Copyright 2024 by Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR). Published by the IAF, with permission and released to the IAF to publish in all forms.

IAC-24-C2.4.8

Landing leg deployment dynamics simulation and excessive deployment test campaign of CALLISTO's Approach and Landing System

Anton Schneider[a*], Jan A. Bertram[a], Silvio Schröder[a], Lars Witte[a]

[a] *Institute of Space Systems, Landing and Exploration Technology, German Aerospace Center (DLR e.V.), Robert-Hooke-Str. 7, 28359 Bremen, Germany*
* Corresponding Author, anton.schneider@dlr.de

Abstract

DLR, JAXA, and CNES are jointly developing and building the VTVL (vertical take-off and vertical landing) first stage rocket technology demonstrator CALLISTO (Cooperative Action Leading to Launcher Innovation in Stage Toss-back Operations). One objective of CALLISTO is to demonstrate the landing leg deployment and subsequently a successful touchdown by means of a deployable four leg landing system, called the Approach and Landing System (ALS). Here, the deployment phase is critical for the re-usability mission objectives, because an unsuccessfully deployed landing system will cause a vehicle loss. The transient phase from stowed to deployed configuration is conducted shortly before touchdown. During this phase an asymmetric load environment is generated by the aerodynamics and vehicle dynamics, and introduced into the ALS landing legs. Additionally, these loads generate disturbance torques and forces that are acting on the vehicle and needs to be compensated by the GNC (Guidance Navigation and Control) prior to touchdown. This harsh and unsteady external load environment challenges the pneumatic deployment subsystem of the ALS. For the purpose of the investigation of the complex interplay of aerodynamics, vehicle's approach trajectory, ALS system parameter and the landing leg deployment dynamics, a numerical simulator has been developed. In order to increase the prediction accuracy of the simulator an excessive single leg deployment test campaign has been performed in the DLR Landing & Mobility Test (LAMA) facility. Both, the studied deployment dynamics and the conducted single leg deployment test campaign are presented in this paper.

Keywords: Deployment dynamics, re-usability, deployment test campaign, simulation, EDL

Nomenclature

Acronyms/Abbreviations

AEDB – Aerodynamic Data Base
ALS – Approach and Landing System
CALLISTO – Cooperative Action Leading to Launcher Innovation for Stage Toss-back Operations
CFD – Computational Fluid Dynamics
CNES - Centre national d'études spatiales
DLR – German Aerospace Center
GHe – Gaseous helium
GNC – Guidane Navigation and Control
JAXA - Japan Aerospace Exploration Agency
LAMA – Landing & Mobility Test Facility, DLR
LLRM – Launch Lock Release Mechanism
VTVL – Vertical Take-off Vertical Landing
OBC – On Board Computer
RLV – Reusable Launch Vehicle
TPS – Thermal Protection System

1. Introduction

Currently, several launch vehicles are under development worldwide with the goal of cost reduction by re-usability. Examples of these launch systems include SpaceX's Starship (USA), Deep Blue Aerospace's Nebula-M Rocket (China), and MaiaSpace (France). In addition to these commercial launch systems, Europe and Japan have research projects such as CALLISTO, which aim to enable and demonstrate the technologies necessary for reusability.
All these launch systems share a common feature: they employ deployable landing legs, offering the advantage of a significantly reduced projected area when stowed compared to the deployed configuration. To capitalize on this benefit, the landing leg system requires a novel deployment mechanism that is relatively new to the space industry. While common deployment operations in space industry have been conducted in near-vacuum or low-density atmospheric conditions, the landing leg system of a reusable launch vehicle (RLV) must perform its deployment in a dense atmosphere, near sea level. This presents unique challenges compared to previous missions and operational environments.

To gain a better comprehension of the characteristics of RLVs regarding the required design and operations, and to mature the required key technologies, CNES of France, DLR of Germany, and JAXA of Japan have chosen to combine their expertise in the CALLISTO project (Cooperative Action Leading to Launcher

Copyright 2024 by Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR). Published by the IAF, with permission and released to the IAF to publish in all forms.

Innovation in Stage Toss-back Operations). The trilateral partners aim to develop, build and test a subscale reusable first stage demonstrator vehicle. Responsibility and tasks are distributed based on the expertise and knowhow of the partners. An overview of this sharing is illustrated in Fig. 1 and well described in [2,3,4,5]. The Approach and Landing System is under the responsibility of DLR. In addition to developing, building, and testing it, a major contribution is the simulation of the landing leg's dynamic behaviour.

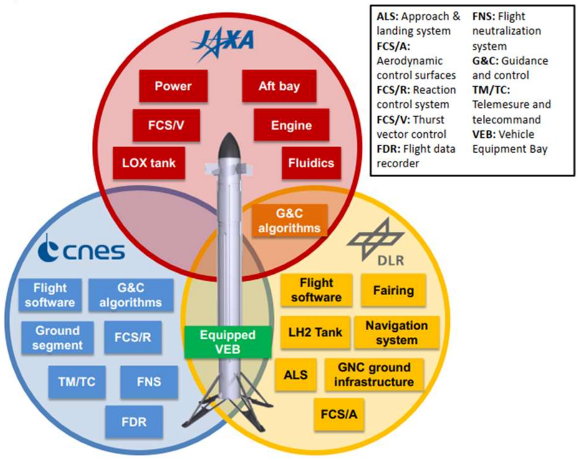

Fig. 1: Vehicle Responsibility sharing.

2. Approach and Landing System

The Approach and Landing System (ALS) supports the vehicle in standing autonomously without the need for ground support equipment. Upon touchdown, the ALS performs several critical functions: (1) absorbing the remaining kinetic energy, (2) ensuring both dynamic and static stability, (3) maintaining ground clearance, and (4) limiting the loads transferred to the rest of the vehicle. The ALS facilitates a safe transition from flight to ground state.

During ascent and descent, the landing legs are folded and secured against the vehicle. Just before touchdown, they are deployed via the pneumatic deployment subsystem. Once fully extended, two latching mechanisms located at the segment interfaces of the telescopic struts engage to prevent retraction under external loads. The legs remain locked in place until retrieval by the ground segment. These two configurations are illustrated in Fig. 2. Additionally, the legs are equipped with an ablative thermal protection system (TPS) to withstand the intense thermal conditions experienced during the final approach and landing phase.

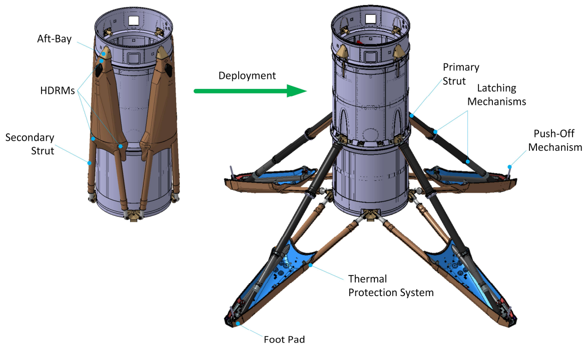

Fig. 2: Configuration change of the Approach and Landing System. Left: stowed configuration prior to deployment. Right: fully deployed configuration, ready for touchdown.

2.1 Landing Leg Deployment Subsystem

The deployment sequence begins with the activation of a solenoid valve connected to the GHe system, which pressurizes the ALS pneumatic subsystem. Once the Launch Lock Release Mechanisms (LLRM) are released, the leg kinematics unfold. Initially, the required actuation torque around the secondary strut hinge is provided by a push-off spring, moving the leg assemblies into a position where the pneumatic drive takes over. The ALS Controller coordinates this process by converting the deployment signal from the On-Board Computer (OBC) into electrical power for the actuators. The deployment sequence concludes when the motion is halted by mechanical end stops, and the telescoping segments latch in place. The specific components and equipment involved in this sequence are detailed in the following subsections.

2.1.1 ALS Controller:

The ALS Controller is an electrical interface box which receives a deployment command (digital logic signal) from the OBC. This signal is used to open the solenoid valve letting pressure from the GHe pressure vessel building up in the feed lines. After a due delay time, the signal is acting on solid state relays to close the electrical circuit to the Launch Lock Release Mechanisms (LLRM). The LLRMs open their individual circuit and consequently release their mechanical pre-load. Besides, the ALS Controller acts as a data acquisition equipment.

Copyright 2024 by Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR). Published by the IAF, with permission and released to the IAF to publish in all forms.

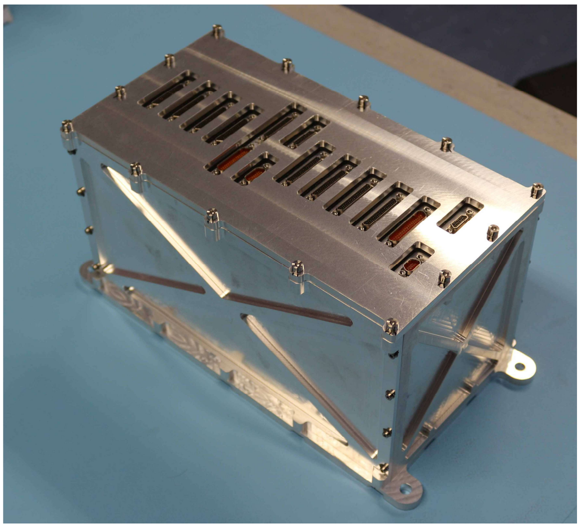

Fig. 3: Development Model of the ALS Controller

2.1.2 Launch Lock Release Mechanisms

The Launch Lock Release Mechanisms (LLRM) are commercial off-the-shelf components used to restrain the folded leg assembly against the aft-bay structure. Each leg assembly is locked by HDRMs against the aft-bay structure in stowed configuration.

2.1.3 Push-Off Mechanism

When the legs are stowed the pneumatic pressure acts vertical and has almost no lever to force the landing leg sideways. Therefore, a Push-Off mechanism is necessary to overcome the first phase of unfolding the legs. CALLISTO's Push-Off mechanism consists of a set of torsion springs located at the end of the footpad. Those springs are connected to a lever that presses itself against vehicle's central core. After releasing the HDRMs this lever pushes the secondary strut away until it loses contact to the rocket. At this point the pneumatic force becomes more effective.

2.1.4 Pneumatic Equipment

Unfolding the landing legs from a stowed to a deployed state is done by applying pneumatic pressure to the inner volume of the telescopic primary struts. The ALS pneumatic subsystem uses the GHe from the high-pressure vessel, as shown in Fig. 4. After the solenoid valve opens, the gas flows from the gas reservoir, through the solenoid valve into the landing legs, where it generates a positive delta pressure wrt. to ambient conditions. A pressure relief valve prevents the primary strut from overpressure and acts as safety feature. The solenoid valve is activated by electrical power coming from the ALS Controller. After latching, the passivation of the deployment system is conducted passively through design features allowing the pressurized gas to escape from the primary strut inner volume.

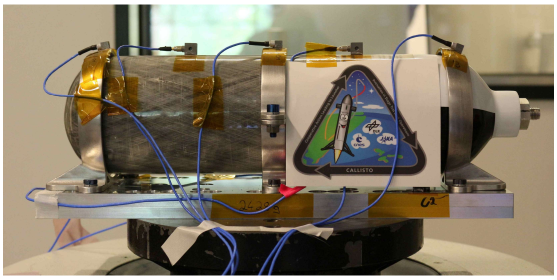

Fig. 4: ALS Pressure Vessel Assembly mounted on a shaker, ready for development tests.

3. Deployment Dynamics Study

The CALLISTO vehicle is designed for a broad variety of trajectories [4] with different energy levels, in which the deployment function is required to be performed. The definition and the purpose of the approach flight domain in which the deployment can occur is described in depth in [1]. For the study of the ALS deployment dynamics a simulator has been developed. The deployment simulator has the capability to predict the deployment dynamics, which is necessary for the verification of the deployment function.

3.1 Deployment Simulator Environment

The non-linearity of external load conditions makes the landing leg deployment a complex process. To evaluate the performance of the ALS during deployment and verify its design, a numerical simulator has been developed. In addition to modelling the leg's kinematics and kinetics, the simulator includes a detailed pneumatic model that calculates the pressure forces and tracks the feed-system pressure evolution throughout the transient deployment phase. It also accounts for segment-to-segment friction caused by the sliding of the primary strut. In addition to the internal force models, the external load environment is also integrated into the simulator. The approach flight domain provides the leg's kinetics model with acceleration data during deployment, while the CALLISTO vehicle's state is input into the aerodynamic database, as outlined in [1]. A simplified block diagram of the deployment simulator is illustrated in Fig. 5.

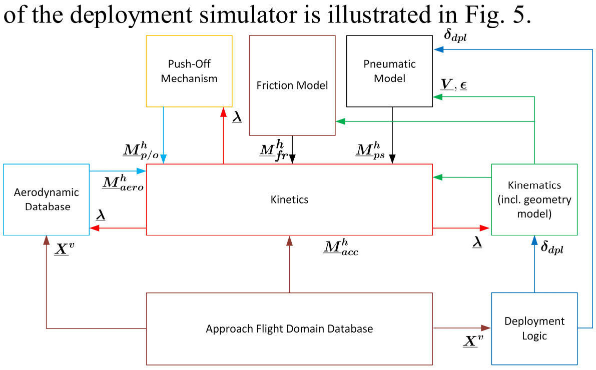

Fig. 5: Block diagram of the deployment simulator, with coloured blocks representing internal and external load models, and arrows indicating the data flow

Copyright 2024 by Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR). Published by the IAF, with permission and released to the IAF to publish in all forms.

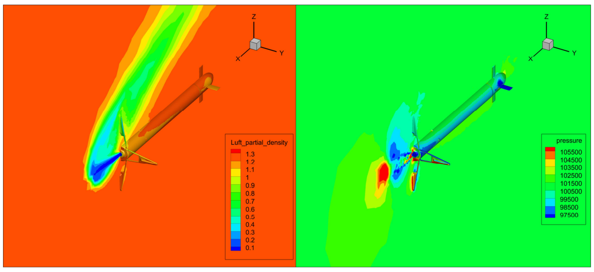

Fig. 6: Complex flow field around CALLISTO with a landing leg opening angle of 90°. Left: density field around CALLISTO. Right: pressure field around CALLISTO

3.2 Deployment Dynamic Key Influences

In addition to vehicle dynamics, the aerodynamic flow field around the landing legs significantly affects deployment dynamics. To accurately capture the impact of aerodynamics on the landing legs, an extensive aerodynamic database has been developed using the DLR TAU Code. The complex aerodynamics of CALLISTO has been analysed by Eckert et al. [6]. An example of the flow field during descent with deployed legs is shown in the Fig. 6. Here, the flow field is strongly non-linear, resulting in asymmetric external load conditions and subsequently leading to asymmetric deployment.

As investigated during a deployment simulation study [1], the deployment dynamics are influenced in a non-linear manner by both the product parameter and the external load conditions, which are mainly introduced by the approach flight domain definition and vehicle dynamics respectively.

It has been shown that an asymmetric flow field causes asymmetric external load environment and hence forces the leeward oriented leg to deploy faster and also subsequently create higher end-stop loads, than the other windward oriented legs.

On the internal parameters, the pressure and flow restrictor have to be adjusted correctly in order to ensure a safe engagement of the landing leg, without exceeding the interface force limits on the one hand, and not to deploy too slow so that the latching cannot be ensured.

This complex behaviour requires high fidelity simulation tools, that are capable to predict the interaction between CALLISTO vehicle and acting internal loads in the ALS structural components. Therefore, an excessive test campaign has been performed.

4. Deployment Development Tests

Development deployment tests have been performed to fulfil the following objectives

(1) to proof the functionality of the ALS deployment subsystem,
(2) to proof the capacity of pneumatic power and
(3) to gather test data for validation of the deployment simulator.

Parameter characterisation tests are prerequisite tests, that are used to improve the prediction quality of the deployment simulator. In this campaign pneumatic characterisation tests and structural response tests (simplified end-stop tests) have been performed. The actual deployment tests parameter varied from no counterweight to max. required counterweight. In Table 1 is a summary list of all performed tests.

The early engineering tests were conducted within the development phase of the ALS. In parallel to the development, numerical simulation tools were developed, that are capable to predict the deployment dynamics on the test stand. The deployment simulator was used to predict deployment dynamics on the test stand and to find product parameters, such as vessel pressure and orifice size, that lead to acceptable loading of the ALS product and adjacent structures. Based on the outcome of the physical tests and test predictions conclusions on the design have been made. The resulting design changes of the ALS load carrying parts are described in detail in [7].

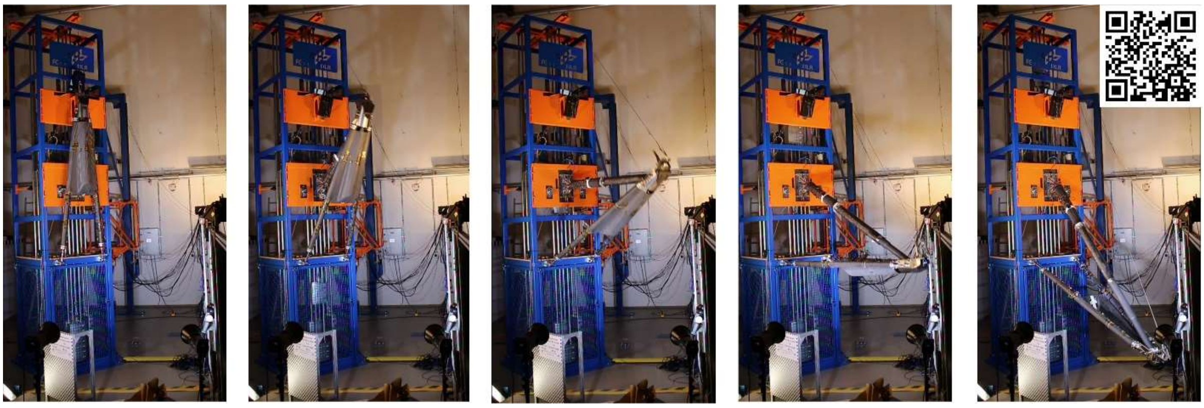

Fig. 7: ALS deployment sequence of the ALS attached to the Ensemble Test Stand in the LAMA. The left image depicts the stowed configuration, with the sequence progressing to the right, showing the stages of deployment. (0°, 25°, 45°, 90°, ~ 110°) Please scan the QR-code for a full deployment video (link to youtube.com).

Copyright 2024 by Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR). Published by the IAF, with permission and released to the IAF to publish in all forms.

Table 1: Summary of conducted tests during the deployment test campaign

Test	Number of tests
Parameter characterisation tests	4 (2x structural, 4 pneumatic)
Safety valve functional test	1
Deployment tests	14
Total number of tests	21

4.1 Test – set Up

Deployment tests under flight-like conditions are not feasible, as replicating the complex plume- leg interaction and overall load environment during the approach phase in a laboratory is either impractical or not economically viable. Achieving this would require a full-scale CALLISTO vehicle. To address this challenge, the Ensemble Test Stand (see Fig. 7) has been designed so that it is capable of replicating the amplitude of the actual external loads. The difference of inertia between test stand and actual ALS landing leg assembly requires to perform system-level deployment simulations.

The Ensemble Test Stand is designed to accommodate four ALS landing leg assemblies incl. pneumatic components, the ALS Controller and test instrumentation. The external load, which is a combination of aerodynamic forces and non-gravitational acceleration of the vehicle, is imitated by a counterweight, which is connected to the footpad via a steel cable. The tests were conducted in the Landing & Mobility Test Facility (LAMA) at DLR Bremen.

4.2 Test campaign

The general test approach began with defining the parameter set, which was an outcome of the deployment study conducted as part of [1]. Based on this, the test parameters—such as counterweight, vessel pressure, and orifice size—were established. Prior to testing, predictions were made to identify differences between the model and actual conditions. An exemplary deployment sequence is shown in Fig. 7. Between each test, the pressure was cautiously increased to ensure a successful deployment without overloading the landing leg and test stand. Starting from this parameter set, the counterweight and pressure were steadily increased in subsequent tests to verify functionality under high external and internal loads. Later test cases were characterized by high rotational velocities at the end-stop contact, resulting in full latching and high interface loads. Additional tests were conducted to assess whether deployment without internal pneumatic pressure is feasible. Several deployment tests were performed to ensure statistical significance. Among others, the opening angle and the vessel pressure have been monitored, as shown in Fig. 8.

The high reliability of the latching mechanisms was also demonstrated. In the event of end stop contact between the primary strut segments, each latching mechanism engaged and was prepared for load transfer during subsequent touchdown

4.3 Deployment Simulator results vs. Test campaign.

One major objective of the deployment test campaign is to gather measurement data in order to improve and to advance the validation of the ALS deployment simulator. Based on the test data, the simulation parameters, such as pneumatic restrictors and interface stiffnesses, have been adjusted, in order to achieve a good correlation between test data and simulation over the entire test range.

Comparing the opening angle and the pressure decay curve during deployment is one indicator of the correlation's quality, as shown in Fig. 8. This figure indicates an exemplary test case for a relatively fast deployment.

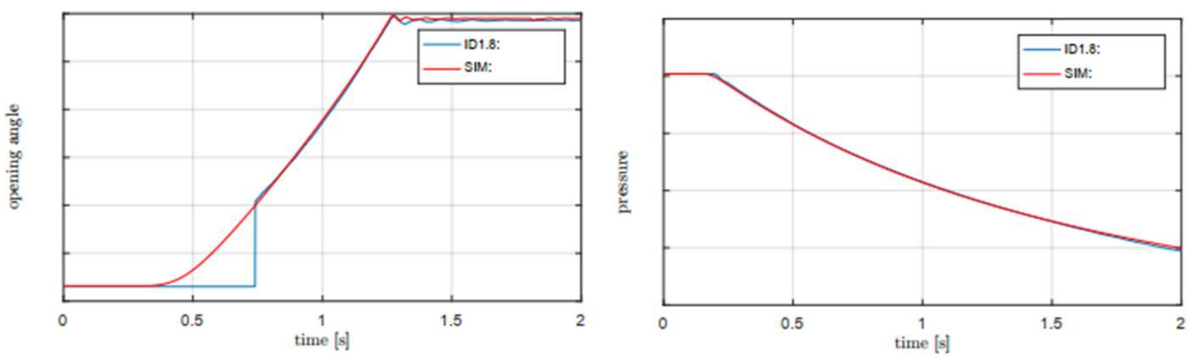

Fig. 8: Comparison of test results (blue curve) and simulation results (red curve) of the opening angle and pressure vessel decay curve. Both show good agreement. Please note that the bump at the beginning of the blue curve is traced back to sensor range limitations.

Copyright 2024 by Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR). Published by the IAF, with permission and released to the IAF to publish in all forms.

5. Summary & Discussion

The deployment test campaign yielded successful results, providing essential parameters for validating simulations and characterizing the interface load environment. These studies significantly enhance the understanding of the deployment dynamics of landing legs in dens atmosphere. While the simulations identified the key parameters for deployment, the tests validated the concept of the deployment subsystem, as well as the design and reliability of the latching mechanisms. Additionally, the test campaign provided insights into the handling and reset of the reusable landing leg. Based on these findings and the acquired knowledge, design improvements were implemented to ensure the reliability of the deployment function.

The ALS, especially the load-carrying structure and latching mechanisms, underwent thorough testing to demonstrate their reliability, ensuring secure locking of the primary strut during touchdown throughout the entire flight campaign. Additionally, this test campaign forms a key part of the overall life-cycle assessment strategy for the ALS landing leg, verifying the component's durability throughout its intended operational lifespan.

The deployment dynamic analysis reveals that the deployment dynamics depend not only on ALS parameters, such as vessel pressure, but also on the approach trajectory design. A significant factor contributing to interface loads and vehicle disturbance torque is an external asymmetric load environment, primarily caused by the interaction between the aerodynamic loads, the engine plume and the leg structure.

References

[1] 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

[2] Dumont, E., Ishimoto, S., Tatiossian, P., Klevanski, J., Reimann, B., Ecker, T., Witte, L., Riehmer, J., Sagliano, M., Vincenzino, S.G., Petkov, I., Rotärmel, W., Schwarz, R., Seelbinder, D., Markgraf, M., Sommer, J., Pfau, D., Martens, H.: Callisto: a demonstrator for reusable launcher key technologies. Trans. JSASS Aerospace Tech. Japan 19(1), 106–115 (2021).

[3] Dumont, E., Ishimoto, S., Illig, M., Sagliano, M., Solari, M., Ecker, T., Martens, H., Krummen, S., Desmariaux, J., Saito, Y., Ertl, M., Klevanski, J., Reimann, B., Woicke, S., Schwarz, R., Seelbinder, D., Markgraf, M., Riehmer, J., Braun, B., Aicher, M.: Callisto: towards reusability of a rocket stage: current status. In: 33rd ISTS Conference (2022). https://elib.dlr.de/185543/

[4] Krummen, S., Desmariaux, J., Saito, Y., Boldt, M., Briese, L.E., Cesco, N., Chavagnac, C., CLIQUET-MORENO, E., Dumont, E., Ecker, T., Eichel, S., Ertl, M., Giagkozoglou, S., Glaser, T., Grimm, C., Illig, M., Ishimoto, S., Klevanski, J., Lidon, N., Mierheim, O., Niccolai, J.-F., Reershemius, S., Reimann, B., Riehmer, J., Sagliano, M., Scheufler, H., Schneider, A., Schröder, S., Schwarz, R., Seelbinder, D., Stief, M., Windelberg, J., Woicke, S.: Towards a reusable first stage demonstrator: callisto-technical progresses and challenges. In: Proceedings of the International Astronautical Congress, IAC (2021). IAC-21-D2.6.1. https://elib.dlr.de/147143/

[5] Desmariaux, J., Cliquet-Moreno, E., Chavagnac, C., Dumont, E., Saito, Y.: Callisto: Its flight envelope and vehicle design. In: 8th European Conference for Aeronautics and Space Sciences (EUCASS), Madrid, Spain (2019). https://elib.dlr.de/133317/

[6] Ecker, T., Ertl, M., Klevanski, J. et al. Aerothermal characterization of the CALLISTO vehicle during descent. CEAS Space J (2024). https://doi.org/10.1007/s12567-024-00561-z

[7] Felix Krziwanie, Waldemar Rotärmel, Sofia Giag-kozoglou Vicenzino, Anton Schneider. Development of the Landing Leg Structure for CALLISTO. JESA 2024 . https://doi.org/10.57350/jesa.168

[8] Langer, S., Schwöppe, A., Kroll, N.: The DLR flow solver TAU—status and recent algorithmic developments. In: 52nd Aerospace Sciences Meeting (2014). https://elib.dlr.de/90979/