Journal of Evolving Space Activities
Vol. 2, Article No. 168, 2024
DOI: 10.57350/jesa.168

Development of the Landing Leg Structure for CALLISTO

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(Received August 23rd, 2023)

In the scope of the project CALLISTO (Cooperative Action Leading to Launcher Innovation in Stage Toss back Operations) DLR, JAXA and CNES jointly develop a demonstrator for a reusable, vertical take-off, vertical landing rocket first stage. CALLISTO aims to demonstrate relevant technologies for the reusability of such vehicles and their structures in order to gather flight data and knowledge for their development. In the context of this project, a variety of challenging thermal and mechanical loads and requirements occur in particular due to descent and landing phase. This paper focuses on the development of the deployable landing legs and presents the evolved structural and thermal design, major FE analysis results and performed test activities to achieve a lightweight and reusable space structure, enduring all present thermal and mechanical loads during its lifetime. Particular attention is hereby placed on dynamic phases such as the deployment of the landing legs and the touchdown that represent the dimensioning load cases for the structural parts made of titanium and CFRP. In order to sustain the combined demanding thermal environment, the landing legs are equipped with a cork TPS.

Key Words: CALLISTO, Reusability, Structure, Landing Legs, TPS

Nomenclature

ALS	:	Approach and Landing System
AoA	:	Angle of Attack
CALLISTO	:	Cooperative Action Leading to Launcher Innovation in Stage Toss-back Operations
CDR	:	Critical Design Review
CFD	:	Computational Fluid Dynamics
CFRP	:	Carbon Fiber Reinforced Polymers
CMC	:	Ceramic Matrix Composite
CNES	:	Centre National d'Études Spatiales
COTS	:	Component of the shelf
DLC	:	Diamond-like carbon
DLR	:	Deutsches Zentrum für Luft- und Raumfahrt e.V.
DM	:	Development Model
EM	:	Engineering Model
FEM	:	Finite Element Method
FM	:	Flight Model
JAXA	:	Japan Aerospace eXploration Agency
LLRM	:	Launch, Lock and Release Mechanism
LM	:	Latching Mechanism
MRO	:	Maintenance and Repair Operations
PDR	:	Preliminary Design Review
PTFE	:	Polytetrafluoroethylene
QM	:	Qualification Model
RLV	:	Reusable Launch Vehicle
TGA	:	Thermogravimetric Analysis
TPS	:	Thermal Protection System
UD	:	Unidirectional
VTVL	:	Vertical Take-off vertical landing

1. Introduction

The space sector is becoming more and more challenging, not only from an economic point of view but also requirements for launch systems are getting progressively demanding.

The implementation of reusable rocket first stages in launch vehicles is highly affecting the competitiveness of such systems as their costs for operation are expected to be significantly lower compared to non-reusable launch vehicles.

In 2017, JAXA, CNES and DLR initiated the CALLISTO project with the aim of jointly develop, manufacture and operate a reusable vertical take-off vertical landing (VTVL) first stage rocket demonstrator. In particular, the project aims to gather important flight data and the relevant experience required for the development and operation of reusable launcher systems, since such expertise does not currently exist in Europe. This know-how will provide valuable knowledge for reusable structures and future reusable launch vehicles (RLVs) and will help to decrease the effort and therefore time and costs for upcoming developments.[1,2)]

In order to achieve these results, a major test and flight campaign is foreseen for the CALLISTO demonstrator. A total of ten flights are currently planned with a preceding test campaign beginning in late 2024. The two last scheduled test flights, the so-called demo flights, will be performed according to a representative flight envelope comparable to the ones that are necessary for operational full-size launch vehicles. This leads to challenging mechanical and thermal conditions and a demanding environment for the vehicle while demonstrating typical maneuvers for a characteristic flight domain.[3)]

With the upcoming critical design reviews (CDRs) of the overall system as well as the individual products of the demonstrator, the project is about to complete Phase C. An overview of the CALLISTO vehicle and the structural responsibility sharing is given in Fig. 1.

Originating from the flight envelope, a large variety of mechanical and thermal loads needs to be considered for the dimensioning. Due to the reusability of the vehicle, the multiple load cycles to which the structures and mechanisms are subjected to must also be considered for the individual products of CALLISTO. With respect to the landing legs, in particular the dynamic life phases such as the deployment of the Approach and Landing System (ALS) as well as the final approach and touchdown phase need to be investigated specifically.[4)]

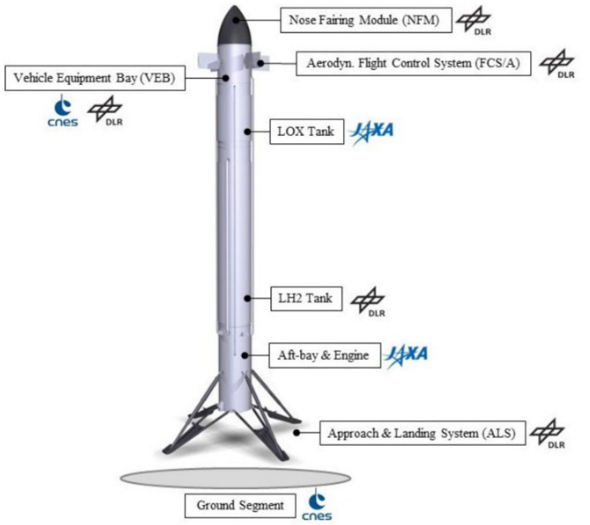

Fig. 1. Main structures of CALLISTO.[5)]

2. Approach and Landing System

The ALS provides the ability for the CALLISTO demonstrator for an autonomously stand on the ground without any ground support equipment. For lift-off configuration as well as ascent and descent during the flight, the deployable system is folded against the vehicle. During the final approach phase the landing legs are then released shortly before touchdown in order to (1) absorb the residual kinetic energy, (2) provide dynamic and static stability, (3) maintain ground clearance limits and (4) limit the loads that are transferred to the adjacent structure and the vehicle.[5,6)] An overview is given in Fig. 2.

In order to provide the mentioned functionalities and to be able to accomplish the deployment, the ALS consists of a retractable telescopic primary strut and a rigid secondary structure, both together forming the main load carrying structure of the overall system. For the purpose of keeping the ALS folded during ascent and descent, each landing leg is equipped with three Launch, Lock and Release mechanisms (LLRMs). At the moment of deployment, these actuators release the landing leg and a pneumatic subsystem is activated in order to perform the unfolding, supported by a spring-loaded mechanism in the beginning. After complete extension of the retractable primary strut, two latching mechanisms (LM) are locking the individual segments of the primary strut at their interfaces in between sustaining the unfolded length of the telescopic structure (see Fig. 3).

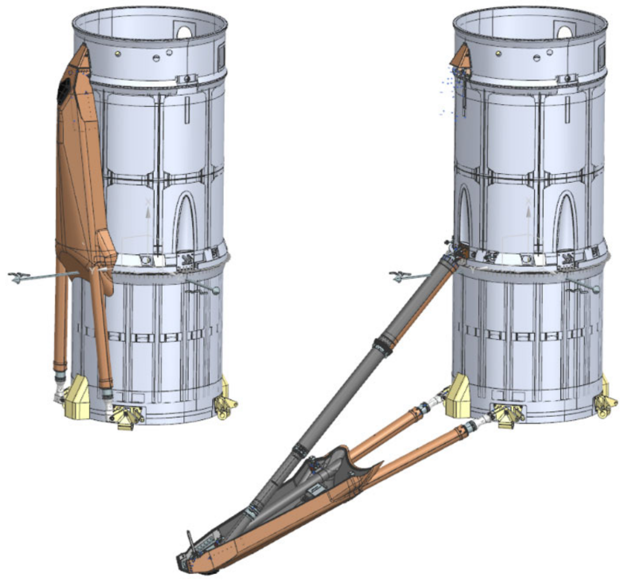

Fig. 2. ALS and Aft-Bay in folded (left) and deployed configuration (right).

The primary strut is divided in three main segments. Each segment is equipped with titanium flanges at its interfaces, that are used for connection and to accommodate the LMs. In total it consists of four CFRP struts, as segment 3 is again subdivided in order to realize a damping system based on a crushable honeycomb structure inside of segment 3a. The titanium flanges are connected to the CFRP structure via structural adhesive and metallic pins.

The interface to the aft-bay is realized by an end dome mounted on top of segment 1, which is connected via ball joint to the upper bracket. The end dome itself is detachably joined to the CFRP strut via threaded pins integrated in the front face of segment 1.

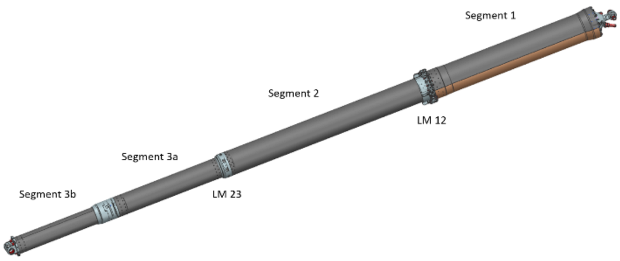

Fig. 3. Primary strut components.

In order to support the deployment and realize a precise functionality with defined and persistent parameters, several coatings are applied to the primary strut. Their purpose is primarily to minimize wear and friction in the system. During the deployment of the primary strut, segment 2 is most affected by the LMs, as their locking devices are sliding on its surface while deploying. For this reason, segment 2 is coated with a diamond-like carbon coating (DLC), which is characterized by an extremely durable and hard surface. Due to geometric limitations of the process, the DLC coating is only applied on the outer surface of the strut. Segment 3a and 3b are coated with a polytetrafluoroethylene-based (PTFE-based) coating in order to reliably minimize the friction and secure a defined and undisturbed damping behavior of the crushable honeycomb system.

The secondary structure consists of two CFRP struts, complemented with a CFRP cover, that is mainly intended for aerodynamic purposes as well as for protection of the primary strut. The interface towards the aft-bay is also connected via ball joints to the lower brackets. On the other end, the titanium footpad is mounted. All connections are designed detachably, in order to realize easy mounting and dismounting capabilities and good operability for Maintenance and Repair Operations (MRO). The footpad primarily represents the connection between the primary and the secondary strut. It also includes the mentioned spring-loaded push-off device, that supports the initiation of the deployment as well as a rubber on the ground facing surface. This rubber provides defined characteristics for touchdown on a specific landing zone. [5]

The pneumatic system, which is responsible for the deployment and based on a GHe-pressure vessel, is accommodated inside the aft-bay.

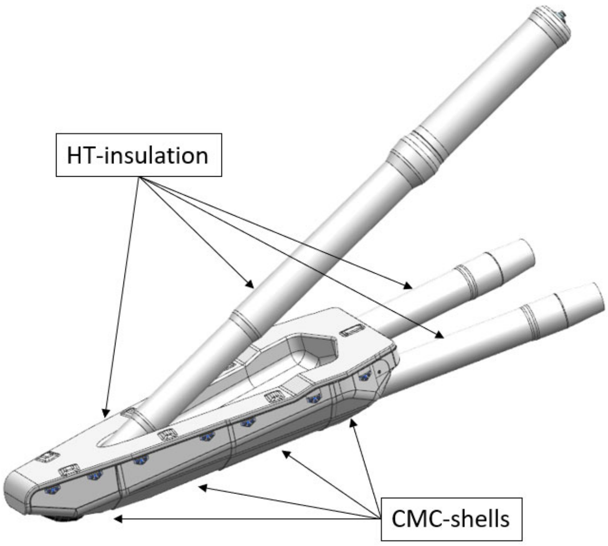

Fig. 4. Auxiliary CMC-based TPS.

In order to sustain the harsh thermal environment especially during the final approach phase and touchdown, the ALS is equipped with an ablative cork-based thermal protection system (TPS) to protect the structural components. During the first test flights, a lift-off with unfolded landing legs is planned (in contrary to the nominal flight configuration, where the landing legs are folded during ascent and descent). Therefore, an additional thermal load is expected due to the engine plume during ignition and lift-off. For this, an auxiliary TPS is designed and foreseen for the first test flights, supplemental to the cork-based TPS. This second TPS is based on ceramic matrix composite (CMC) shells for the area most exposed to the engine plume, complemented by high-temperature insulation cushions for the remaining zones (see Fig. 4).

3. Development Tests of the ALS and its Evolution

Since 2017, the ALS experienced a development from first sketches and concepts to various prototype models. Until now, two types of models were built and extensively tested, namely the development model (DM) and the engineering model (EM). The former was tested with an incremental step-by-step approach during a first deployment test campaign. With the EM extensive touchdown and further deployment test campaigns were carried out gaining important data and knowledge for the development and the characteristics of the structure. [5] The experience gained was consistently used to further develop and improve the design of the ALS, which converges in the Qualification Model (QM) at CDR-P status.

3.1. Deployment test campaign with DM

The first deployment test campaign was carried out using the DM. The DM mainly consists of metallic components (aluminum and stainless steel), as it was primarily used to proof the kinematic behavior and overall functionality of the ALS and its deployment capabilities. In order to gain data and experience of multi-load cycling of structures from the outset, segment 2 was manufactured in its later CFRP design (see Fig. 5). In this way, the same segment can also be used for subsequent test models. The same logic is valid for the latching mechanisms, that are also to be re-used for subsequent test campaigns.

Fig. 5. ALS Development model in deployed configuration.

During this first deployment test campaign, the overall functionality with respect to the deployment and the complete functional chain (release of LLRMs, activation of pneumatic system, deployment and latching of LMs) could be successfully demonstrated.[5] Also, it was shown that the CFRP-titanium interface on segment 2 withstood the present loads and no damages occurred on the structural components. The test campaign also has shown, that special attention needs to be paid for the telescopic structure in terms of tolerances between the various segments of the primary strut. The dimensions between the segments need to be adjusted very precisely in order to provide sufficient freedom for a smooth-running deployment maintaining simultaneously sufficient stiffness and alignment to sustain a good linear load path along the primary strut. This alignment reduces occurring bending moments for the interface in between the segments and thus enables more lightweight and optimized structures. In addition, segment 2 did not show any noteworthy degradation due to multiple deployment sequences. Only slight marks could be observed on the inner surface, where no DLC-coating is applied.

3.2. Touchdown and further deployment tests with EM

The first touchdown test campaign was performed already using the EM. While the DM mainly consists of metal parts as described above, the EM was the first prototype with structural components made out of titanium and in particular all main structures made out of CFRP parts, that are later envisaged as CFRP for the QM and flight model (FM). For the EM, the first experience gathered from the deployment test campaign of the DM was already considered. Among others, the dimensions of the segment interfaces were therefore slightly adapted. As intended, segment 2 and the LMs were re-used from the previous model.

This first touchdown test campaign was conducted without the PTFE-based coating on segment 3a and b. With the single leg test stand (displayed in Fig. 6), various test parameters – such as different touchdown angles and velocities – were tested. These parameters were chosen in order to approximate a flight-like condition and loads that are representative for later operation. Main focus was on the energy absorption capability of the honeycomb cartridge and the proof of mechanical strength of the ALS.

Fig. 6. Single leg touchdown test configuration with EM.

In conclusion, it was shown, that the ALS is capable of conducting touchdowns under laboratory conditions maintaining the structural integrity of the landing leg. Only minor lateral scratches inside of segment 3a were observed after a disassembly for inspection. The absorption capability of the honeycomb could be demonstrated in general and essential experience with respect to the operation and maintenance for later flight campaign was gathered.[5)]

The measured test data showed that there are expected shock-like loads during touchdown. These loads are characterized by an oscillating load spectrum with high transient peak loads in the moment of touchdown that settle to a certain quasi-static load level (see Fig. 7). During this first touchdown test campaign, these initial peak loads were higher than expected whereas the damping behavior of the honeycomb was lower than assumed.

Subsequently, a continuing touchdown test campaign was carried out with the EM. With then implemented PTFE-based coating (on segment 3a and 3b), improved characteristics could be demonstrated. A direct influence of the coating was observable and the new data together with the data from the first touchdown test campaign enabled an evaluation of the coating effects: Primarily, the friction was consequently reduced due to the coating purpose itself. As a result, the overall load level, that was transmitted through the ALS towards the adjacent structures (resp. the aft-bay) could be decreased. This can be explained by the fact that the honeycomb acted earlier in its function as the dissipating energy absorber during the touchdown sequence. Due to higher friction in the configuration without coating, loads were transmitted through the CFRP struts past the honeycomb and dissipating energy due to the honeycomb crushing set in slightly delayed, not damping the initial high peak loads. In addition, a more precise alignment was realized due to the coatings as the clearance between the moving segments could be defined very precisely. This more precise alignment

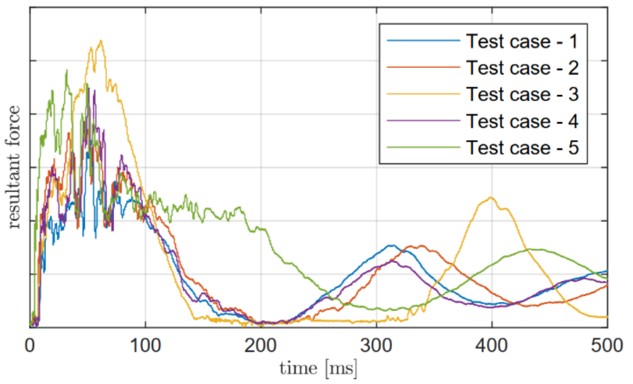

Fig. 7. Load spectra of the first touchdown test campaign with resultant force measured on the upper connection towards the touchdown test stand for test cases with various touchdown velocities.

minimized transversal loads inside the primary strut as the initial retraction began. Therefore, normal forces that enhance higher contact friction levels were again decreased, resulting in smoother touchdown characteristics of the landing leg.

With the EM, also a follow-up deployment test campaign was conducted in the LAMA ("Lande- und Mobilitätsanlage") at DLR Bremen. Various external load and internal pneumatic parameters were tested in order to estimate limit boundary conditions for which the ALS is still capable of successfully deploying the landings legs (with respect to the deployment system such as pneumatic pressure, etc.). Special attention was paid to the interface loads and the capability to create pneumatic power in order to enable a deployment within

CALLISTO's approach flight. A reliable deployment capability of the ALS could be demonstrated.

In the course of these campaigns, it was subsequently possible to simulate the repetitive load cycles under laboratory conditions that the structure will face in later use. In total the EM and its structures experienced a set of 17 deployment and 12 touchdown cycles with various boundary conditions (in terms of velocity and touchdown mass or angles). In summary, no major degradation was observed and the components maintained structural integrity. Nevertheless, a detectable wear of coatings could be found, in particular for segment 3a and 3b, which will be discussed in chapter 4.4. On the basis of the performed test campaigns, high quality data was gathered. The generated data is in particular of crucial importance to validate and improve the numerical tools and models used for system level studies and the dimensioning of the ALS. The interaction between the vehicle dynamics, engine plume, aerodynamics and landing leg deployment dynamics have been discussed in-depth in [6].

4. Latest Implemented ALS Design Improvements

As a result of the various test campaigns as well as other external factors impacting the ALS, the landing legs experienced several design iteration and improvements during their development. In the following, the latest improvements are explained that are targeting the QM as well as the Flight Model (FM).

4.1. Aeroshape and outer contour of ALS

As the ALS and its kinematics are a complex and highly aligned system, the design is very sensitive to geometric changes and other boundary conditions affecting the layout.

Due to kinematic constraints during its development, a shift of the lower rotation axes of the secondary strut slightly further outwards of the vehicle was necessary, which affected the overall layout of the ALS. Therefore, the secondary structure was moved further outwards and the angles (between primary and secondary strut as well as to the vehicle) have changed. This shift required an adaption of the CFRP cover and therefore of the outer shape of the ALS. Secondly, this adaption was used to optimize the outer contour with respect to MRO activities (due to a change of the TPS design baseline, see chapter 4.5).

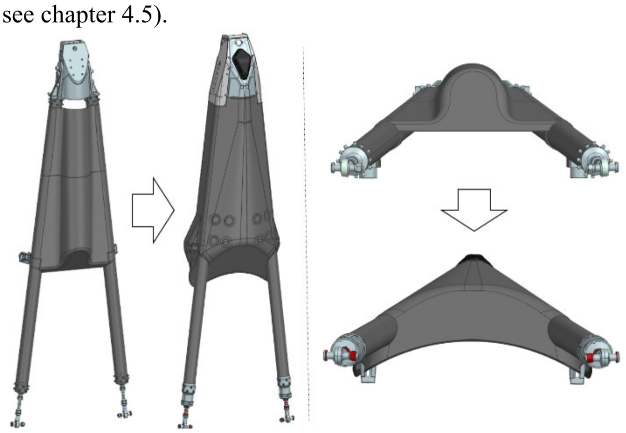

Fig. 8. Aeroshape adaption from EM to QM.

There were two main objectives and boundary conditions for the new aeroshape that needed to be considered: Minimizing drag and improving MRO capabilities regarding the TPS refurbishment.

As the ALS has a direct impact on drag due to its location and as a part of the outer shape of the vehicle, the landing legs therefore also have a direct influence on the performance of CALLISTO. In order to minimize the drag in general and in particular due to the shift outwards, a limited increase of the projected area was targeted. Besides that, the adaption was used to ensure a minimal effort with respect to MRO activities in the context of the TPS refurbishment.

Driven by these targets and other geometric boundary conditions, the design led to the convex layout displayed in Fig. 8. Additionally, a watertight closure towards the aft-bay and the aerodynamic covering of the lower LLRMs were implemented in the new design loop.

In general, the volume below the CFRP cover needed to be increased due to other factors. This, combined with the closure towards the aft-bay and the LLRM covering, resulted in an increase in the overall mass of the secondary structure. But comparing the old EM design (that is upscaled for the increased size) with the new convex design showed, that approx. 7% of mass saving is possible with the new layout. On the contrary, the projected area of the upscaled design only increases 0,16 % (compared to the condition prior to the shift). With the convex design the increase is about 0,41 %. A trade-off was made subsequently. Due to advantages for MRO activities, lower mass and expected beneficial characteristics with respect to lateral aerodynamics, the convex design was favored for the ALS.

4.2. CFRP titanium interface design

Various types of CFRP-titanium interfaces are already described in chapter 2. The detachable connection technique used for the secondary structure has proven to be robust during operation and practical for handling. Due to the telescopic structure of the primary strut, its required extension capability and the resulting limited design envelope, the interface for the primary strut segments are joined as presented in chapter 2. The manufacturing of the first prototype (segment 2 for the DM) turned out to be quite extensive among others due to a small diameter for the metallic pins. The EM design (segment 1, 3a and 3b) was then improved for manufacturing, simultaneously targeting a minimized lead time. Also, a change of material and process was implemented for these CFRP parts: Instead of a winding process, twill fabric and unidirectional prepregs were used for the EM struts. In principle, the adaption of the interface design worked and showed advantages for manufacturing. But it also revealed the necessity of more precise definition of tolerances. The latest design considered all previous experience, pin type and diameter and the joining tolerances. The order of manufacturing is adapted accordingly. Fig. 9 shows the latest interface design for segment 2.

Furthermore, the conducted test campaigns have shown, that the deployment load case can be most demanding for some specific structures (depending on the deployment parameters that are strongly linked to the flight domain). The most stressed area identified was the lower CFRP-titanium interface of segment 2. For this, dedicated uniaxial tests of this latest interface design are planned to estimate the maximum bearable load limit (compared to FE-analysis and occurring loads during operation). Compared to the planned uniaxial tests, the loads during touchdown or deployment are a mixture e.g. from longitudinal and bending loads due to inertia and deflection of the primary strut. But the planned test is an important contribution to characterize the designed interfaces and to validate the FE model.

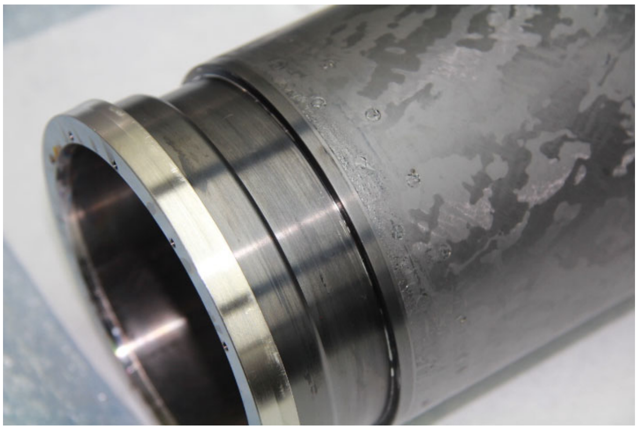

Fig. 9. Latest interface design of segment 2.

4.3. Improvement of structural design

The realized test campaigns (deployment and touchdown test campaigns) have shown, that there are high transient peak loads to be expected for the structure and the adjacent components of the vehicle (see again Fig. 7), that are partially above the expected magnitudes. System analysis (with the touchdown and deployment simulator) have shown, that additional dampers implemented in the structural design are - among other results - suitable to decrease these first peak loads. With this decrease, the shocks to the ALS and its adjacent structures can be limited and therefore it reduces the risks and optimizes the landing leg system.

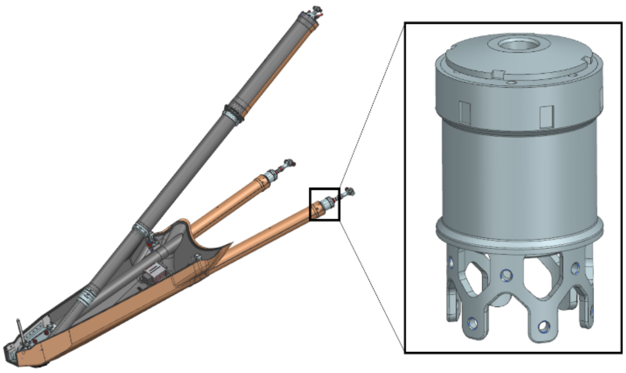

Fig. 10. Damper element design on secondary strut.

For this, a compact design considering a damper integration in existing components of the ALS was developed, that is easily inspectable, replaceable and based on low cost elastomer COTS elements. In addition, an increased capability for compensating manufacturing and mounting tolerances is present due to the usage of non-rigid elastomer components. In the first place, this design concept includes damper elements integrated inside the titanium footpad, that are arranged to operate in parallel operation, damping mainly the load introduction towards the primary strut. Secondly, further damping elements are integrated in the secondary strut inside a structural housing towards the lower interface to the aft-bay and the lower brackets. The design of this housing enables the possibility to be adapted for damping elements with other diameters as well as an increasing number in case of a series operation of e.g. two dampers. In addition, the complete damping element (housing including damper) can easily be replaced or dismounted for inspection. The compact design is displayed in Fig. 10.

These compact dampers of course cannot dissipate the same amount of energy as the honeycomb cartridge and, once the elements reach the end-stops the force is transmitted directly from the footpad to the interfaces.

As mentioned, the need for this damper has been identified in the multiple conducted touchdown and deployment test campaigns as well as in system level touchdown and deployment analyses. Main purpose of this elements is to (1) to reduce the high frequency part of the induced shock response spectrum in the interfaces of CALLISTO's aft-bay and as a side effect (2) to mitigate force spikes. The adjacent structure is designed to withstand the directly transmitted force once the elements reach their end-stops. Additionally, in the following test campaigns the performance of these elements will be investigated in detail, and subsequently the test results will be used for validation of our simulators.

4.4. Functional features (coatings)

As described in chapter 3, the two applied coatings (DLC as well as PTFE-based coating) are suitable to improve the deployment and touchdown characteristics of the ALS and its durability in terms of multi-load cycles. In particular segment 2 does not show any remarkable degradation in consequences of the several conducted test campaigns maintaining constant deployment characteristics due to stable surface properties.

Fig. 11. Clearly detectable wear of the PTFE-based coating on upper area of segment 3b due to multiple touchdown cycles.

Regarding segment 3a and 3b with the applied PTFE-based coating, a degradation of the surface is visible after seven touchdown tests. As intended, after initial use the coating is characteristically partially deposited on the uncoated counterpart during operation (that is also not coatable due to limits in the manufacturing process). Therefore, the visible degradation does not automatically imply worse characteristics and a need for instant replacement of specific parts after each load cycle.

As shown in Fig. 11, the degradation is very localized on specific parts and in particular towards edge areas. This again can be traced back to a very slight deflection from the ideal straight load path during touchdown of the primary strut, localizing loads on small hot spots. The design is consequently adapted and optimized for the QM in order to reduce the extent of this degradation.

4.5. Thermal protection system

During ascent and descent, the landing legs are exposed to a demanding thermal environment. In particular during the descent and the final approach phase with deployed landing legs, high heat fluxes are expected due to the retro propulsion maneuvers. When the engine is reignited for deceleration, hot gas from the engine plume gets in contact with the structures of CALLISTO until engine cut-off on the ground after touchdown.

For this, an ablative cork-based TPS is planned for the ALS. The dimensioning is done on the basis of an aerothermal database, generated by steady state CFD simulations. This database provides maximum heat flux predictions, that are used for the design. In order to adjust and optimize the TPS for the expected thermal loads, the ALS was subdivided in various zones in the post-processing of the CFD data.[7]

In the beginning, the design baseline for the TPS was planned to be designed for the complete lifecycle (covering all ten scheduled flights) in order to minimize the effort for the refurbishment in between the flights and therefore time and costs for vehicle operation during the campaign.

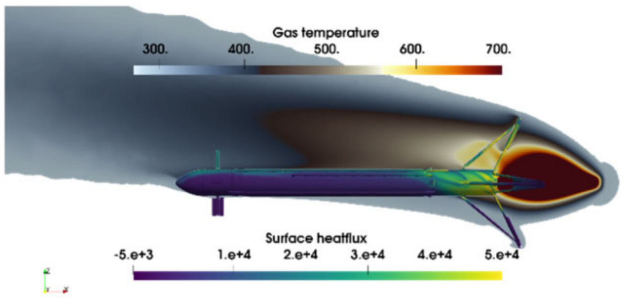

Fig. 13. Temperature field in K and surface heat flux in W/m2 for a configuration of CALLISTO with deployed landing legs at M=0.5, AoA=170°, engine thrust 100%, sideview.[5]

During project phase B, a simplified FEM-model was used in Ansys[8] for the dimensioning of the TPS. For this, a block model (see Fig. 12) was set up, representing the ablative cork-based TPS on top of the structural CFRP of the ALS.

For the dimensioning, a target temperature for the boundary interface layer between cork and CFRP was set, for which no significant degradation of the mechanical properties of the CFRP is expected. The simulations were then conducted on the basis of the aerothermal database as input parameters for the various zones of the ALS using a customized set of material data. The cork material was defined in such way that the material parameters up to a defined limit temperature correspond to those of the virgin material. Above this limit temperature, the material characteristics switch corresponding to charred parameters. In particular, this refers to the density, the thermal conductivity and the specific heat. The data for this material data set are based on thermogravimetric analysis (TGA) of ablative materials.[9] For this analysis, the conservative assumption was made that the transition from virgin to charred cork material does not absorb any thermal energy (due to occurring pyrolysis). This assumption clearly overestimates the layer thickness of the system. It is planned to refine and detail the analysis and the simplified material model based on later measurements and experience gained during further test campaigns and also during first test flights of CALLISTO.

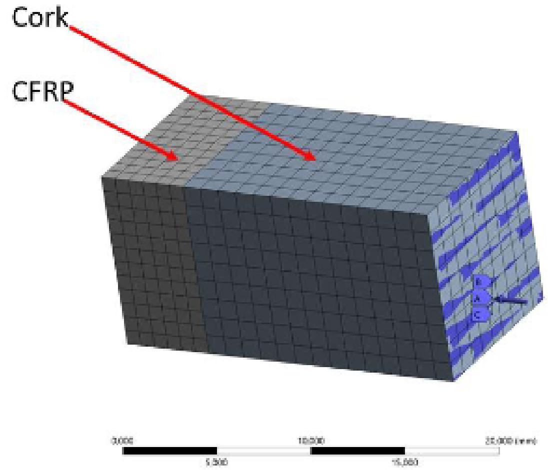

Fig. 12. Simplified thermal block model in Ansys.[8]

Based on this conservative approach, the mass of the TPS sized for the complete lifecycle was not reasonable and exceeded targeted limits for the ALS. A second major reason for the high thickness of the TPS and therefore its mass was caused by high thermal heat fluxes originating from the ground segment after touchdown. Due to the engine plume interacting with the ground segment, very high ground segment temperatures were assumed, that contribute to the thermal loads of the vehicle. In order to mitigate this influence, a comparative high insulation capability of the TPS was required, for which an ablative material might not be best suited with respect to its mass. Also, the TPS needs to be refurbished on any case in between two flights, even if the thickness is designed to withstand the complete lifecycle. After flight, the surface needs to be restored, in terms of removal of the charred layer in order to prepare the surface for further MRO steps (such as coating with anti-static paint, etc.) and a potential drying (due to rain or other environmental effects). A rough estimation of the order of magnitude for the required time necessary for these MRO activities did not provide a significant benefit in time. Therefore, and due to the mass penalty (caused by the conservative approach and high ground heat fluxes), a change of the baseline for TPS design was done, sizing its thickness only for one single flight. Simultaneously, the ground heat fluxes were refined and decreased. In this way, a significantly reduction of the ALS system mass was achieved. In addition, the new baseline enables the possibility to adjust and refine the TPS after the first test flights are accomplished and first real test flight data and experience is available, which can be used to minimize the uncertainties in the aerothermal database and the dimensioning of the TPS.

Concerning the auxiliary CMC-based TPS for the first test flights, the design was refined during the detailed design phase after the PDR-P of the ALS. The so-called Clip-on TPS consists of a CMC shell, high-temperature insulation cushions and a structural frame for the attachment to the ALS structure. For the CMC an oxide ceramic matrix composite is planned that is manufactured using a near net-shaped fabrication method. The IFOX® process is a newly developed vacuum infiltration technology for the fabrication of oxide CMC by the DLR Institute of Materials Research (Department of Structural and Functional Ceramics), that has proven to be very promising for this kind of application.[10,11] The CMC shell was intended as a single shell in the preliminary design. This was adapted to a segmented architecture because of two main reasons: First, the segmented design enables advantages with respect to the manufacturing. In particular, the draping of the dry fabrics is less complex for smaller segments and produces less warpage and distortion of the fibers. Also, in case of a damage during manufacturing and in particular during later usage during the flight campaign, single segments can be replaced instead of a complete shell. This limits the risks and costs of a possible failure. Secondly, the segmented design creates a partially decoupled construction, that is capable of sustaining the displacement of the landing leg without inducing additional loads to the CMC shells due to a certain degree of freedom for each segment. In addition, the insulation cushion is assumed to provide a slight damping characteristic, that needs to be reviewed in the scope of mechanical FEM-analysis prior to the CDR-P of the ALS.

5. Conclusion

The Approach and Landing System is a heavily stressed main structure of the CALLISTO vehicle and a crucial system for the operation of the demonstrator. It is subjected to a harsh environment typical for VTVL RLVs, in particular due to demanding mechanical loads during deployment and touchdown in combination with high thermal loads due to the vicinity of the engine. During its development beginning in 2017, the different manufactured and extensively tested models have shown the functionality and overall capability of the ALS of withstanding present loads under laboratory conditions maintaining its structural integrity. In addition, first experience is gathered with respect to its operation and MRO activities for later flight campaign. After the challenging test campaigns considering in particular the multi load cycling in the scope of reusable structures, the development is now strongly targeting CDR status of the product with an advanced design for the upcoming qualification prior to the flight campaign.

Acknowledgments

The authors would like to thank the entire CALLISTO project team at CNES, JAXA and DLR for their remarkable efforts and collaboration over the past years.

References

1) Dumont, E., Ishimoto, S., Tatiossian, P., Klevanski, J., Reiman, 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, *Trans. JSASS Aerospace Tech. Japan.* **19**, 1 (2021), pp. 106-115, https://doi.org/10.2322/tastj.19.106.
2) Ishimoto, S., Tatiossian, P. and Dumont, E.: Overview of the CALLISTO Project, 32nd International Symposium on Space Technology and Science, Fukui, Japan, 2019-o-1-05, 2019, https://elib.dlr.de/132886/.…
3) Guédron, S., Ishimoto, S., Dumont, E., Tatiossian, P., Chavagnac, C., Desmariaux, J., Monchaux, D., Frenoy, O., Cliquet Moreno, E., Deremaux, C., Lidon, N., Cesco, N., Witte, L., Sagliano, M., Seelbinder, D., Klevanski, J., Ecker, T., Reimann, B., Riehmer, J., Ertl, M., and Krummen, S.: CALLISTO DEMONSTRATOR: Focus on system aspects, 71st International Astronautical Congress (IAC), online, 2020, https://elib.dlr.de/138808/
4) Desmariaux, J., Cliquet Moreno, E., Chavagnac, C., Tatiossian, P. Saito, Y. and Dumont, E.: CALLISTO Reusable Vehicle System Design, 32nd International Symposium on Space Technology and Science, Fukui, Japan, 2019-g-02, 2019, https://elib.dlr.de/132889/
5) Giagkozoglou Vincenzino, S., Eichel, S., Rotärmel, W., Krziwanie, F., Petkov, I., Dumont, E., Schneider, A., Schröder, S., Windelberg, J., Ecker, T., and Ertl, M.: Development of Reusable Structures and Mechanisms for CALLISTO, 33nd International Symposium on Space Technology and Science, Oita, Japan, 2022 Reusable strcutres
6) Schneider, A., Desmariaux, J., Klevanski, J. *et al.* Deployment dynamics analysis of CALLISTO's approach and landing system. *CEAS Space J* **15**, 343–356 (2023). https://doi.org/10.1007/s12567-021-00411-2
7) Krummen, S., Desmariaux, J., Yasuhiro, S., Boldt, M., Briese, L., Cesco, N. Chavagnac, C., Cliquet Moreno, E., Dumont, E., Ecker, T., Eichel, S., Ertl, M., Giagkozoglou Vincenzino, S., Glaser, T., Grimm, C., Illig, M., Ishimoto, S., Klevanski, J., Lidon, N., Mierheim, O., Niccolai, J., Reershemius, S., Reimann, B., Riehmer, J., Sagliano, M., Scheufler, H., Schneider, A., Schröder, S., Schwarz, R., Seelbinder, D., Stief, M., Windelberg, J. and Woicke, S.: Towards a Reusable First Stage Demonstrator: CALLISTO - Technical Progresses & Challenges, 72nd International Astronautical Congress (IAC), Dubai, United Arab Emirates, IAC-21-D2.6.1, 2021, https://elib.dlr.de/147143/.
8) *Ansys® Mechanical, Enterprise, Release 2022 R2*
9) Böhrk, Hannah und Stokes, Jamesa (2015) *Kinetic Parameters and Thermal Properties of a Cork-Based Material.* 20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Jul. 2015, Glasgow, UK. doi: 10.2514/6.2015-3532.
10) Rickmers, Peter und Bauer, Waldemar und Stappert, Sven und Sippel, Martin und Redondo Gutierrez, Jose Luis und Seelbinder, David und Bernal Polo, Pablo und Razgus, Bronislovas und Theil, Stephan und Acquatella B., Paul und Wartemann, Viola und Merrem, Clemens Hans-Joachim und Ruhe, Tobias und Elsaesser, Henning und Welter, Michael und Schmidt, Alexander und Damp, Lloyd und Williams, Peter (2021) *The Reusability Flight Experiment – ReFEx: From Design to Flight – Hardware.* In: Proceedings of the International Astronautical Congress, IAC. International Aeronautical Congress 2021, 25.-29. Oct. 2021, Dubai, VAE. ISSN 0074-1795.

11) Welter, Michael und Herzog, Peter und Leisner, Vito (2021) *Towards the automatable, near-net shape fabrication of all oxide ceramic matrix composites.* DLR Materials Colloquium 2021, 07. Dez. 2021, online.