Compliant Mechanism based on Additive Manufacturing

Lionel Kiener[1], Hervé Saudan[1], Florent Cosandier[1], Gérald Perruchoud[1], Antoine Ummel[1], Vaclav Pejchal[1], Paolo Zaltron[2], Yoël Puyol[3], Marc Lichtenberger[3]

[1]*Centre Suisse d'Electronique et de Microtechnique (CSEM), Neuchâtel, Switzerland*
[2]*European Space Agency (ESA), Noordwijk, Netherland*
[3]*Almatech SA, Lausanne, Switzerland*

lionel.kiener@csem.ch
ORCID 0000-0001-7855-9945

Abstract

An innovative concept of building compliant mechanisms by Additive Manufacturing (AM) developed at CSEM is presented. Bringing together CSEM's experience in the design and development of high-performance flexural elements and mechanisms for more than 30 years has opened the doors to new opportunities.

The complete development of compliant structures for AM enables CSEM to develop innovative concepts to drastically reduce the need of machining after additive manufacturing. Support structures under flexure blades are integrated to the flexures with no need for removal, which makes the overall process becomes more streamlined.

Thanks to this concept, CSEM has developed new architectures of Compliant Mechanisms based on Additive Manufacturing (COMAM) for the European Space Agency (ESA).

These demonstrators will be used as use-case for future high-precision and harsh environment applications such as cryogenic and space.

The complete development workflow, starting with the design, topology optimization, manufacturing, post-processes, validation, up to performance and environmental testing will be presented.

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

Keywords

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

Declarations

Funding

This project has been funded by the Swiss Space Office of the State Secretariat for Education, Research and Innovation SERI.

Conflicts of interest/Competing interests

The authors declare that they have no conflict of interest/competing interests.

Availability of data and material

Not applicable

Code availability

Not applicable

Authors' contributions

Conception or design of the work: L. Kiener, H. Saudan, F. Cosandier, G. Perruchoud, A. Ummel, P. Zaltron

Data collection: L. Kiener, H. Saudan, F. Cosandier, V. Pejchal, Y. Puyol

Data analysis and interpretation: L. Kiener, H. Saudan, F. Cosandier, G. Perruchoud, A. Ummel, P. Zaltron, M. Lichtenberger

Drafting the article: L. Kiener

1. Critical revision of the article: P. Zaltron
2. Final approval of the version to be published: P. Zaltron

1 INTRODUCTION

Mechanisms with friction present significant drawbacks with the need for 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 precise positioning between all parts. Today, this paradigm is questioned by the possibilities offered by AM technologies, notably the 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 concept (patent pending): 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 possible using 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.

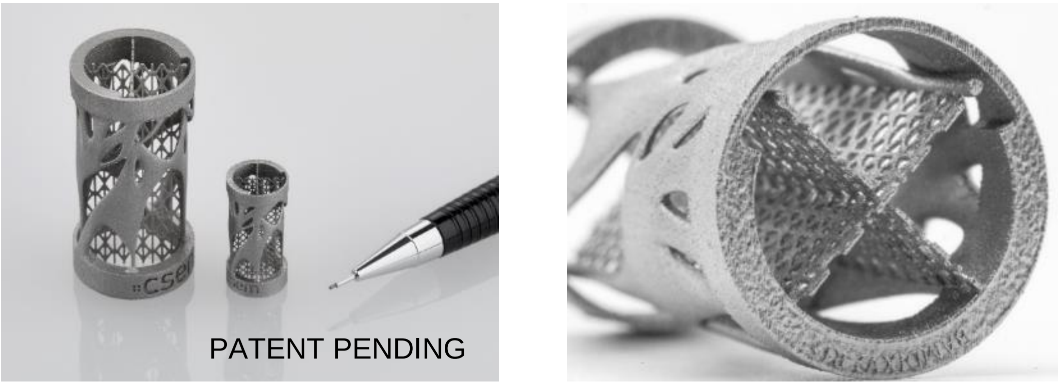


Figure 2: Redesign of a C-flex type pivot with interlocked crossed flexure blades

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 present paper presents the complete development process, including the definition of the architecture, the design with the integration of the interlocked flexures before the topology optimization, manufacturing, post-processing and testing of the Compliant Rotation Reduction Mechanism (CRRM) as shown in Figure 1.

2 PROJECT OVERVIEW

2.1 Project goal

Based on the state-of-the-art analysis performed at the beginning of the project, we can observe that such compliant mechanisms with complex architecture are generally composed of a lot of precise parts to be machined, verified, aligned and assembled together. One of the major advantages to build a mechanism by AM is the drastic reduction of the assembly process and the possibility to build more complex 3D compliant structures. **The COMAM project demonstrated the advantages of building a compliant mechanism by additive manufacturing.**

2.2 Project workflow

The project workflow is shown in Figure 3. The first task was the establishment of a survey for potential space applications for such mechanisms and the refinement of the requirements. In parallel, a state-of-the-art on compliant mechanisms and AM technologies was issued.

The preliminary design and analysis was performed on three different mechanism architectures to be concluded by a trade-off to select the most relevant mechanism for the next phase, which was the detailed design and optimization. In parallel, critical features were selected, designed, manufactured and tested to reduce the identified risks.

After the Critical Design Review, two mechanisms were manufactured and inspected at each step of the post-processes. Lately, they were tested to assess the functionality, the performances, and the sustainability to space environment. Finally, a roadmap was established for the next steps, taking into account the lessons learned and the most critical points to address in the near future.

The main tasks and achievements are resumed in the next chapters.

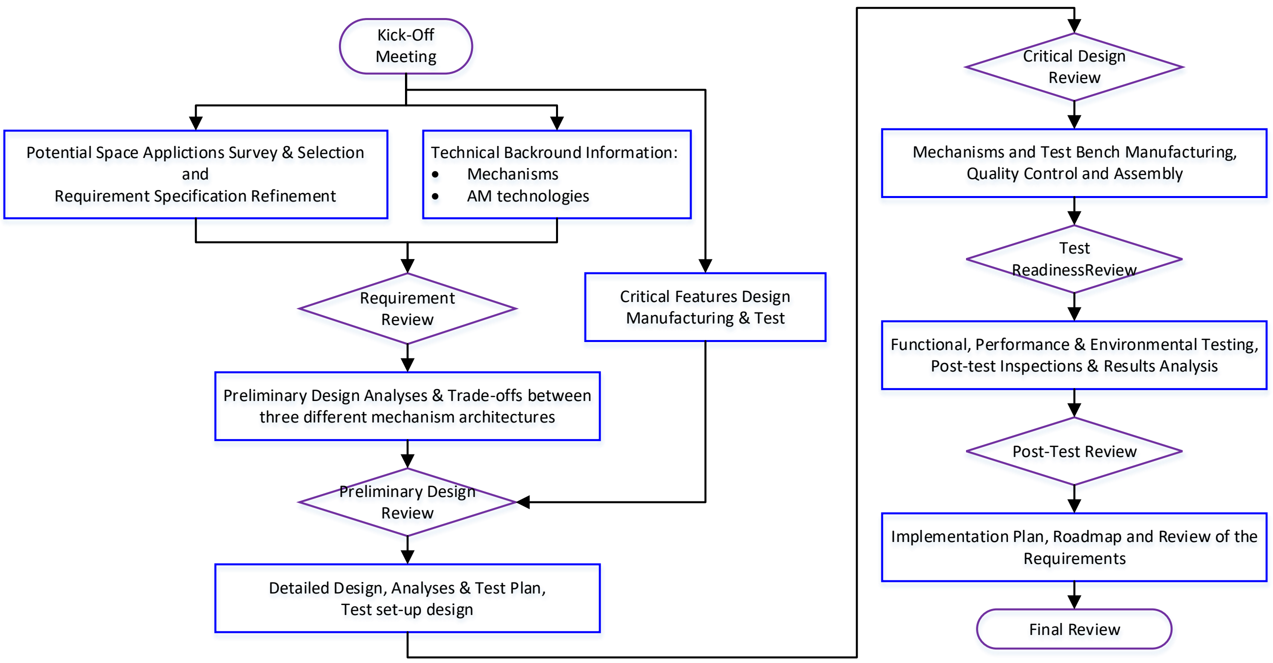


Figure 3: COMAM project workflow

2.3 Technical background information, refinement of the specifications based on potential applications

The first part of the project included a review of the relevant state-of-the-arts for:

- Compliant mechanism designs and architectures, including the associated risks
- Conventional manufacturing technologies
- Post-manufacturing treatments
- Additive Manufacturing (AM) materials, processes and post-processes for metals
- Validation and testing of compliant mechanisms (destructive and non-destructive methods).

A workflow for the design and analysis of AM-based compliant mechanisms has been established. All this information helped us to highlight the potential benefits of such mechanisms and the related risks have been discussed.
The main advantages of monolithic AM compliant mechanisms are:

- Design freedom for complex 3D shapes, novel kinematic topologies
- Highly optimized parts (mass, stiffness, eigen-frequencies, volume, thermal)
- Increased reliability by reducing the assembly, number of fasteners, etc.
- Reduced lead time, increased production capacity, especially for small satellites, constellations
- Addition of functions: electrical conductors, integrated sensors, thermal functions

2.4 Additive manufacturing materials, processes and post-processes

The most common metallic AM processes have been reviewed. The choice has been made to use the **Selective Laser Melting (SLM)** process, which was at that time the most common and well mastered metallic AM process, at least for space applications.

In parallel, the chosen material was the high-performance **stainless steel 17-4PH** (Concept Laser CL92PH powder) [2]. The major drawbacks of this material are the high density and the need for thermal treatments. Aluminium or titanium alloy would have been more advantageous, but the lifetime aspect has been more important.

Regarding the **post-processes**, the good fatigue results obtained during the previous activity [2] with raw (unmachined, unpolished) flexure surfaces led us to avoid any mechanical process of the flexure surfaces after printing. Therefore, the post-processes for COMAM were:

1. Cleaning assessment
2. Hot Isostatic Pressing (HIP)
3. Solution annealing and age hardening, which are mandatory for this alloy to obtain the suitable mechanical properties
4. Interfaces machining
5. Separation from build plate
6. Cleaning

3 DESIGN, ANALYSIS AND OPTIMIZATION WORKFLOW

3.1 Trade-off between three architectures

A trade-off between three different mechanisms architectures was proposed. The three mechanisms which were designed and analyzed are shown in Figure 4.

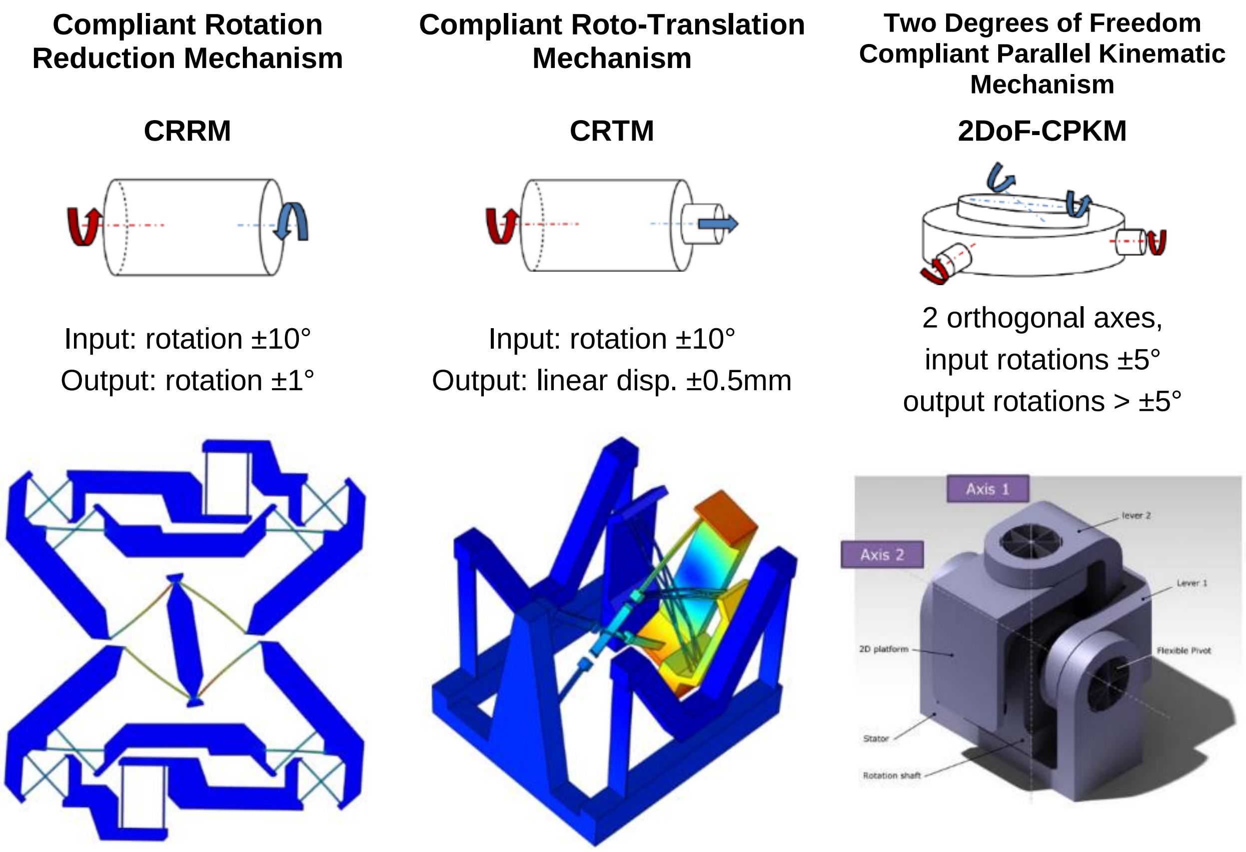


Figure 4: Views of the three mechanisms

Three categories with multiple criteria were defined to compare the mechanisms:

1. General aspects: innovation, adaptability, technical risks, compatibility with envisioned applications,
2. Additive manufacturing related aspects: benefits, orientation, risk of distortions, support structure removal easiness,
3. Performances: linearity, repeatability, stiffness, torque, stress level, parasitic motions, etc.

Trade-off conclusion

The CRRM shows the best general and performance evaluations, while the CRTM is in the second place and the 2DoF-CPKM in the third place.

From a performance point of view, the CRTM is close to the CRRM, but on the more general aspects, such as adequacy with additive manufacturing, it is seen as riskier. The reducer 3D building – thin and long overhanging structure – is seen as very challenging.

Even with an innovative architecture, the 2DoF-CPKM ranking is below the two other mechanisms. The behavior under random vibrations sanctions significantly the mass and volume. Moreover, the CPKM is the only mechanism that cannot be monolithically 3D printed and requires important re-machining of all the parts for assembly.

3.2 CRRM working principle

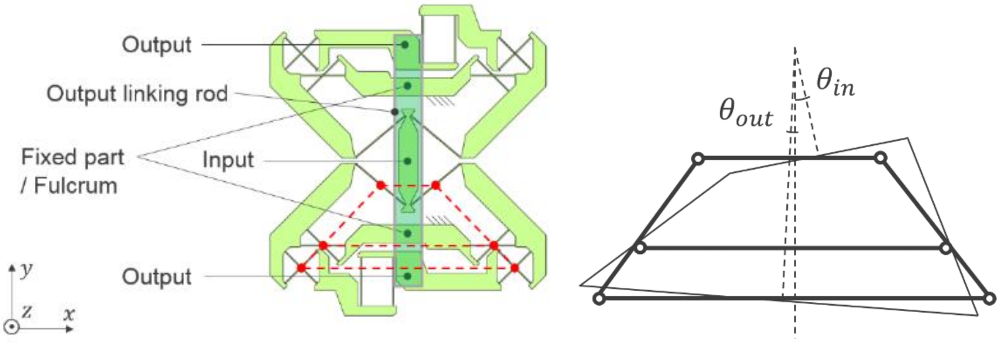


Figure 5: CRRM working principle and terminology

The working principle is explained on Figure 5. The whole mechanism has a vertical symmetry of a double Remote Center of Compliance (RCC). The double RCC has six pivots linking three horizontal rods: respectively from the top to the bottom, the input, the fixed frame (fulcrum) and the output. When the input rotates around the center by an angle θ_{in}, the output is forced to rotates by an angle $\theta_{out} = -\theta_{in}/R$, where R is the reduction ratio. The output angle goes in the opposite direction compared to the input angle; **the mechanism is a reducer and an inverter at the same time**. Therefore, the RCC levers impose the rotations of the distal and proximal rods while applying the desired reduction ratio.

Also, the length of the distal rod will increase, when rotating the mechanism. Thus the decoupling stage is added as well as the stage rod, so the distal rod is free to expand.

The mechanism is doubled and has a horizontal axis symmetry. The reason is due to the non-compliance of the centre shift requirement in case where only one mechanism (one double RCC) is used.

The CRRM has the input and output axis coaxial and an axial-symmetric mounting of actuator, housing and payload. Thus the thermo-elastic deformations are minimized.

3.3 CRRM detailed design and optimization

The optimization workflow for a compliant mechanism is presented in Figure 6. The optimization workflow of the flexures is not represented here as it was performed separately (see paragraph 3.3.2), due to the fact that commercial topology optimization software is actually set only for rigid bodies, where the compliance shall be minimized.

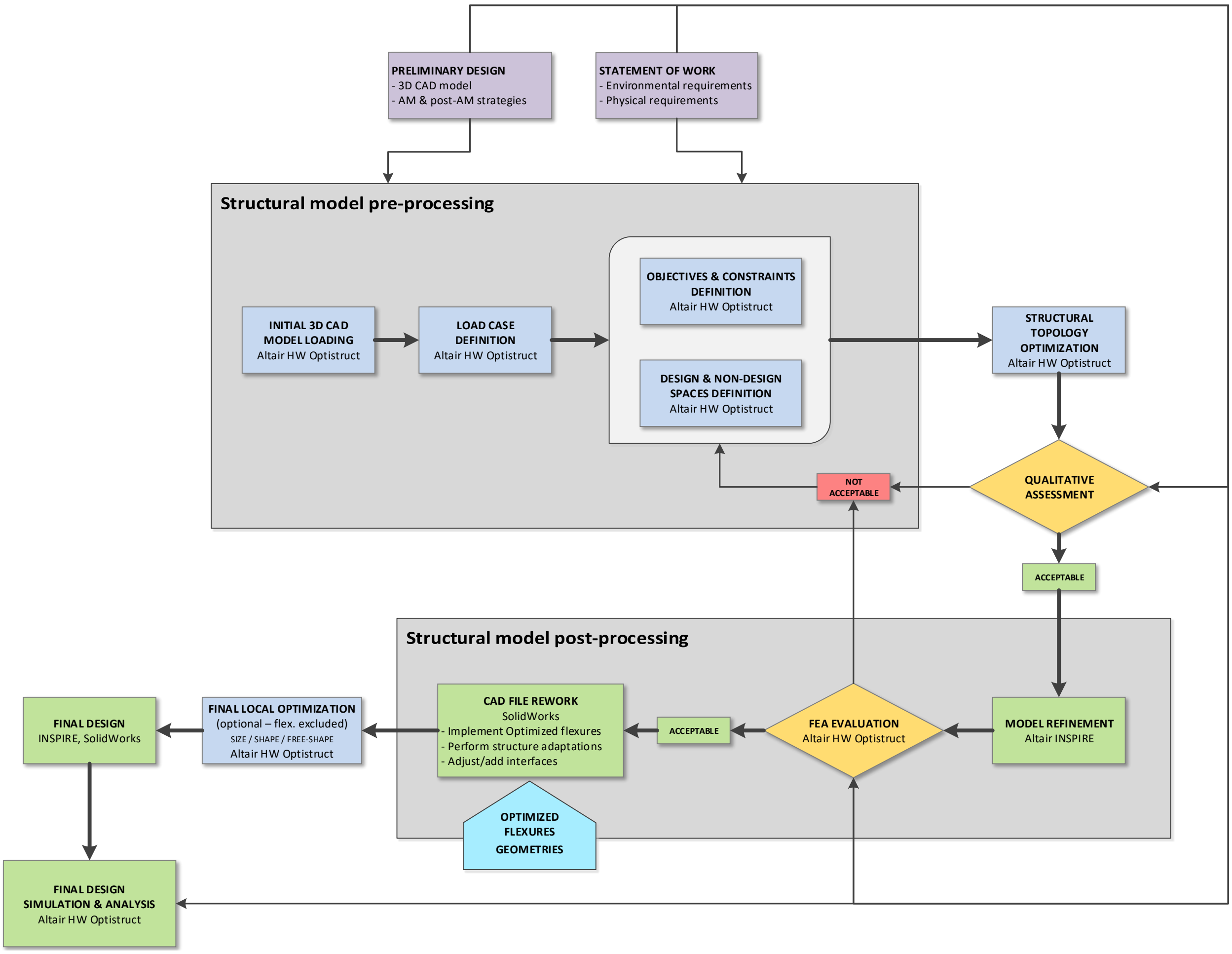


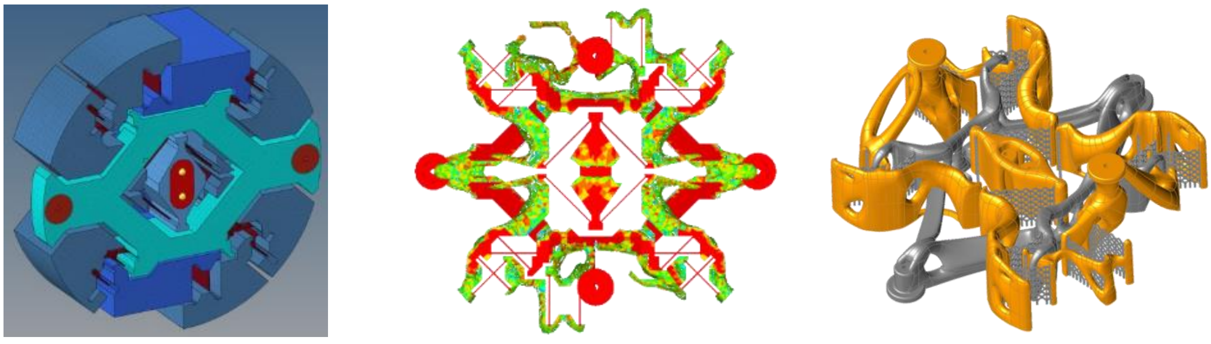
Figure 6: Optimization workflow for a compliant mechanism.

3.3.1 Topology optimization of rigid parts

The rigid parts optimization workflow has been performed with ALTAIR™ FEA software package. The optimization solver is part of the Optistruct™ module.

The main phases are the following:

1. The design and non-design spaces are defined, based on the preliminary design concept.
2. The boundary condition and the loads cases are defined.
3. The optimization parameters are defined (constraints and objectives).
4. The results are interpreted.
5. A CAD smoothing and/or rebuilt is performed at the end.
6. The design is finalized with the implementation of the interface features, snubbers, end-stops.
7. A reanalysis with the new shape could be already performed.



Phase 1 **Phase 4** **Phase 6**

Figure 7: Illustrations of rigid parts topology optimization phases

3.3.2 Lattice flexures optimization

As the lattice flexures are not intuitively understood throughout the sizing of their pattern, an optimization procedure has been performed to find a good compromise in terms of mechanical performances. A Monte Carlo optimization algorithm was used.

The following procedure was applied in order to optimize the lattice flexures:

- Formulation of the problem
- Generation of sets of parameters
- Output assessment
- Optimization process
- Verification of the optimal solution.

The stress during operational deflection (not during launch vibration) are actually lower due to the lower bending stiffness, at the same level of displacement. However, the stress during vibration tests can be higher.

Compared to plain flexure blade, the lattice is a good compromise to obtain adequate transversal stiffness while keeping the rotation stiffness as low as possible. The price for this is a more complex design, but it is not an issue for additive manufacturing.

3.4 CRRM detailed analysis

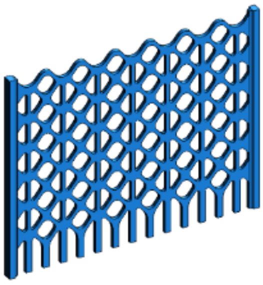
Detailed analyses have been performed to verify the mechanism integrity:

1. Quasi-static analysis
2. Modal analysis
3. Functional analysis
4. Sine analysis
5. Random analysis
6. Shock analysis
7. Fatigue analysis
8. Manufacturing prediction analysis

To perform these analyses a complete FE model has been built, based on the final topology and lattice optimization results and CAD smoothing.

4 MANUFACTURING ASSESSMENT

In parallel to the design and optimization of the mechanism, investigations were performed to assess the AM-SLM process and post-processes for compliant structures. First, critical features have been identified, manufactured and tested:



- Flexure blades uncoupled from the build plate
- Co-planar flexure blades
- Crossing flexures (cross pivot)
- Overhanging (joint) flexures
- Low stiffness flexures
- Warpage induced by SLM process
- Warpage reduction by variation of the SLM layer thickness
- Warpage due to thermal treatments: HIP, solution annealing and age hardening

The minimum thickness achievable with SLM may be considered as a critical feature when low stiffness flexures are to be produced. In this case, the preferred approach is to implement lattice geometries but to respect the minimum thickness value of approx. 300 µm.

The use of the following technologies has been assessed with representative samples:

- **SLM simulation software:** predictions of the distortions anticipated with Amphyon® software
- **Laser micro-jet cutting** for sample machining and separation of mobile stage bridges
- **Shot peening**
- **Thermal treatments** (HIP, stress annealing & age hardening) criticality with respect to **warpage**
- **2D optical and 3D laser scanner metrology**

In addition, the following material, process and post-processes characterizations have been performed:

- Flexure thickness, roughness
- Microstructure: grain size, porosity, homogeneity
- Chemical composition
- Dissolved gases
- Residual stresses: a compressive residual stress was present in the surface of all samples, reaching 10 to 20 % of the yield strength, probably due to the heat-treatments such as HIP and quenching. It shall be beneficial to improve the fatigue resistance.
- Tensile tests
- Corrosion and Stress Corrosion Cracking resistance; see next page
- Micro-hardness
- Fatigue: the behavior of CL92PH (17-4PH) material has already been defined in previous project [2] with an alternate bending fatigue test bench. Additional fatigue tests have been performed in COMAM to consolidate the results, including lattice flexure blades. The number of cycles before failure of plain flexure blades are comparable to the previous data.

  For the lattice flexure blades, two samples are significantly below the nominal fatigue curve of the previous project AMFLEX [2]. No clear explanations have been found. Nevertheless, at least 7.6 million cycles have been performed with a stress of 540 MPa. The results can be visualized on the stress-life diagram in Figure 8.

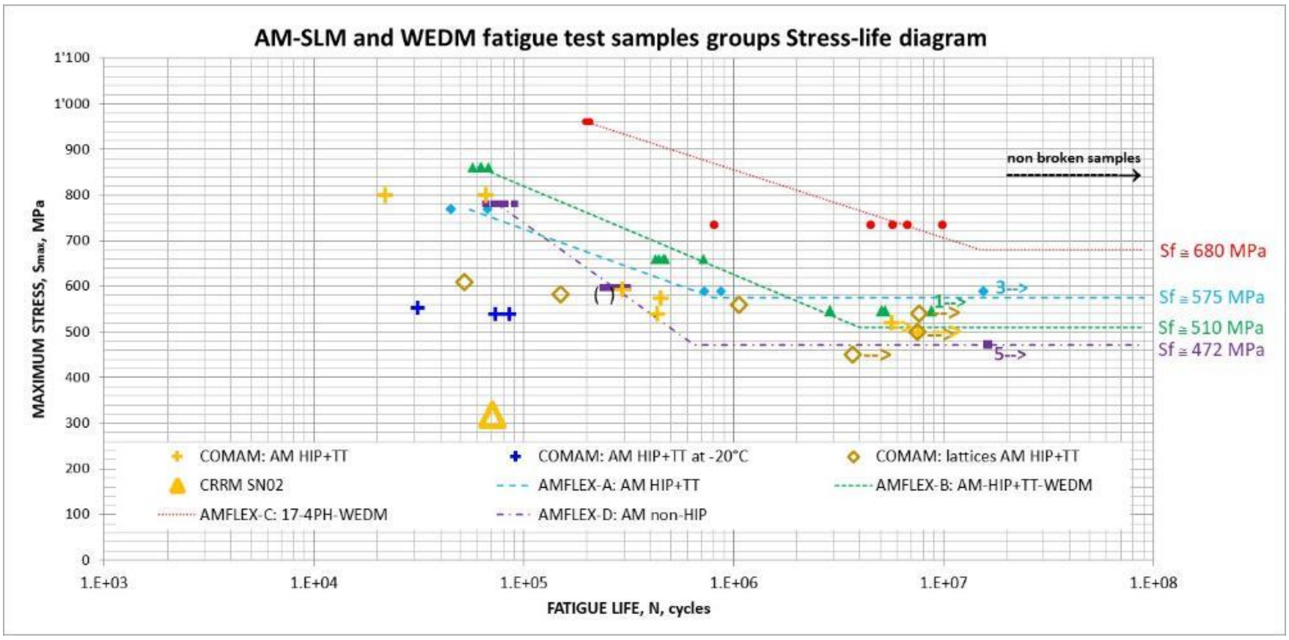


Figure 8: 17-4PH fatigue test results

The heritage data of AMFLEX project [2] were confirmed with material properties conforming to the specifications and comparable to bulk 17-4PH.

The only issue is the presence of intergranular corrosion after 24 to 96h of Neutral Salt Spray test, as shown in Figure 9. The main cause has been identified to the high surface roughness of tested samples which affect the wettability and time of exposure of the surface by salt spray droplets. **It is therefore expected that corrosion resistance can be considerably improved with an improved surface finish.**

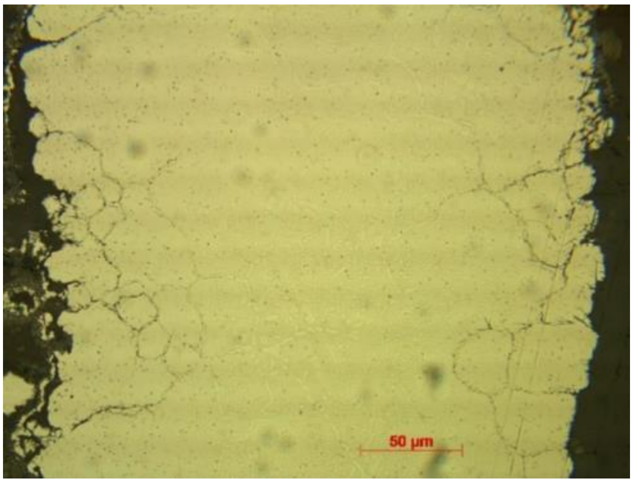


Figure 9: Optical micrograph of the sample blade part after 24h neutral salt spray exposure.

5 CRRM MANUFACTURING AND POST-PROCESSES

Figure 10 illustrates the manufacturing and post processing sequence for the two printed mechanisms and for the witness samples.

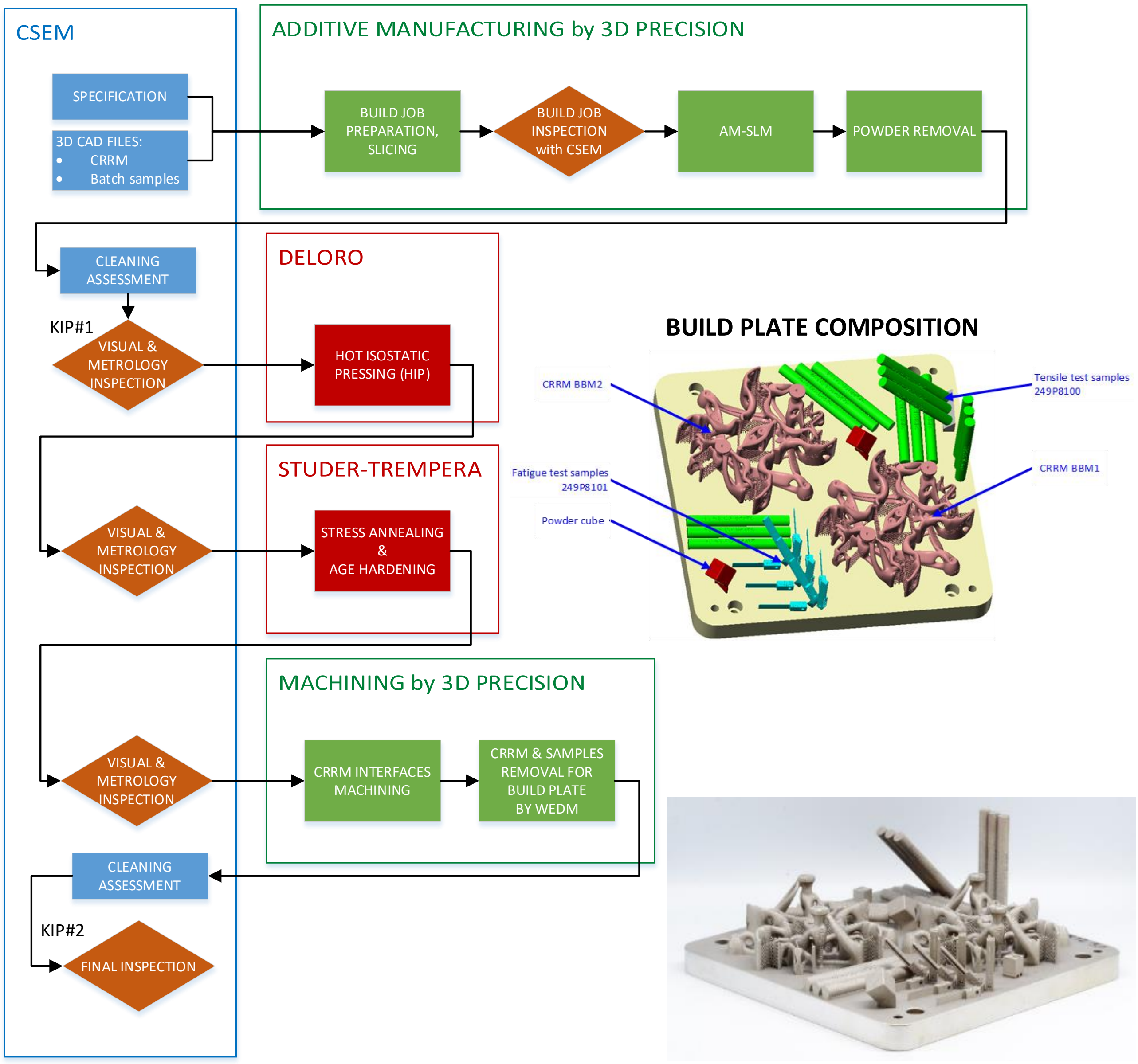
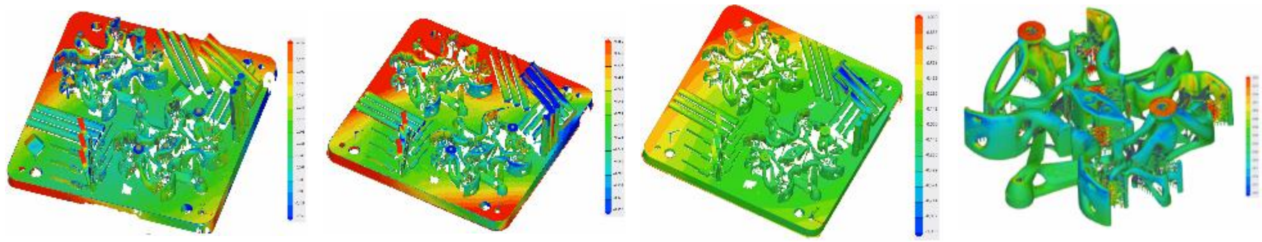


Figure 10: CRRM and witness samples manufacturing and post-processing sequence

5.1 Inspections and metrology

Visual and metrology inspections have been performed after each manufacturing steps: after AM-SLM, after HIP, after stress annealing-age hardening (SA-AH) and after machining. They have been performed with a 2D optical system and with a 3D laser scanner. The two methods are complementary since the small flexure blades are only hardly reconstructed by the laser scanner.

1. After SLM, the global deformation of the build plate was of ~0.2 mm in Z direction
2. After HIP, increase of the build plate deformation, ~0.2 mm for each mechanism.
3. After SA-AH, further increase of the deformation, ~0.3 mm for each mechanism.
4. After separation from the build plate and machining, for each mechanism the global deformation was up to 0.3mm.



1. After AM-SLM **2. After HIP** **3. After SA-AH** **4. After machining**

Even with all precautions to ensure a satisfactory SLM production, such as a 18mm thick build plate made of 17-4PH and stress annealed, the build plate was nonetheless deformed during the process.

5.2 CRRM batch witness samples test results

The microstructure shows homogeneous martensitic microstructure with visible micropores in a size < 3 µm. Compared to previous microstructural observations on the validation batch samples, no coarse precipitates were observed for CRRM batch witness sample.

The dissolved gases and tensile test results are consistent with the results from the previous batch.

The material and process characterization witness test sample results are within the specifications.

6 TESTING

Following the manufacturing and metrology inspections, the two mechanisms were tested to verify the compliance with the requirements. The performed tests were:

- Mass and overall dimensions
- Cleanliness ability
- Motion range (input, output), reduction ratio
- Output torques and forces
- Parasitic motions at output
- Repeatability with and without output load
- Elastic torque
- Mechanical end-stops repeatability
- Stiffness
- Thermo-elastic behavior
- Sine and random vibrations
- Shocks; dropped since EBM1 damaged during vibration test
- Thermal cycling
- Lifetime

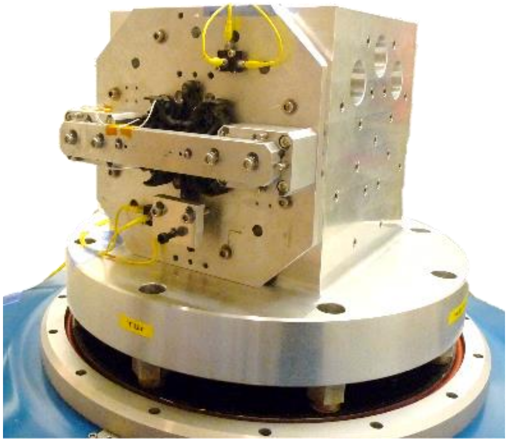


Figure 11: Vibration test bench on the shaker

The overview of the test results compared to the specifications is shown in chapter 7.

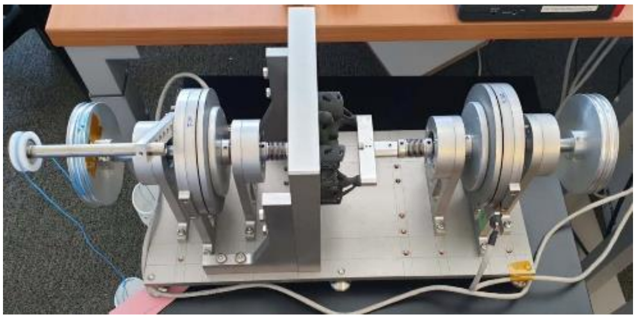


Figure 12: Performance test bench

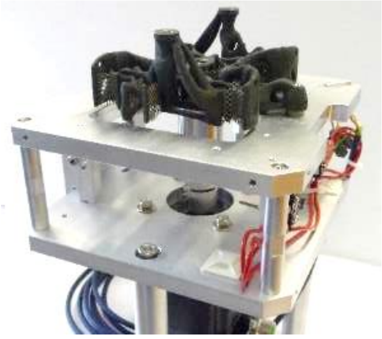


Figure 13: Lifetime test bench

Figure 14: Damage of EBM1 following vibration test

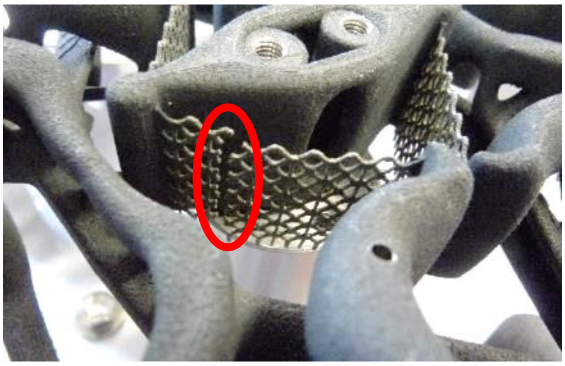


Figure 15: Damage of EBM2 following lifetime test

7 REQUIREMENTS, TEST RESULTS AND COMPLIANCE STATUS

Table 1 summarizes the final status and the compliance of the main requirements.

Table 1: Resume of the main results and compliance with requirements for the CRRM

<table>
<tr><th>Ref.</th><th>Requirement</th><th>Compliant / NC</th><th>Details</th></tr>
<tr><td>RS 1</td><td>Frictionless rotation</td><td>C</td><td></td></tr>
<tr><td>RS 2</td><td>Motion range and reduction ratio</td><td>C</td><td>Input rotation range: ±10°
Output rotation range: ±1°
Reduction ratio 10</td></tr>
<tr><td>RS 3</td><td>Output torques, moments and forces</td><td>C</td><td>Ability to operate with the following static output forces and moments:
Along motion DoF (resistive loads), constant in the full motion range, opposite to motion direction: 0.7 Nm
Along constrained DoF, along any axis:
- Lateral at the output I/F: > 7 N
- Bending on lateral I/F: > 0.7 Nm</td></tr>
<tr><td>RS 4</td><td>Parasitic motions at the output I/F</td><td>NC</td><td>
<table>
<tr><th>Direction</th><th>Measurement</th><th>Prediction</th><th>Specification</th></tr>
<tr><td>X</td><td>4-89 µm</td><td rowspan="2">< 1 µm</td><td rowspan="3">< 10 µm</td></tr>
<tr><td>Y</td><td>13-17 µm</td></tr>
<tr><td>Z</td><td>13-77 µm</td><td>< 22 µm</td></tr>
<tr><td>R_X</td><td>0.033-0.049°</td><td>< 0.0002°</td><td rowspan="2">< 0.01°</td></tr>
<tr><td>R_Y</td><td>0.017-0.044°</td><td>< 0.0001°</td></tr>
</table>
</td></tr>
<tr><td>RS 5</td><td>Repeatability in position with zero output loads</td><td>NC</td><td>Specification: < 1% (1/200 of output motion range)
Measurements: 5 to 9% (with friction from test bench ball-bearings)</td></tr>
<tr><td>RS 6</td><td>Accuracy with maximum output resistive loads</td><td>NC</td><td>Compliant for reduction ratio:
Specification: ≥ 10
Measurements: 10.6-11.8
Non-compliant for reduction ratio variation (vs without load):
Specification: ≤ 5%
Measurements: 6-18%</td></tr>
<tr><td>RS 7</td><td>Stiffness</td><td>PC</td><td>PC since no required values, but measurements significantly lower than predictions:
k_X: -60% to -72%
k_Y: -54% to -58%
k_Z: -26% to -28%
kR_X: -54% to -56%
(kR_Z: -97% to -98%) values to be confirmed</td></tr>
<tr><td>RS 8</td><td>Elastic torque</td><td>C</td><td>Ratio between nominal input torque needed to move the CRRM without output load and input torque needed to move the CRRM with the maximum resistive load: < 0.7</td></tr>
<tr><td>RS 9</td><td>Mechanical end-stops repeatability</td><td>C</td><td>Specification for input < 0.1° (1/200 of 20° input motion range)
Specification for output < 0.01° (1/200 of 2° output motion range)
All measurements better than 2*standard deviation (0.003-0.013)</td></tr>
<tr><td>RS 11</td><td>Thermo-elastic behavior</td><td>NC</td><td>
<table>
<tr><th>Direction</th><th>Measurement for +20° to +40°C</th><th>Measurement for +20° to -7°C</th><th>Spec.</th></tr>
<tr><td>X</td><td>-29 µm</td><td>+23 µm</td><td rowspan="3"><10 µm</td></tr>
<tr><td>Y</td><td>-46 µm</td><td>+43 µm</td></tr>
<tr><td>Z</td><td>-24 µm</td><td>+44 µm</td></tr>
<tr><td>R_X</td><td>-13 mdeg</td><td>+21 mdeg</td><td rowspan="3"><20 mdeg</td></tr>
<tr><td>R_Y</td><td>-6 mdeg</td><td>+29 mdeg</td></tr>
<tr><td>R_Z</td><td>+20 mdeg</td><td>-26 mdeg</td></tr>
</table>
</td></tr>
</table>

RS 12	Interface requirements	**C**	Design integrates attachments at CRRM fixed, input and output IF with threaded holed for fixation as well as centering holes for precise positioning (e.g. with pin).
RS 13	Temp. ref. point	**C**	
RS 14	Misalignments at output I/F during vibration	**C**	**Ability to withstand the following static misalignments on the output I/F: 0.02 mm for each axis, simultaneously.**
RS 16	Quasi-static acceleration	**C**	Ability to withstand 60g per each axis, not simultaneously. Performed by analysis
RS 17	Launch sinusoidal vibration	**NC**	Qualification levels, all axes, 0-peak: 5 - 20 Hz: 15 mm 20 -60 Hz: 24g 60 -100 Hz: 8g, 1 sweep 2 oct/min
RS 18	Launch random vibration	**NC**	Qualification level 18.4 g_{RMS} **CRRM survived -3dB test along X axis (13 g_{RMS})** before being damaged when the fixed structure moved because of a machining non-conformance.
RS 19	Shock level	**(NC)**	Not tested
RS 20	First natural frequency	**C**	**First eigen-frequency in locked configuration**: Specification > 100 Hz Prediction 729 Hz **Measurement 555 Hz**
RS 21	Thermal cycling	**C**	
RS 22	Mass	**C**	Specification < 400 grams Measurement 330 – 336 grams
RS 23	Envelope	**C**	Diameter <120 mm. Height 50mm specified, <41 mm designed and measured
RS 24	Lifetime	**NC**	**Compliant on fatigue witness samples** (see chapter 0)**.** Specification > 100'000 cycles at ±10° (1M cycles goal) Prediction: infinite lifetime **CRRM EBM2: failure at ~71'000 cycles**
RS 25	Monolithic structure	**C**	
RS 26	Production via AM	**C**	Only interfaces were machined, not the flexure blades.

8 LESSONS LEARNED

The main lessons learned are summarized here.

Design consideration

Trade-offs between several mechanism architectures was performed to choose the best candidate for the detailed design. It allowed us **to generate and improve many kinematic ideas.**

The **topology optimization for rigid structures is very powerful** and allows us to improve the dynamic behavior of the CRRM, increasing the first eigen-frequency to more than 700 Hz.

Regarding the performance prediction, the difference between the cross-coupling responses predicted by FEA and measured by test is hard to explain. The real mechanism seems to have more cross coupling than predicted.

The **FEM would need some correlations which are difficult to perform** due to the complexity of the mechanism and due to the significant number of modes above 1000 Hz. Nevertheless, **the global behavior of the item has been correctly predicted**, keeping in mind that the FEM lack of response / amplification leads to lower computed stresses.

Additive manufacturing process

The risks associated to the design of conventional compliant mechanisms raised in section 2.3 are also valid with Compliant Mechanisms built by additive manufacturing. Moreover, **the difficulty to achieve fine tolerances and sensitivity to the flexure blade straightness, roughness is exacerbated with actual AM production equipment.**

The **AM process simulations provide useful information on deformations during the process.**

To reduce the deformations along the additive manufacturing and post-processing workflow, the thickness of the build plate shall be increased to improve its stiffness. The material of the build plate shall also be changed to select a new material showing lower susceptibility to geometrical deformations induced by the thermal post-processes.

It has been noticed that **the significant surface roughness dramatically affects the cleanability** of surfaces. **A suited surface finishing post-process should drastically improve this aspect.** We are confident that **the resistance to corrosion and lifetime can be improved with a good surface finish.**

Testing

The validation of the material, process and post-process has been successful, with the CRRM batch witness samples test results fully in-line with the specifications for this material.

Motion range and reduction ratio: some margin shall be taken on the geometry (lever's ratio) to ensure a kinematic and a reduction ratio within the specifications.

Parasitic motions: they are out of specification due to severe distortions. Nevertheless, the mechanism is able to operate with global guiding performances one order of magnitude lower than the amplitude of the severe deformations. These aspects allow us to be confident being able to fulfil stringent guiding performances and highlights a fairly good robustness of the kinematic.

The vibration tests should be performed again prior to correlation with FEM predictions in order to gain understanding on the behavior of such mechanisms. The main aspects are the difference in stiffness, the cross-couplings and the quality factor.

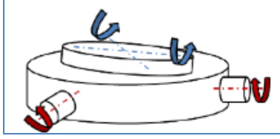
Fatigue testing: the mechanism broke during lifetime test below the expected 100'000 cycles. Again, this is due to the severe distortions inducing additional stress in the flexure blades. The fatigue tests performed on the witness samples of the characterization batch have a much higher lifetime, which is compatible with space applications.

9 DEVELOPMENT PLAN

9.1 Potential applications

The potential applications for each mechanism have been identified at the beginning of the project. **The main advantage of all three mechanisms is that they can be actuated by rotation.**

Table 2: Summary of the main characteristics for each type of mechanism

Mechanism type	Advantages	Drawbacks
CRRM 	• The reduction allows a higher resolution at output with a lower resolution encoder at the input. • Opens the door to conventional rotational motors instead of voice-coil actuators: e.g. steppers, brushless DC. • Unpowered static position can be maintained with a stepper motor.	• Low output angular range. • Potential non-linear effect between input and output: request characterization over the complete operational range. • Pointing accuracy to be assessed
CRTM 	• Simple control of an accurate linear position via a large input rotation. • Can be driven by conventional rotational motors instead of voice-coil actuators. • Motor can be combined with a lower resolution rotary encoder.	
2 DoF CPFKM 	• Compact and robust design for 2 axis scanning. • Reduced mass and inertial compared to conventional serial 2 DoF mechanisms.	

9.2 Future perspective based on the outcomes of this project

The following points summarize the development plan elaborated by Almatech and CSEM.

Identification of **key advantages of a compliant mechanism built by additive manufacturing**:

- **High versatility and tunability,** possibility to configure and modify the design to better cope with requirements for each application. Easy to implement e.g. stiffness changes with the same design.
- **Design freedom for complex shapes, including complex 3D flexures architectures**
- **Integration of several functions in one mechanism**: rotation, translation, reduction, multi-DoF, etc.
- **Compactness, mass reduction**
- **Less or no assembly**
- With topology optimization: lower mass and **better dynamic behavior**
- **Validation could be anticipated** with prototypes and test models easier to produce and available at earlier stage

10 CONCLUSION

COMAM was a challenging project with many different aspects regarding the design, optimization, manufacturing, post-processes, validation and testing. A lot of lessons learned were collected in all these domains.

Several improvements have been identified to increase the future performances and CSEM is currently working in two main areas, i.e. reduction of distortions and of surface roughness with promising results.

The major advantages of building compliant mechanisms by additive manufacturing have been demonstrated and confirmed during this project, such as the lead time reduction thanks to the suppression of precise assembly and the realization of complex 3D parts in a reduced volume.

CSEM is confident that compliant mechanisms built by additive manufacturing will fulfil the requirements for high-precision space applications in near future.

11 REFERENCES

1. Merriam, E. G. (2016), Stiffness Reduction Strategies for Additively Manufactured Compliant Mechanisms, All Theses and Dissertations. Paper 5873.

2. Saudan, H., Vaideeswaran, K., Kiener, L., Mehdi, D. M., “Additive Manufactured Metallic Flexible Structures, a Focus on Manufacturing Strategies, Material Analysis and Fatigue Verification”, ECSSMET 2016, Toulouse, France

3. 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.

4. Rouvinet, J., Ummel, A., Cosandier, F., Nguyen, D., Schaffter, V., “PULSAR: Development of a mirror tile prototype for future large telescopes robotically assembled in space.” Proc. SPIE 11451, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation IV, 114512N (2020).

5. Spanoudakis, P., Schwab P., Kiener L., Perruchoud G., Saudan H., Gumy M., Regamey Y-J., “Corner Cube Mechanism (CCM) for MTG IRS: qualification and acceptance test campaign results and lessons learned” Proceedings of the 18th European Space Mechanisms & Tribology Symposium, Munich, Germany, 18-20 Sept. 2019.

6. Verhaeghe A., Perruchoud G., Schwab P., Gumy M., Rouvinet J., Kiener L., “Challenges of the development of a compliant focus mechanism submitted to the harsh Martian environment for the ExoMars rover mission” Proceedings of the 45th Aerospace Mechanisms Symposium, 2020, ref. NASA/CP-20205009766.