INNOVATIVE CONCEPT FOR ADDITIVE MANUFACTURING OF COMPLIANT MECHANISMS

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ABSTRACT

The new geometric possibilities offered by Additive Manufacturing (AM) combined with a complete redesign of compliant mechanisms have allowed CSEM to develop innovative concepts (patent pending) 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 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 new architectures of Compliant Mechanisms based on Additive Manufacturing (COMAM) for the European Space Agency (ESA) in the frame of a GSTP research project.

1 INTRODUCTION

Compliant Mechanisms (CM) 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. 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 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.

2 DESIGN AND SIMULATION PROCESS FOR AM-BASED COMPLIANT MECHANISM

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

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

Figure 2. Compliant Rotation Reduction Mechanism (CRRM) developed following the approach presented in this paper.
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\text{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.](image)

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 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 (Figure 4).
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 5.
6. A final analysis with the new shape is performed.

![Figure 4. Definition of the design spaces for the CRRM.](image)
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 necessity to include support structures while producing thin flexure blades by AM is a critical aspect that must be taken into account when 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 removal 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 6.

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 [1], 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.
Interlocked lattice 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 rotational pivot with a high axial stiffness and which can be additively build with very little support structure.

![Interlocked lattice structures](image)

Figure 8. Rotation pivot composed of two latticework blades.

2.4 Thermal warpage compensation

To quantify the warpage induced by the thermal history accumulated during the SLM process, samples were produced and measured. A simulation software was used to simulate the deformation of the part during the SLM process. The simulation results were compared with the manufactured part. In a second step, a pre-deformed 3D model of the part was generated by the software. This pre-deformed model was manufactured, 3D-scanned and compared with the nominal design.

The simulation software uses calibration samples as an input to estimate the stress intensity. These samples are manufactured with the same SLM process parameters as the final part and are subjected to the same thermal post-processing to ensure a full representativeness.

To verify the simulation results and the ability of the software to obtain the desired shape, two Butterfly Hinge pivots were manufactured by SLM, one with the nominal geometry and the other with the pre-deformed geometry shape as generated with the process simulation software.

The two parts were measured with a laser 3D scanner to quantify the geometrical deviations between them.

![Thermal warpage compensation](image)

Figure 9. Top: emphasis of the deformed shape obtained by Amphyon. Bottom left: built pivot with the nominal geometry. Bottom right: built pivot with the pre-deformed shape.

The optical metrology measurement results tend to confirm the improvements enabled by the use of pre-deformed models generated with the process simulation software. Currently, local geometry deviations in the range of 100-150 µm are still observed and the way forward for further improvement is currently discussed with the software provider.

3 SAMPLES CHARACTERIZATION TEST RESULTS

The preliminary material, process and post-process test results have already been presented during ESMATS 2017 [1]. During the current project, these results will be 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). At the time of writing, the tensile, hardness, roughness and preliminary fatigue test results are available, while the other tests are ongoing.
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 remained relatively high reaching near 7%.

Figure 10. 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 in H925 condition.

Figure 11. 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 [1]. Additional fatigue tests are currently being carried out to consolidate the results, including the lattice flexure blades. The tests are ongoing, but the first results indicate that the values of plain flexure blades are comparable to the results previously obtained by CSEM.

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 GSTP project 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 next conferences.

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

REFERENCE