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Innovative concept of compliant mechanisms made by additive manufacturing

Lionel Kiener[1,*], *Hervé* Saudan[1], *Florent* Cosandier[1], *Gérald* Perruchoud[1] and *Peter* Spanoudakis[1]

[1]Centre Suisse d'Electronique et de Microtechnique (CSEM), Neuchâtel, Switzerland

Abstract. The complete redesign for Additive Manufacturing of compliant mechanism structures enables CSEM to develop innovative concepts to drastically reduce the need of machining and assembly after additive manufacturing. Support structures under flexure blades are thus minimised and the overall process becomes more streamlined. Moreover, this concept allows us to easily design and produce monolithic cross flexure pivots with interlocked flexible blades. Based on this concept, CSEM is now developing new architectures of Compliant Mechanisms based on Additive Manufacturing (COMAM) for the European Space Agency (ESA) in the frame of a GSTP research project. The past and current work of design, 3D printing and testing on several compliant mechanisms are presented. These demonstrators will be used as use-case for future high-precision and harsh environment applications such as cryogenic and space.

1 Introduction

Compliant Mechanisms (CM) can achieve macroscopic linear and rotary motion without any friction, wear, backlash, and with extremely high fatigue performance thanks to the elastic deformation of flexible structures. To date, the extreme complexity of such 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 and a stiff mechanism.

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). 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 [1].

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

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[*] Corresponding author: lionel.kiener@csem.ch

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 here with three different examples.

2. Re-design for Additive Manufacturing

The heritage of 30 years in the development of compliant mechanisms (CM) for space combined with the in-depth knowledge acquired for the design, manufacture and testing of metallic CM made by additive manufacturing allow CSEM to present some achievements. The first one is the redesign of a slip ring rotor where the number of parts to be assembled has been drastically reduced, as shown in chapter 2.1. The second is the interlocked lattice flexure blades, allowing us to improve the manufacturability and scalability of the crossed blade pivot (see chapter 2.2). This configuration has also been reused for the ongoing research project for the European Space Agency (ESA), as presented on chapter 2.3.

2.1 Redesign of a slip ring rotor assembly

A novel design concept based on an Additive Manufacturing, enabling the development of mechanical parts featuring built-in electrical wires and interfaces has been developed and tested [2] & [3]. The concept has been successfully applied to re-design the rotor of a SlipRing Assembly (SRA) intended for space applications. The implementation of the concept leads to a significant simplification of the physical architecture of the product, with subsequent reduction of the manufacturing and assembly operations, as presented on Fig.1. Considering a rotor featuring 12 channels, the new architecture involves only one SLM-made structure instead of more than 30 high precision components.

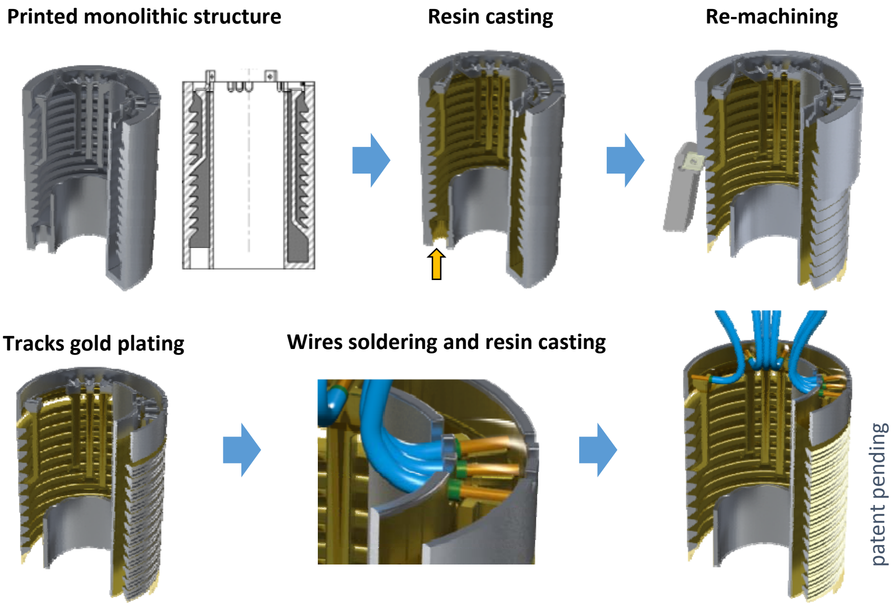

Fig. 1. New SRA rotor manufacturing sequence

Several prototypes were manufactured and validated through a set of standardized functional and performance tests. The project is ongoing with the production of fully functional rotor models of 30 tracks, which will be intensively tested and qualified for space flight applications.

The original design and manufacturing concept invented allowed developing and validating a cable-less SRA rotor intended for space applications. This concept can be advantageously applied to other electro-mechanical components and assemblies, with the same potential to simplify their architecture.

2.2 Interlocked lattice flexure blades

A major challenge of building compliant structures by powder-bed additive manufacturing is the requirement to a add support structure under overhanging areas. When producing thin flexure blades, this critical aspect must be taken into account. While looking for the most appropriate design for flexure blades, CSEM innovated with a lattice structure (Fig. 2, 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.

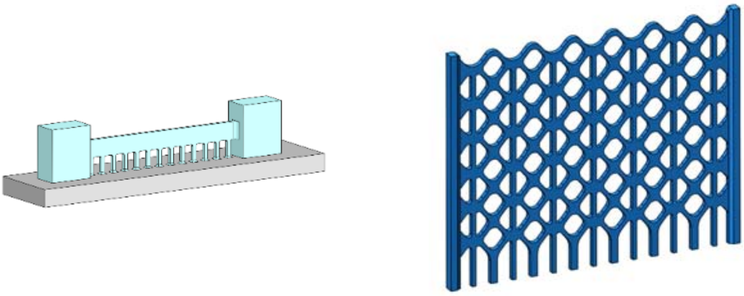

Fig. 2. Example of minimization of the attachment points of flexure blades on the AM build plate.

Thanks to these optimized lattice structures as well as the opportunities given by AM, interlocked lattices flexures as illustrated in Fig. 3 can now be proposed. This architecture forms a rotational pivot with a high axial stiffness and which can be additively built with very little support structure.

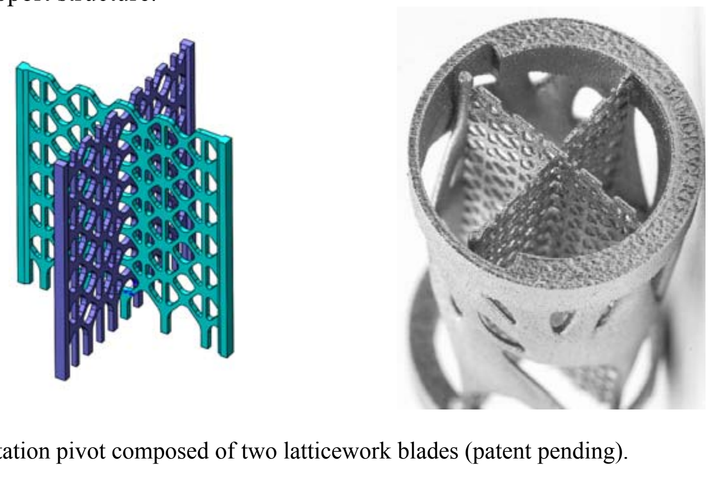

Fig. 3. Rotation pivot composed of two latticework blades (patent pending).

Several advantages can be combined to form a new product, such as the combination of multiple parts to avoid the necessity of assembly and to improve the scalability. An example is illustrated in Fig. 4 with the redesigned of a C-flex type pivot (patent US 3073584).

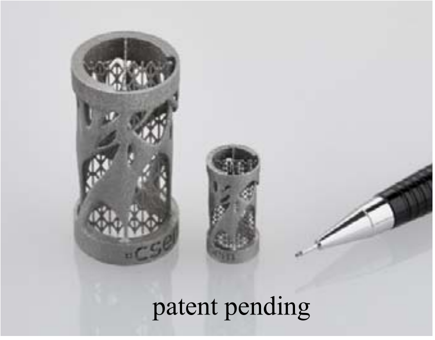

Fig. 4. Example of the redesign of a C-flex type pivot with interlocked flexure blades.

2.3 Monolithic compliant mechanism based on additive manufacturing

2.3.1 Specifications

The principal specifications for the Compliant Rotation Reduction Mechanism (CRRM), at the general design and interface levels, are that the mechanism shall be friction-free. In terms of performance, the input angle shall be ±10° while the output angle shall be ±1°, meaning that the amplification ratio of the mechanism shall be 1 : 10. The repeatability of the system implies that the parasitic motion at the 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.

2.3.2 Preliminary design

The preliminary design activity of an AM-based compliant mechanism can be divided into two phases. The first one consists of 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 5.

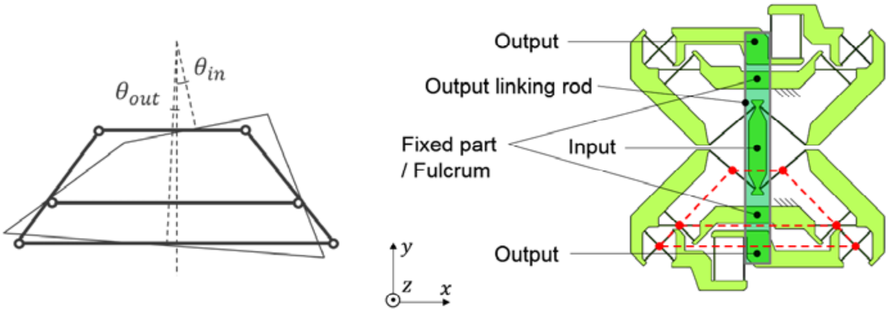

Fig. 5. Architecture and pre-design of the CRRM.

The pre-design is then considered under the perspective of the foreseen AM process. Here, the AM process selected is Selective Laser Melting (SLM). The optimum build-up orientation must be chosen, the critical geometry identified and the AM process strategy (support material and part separation) to be 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 removal 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 then defined in accordance with the specific requirements for compliant structures, such as temporary fixation of mobile or intermediate stages and the considered material foreseen.

2.3.3 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 (Fig. 5).
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 Fig. 6.
6. A final analysis with the new shape is performed.

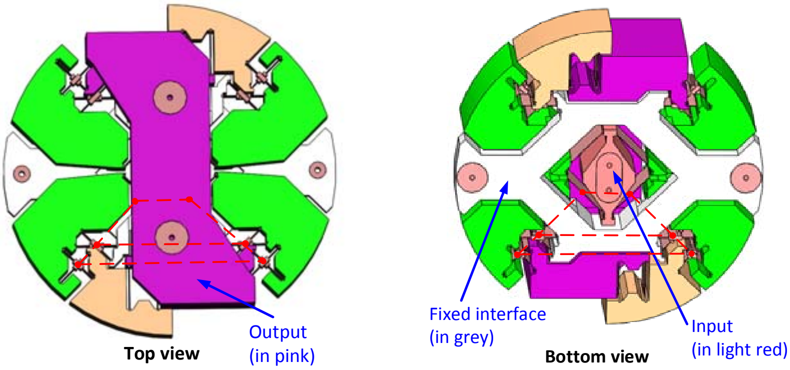

Fig. 5. Definition of the design spaces for the CRRM.

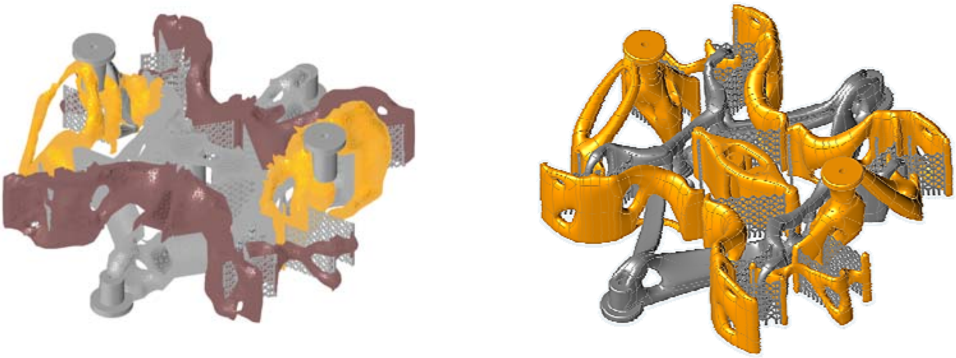

Fig. 6. Result of the topological optimization (left); design example after smoothing and enhancement of the optimization results (right).

The first prototypes of the CRRM have been successfully produced by AM-SLM, as shown in Figure 7. The next steps are the performance measurements to validate the design, followed by the vibration, shock and thermal testing.

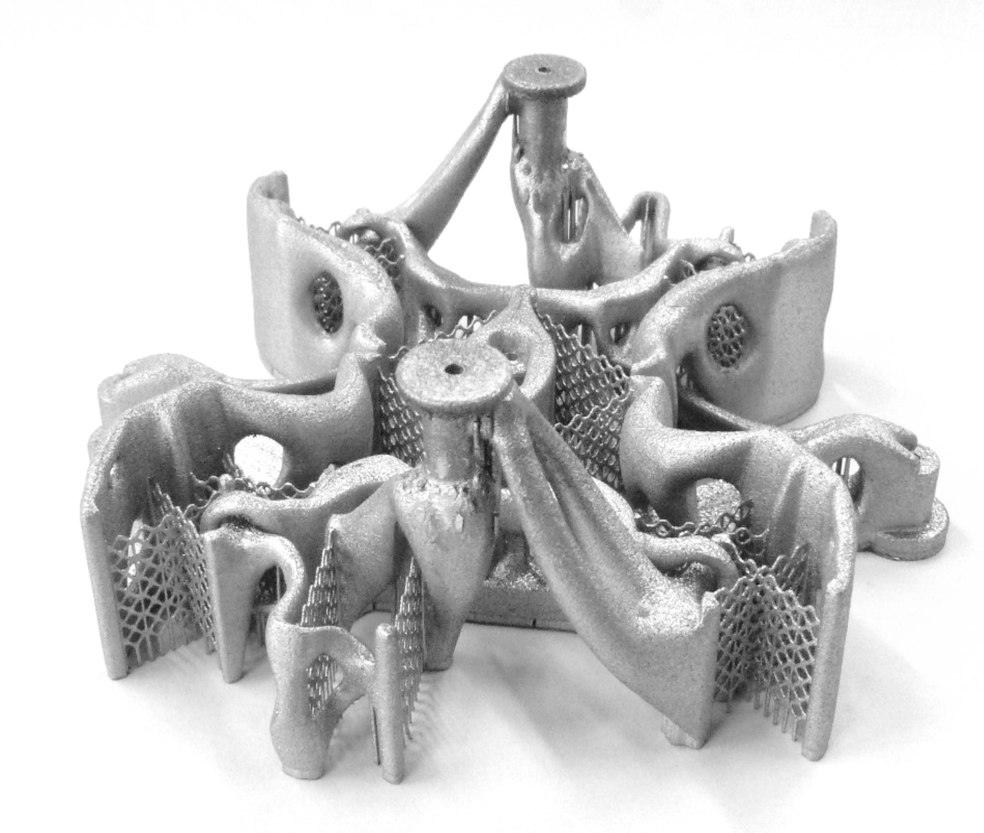

Fig. 7. Picture of the first monolithic CRRM prototype.

Conclusion

This paper highlights the methodology developed at CSEM to design, optimize and verify the development of innovative compliant mechanisms made by additive manufacturing, while trying to take the best of this technology and surpassing the new limitations. Several examples are presented to demonstrate the capabilities of this new manufacturing method. CSEM continues to work on the ultimate goal to have a global tool for the optimization of compliant mechanisms.

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