Compliant Mechanisms Made by Additive Manufacturing

Lionel Kiener*, Hervé Saudan*, Florent Cosandier*, Gérald Perruchoud*, Vaclav Pejchal*, Sébastien Lani* and Antoine Verhaeghe*

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). The development methodology, the AM process and post-process and the testing approach are detailed in this paper.

![Figure 1. Compliant Mechanism built by Additive Manufacturing.](image)

Introduction

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

To overcome these important limitations, 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 environments such as vacuum, cryogenic and space combining high-precision and a long lifetime capabilities.
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). While the largest part of the research presently reported is focused on developing and optimizing designs of what could be described as “structural or massive parts”, little work has been published up to now to determine the limits related to the manufacturing of thin, flexible structures used in compliant mechanisms [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]. Over the last few years, CSEM has acquired an expertise in the computerized optimization of such mechanisms for AM and has proceeded further by inventing a totally new design concept: 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 2.

![Figure 2. Example of the redesign of a C-flex type pivot with interlocked flexure blades.](image)

**Compliant Mechanisms Heritage**

CSEM is active in the design and development of very high performance flexural elements and mechanisms for more than 30 years. Notable examples for space applications are the HAFHA flexural pivot and the Corner Cube Mechanism which is currently operated in the IASI instrument on board MetOp satellites, to date with more than 1 billion cycles (linear stroke of ±15 mm) achieved in 14 years. Two flight models of Corner Cube Mechanism has also been delivered last year for the infrared sounder onboard two Meteosat Third Generation satellites. Another example is the CLUPI linear Focus Mechanism for ExoMars rover. Other mechanisms (e.g., Slit Mask, tip-tilt and chopper) have been developed and produced for ground based telescopes as well as for the airborne SOFIA telescope.
In the same philosophy, the elaboration of new mechanisms made by additive manufacturing has been investigated at CSEM over several years targeting the general goals of assessing the benefits and weaknesses of the AM fabrication process for compliant mechanisms and getting a sufficient level of expertise on AM produced compliant mechanisms in perspective of future projects.

**Design Methodology for AM-Based Compliant Mechanisms**

The methodology to develop Compliant Mechanisms built by AM is not straightforward since the software tools do not always have a sufficient maturity for these kind of systems. The development workflow has been developed by CSEM to best utilize the strengths of all design, AM process and post-process simulation software. It consists of multiple steps as described herein. 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 Modelling simulations are performed to verify the compliance to the requirements.

The principal steps of the design flow that have been elaborated by CSEM 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 3.

![Figure 3. Compliant Rotation Reduction Mechanism (CRRM).](image)

The development of this CRRM is made for the European Space Agency (ESA) for a research project.

**Specifications**

The principal specification for the CRRM is that the mechanism shall be totally 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 input and output are also inverted, for a 10° clockwise rotation, the 1° output is counter clockwise.

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 gRMS and shocks of 1000 g.
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 4.

![Figure 4. Architecture and pre-design of the CRRM.](image)

Design for Additive Manufacturing
This pre-design is then considered under the perspective of the manufacturing process, i.e., Selective Laser Melting (SLM). The following aspects are chosen during this phase:
- optimum build-up orientation,
- identification of the critical geometries,
- geometry of interfaces; fixation areas, positioning features, reference surfaces,
- AM process strategy (support material and its future separation from the part).

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 which have been developed at CSEM.

The manufacturability of the design should then be assessed. This is done thanks to SLM process simulation software. A post-processing sequence, including thermal & mechanical post-processes and a verification strategy is defined in accordance with the specific requirements for compliant structures, such as temporary fixation of mobile stages and the addition of features for metrology.

Detailed design
The detailed design comprises two main phases:
- Topology optimization of the rigid structure,
- Shape 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.

The workflow 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 defined in the preliminary design. See Figure 5.
2. The boundary conditions and the load cases are defined.
3. The optimization parameters are defined.
4. The results are interpreted.
5. A shape smoothing and/or rebuild is performed at the end as illustrated in Figure 6.
6. A final finite element analysis with the new shape is performed to ensure fulfilling the requirements.

**Figure 5. Definition of the design spaces for the CRRM.**

**Figure 6. Result of the topological optimization (left); design example after smoothing (right).**

**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 no single solution allows for simultaneously optimizing the rigid and the flexible part of the mechanism [3, 4], a dedicated procedure is devoted to this task.

**Lattice flexure blades**
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.

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, as shown in Figure 7.

![Figure 7. Stress distribution for one particular design (left); optimal lattice leaf spring pattern (right).](image)

**Interlocked lattice flexible structures**
Thanks to these optimized lattice structures as well as the opportunities given by AM, interlocked lattices flexures as illustrated in Figure 8 can be proposed. This architecture forms a monolithic rotational pivot with a high axial stiffness and which can be additively build with very little support structure.
Based on these interlocked lattice flexures, the CRRM has been designed and the first prototypes of the CRRM have been successfully produced by AM-SLM.

Final simulation results
The simulation results after optimization show that the Statement of Work requirements are globally fulfilled, as presented in Table 1.

Table 1: Comparison of requirements with simulation results

<table>
<thead>
<tr>
<th>Main requirements</th>
<th>Statement of Work</th>
<th>Simulation results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input angle</td>
<td>±10°</td>
<td>±10°</td>
</tr>
<tr>
<td>Output angle</td>
<td>±1°</td>
<td>±1°</td>
</tr>
<tr>
<td>Diameter</td>
<td>100 mm</td>
<td>120 mm</td>
</tr>
<tr>
<td>Length</td>
<td>50 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td>Center shifts</td>
<td>&lt; 10 µm</td>
<td>&lt; 2 µm</td>
</tr>
<tr>
<td></td>
<td>&lt; 350 µrad</td>
<td>3 µrad</td>
</tr>
<tr>
<td>First eigen mode</td>
<td>&gt; 100 Hz</td>
<td>740 Hz (400 Hz before optim.)</td>
</tr>
<tr>
<td></td>
<td>with blocked IF</td>
<td></td>
</tr>
<tr>
<td>Input torque</td>
<td>to be minimized</td>
<td>0.24 Nm</td>
</tr>
<tr>
<td>Lifetime</td>
<td>min. 100,000 cycles</td>
<td>1 mio (goal)</td>
</tr>
<tr>
<td></td>
<td>-60° to +80°C</td>
<td>Stainless steel 17-4PH</td>
</tr>
</tbody>
</table>
Manufacturing

Manufacturing assessment
The additive manufacturing assessment has been made with the help of the Amphyon software tool, which simulates the Selective Laser Melting (SLM) process to give information about the internal stresses generated during layer manufacturing. These stresses could be responsible for macroscopic deformations of the parts as shown in Figure 9.

![Figure 9. Manufacturing layer by layer thermo-mechanical simulation.](image)

Based on these simulations, this tool generates a pre-deformed 3D geometry of the part to overcome these deformations with the aim of having a geometry that conforms to the nominally designed shape. Based on preliminary tests with thin and flexible structures, the residual deformations were in the range of 0.1 mm.

Material, process and post-process testing
The preliminary material, process and post-process test results have already been presented during ESMATS 2017 [3]. During the current COMAM project, these results have been consolidated with new tests such as residual stresses, dissolved gases, tensile, hardness, roughness, general corrosion, stress corrosion cracking and fatigue. In parallel, the microstructure was verified as well. These tests are performed on representative samples which 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., Hot Isostatic Pressing (HIP), solution annealing and age hardening).

In complement, the entire COMAM mechanism will be tested following the classical space approach with performance, vibrations, shock and thermal cycling. The first results are presented in the next chapter Mechanisms testing.

Tensile test results
Ten tensile samples machined out of AM-built cylinders were characterised. At room temperatures, measured values of Yield strength (\(R_{p0.2}\)) and Ultimate tensile strength (UTS) were very similar for all tested samples and varied from 1280 to 1330 MPa and 1380 to 1450 MPa for yield strength and UTS, respectively (Figure 10). For comparison, typical values for extruded forms are \(R_{p0.2}\): 1070 MPa and UTS 1170 MPa.

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 low temperature (-40°C), the ductility remains relatively high reaching nearly 7%.

Figure 10. Left: stress-strain curves of six tensile tests performed at room temperature; right: hardness measurement results.

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.

Roughness test results
The surface quality 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 8 µm (±1.5 µm) 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.

Fatigue test results
The fatigue behavior of this material has already been defined during a previous activity at CSEM with an alternate bending fatigue test bench. Additional fatigue tests have been carried out to consolidate the results, including the lattice flexure blades. The results indicate that the values of these AM-flexure blades are comparable to the results previously obtained by CSEM [2].
Mechanisms testing

Cleanliness assessment
The whole build plate was thoroughly cleaned after SLM in order to remove unfused metal particles and other potential contaminants before the HIP treatment. During the cleaning process performed in ultrasonic (US) bath, cavitation was visibly very homogenous, which indicates optimum US exposure. A significant amount of metallic particles was collected. In total 0.55 g for a total build mass of 1251 kg, representing 0.044%.

This process was repeated after HIP to see if more unfused particles could be removed. Here, only few particles have been collected for a total mass of 0.03 gram. They can be classified in four categories: raw powder, round dark particles, flakes (probably contaminants during HIP process) and a few bigger particles which should be partially melted powder aggregates, as shown in Figure 11.

Metrology
A combination of 2D optical metrology and 3D laser scan has been performed in order to evaluate the global build plate deformations which are mainly due to the stress generated during the SLM and thermal post-processes (HIP, solution annealing and age hardening). The metrology has been performed first after SLM, then after HIP and finally after SA-AH (still to be done at the time of writing). The comparisons are done first with the 3D CAD model, then between the step before and the actual state. The first results are shown in Figure 12. More work is ongoing to assess the impact of these deformation on performance.
Next Steps

The next step of the COMAM project is the final metrology measurements following the thermal treatments and the machining. This will be followed by performance measurements, vibration, shock and thermal cycling testing. The performance measurements will be compared with the simulation results to validate the design and ensure the compliance with the requirements.

Conclusions

We have described CSEM’s methodology developed to design, optimize and verify the development of an innovative compliant mechanism made by additive manufacturing. We have surpassed challenges and pushed this technology forward to implement innovative solutions.

The ESA COMAM project is ongoing. The next steps are the manufacturing of two Elegant Breadboard Models followed by the test campaign; performance, vibration, shocks, thermal cycles and lifetime. In parallel, the testing of the characterization samples is in progress.

CSEM continues to work on the ultimate goal to have a global tool for the optimization of compliant mechanisms. In parallel, functionalization of AM parts has been demonstrated and further projects will bring new examples of adding electrical, thermal and optical features.

References


