ADDITIVELY MANUFACTURED AND TOPOLOGICALLY OPTIMIZED COMPLIANT MECHANISMS: TECHNOLOGICAL ASSESSMENT APPROACH, LATEST ACHIEVEMENTS AND CURRENT WORK IN PROGRESS

Hervé Saudan [(1)], Lionel Kiener, Gérald Perruchoud, Kaushik Vaideeswaran, Mohammad Mehdi Dadras

[(1)] CSEM SA, Rue Jaquet-Droz 1, CH-2002 Neuchâtel, +41327205111, hsa@csem.ch

ABSTRACT

The use of Additive Manufacturing (AM) processes for space applications is a constantly growing topic of interest from the main actors in the space industry. In the specific field of spacecraft structures, an increasing number of successful AM-based developments were reported during the last ECSSMET symposium, with a clear focus on reproducing and optimizing designs of structural parts, thanks to metallic AM combined to powerful tools such as topology optimization. This trend seems to be less pronounced in the field of space mechanisms where little work has been published so far.

This paper exposes the current status of the R&D activities carried out at CSEM with the aim to produce novel designs of compliant mechanisms based on Selective Laser Melting. The general development strategy is presented, followed by material analysis and testing experimental results. The latest results obtained with the topology optimization of an elementary compliant mechanism are also presented.

1. INTRODUCTION

Compliant structures and mechanisms such as those illustrated by Figure 1. can achieve macroscopic linear and rotary motion without friction, wear, backlash, and with extremely high fatigue performance thanks to the elastic deformation of flexible structures arranged in a special manner. In spacecraft, they assume various functions as launch locking, linear or rotary scanning for ultra-high precision optical instruments, pointing mechanisms for antennas, and more.

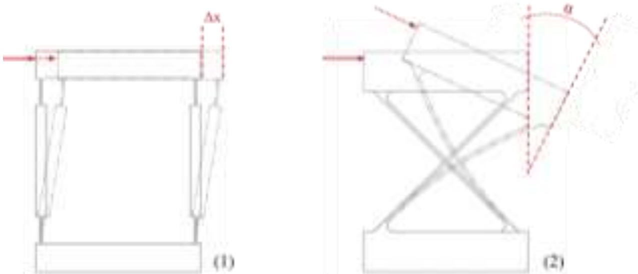

Figure 1. Examples of two elementary compliant structures: (1) linear stage parallelogram (2) pivot

To date, their very high complexity has required highly sophisticated and expensive manufacturing methods, the gold standard being the wire electro-discharge machining (WEDM) from a bulk material block with consecutive large material losses and very long and delicate machining procedures. By nature, the *wire cutting* of flexible structures is a major design driver, since only *2.5D* or *pseudo 3D* parts can be produced with reasonable process failure risks associated to the WEDM process complexity. The main consequence of this limitation is that compliant mechanisms are often composed of several elementary compliant structures – such as pivots, membranes, parallelograms – assembled interfaced to one or several structural parts which constitute the backbone of the mechanism.

Today, this paradigm is questioned by the new possibilities offered by powder based Additive Manufacturing technologies such as Selective Laser Melting (SLM) or Electron Beam Melting (EBM). By nature, these technologies offer an increased design freedom, with a high potential for the development of novel kinematic topologies. The design of monolithic compliant mechanisms is also simplified, with a subsequent potential for improved mass/stiffness optimization thanks to design tools such as topology optimization software. Nevertheless, usual weaknesses attributed to AM processes – such as surface roughness, material porosity & internal stresses, often leading to material anisotropy – may become showstoppers for the design of compliant mechanisms where very thin and flexible structures are required. It is worthwhile to mention that designing compliant mechanisms also implies the association of these elementary flexible structures to their stiff structural segments providing the basic functions of any mechanical part. The association of these very heterogeneous geometries into a single monolithic part manufactured with AM technology is a challenge in itself.

2. DEVELOPMENT STRATEGY

Considering a generic synoptic diagram of design and MAIT (Manufacturing, Assembly, Integration and Test) such as Figure 2., a development roadmap was defined. The overall approach relies on the reasonable assumption that the prerequisite to any reliable design innovation is a well consolidated proof of concept. In the case of a compliant mechanism based on SLM, the following essential steps were defined, targeting a TRL3 (Technology Readiness Level):

1. verify the **feasibility** of manufacturing by SLM an elementary flexible structure geometry. At this level, a well mastered SLM material is used

2. **develop** and **validate** an end to end SLM-based manufacturing and post processing protocol for high performance flexure elements.

3. enable **innovation** by defining a use case mechanism to be re-designed for AM by integrating the know-how acquired in the previous steps, as well as a topology optimization tool.

Figure 2. SLM compliant structures development steps

3. FEASIBILITY

The case-study of Figure 3. – a 6 mm × 8 mm stroke 2DoF compliant linear stage – gathers simple & double parallelogram arrangement. It was defined and sized to be typical of compliant structures encountered in real applications. SLM was chosen for its high TRL and subsequent ease of access at industrial level. In the same spirit, a well mastered 316L stainless steel powder equivalent was selected in order to benefit from a solid base of expertise.

The preliminary results revealed that the thermal gradients occurring during the SLM process were generating internal stresses and a consecutive macroscopic warpage as the part was manufactured on low density material support. Manufacturing the final part on a fully dense substrate and implementing an annealing step prior to separating the part from its substrate successfully addressed the warpage issue.

The research for the optimum SLM parameters showed that those had to be accurately tuned and optimized depending on the type of segment in presence – i.e. structural or flexural. Preliminary inspection and material analysis revealed poor surface quality compared to WEDM processed surfaces, visible material porosity and rather irregular microstructure, which were all suspected to affect the tensile and fatigue properties. These observations were used as inputs for the next development phase.

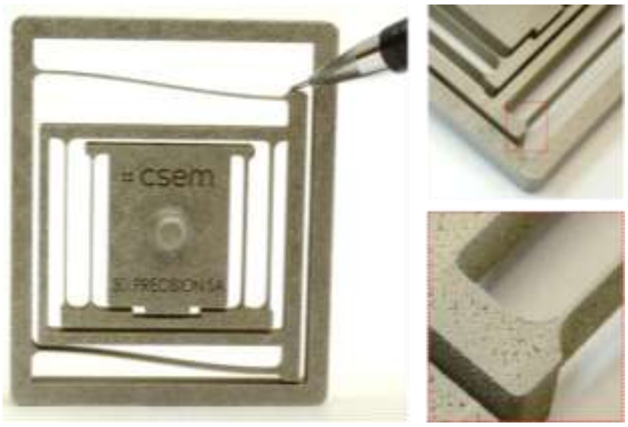

Figure 3. AM-SLM produced 316L stainless steel 2DoF linear stage. Flexures thickness = 300 µm, aspect ratio respectively 80 and 123 for the blades of the double and simple parallelograms

4. HIGH PERFORMANCES MATERIAL DEVELOPMENT AND VALIDATION

Based on the results of the feasibility study, a set of objectives was defined to achieve the general goal of developing and validating an AM-SLM based production method for compliant structures dedicated to space applications. These objectives are to:

1. select the best suited material candidate
2. optimize the AM-SLM fabrication parameters
3. define the best post-processing strategy
4. validate the production protocol established through fatigue and tensile testing

4.1 Material selection

The material choice was oriented toward high strength stainless steel alloys available in powder form, with the aim to approach the exceptional mechanical properties and SCC resistance of MARVALX12, the material usually chosen by CSEM for demanding applications. This high strength precipitation hardenable stainless steel offers both high stress corrosion cracking (SCC) resistance [1] and high fatigue resistance when it is submitted to alternate bending deformation, a parameter which was experimentally verified through several internal fatigue test campaigns (see Figure 8.). Given this first direction, the best candidate was then selected according to a trade-off analysis based on:

a) the list of available powder materials for AM-SLM and their final mechanical properties as they are specified by the powder supplier

b) the data available for chemically equivalent commercial grade raw materials, with the aim to compare the final properties of the AM-SLM parts with those of the corresponding material

c) ECSS stress corrosion cracking material selection tables

The alloy chosen – Concept Laser's CL92PH – is an equivalent of the widely used and studied 17-4PH martensitic precipitation-hardening stainless steel [2,3]. The fact that two publications treating of 17-4PH in its additively manufactured form was considered as an advantage [4,5].

4.2 Process and post-process

SLM process optimization

The optimization of the SLM parameters was performed in an iterative manner with the aim to get minimized and homogenized porosity, micro-structure and surface roughness. The fatigue samples were chosen as reference geometry, since they were gathering both structural and flexure areas. The parameters being tuned were the layer thickness, laser beam power, focus point, scan speed and the laser patterns applied to different areas of the samples. The laser pattern was confirmed to be the key parameter leading to homogenous material quality on both massive and thin geometries, as shown on Figure 2. After SLM manufacturing, the thin sections were showing thickness variations of ±18 µm at 3σ, with an average thickness of 380 µm, whereas the reference value was 350 µm.

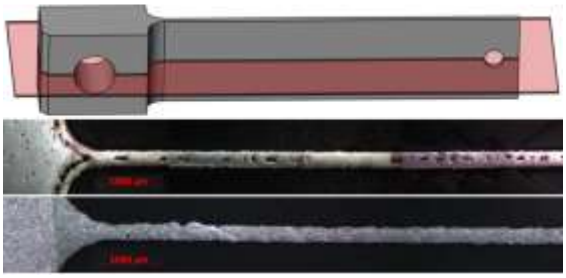

Figure 4. Fatigue sample cuts before and after SLM parameters optimization. Note the presence of residual porosity on the lower picture.

Thermal post-process sequence definition

The post-processing optimization consisted in assessing the benefits of Hot Isostatic Pressing (HIPing) reported in literature [6]. The analysis confirmed the removal of the residual porosity and the improvement of the microstructure in terms of homogeneity and grains size, as depicted by Figure 3. Although the dimensional accuracy of the flexures was not affected, a visible warpage of the base plate holding the samples was observed. For both conditions (i.e. HIP and non-HIP), the samples were applied a solution annealing and age hardening H925 sequence.

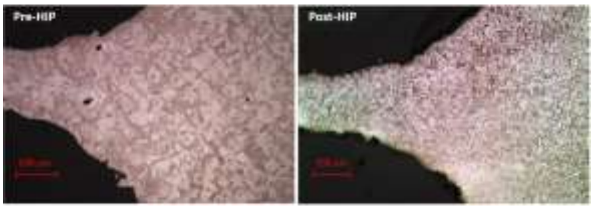

Figure 5. Sample cuts before and after HIPing.

4.3 Tensile test campaign

The tests were conducted for HIPed and non-HIPed material condition with a total of thirty samples produced according to the 3 manufacturing directions (five samples per direction). The samples were designed according to the ASTM E8/E8M − 15a standard. Raw rods were produced, heat treated, machined to their final geometry and finally tested.

The results of Table 1 show that for both heat conditions, the SLM produced samples show similar or higher R_m and $Rp_{0.2}$ compared to the commercial grade *17-4PH*. The elongation at break for non-HIPed samples tend to show a fragile behavior which is confirmed by the fracture inspection (see Figure 4). The fracture inspection proves that HIPing also improves the intergranular cohesion, leading to enhanced tensile properties.

Table 1. Tensile test results and comparison with commercial grade 17-4PH. For MARVALX12, R_m, $Rp_{0.2}$ and A_5 are respectively 1246, 1214 N/mm² and 15.5 %.

TENSILE TESTS RESULTS			17-4PH Böhler	CL92PH X-Y-Z mean values ±1σ	
Material heat condition - Solution Annealed (*SA*) - Age Hardened (*AH*)			*SA / AH*	*SLM/ SA/AH*	*SLM/***HIP/** *SA/AH*
UTS	Rm	N/mm²	1170	1412±32	1415±18
Yield strength	*Rp0.2*	N/mm²	1070	1034±43	1335±21
Elongation	A_5	%	8	3.1	9

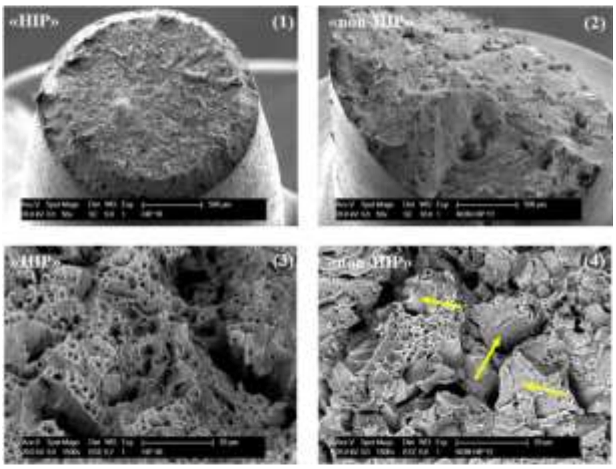

Figure 6. Tensile samples SEM fracture surfaces. On picture (4), the areas showing a lack of intergranular cohesion are pointed by the yellow arrows.

4.4 Fatigue tests campaign

The general principle of the alternate bending fatigue test bench is illustrated by Figure 7. The test bench was developed in the framework of the MTG program to qualify the material used to manufacture the flexure elements used in the Corner Cube Mechanism (CCM) of the Infra-Red Souder (IRS) instrument.

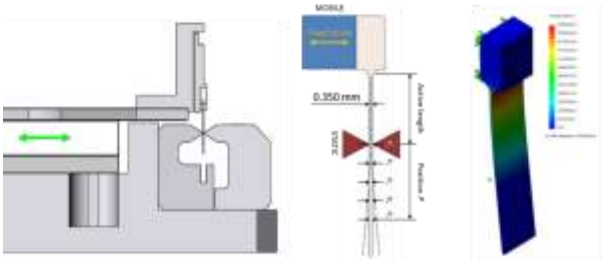

Figure. 7. Fatigue test setup and samples illustrations

For this campaign, HIPed and non-HIPed flexure samples were produced by SLM, each group consisting of at least 10 samples, with 5 samples per stress level. A third group was machined by WEDM from 17-4PH, applying the standard protocol followed for MTG. To benefit from comparative data, the geometry of the samples and of the test apparatus were kept identical to those used in MTG. Under standard lab conditions, the samples were applied a ±1 mm shuttle motion at 15 Hz. The *S-N* curve and fatigue limit S_f estimates illustrated by the graph of Figure 8. show that SLM manufactured flexure performances remain in the same order of magnitude, with a decrease limited to 15 % for HIPed samples and 30 % for the non-HIPed samples. The heterogeneous samples fracture surfaces of SLM manufactured samples (Figure 9.) confirms the presence of internal defects affecting the fatigue performances.

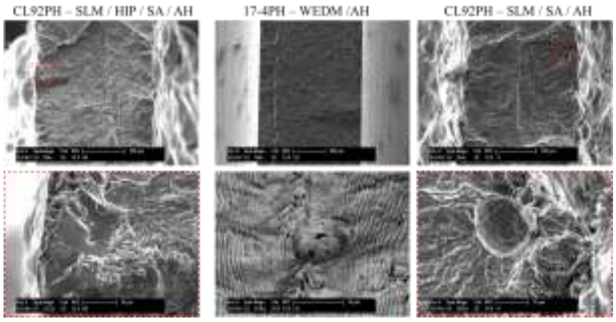

Figure 9. Fatigue samples fracture surface micrographs

4.5 Conclusions

In this study, an end-to-end SLM-based manufacturing and post-processing protocol was developed for a high strength stainless steel. The beneficial effects of HIPing on material performances were confirmed, with a tensile yield strength comparable to that of a commercial grade 17-4PH. This study shows that compliant structures offering lifetime above fifteen million cycles under realistic load cases can be produced, proving the potential eligibility of SLM-based compliant structures for space applications. Nevertheless, the geometry of the SLM manufactured samples was less accurate than those produced by WEDM. It was also observed that HIPing may affect the geometrical accuracy of larger parts, which might be a real challenge when it comes to producing more complex shapes whilst preserving high accuracies. These aspects show that SLM-based high quality compliant structures are not straightforward to produce. Therefore, the technical challenges to be addressed must be counterbalanced by concrete advantages in terms of design innovation, which is the topic treated in the present paper.

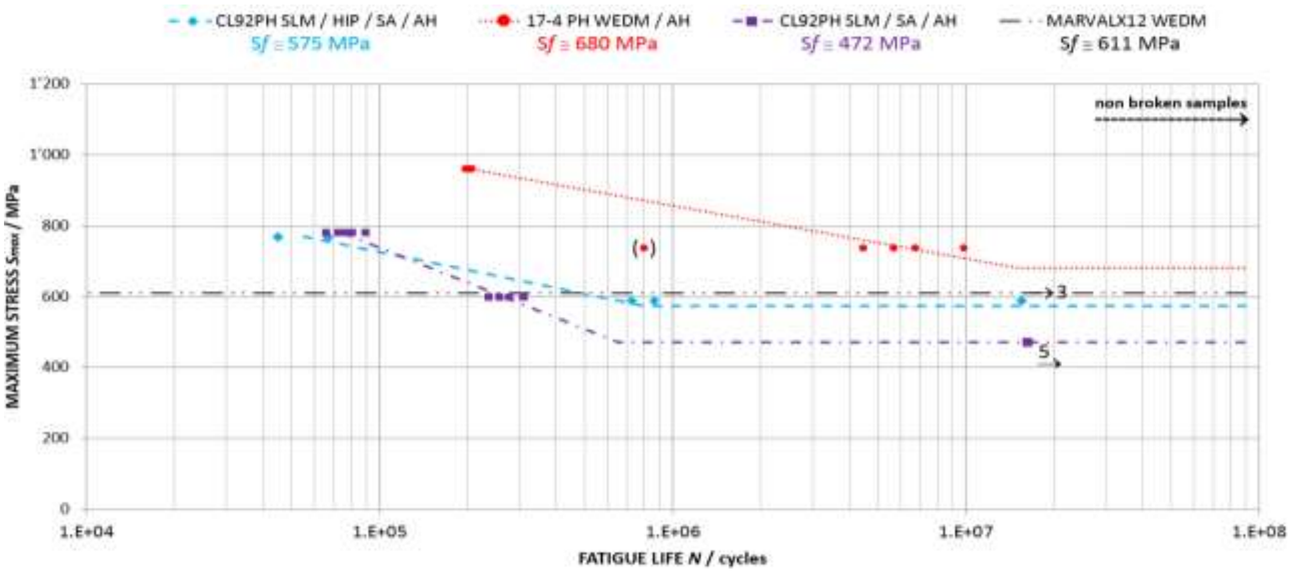

Figure 8. S-N curves estimates for SLM (CL92PH) and WEDM (17-4PH) samples. The fatigue limit of MARVALX12 was obtained experimentally during the MTG-CCM test campaign.

5. COMPLIANT MECHANISMS BASED ON TOPOLOGY OPTIMIZATION AND SLM

In the automotive and aerospace engineering fields, topology/parametric optimization software is a common tool which contributes to design high performance structural parts. To date, those parts were essentially manufactured by conventional means. However, the integration of AM technologies in the industrial supply chains shows a rapid increase.

In the specific field of spacecraft structures, number of successful SLM-based developments were reported during the last ECSSMET conference, with a clear focus on reproducing and optimizing designs of structural parts, thanks to metallic SLM combined to topology optimization. This trend is much less pronounced in the field of space mechanisms where little work has been published so far, although there are no doubts that AM processes have the potential to enable significant improvements.

5.1 Design of compliant structures for SLM

Although SLM allows a large freedom to design complex shapes, a major limitation of the process is the need for low density support material which is mandatory to support overhanging areas of the part being manufactured. The general rule is that any overhanging structure whose angle is less than 45 to 50 degrees with respect to the horizontal plane needs to be supported. The removal of this support material after SLM is performed either manually or by means of post machining – provided the access is possible. The mechanical stress experienced by the part during this step is usually not critical for structural parts but may become very problematic for compliant structures. Therefore, abrupt overhanging geometries featuring angles smaller than 45° shall be avoided as much as possible and replaced by progressive angle overhangs. Early in the design process, the orientation of the part during SLM shall be considered and the design shall be made so that the support material is limited to strategically defined areas.

Once these elementary constraints and associated design rules are known, the mechanical designer can take advantage of the design freedom offered by SLM and enter the design and optimization steps.

5.2 General aspects of compliant mechanisms and topology optimization considerations

Like structural parts, space mechanisms are designed to withstand specific shock and vibration spectra during the rocket launch, orbit insertion and satellite commissioning phases. During those, the mobile parts of mechanisms – showing low stiffness with respect to their natural Degrees of Freedom (DoFs) – are protected by Launch Locking Devices (LLD) or Hold Down and Release Mechanisms (HDRM). From the perspective of mechanical design & analysis applied to a compliant mechanism, this implies that *two* configurations must be considered, i.e. mechanism "locked" and "released". Moreover, in the "locked" configuration, the compliant structure may be such that intermediate stage(s) remain(s) unlocked during launch. The key here is to purely avoid these internal degrees of freedom "by design" or to reduce the associated contributive masses and therefore limit the criticality of the mode. In such a case, topology optimization can significantly contribute to reduce this criticality.

From the general mechanical architecture point of view (see Figure 10.), any compliant mechanism comprises purely structural parts giving the assembly its overall stiffness. The second essential function of the main structure is to provide mechanical interfaces to the sub-systems of the mechanism and to the spacecraft. Also attached to this backbone, the thickest areas of the compliant structures provide interfaces for actuator's and sensor's mobile parts, as well as mechanism's payload, while the flexure elements give the mechanism its degrees of freedom. As a consequence, compliant structures themselves feature *structural* segments in addition of the *compliant* segments. The structural segments themselves are sub-divided in two categories: mobile and fixed. Furthermore, the state – mobile or fixed – of the *mobile* structural segments depends of the stated of the LLD/HDRM. All of these segments could benefit from a topology optimization. Nevertheless, due to their very different geometrical properties – thick vs thin – and functional states – fixed vs mobile –, the use of a unique optimization algorithm shows little chances of success.

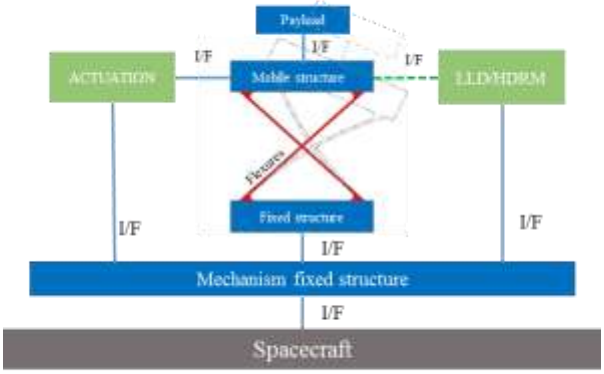

Figure 10. Compliant mechanism generic architecture

5.3 Topology optimization of compliant mechanisms: plan, objectives and constraints

Since AM makes it easier to design and manufacture complex monolithic parts, it is assumed that the design and optimization process should seek at merging the whole compliant structure to the structural parts of the mechanism.

Based on this general objective, three strategic options were considered:

a. optimize structures and flexures simultaneously
b. optimize the flexures only
c. optimize the structures only

As introduced in the previous chapter, the use of a unique optimization tool to achieve option "*a"* was judged too risky and therefore it was decided to consider it as an ultimate long term objective. The option of starting two parallel activities to address options "*b*" and "*c*" was retained and both our currently ongoing. In the next part of the present paper, the current status of option "c" is presented. The main objectives associated to an optimization focused on structures are:

1. to maximize stiffness
2. to reduce mass
3. to optimize volumes

The two first objectives will be quantified in the optimization software. The third one – volume optimization – is linked to the very first step of the present work, which consists in defining a design case-study (see next chapter) to be introduced in the optimization software (Optistruct). The following generic sequences describes the main steps to be carried out. Depending on the results obtained, the total sequence or a part of it may be repeated iteratively until the expected results are obtained.

1. Define the initial model geometry in the optimization software environment
2. Define the load case, the optimization constraints and objectives
3. Launch the optimization process and evaluate the quality of the output geometry
4. Refine the raw output geometry by using the specific tool of the optimization software and final rework in CAD
5. Validate the final design through FEA

5.4 Definition of the design case-study

The function of the case-study mechanism – an angular pointing mechanism based on two Butterfly Hinge (BFH) flexure pivots – was defined to meet a wide scope of applications. Conventionally, such a mechanism would be made of several parts fastened together, as illustrated by Figure 11. In the present case, a flat mirror reflector was defined as payload. This choice was made with the assumption that the reflector could potentially be directly integrated to the structure, meaning that the whole mechanism could be designed, optimized and manufactured as a monolithic compliant mechanism including its own payload, thanks to SLM manufacturing and post-processing such as precision re-machining, mirror surface polishing and in-situ metallic coating. In case of success, the aim of the demonstrator was to demonstrate the benefits enabled by SLM with regard to the simplification of assembly and integration phases.

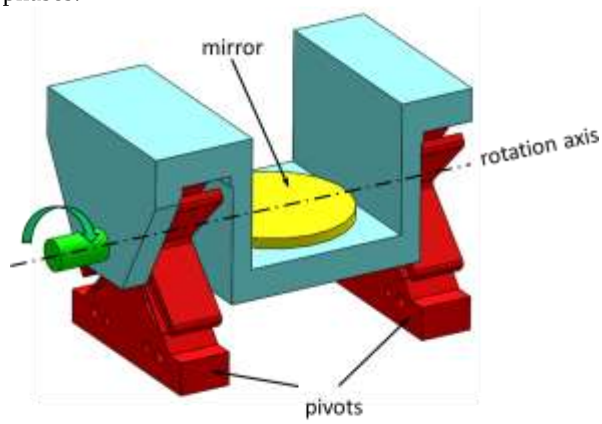

Figure 11. Case-study mechanism initial design

5.5 Optimization approach

Once defined, the case-study was considered from the perspective of the topology optimization goals and strategy exposed in §5.3. Due to the exploratory nature of this work, a step by step approach was chosen. First, a topology optimization was performed on the structural segments of a single BFH pivot. The left picture of Figure 12. illustrates the definition of the initial conditions: the permitted volumes for optimization are shown in blue, while the forbidden volumes are colored in red (flexures and mechanical interfaces). An arbitrary off-centered mass of 0.1 kg under a gravity load of 1 g was applied and a set of constraints were defined for the optimization:

1. Maximize stiffness
2. Limit the displacement of the mass point of application to 0.75 mm under load case
3. Remove at least 80% of the volume allowed for optimization

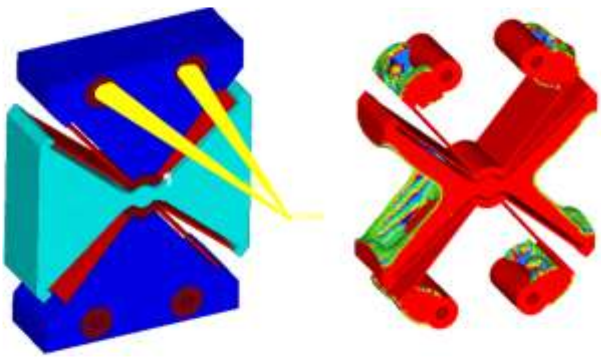

Figure 12. Butterfly Hinge pivot optimisation example

The results obtained confirmed that the structural segments of a compliant structure could be optimized without major difficulties, as long as the flexure segments were excluded from the optimization.

For the next step, the whole design case-study was considered. As for the pivot, forbidden volumes were defined for the flexures, the mechanical interfaces and the payload. The volume available for optimization was kept as small as possible to verify how the algorithm would manage to converge to a solution. In this configuration, the three first Eigen modes of the mechanism were:

1. θ_X pivots rotation (natural mode)
2. Pivot intermediate stages (internal mode)
3. X translation of the whole mechanism

A gravity load of 10 g was applied along the three orthogonal axes and a mass of 1 kg was assigned to the mirror. A symmetry plane O_{XZ} coincident with to the rotation axis was imposed in order to avoid asymmetric solutions. The optimization objectives and constraints were defined as follows:

a) Maximize stiffness
b) Limit the displacement of the mirror center point to 0.05 mm under load case
c) Target 100 Hz as 3rd mode instead of 87 Hz for the initial design (i.e. before optimization)
d) Remove at least 70% of the volume allowed for optimization

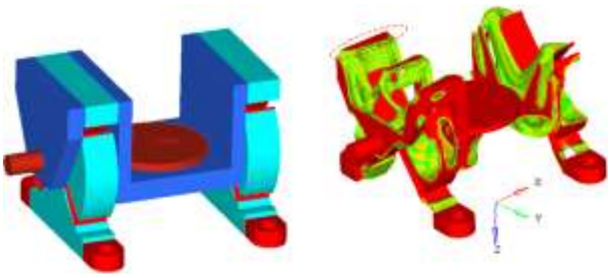

Figure 13. Angular pointing mechanism first optimization configuration with reduced volume allowed for optimization. The area circled in red illustrates a typical example of insufficient initial volume.

As shown on Figure 13., the algorithm succeedeed in converging to a solution. Nevertheless, a portion of the final volume was coincident with respect to the boundaries of the initial volume, which was suggesting a “lack” of initial volume to produce more harmonious geometries. Consequently, the flattened shapes produced by the algorithm revealed to be difficult to refine during the geometry refinement step. On the other hand, an important asymmetry was noticed with respect to the O_{YZ} plane, due to the unilateral single actuation and LLD/HDRM of the design case-study.

Based on the results obtained with the first optimization run, the following adaptations were implemented for the next iteration: A bi-lateral redundant actuation and LLD/HDRM was integrated to the baseline design, in order to produce symmetric solutions with respect to O_{XZ} and O_{YZ} planes. Furthermore, the permitted design volume was increased and an exlusion volume dedicated to the optical path was added. Apart from these two adaptations, the same optimization objectives and constraints were applied.

As shown on Figure 14., the solution produced by the optimization algorithm was almost free of flattened shapes, excepted the design volume of the pivot (shown in light blue) which could have been increased to possibly improve the arched shapes located on the pivots. As expected, the solution shows now a perfect symmetry with respect O_{XZ} and O_{YZ} planes.

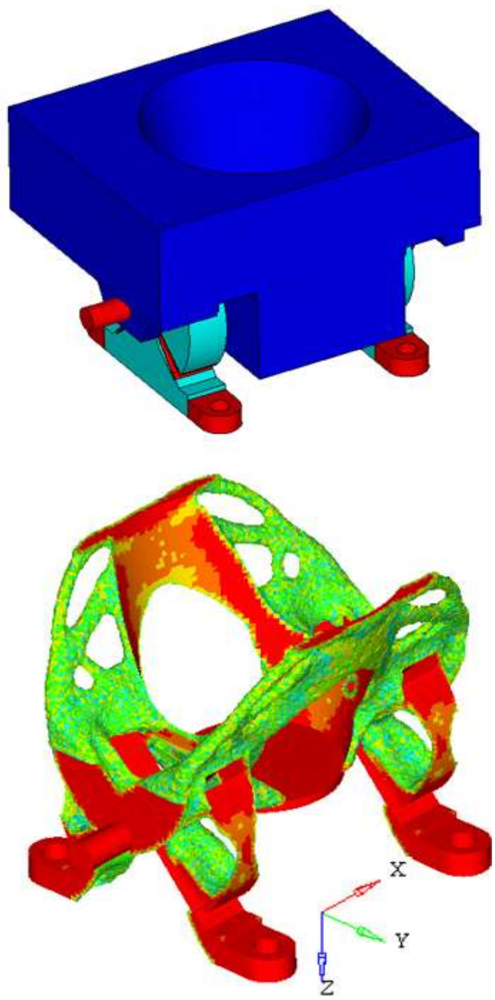

Figure 14. Angular pointing mechanism second optimization configuration with increased volume allowed for optimization.

Although the geometry produced by the algorithm fullfills the objectives and constraints specified, the aspect ratio of the two wings is such that their mode is likely below that of the 3rd structure mode which was one of the objectives of the optimization. This indicates that the definition of the constraints and objectives could be refined in order to better drive the optimization process and therefore avoid scenarios such as this one, where the algorithm succeed to produce a solution but creates a new issue to be solved with a new iteration.

5.5 Conclusions

The paper was finalized with this current progress status. The main lessons learned thus far are that the definition of the optimization constraints and objectives is one of the key aspects to be considered, since the results produced by the algorithm are very interrelated. The same observation was made regarding the definition of the volumes. In this particular case, the boundaries of the volume allowed were arbitrarily defined, with a very significant impact on the geometries produced by the algorithm. In the case of a real development, the volume allocated to the mechanism is usually better defined, which helps to set a clear scope for the design and optimization phases.

6. GENERAL CONCLUSIONS

In this study, the feasibility of using AM technologies and topology optimization tools to design and manufacture compliant mechanisms was proven. By combining them, very promising design advances are foreseen. Nevertheless, number of new rules and limitations were discovered and shall now be "tamed" to further progress. Hence, the experience acquired by the engineers involved in this endeavor is crucial. It is now confirmed that the use of AM and topology optimization implies to deeply reconsider the way compliant mechanisms are designed and conceived.

The study is continuing with the refinement of the objectives and constraints, which aims at consolidating the quality and relevance of the geometries coming out of the optimization process. Once this step will be fully mastered, the next steps will be addressed. The design will be refined and validated through FEA, before being manufactured by SLM according to the protocol specifically developed for compliant structures. Finally the model produced will be characterized experimentally to confirm the FEA predictions.

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