A TRADE OF STUDY FOR THE STRUCTURE OF THE CALLISTO VEHICLE EQUIPMENT BAY

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KEYWORDS

Launch Vehicle, VEB, Structural Analysis, Design, Trade of, Lay-out, AIT, MRO, Reusable

ABSTRACT

During the preliminary design of the Vehicle Equipment Bay (VEB), a section of the CALLISTO experimental launcher, three structural concepts emerged. This paper gives an insight into the trade of study, leading to a consolidated concept for detailed design.
The different concepts of accommodation are described. From a mechanical standpoint, structural analyses for strength, stability and stiffness are presented. The VEB is loaded by aerodynamic forces acting on the fins (the aerodynamic control system FCS/A), longitudinal loads from the Nose Fairing, acceleration loads on equipment unit's and ground load cases (handling for verticalization and lifting of the vehicle). Based on simplified assumptions, each concept is sized to obtain a feasible design. The resulting masses and amplifications are compared and used for the trade of study. Furthermore, the evaluation of the concepts from an Assembly, Integration and Test (AIT) point of view (demonstrate feasibility of mounting/dismounting of equipment's, access to screw connectors and equipment screws, accessibility, harness length, growth potential), from a Maintenance and Refurbishment Operations (MRO) standpoint (access to batteries, specific access to some critical items) and from a safety point of view (position and segregation of the safety chains) is presented. The results are sorted and compared in a trade of table.
The final design again is checked for feasibility and key performance values like mass and stiffness. An outlook is given on the impact of certain unit requirements like e.g. a horizontal integration.

1. INTRODUCTION

In order to make access to space more affordable for both scientific and commercial activities, the Japanese Aerospace Exploration Agency (JAXA), the French Space Agency (CNES) and the German Aerospace Center (DLR) are joining their forces in a trilateral demonstrator project 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 to be built and tested [1,2,3 and 4].
The VEB is a cylindrical section just below the Nose Fairing of the rocket (see [5]) that accommodates the avionic components, the aerodynamic surfaces flight control system, the reaction flight control system and the control of the flight neutralization system.
Several concepts were suggested in terms of structural architecture and accommodation of all the items inside the VEB Module. A trade of study has been done to consolidate these concepts and find the most promising concept in terms of:

- → Lay-out
- → Mechanical design,
- → Assembly, integration and testing
- → Access to several equipment units between two flights
- → Maintenance, refurbishment and operations
- → Safety

The paper starts with an overview of the test vehicle and the vehicle equipment bay. It then describes the different structural concepts to accommodate the units within the VEB, followed by the criteria and constraints to rate the different concepts.

The structural concepts are described and sized to fulfil the structural requirements. Finally, the concepts are compared and rated towards the requirements and a final merge of results is done to combine the beneficial features.

2. OVERVIEW OF THE CALLISTO LAUNCHER AND THE VEHICLE EQUIPMENT BAY (VEB)

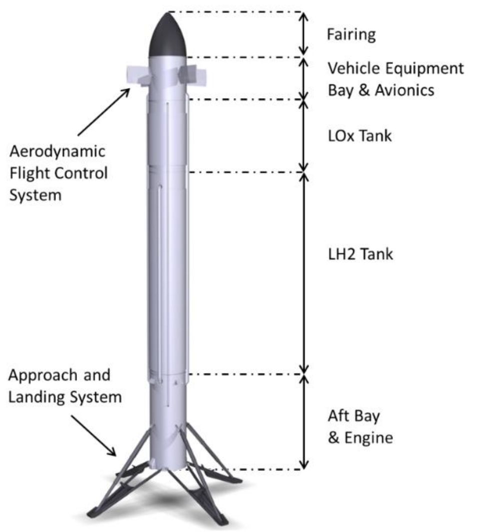

Figure 1: Vehicle Overview

CALLISTO is an about 13 m high and 3.8 tons heavy vehicle running on LOx and LH2. It is being designed to fly 10 times from the European Spaceport in Kourou.

The VEB situated in the upper part of CALLISTO contains most avionic units and in particular the on-board computer and the hybrid navigation system. In addition, it hosts four fins that aerodynamically control and stabilize CALLISTO during descent and landing as well as the reaction control system (FCS/R) for further control, when the fins are not operated.

The VEB cylindrical structure is roughly 1.2m high and 1.1m in diameter. It can be seen in three major sections. The top is holding the reaction control system with a central fuel tank. Below is the interface to the fins which is strengthened by a structure called the “inertia box”. This section consists of two big frames connected to each other. Below the inertia box is a third section dedicated to additional equipment units.

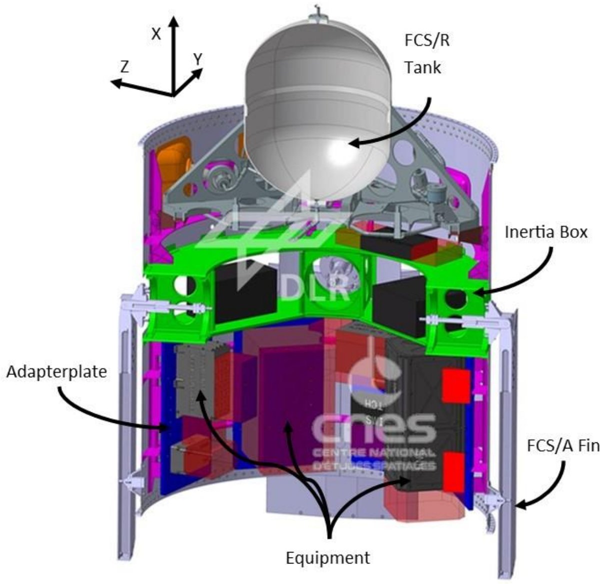

Figure 2: Vehicle Equipment Bay (VEB) overview

3. OVERVIEW OF THE SCOPE OF THE TRADE OF STUDY

3.1. Description of Accommodational Concepts

Three concepts are compared. For better differentiation the concepts are numbered from 1 to 3

1 2 3

Figure 3: Concept Overview

The main difference of the concepts is the accommodation of the units. The position of the aerodynamic fins and the reaction system is the same for all concepts. This includes that the inertia box as support of the fins is geometrically similar across the concepts. The structural material is set to be aluminium.

3.1.1. Concept 1

In the first concept the units are distributed on the inertia box frames and on an additional frame at the very bottom of the VEB. Concept 1 does not rely on stringers to attach the equipment, but can have stringers and additional frames if structurally needed.

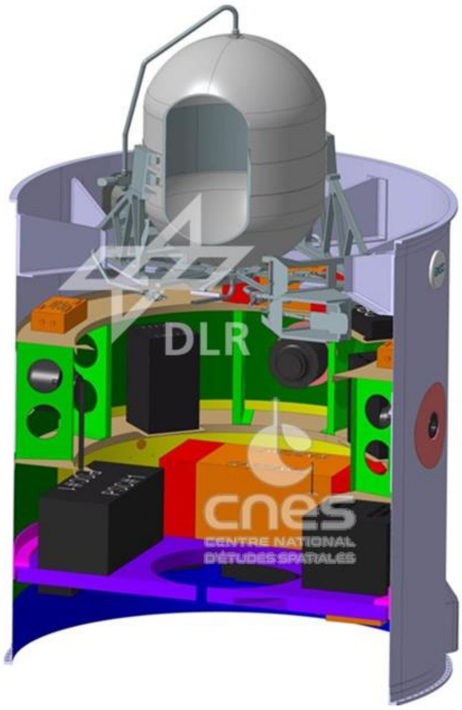

Figure 4: Layout of Concept 1

3.1.2. Concept 2

The second concept is based on equipment adapter plates for the units. These plates are attached to the stringers and frames. The frames and stringers stiffen the cylinder skin and thus prevent buckling while at the same time provide strong support in all axis to the units. 8 adapter plates are positioned in the lower region of the VEB and 6 above the inertia box. The upper adapter plates are supported by the inertia box and one additional frame. Note that the purest depiction of concept 2 in Figure 5 is the FE-Model. The CAD model depicted is a working state of concept 2 and has also units attached to the inertia box.

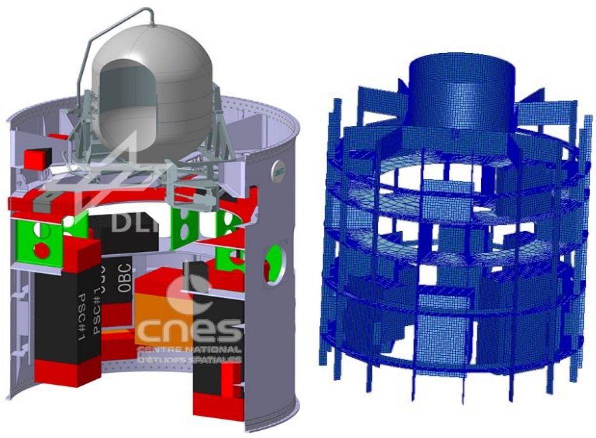

Figure 5: Layout of Concept 2

3.1.3. Concept 3

The third concept is quite similar to the first one but has a double decker platform in the lower part of the VEB to support the units. Like the first concept it does not rely on stringers for equipment support but can have stringers and additional frames if structurally needed. The concept provides a lot of room to accommodate the different units. Equipment is placed on and below the two platforms and on the walls in between. Some equipment is also placed on the inertia box.

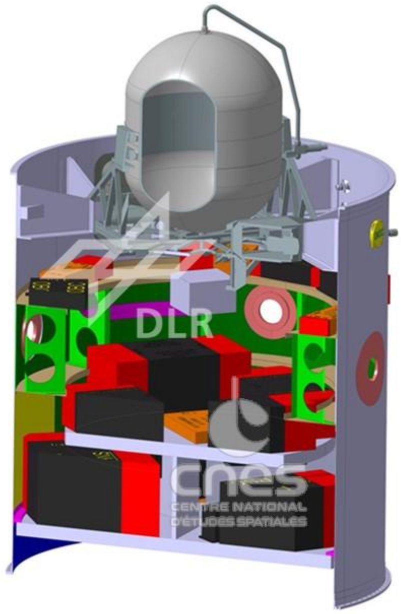

Figure 6: Layout of Concept 3

3.2. Criteria to Rate the Concepts

3.2.1. Loads considered for the study

Some representative load cases from the actual requirement specifications [7] are used for the study. The loads are (due to confidentiality reasons no specific values can be given):

- → A compression load around the circumference of the cylinder.
- → Fin loads, primarily acting at two opposing fins and introducing a global torsion as well as local bending moments, mainly in longitudinal direction.
- → Inertial accelerations in longitudinal and in transversal directions.

A minimal Eigenfrequency had to be reached for most of the equipment units.

For all concepts a few design features are kept similar. Those are the FCS/R system, and the support of the FCS/A system. For the FCS/R system a hash like structure is roughly simulated.

- → The supports of the FCS/A system are simulated as two main frames with dedicated stiffening. These are also used for the support of units in concept 1 and 3. To reduce the number of variables the FCS/A support is kept similar for the concepts.
- → No cut outs for mass reduction are considered. This is similar for all versions. Significant mass

reductions can be expected for concept 2 and 3, slightly smaller ones for version 1

- Inserts and bolts are not considered. Especially inserts have a significant impact on the mass. The number of inserts for unit integration is (nearly) the same for all concepts. The only big difference between the concepts comes in place, if a bigger core thickness increases the insert dimension.
- Cut-outs in the cylinder are not considered
- A minimum first Eigen frequency is considered. Higher natural frequencies required for some system are not considered for the different concepts.
- Safety factors are not considered. This has no impact for the stress design as stress is not a driving factor.
- Buckling is considered with a safety factor of one. Cylinder Buckling is considered by use of the NASA SP8007 which leads to a knock down factor of roughly 3. Linear buckling involving the cylinder is considering an Eigen value of 3.

3.2.2. Mass restrictions

As is common in early design phase mass budgets are allocated to the different subsystems. Thus, the VEB structure has a mass restriction.

3.2.3. Accessibility for assembly, integration, maintenance and operation

As for all spacecraft, it needs to be checked that the design chosen can be manufactured and integrated, preferably with ease. But since the CALLISTO test stage is foreseen for several flights there are additional needs to access some equipment units in between flights. Examples are the batteries, the flight neutralization system and different versions of the onboard computer. Certain areas are easier to reach than others. The section above the inertia box can only be maintained before the reaction system is installed. A maintenance through the pipes and other systems is not feasible.
In the following the accessibility to the equipment units in the lower part of the VEB is described.
Concept 1:
The access for assembly is provided by the hole in the centre of the additional frames. The concept is able to accommodate all equipment including the harness. The adapter can be preassembled and then integrated in the VEB.
Concept 2:
There is a good access to the equipment units from the bottom of the VEB. The challenge is to handle all equipment during integration. For this, the VEB must be positioned horizontally and turned so that each equipment can be installed on a horizontal surface, i.e. on the lower internal side of the VEB.
Concept 3:
For accommodation reasons the double stacked platform in the lower part of the VEB has to be removable. It can be joint to the VEB after its preassembly with corresponding units. This allows a very easy integration before the equipment adapter is installed in the cylinder. After installation, direct access to equipment is no longer possible without dismounting the whole adapter.

4. DESCRIPTION OF STRUCTURAL CONCEPTS

In the scope of this study the main loads are introduced at the top of the VEB and at the fin interfaces inside the inertia box. In addition, the acceleration loads from the equipment units have to be considered.
The bearing is at the bottom of the VEB. This leads to several areas of interest.
The cylinder of the VEB is the main load path. The cylinder is a thin structure, which thus is prone to buckling and strength failure. It also influences the natural frequencies of the entire VEB.

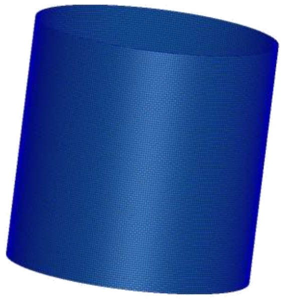

Figure 7: cylinder

The inertia box is loaded by the fins. In concept 1 and 3 the inertia box is also used as support for units. The fin loads are introduced into a box shaped structure. Vertical loads are taken by the sidewalls of these boxes and horizontal loads are taken by the frames.

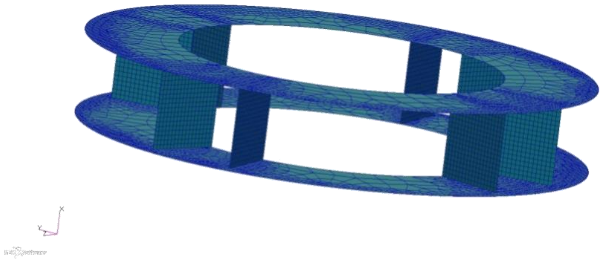

Figure 8: inertia box

The unit adapter concepts are the most diverse parts in between the concepts. In concept 1 the adapter is a round plate near the bottom of the VEB. In the middle, there is a round cut-out for harness routing. The equipment adapter of concept 1 has its challenges in the bending stiffness and thus the required minimal eigenfrequency.

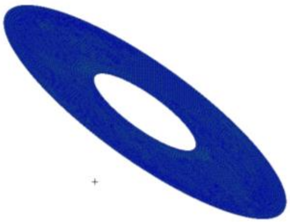

Figure 9: equipment adapter concept 1

Concept 2 has 8 adapter plates positioned around the lower part of the VEB and 6 positioned above the inertia box. All adapters are connected to two stringers and either two frames in case of the lower adapters or a frame and the inertia box in case of the upper adapters.

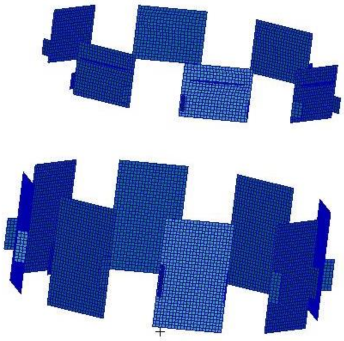

Figure 10: equipment adapter concept 2

Concept 3 has a double decker equipment adapter. The two stages are connected by three vertical walls that are positioned in angles of 120° and are connected to each other in the middle. The vertical walls provide a lot of stiffness against bending to the equipment adapter. The upper deck of the adapter is lacking torsional stiffness though.

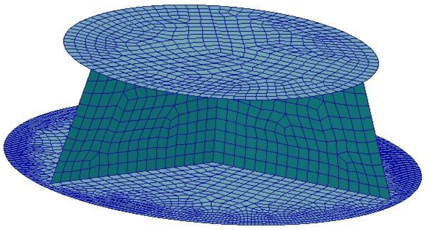

Figure 11: equipment adapter concept 3

Stringers and frames can be considered. As written before they are mandatory for concept 2.

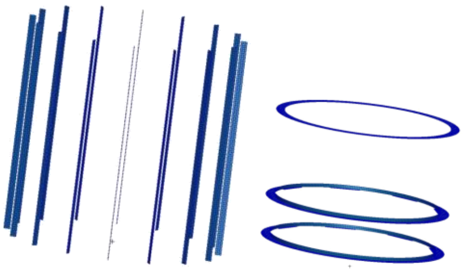

Figure 12: stringers and frames

5. SIZING OF STRUCTURAL CONCEPTS

The models to size the different concepts with the goal of comparison is kept to a low level of detail. The focus is on the comparability between the different concepts. Also, not all equipment is modelled but smaller units are combined to bigger boxes representing the mass of the units.

The sizing is done for the following parts.

- The cylinder
- The inertia box divided into
  - Upper sandwich panel
  - Lower sandwich panel
  - Side walls
- Stringers
- Frames
- Equipment adapters
  - Concept 1:
    - Core thickness
    - Facesheet thickness
  - Concept 2:
    - Core thickness
    - Facesheet thickness
    - Connecting clips to frames and stringers
  - Concept 3: the core thickness and the facesheet thickness are sized for:
    - The lower plate
    - The three vertical walls
    - The upper plate

The sizing is done by manually changing the parameters in an iterative process. This is done because not only the final sized result is of interest but also the effects the structural elements have on one another.

6. COMPARISON OF CONCEPTS

6.1. Concept Evaluation Regarding accommodation, Maintenance, refurbishments and operation criterias

Concept 1 has sufficient space to allow for the installation of all equipment units.
At a first step all equipment in the inertia box needs to be installed, except for batteries that need a late access and therefore will have inspection covers in the outer cylinder.
The equipment placed on the lower equipment plate is preinstalled before the equipment plate is installed in the VEB. Once the equipment plate is in the VEB only the units at the bottom of the plate are still accessible.
In summary the concept 1 has sufficient space for unit allocation however, there was still a problem with the excess length of the harness when installing the equipment plate.

Concept 2 has bigger challenges in accommodation because the adapters are smaller, even though there are more of them. This gives less opportunities to arrange the equipment. There are options that allow the accommodation but it is difficult taking all electrical interfaces and additional space for integration into account.

The integration is more accessible but requires a mechanical ground support equipment (MGSE) that is able to hold the VEB on the side and rotate it for each equipment adapter to be on the lower side while the equipment is being installed.
In summary the concept 2 has more challenges but is possible with close attention.

Concept 3 has lots of available space for equipment integration. Like in concept 1 the double decker stack has to be pre-integrated before installation into the VEB. After the final integration, only the units below the lower frame are accessible however, like in concept 1, there was still a problem with the excess length of the harness when installing the equipment plate.

6.2. Structural concept evaluation

6.2.1. Model description

The finite element model is built and evaluated with MSC Patran, the model analyses is done with MSC Nastran. The model consists of one- and two-dimensional elements. Only the fin actuators are modelled by 1d beam elements.

6.2.2. Sizing load cases for structural parts

Cylinder

The dimensioning load case for the cylinder is the compression load case in combination with the fin load case. Therefore, the skin of the cylinder is put under compression and shear stresses. The dimensioning failure mode is skin buckling.
A pre-study is done for the cylinder. It includes the cylinder, the inertia box and frames and stringers in different variants. The inertia box, and a frame at the lower end of the VEB are not varied as they are needed in all concepts. The mass is evaluated for the cylinder including frames and stiffeners, but excluding the inertia box.
The starting point is a cylinder with just 1mm thickness. Considering no stringers and additional frames a buckling factor of 1.3 is reached (Figure 13). Note that the buckling factor is highly depending on the distance between the inertia box and the next lower frame (Figure 13 shows the geometrical positions of the stringers but they are not considered in the calculation). The mass of the cylinder with a thickness of 1.0mm together with the lower frame is 12.2kg.

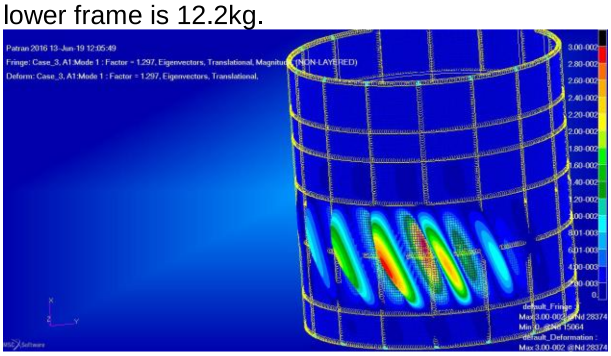

Figure 13: buckling of a cylinder without stiffener, skin thickness of 1.0mm

The skin needs to be thickened to 1.6mm to reach a buckling factor of three. The mass raises to 18.4kg.

Considering the cylinder of 1mm, 16 stringers and an additional frame to lower the buckling size a buckling factor of 2.2 is reached (Figure 14). The stringers and frames are dimensioned to prevent any global buckling (buckling of the skin-stringer-frame combination). That means the buckling is reduced to just skin buckling in between the stringers and frames. The mass is raised to 20.9kg.

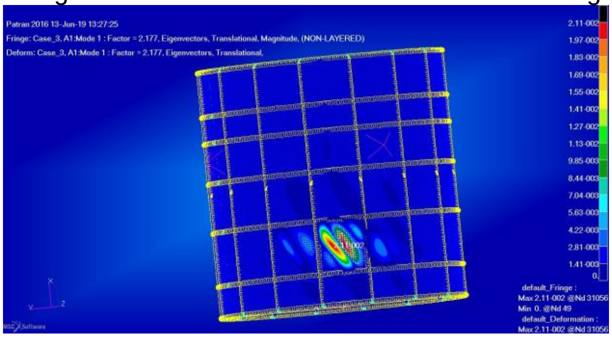

Figure 14: buckling of a cylinder with 16 stiffeners, one additional frame and a skin thickness of 1.0mm

In the next step the skin thickness is increased and the stringer cross-section decreased until a buckling factor of 3 is reached and global buckling is prevented. The result is a skin thickness of 1.2mm. Including the stringers and frames the mass is 17.5kg.

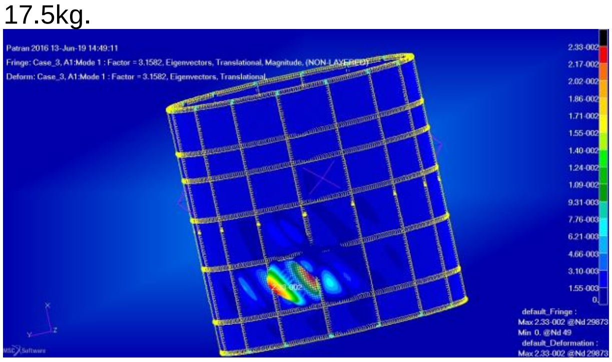

Figure 15: buckling of a cylinder with 16 stiffeners, one additional frame and a skin thickness of 1.2mm

This cylinder is used for all three concepts in the comparison. Even though concept 1 and 3 are actually planned to have no stringers the cylinder sizing has shown that all concepts require a cylinder stiffening. Considering concept 1 and 3 without stringers the total mass turned out to be uncompetitive.

Equipment Adapters

The sizing of the equipment adapters is naturally the most diverse between the three concepts. The equipment adapters are sized by the natural frequency requirement.
Concept 1

The equipment adapter in concept 1 is a simple aluminium sandwich plate. Dimensioned to fit the required Eigenfrequency the sandwich core has a thickness of 50mm and the facesheets have thickness of 2.8mm. That leads to a mass of the equipment adapter of 10.5kg. The given equipment adapter leads to a first natural frequency of 62.5Hz with a bending mode of the equipment plate.

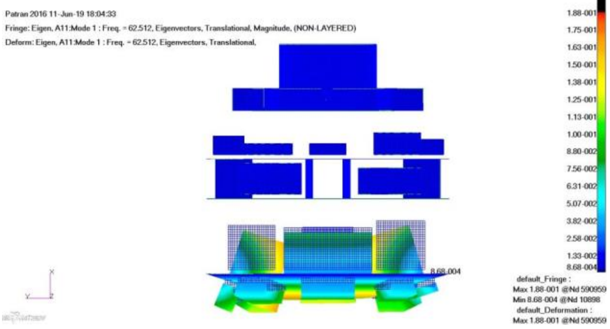

Figure 16: first natural mode of concept 1

Concept 2

The 8 equipment plates in the lower section and the 6 equipment plates in the upper section are aluminium sandwich plates as well. Unlike in concept 1 the thickness of the core is just 10mm and the facesheet thickness of 1mm. The first mode at 61.1Hz is a sideways movement of one of the adapters in the lower section. Also, the first mode of the FCSR system is close by, as can be seen by the deformation of the stringers at the very top. The total mass of the adapter plates is 6.3kg.

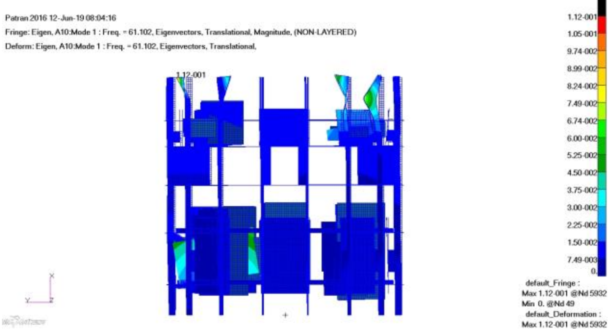

Figure 17: first natural mode of concept 2

Concept 3

In concept 3 the equipment adapter is also made from aluminium sandwich. The lower plate has a core thickness of 50mm and facesheet thickness of 1.5mm. The vertical walls and the upper plate have a core thickness of 40mm and facesheet thickness of 1.5mm.

The first mode is a rotation of the upper wall on the vertical wall with a slight tilting from one side to the other.

The mass of the equipment adapter is 14.2kg.

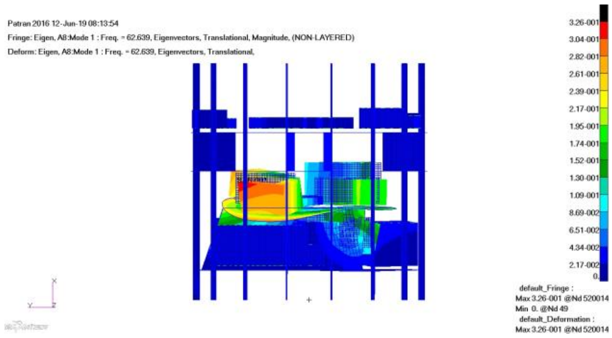

Figure 18: first natural mode of concept 2

Inertia box:

The inertia is dimensioned by the buckling of the inertia box itself, strength criteria and the stiffness if units are attached. The attached units in concept 3 are no driving factor. In concept 1 the inertia box had to be reinforced to match the eigenfrequency criteria.

Table 1: Concept Masses

Region [kg]	Concept 1	Concept 2	Concept 3
Cylinder	12,1	12,1	12,1
Stringers	2,3	2,3	2,3
Inertia box	10,0	7,85	7,89
Frames	2,5	3,4	2,5
Equipment Adapters	10,5	6,27	14,16
Total Mass	**37,4**	**31,9**	**38,9**
Total Mass 20% margin	**44,9**	**38,3**	**46,7**

7. DYNAMIC RESPONSE OF THE CONCEPTS

A frequency response calculation (sol111 [6]) is done with the input at the base of the VEB and the reaction at different locations of equipment attachments. The calculations consider a critical damping of 2.5%.

A required boundary of acceleration is shown in the graph that should not be crossed by the amplified acceleration of the units. Input and boundaries are normalized to an input of 1g.

The following graphs are depicted with one equipment unit in the lower part of the VEB and one for the upper part. The equipment with the highest acceleration is chosen.

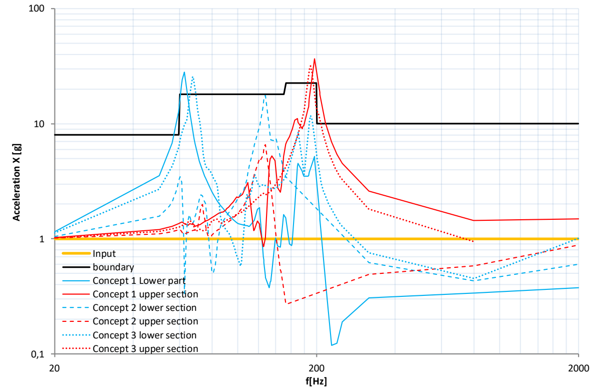

Figure 19: dynamic response in axial direction (X). All results are normalized to an input of 1g

In the axial direction concept 1 und 3 have responses above the required boundary. The reason for that is the bigger flexible plane in the lower equipment adapters and the bending deformation of the inertia box sandwich. The equipment adapters in concept 2 amplify the input much less.

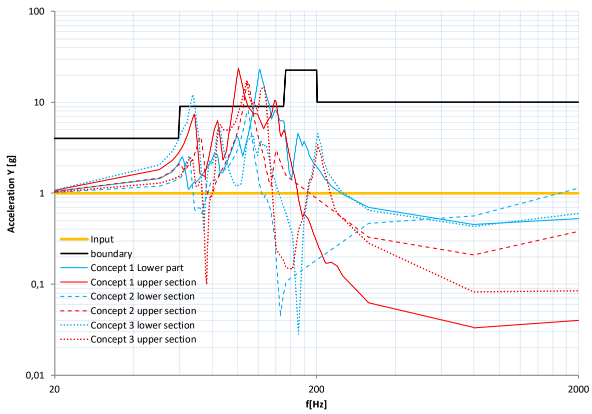

Figure 20: dynamic response in sideways direction (Y). All results are normalized to an input of 1g

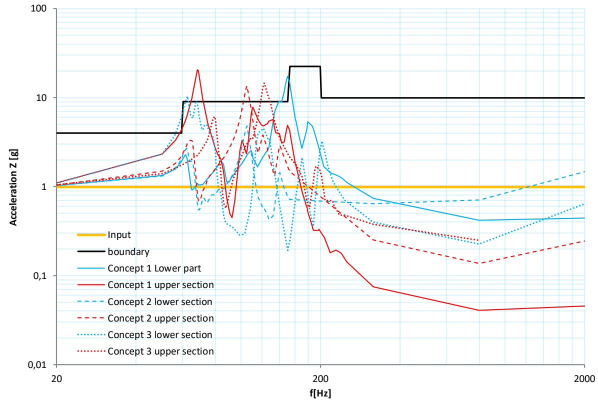

Figure 21: dynamic response in sideways direction (Z). All results are normalized to an input of 1g

In the sideways direction (Y and Z) all concepts exceed the required boundary in the upper part of the VEB. This is independent from the equipment installation concept but caused by the movement of the VEB as a whole. In the lower part the equipment adapters of concept 1 and 3 exceed the required amplification, only concept 2 stays within the boundaries.

8. CONCEPT RATING MATRIX

Following the rating matrix of the trade-off is shown. The table includes the ranking of several parameters with respect to the previous described structural analysis represented by the mass as well as several aspects of MRO (Maintenance, Repair, Operation) and AIT (Assembly, Integration, Testing) aspects. The presented Tab. 2 is just a synopsis of a much larger evaluation form that would go beyond the scope of the paper. As can be seen in the total sum of the rating the concept 2 leads with -11 points 2 points before concept 1 and 11 points before concept 3. The major impact on the poor ranking of concept 3 was the lack of MRO accessibility as well as the higher structural mass. In comparison to concept 2, concept 1 has a higher mass and less accessibility to harness and equipment in the lower and bottom part of the VEB.

Table 2: Trade-Off Synthesis

MECHANICAL	**Concept 1**	**Concept 2**	**Concept 3**
Mass of the structure fulfilment	-2	-1	-3
Support main frequency fulfilment & mass impact	-2	-1	-2
Acceleration level at equipment interface fulfilment	-2	-1	-2
ASSEMBLY INTEGRATION TEST			
AIT	-1	-2	-2
Maintenance, Refurbishment, Operation			
Specific accessibility to equipment's after LOX tank and Fairing disassembly	0	0	-2
Adaptability to the mission	0	0	-2
Accessibility for healthiness check (Bottom part of the VEB)	-1	0	-2
Accessibility for healthiness check (Middle part of the VEB)	-1	0	-1

Additional equipment accommodation	-1	-2	-3
Mounting / Dismounting the FCS/A by the inside	-1	-2	-1
Fulfilment of handling bracket interface	-1	-1	0
SAFETY			
Safety chains farthest from FCS/R	-1	-1	-2
Access to the batteries at VPH to plug / unplug them	0	0	-1
TOTAL	**-13**	**-11**	**-23**

9. MERGING OF RESULTS FOR FINAL CONCEPT

All the previous concepts have their issues, being it for mass, stiffness, accessibility or available space. So, the final step after the trade-off is to merge the advantages of each concept. In the lower part of the VEB the concept 2 showed the best performance in terms of mass, stiffness and amplification. But the available space for accommodation is limited. Concept 1 and 3 use also the inertia box for accommodation of units. Up to a certain mass and size of equipment this proved to not influence the structural mass too much.
Therefore, a final configuration was evaluated that used the equipment adapters of concept 2 in the lower part of the VEB and the inertia box to accommodate units in the upper part of the VEB (Figure 2).

10. CONCLUSION

The presented study sized and rated different concepts for the VEB of the CALLISTO stage toss back experiment. The concepts suggested different layouts and structural concepts for equipment accommodation. Two concepts suggested dedicated equipment platforms in the middle of the cylinder while one suggested several equipment adapters attached to the structural reinforcements of the cylinder skin. The cylinder mass of the VEB is barely influenced by the concepts as the lowest mass is found with stringers and stiffeners anyway. While the dedicated platforms make it easier to find suitable accommodation layouts they are significantly heavier and tend to create common dynamic modes in between units. Based on the pros and cons, a mixed concept was created that combines the advantages of the different concepts.

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Etienne Dumont – DLR Project Lead
Sven Krummen – DLR System Engineer
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