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Damping of flexure blades based on bi-material additive manufacturing

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Abstract
Flexure-based mechanisms have become state-of-the-art solutions for the design of high-precision mechanisms, free from friction wear, backlash, and lubrication. These properties which are necessary for applications in ultraclean or harsh environments, nevertheless usually come with the drawback of very high quality factors. High quality factors can lead to adverse vibrations in the case of highly dynamic motions, or even fractures in the case of mechanical resonances. In space applications for instance, the mechanisms experience shocks and vibrations resulting from the rocket launch and from the other subsystems during operation. To tackle this challenge, CSEM developed and validated a concept of damped flexure blades based on bi-material additive manufacturing. The blades consist of a sandwich of two planar parallel metallic lattice patterns with an elastomer impregnated in-between (125 µm gap). The blades are made of 17-4PH stainless steel manufactured by Laser Powder Bed Fusion. The damping effect results from the energy dissipation occurring in the viscoelastic material as the blades and the elastomer deform. These blades were assembled in a simple parallel-spring-stage configuration and characterized under free and forced sinusoidal oscillations. Compared with reference mono-material "undamped" flexures, the damped flexures show quality factors Q reduced by a factor of 64. This reduction implies an improved damping action with a calculated viscous damping coefficient increased by a factor of 97. These first experimental results open promising perspectives for compliant mechanisms operating under vibrations and shocks. Moreover, new types of dampers could be developed based on the presented designs.

Flexure-based Mechanisms, Compliant Mechanisms, Bi-material Additive Manufacturing, Damping, Elastomer, Vibrations, Precision Mechanisms

1. Introduction

In the field of precision mechanisms, friction-based motion guiding solutions generate numerous disadvantages, one of them being wear. Lubrication improves the quality of the motion and minimizes wear. However, it cannot be excluded that debris form or that uncontrolled stick-slip motion occurs making closed-loop motion control hardly possible. More particularly, in the space domain where cleanliness, wear-free motion, and a very long lifetime are primordial, this aspect becomes critical. Thereby, compliant mechanisms are of great interest. Indeed, as they are made of flexible elements that bend to allow the desired motion, no solid friction is observed. High-precision strokes can be achieved for long periods of time as the deformations remain in the elastic domain. Considering material fatigue, compliant mechanisms show high lifetime performance, even in the harsh environment of space. Another advantage of such mechanisms is the possibility to manufacture them using additive manufacturing (AM) techniques. AM, in addition to be more eco-friendly [1], increases the design freedom [2].

A key requirement of any space mechanism is to withstand vibrations and shocks resulting from the rocket launch (or landing), and the commissioning of the payload. Additionally, during operation, a space mechanism can be exposed to micro-vibrations produced by other subsystems (e.g., cryocoolers and reaction wheels). These micro-vibrations can affect the mechanism performance and, consequently, those of the instrument containing it [3]. Furthermore, for some complex compliant mechanisms, the presence of internal degrees of freedom aggravates the criticality of vibrations due to the presence of internal modes which can neither be controlled nor locked. The need for robust and reliable damping systems is therefore of great importance.

To damp a flexure blade, a solution consists in adding an elastomer that will deform with the flexure in operation. Indeed, as elastomers show viscoelastic properties, they dissipate significant energy when subjected to cyclic stress. This characteristic results from the molecular motion inside the elastomer that induces internal friction. As opposed to elastic materials which return nearly all the energy injected, elastomers exhibit a hysteresis behavior where part of the strain energy is dissipated into heat [4-5]. CSEM patented such a concept for small size mechanical components [6]. Its applicability to centimeter-scaled flexures is nevertheless nearly impossible, due to difficulty in adding the viscoelastic material in difficult to access areas.

To overcome this problem, CSEM proposed to take advantage of AM to design and produce a *lattice flexure* (instead of a plain flexure) which is split into two blades. A small gap lies between them. Unlike plain flexures, the latter can be easily impregnated with a viscoelastic material in a liquid phase which flows to fill all voids between the two blades and solidifies.

2. Methodology

2.1. Flexures design

The novel flexures designed in this project were so called double blades with lattice features. As illustrated in Figure 1, the double blade is composed of a *master* blade and a thinner *slave* blade. The master blade, which is thicker, leads the double blade motion. Table 1 lists the dimensions of these flexures.

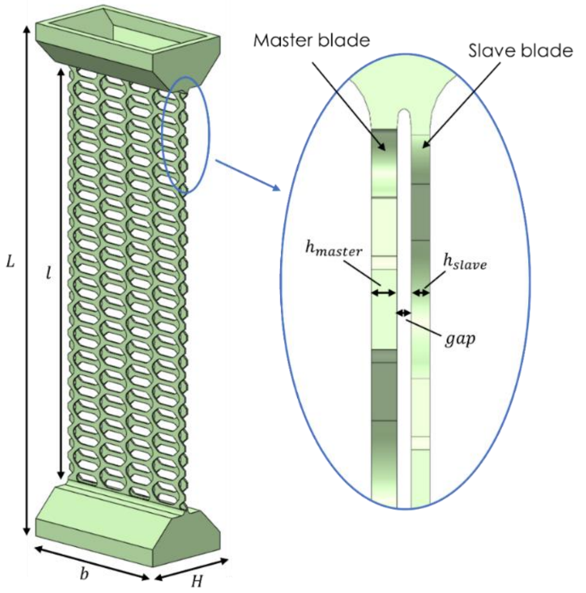

Figure 1. Elements and dimensional parameters of the flexures.

Table 1. Design parameters of the flexures.

Parameter	Symbol	Value	Unit
Blade length	l	47.6	mm
Blade width	b	18.2	mm
Blade thickness (master)	h_{master}	220	µm
Blade thickness (slave)	h_{slave}	160	µm
Gap between blades	gap	125	µm
Total length (with supports)	L	58.6	mm
Total thickness (with supports)	H	10.5	mm

Two blade's configurations were implemented to compare their damping performances and select the most promising geometry. In addition to the "clamped-clamped" flexure presented in Figure 1, a "clamped-free" configuration was also designed as shown in Figure 2. This second blade design is characterized by the release of the upper extremity of the slave blade, which is not clamped to the upper support.

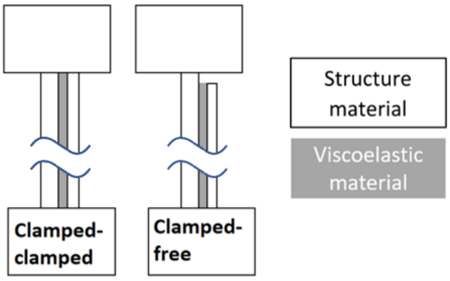

Figure 2. "Clamped-clamped" and "clamped-free" blade configurations.

Moreover, small 3D structures – called *spikes* – were added on the horizontal parts of the lattices as illustrated in Figure 3. These aimed at increasing the strain and thus the damping in the elastomer when the flexures are bent. Configurations with and without spikes were both tested and compared (see Table 2).

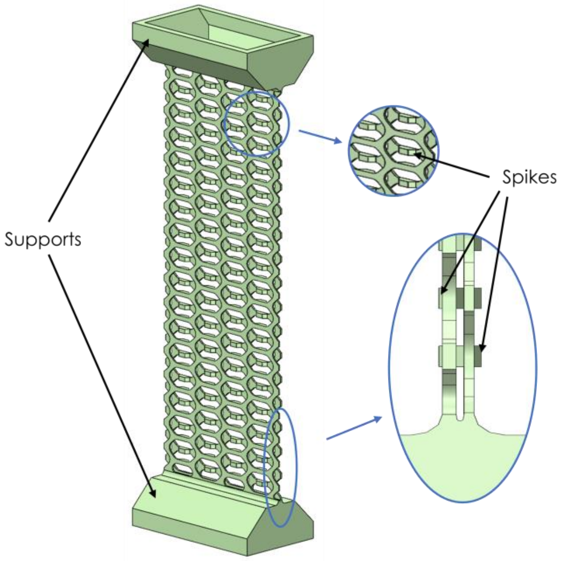

Figure 3. Flexures with spikes.

2.2. Flexures manufacturing and impregnation

The flexures were additively manufactured in 17-4PH stainless steel using a Laser Powder Bed Fusion (LPBF) process. Then, after undergoing a stress relief treatment and removed from the build-plate, the flexures were impregnated with an elastomer. Based on a state-of-the-art search, the polyurethane acrylate UVEKOL S and the silicone Alpha gel C were selected. These two viscoelastic materials were deposited on the blades using a syringe and crosslinked using UV light. After this process, the impregnated flexures (shown in Figure 4) were ready to be tested under vibrations.

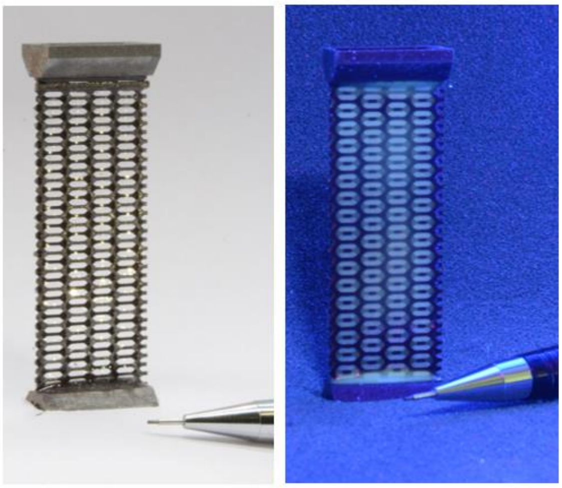

Figure 4. Final impregnated flexures (under UV light on the right).

2.3. Test bench design

Prior to starting the test campaign, a test bench, illustrated in Figure 5, was designed to perform free oscillation tests. Two identical flexures are mounted in a parallel-spring-stage configuration on a base (violet pieces) that is fixed to a baseplate. A rotating DC motor, attached to the base, is then used to bring the moving part (yellow part) to a specific stroke. Finally, the moving part is released, and a linear encoder records its position with respect to time.

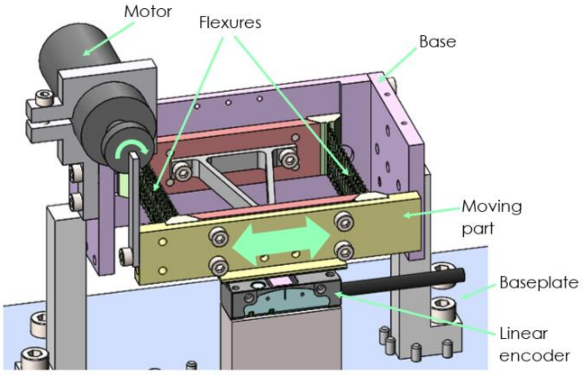

Figure 5. Test bench design.

2.4. Test plan

The test plan consisted in testing the different blade configurations listed in Table 2 in free oscillation. The reference blade is a simple – not split – blade with the same lattice pattern as the other tested flexures. However, its thickness is set to 245 µm to obtain the same stiffness and resonance frequency as the double blades. This reference allows the comparison of the impregnated double blades with the already existing state-of-the-art single blades.

Table 2. List of the seven blades to be tested.

Blade types		Clamped -clamped	Clamped - free	Ref.
UVEKOL S *PU acrylate*	Without spike	X	X	
	With spikes	X	X	
Alpha gel C *Silicone*	Without spike			
	With spikes	X	X	
Without elastomer	Without spike			X
	With spikes			

From the recorded motion of the moving part in free oscillation, curves similar to the one shown in Figure 6 are expected. A decreasing exponential curve is then fitted to the maximum amplitude of each oscillation.

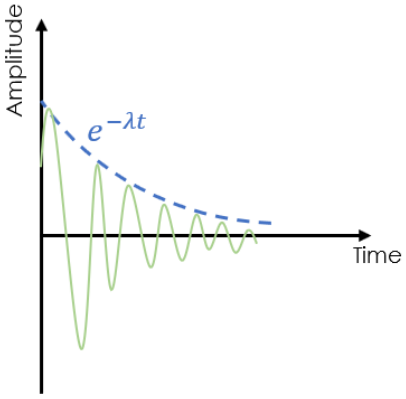

Figure 6. Typical graph obtained in a free oscillation test.

The quality factor Q and actual damping c are computed from these exponential models to assess and compare the damping performances of the different blades. The following formulae are used:

$$Q = \frac{\omega_0}{2\lambda} \quad \text{and} \quad c = 2m\lambda.$$

Where ω_0 is the angular pulsation obtained from the oscillation period (T_0): $\omega_0 = 2\pi/T_0$, λ is the damping coefficient obtained from the model and m the mobile mass. The smaller the quality factor is, the larger the damping is, and inversely for the actual damping.

3. Results and discussion

From the gathered data illustrated in Figure 7, two qualitative observations are made. First, adding the elastomer greatly enhances the damping performances. Indeed, in Figure 7, the reference continues to oscillate after hundreds of seconds while the impregnated blades stop moving after about ten seconds. Secondly, one can say that the UVEKOL S impregnated blades have higher damping performances than with Alpha gel C.

Following the exponential curve fitting on the measured time-domain datapoints, the damping parameters listed in Table 3 are obtained. The values mentioned in the table are the mean values of five different free oscillation tests performed for each blade configuration.

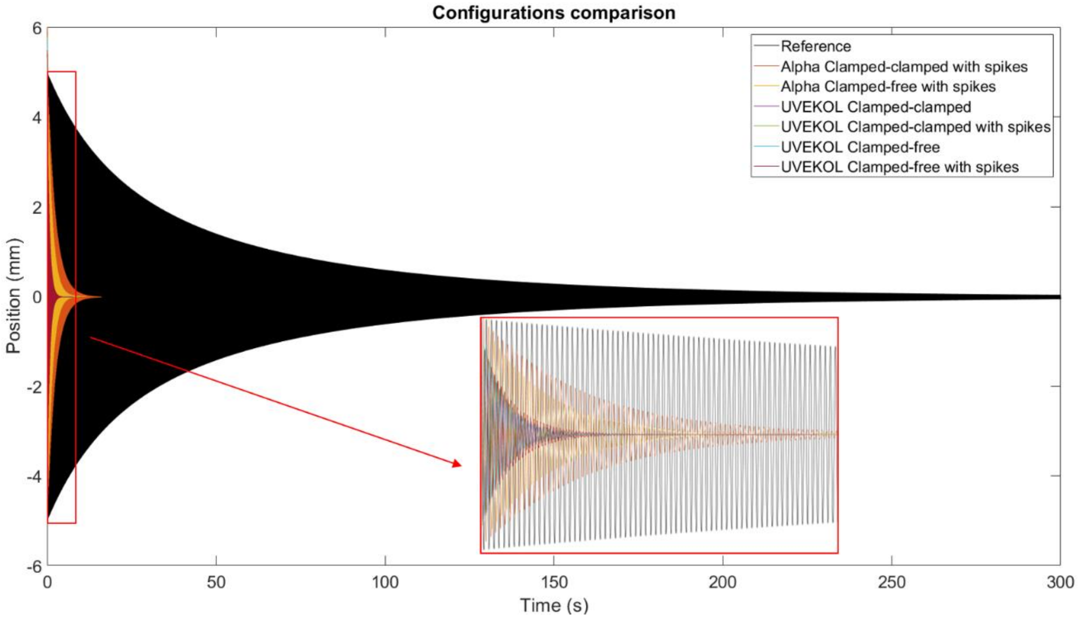

Figure 7. Free oscillation test results of all the different blade configurations.

Table 3. Results of the free oscillation tests.

Blade configuration	Elastomer	Quality factor	Actual damping	Resonance frequency
		Q [-]	c [kg/s]	f_0 [Hz]
Reference	-	1250.36	0.0024	8.65
Clamped-clamped	UVEKOL S	24.27	0.1981	13.91
Clamped-clamped with spikes	UVEKOL S	23.82	0.2039	14.05
	Alpha gel C	66.63	0.0472	9.09
Clamped-free	UVEKOL S	19.49	0.2339	13.19
Clamped-free with spikes	UVEKOL S	27.54	0.1677	13.37
	Alpha gel C	39.16	0.0777	8.81

These quantitative parameters confirm the observations made previously with impregnated flexures exhibiting a greatly improved damping. The quality factor Q is reduced from 18.8 to 64.2 times and the actual damping c is increased from 19.7 to 97.5 times for the impregnated blades compared to the reference.

Additionally, the UVEKOL S polyurethane acrylate shows improved damping with Q values ranging from 20 to 30, compared to the Alpha gel C having Q values of 40 and 67. The similar tendency is observed with the parameter c. The lower damping effect of the Alpha gel C comes from its gel form that makes it softer than the UVEKOL S. With the large deformations of the blades, the Alpha gel C that is softer than the UVEKOL S brings lower damping to the blades. Thus, the UVEKOL S is more interesting for the present application.

Concerning the geometry of the flexures, the most promising blade configuration to increase the damping effect is clamped-free with UVEKOL S. The spikes do not seem to improve the damping of the flexures. These lower performances could be explained as, in these configurations, less elastomer is impregnated between the blades as the spikes locally fill the gap. Since less elastomer induces less energy stored in and dissipated, this results in a reduced damping of the blade motion. Moreover, the clamped-free configuration shows a higher damping than the clamped-clamped configuration. This improved performance of the clamped-free configuration is due to its free end not being directly linked to the motion of the moving part. The motion transmission to this free end is only made by the elastomer, causing it to deflect more. More stress is synonym of more energy dissipated in the elastomer which finally induces more damping of the blade motion.

In addition to their characterization in free oscillation, the flexures were also tested under external excitation. The obtained data show similar damping performances for the impregnated blades and confirm the results obtained in free oscillation.

4. Conclusion and outlook

The present article detailed the complete process of the development, manufacturing and testing of a novel flexure type that integrates a damping property. These newly developed flexures exhibit greatly improved damping performances with a quality factor reduction of up to 64 times and an actual damping increased by up to 97 times compared to reference simple flexure blades. Therefore, the impregnated lattice blades produced are an innovative solution to withstand vibrations and shocks for compliant precision mechanisms.

Additionally, they could represent an alternative architecture to state-of-the-art spring dampers. Indeed, they could be used to minimize acoustic noise and exported vibrations emissivity of a variety of sources such as pumps in coffee machines or cryo-coolers in satellites. Reversely the vibration susceptibility of systems such as metrology instruments, optical setups and industrial vision systems could be reduced thanks to a decoupling from the surrounding environment.

From this research, several topics could be further investigated in the future:

- **Impregnated flexures modelling:** Developing a model will allow predicting the damping performance of the flexures during the design phase, thus facilitating the tailoring of the flexures' geometry and the choice of the elastomeric material for a specific application.
- **Hysteresis measures:** The flexures' damping can alternatively be measured by studying their hysteresis curves [7]. This method would bring new interesting information at a single frequency as, for instance, allowing identifying the nonlinearities of the damping behaviour by changing the excitation amplitude.
- **Further testing:** Tests under forced oscillation with varying excitation frequencies (sine sweep) were conducted, but without conclusive results in some cases due to a limited position sensor resolution. Those shall be repeated after having improved the test bench. Additional characterization such as fatigue tests is necessary to assess the flexure performance during its complete lifetime. Behaviour at different temperatures or under vacuum would also be interesting to study in order to analyse the elastomer ageing phenomenon as well as its damping behaviour with changing conditions.

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