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6 Design principles for SLM-based compliant mechanisms

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Abstract

This work discusses 6 design principles useful to optimise compliant mechanisms for Additive Manufacturing (AM) and more specifically Selective Laser Melting (SLM). The design principles are: 1) lattice flexures, 2) interlocking flexures, 3) embedded support structures, 4) flexure shape optimization, 5) structural topology optimization and 6) thermal warpage compensation. These six design principles are first illustrated with the example of a simple pivot. Lastly, they are applied to a compliant rotation reduction mechanism.

Structural topology optimization, Lattice flexures, Selective Laser Melting (SLM), Support structures, Interlocked flexures, Compliant mechanisms.

1. Introduction

Selective Laser Melting (SLM) presents many opportunities for precision mechanisms, among which further integration and part reduction. In past work, we have optimized and tested relevant process related parameters for mechanisms, such as material selection, post-process selection, tensile tests and fatigue tests [1].

To apply this knowledge to a design in an optimal way, additional considerations are needed for the minimum feature size, overhang angle, geometrical distortions, support and part removal. Other works such as Merriam [2] have discussed strategies for stiffness reduction to cope with the high stiffness imposed by the typically large minimum feature size.

This paper presents a methodology for Additive Manufacturing (AM) design for compliant mechanisms centred around a typical classical commercial pivot such for example the one offered by flexpivots[3]. Lastly, the elaborated design methodology is applied to a more complex use-case of a compliant rotation reducer mechanism.

2. AM design principles for flexures

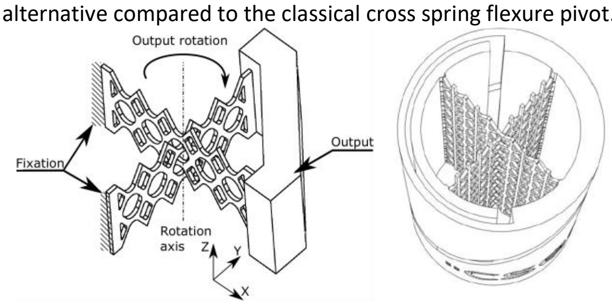
This chapter discusses 6 design principles used to optimise cross spring flexure pivot, namely: 1) lattice flexures, 2) interlocking flexures, 3) embedded support structures, 4) flexure shape optimization, 5) structural topology optimization and 6) thermal warpage compensation.

2.1. Lattice flexures for stiffness reduction

To reduce stiffness, as the minimum thickness is limited by the SLM resolution, we applied lattice flexures [2]. By using this typical stiffness reductions ranging from 50 to 88.6 % can be obtained. Which allow for realizing pivots that are not too stiff even when realised with relatively large flexure thicknesses common in SLM.

2.2. Interlocking flexures for symmetry and overhang

To cope with the multiple overhangs in a classical pivot we propose an interlocking flexure (Figure 1), where over the entire stroke of the pivot the individual flexure blades do not touch. The flexure blades interlock and provide a more symmetric alternative compared to the classical cross spring flexure pivot.



Patent pending

a b

Figure 1. a) An interlocking flexure, allowing a symmetrical flexure structure that does not touch itself in static or dynamic operation. In addition, the overhang angle of 45 Deg angle from the Z-axis is directly integrated by design. B) A top view of an interlocked flexure integrated into a pivot.

2.3. Embedded support structures for easy post-processing

To guarantee a single post processing plane, the support structures are embedded into the flexures (Figure 2). This makes the post-processing a lot easier by avoiding multiple post processing planes and makes the plane for part removal the same as for support removal, limiting post-processing time and cost.

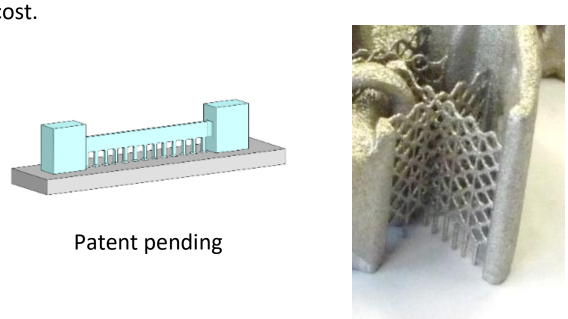


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Figure 2. a) A first example of an embedded support structure for a flexure element that has too much overhang to be fabricated without supports. b) A realised pivot with embedded support structures

2.4. Flexure shape optimization for optimal performance

In order to optimize the lattice flexures for optimal mechanical performance, a 9 dimensional Monte-Carlo based shape optimization was performed.

First the element that defines the lattice and its parameters was defined (Figure 3a). The element consists of a pre-defined length and 9 parameters for the Monte Carlo (d_i, r_i and H). After 5000 parameter sets were generated, of which a subset is illustrated in (Figure 3b).

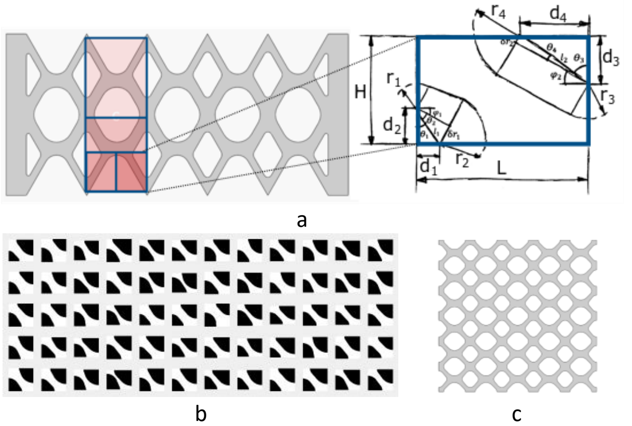

Figure 3. a) The element decomposing the lattice and its parameters. b) A set of Monte Carlo generated lattice flexures. c) The optimal flexure solution considering linearity, homogeneous stress distribution high-off axis stiffness and a low actuation torque.

The parameter sets that didn't respect the 45 Deg overhang angle and the minimum feature size of 0.4 mm were removed, after which the remaining 348 sets were simulated to optimised for two load cases of which the first is a fixed-transversal displacement of 20 microns and the second is an imposed rotation of 6 degrees. Combining the results of stress and stiffness for both load cases together with an evaluation of the variation of the elements cross section, the optimal solution was found.

These parameters were chosen to favour stiffness linearity, a homogeneous stress distribution and a high off-axis stiffness and low actuation torque.
The final result is the optimal lattice leaf spring pattern shown in Figure 3c.

2.5. Structural topology optimization for mass reduction

To have a first idea of the mass reduction a simple pivot made of stainless steel with a density of 7800 $\frac{kg}{m^3}$ is optimised. The loadcase used for the optimization is, an x and y load applied in the centre of 10 N and a moment of 10 Nmm. In addition, the first non-desired eigenmode was specified to be higher than 200 Hz. For the optimization Altair Optistruct® was used with the default solver. The result was a 59 % reduction of the structural mass (excluding the flexure), resulting in a pivot with a total mass of 15.4 gram with its lowest non-desired eigenmode at 230 Hz.

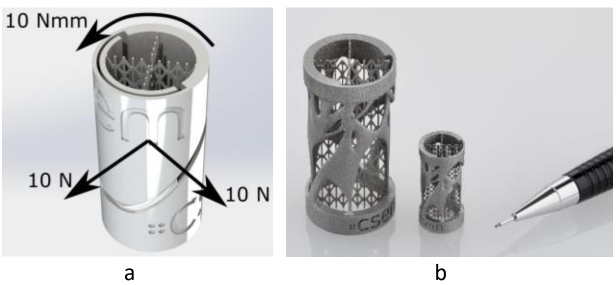

Figure 4. a) The original pivot and the loads applied for the structural optimization. b) The final realised result of the structural optimization.

2.6. Pre-deformed geometry for thermal warpage compensation

To compensate for deformations due to the thermal history accumulated during the SLM process, samples were produced and after analysed with a 3D scanner. These benchmarking samples served as inputs to be used in Amphyon, where a pre-deformed geometry was generated in order to compensate geometry deviations due to thermal warpage. The first results are promising and have shown a significant reduction of manufacturing related stress in the flexures.

3. AM design applied to a compliant rotation to rotation reducer mechanism

The aforementioned developments were applied to a novel compliant rotation reducer mechanism, comprising 11 rigid bodies and 24 flexure elements. The concept of this compliant reducer mechanism is illustrated in Figure 5. The principle is two Remote Centre of Compliance mechanisms attached to a single fixed body allowing for a reduction factor of more than 10.

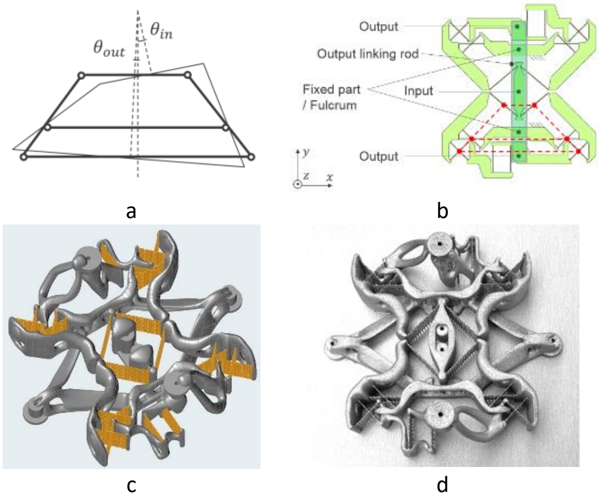

Figure 5. a) The concept of the compliant rotation reducer mechanism. b) The first implementation of the reducer mechanism. c) The optimised reducer mechanism with the flexures highlighted d) The SLM fabricated rotation reducer mechanism.

The first results are an increase of the first non-desired mode from 400 to 1000 Hz, an easier process workflow and an optimised monolithic compliant mechanism.

4. Summary conclusion and future work

This work allows for dealing with 6 challenges encountered during SLM. These are 1) minimum feature size, 2) overhang, 3) support removal, 4) flexure optimization 5) mass reduction and 6) thermal warpage, through 6 design principles. These 6 design principles are respectively: 1) lattice flexures, 2) interlocking flexures, 3) embedded support structures, 4) flexure shape optimization, 5) structural topology optimization and 6) pre-deformed geometry.

The design principles were applied to a simple pivot and a novel compliant rotation reducer mechanism was realised with the above stated design principles.

Future work consists of more detailed fatigue tests on lattice flexure blades, to validate their performance under high cycle fatigue conditions. The compliant rotation reducer mechanism is part of a European Space Agency project currently ongoing at CSEM, and will be presented in more detail in the future.

5. Acknowledgement

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6. References

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