas streams over a pressure reducer to a 5/3-directional valve, which receives another opening command to let the gas pass through. A scheme of the valve logic can be seen in Figure 11.

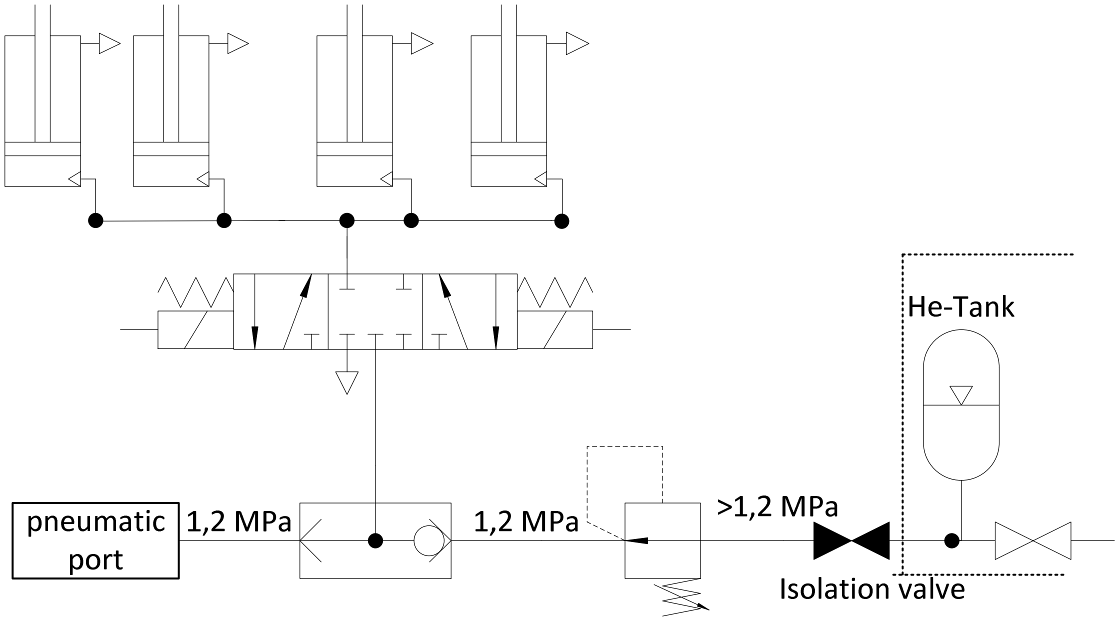


Figure 11: Scheme of vale logic

When the legs are fully deployed the directional valve closes the path and the gas remains in the lines. A latch mechanism in the first two segments of the primary strut takes care that the segments are locked and do not glide back even if the pressure drops.

The deployment is confirmed by a latching sensor system in the primary struts. After an independent measuring method has proven the stable configuration of the landed system at touchdown, the directional valve opens to evacuate the feed lines.

For ground tests an additional pneumatic port is installed to have a separate feedline for providing the pressure.

The whole system is reusable including valves and actuators; the only nominal part which has to be exchanged is the honeycomb damper above the footpads. This can be done easily and with low cost. After depressurizing the system the latch mechanisms can be retrieved and the landing legs can be folded back to the stowed configuration. Then the LLRM is reset to hold the secondary strut.

Touchdown dynamics simulation and landing load cases

A numerical system level simulation has been set up to support the design and development of the ALS on a virtual basis. Purposes of this simulator are in particular to assess: the vehicle's key performance with regard to (i) landing stability, (ii) loads on the vehicle's central core, (iii) engine ground clearance after touchdown, and (iv) the landing gear's energy absorption capability. Thereby, it supports to define the landing gear's force-displacement characteristics of its energy absorbing elements as requirement towards the ALS product. Third purpose is to constrain/confirm the flight domain for a safe touchdown with regard to vehicle motions states for this flight phase.

The simulator is realized with the Multi Body Simulation (MBS) tool SIMPACK. The CALLISTO model structure considers the vehicle's central core including residual fuel quantities and sloshing fuel masses, the landing gear assemblies consisting of their strut frame work, telescoping strut elements and energy absorbers as well as dedicated force elements to capture surface contact conditions, wind effects and engine thrust trail-off characteristics at Main Engine Cut-Off (MECO). The simulation is initialized at MECO marking the beginning of the landing phase ultimately before touchdown. All initial motion states and system properties are parameterized to allow parameter variation studies and Monte Carlo simulations.

Sizing load cases with regard to the ALS structural design in terms of dimension and strength are touch downs at the flight domain's maximum velocities and in a vehicle orientation with one leg leading into direction of flight ("1-2-1 landing") and with two leading legs ("2-2 landing"). The 1-2-1 landing occurs in the symmetry plane and exerts a maximum compression force onto the leg assembly and also yields the largest load limiter stroke. The 2-2 case exerts the largest out-of-plane force to leg assembly and is also called the stability load case as it is the case most susceptible for a vehicle tip-over.

For illustration, the following figures show a landing in 1-2-1 orientation with animation snap shots in Figure 12 and associated time series data in Figure 13a and 13b.

Touchdown with the leading leg occurs at a simulated time of t = 0.756 s. The vehicle tips into the momentary flight direction (towards right side of image) and the crushable load limiter start to yield. Due to rebound, the vehicle tilts back and forth between opposing leading and trailing leg which yields a second time at approximately 1.2 s. The tipping lasts several seconds until the vehicle comes to a full rest (not shown).

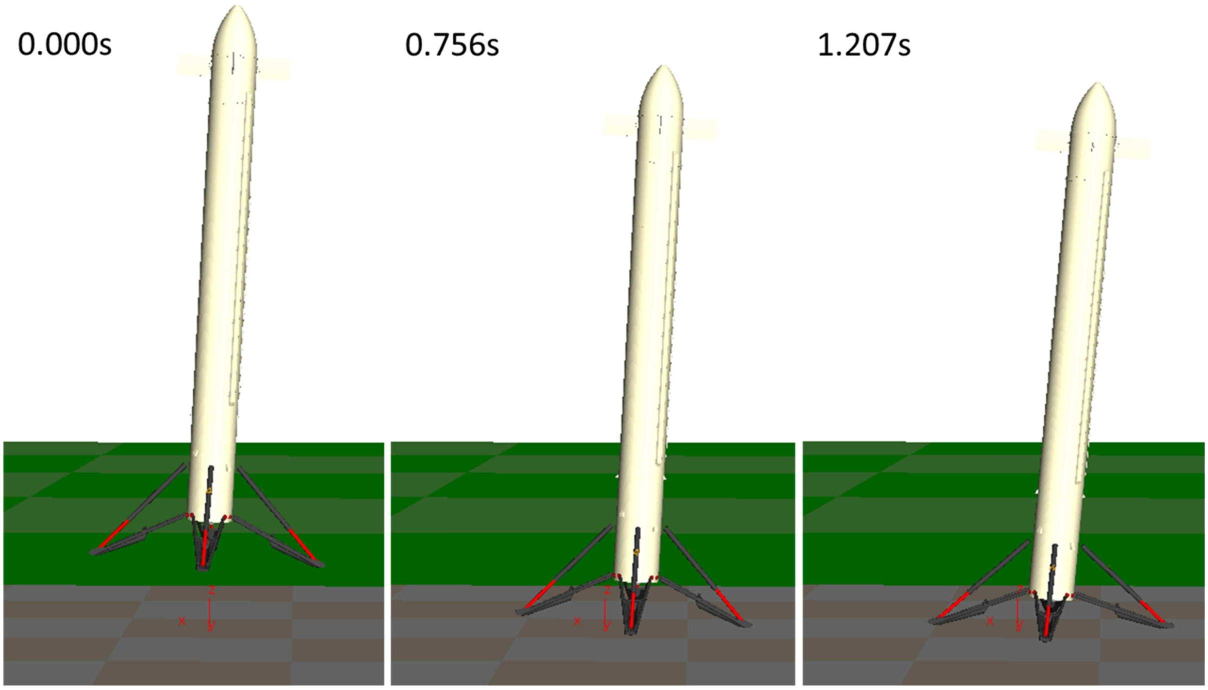


Figure 12 – Landing scenario with touchdown into leading leg (here: right leg assembly)

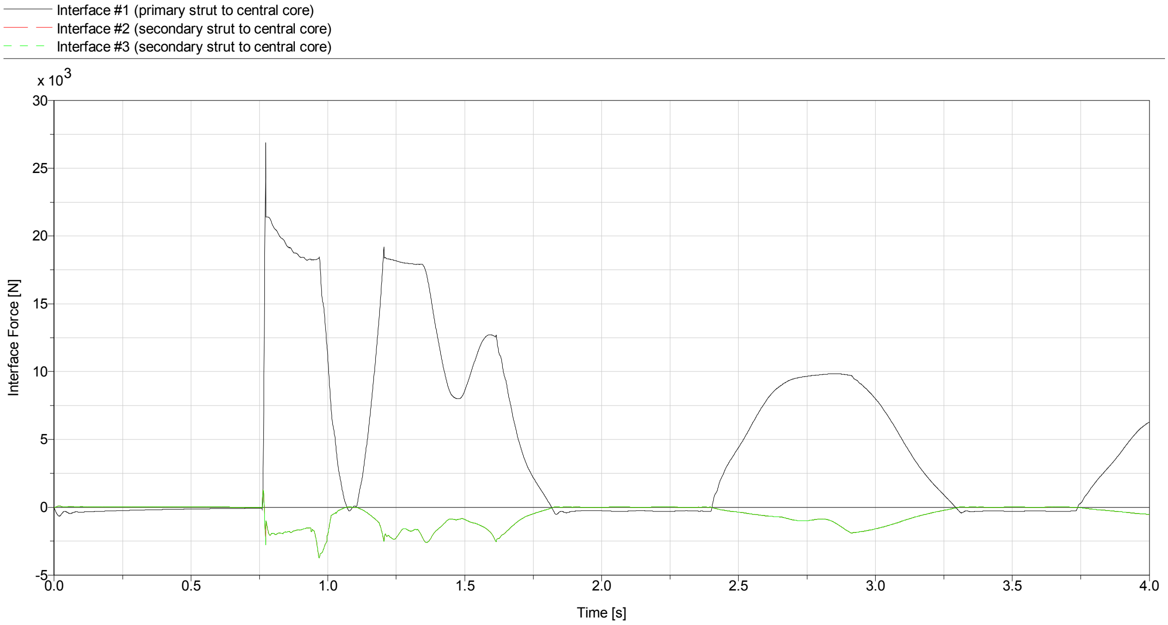


Figure 13a – Interface forces between leading leg struts. Primary strut (black) experiences peak force of 27kN. Secondary struts peak at approximately -3kN (green and red, interface #2 force is hidden behind #3 curve in this symmetric case)

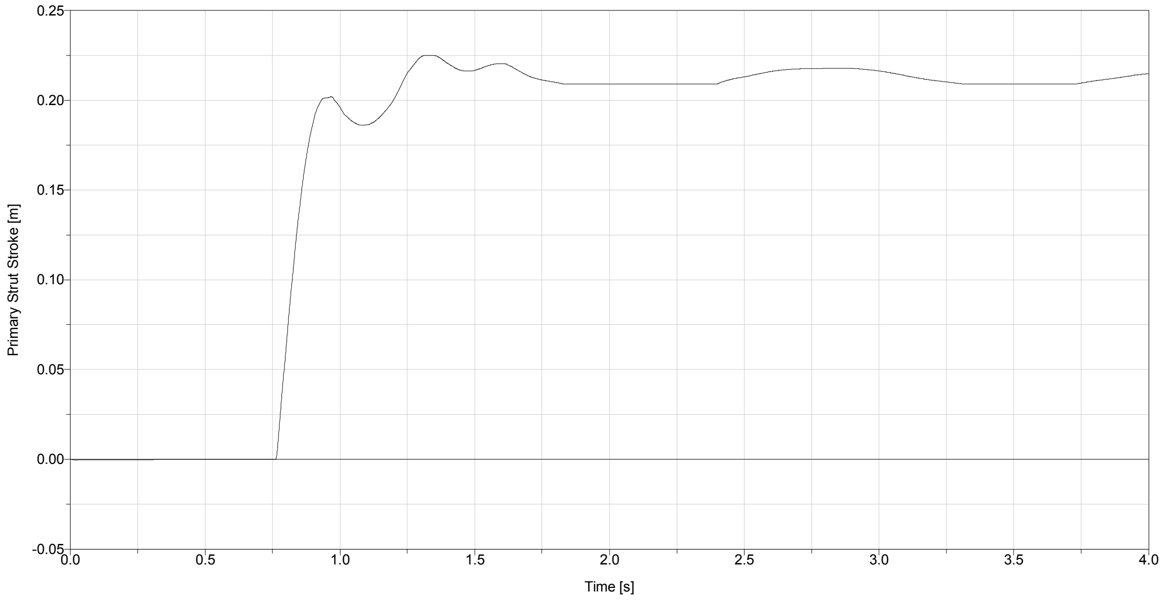


Figure 13b – Primary strut's telescoping segment displacement due to elastic-plastic deformation of crushable energy absorber

FEM Analysis

Based on the results of the numerical touchdown simulation, ANSYS FEM structural analyses have been performed for optimization of the leg components. The input loads are the maximum resulting contact forces at the footpad that occur during touchdown. This load case represents the most critical and realistic condition compared to real flight scenario. The distribution of the structural deformation is given in Figure 14, scaled with the factor 1 000 to underline the possible failure mode. The pivot-mounted attachments lead to a bending stress that is highest for the secondary structure towards footpad (visualized by the red zone deformation). For further structural optimization this is the area of interest.

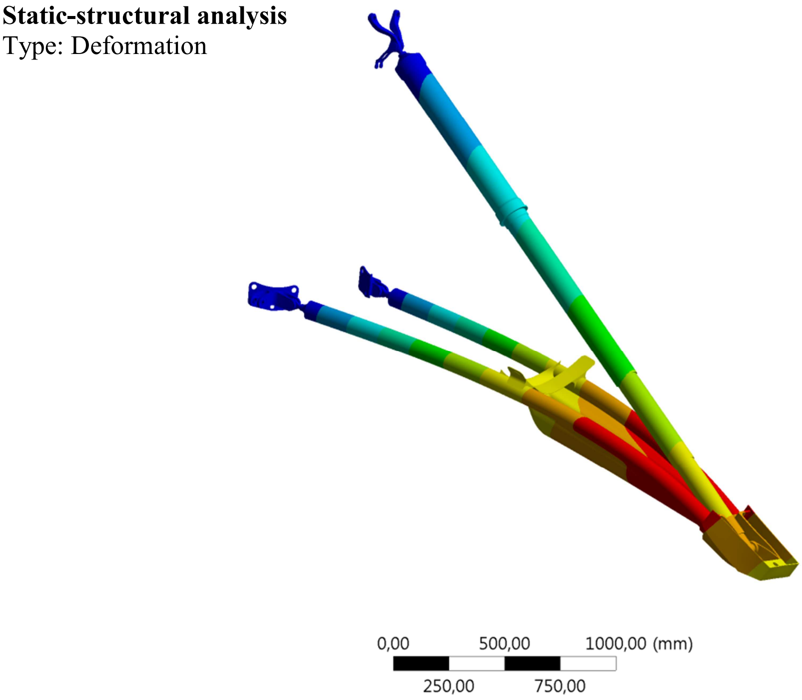


Figure 14: Deformation results based on static-mechanical analysis with the software ANSYS

Due to the complexity of this product, the sizing is an iterative process that has to be optimized for significant changes in the nominal trajectory coming from system level. The thermal aspect has to be analysed in detailed for the next project steps. Examination of the necessary TPS design has not been completed at this stage of the project. One first assessment is that thermal loads are not sizing for the landing legs but can strongly influence the total mass of the system. The TPS is therefore heavily depending on the entire load duration and load maximum values of the number of relevant load cycles. As already mentioned, the primary need for TPS are engine stream ground effects during approach. The aerothermal analysis of these effects is still under investigation and has to be examined in the next step for final TPS sizing.

4. Conclusion

The design process has to include aspects of trajectory, aerodynamic result, number of load cycles and maximum thermomechanical loads by iterative analysis and calculations. The current reference design of CALLISTO's products is mainly driven by flight performance requirements resulting in the need to find best compromise between stiffness and mass. At present mission stage complete design approaches are available taking into account ground handling and MRO operations, but still are in its developmental phase with the capacity of optimization with respect to mission requirements. First concepts of structural optimization are determined by the performance of FEM analyses increasing the comprehension of critical load cases and indicating potential for mass saving. Results confirm sufficient design margins in terms of successive flight tests and reusability. Regarding these aspects especially the foldable structures are designed capable to return back to flight readiness configuration after flight.
Next step of the design process is the performance of detailed thermal analysis based on aerothermal calculations for critical mission scenarios.

References

[1] Dumont, E., Ecker, T., Chavagnac, C., Witte, L., Windelberg, J., Klevanski, J. and Giagkozoglou, S.: CALLISTO – Reusable VTVL launcher first stage demonstrator. Space Propulsion Conference 2018, Seville, Spain, SP2018_00406, 2018.

[2] Tatiossian, P., Desmariaux, J. and Garcia, M.: CALLISTO Project - Reusable first stage rocket Demonstrator, 7th European Conference for Aeronautics and Space Sciences, Milano, Italy, DOI: 10.13009/EUCASS2017-680, 2017.

[3] Ishimoto, S., Tatiossian, P., and Dumont, E.: Overview of the CALLISTO Project, 32nd International Symposium on Space Technology and Science (ISTS), Fukui, Japan, 2019-o-1-05, 2019.

[4] Dumont, E., Ishimoto, S., Tatiossian, P., Klevanski, J., Reimann, B., Ecker, T., Witte L., Riehmer, J., Sagliano, M., Giagkozoglou Vincenzino S., Petkov, I., Rotärmel, W., Schwarz, R., Seelbinder, D., Markgraf, M., Sommer, J., Pfau, D. and Martens, H.: CALLISTO: a Demonstrator for Reusable Launcher Key Technologies, 32nd International Symposium on Space Technology and Science (ISTS), Fukui, Japan, 2019-g-03, 2019.

[5] John D. Anderson, Jr.: Hypersonic and High Temperature Gas Dynamics. McGraw-Hill, 2nd edition, 1989.

[6] Klevanski J., Ecker T., Riehmer J., Reimann B., Dumont E., Chavagnac C., Aerodynamic Studies in Preparation for CALLISTO - Reusable VTVL Launcher First Stage Demonstrator. 69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018.

[7] ANSYS®, Release 19.2.