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Additive manufacturing: innovative concept of compliant mechanisms

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Abstract

Several compliant mechanisms have been completely redesigned for Additive Manufacturing (AM) and have allowed CSEM to develop an innovative concept. In addition to the new geometric possibilities offered by AM, the need for machining and assembly after printing are drastically reduced. Support structures under flexure blades are thus minimised and the overall process becomes more streamlined. Moreover, this idea allows us to easily design and produce monolithic cross blade flexure pivots with interlocked flexible blades.

Thanks to this concept, CSEM is now developing and testing new architectures of Compliant Mechanisms based on Additive Manufacturing (COMAM) for the European Space Agency (ESA) in the frame of a GSTP research project.

Compliant mechanisms, frictionless, Additive Manufacturing, Selective Laser Melting, fatigue testing, flexure blade, monolithic cross flexure pivot

1. Introduction

Mechanisms with friction present significant drawbacks with the need of lubrication, the generation debris, backlash and stick slip. In cryogenic and space environments, suitable lubricants are very limited when not prohibited. Wear generation can pollute optics, obstructing a smooth motion and can even lead to early failures.

To overcome these important limitation, Compliant Mechanisms (CM) are usually proposed. They 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. They are used in harsh environment such as vacuum, cryogenic and space, where friction is to be avoided, high-precision and a high lifetime are required.

To date, the extreme complexity of compliant mechanisms 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. Moreover, the assembly has actually to be realized with many precautions to ensure a very precise positioning between all parts.

Today, this paradigm is questioned by the possibilities offered by AM technologies, notably the metallic powder bed processes such as the Selective Laser Melting (SLM) [1].

After more than 30 years of successful developments using compliant mechanisms produced by conventional manufacturing methods, CSEM demonstrated in 2016 the feasibility of high performances compliant structures made by AM [2]. CSEM has over the last few years, acquired an expertise in the computerized optimization of such mechanisms for AM and has proceeded further by inventing a totally new design concept: the interlocked lattice flexures. This new type of compliant structure geometry and arrangement is such that the flexure elements cross, but never touch each other, even when deformed. This new architecture – made only possible by AM technologies – creates the opportunity to develop completely new flexure topologies but also to improve existing ones, as demonstrated with the example of a redesigned C-flex type pivot (patent US 3073584) illustrated in Figure 1.

The complete design process, including the definition of the architecture and, the integration of the interlocked flexures before the topology optimization, will be detailed in the next chapter. Then, several compliant mechanisms conceived and manufactured will be presented. The microstructure, tensile, fatigue test results will be detailed and finally, next steps and conclusion will be drawn.

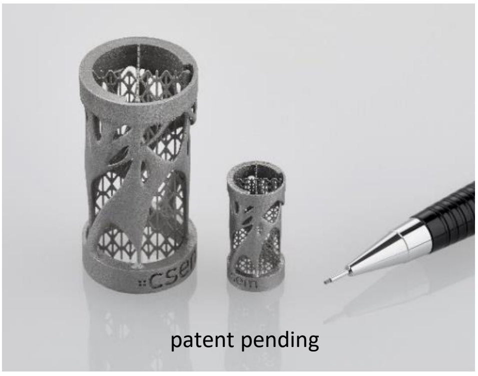


Figure 1. Example of the redesign of a C-flex type pivot with interlocked flexure blades.

2. Design methodology for AM-based Compliant Mechanisms

The development methodology for CM buid by AM consists in multiple steps to ensure fulfilling the specification. First, the preliminary design is performed with the definition of the global compliant architecture and a preliminary sizing. Then, the design is refined in two parallel processes: topology optimization of the rigid structure and shape optimization of the flexures. Finally, complete Finite Element Modeling (FEM) simulations are performed to verify the compliance with the requirements.

The principal steps of the design flow that have been elaborated to successfully achieve the development of a compliant mechanism based on AM are presented hereafter and illustrated by the example of the Compliant Rotation Reduction Mechanism (CRRM) shown in Figure 2.

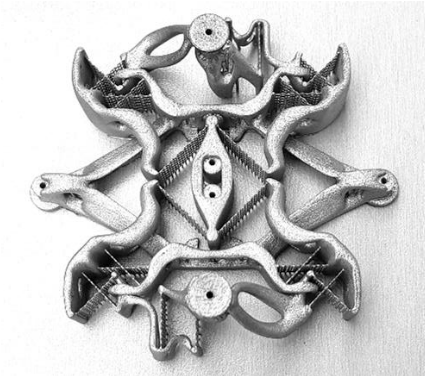


Figure 2. Compliant Rotation Reduction Mechanism (CRRM).

2.1 Inputs to the design

The principal specifications for the CRRM, at the general design and interface levels, are that the mechanism shall be frictionless. In terms of performance, the input angle shall be ±10° while the output angle shall be ±1°, meaning that the reduction ratio of the mechanism shall be 1:10. The repeatability of the system implies that the parasitic motion at output shall be smaller than 10 µm in the lateral and axial directions and that the parasitic tilt shall be smaller than 1/100°. Its dimensions shall be 120 mm x 50 mm and its mass shall be a maximum of 0.4 kg. For environmental performances, the mechanism shall withstand launch sinusoidal vibrations of 24 g, random vibrations of 18.4 g_{RMS} and shocks of 1000 g.

2.2 Preliminary design and trade-off

The preliminary design activity of an AM-based compliant mechanism can be divided into two phases. The first one consists in conventional pre-design activities. The flexure topologies and the overall physical architecture forming the basis of the design are defined, involving the analytical pre-sizing of various alternatives. A pre-design example of the CRRM is given in **Figure 3.**

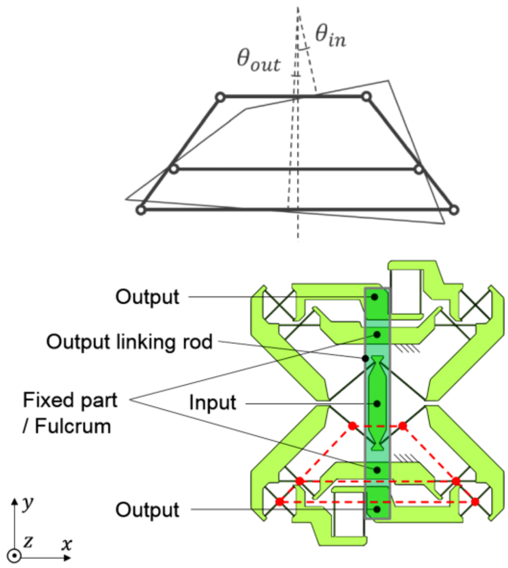


Figure 3. Architecture and pre-design of the CRRM.

The pre-design is then considered under the perspective of the Selective Laser Melting (SLM) process. The optimum build-up orientation is chosen during the design phase, the critical geometries are identified and the AM process strategy (support material and its future separation from the part) is defined. This is performed by taking into account support structure minimization in critical locations – where post-AM machining could be difficult if not impossible, post-process strategy (thermal treatment before/after removal) and separation from the build plate.

These activities are realized in accordance with the general design rules for AM and the specific rules for compliant structures. The manufacturability of the design should then be assessed. This is done thanks to SLM process simulation software. A post-processing sequence and a verification strategy is defined in accordance with the specific requirements for compliant structures, such as temporary fixation of mobile or intermediate stages and the considered material foreseen.

2.3 Detailed design

The detailed design comprises two main phases:

- Topology optimization of the rigid structure,
- Optimization of the compliant structure, i.e. the flexure blades.

Rigid structures optimization

A topology optimization of the rigid structure is performed on the initial design in order to improve its mechanical characteristics, especially the overall rigidity, together with a mass reduction goal. The work flow is the following:

1. Definition of the design and non-design spaces, where the design space is the part of the item where the optimization solver will be active. The non-design spaces are mainly the interfaces and other peculiar locations which need to be conserved as-is.
2. The boundary conditions and the load cases are defined.
3. The optimization parameters are defined.
4. The results are interpreted.
5. A CAD smoothing and/or rebuild is performed at the end as illustrated in Figure 4.
6. A final analysis with the new shape is performed.

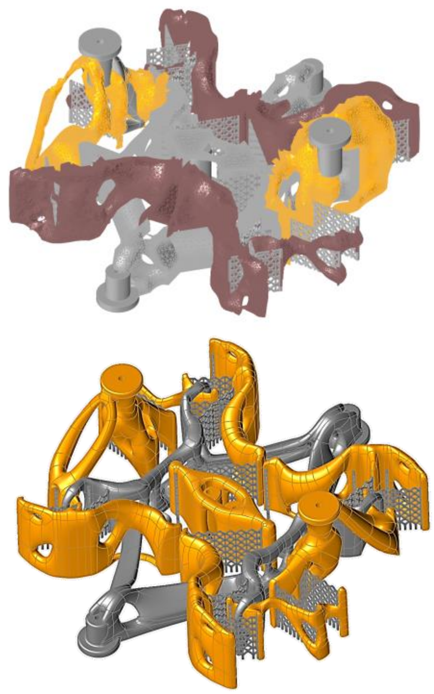


Figure 4. Result of the topological optimization (top); design example after smoothing (bottom)

Flexure blades optimization

The compliant structure shall be optimized separately to ensure an optimum solution with regard to performances, but also to ease as much as possible the manufacturing and the post-treatments, mainly the removal from the build plate.

The need to include support structures while producing thin flexure blades by AM is a critical aspect that must be taken into account while designing CM. The support structure is minimized and the attachment points of the support structure to the flexure are weakened in order to make its removal easier. The separation is performed when the part is cut off from the build plate. This concept has been successfully tested with several designs, as shown in **Figure 5.**

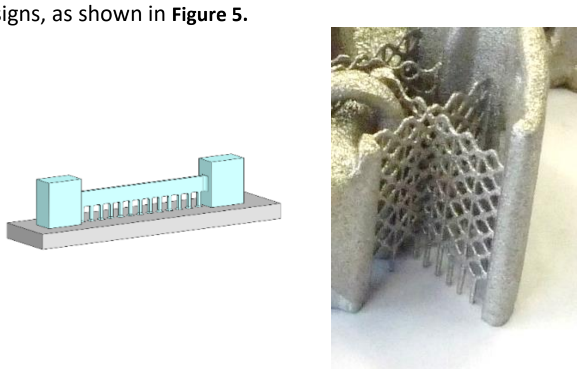


Figure 5. Example of minimization of the attachment points of flexure blades on the AM build plate.

While looking for the most appropriate design for flexure blades, CSEM innovated with a lattice structure (patent pending) having the main advantages of:

- Lowering the bending stiffness while maintaining a sufficient thickness for manufacturing,
- Avoiding internal support structure thanks to the overhang angle,
- Ability to be interlocked to form a pivot.

As no single solution allows for simultaneously optimizing the rigid and the flexible part of the mechanism [2], a dedicated procedure is devoted to this task.

We start by defining a unitary lattice cell from which the whole blade pattern will be generated applying symmetry operations. Then, this unitary cell is geometrically parametrized. Next, a large number of different cells are generated using a Monte Carlo method. Some rules must be respected regarding the manufacturing and integrity of the structure. Therefore, only the designs that are compliant to those rules are considered. For these remaining solutions, an objective function is defined based on different mechanical parameters with dedicated weighting factors. Example of such parameters are transverse stiffness and stresses. Another criterion to be assessed is the constancy of the section area along the longitudinal axis of the leaf spring.

The goal is to select a lattice that has a cross-sectional surface as constant as possible in order to avoid having a polygonal effect, to maintain a constant curvature of the leaf spring and to mimic at best the behaviour of a plain leaf spring. Finally, one of the remaining designs is selected as candidate for the final, detailed design.

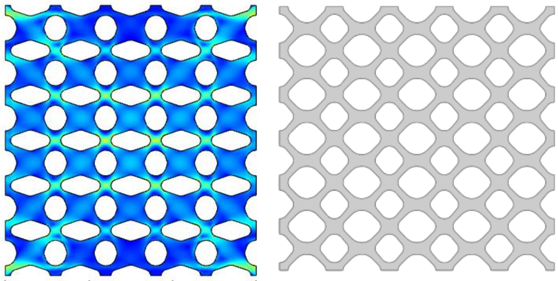
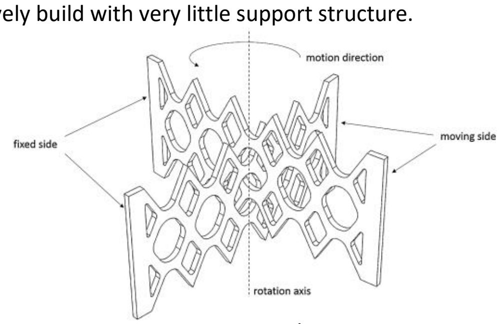


Figure 6. Stress distribution for one particular design (left); optimal lattice leaf spring pattern (right).

Interlocked lattice structures

Thanks to these optimized lattice structures as well as the opportunities given by AM, interlocked lattices flexures as illustrated in **Figure** 7 can be proposed. This architecture forms a rotational pivot with a high axial stiffness and which can be additively build with very little support structure.



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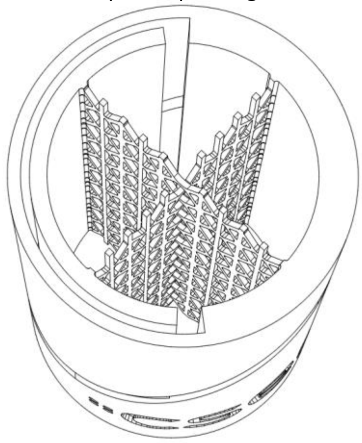

Figure 7. Rotation pivot composed of two latticework blades.

3. Test results

The preliminary material, process and post-process test results have already been presented during ESMATS 2017 [2]. During the current project, these results are consolidated with new tests such as residual stresses, dissolved gases, tensile, fracture toughness, hardness, roughness, general corrosion, stress corrosion cracking and fatigue. In parallel, the microstructure is verified as well. These samples have been additively manufactured in a high-strength stainless steel 17-4PH. They have seen the same post-processing treatments as foreseen for the final mechanism (i.e. HIP and solution annealing and age hardening).

3.1 Tensile test results

Ten tensile samples machined out of cylinders were characterised using a tensile test. Measured values of Yield strength ($R_p0.2$) and Ultimate tensile strength (UTS) were very similar for all tested samples at room temperature and varied from 1280 to 1330 MPa and 1380 to 1450 MPa for yield strength and UTS, respectively. The yield strength was slightly higher at

1410 MPa and 1440 MPa for samples tested at -40°C while UTS remained relatively unchanged. Measured Young's modulus E is between 190-210 GPa.

Elongation at failure exhibited the highest degree of variation from 1.2 to 6 %. Fractography revealed the presence of lack-of-fusion defects in the specimen with the lowest elongation (1.2%). For the rest of the samples tested at room temperature, necking occurred outside the measured gauge length, which contributed to the overall spread in measured elongations.

At -40°C the ductility remaines relatively high reaching near 7%.

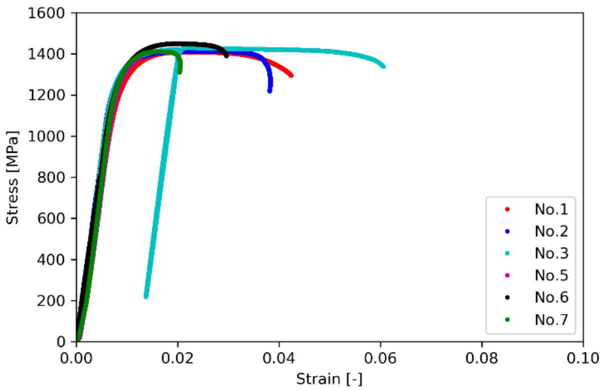

Figure 8. Stress-strain curves of six tensile tests performed at room temperature.

3.2 Hardness test results

Micro-hardness was measured on both ends of tensile samples after machining from cylinders. HV0.3 results lie within 450 and 500 which is a spread in values typical for micro-hardness measurements (ca. 10%). HV0.3 between 450 and 500 corresponds to approximately 48 HRC which is near the upper end of expected hardness values of 17-4 PH for this thermal condition.

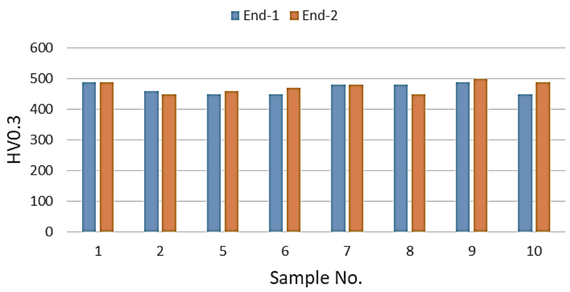

Figure 9. Hardness measurements.

3.3 Roughness test results

The roughness has been measured with a surface roughness tester on the fatigue test samples. No mechanical process has been performed on the surface. The mean Ra value is 8µm (±1.5µm) and is independent of the direction of printing and of the thermal treatments performed after printing. Compared to surfaces obtained by machining, this value could be seen as much higher but the roughness is only an indicative value. The fatigue test results are much more important with regard to the behavior of the compliant mechanism.

3.4 Fatigue test results

The fatigue behavior of this material has been already defined during a previous activity at CSEM with an alternate bending fatigue test bench [2]. The results highlight that, for flexure blades without surface improvement and therefore with a high rougness, the fatigue limit is only 15% under the one for flexure blades obtained by WEDM.

Additional fatigue tests have been carried out to consolidate the results, including the lattice flexure blades. The results indicate that the values of plain flexure blades are comparable to the results previously obtained by CSEM [2].

3.5 Performance tests

The performance tests will start soon and the results will be available in June. The following parameters will be measured and compared with the requirements and the simulation results:

- Dimensions with 2D optical and 3D laser scanner,
- Mass,
- Parasitic motions,
- Output torques and forces,
- Repeatability of the trajectory without output load,
- Accuracy of the trajectory with maximum output load,
- Stiffness; along and perpendicular to the motion,
- Elastic torque.

These performance tests will be followed by the environmental tests, comprising thermal cycling, vibration, shock and lifetime.

4 Conclusion

This paper highlights the methodology developed at CSEM to design, optimize and verify the development of innovative compliant mechanism made by additive manufacturing, while trying to take the best of this technology and overpassing the new limitations.

The ESA project COMAM is ongoing. The next steps are the manufacturing of two Elegant Breadboard Models and the tests; performances, vibration, shocks, thermal cycles and lifetime. In parallel, the testing of the characterization samples is in progress. All these results will be presented during the conference.

CSEM continues to work on the ultimate goal to have a global tool for the optimization of compliant mechanisms.

Reference

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[2] Saudan H, Kiener L, Perruchoud G, Vaideeswaran K and Dadras M, Additively manufactured and topologically optimized compliant mechanisms: technological assessment approach, latest achievements and current work in progress *Proceedings of the 17th European Space Mechanisms & Tribology Symposium*, Hatfield, United Kingdom, 20-22 Sept. 2017