DESIGN OPTIMISATION AND MASS SAVING OF THE STRUCTURE OF THE ORION-MPCV EUROPEAN SERVICE MODULE

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Abstract

This paper presents an overview of the design optimisation measures that have been proposed and analysed in order to reduce the mass of the structure, including the MMOD (Micro-Meteoroid and Orbital Debris) protection system, of the ESM (European Service Module) for the “Orion” MPCV (Multi-Purpose Crew Vehicle).

Under an agreement between NASA and ESA, the NASA Orion MPCV for human space exploration missions will be powered by a European Service Module, based on the design and experience of the ATV (Automated Transfer Vehicle).

The development and qualification of the European Service Module is managed and implemented by ESA. The ESM prime contractor and system design responsible is Airbus Defence and Space. Thales Alenia Space Italia is responsible for the design and integration of the ESM Structure and MMOD protection system in addition to the Thermal Control System and the Consumable Storage System.

The Orion Multi-Purpose Crew Vehicle is a pressurized, crewed spacecraft that transports up to four crew members from the Earth’s surface to a nearby destination or staging point. Orion then brings the crew members safely back to the Earth’s surface at the end of the mission. Orion provides all services necessary to support the crew members while on-board for short duration missions (up to 21 days) or until they are transferred to another orbiting habitat. The ESM supports the crew module from launch through separation prior to re-entry by providing: in-space propulsion capability for orbital transfer, attitude control, and high altitude ascent aborts; water and oxygen/nitrogen needed for a habitable environment; and electrical power generation. In addition, it maintains the temperature of the vehicle's systems and components and offers space for unpressurized cargo and scientific payloads. The ESM has been designed for the first 2 Lunar orbit missions, EM-1 (Exploration mission 1) is an un-crewed flight planned around mid-2020, and EM-2, the first crewed flight, is planned in 2022.

At the time where the first ESM is about to be weighted, the predicted mass lies slightly above the initial requirement. For future builds, mass reduction of the Service Module has been considered necessary. This is being investigated, together with other design improvements, in order to consolidate the ESM design and increase possible future missions beyond the first two Orion MPCV missions. The mass saving study has introduced new optimised structural concepts, optimisation of the MMOD protection shields, and optimised redesign of parts for manufacturing through AM (Additive Manufacturing).

Keywords: Orion-MPCV, Structure, Mass-saving, Additive Manufacturing

Acronyms/Abbreviations
AM = Additive Manufacturing
ATV = Automated Transfer Vehicle
AUX = Auxiliary Thrusters
BEE = Best Engineering Estimation
CAD = Computer Aided Design
CFRP = Carbon Fiber Reinforced Polymer
CM = Crew Module
CMA = Crew Module Adapter
CSS = Consumables Storage System

EM = Exploration Mission
ESM = European Service Module
FAA = Federal Aviation Administration
FEM = Finite Element Method
FM = Flight Model
HDRS = Hold Down and Release Support
HTP = High Temperature Thermal Protection
HVI = Hyper-Velocity Impact
LAS = Launch Abort System
LOC = Loss of Crew
LOM = Loss of Mission
MLI = Multi-Layer Insulation
MDPS = MMOD Protection System
MMOD = Micro-Meteoroids and Orbital Debris
MPCV = Multi-Purpose Crew Vehicle
OEM = Original Equipment Manufacturer
OMS-E = Orbital Manoeuvring System Engine
PSS = Propulsion Sub-System
PSR = Pre-Shipment Review
PWR = Power subsystem
RAMS = Reliability, Availability, Maintainability, Safety
RCS = Reaction Control System
RPD = Rapid Plasma Deposition
SADE = Solar Array Drive Electronics
SADM = Solar Array Drive Mechanisms
SAJ = Spacecraft Adaptor Jettison
SAW = Solar Array Wing
SAHDRS = Solar Array Hold-down and Release Mechanism Support
SLS = Space Launch System
STA = Structural Test Article
TCS = Thermal Control System
T/O = Threat / Opportunity
UPC = Unpressurized Cargo

1. Introduction

The “Orion” MPCV is a spacecraft intended to carry a crew of astronauts to destinations at or beyond low Earth orbit. Orion is currently under development by NASA, with prime contractor Lockheed Martin Co., for launch on the SLS (Space Launch System). The development and qualification of the ESM is managed and implemented by ESA. The ESM prime contractor and system design responsible is Airbus Defence and Space. Thales Alenia Space Italia is responsible for the design and integration of the ESM Structure and MDPS (Micro-Meteoroids and Orbital Debris Protection System) in addition to the Thermal Control System and the Consumable Storage System.

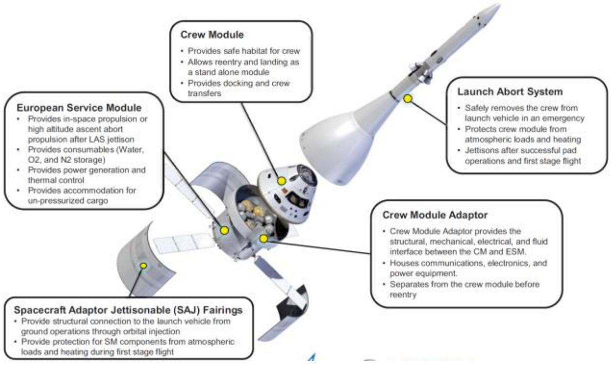

Fig. 1: The Orion MPCV spacecraft.

The ESM has been designed for the first 2 Orion MPCV lunar missions. EM-1 (Exploration mission 1) is an un-crewed flight planned around mid-2020, and EM-2 (Exploration Mission 2) is the first crewed flight planned in 2022.

Besides a first batch of mass saving opportunities implemented on FM-02, a further reduction of the mass of the Service Module has been considered necessary. This is being investigated together with many other improvements in order to consolidate the ESM design and make possible future different missions from the third flight model onwards. Therefore, an additional mass saving exercise has been conducted for all the ESM’s systems. This paper focuses on the structure, which is one of the major contributors to the dry mass of the spacecraft. The structure mass reduction study focused on the possibility to introduce new optimised structural concepts, updated MMOD protection shields, and redesign of parts for manufacturing through Additive Manufacturing technologies.

2. The European Service Module

The ESM is the service module component of the Orion spacecraft, serving as its primary power and propulsion component until it is discarded at the end of each mission. The service module supports the crew module (Fig. 2) from launch through separation prior to re-entry. It provides in-space propulsion capability for orbital transfer, attitude control, and high altitude ascent aborts. It provides the water and the gaseous oxygen/nitrogen needed for life support, generates electrical power, and maintains temperature in the acceptable working range for the vehicle's systems and components. The ESM can also transport small unpressurized cargo (UPC) and scientific payloads.

Fig. 2: The Crew Module

3. ESM Mechanical Architecture

The European Service Module connects the SLS launcher, through a conical Spacecraft Adapter (SA), to the Crew Module Adapter (CMA), the Crew Module (CM) and the Launch Abort System (LAS) (Fig. 3).

Fig. 3: Engineering model of the Orion stack (from bottom-up): SA / ESM / CMA/ CM

The ESM structure provides structural rigidity to the Orion spacecraft, absorbs the vibrations and the acoustic pressure generated during launch, and protects the spacecraft from micro-meteoroids and space debris. The service module's secondary structure supports elements such as the spacecraft's thrusters, the gas tanks, the water tanks, the propulsion lines and valves, etc. The service module internal volume is protected by a multilayer material that absorbs impacts from tiny, high-speed objects in space, micro-meteoroids and orbital debris (MMOD). Any MMOD that strikes the shield breaks into fragments on impact with the outer metallic structure, and then the inner multilayer stops anything from penetrating the vessel and its mission-critical hardware.

3.1 Primary and Secondary Structure

The primary structure of the ESM is composed of various structural parts. The main elements are:

- Six Longerons, each machined in a single aluminium alloy plate, which transmit loads from the launcher to the CMA. The longerons are the main contributors in the primary load path.
- The Tanks Bulkhead (or tanks platform), composed of two machined aluminium alloy parts, assembled together with riveted junction.
- The Lower Platform Assembly, made also of two machined aluminium alloy parts and assembled together with riveted junction.
- The Web Assembly, composed of ten sandwich panels with carbon-epoxy skins and aluminium honeycomb core, assembled together and attached to the two platforms through metallic corners (cleats) bolted to the web panels.
- The Central Core of ESM (tank platform + web assembly + lower platform) accommodates all equipment (tanks, radiators, solar arrays, etc.) and stiffens the longeron assembly in lateral directions for stability. Central core and longerons are free of movement in longitudinal axis through series of “spherical bearing” joints, so that all the main loads pass from the CMA through the tank platform and then split between SAJ panels and the longerons.

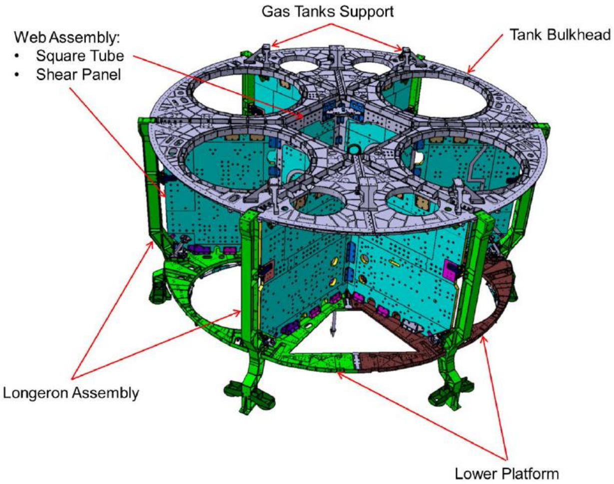

Fig. 4: ESM primary structure.

The secondary structure of the ESM is composed of all the structures needed to accommodate and support the main engine, the auxiliary thrusters, tanks, radiators, avionics equipment, RCS thruster pods, solar arrays, and the micro-meteoroids and Debris Protection System (Fig.5).

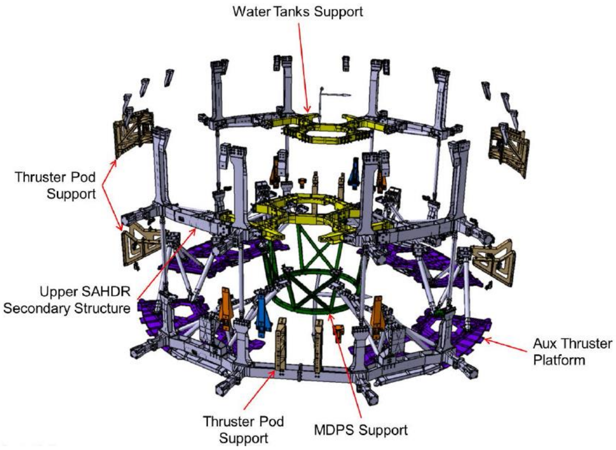

Fig. 5: ESM secondary structures.

3.2 Micro-meteoroids and Debris Protection System

The MDPS of the ESM is designed in order to maximise the protection capability of already existing structures. Indeed, for instance, around the ESM circumference, the radiator panels are used as 1st wall (bumper) to protect against MMOD impacts. Specific MMOD protection structures are implemented to protect any other area (in particular the "tank assembly" and the "spider web" assembly), on the rear of the ESM.

The MDPS architecture generally includes a double wall protection concept (Fig. 6):

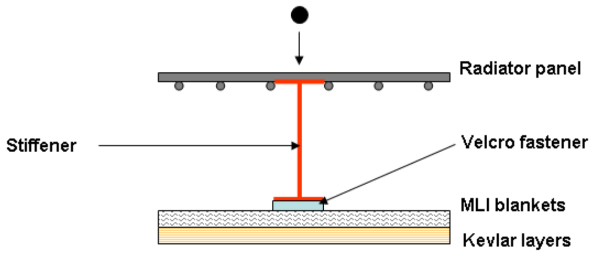

Fig. 6: Typical MDPS architecture on ESM

The 1st wall is made by a metallic bumper plate (it can be one radiator panel, or an existing structure, or a dedicated MDPS panel). The 2nd wall consists of another structural item not sensitive to the impact of MMOD, or of a specifically added stack of Kevlar fabrics and MLI. External hardware elements (i.e. RCS thruster pods, SADM, etc.) have their own MMOD protections.

The design of the MMOD protections differs depending on where it is installed by adjusting the amount of Kevlar layers, the length of the stiffeners, and the design of the 1st barrier (stiffness, material, shape…).

4. Mass savings strategy at structure level

At the time being, the first flight unit of the ESM is about to be weighed before delivery and shipment to NASA integration facilities in the USA. The consolidated mass budget predicts a total mass around 300 kg beyond the initial ESM generic requirement. This represents about 6% of the dry mass of the ESM. A waiver logic has been set up in order to cope with this exceedance on the first ESM, and then reduce the mass step-by-step in order to be able to reach the target by the flight model 4.

As a result, a number of mass savings opportunities on the FM-02, 03, and 04 have been proposed, analysed and traded as a function of the benefits and cost. Planning, programmatics, costs, technical risks, and synergies with other required modifications constrains were also key to build up such a strategy and assess on which flight model the changes would make more sense. Mass savings opportunities have been identified in all the subsystems of the ESM: structure, propulsion, thermal, consumables, avionics & power. At system level, relaxing some requirements or design constraints has also been considered. For each track the mass reduction considered in the global ESM prevision is the combination of the best engineering estimate of the expected savings (weighted values, CAD/FEM models and comparison with the previous design) and a weighting factor in percent counting for both the probability of implementing this track and the reliability of the best engineering estimate. If a track is retained it is set first to a minimum value of 25%. It increases then as soon as the saving intends to be effectively implemented on the hardware, as the definition modifications are better known, and the impacts on the rest of the ESM are investigated.

These investigations allowed drawing a realistic ESM mass reduction plan to retrieve compliance with the mass target (Fig. 7):

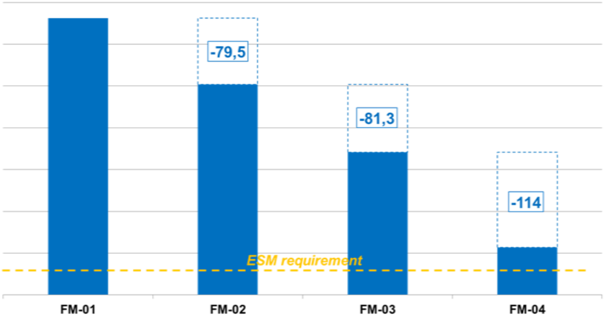

Fig. 7: ESM mass reduction plan up to FM-04

This mass reduction plan uses the weighting factors as well as the best engineering estimate in a conservative manner. The main hypotheses to set up such a mass prediction are summarized hereunder:

- Reference mass budget is based on ESM FM-01 generic case:
  - generic BEE mass values from CAD correlated with weighted values for as many items as possible
  - associated uncertainty according to the ESM margin policy document;
  - remaining FM-01 weighted threats and opportunities considered;
  - ground test instrumentation staying on board after final tests and development flight instrumentation specific for first flights are not counted in the ESM mass budget.
- FM-02, 03, 04 mass budgets cascaded from both FM-01 cases and the related weighted T/O.
- Propellant mass savings are not to be considered, only dry mass opportunities counts.
- Propellant residuals are considered as dry mass and are derived from FM-01 propellant budget.
- An implemented track is incorporated in the expected mass and does not count as T/O anymore.

Besides threats and opportunities identified, a global 87 kg uncertainty margin is included in the mass budget for all the FM. It aims at covering:

- Project margins for FM-01 unknowns (forgotten items, RFW, last minute changes, etc.);
- Gaps between BEE and measured mass for weighted items;
- Measurement inaccuracies of the FM-01 weighted dry mass at PSR in Bremen;
- Mass of non-weighted items not considered in the mass breakdown (glue, ty-raps, etc.).

This amount is meant to decrease over time as the FM-01 is being integrated and its items weighted until the final weighting in Bremen for the shipment.

Potential interactions between tracks have been identified from a qualitative point of view so that any interferences are foreseen. This might include technical, programmatic or schedule implications. In such a case the corresponding opportunities have been grouped together and proposed as a consistent package. Nevertheless, possible mass synergies or penalties coming from a coupled implementation of several tracks could not be properly considered at this stage of the project. As a result, the total mass savings counted are always the sum of each weighted individual opportunity as if it was implemented alone.

For the new ESM to be designed after FM-02, the different mass savings retained were distributed over the different subsystems as shown in Fig. 8.

Keeping constant the mission and the functional requirements, the highest value mass opportunities can be found in the structure and MDPS, representing more than 50% of the total savings.

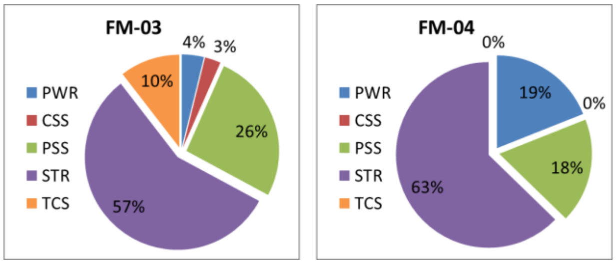

Fig. 8: Distribution of mass savings over the subsystems

The mass saving strategy for the structure on FM-03 and 04 has been developed along several lines, for instance:

- Design optimisation of primary structure and supporting brackets for lines and harness (including also a new insert layout of the CFRP panels).
- Replacement of the high density Steel fasteners with lighter Titanium alloy fasteners.
- Optimisation of the mechanical architecture of the rear part of the module, implying also the redesign of the MDPS 1st bumpers and the reduction of the Kevlar layers.
- Redesign of secondary structures for Additive Manufacturing.
- Replacement of composite web panels by metallic machined ones.

Some of these measures provide a very high potential for mass reduction, but also requiring not a negligible design effort. In this paper, the most promising mass saving opportunities are presented.

The MDPS mass savings are going to be implemented starting on FM-02 which is currently in manufacturing and integration. It consists in reducing the amount of Kevlar layers from 5 to 2 for all the MMOD protections blankets installed on the radiators and the aft side of the ESM. In order to implement such a 31 kg mass saving, the level 0 and level 1 requirements related to reliability of the MMOD of the ESM given by the RAMS team have been modified. In fact, the reduction of the amount of Kevlar layers increases automatically the probability of penetration of MMODs. Nevertheless, it has been demonstrated that such a performance reduction of the shield has a negligible impact on the overall reliability of the ESM given by its LOM (Loss of Mission) / LOC (Loss of Crew) criteria.

5. Refinement of the structure design

The basic idea is to reduce mass by reducing the thickness of some elements that have showed high margins, confirmed by the structural qualification tests.

Different options are possible:

- To use less conservative inputs such as updated and refined set of loads. This concerns potentially all the primary structures, but the most promising ones are the longerons;
- To reduce the safety factors used for the dimensioning according to the data of the structural tests and the correlation of the models. This is applicable mainly for the upper tank platform;
- To use less conservative stress computation on the structure thanks to the integrated stress analysis method. It concerns the web assembly cleats, the tanks flexure tabs, the lower platform, and the OMS-E engine support.

In synergy with the primary structure optimisation, some brackets will be removed, redesigned, or merged with other existing brackets. To do so, four options are possible:

- To redefine an optimised global insert layout for the whole circuit, in particular on the Web panels, taking the return of experience of FM-01 and the better ESM definition knowledge;
- To adapt the brackets to an optimised routing using the return of experience on FM-01 and not considering the keep out zone for the unpressurized cargo;
- To consider a 100 Hz frequency requirement for the piping attachment points instead of 140 Hz original requirement, since 100 Hz is sufficient to ensure the decoupling of the piping from structural modes, based on actual test results;
- To optimise the shape or the thickness of the brackets, or combine them with already existing ones.

This track concerns the bracketry of both the TCS and CSS circuits and is particularly interesting for the zones where the brackets density is high, notably the Web panels (Fig. 9).

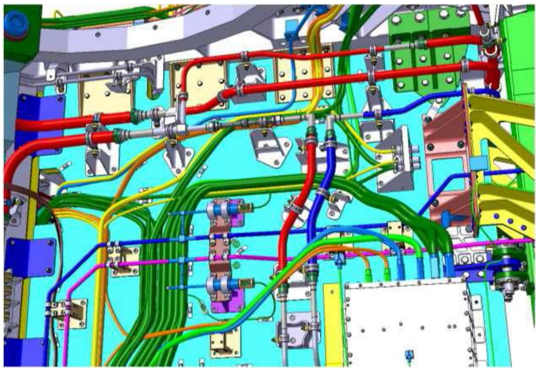

Fig. 9: Web panel zone with high brackets density

6. Optimisation of the mechanical architecture of the rear part of the module

For the original design of the ESM secondary structures below the lower platform, the ambitious schedule led to the implementation of not fully optimised PSS walls, needed to attach many propulsion components such as valves, regulators, lines and pressure transducers, with other secondary structures already present in the area (MDPS support, Auxiliary thrusters platform and lower SAHDRS). Therefore, a complete redesign of the aft part of the ESM was deemed to lead to a remarkable mass saving. The idea was to remove completely the PSS walls, the MDPS support and the AUX platforms (also called AUX and RCS panels) and replace them by a new optimised structure which could support all the equipment needed in that region of the module (i.e. PSS lines, AUX thrusters, rear MDPS, lower HDRS, etc.). After various trade studies, the "basement" design concept was selected as the most promising solution.

7. "Basement" design concept

An optimisation of the design architecture below the Lower Platform lead to combine various secondary support structures to a single integrated structure, called "basement", that provides support to the PSS on the after side of the module, to the eight Auxiliary Thrusters, and to the lower SAHDRS structures (Fig. 10)

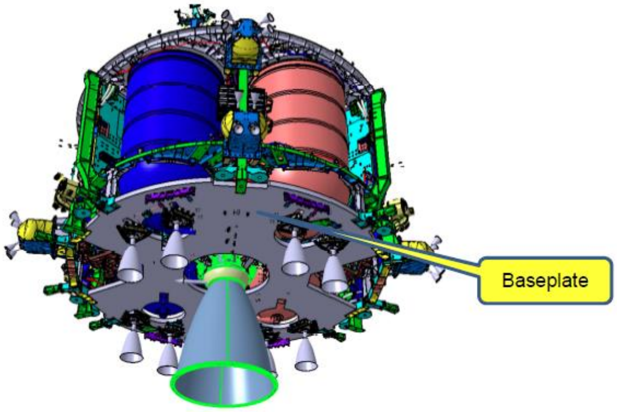

Fig. 10: Sketch of the "basement" plate option

The inner part of the large baseplate is connected to the lower platform by a multi-struts architecture (Fig. 11):

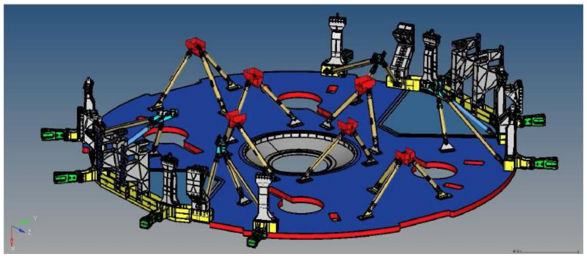

Fig. 11: Sketch of the connection between lower platform and "basement"

This architecture allows saving mass as the baseplate integrates in one single light Aluminium sandwich structure all the functions that in the original design are provided by a large number of secondary structures interconnected together. In addition, the "basement" panel would replace the support structure of the Kevlar-MLI blankets acting as 2nd wall of the MDPS in the aft side of the service module (known as "Spider-net").

Furthermore, the 1st bumper of the MDPS baseline design (a thick Aluminium plate) protected by a High Temperature Thermal Protection (HTP), would be replaced by only one layer of HTP. Indeed, it has been demonstrated through some preliminary Hyper-Velocity Impact tests conducted by NASA at the HVI test facilities in White Sands Labs, that one slightly thicker layer of HTP has approximately the same ballistic performance as the original assembly made by HTP and Aluminium plate. As a consequence, the thick Al panels could be potentially removed.

The total estimated mass saving from the Basement concept amounts to around 161 Kg.

8. Metallic machined web panels

The idea for this mass opportunity is to replace the 8 current composite web panels of the ESM primary structure by aluminium honeycomb and CRFP skin by 8 machined web panels made of Aluminium (Fig.12):

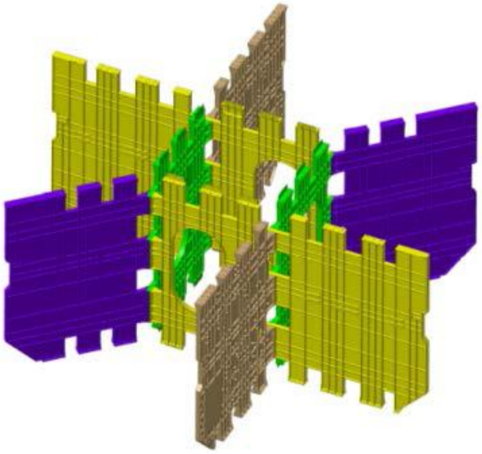

Fig. 12: Full metallic machined web panels

In itself this change is expected to bring a mass penalty compared to the composite web panels, and is directly depending of the new thickness of those panels. However, this can be compensated by several other optimisations, and in the end a mass saving is foreseen with the following preliminary design proposed:

- All the junctions between panels will be obtained from the Aluminium plate saving mass coming from the fasteners and from the increased local thickness;
- The interfaces for the helium tanks can be obtained directly from the machined panels;
- In correspondence of the SADE, the machined panels will present a complete flat surface absorbing the heat load so that the dissipation can be done through the aluminium panel without the need of a dedicated cold plate;
- If cold plate are still needed, deletion of the cold plate baseplate and the integration of the cold plate loop in the machined panels;
- The overall length of the TCS and CSS lines can be reduced by implementing additional cut-outs and shortening the routing;
- The brackets supporting the lines can be smaller and their geometry simplified by optimising the insert layout with less constraints than in the sandwich panels to drill the holes. About 270 brackets, of various dimensions, installed on Web Assy have been considered as candidate for replacement, leading to a potential mass saving of around 15 kg.

Besides the mass savings, this track is also expected to bring significant recurring costs saving compared to the composite panels: simpler design, cheaper to manufacture, less parts needed, easier to inspect and to mount, brackets interfaces can be implemented at a very late stage.

The mass saving associated to this significant design change depends mainly on:

- The final minimum thickness of the machined panels that will be defined to withstand mechanical and thermal loads;
- The actual possibility to remove and integrate in the panels the SADE (Solar Arrays Drive Electronic) cold plates.

These two points are being verified in a complementary analysis and this track will be traded. System and programmatic impacts also have to be considered including the delta qualification logic and the possible need of a new STA test for such a significant structural modification.

9. Redesign of secondary structures for additive manufacturing

Additive Manufacturing has been used in the past decades to create prototypes (mainly made by polymeric materials) during the development phase of many types of engineering projects. Recently, additive manufacturing technologies have evolved to the point that functional parts can be produced directly from specific metal powders or metal wires using similar layer-by-layer consolidation techniques. The possibility to manufacture almost any kind of complex shape and to remove or integrate in the redesigned parts joints and fasteners (provided that the global properties are comparable) led the team to try to apply these advanced design approach and related manufacturing technologies to the ESM mass reduction study.

9.1 Supporting bracket for RCS thrusters pod. Option 1.

The ESA engineering team, with the support of TAS-I team, studied the re-design of the original 4-parts assembly of one of the ESM Aluminium alloy 7075 upper thruster Z-pods (Fig. 13) into a single part to be manufactured with Additive Manufacturing (AM).

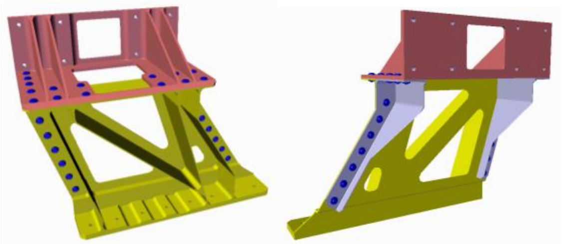

Fig. 13: Original design of the 4 parts supporting bracket for the upper thruster pod in Aluminium alloy

The opportunity came about through a current ESA contract for technology development of AM Titanium alloy (Ti-6Al-4V) parts for space application with the company Norsk Titanium (http://www.norsktitanium.com/) for which a demonstrator for space application was sought. The Rapid Plasma Deposition ™ (RPD™) is a patented AM technology developed by Norsk Titanium, in which Titanium wire is melted in an inert atmosphere and built up in layers to a near-to-net shape part. This results in significantly less machining for achieving finished parts compared with conventional manufacturing methods. It is important to remark that Norsk Titanium commitment to testing and quality assurance has resulted in being the first supplier of aerospace-grade 3D-printed structural Titanium parts with FAA certification for commercial aerospace OEM parts.

Instead of a full redesign of the component, which would have required much more time and resources than available, a simplified redesign approach was chosen for the selected upper thruster Z-pod assembly that would nevertheless clearly demonstrate the advantages offered by this specific AM technology. The simplified re-design consisted essentially of merging the 3D model of the original assembly of 4 Aluminium parts into a single Titanium part showing essentially the same shape and having its walls made thinner to achieve same stiffness.

Various iterations of FEM analysis were also applied to verify and optimise the simplified re-design of the merged part.

Areas with low strain arising under the required loads saw a higher mass reduction in thickness while areas with high strain had a lower mass decrease. Furthermore, these iterations led to the introduction of cut-outs in areas where the thickness couldn't be further reduced and removing material in the fastened areas of the original 4 parts design.

The AM design (Fig. 14) was verified in terms of stiffness, strength and buckling. Strength and buckling were verified using the original interface boundary conditions of the original design resulting in a total of 16 different load cases.

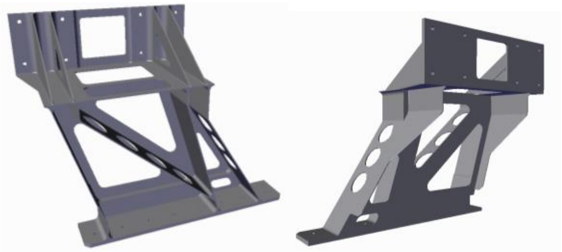

Fig. 14: Simplified single-piece design of the supporting bracket for the upper thruster pod in Titanium alloy (option 1)

It is important to remark that the predicted gain in weight is partly due to the elimination of the fasteners (50% ca.) and partly to the redesign of the "merged" bracket to be manufactured with AM technology in Ti-6Al-4V. The original mass of the assembly of the original 4 parts that formed one bracket is 3.636 kg (3.397 kg without fasteners). The optimised design achieved a final mass of 3.140 kg, with a net mass gain of around 0.5 kg (-13% ca.). Since there are 12 similar brackets in the full assembly of the ESM, by just extrapolating this preliminary results, is it possible to estimate a potential mass saving in the order of 6 kg.

However, additional savings may be achieved by re-designing completely from scratch the part to be manufactured with AM technology.

9.2 Supporting bracket for RCS thrusters pod. Option 2.

A second step in the re-design of the brackets was performed by the ESA engineering team moving to the topological optimisation approach. The optimisation software Optistruct^{TM} of Altair optimisation software has been applied to perform a topology optimisation of the part. The design space was expanded from the original part to a larger volume to give more freedom to the solver and the interfaces to the surrounding structure were considered part of the non-design space. For this re-design, the Aluminium Powder Bed manufacturing technology was assumed, with mechanical properties based on typical values found in the literature. Once the solver identified the load path of the structure, a final solid design was created using PolyNURBS tool of the Altair Inspire^{TM} (Fig. 15).

The resulting mass is 2.558 kg, which is 582 g lighter than the previous optimised model in Titanium, resulting in a mass saving of around 1 kg per bracket, which is 29% of mass gain with respect to the baseline model.

This model satisfies the requirement of maintaining the same stiffness as the original one. The first frequency is higher than in the original model, and the displacements, when applying loads in different directions, are lower. Therefore, in reality this design is slightly stiffer. Strength and buckling were also verified and presented positive margins of safety.

Fig. 15: Topological optimised single-piece design of the supporting bracket for the upper thruster pod in Aluminium alloy (option 2)

By extrapolating the mass saving achieved for this bracket to the 12 similar brackets that support the 6 RCS pods, the potential mass saving can be estimated to sum up to about 12 kg.

9.3 Supporting bracket for RCS thrusters pod. Option 3.

The case where Titanium is used instead of Aluminium in the previous optimised re-design was also considered by the ESA engineering team. Because the specific stiffness (Young modulus/density) is similar for Aluminium and Titanium, the mass saving obtained for the Titanium part is in the same order as the one obtained with Aluminium, although the Titanium part section is slightly slenderer. This design leads (Fig. 16) to a mass of 2.688 kg, resulting in a mass saving of 26% with respect to the baseline model. On the other hand, it has to be recalled that AM Titanium parts in principle results with better properties, in particular with higher fracture toughness, in comparison with AM Aluminium parts.

Fig. 16: Topological optimised single-piece design of the supporting bracket for the upper thruster pod in Titanium alloy (option 3)

9.4 Supporting brackets ("Rusty Towers") for pipes and lines

A topology optimisation was also applied by the ESA engineering team, in cooperation with the Airbus team, to three solid brackets (called "Rusty Towers") supporting pipelines, test ports, etc., that are installed on top of the tank bulkhead. As in the case of the RCS thruster Z-pods, the initial design of each of the three towers consisted of a fastened assemblies of many parts (Fig. 17).

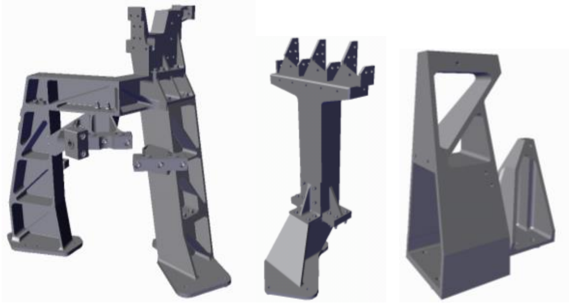

Fig. 17: Original multi-parts design of the "Rusty Towers"

In order to optimise the design, these parts were merged and the design space was considered to be similar to the initial design but with all of the holes filled with material. Then, Optistruct^{TM} was used to evaluate the load path and create the resulting solid model. The re-designed models were verified in terms of stiffness, strength and buckling, according to the requirements for these structures. To verify the stiffness, the first natural frequency was considered. For strength and buckling, one enveloping load case was used for the verification. The material considered for the re-design was typical Aluminium Powder Bed, from literature.

The preliminary results are rather promising:

For the first tower (Fig. 18), the mass could be reduced from 5.578 kg to 3.527 kg (36% mass gain).

Fig. 18: Design of the first "Rusty Tower" bracket obtained by topology optimisation

For the second tower (Fig. 19) from 3.721 kg to 3.053 kg (17% mass gain). For the third tower (Fig. 20) from 1.358 kg to 0.728 kg (46% mass gain).

Is important to mention that the certification for flight of AM parts, especially if based on Aluminium powder bed technology, needs still further development activities and careful attention due to the intrinsic diffuse presence of small defects and porosity.

Fig. 19: Design of the second “Rusty Tower” bracket obtained by topology optimisation

Fig. 20: Design of the third “Rusty Tower” bracket obtained by topology optimisation

10. Conclusions

The ESM (European Service Module) of the NASA “Orion” MPCV has been designed, developed, and is undergoing qualification under the management of ESA, the European Space Agency. Airbus Defense & Space is the industrial prime contractor of ESA and is the ESM system architect. The mechanical structure of the ESM, including the MMOD protection system, is designed and manufactured by Thales Alenia Space Italia.

For ESM-1, the first flight model of ESM, the consolidated mass budget predicts a total mass around 300 kg beyond the initial ESM generic requirement.

The mass optimisation exercise presented in this paper, shows that there are various opportunities for mass savings of the ESM for the upcoming flight models FM-02, FM-03, and FM-04. Several mass saving opportunities have been proposed, analysed, and traded as a function of benefits, planning, programmatics, costs, technical risks, and synergies with other required modifications.

The first proposed mass saving consists in a refinement of the primary structure design based on the idea to reduce the thickness of some elements that have showed high design margins, also confirmed by the results of the STA structural qualification tests. Linked and in synergy with such primary structure optimisation, some brackets could be removed, redesigned, or merged with other existing brackets.

As second option, the “basement concept” has been presented: by combining in a single integrated structure all the supporting structures placed in the rear part of the vehicle for attaching the PSS components, as well as the MMOD protections, the AUX and SADM support brackets, this option could provide up to 161 kg in mass saving.

Another option presented here consists in the redesign of the panels that forms the web assembly. Despite the fact that the baseline design composite sandwich panels are proposed to be replaced by Aluminium machined panels, the increased design flexibility and the possibility to integrate joining elements and heat dissipation elements in one single piece, could provide for potential mass saving and cost saving opportunities.

Finally, a promising mass saving opportunity has been analysed and developed through the application of Additive Manufacturing technologies together with topological optimization software. A particular effort was carried-out at ESA for proposing the AM re-design option for several secondary structures of the ESM. Few examples of single-piece redesign of complex shape brackets, originally composed of many parts fastened together, have been presented. The results obtained are quite encouraging since it was possible to predict significant mass reductions (in the order of up to 46%). The certification for flight of AM parts needs still further development activities.

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