

Design for Additive Manufacturing of Cryogenic Flexible Pivot Enabling On-Demand Customization, and Reducing Failure Risks

Guilain Lang

Swiss Center for Electronics and Microtechnology

Lionel Kiener

lionel.kiener@csem.ch

Swiss Center for Electronics and Microtechnology

Maxime Lautenbacher

Swiss Center for Electronics and Microtechnology

Florent Cosandier

Swiss Center for Electronics and Microtechnology

Etienne Lallemand

University of Liège

Tanguy Thibert

University of Liège

Herve Saudan

Swiss Center for Electronics and Microtechnology

Research Article

Keywords: Additive Manufacturing, Compliant Mechanisms, Cryogenic Mechanisms, Flexible Pivot, DfAM, Functional AM, Optimization

Posted Date: January 9th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-8375017/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Design for Additive Manufacturing of Cryogenic Flexible Pivot Enabling On-Demand Customization, and Reducing Failure Risks

Guilain Lang^{a,b}, Lionel Kiener^a, Maxime Lautenbacher^a, Florent Cosandier^c, Etienne Lallemand^d, Tanguy Thibert^d, Herve Saudan^a

*^aPrecision Mechanisms Group, CSEM SA, Rue de l'Observatoire
58, Neuchatel, CH2000, Switzerland*

^bDepartment of Mechanical and Process Engineering, ETH Zurich, Switzerland

^cInstant Lab, School of Engineering, EPFL, Switzerland

^dCentre Spatial de Liège, University of Liège, Belgium

Abstract

Compliant mechanisms achieve motion through elastic deformation rather than contact surfaces, eliminating friction, wear, and lubrication requirements. Their design and adoption in cryogenic and space applications have historically been constrained by conventional manufacturing processes that limit geometric complexity.

This work exploits the design freedom of Laser Powder Bed Fusion (LPBF) to propose a streamlined Design for Additive Manufacturing (DfAM) workflow for optimizing and customizing a flexure pivot operating at 4.2 K within the Mode Selector Mechanism (MSM).

The methodology comprises three stages: (i) material selection and post-processing - 316L stainless steel combined with stress annealing and HIP - to ensure cryogenic compatibility and fatigue strength; (ii) optimization of the Interlocked Lattice Flexure (ILF) geometry considering performance metrics (stroke, stiffness, guiding accuracy) and AM constraints (overhang, minimum feature size); and (iii) flexure thickness tuning to meet project-specific requirements while mitigating AM-induced variability, enabling rapid customization.

Email address: `lionel.kiener@csem.ch` (Lionel Kiener)

Numerical and experimental validation confirmed compliance with design targets: ± 3.5 deg stroke, stiffness of $3.97 \text{ mN}\cdot\text{m}/\text{deg}$, and fatigue life exceeding 10^6 cycles under over-testing conditions (115% of operational range). Failure analysis further demonstrated that the ILF design inherently localizes damage, preventing catastrophic failure and enhancing robustness for aerospace applications.

These results underscore the transformative potential of AM for high-performance, customizable compliant mechanisms in extreme environments.

Keywords: Additive Manufacturing, Compliant Mechanisms, Cryogenic Mechanisms, Flexible Pivot, DfAM, Functional AM, Optimization

1. Introduction

Compliant mechanisms are mechanical systems that achieve motion through the elastic deformation of their constitutive elements, rather than relying on traditional contact-based joints [1]. This intrinsic characteristic eliminates several drawbacks typically associated with contact-based mechanisms, including friction, backlash, stick-slip phenomena, wear, and the need for lubrication. As a result, compliant mechanisms are particularly well-suited for high-precision applications and operations in harsh environments, including vacuum and cryogenic conditions [2, 3].

Historically, the design of compliant mechanisms has been constrained by conventional manufacturing limitations, which restricted their geometry [4]. The emergence of Additive Manufacturing (AM), however, has introduced unprecedented design freedom, enabling the fabrication of complex, monolithic structures with tailored mechanical properties. This technological shift opens new avenues for enhancing the performance, compactness, and reliability of compliant systems, while also enabling on-demand customization and manufacturing [5, 6, 7].

In this work, we explore the disruptive potential of AM in the context of space and cryogenic scientific instrumentation. Specifically, we present a Design for Additive Manufacturing (DfAM) of a flexible pivot intended for cryogenic operation within the Mode Selector Mechanism (MSM) - a bi-stable cryo-actuator developed by the Centre Spatial de Liège (CSL) and operated at 4.2 K [8]. Leveraging the geometric flexibility of AM, the proposed com-

pliant pivot integrates Interlocked Lattice Flexures (ILF, patented). This innovative feature not only circumvents AM-specific limitations, such as minimum feature size - by reducing the stiffness of the compliant elements without compromising structural integrity - but also enhances the compactness of the design and mitigates the risk of catastrophic failure by preventing the propagation of cracks in compliant elements. We demonstrate the potential of AM for on-demand manufacturing, highlighting its capacity for customization in both design and material selection. This approach not only meets the stringent requirements of cryogenic applications but also offers economic and lead-time advantages, making it a compelling solution for future space instrumentation.

2. Design and Customization

This section details the DfAM and customization of the ILF compliant pivot to meet the specific operational requirements of the MSM (see Figure 1). The key design requirements addressed in this study are as follows:

- **Stroke:** The pivot shall accommodate an operational angular stroke of ± 3.5 deg.
- **Stiffness:** The natural torsional stiffness of the pivot shall lie within the range of 1.0 to 4.0 mN·m/deg range.
- **Thermal Environment:** The pivot must remain functional across the full operational temperature range, from 4 to 353 K.
- **Envelope and Interfaces:** The pivot's external dimensions and interfaces shall be compatible with commercially available counterparts, specifically a diameter of 12.7 mm and a length of $l = 20.3$ mm.

Customization begins with material selection, particularly in response to the stringent thermal requirements. Subsequently, the lattice geometry and blades' thickness are optimized to satisfy both functional performance and manufacturing constraints. Finally, pivots' interfaces are customized to match MSM configuration.

2.1. Material Selection

Material selection is a critical aspect in the design of compliant mechanisms for cryogenic applications. While 17-4-PH stainless steel has been widely used for AM compliant mechanisms due to its high strength and favorable mechanical properties [6, 9], its micro-structural transition temperature near -20°C renders it unsuitable for cryogenic environments [10]. To overcome this limitation, 316L stainless steel is proposed. This alloy maintains acceptable mechanical performance at cryogenic temperatures (at least in its bulk form). Although it exhibits slightly lower strength than 17-4-PH, 316L offers a significant advantage in additive manufacturing: it does not require age-hardening thermal treatments, thereby avoiding the distortions typically associated with such post-processing [11]. This characteristic makes 316L particularly suitable for fabricating precision components with tight dimensional tolerances.

Property	Symbol	Unit	Value
Young's Modulus	E	GPa	193.0
Poisson's Ratio	ν	-	0.27
Density	ρ	kg/m ³	7870
Yield stress, yield	σ_{yield}	MPa	460
Yield stress, ultimate	$\sigma_{ultimate}$	MPa	617

Table 1: 316L Room Temperature Bulk Properties

2.2. Pivot optimization

To tailor the flexible pivot to the specific operational requirements of the MSM, a three-step design optimization strategy was employed, leveraging the design freedom offered by AM: (1) lattice geometry optimization, (2) thickness adaptation, and (3) interfaces' design.

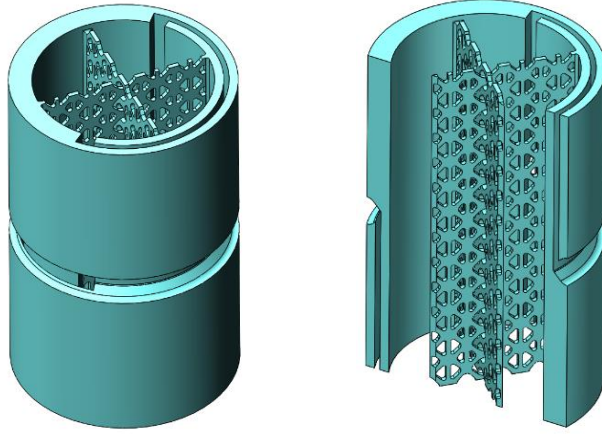


Figure 1: CAD Renderings of the Interlocked Lattice Flexure Pivot
The left image shows the complete pivot, while the right image includes a sectional cutout revealing the internal lattice blades.

2.2.1. Lattice Geometry Optimization

The first step involves optimizing the lattice cell geometry while maintaining a constant blade thickness. The objective is to minimize the natural torsional stiffness (K_{θ_z}), maximize the allowable stroke by minimizing stress (σ_{θ_z}), and enhance guiding performance. The latter is quantified by the ratio of transverse to natural stiffness (K_z/K_{θ_z}), which reflects the mechanism's ability to reject external perturbations.

To assess the influence of design parameters onto performance and the relevance of ILF for this use-case, the simplified parametrization shown in Figure 2 has been used:

- **Natural Stiffness:** Across the explored parameter space, the natural stiffness was reduced by a factor of 3 to 7 compared to plain blades with identical envelopes. This reduction is beneficial for AM, as it allows for

increased blade thickness at constant stiffness, thereby improving manufacturability.

Width, radius, and length were identified as the most influential parameters. A strong correlation was also observed between stiffness and the "density ratio" - an extrapolated metric estimating the surface area ratio between lattice and plain blades (see Figure 3).

- **Stroke:** The lattice structure increases stress by approximately 5% to 35% resulting in a corresponding reduction in allowable stroke.
- **Guiding performance:** Guiding performance (i.e., stiffness ratio) is significantly reduced - 65% to 90% - as transverse stiffness decreases more rapidly than natural stiffness. The same qualitative trends observed for natural stiffness also apply here.

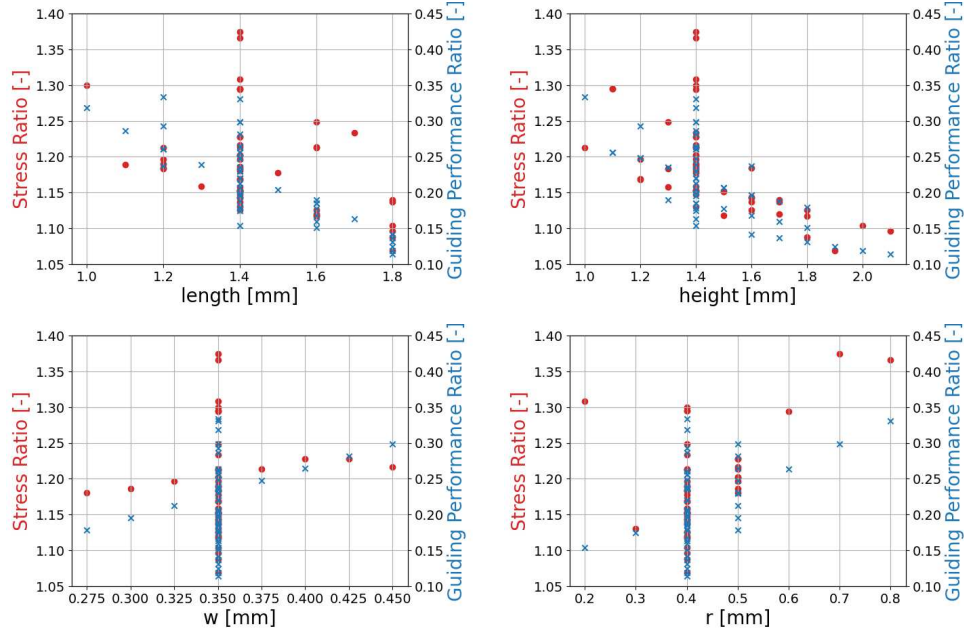


Figure 2: Impact of Parameters on Stress and Guiding Performance Ratio
Ratios computed as the lattice blade performances over a plain blade with the same external dimensions.

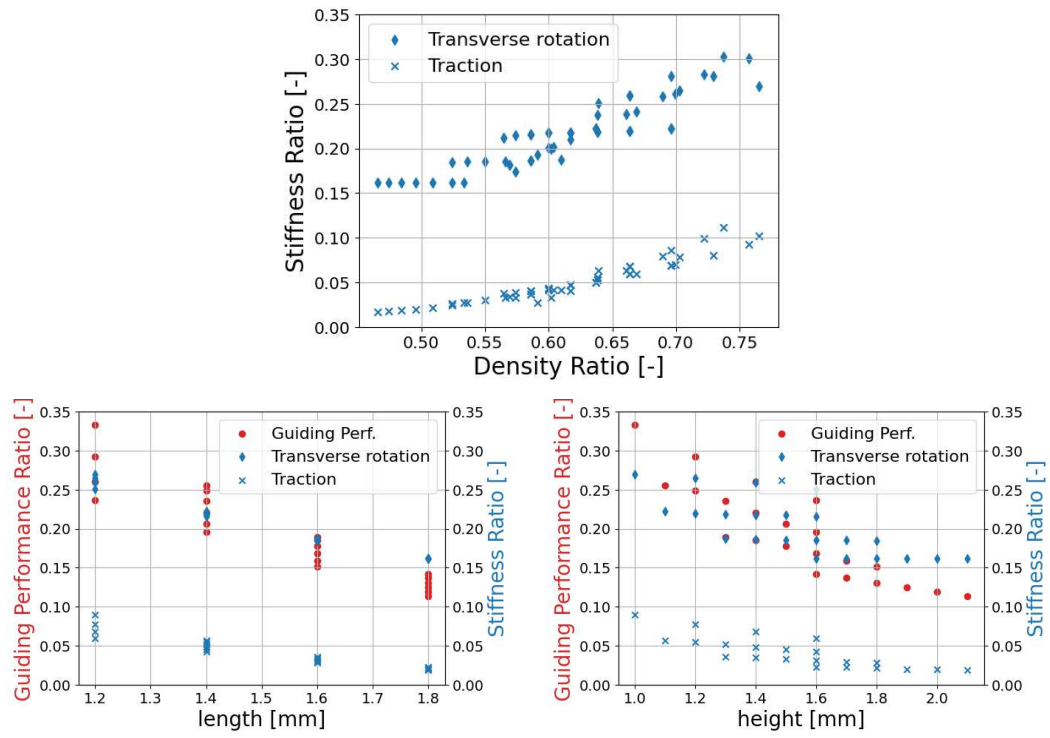


Figure 3: Detailed Impact of Density Ratio, Length and Height on Natural Stiffness, Transversal Stiffness, Traction Stiffness, and Guiding Performance

These findings underscore the need for Multi-Objective Optimization (MOO), as the performance criteria are inherently conflicting [12]. In such cases, no single optimal solution exists; instead, a Pareto-optimal set of non-dominated solutions must be considered.

For practical implementation, a pseudo-MOO approach was adopted using a weighted objective function. Using the complete parametrization, shown in Figure 4, the optimization formulation is as follows:

$$\begin{aligned}
& \min_{r_i, d_i, H} \{G_{obj}\} \\
s.t., \quad & r_1, r_3 \in [0.5, 0.9] \text{ mm} \\
& r_2, r_4 \in [0.3, 0.5] \text{ mm} \\
& d_1 \in [\min(r_2 - r_1, 0.1), 0.3] \text{ mm} \\
& d_2 \in [\min(r_1 - r_2, 0.3), 0.3] \text{ mm} \\
& d_3 \in [\min(r_4 - r_3, 0.05), 0.1] \text{ mm} \\
& d_4 \in [\min(r_3 - r_4, 0.5), 0.9] \text{ mm} \\
& H \in [1.1, 1.4] \text{ mm} \\
& H - d_1 - r_1 \in [0.2, 3] \text{ [mm]} \\
& H - d_3 - r_3 \in [0.2, 3] \text{ [mm]} \\
G_{obj} = & w_{C_z} \frac{C_z/\bar{C}_z - 1}{STD(C_z/\bar{C}_z - 1)} + w_{\sigma_z} \frac{\sigma_z/\bar{\sigma}_z - 1}{STD(\sigma_z/\bar{\sigma}_z - 1)} \\
& + w_{C_{\theta_z}} \frac{C_{\theta_z}/\bar{C}_{\theta_z} - 1}{STD(C_{\theta_z}/\bar{C}_{\theta_z} - 1)} + w_{\sigma_{\theta_z}} \frac{\sigma_{\theta_z}/\bar{\sigma}_{\theta_z} - 1}{STD(\sigma_{\theta_z}/\bar{\sigma}_{\theta_z} - 1)} \\
& + w_{A_{const}} \frac{A_{const}/\bar{A}_{const} - 1}{STD(A_{const}/\bar{A}_{const} - 1)} \quad (1)
\end{aligned}$$

Where, w_i are the optimization weights ($w_{C_z} = 0.6$, $w_{\sigma_z} = 0.8$, $w_{C_{\theta_z}} = 0.9$, $w_{\sigma_{\theta_z}} = 0.5$, $w_{A_{const}} = 0.4$), $C_i = 1/K_i$ denotes compliance along axis i , and A_{const} represents the constancy of the cross-sectional area, which is correlated with printability risk. Finally, $\bar{x}$ and $STD(x)$ are the mean and standard deviation of each objective, used for normalization.

The optimization weights were selected based on a utility analysis that considered both stakeholder priorities and manufacturability constraints. Within the explored design space, the resulting optimal lattice geometry is summarized in Table 2.

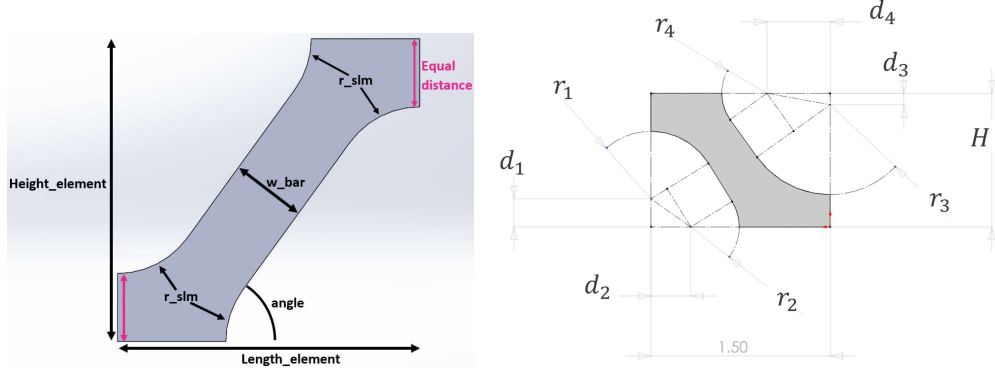


Figure 4: Simplified (left) and Complete (right) Parametrization For Lattice Geometry Optimization

The final ILF geometry was constructed, and the maximum stroke before mechanical interference in the interlocking region was numerically determined to be $\theta_{max} = 18$ deg, providing a substantial safety margin relative to the design requirement.

To increase transverse stiffness, strategically placed stiffeners were integrated into the lattice architecture, thereby enhancing guiding performance.

parameter	value mm	parameter	value mm
r_1	0.499	d_1	0.283
r_2	0.364	d_2	0.411
r_3	0.782	d_3	0.0999
r_4	0.420	d_4	0.609
H	1.19		

Table 2: Final Lattice Parameters After the Optimization Defined by Equation 1

2.2.2. Thickness Adaptation:

Building upon the optimized lattice geometry established in the previous section, the second step of the design process involves adapting the blade thickness. This stage aims to enhance manufacturability while ensuring compliance with the specific performance requirements of the MSM use-case.

The optimized lattice configuration exhibits a reduction in both stroke and stiffness - by approximately 18% and 68%, respectively - compared to a plain blade of equivalent dimensions. This simplified relationship between lattice and plain blade performance enables rapid estimation of the ILF pivot’s behavior as a function of the nominal blade thickness.

As illustrated in Figure 5, stroke is not a limiting factor for the MSM use case. The feasible design space for blade thickness is bounded by two primary constraints: the minimum printable feature size for additive manufacturing ($h_{AM, \min} = 200 \mu\text{m}$) and the maximum allowable thickness to meet stiffness requirements ($h_{K, \max} = 214 \mu\text{m}$).

However, an additional consideration is the sensitivity of performance to AM-induced defects, such as surface roughness and porosity. The relative sensitivity (i.e., relative error) of both stroke and stiffness decreases with increasing blade thickness. Consequently, a nominal blade thickness of $h_0 = 215 \mu\text{m}$ was selected.

Prior studies have reported a deviation between nominal and effective thicknesses of approximately $[-20, 0] \mu\text{m}$ under optimized LPBF parameters. This variability is represented by the dashed lines and the “uncertain design space” in Figure 5. Consequently, the selected thickness ensures that the manufactured component meets all performance requirements while minimizing the impact of AM-induced variability.

In summary, the proposed two-step design methodology ensures both mechanical robustness and functional reliability under cryogenic conditions, while enabling rapid and flexible customization of the compliant pivot.

Notably, the resource-intensive lattice optimization is performed on normalized parameters, allowing the final tuning phase to focus solely on blade thickness. This significantly reduces design iteration time and simplifies adaptation to specific requirements. Such modularity in the design process is particularly advantageous in complex aerospace projects, where mechanism-level specifications - such as stiffness, stroke, or spatial constraints - may be revised throughout development phases.

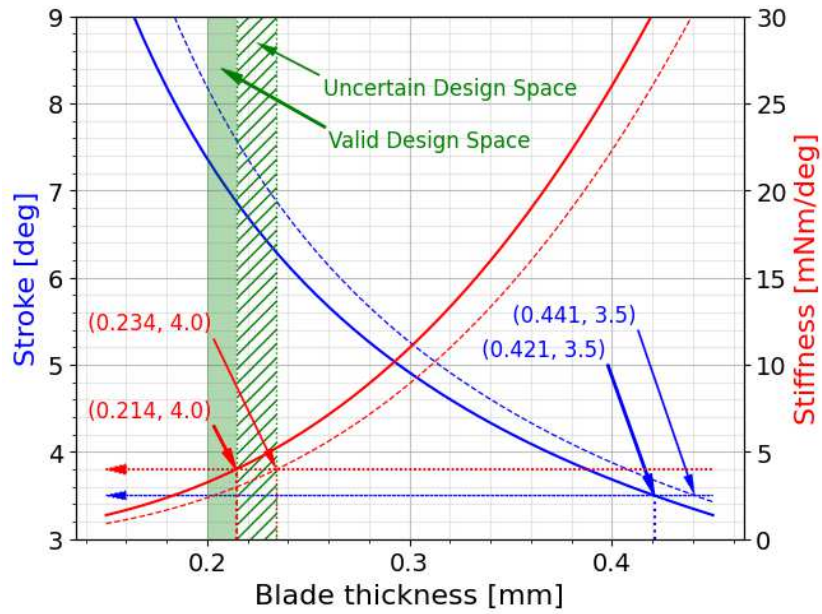


Figure 5: ILF Pivot's Estimated Stroke and Stiffness in Function of its Blades' Thickness.

Dashed lines represents performances variations due to typical deviations in effective thickness ($[-20, 0] \mu\text{m}$). The acceptable design space is bounded by the minimum printable blade thickness ($200 \mu\text{m}$), and the maximum thickness constrained by stress and stiffness requirements. Stroke is computed using the yield stress as the limiting criterion.

2.2.3. Design for AM and interface customization

Beyond performance optimization, one of the key advantages of AM lies in its capacity for geometric customization - particularly in the design of component's interfaces. In the case of the ILF pivot, this flexibility enables the adaptation of interface geometries without compromising mechanical performance or significantly affecting manufacturing cost. This capability is especially valuable in aerospace applications, where integration with existing systems often requires strict dimensional compatibility.

In response to a specific request from CSL, the ILF pivot was designed to be fully interchangeable with available COTS counterparts. The required envelope dimensions were a height of $h_{pivot} = 20.3$ mm and a diameter of $D_{pivot} = \varnothing 12.7$ mm. These constraints were incorporated into the design without impacting the performance of the compliant blades, which remain the primary functional elements of the mechanism.

The printability of the ILF pivot was ensured through careful design of both the self-supporting lattice structure (see previous sections) and the interface geometries. The bottom interface is fully printable without support structures, while the top interface requires minimal support - limited to its lower planar ring surface. To facilitate post-processing and ensure structural integrity during machining, a bridging structure was introduced between the top and bottom interfaces. This bridge serves a dual purpose: it acts as a support structure during printing and provides mechanical stability during post-machining operations. It is subsequently removed during the final machining step, which is aimed at achieving high dimensional accuracy of the interface diameters.

The manufacturing workflow for the ILF pivot is structured to balance precision, performance, and cost-efficiency. The process consists of the following steps:

- **Additive manufacturing:** The pivot is printed through LPBF with dimensional margins to allow for precision post-machining (see Figure 6).
- **Thermal treatments:** Stress annealing is applied to relieve internal stresses and enhance ductility, followed by Hot Isostatic Pressing (HIP) to improve material density, structural anisotropy, and fatigue life (see section 3.1).

- **Build Plate Removal:** The printed part is detached from the build plate.
- **Final Machining:** The bridge and interface surfaces are machined in a single setup using a lathe or grinding machine (see Figure 6). This final machining is essential to reach a high dimensional accuracy and low surface roughness (typ. $Ra \leq 1.6 \mu\text{m}$), ensuring the compatibility and interchangeability with COTS counterparts.



Figure 6: Manufactured Interlocked Lattice Flexure Pivots.

The left image shows the pivots in their as-built state on the build plate used during LPBF, while the right image presents the components after post-processing and re-machining to achieve final dimensional accuracy and surface finish.

This streamlined production strategy enables on-demand manufacturing of compliant pivots, thereby simplifying the supply chain through the use of digital inventories and decentralized production. Beyond rapid fabrication, the use of AM enables on-demand customization of each pivot within the same build plate. By leveraging the modularity of the ILF design and the normalized optimization framework, individual pivots can be tailored to meet varying performance requirements without altering the overall production workflow. The ILF pivot thus combines economic efficiency with high adaptability, positioning it as a compelling solution for precision mechanisms in demanding environments.

In summary, the use of AM not only enables performance-driven customization of compliant mechanisms but also facilitates interface adaptation and cost-effective production. The ILF pivot exemplifies how advanced manufacturing techniques can meet stringent aerospace requirements while maintaining compatibility with existing hardware and budgetary constraints.

3. Characterization

With the design finalized, this section presents the numerical and experimental characterization of the customized ILF pivot, focusing on its fatigue behavior, stroke, and stiffness performance.

3.1. Fatigue behavior

The fatigue behavior of the ILF pivot is a critical factor in predicting its operational stroke under cyclic loading. Among the various mechanical properties, the fatigue strength - typically represented by the Wöhler (S-N) curve - is particularly sensitive to part geometry, process parameters, and post-processing operations. While properties such as Young's modulus and Poisson's ratio are also relevant, they exhibit less variability under AM conditions.

To accurately assess the fatigue performance of the 316L lattice blades, an experimental campaign was conducted using representative specimens (same lattice geometry) fabricated via the same LPBF process as the final pivot. The study also evaluated the influence of post-processing on fatigue response. The experimental setup, consistent with previous studies [13], involved subjecting representative compliant blades to cyclic loading of varying amplitudes. Blade integrity was monitored using force sensors, and fatigue life was defined as the number of cycles at which a 10% drop in force was detected - indicative of critical fracture.

Following the staircase method outlined in ISO 3800, approximate Wöhler curves were generated for two post-processing conditions: stress annealing (SA) alone, and SA followed by Hot HIP. The results, shown in Figure 7, indicate that SA+HIP samples exhibit an increase in fatigue strength of approximately 30 MPa ($\sim +5.8\%$) compared to SA-only samples.

Based on these findings, HIP was selected as a post-processing step for the ILF pivot. The fatigue strength of AM 316L under this condition was determined to be:

- Finite life (10^4 cycles): $\sigma_{finite} = 538$ MPa

- Infinite life ($> 10^7$ cycles): $\sigma_{\infty} = 303$ MPa

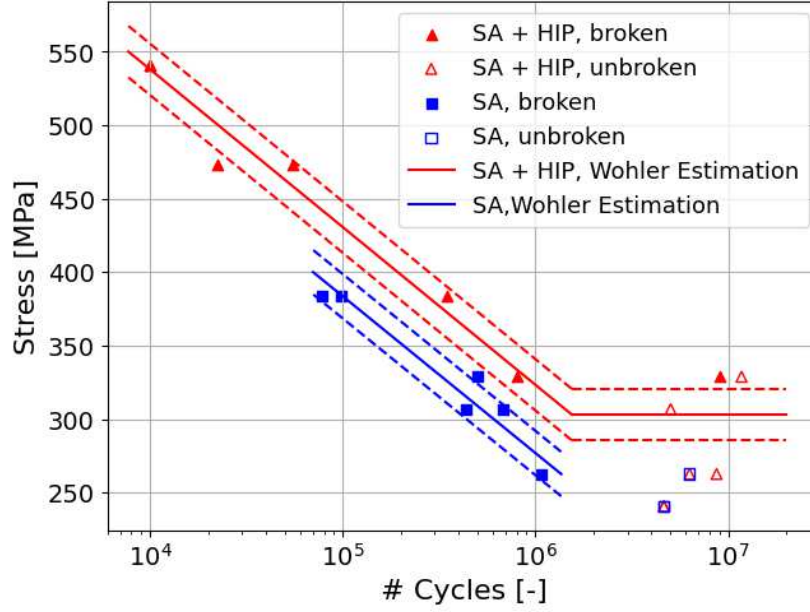


Figure 7: Wöhler Curve of AM 316L Lattices Compliant Blade Subjected to Different Post Processes

SA = Stress Annealed, HIP = Hot Isostatic Pressure. Before the significant increased of strength of SA+HIP sample, only the finite lifetime of the Wöhler curve has been conducted for SA samples.

3.2. Characterization of stroke

With the fatigue behavior of the LPBF-processed 316L established, the stroke of the custom ILF pivot was evaluated numerically.

In the non-linear Finite Element Analysis (FEA), one interface of the pivot was fully constrained (all degrees of freedom), while a varying torque was applied to the opposite interface. The resulting angular displacement and maximum von Mises stress were recorded across the whole geometry.

Figure 8 illustrates the relationship between applied rotation and maximum stress. At the maximum required stroke of $\theta = \pm 3.5$ deg, the peak stress reaches $\sigma_{max} = 237$ MPa.

Using the fatigue strength values from the previous section, the factors of safety (FOS) for finite and infinite life can be computed as:

$$FOS_{finite} = \frac{\sigma_{finite}}{\sigma_{max}} = \frac{538 \text{ MPa}}{237 \text{ MPa}} = 2.27 [-] \quad (3)$$

$$FOS_{\infty} = \frac{\sigma_{\infty}}{\sigma_{max}} = \frac{303 \text{ MPa}}{237 \text{ MPa}} = 1.28 \quad (4)$$

The results confirm that the ILF pivot meets the required stroke specifications with considerable safety margins. Fatigue testing performed on three compliant pivots further validates these findings, as each specimen successfully endured between $1 \cdot 10^6$ to $3 \cdot 10^6$ cycles under an equivalent stress of 270 MPa.

Although these safety margins may appear conservative relative to the operational conditions of the MSM, they provide critical robustness against minor manufacturing imperfections and, more importantly, guarantee fail-safe behavior - a topic discussed in detail in Section 4.

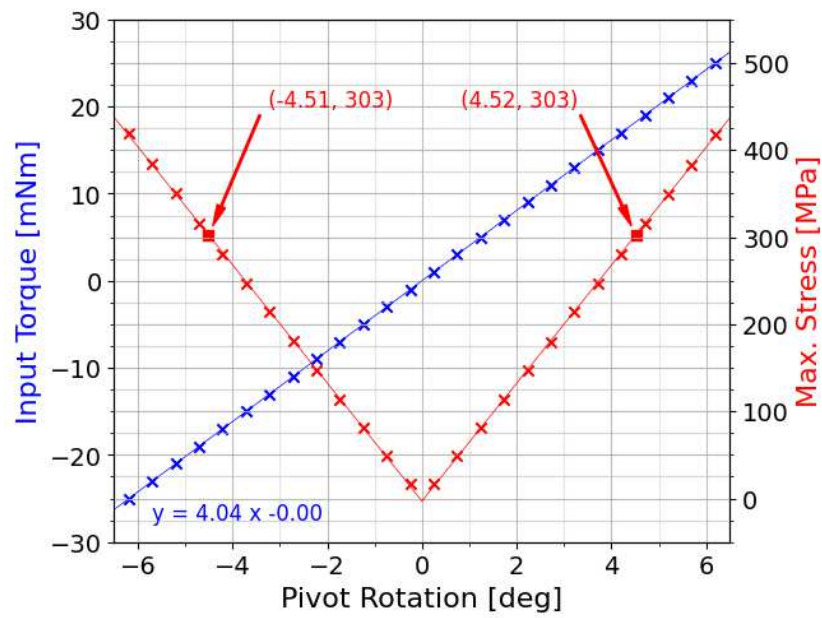


Figure 8: Pivot's Rotation, Reaction Torque, and Maximum Stress in the ILF Pivot
The two highlighted points represents the fatigue limit of the ILF Pivot.

3.3. Characterization of stiffness

The same FEA model was used to estimate the natural stiffness of the ILF pivot. As shown in Figure 8, the torque-rotation relationship is highly linear within the ± 6.5 deg range, with a coefficient of determination $R^2 = 1 - 3.4 \cdot 10^{-7}$. The stiffness was thus calculated as the slope of the linear fit to the torque-rotation data, yielding a value of: $K_\theta = 4.04$ mN·m/deg. This value slightly exceeds the upper bound of the stiffness requirement. However, as discussed in Section 2.2.2, prior studies have shown a typical deviation of $[-20, 0]$ μm between nominal and effective thickness in AM-fabricated compliant elements. Therefore, this 1% overshoot is considered acceptable.

To validate the numerical prediction, the effective stiffness of seven manufactured ILF pivots was experimentally measured at room temperature. As shown in Figure 9 and Table 3, the average measured stiffness was: $\bar{K}_\theta = 3.97$. This result confirms the validity of the numerical model and demonstrates compliance with the design specification. Moreover, the standard deviation of the measured stiffness was $\sigma_{K_\theta} = 0.30$ mN·m/deg (which correspond to a variation of the effective thickness of ~ 20 μm), indicating good repeatability of the LPBF process. For comparison, a characterization of commercial C-FLEX compliant pivots revealed a 45% to 60% relative error between expected and measured natural stiffness. This highlights the competitive performance consistency of the ILF pivot relative to COTS alternatives. Note that these experimental results are coherent with the cryogenic tests conducted by CSL [8].

Pivot ID	Stiffness mN·m/deg	R^2 value [-]
SN01	4.28	1.000
SN02	3.95	0.997
SN04	3.65	0.998
SN06	4.48	1.000
SN08	3.95	0.997
SN10	3.54	0.994
SN11	3.91	0.996

Table 3: Result of the Experimental Stiffness Evaluation of 7 Manufactured 316L ILF Pivots

The R^2 values describe the linear fit error of the Torque-Rotation data.

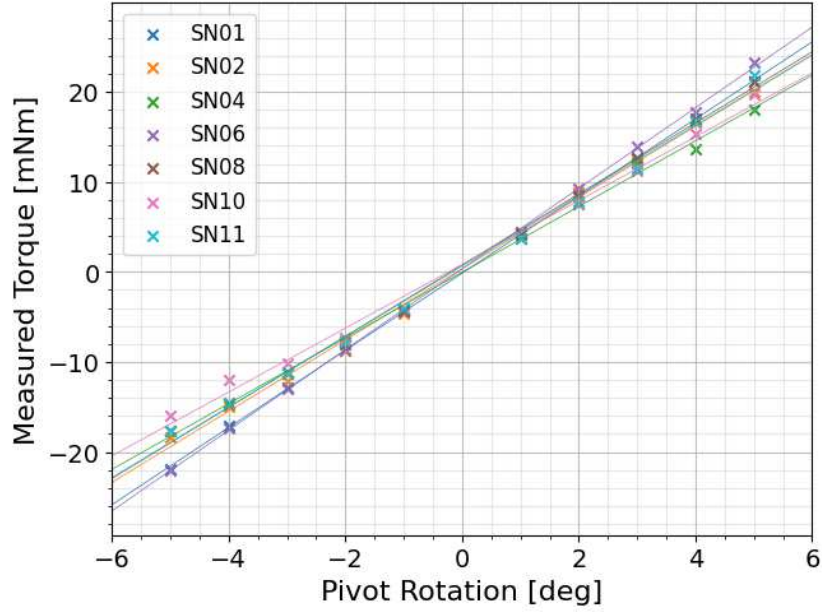


Figure 9: Measured Reaction Torque against Rotation for 7 Manufactured 316L ILF Pivots along with linear approximation

4. Single Failure Point Avoidance

As with most mechanical systems, compliant mechanisms often represent single point of failure. The functionality and performance of a compliant mechanism cannot be guaranteed if a critical rupture occurs within one of its flexural components. Consequently, compliant joints are typically designed either for virtual infinite lifetime - by maintaining stress levels below fatigue thresholds - or with high safety margins to account for potential degradation over time.

However, real-world conditions such as manufacturing defects, assembly misalignments, or unforeseen out-of-range operations can lead to localized stress concentrations, increasing the risk of crack initiation. In conventional compliant blades, such cracks tend to propagate through the entire flexure, ultimately resulting in catastrophic failure.

The ILF lattice design, by contrast, inherently mitigates this risk. Its segmented architecture localizes damage, preventing crack propagation beyond a single truss element and thereby eliminating the single-point failure characteristic of plain flexures.

To evaluate the structural integrity of the ILF pivot under partial fracture conditions, a series of FEA was conducted: artificial cracks were introduced at eight critical locations within a representative lattice mesh, as illustrated in Figure 10.

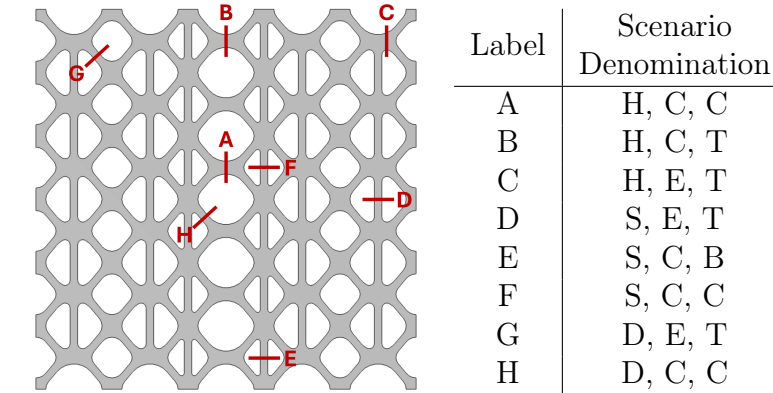


Figure 10: Fracture Scenarios for Failure Analysis

H: Main lattice, horizontal truss, T: Main lattice, diagonal truss, S: Stiffener, C: Centered, E: Extremity, B: Bottom

Among the eight scenarios, only three resulted in a stress increase exceeding 10%, with the most severe case (Scenario B) showing a maximum stress rise of +59.0%. Despite this, the stress within the ILF pivot remains within acceptable limits for its intended operational life. Specifically, the finite-life margin of safety (127%, as established in Section 3.2) ensures that the pivot can tolerate such localized damage without compromising functionality over its full expected lifetime.

While the infinite-life margin of safety is exceeded in Scenario B, the other cases remain within safe bounds. This indicates that the ILF pivot retains a high degree of robustness even under partial fracture conditions.

These findings demonstrate the inherent fault tolerance of the ILF architecture. By localizing damage and preventing full structural failure, the lattice design significantly enhances the reliability of compliant mechanisms, effectively eliminating traditional single-point failure modes.

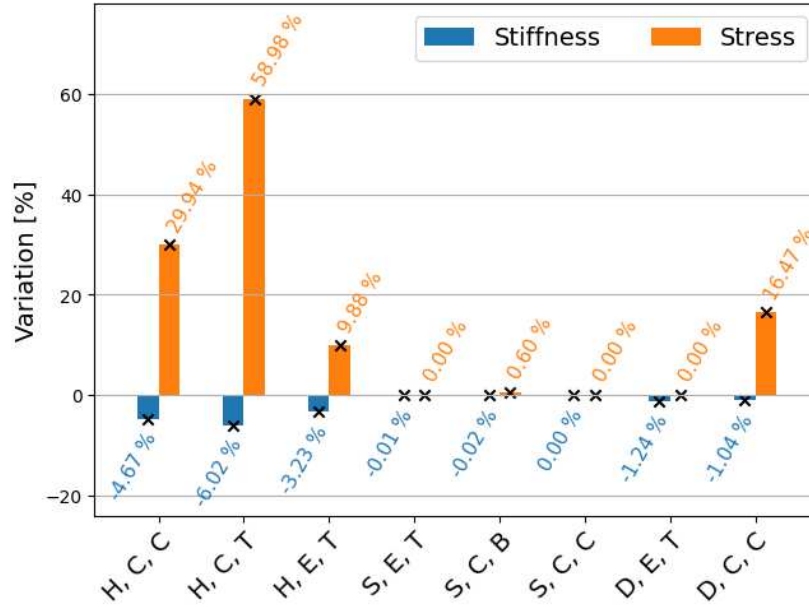


Figure 11: Variation in Von Mises Stress and Stiffness for a 6 deg Rotation Under Different Fracture Scenarios

Reference: nominal blade. H: Main lattice, horizontal truss, T: Main lattice, diagonal truss, S: Stiffener, C: Centered, E: Extremity, T: Top, B: Bottom

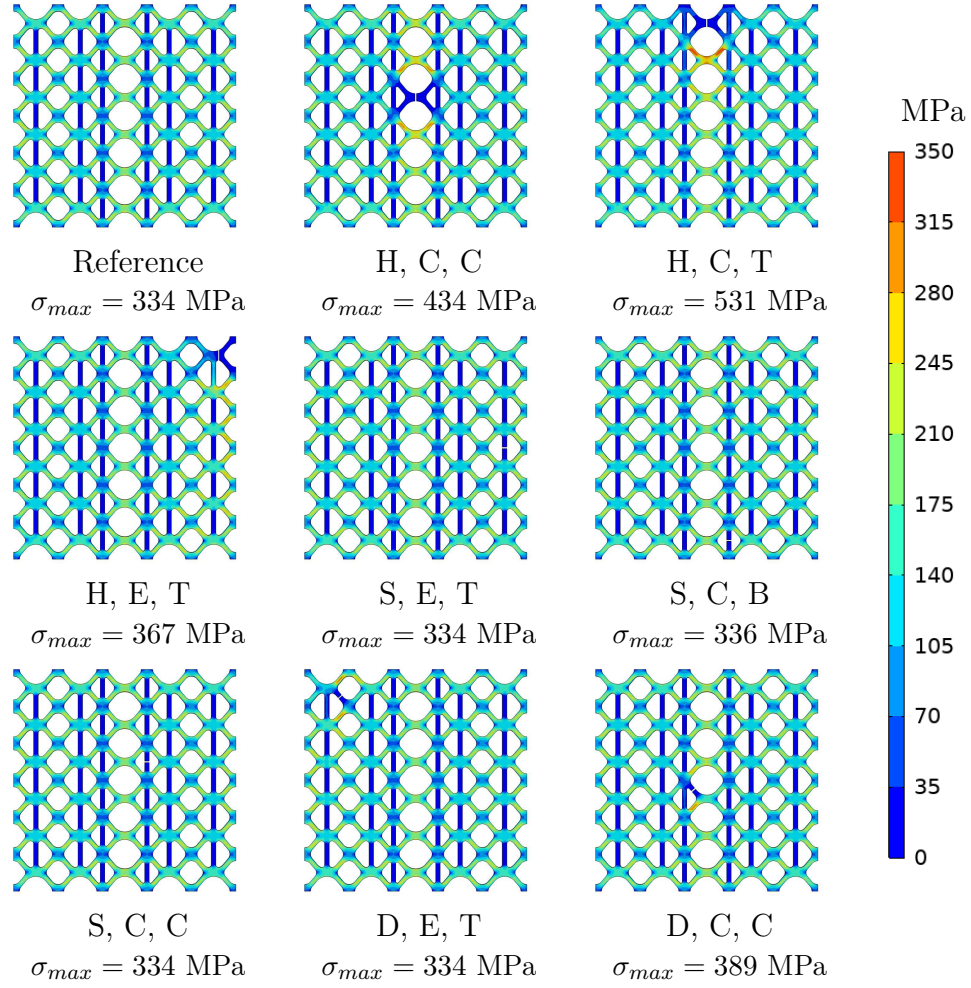


Figure 12: Von Mises Stress Distribution in Lattice Blades for a 6 deg Rotation Under Different Fracture Scenarios

H: Main lattice, horizontal truss, T: Main lattice, diagonal truss, S: Stiffener, C: Centered, E: Extremity, T: Top, B: Bottom

5. Conclusion

This work presents a comprehensive DfAM approach for a customized compliant pivot intended for cryogenic operation within the MSM. Leveraging the geometric freedom afforded by AM, the proposed ILF architecture addresses several longstanding challenges in compliant mechanism design, including on-demand performance optimization, fast interface adaptability, and failure robustness.

The design methodology integrates multi-objective optimization to balance conflicting performance criteria - namely stroke, stiffness, and guiding accuracy - while ensuring manufacturability within the constraints of LPBF. The ILF lattice geometry enables a significant reduction in natural stiffness (up to 7 times compared to plain blades), thereby allowing increased blade thickness and improved printability without compromising functional performance.

The subsequent thickness adaptation step further refines the design, accounting for AM-induced variability and ensuring compliance with operational requirements.

Material selection was guided by the stringent thermal and mechanical demands of cryogenic environments. 316L stainless steel was chosen for its favorable behavior at low temperatures and its compatibility with AM processes. Post-processing treatments, including stress annealing and HIP, were shown to significantly enhance fatigue strength, with experimentally derived Wöhler curves confirming the suitability of the material for long-term cyclic operation (at least at room temperature).

Numerical and experimental characterizations confirmed the performance of the ILF pivot. Non-linear FEA demonstrated that the pivot meets the required ± 3.5 deg stroke with substantial safety margins - 2.27 for finite life and 1.28 for infinite life - based on experimentally derived fatigue strength values.

The simulation predicted a natural stiffness of 4.04 mN·m, representing a 1% exceedance of the upper bound of the design specification. However, this deviation is considered acceptable due to known effects of the LPBF process, which typically results in a reduction of effective blade thickness.

To validate these findings, experimental stiffness measurements were con-

ducted on seven manufactured ILF pivots. The results yielded a mean stiffness of 3.97 mN·m, aligning with the design requirements. Furthermore, the standard deviation of 0.30 mN·m indicates good process repeatability, consistent with COTS flexible pivots which exhibit similar variability. These results confirm that the ILF pivot not only meets its functional specifications but also achieves reliable performance across multiple units, reinforcing its suitability for precision applications in cryogenic environments.

A key innovation of the ILF design lies in its inherent resistance to single-point failure. Owing to its segmented lattice architecture, the compliant blades effectively inhibit crack propagation, thereby preventing catastrophic failure of the pivot.

Targeted fracture simulations revealed that localized damage within the lattice structure leads to a stress increase of up to 60%, which remains within the finite-life safety margin of 127%. As a result, the structural integrity of the pivot is preserved throughout its expected operational lifespan.

This fault-tolerant behavior significantly enhances the reliability of compliant mechanisms, making the ILF pivot particularly well-suited for critical aerospace applications where robustness and fail-safe operation are paramount.

In addition to functional optimization, AM enabled the customization of interface geometries to meet integration requirements with existing COTS components. The inclusion of a removable bridging structure facilitated post-machining and dimensional accuracy, while maintaining cost-efficiency.

In summary, the ILF pivot exemplifies the transformative potential of AM in compliant mechanism design. It demonstrates how advanced manufacturing techniques can be harnessed to achieve high-performance, customizable, and robust components tailored to demanding operational environments. This approach not only meets the specific needs of the MSM but also lays the groundwork for broader adoption of AM-enabled compliant mechanisms in future space and cryogenic instrumentation.

6. Acknowledgment

We would like to thank ESA and PRODEX office for the opportunity to work on this project with innovative solutions. It has been a rewarding experience in all areas of engineering.

7. Funding details

The authors declare that no external funding was received for this work. All resources were provided through their affiliated organization, covering salaries and subcontracting costs.

8. Disclosure statement

The authors report there are no competing interests to declare.

9. Data availability statement

The datasets supporting the findings of this study are proprietary to CSEM SA and are therefore not publicly available. However, the data can be provided by the corresponding author upon reasonable request.

10. Authors' contributions

According to the CRediT taxonomy, the authors contributed to this work as follows:

- **Guilain Lang:** Conceptualization (for publication), Data curation (whole paper), Formal analysis (whole paper), Investigation (data analysis for the whole paper), Validation (whole paper), Visualization (whole paper), Writing - original draft.
- **Lionel Kiener:** Conceptualization (whole project), Funding acquisition, Investigation (Sections 3.1, and 3.2), Methodology (whole paper), Project administration, Validation (whole paper), Writing - review & editing.
- **Maxime Lautenbacher:** Data curation (original for Section 2.2.1) , Formal analysis (original for Section 2.2.1), Methodology (original for Section 2.2.1).
- **Florent Cosandier:** Data curation (original for Section 4), Formal analysis (original for Section 4).
- **Etienne Lallemand:** Project administration, Supervision, Writing - review & editing.

- **Tanguy Thibert:** Project administration, Supervision, Writing - review & editing.
- **Herve Saudan:** Project administration, Supervision, Writing - review & editing.

References

- [1] L. L. Howell, S. P. Magleby, B. M. Olsen, Handbook of compliant mechanisms, Wiley, Chichester, 2013.
- [2] F. Cosandier, S. Henein, M. Richard, L. Rubbert, The Art of Flexure mechanism Design, 1st Edition, EPFL Press, 2017.
- [3] S. Henein, P. Spanoudakis, S. Droz, L. I. Myklebust, E. Onillon, Flexure pivot for aerospace mechanisms, in: Proc.10th European Space Mechanisms and Tribology Symposium, San Sebastian, Spain, 2003, p. 1–4.
- [4] P. Spanoudakis, P. Schwab, L. Kiener, H. Saudan, G. Perruchoud, Development challenges of utilizing a corner cube mechanism design with successful iasi flight heritage for the infrared sounder (irs) on mtg; recurrent mechanical design not correlated to recurrent development, in: 16th European Space Mechanisms and Tribology Symposium – ESMATS 2015, Bilbao, Spain, 2015, p. 1–8.
- [5] E. G. Merriam, J. E. Jones, S. P. Magleby, L. L. Howell, Monolithic 2 dof fully compliant space pointing mechanism, Mechanical Sciences 4 (22) (2013) 381–390. doi:10.5194/ms-4-381-2013.
- [6] L. Kiener, H. Saudan, F. Cosandier, G. Perruchoud, V. Pejchal, J. Rouvinet, F. Boudoire, N. Kalentics, Validation of compliant mechanisms made by metallic additive manufacturing, in: R. Geyl, R. Navarro (Eds.), Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation V, SPIE, Montréal, Canada, 2022, p. 30. doi:10.1117/12.2629199.
- [7] G. Lang, J. Rouvinet, L. Kiener, M. Meboldt, Automated rigid bodies synthesis for am compliant mechanisms, Virtual and Physical Prototyping 20 (2025) e2551083. doi:10.1080/17452759.2025.2551083.

- [8] E. Lallemand, T. Thibert, B. Marquet, J.-Y. Plessier, F. Henrotte, C. Geuzaine, L. Kiener, G. Lang, H. Saudan, N. Kalentics, The mode selector mechanism (msm): a bi-stable cryo-actuator operated at 4.2k, IOP Conference Series: Materials Science and Engineering 1327 (1) (2025) 012163. doi:10.1088/1757-899X/1327/1/012163.
- [9] L. Kiener, H. Saudan, F. Cosandier, G. Perruchoud, A. Ummel, V. Pejchal, P. Zaltron, Y. Puyol, M. Lichtenberger, Compliant mechanism based on additive manufacturing, CEAS Space Journal 15 (11) (2023) 37–53. doi:10.1007/s12567-021-00394-0.
- [10] Z. Geng, J. Guo, X. Su, C. Zhang, J. Li, J. Gong, H. Yang, N. Zhao, Z. Sun, S. Ren, Tailoring the properties of 17-4 ph steel via cryogenic treatment, Journal of Materials Engineering and Performance (Nov. 2025). doi:10.1007/s11665-025-12681-6.
URL <https://doi.org/10.1007/s11665-025-12681-6>
- [11] J. K. Veetil, M. Khorasani, A. Ghasemi, B. Rolfe, I. Vrooijink, K. Van Beurden, S. Moes, I. Gibson, Build position-based dimensional deviations of laser powder-bed fusion of stainless steel 316l, Precision Engineering 67 (2021) 58–68. doi:10.1016/j.precisioneng.2020.09.024.
- [12] H. Afshari, W. Hare, S. Tesfamariam, Constrained multi-objective optimization algorithms: Review and comparison with application in reinforced concrete structures, Applied Soft Computing 83 (2019) 105631. doi:10.1016/j.asoc.2019.105631.
- [13] H. Saudan, L. Kiener, G. Perruchoud, K. Vaideeswaran, M. M. Dadras, Additively manufactured and topologically optimized compliant mechanisms: Technological assessment approach, latest achievements and current work in progress, in: Proc. ‘ESMATS 2017’, Hatfield, U.K., 2017.