LARGE ANGLE FLEXURE PIVOT DEVELOPMENT FOR FUTURE SCIENCE PAYLOADS

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ABSTRACT

An innovative design of a Large Angle Flexure Pivot (LAFP) is described. It combines the advantages of flexure mechanisms while surpassing one of their few flaws, small displacement strokes. The LAFP design exceeds these angular limitations to reach a deflection of 180° (±90°). The centre shifts laterally by less than 10 µm throughout the full rotation range. The LAFP is meant to be mounted in pairs, coaxially and with the payload between them. The intended application of the LAFP is to angularly guide an optical component in a space environment for future science missions operating in a cryogenic environment.

A dedicated performance test bench was developed and manufactured to test the pivot characteristics notably the lateral shift using Eddy current sensors. The test bench incorporates a representative dummy payload for mass and inertia.

Extensive FEM analysis has been performed to validate the design at component level and further analysis with the pivots mounted with a representative payload on a test bench for random vibration, shock and thermal cycling environment. The second test bench for the vibration and shock tests has been manufactured incorporating a simplified launch locking device.

The performance tests have confirmed a lateral shift of less than 10 µm over an angular range of ±90°. The pivots have been successfully tested and survived vibration loads for high level sine at 24 g and random vibration at 12 grms in all three directions.

1 INTRODUCTION

An innovative design of a Large Angle Flexure Pivot (LAFP) has been developed (Fig. 1) combining the advantages of flexure mechanisms – no friction, no backlash, no need for lubricant, no wear – while surpassing one of their few flaws, small displacement strokes. These are usually comprised between 10° and 20° for typical flexible angular pivots. The LAFP design exceeds these angular limitations to a range where previously only ball bearings would be adequate. The angular stroke can reach a deflection of 180° (±90°) and can easily meet a lifetime of three million cycles. If the stroke is limited to ±70°, infinite operational lifetime is obtained.

The LAFP is 120 mm in diameter, 60 mm in length and weighs less than 500 g. A pair of pivots has been sized to carry a payload of 1.8 kg (including interfaces) and offers a low rotational stiffness while ensuring high lateral and transverse stiffness. In order to meet future science missions in a cryogenic environment, they can operate in a temperature ranging from -140°C to +65°C. The centre shifts laterally by less than 10 µm throughout the full rotation range. The LAFP is mounted in pairs, coaxially with the payload between them. The intended application of the LAFP is to angularly guide an optical component in a space environment.

The concept of CSEM’s LAFP is described in section 2 with its configuration of its leaf springs, analysis and remarks on its stiffness asymmetry. Performance assessment predicted by FEA is presented though a comparison of results obtained by COMSOL and NASTRAN. The experimental setup, test results and remaining test programme is addressed in the final section.
2 LARGE ANGLE FLEXURE PIVOT CONCEPT

Within the diversity of flexure mechanisms, many are dedicated to very high precision, but only few go beyond the inherently short limit of their displacements strokes. In the frame of an ESA project, CSEM surpassed this restriction by developing a flexure pivot with a very large stroke, which is endowed with excellent performance [1]. With a long heritage in the design of compliant mechanisms, CSEM has especially conceived the iconic Butterfly pivot [2], which offers a ±15° stroke. Examples of large stroke flexure pivot exist in literature. One should notice the FLEX 16 [3], whose stroke is ±90°. However, its centre shift is high and stiffness is low. Another example is the infinity-hinge [4] which proposes large strokes of ±45° while preserving adequate radial stiffness.

In the presented design, there are two identical half-pivots assembled in a series configuration (Fig. 2a) and linked by a coupling triangle. Each of the half-pivots has six main radial leaf springs and six coupling leaf springs. The main leaf springs are laid out by pairs serially linking the rim to the coupling triangle, via three rigid portions. These are linked by pairs through coupling stages, which are composed of two short parallel leaf springs. When the pivot is rotated (Fig. 2b), the rigid portions move away from the central axis so as to let the main leaf springs shorten. It is not possible to rigidly link the portions to each other, as the stroke would be diminished.

Conversely, not linking these portions would result in blade warping and a drop in stiffness. The coupling stages link the portions correctly, permitting the desired synchronous and radial movement.

2.1 Radial leaf springs deformation and shortening

Fig. 3a illustrates the shortening of a long leaf spring, whose left side is fixed to the rim and right side rotates with the rigid portion around the z-axis by an angle θ. It results in a shortening $\lambda$ from which one can calculate $s$ the stroke of the coupling stage. Regardless of the rotation direction of the LAFP, its coupling stages always travel in the same direction. Thus, it is possible to preload the coupling stage to obtain a stroke of $-s/2$ to $+s/2$, instead of 0 to $+s$. This reduces the maximum stress in the stages and enhances their performance. The preload gap (see Fig. 3b) is adjusted as part of the assembly process.

2.2 Stiffness asymmetry

The arrangement by pairs of the main leaf springs allows them to either be moved away or brought closer together when the pivot rotates. In the two situations the load cases are not similar, such that the stress and stiffness exhibit asymmetric behaviour. Consequently, the angular end-stops are not symmetric, as shown in Fig. 4a. However, the half LAFPs act inversely: when the pairs of long leaf springs of one half LAFP move away, the other half’s get closer to each other. Globally, the LAFP behaves symmetrically.

2.3 FEA performance evaluation

Extensive FEM analysis has been performed to validate the design at component level and further analysis with the pivots mounted with a representative payload on a test bench for random vibration, shock and thermal cycling environment. The preliminary FEA was performed by CSEM with COMSOL and in a second phase by Heron using NASTRAN. Generally, simulating the LAFP is complex due to very large deformations exerted on leaf springs with high slenderness ratios and the preload. In COMSOL, the simulations were realized on a model with rigid connectors, representing the structural parts. The simulations concerned static (torque, stiffness, stress, centre shift, buckling) and modal aspects (Fig. 5).
Preloading was added to the simulation through a semi-analytical model. With Nastran, the real bow-tie tapered profile of the leaf springs was implemented on shell elements, which were connected by realistic rigid parts. Preliminary simulations were redone for validation. Additional simulations were performed concerning dynamic (shocks, random and sine vibrations) and thermal aspects. Also, dynamic simulations at the system level were made in order to size a launch locking device. The preload is performed by symmetrically adjusting the gaps of each stage during the assembly procedure then gluing them using EC2216.

Pivot requirements

The high level requirements for the pivot mounted in pairs with a mobile payload are:

- Angular range $\pm 70^\circ$ (target for lifetime)
- Central shift $<10\ \mu m$ (no load, max rotation)
- Angular stiffness Minimise ($@90^\circ$)
- Payload mass 1.2 kg
- Number of cycles 2.4 million
- Pivot mass 150 g
- Temperature range $-125^\circ$ to $+50^\circ$C (oper.)
- Random vibration 18.4/12.2grms (X / Y&Z)

For one LAFP, the performance based on analytical and FEM results are:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque $@90^\circ$</td>
<td>0.53</td>
<td>Nm</td>
</tr>
<tr>
<td>Natural stiffness $@0^\circ$</td>
<td>70</td>
<td>mNm/rad</td>
</tr>
<tr>
<td>Natural stiffness $@90^\circ$</td>
<td>340</td>
<td>mNm/rad</td>
</tr>
<tr>
<td>Transversal stiffness $@0^\circ$</td>
<td>832</td>
<td>kN/m</td>
</tr>
<tr>
<td>Transversal stiffness $@90^\circ$</td>
<td>22</td>
<td>kN/m</td>
</tr>
<tr>
<td>Axial stiffness $@0^\circ$</td>
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<td>kN/m</td>
</tr>
<tr>
<td>Axial stiffness $@90^\circ$</td>
<td>125</td>
<td>kN/m</td>
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<tr>
<td>Diameter</td>
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</table>

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transversal center shift XY</td>
<td>&lt; 3</td>
<td>um</td>
</tr>
<tr>
<td>Axial center shift Z</td>
<td>13</td>
<td>um</td>
</tr>
<tr>
<td>Lateral buckling load</td>
<td>21</td>
<td>N</td>
</tr>
<tr>
<td>Axial buckling load</td>
<td>52</td>
<td>N</td>
</tr>
<tr>
<td>Von Mises stress $@70^\circ$</td>
<td>554</td>
<td>MPa</td>
</tr>
<tr>
<td>Von Mises stress $@90^\circ$</td>
<td>864</td>
<td>MPa</td>
</tr>
<tr>
<td>1st vibration mode in translation</td>
<td>704</td>
<td>Hz</td>
</tr>
<tr>
<td>Mass</td>
<td>467</td>
<td>g</td>
</tr>
</tbody>
</table>

In the end, results from both FEM software are in good agreement, see Fig. 6 & 7. Performance of the pivot satisfied the specifications, regardless of the decrease in lateral stiffness that is typical for large deformation flexure pivots, see Fig. 8.

Fatigue test results

Fatigue tests were conducted on Marval X12 leaf spring samples to validate the WEDM (Wire electrical discharge machining) process and to ensure that the infinite life of the pivot is guaranteed for $\pm 70^\circ$ and 3 million cycles for $\pm 90^\circ$. The test results presented in Fig. 9 show that the LAFP results fit well with the MTG-CCM (Corner Cube Mechanism) fatigue curve taken as reference. Although the effective fatigue limit (stress for infinite number of cycles) cannot be formally expressed, a stress of 700 MPa can be taken as a limit considering the unbroken samples tested up to ~11 million cycles. This stress level corresponds to a pivot stroke of $\pm 80^\circ$. 

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3 EXPERIMENTAL SETUP

Once produced by Wire Electro-Discharge Machining (Fig. 10) and assembled, the two pivots were tested at component level.

Among the tests performed, the pivot rotary stiffness was measured using a Kistler torque sensor and compared with the FEM values which show a very good correlation. The maximum torque at 90° (FEM: 0.53Nm) for each pivot is:

- SN01: 0.51Nm (+90°), 0.51Nm (-90°)
- SN02: 0.52Nm (+90°), 0.53Nm (-90°)

The two pivots were then integrated coaxially in the Engineering Model (EM) test bench (Fig. 12) for functional and performance tests.

3.1 EM Test Bench

A dedicated performance test bench was developed and manufactured to test the pivot characteristics. The EM test bench (Fig. 12) illustrates a typical mechanism configuration with its representative dummy payload for mass and inertia in the form of a wheel on a shaft between two pivots. The objective of the test bench is to verify pivot performance notably the parasitic lateral (or centre) shift, angular range and angular stiffness. The same test bench is used for the TVAC (Thermal Vacuum and Cycling) and Lifetime tests.
Performance tests of the pivot are performed with the EM test bench in the vertical position (Fig. 14) to represent 0-g conditions and to avoid shaft lateral deflection due to gravity. Gravity compensation acts in the axial (Z) direction.

3.2 EM Functional Test Results

Lateral shifts on EM test bench are measured through eddy current sensors. They are mounted on a sensor ring which is fixed on the test bench. Their target is a cylinder directly connected to the shaft on which the pivots and the inertial wheel are connected.

To mitigate the different sources of error that affect the eddy currents sensors (e.g. non-linearity due to feedthrough and temperature effects), a corrective chain was implemented with a step-by-step characterization by using Micro-Epsilon optoNCDT sensors (Fig. 15 & 16) as a reference to discriminate for the inaccuracies and parasitic phenomena introduced by the eddy currents sensors.

The Micro-Epsilon and Eddy current sensor lateral shift results provided below for the X-direction (Sensor 1) are preliminary but compare well (Fig. 17). The latter sensor will be used during the low temperature testing during TVAC. The results indicate that the lateral shift error for ±70° pivot rotation is in accordance with requirements of < 10 µm.
3.3 Vibration Test Bench

Following the functional tests, the pivots were transferred and mounted on the vibration test bench (Fig. 18 & 20). The test bench for the environmental vibration tests is a similar configuration to the EM performance test bench but without the actuator and instrumentation. It is a dedicated test bench incorporating a representative payload and a launch locking device (LLD). The pivot vibration tests with a representative mobile mass and inertial wheel payload are intended to cover the widest range of possible future applications.

A simple dummy LLD reproduces the general interface features required to guarantee survival of the flexure pivots in a typical configuration where the mobile payload is blocked. The LLD represents two simple, identical clamping devices, attached to the pivot interface flanges at both payload shaft ends. Thereby, due to the rather large distance between pivots, the preferred locking configuration has four attachment points.

The locking device is sized to obtain representative and realistic mechanical characteristics of the stiffness as would be feasible with a mechanical gripper actuated in a clamping configuration. In the X and Z directions, the stiffness is determined by the dimensions (diameter and length) of the inserts (Fig. 19). In the Y direction, the stiffness is determined by the U-shaped holder (Ti6Al4V) blade length and thickness. The U-shaped blades are slightly preloaded to avoid hyper-static mounting conditions. This allows for very small movements with high damping compatible with flexure pivot stiffness and strength in vibration environments. The complete vibration test bench with pivots and locking device was analysed by FEM for both eigen-frequencies and stresses.

3.4 Vibration Test Results

The high level sine and random vibration tests were performed in all directions with the sequence being Y-direction, Z-direction and finally X-direction. The specified levels for each direction were:

**Sinusoidal vibration specifications (all axes):**
- 5-20 Hz: ± 15 mm prescribed motion
- 20-100 Hz: 24 g

**Random vibration specifications:**
- Y and Z axis **12.2gRMS**
  - 20-100 Hz, +3 dB/oct
  - 100-400 Hz, 0.22 g^2/Hz
  - 400-2000 Hz, -6 dB/oct
- X axis **18.4gRMS**
  - 20-100 Hz, +3 dB/oct
  - 100-400 Hz, 0.5 g^2/Hz
  - 400-2000 Hz, -6 dB/oct

The Y and Z direction tests were completed successfully for both the sine tests and random vibration. However, the inspection performed after the X-direction high level Sine test showed the start of a crack at the base of one of the pivot blades (see arrow in Fig. 21 & 22).
Upon closer inspection with an endoscope, the crack was confirmed and covered approximately 1/3 of the blade width (~8 mm long). A verification of the videos recorded during the Z-direction tests (12 grms) showed a bi-stable buckling phenomena at the base of the blade where the crack was discovered (Fig. 23).

Since the crack was not generated due to stresses from the vibration loads but due to an assembly error, it was decided to locally consolidate the base of the blade (since the blade was still intact) with a quick set epoxy and to continue with the tests for the final, X-direction. The tests ensued with the random vibration tests in the X-direction as planned. Two notches has been planned and implemented to reduce the amplification of the wheel (Fig. 26).

Upon analysis of the trend of the response levels coupled with the high cross-coupling of the system, it was decided to limit the X-direction test to the -3dB level (12 grms) with respect to the specifications keeping the levels to the same as those tested in the Y and Z directions. Continuing the tests to the specified level to 17 grms was considered too risky with the possibility of severely damaging the remaining pivot considering the state of one of the two pivots. The objective was to complete the vibration tests with the mechanism intact to allow the next phase of testing to proceed with thermal vacuum cycling and lifetime tests.

The pivots were disassembled from the test bench and a visual inspection showed no other damage. The consolidated blade with the epoxy survived the tests and the pivot was easily rotated to its maximum angle (+90° to -65° until contact with epoxy).
If a replacement part cannot be procured to exchange the damaged part and the lateral shift results are acceptable, the excess epoxy will be removed (see Fig. 27) in order to perform the TVAC tests and possibly the lifetime tests.

3.5 TVAC and Lifetime Tests at Cedrat Technologies

TVAC testing

The next segment of the tests are the TVAC and Lifetime tests. The cryo test TVAC chamber (Fig. 28) is comprised of:

- Interfaces and component selection driven by cryogenic temperature operation
- Eddy current sensors (lateral shift)
- Renishaw rotary encoder read head is removed since not compatible with cryo temperature operation
- Angular position knowledge to be read for predefined angles using reed switches mounted on wheel
- Functional operation of mechanism to be controlled in open loop

Lifetime testing

An accelerated lifetime test approach at ambient temperature has been defined where the flexural pivot mechanism assembly shall be actuated at around 1 Hz. According to this frequency range, the test duration will be between 30 to 40 days to achieve the target of 3.1 million cycles.

4 CONCLUSION

The performance tests have confirmed a lateral shift of less than 10 µm over an angular range of ±90°. The pivots have been successfully tested and survived vibration loads for high level sine at 24 g and random vibration at 12 grms in all three directions. Even though one of the pivot blades was damaged due to misalignment from an assembly error, the test campaign should be able to continue as planned. Additional results will be available as the project test campaign progresses.

Thanks to the LAFP concept, it is now possible to overcome one of the major historic drawbacks of the rotary compliant mechanisms, short angular strokes. Indeed, it reaches beyond state-of-the-art performances in terms of stroke and guiding quality. Once all the validations are passed, this mechanism will be qualified for concrete use in the frame of a future space science missions. The patented design is suitable for various applications in different domains.

ACKNOWLEDGMENTS

The authors would like to thank ESA which is funding this development through the project n° AO/1-8645/16/NL/BW and to our partners Heron Engineering and Cedrat Technologies.

REFERENCES


4. Gunnink, K., Aarts, R., and Brouwer, D., Performance optimization of large stroke flexure hinges for high stiffness and eigenfrequency, 2013, 28th Annual Meeting of the American Society for Precision Engineering (ASPE)

Key words: compliant mechanism, large angle flexure pivot, space environment, precision opto-mechatronics, cryogenic