ADD FLEXIBILITY TO YOUR SYSTEMS WITH COMPLIANT MECHANISMS BUILT BY ADDITIVE MANUFACTURING

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KEYWORDS

compliant mechanisms, additive manufacturing, selective laser melting, laser powder bed fusion, fatigue testing, flexure blade, monolithic cross flexure pivot

ABSTRACT

Based on a new concept developed at CSEM to build flexible structures by means of metal 3D printing, several compliant mechanisms have been redesigned for Additive Manufacturing (AM). In addition to the new geometrical possibilities offered by AM, the needs for machining and assembly after printing are drastically reduced. Support structures under flexure blades are thus minimized and the overall process becomes more streamlined. Moreover, this patented idea allows one to advantageously design and produce monolithic cross blade flexure pivots with interlocked flexures.
Thanks to this concept, CSEM has developed, manufactured and tested new architectures of Compliant Mechanisms based on Additive Manufacturing (COMAM) for the European Space Agency (ESA) as shown in Figure 1.

Figure 1: Compliant Rotation Reduction Mechanism (CRRM) built by Additive Manfacturing

1. INTRODUCTION

Mechanisms with friction present significant drawbacks with the need of lubrication, the generation of debris 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 disadvantages, Compliant Mechanisms (CM) are usually proposed. They can achieve macroscopic linear and rotary motions without friction, wear 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, where friction is to be avoided, and when high-precision and long 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. Moreover, the assembly involves heavy tooling as well as long and delicate manual operation to ensure a precise positioning between all parts. Today, this paradigm is questioned by the possibilities offered by AM technologies, notably the metallic Laser Powder Bed Fusion (LPBF) [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], [3]. CSEM has acquired an expertise in the computerized optimization of such mechanisms for AM and is proposing a novel patented concept: the interlocked lattice flexures. This new type of compliant structure is such that the flexure elements cross, without touching each other, even when deformed. This new architecture – made only possible thanks to AM technologies – creates the opportunity to develop completely new flexure topologies but also to improve existing ones. This is demonstrated with the example of a redesigned C-flex type pivot (patent US 3073584) illustrated in Figure 2.

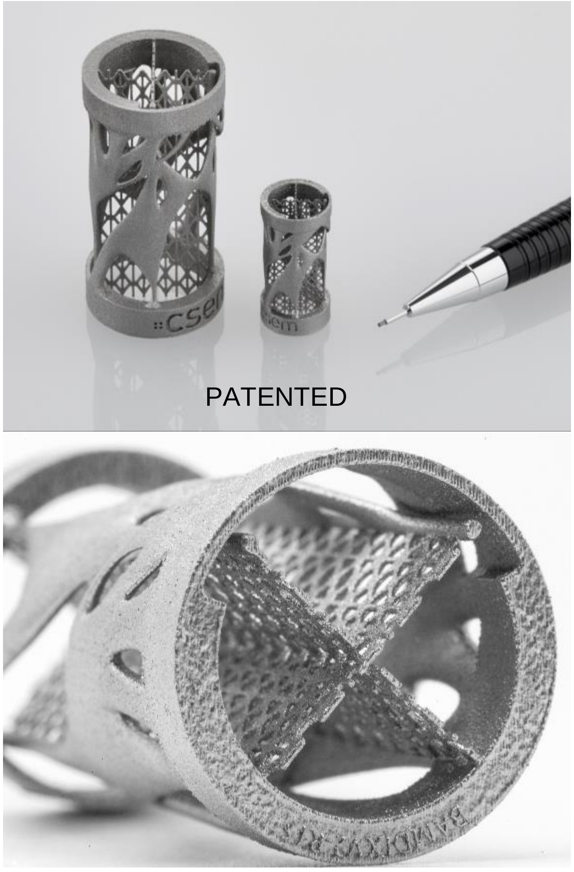

Figure 2: Redesign of a C-flex type pivot with interlocked crossed flexure blades

The successful integration of these pivots in a mirror tile prototype for future large telescopes robotically assembled in space has been detailed in [4]. The complete design process, including the definition of the architecture and, the integration of the interlocked flexures before the topology optimization, has been detailed in a previous publication [5].
The present paper focuses on the design, manufacturing, post-processing and testing of the Compliant Rotation Reduction Mechanism (CRRM) as shown in Figure 1.

2. DESIGN METHODOLOGY

The development methodology for compliant mechanisms built by AM involves multiple steps to ensure fulfilling the target 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 structures [2] and parametric shape optimization of the flexures. The final 3D model is then consolidated with the assembly of the results of both optimizations, with the addition of the mechanical interfaces (Figure 3). Finally, complete Finite Element Modelling (FEM) simulations are performed to verify the compliance with the requirements, in terms of performances and environmental considerations.

These steps are further detailed in [5].

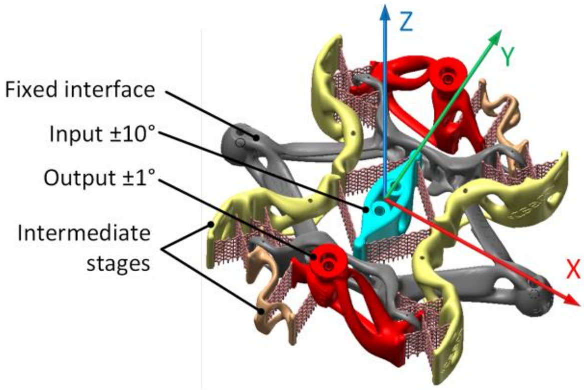

Figure 3: Final design of the mechanism

3. MANUFACTURING AND POST-PROCESS

SLM process simulation has been performed with the final 3D design to check that no overheating will occur and to anticipate distortions due to thermal effects during printing. The use of the manufacturing process simulation software Amphyon™ helped to reduce the deformations by generating a pre-deformed 3D shape which was used as input file for the SLM process.
Two mechanisms have been printed on one build plate with the batch samples (Figure 4). These latter are composed of tensile rods, bending fatigue test samples, powder cubes, fused cubes for density, hardness and microstructure that have been analysed for the validation of the build job.

Figure 4: Build plate with two mechanisms and the batch samples

The metrology inspection has been performed with a 2D optical system and with a 3D laser scanner. These two methods are complementary since the small flexure blades are only hardly reconstructed by the laser scanner. The advantage of the 2D optical system is that its resolution, coupled with the fact that all the flexures are vertical and visible from above, allow to precisely measure the location and eventual distortion of any of the 24 flexible lattice blades.
Even with all precautions set to ensure a conform SLM production, the build plate deformed during the process. The global plate deformation was approx. 0.2 mm in the building direction. These distortions have been partially compensated after the thermal

treatments during the machining, but the compliant architecture could not fully recover its nominal straightness and therefore the guiding performances are affected. The residual distortions at the flexure interfaces are in the range of 0.05 to 0.2 mm, as shown in Figure 5. New strategies are now tested to reduce these deformations.

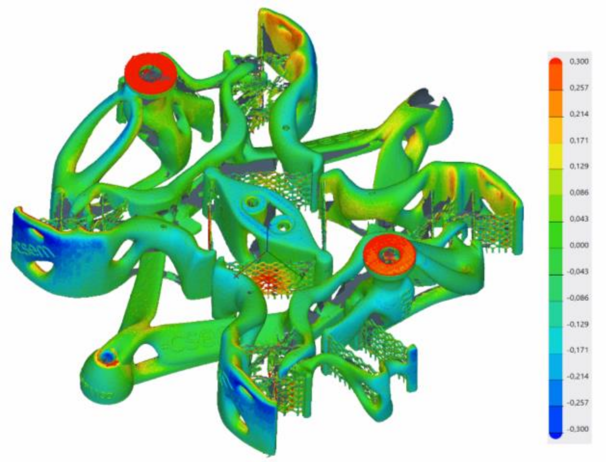

Figure 5: Deformation of the mechanism compared with 3D CAD model (scale in mm)

4. TEST RESULTS

4.1. Performance test results

The functional and performance test results are resumed and compared with the requirements and the predictions in Table 1.
The geometrical and cinematic aspects (input and output angle limits, reduction ratio) are well respected, even with strong distortions as shown in chapter 3.

Table 1: Comparison of requirements with simulation and measurement results

	Required	Predicted	Measured
Input angle	±10°	±10°	+10.2° -9.97°
Output angle	±1°	±1°	+1.03° -1.06°
Reduction ratio	10	10	9.93-9.98
Diameter	< 120 mm	117 mm	117 mm
Length	< 50 mm	40 mm	40 mm
Mass	< 400 g	349 g	330-336 g
Parasitic motions	< 10 µm	< 2 µm	see Figure 6
	< 350 µrad	3 µrad	see Figure 6
First eigen mode (locked)	> 100 Hz	729 Hz	555 Hz
Input torque	to be minimized	0.24 Nm	0.25 Nm
Lifetime cycles	> 100'000	Infinite life	see § 0

The parasitic motions are higher than the specification, except for one value, as shown in Figure 6. This is explained by the severe distortions due to SLM process and thermal treatments that induce an improper cinematic. It shall be noted that for the second mechanism (EBM2), the values are not far from the specified ±10 µm, even with distortion up to 200 µm near the flexure fixations. It indicates that with reduced distortions, the mechanism can fulfil these stringent requirements.

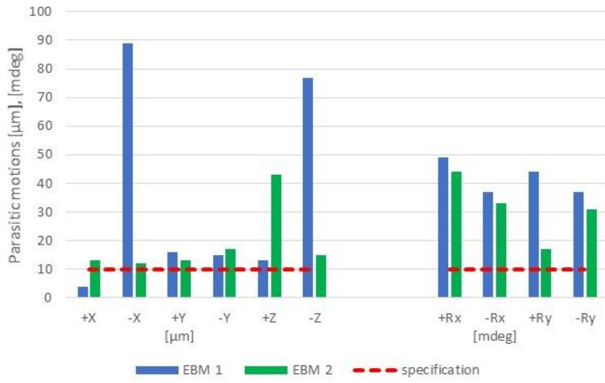

Figure 6: Parasitic motions at output I/F

The repeatability in position (without output loads) is below the specified 0.5% of the output motion range with results between 0.37% and 0.42%. The repeatability of the mobile stage coming in contact with the end-stops is even better. This good precision between two un-machined surfaces (raw from SLM, with a roughness R_a around 8 µm) indicates that the end-stops could be used as position reference to initialize an open-loop system. The input torque is also conforming to the prediction at 0.25 Nm compared with the predicted 0.24 Nm.

4.2. Vibration test results

The first mechanism was integrated in locked configuration in the vibration test bench to be representative of the space launch conditions. The fixed input and output interfaces were aligned with shims and secured by screws to ensure an additional stress induced by an offset of 20 µm in each X, Y & Z directions at the output structure.
The first eigen-mode has been measured at 555 Hz in locked configuration, lower than the predicted 729 Hz. This can be explained by the lower stiffness of the mechanism. This comes from the flexure blades which have a thinner participative section because of their high roughness. Note that these values are far above the requirement of 100 Hz minimum, thanks to the topology optimized structure.
The mechanism survived the test at -3dB in X direction before being damage during 0dB test. After inspection with the 3D laser scanner, it was found that the fixed interface slipped during the test. This is due to a manufacturing non-conformance, where the centring oblong hole has been machined with a wrong orientation. Despite this failure, the mechanism survived at least 13 g_{RMS}, and based on the predictions, it shall sustain 18.4 g_{RMS} in random and 24 g in sine mode when correctly fixed.

4.3. Lifetime test results

The second mechanism was used to verify the lifetime. It was integrated on a fatigue test bench able to rotate the input stage of the mechanism with a stroke of ±10°. While the predictions based on the nominal stress computation indicated an infinite lifetime, one flexure blade broke prematurely between 70'000 and 80'000 cycles (Figure 7) whereas the target specification is 100'000 cycles.

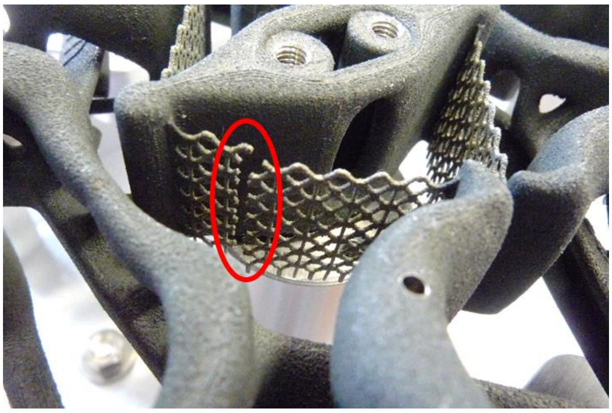

Figure 7: Fatigue fracture of input flexure blade

As this result did not correspond with the values obtained during the fatigue tests performed previously on representative flexure blade samples (typically 10 Mcycles under representative stress level), investigations were performed to understand the root cause. The blade which failed was significantly deformed due to the SLM process and thermal treatments, as explained in chapter 3 and highlighted in Figure 8. The results of this root cause analysis and the extensive amount of experimental fatigue on flexure blades allows us to assume that in case of non-deformed flexures, the lifetime specification shall not be an issue.

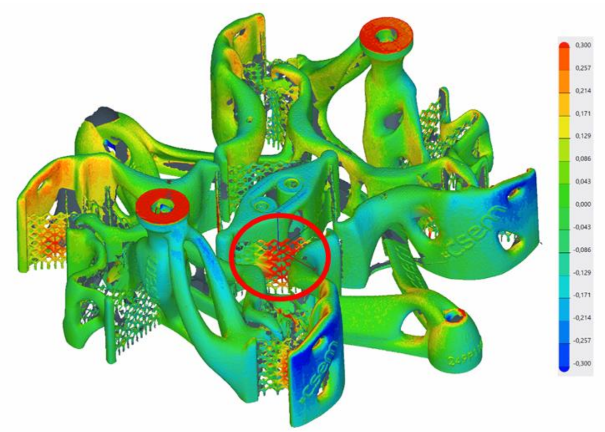

Figure 8: 3D laser scan with a highlight of the deformed flexure blade (scale in mm)

5. CONCLUSION

This project allows to take benefit of major advantages of the additive manufacturing, such as the design freedom and the possibility to build monolithic complex shapes.
This design – integrating 24 flexure blades among which 16 are interlocked to form crossed pivots and 8 intermediate stages – would not be possible in such a small volume without the use of AM. Moreover, no alignment is needed between the flexure structures to ensure a proper cinematic.
Thanks to a thorough combination of parametric and topology optimizations, the mass and eigen-frequencies have been significantly improved, e.g. with the first eigen-mode higher than 550 Hz.
The performance and lifetime test results suffer from the significant distortion of the two compliant mechanisms. Investigations are ongoing to reduce these distortions to an admissible value. This will ensure that the performances of compliant mechanisms built by additive manufacturing will be compatible with the high-precision guiding requirements.

A video of the moving mechanism can be seen here: https://youtu.be/0oBJe5uF40I

6. ACKNOLEDGMENTS

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