INNOVATION IN LARGE ANGLE FLEXIBLE PIVOT DESIGN & MATERIAL ACCELERATED FATIGUE SCREENING TESTS RESULTS

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ABSTRACT

In the last decades, more and more space applications required actively controlling the orientation of certain devices like scanning mirrors, antennas, calibration units mounted on satellites and spacecraft. The benefit of using compliant mechanisms for such applications is multiple. First, frictionless flexible joints present no generation of wear particles and do not require lubrication which allows to use flexures near optical surfaces. Second, lifetime including long time storage can be extended to infinite as material is used below its infinite fatigue limit. Third, micro-vibration can be damped by tuning the stiffness of the flexure to obtain first eigenfrequency of the system far below micro-vibration excitation frequencies. Finally, compliant joints accommodate easily thermo-elastic constraints between the surrounding structure and the supported payload. Flexible pivots are therefore most often the retained choice in the context of long life, clean and precise applications for space applications.

The AlmaFlex is a novel flexure design family that has been invented and patented by Almatech SA. The pivot design has been further developed in the frame of the associated Core Technology Program (CTP) which led to the Large Angle Flexible Pivot (LAFP): a flexible pivot capable of ±70° rotations for infinite life in cryogenic conditions while maintaining the centre shift below 10µm and keeping actuation torque in the Newton meter range. To achieve targeted performances, efforts have been set on design optimization, material selection, manufacturing processes and post-treatments.

This paper presents the design of the LAFP, its optimization process as well as the accelerated fatigue test results performed on an extensive selection of test samples.

The Almaflex design is based on pure bending deformations of blades. The flexure consists in two symmetric identical rings, a rotor and stator mounted on a synchronizing ring. Each stage comprises a set of four blades plus T-bars connecting the ring to its center which is then connected to the synchronizing ring via connecting members also using T-bars. Larger angular ranges can also be obtained by using additional stages. This design allows very good decoupling between each DoF which is particularly useful for stiffness optimization considering in-orbit operations, launch locking, gravity sag adjustments, thermo-elastic aspects...

Figure 1. Design Overview of the Almaflex

ALMAFLEX OPTIMISATION PROCESS

The Almaflex design is a family of design that can be optimized to specific performances. The Large Angle Flexible Pivot (LAFP) is the result of an optimisation in response to the European Space Agency (ESA) CTP specifications.

A software tool called FlexOptim has been developed to efficiently find an optimized design within the Almaflex design family that matches best the customers' requirements.

Rotational angle, applied loads and launch configuration are given as input to FlexOptim as well as stiffness requirements for radial, axial, torsional and bending cases. The optimization process starts with a baseline set of variables and associated boundaries defining the initial geometry. A set of constants defining material properties and weighting factors are also input. Depending on the configuration during launch: locked or not, a set of design forces is retained for the optimization process. According to the requirements, variables and constants given as input, constraints are generated and cover geometry consistency, targeted stiffness and angle, stress limit and buckling factors. From the initial state, the optimization process can start. The optimization process is done in two steps. Optimization loops are performed using analytical formulas that calculate axial, radial, bending and torsional stiffness as well as the stresses in these directions. Axial and radial buckling factors are calculated too. Consistency of these formulas has been correlated with finite element analysis during process development. The optimization aims at minimizing torsional stiffness, volume and the deviation between targeted and computed rotation angles while maximizing buckling factors and stress performances. In a second step, a complete finite element loop is performed to evaluate the requirements. Correction factors between FE analysis and analytical approach are then computed and considered in the next analytical iterations. The optimal solution is reached when convergence of these correction factors is met.

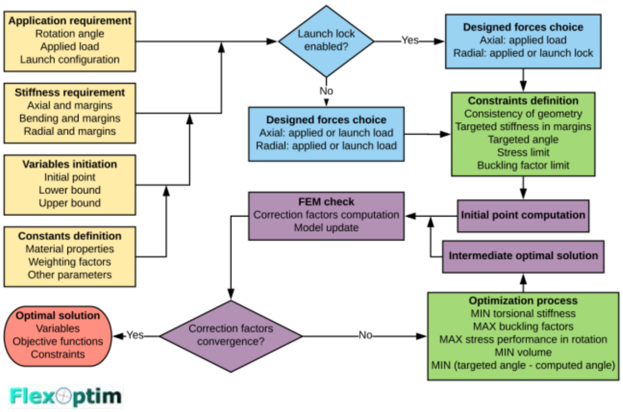

Figure 2. Optimization methodology

The optimization tool used in FlexOptim to minimize or maximize the objective functions is MIDACO (Mixed Integer Distributed Ant Colony Optimization). MIDACO is a metaheuristic optimizer developed by European Space Agency (ESA) based on the behaviour of ants looking for food around their hill, so its basis of functioning is the exploration of the available space for the variables and the storage of the current best solution. The constraints are handled by using an oracle penalty method. As shown on Fig. 3 different levels of exploration can be observed and finally a smaller area around the optimal solution is investigated.

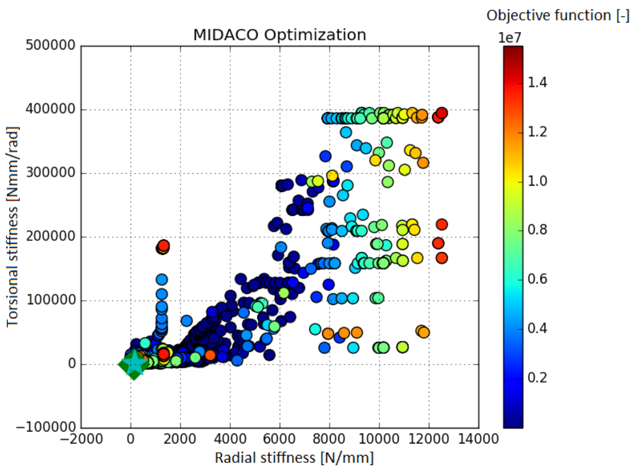

Figure 3. Example of optimization results from MIDACO

Once optimum geometry fulfils customer's requirements the new set of geometry variables are sent automatically to a 3D design software that updates the design.

MATERIAL SELECTION

Almaflex design family can be manufactured in many different materials. To name some, Almaflex can be made out of titanium, stainless steel, or even polymer. The choice of the material is derived from the customers' requirements, including not only performances but costs and planning.

For the ESA CTP project, the LAFP material was chosen to maximize large deformations while assuring infinite life. The ratio between fatigue stresses and Young's modulus defines exactly this requirement:

$$\sigma_{fatigue} / E \tag{1}$$

Literature review revealed that Titanium Ti6Al4V is the best suitable material for the LAFP application with a great level of confidence considering available material heritage. This material has thus been selected.

ALMAFLEX OPTIMIZED DESIGN

Thanks to the FlexOptim tool, the final design of the Almaflex answering to the CTP requirements could be achieved.

Conventional flexural pivots present limited rotational angle capability and rather high actuation torque. The great benefit of the AlmaFlex design family is that large rotation can be obtained up to 70° while keeping the actuation torque very low. In the LAFP application, the actuation torque was kept in the Nm range which is a plus in terms of motorization margin. Volume also has been constrained to a diameter of 100mm and a height of 45mm. Meanwhile, the radial and axial stiffness are

maintained at relevant values, suitable for targeted space applications.
Non–linear behaviour has only been observed in the torsional case. Stiffness results from non-linear analyses are presented in Table 1.

Table 1: Almaflex FE computed stiffness

Radial [N/m]	**Axial [N/m]**	**Torsional @ 70° [Nm/rad]**
1.32E+05	5.80E+05	0.99

The most critical point for compliant mechanisms is to achieve large displacements with low actuation while still satisfying strength driven by the fatigue limit of the material. FlexOptim allows to optimize the stress within the whole flex structure and to keep the stress during the optimization below the fatigue stress.

As non-linearity has been observed on the rotational stiffness during optimization, it has been further investigated as this would drive the power budget of the axis actuator. Furthermore, most applications require controlled axis that would have to consider this behaviour. The required torque to rotate the LAFP over its entire range has been computed and is presented on Fig. 4. It can be remarked that the stiffness is quasi-linear till 12° and is increased by three times at 70°. However, the stiffness at full rotation still is below 1Nm/rad which corresponds to a maximum torque of 1.20Nm. In addition, required torque also has been calculated considering initial operational load in radial and axial directions. It shall be noted that the radial and axial loads do not impact the torsional stiffness, as can be seen on Fig. 4.

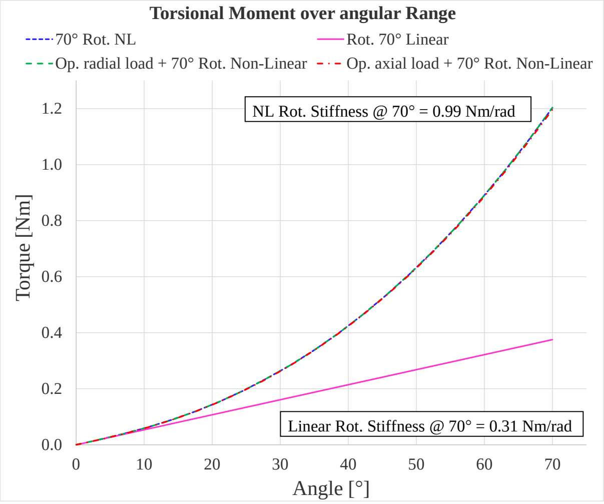

Figure 4. Almaflex Torsional Moment over rotational Range

Optical applications usually require limited centre shift of the axis. The Almaflex intrinsically present no theoretical centre shift due its symmetrical design. Centre shift can however occur in case manufacturing tolerances are not equally distributed. A sensitivity analysis on the blade thickness has been performed to quantify the impact of manufacturing tolerances on the maximum centre shift. Worst case scenario shows that the maximal centre shift is smaller than 7µm at maximal rotation angle. Fig. 5 shows the results of this sensitivity analysis.

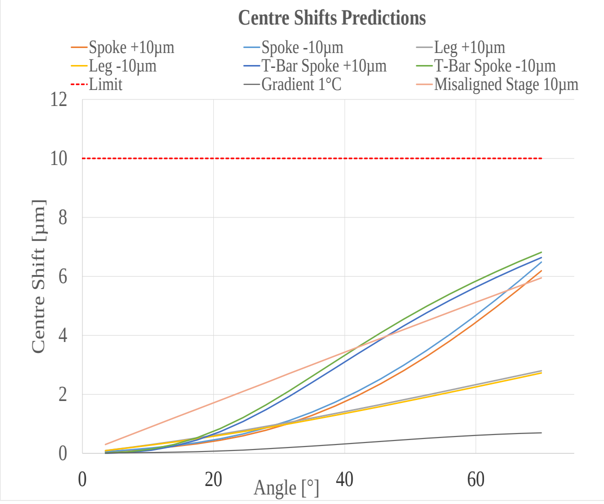

Figure 5. Almaflex Centre Shift Predictions

All the LAFP requirements: rotational range, stiffness, operational & launch loads and volume have been achieved while optimizing the stresses seen by the flexure to provide infinite life capability. The optimization of the Almaflex and the associated FE results presented have been performed using a target value for the fatigue limit based on literature review. This is a driver for the hardware fatigue performance. Thus, fatigue limit has been investigated to refine its best achievable value before freezing the design. As it is conditioned by the material and manufacturing processes including post-treatments, critical samples have been produced for fatigue testing. Activities performed on these critical samples are presented in the following sections.

MANUFACTURING PROCESSES & POST TREATMENTS

Main challenge in the manufacturing of the Almaflex is to obtain long thin blades with good precision. The following manufacturing processes have been selected:

- Wire Electro-erosion in water is a well-known process that allows for contactless machining, the thermal affected zone is very local. It is well suited for thin walls processing and offers very good surface roughness. Attention has to be paid on alpha-case generation on the thermally affected zone.

- Wire Electro-erosion in oil present the same advantages as conventional EDM at the difference that oil better contains the spark due to its low conductivity which makes the process less aggressive and allows for better accuracy and better surface roughness too.
- Micro-waterjet cutting is a cold cutting process which benefits are low mechanical forces, no residual stress and no microstructure modification. On the counterpart, achievable tolerances are rather large, obtained surface roughness is poor and it is limited to small thickness to avoid flaring.
- Additive Manufacturing is a constant improving technology that allows for complex, even hollow geometries. However, the achieved roughness is rather poor, and the internal residual stresses can be high. In addition, geometry distortion can build up, limiting the achievable blade aspect ratio.

To evaluate each manufacturing techniques, samples have been manufactured and tested. This is described hereafter.

CRITICAL SAMPLE DEFINITION

In order to allow for comparison of the fatigue performances of the above mentioned manufacturing processes, a representative sample of the application has been defined. This critical sample, shown on Fig. 6, is meant to be tested in bending and has thus naturally a blade shape clamped in its support on one end and free on the other side where a dummy mass is integrated in the design. The geometry has been defined to suit testing on Almatech's dedicated facility which consists in a shaker that can vibrate the blade, see Fig. 9. Blade's thickness is representative of the full Almaflex design and dummy mass is such that frequency for fatigue test is in line with the shaker capability.

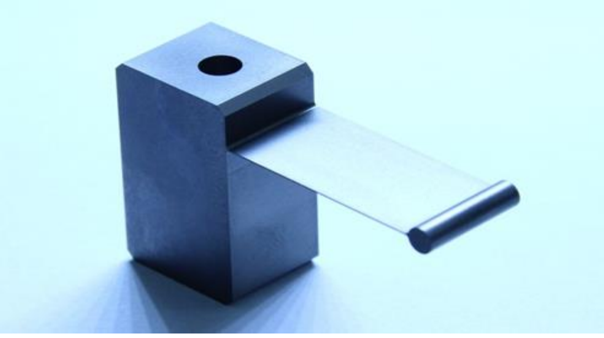

Figure 6. Critical Sample Design

As the sample is quite simple, the stress level can accurately be derived from analysis. A mesh convergence analysis has been performed in order to define the maximum stress level computed at the base of the blade sample. This also permitted to derive the stress concentration factor w.r.t. the analytic formula of a clamped-free beam. These considerations are mandatory to derive the displacement to be imposed to the blade during fatigue test.

INVESTIGATIONS PERFORMED ON CRITICAL SAMPLES

First of all, dimensions of the manufactured critical samples have been inspected.

The samples produced via µwater jet cutting and additive manufacturing present the largest deviations from the manufacturing drawing. The SLM & DMLS parts also present large deviation. On the other hand, critical samples manufactured via EDM present dimensions within manufacturing tolerances. Thus EDM samples were used for further investigations as they gave the best results.

Using metallographic investigation, the presence of alpha-case layer is searched at the surface of the EDM samples. The results depend on the manufacturer. Some manufacturers succeeded in delivering samples without alpha-case, and this without post treatments. However, thin layer of alpha-case is observed in some cases. It shall be noted in the worst case, the maximal alpha-case thickness was smaller than 4µm.

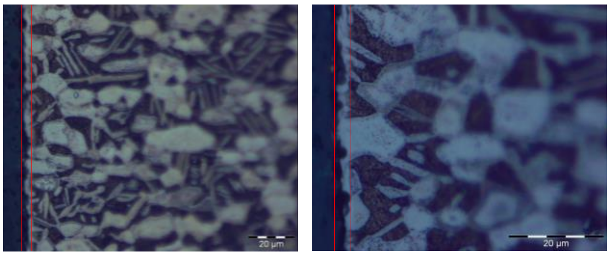

Figure 7. Micrography of Sample with Alpha-case Layer

Nevertheless, different surface treatments have been applied after manufacturing. The aim of these surface treatments is to remove alpha-case and also decrease the surface roughness. The selected surface treatment has proven to be effective on these two aspects. Indeed, surface roughness measurements before and after treatment demonstrated a roughness improved by a factor two. Uniform roughness values also have been observed over both surfaces of the blade. Following figure shows a sample before and after surface treatment, improvement even is visible to bare eyes.

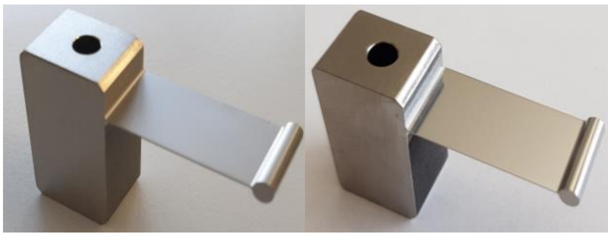

Figure 8. EDM Sample before (left) and after (right) Surface Treatment

FATIGUE TEST FACILITY

Almatech developed and manufactured an accelerated fatigue test bench. The facility is an ad hoc shaker that excites the blade's first eigenmode. The targeted frequency for this test campaign is around 100Hz. As no lubricant or friction is implied in this test, accelerated test is representative of low speed excitations. In addition, this bench allows to test 50 million cycles at desired stress level in less than 6 days. The shaker facility is built around a voice coil motor guided by two flexible diaphragms designed for infinite life. The acceleration of the excitation plate is measured via an accelerometer whereas the acceleration at blade's end is derived from the position measurement using a laser. A PID control loop is implemented to constantly adjust the excitation to match the targeted stress level in the blade. The number of cycles is recorded until the end of the test.

Failure of the sample is detected by the measurement of the deflection of the blade. In case the change in deflection is larger than a given threshold, the test is aborted. A frequency search is then conducted to monitor any frequency shift due to possible damage of the blade.

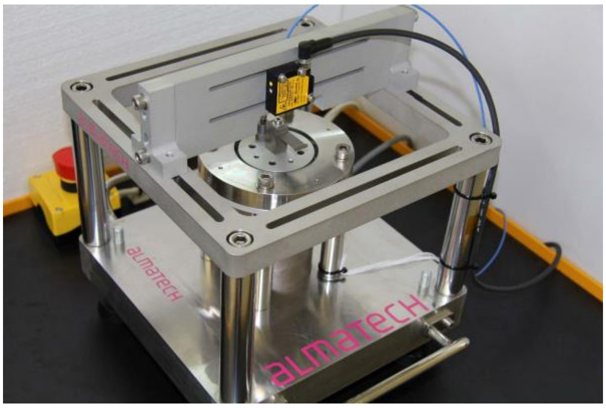

Figure 9. Almatech's Fatigue Test Facility

FATIGUE TEST RESULTS

In the frame of this project, the test campaign has been performed on 15 samples in total. In order to have a good confidence on the repeatability, 3 samples are manufactured for each tested combination of manufacturing process and post-treatment. All samples have been tested at the same stress level. The results of the fatigue test are presented in Tab. 2.

Water jet cut samples do not show high fatigue strength and failed rapidly. Their surface was rather rough and surface treatment did not improve performances.

Results on SLM sample is more contrasted. One sample failed after only 70'000 cycles, when another did not fail after 20 million cycles. This is very encouraging, showing that high fatigue stress could be achieved using additive manufacturing. However, trials and consolidation are still necessary to achieve results comparable with traditional manufacturing process.

Fatigue results on EDM samples show the best results. However, the results highly depend on the manufacturer. The samples coming from the first manufacturer failed to achieve the targeted 20 million cycles. The second manufacturer had 2 amongst three samples that reached this value and even survived more than 20 million cycles. However, one sample failed early, and far below the required target. The last manufacturer delivered premium quality samples. None of the sample failed after reaching 20 million cycles. Two samples were further tested and reach 130 million and 309 million cycles without failing. The tests were aborted because of time constraint, but not for sample degradation. Eigenfrequency shift between beginning and end of testing was below 0.2% which is within by measurement inaccuracies. Consequently, EDM and manufacturer 3 is selected for manufacturing of the LAFP as part of the ESA CTP.

Manufacturing Process	n° of cycles achieved [-]	Comment
SLM	20'000'000	
	70'000	
µWater Jet	151'000	
	21'000	
	126'000	
EDM	333'000	Manufacturer 1
	542'000	
	28'225'000	Manufacturer 2
	43'494'000	
	277'000	
	20'000'000	Manufacturer 3
	130'000'000	
	309'000'000	

n° cycles: test finished as significant frequency shift is observed

n° cycles: test stopped but fatigue limit not reached

Table 2. Fatigue Test Results

CONCLUSION & ONGOING DEVELOPMENTS

FlexOptim design optimisation software allows to quickly optimize an Almaflex to fulfil customer's requirements in terms of stiffness, strength, buckling and fatigue performances.

Material and process trade-off performed as part of the CTP permitted to select material and processes capable of harsh environment and high fatigue applications. All samples using the selected process achieved more than 20 million cycles, reaching up to 309 million cycles.

Transposition of these processes to complete Almaflex also has been verified by manufacturing blade samples presenting the same geometry as the Almaflex design.

Tolerances achieved also bring confidence to maintain the centre shift below 10µm and to match the predicted stiffness.

The trade-off also highlighted great potential for the SLM process looking at fatigue results, see Tab. 2. Furthermore, the complexity of geometries achievable by additive manufacturing emphasizes this potential. It has been decided to further investigate this process trying to improve repeatability on the manufacturing of blade samples. A complete Almaflex also has been printed via this SLM process, as shown on Fig. 10.

Figure 10. SLM manufactured Almaflex

An ongoing study at Almatech SA is looking at the possibility to further push the Almaflex design using exotic material such as metallic glass.

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