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Design of the Actuation System for the Hexafly-Int Hypersonic Glider

Jean-Yves Andro¹, Waldemar Rotärme², Francesco Nebula³, Gianfranco Morani⁴, Johan Steelant⁵

Abstract

This paper describes the design process of the Actuation System for the HEXAFly-Int hypersonic glider, composed by two control surfaces, hereafter named elevons. In the first part, the high-level architecture of the Actuation System is presented. Then, the requirements generation process is briefly laid out; attention is paid to the procedure used to obtain a reference trajectory compliant with both the mission requirements and the maximum hinge moment not to exceed, coming from the experimental tests. The second part deals with the mechanical design of the Actuation System of each control surface, which is mainly composed of a servo-actuator, a titanium actuation lane, a CMC torsion bar – elevon assembly. A particular attention is dedicated to the innovative design of the torsion bar in terms of CMC manufacturing and mechanical interface with the actuation lane to increase the maximum hinge moment and to minimize its torsional thermo-mechanical deformation for an easier control of the vehicle. This paper concludes with the results of the preliminary ground tests of the torsion bar – elevon assembly.

Keywords: *Actuation system, Elevon, Actuator, CMC*

Nomenclature

CMC	Ceramic Matrix Composite
C/C	Carbon fiber in Carbon Matrix
C/C-SiC	Carbon fiber in Carbon Matrix covered with SiC
CFRP	Carbon fiber reinforced plastic
DoF	Degree of Freedom
ECU	Electronic Control Unit
FCC	Flight Control Computer
FM	Flight Mechanics
GNC	Guidance Navigation Control
HM	Hinge Moment
IF	Interface
MC	Monte Carlo
OML	outer mould line/ outer surface of the vehicle
LSI	Liquid Silicon Infiltration

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1. Introduction

The HEXAFLY-Int vehicle is a 3 m long hypersonic glider, which will be launched on top of a single stage sounding rocket up to an altitude of nearly 90 km. After separation from the sounding rocket prior to reach the apogee, the vehicle attitude will be stabilized at very high altitude thanks to a cold gas system located on a service module. This module will be ejected during the entry into the stratosphere and the vehicle will use its own two elevons for performing a pull-out manoeuvre and initiating a Mach 8 glide at an altitude of nearly 30 km during few hundreds of seconds.

The glider aeroshape design makes maximum use of databases, expertise, technologies and materials elaborated in previously European community co-funded projects LAPCAT I & II [1][2], ATLLAS I & II [3][4] and HEXAFLY [5].

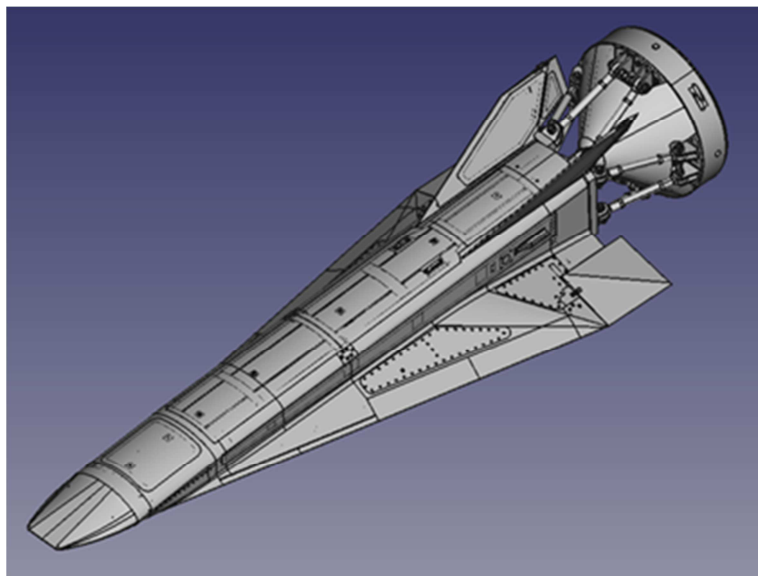


Fig 1. Experimental flight test vehicle and its stabilizing flare

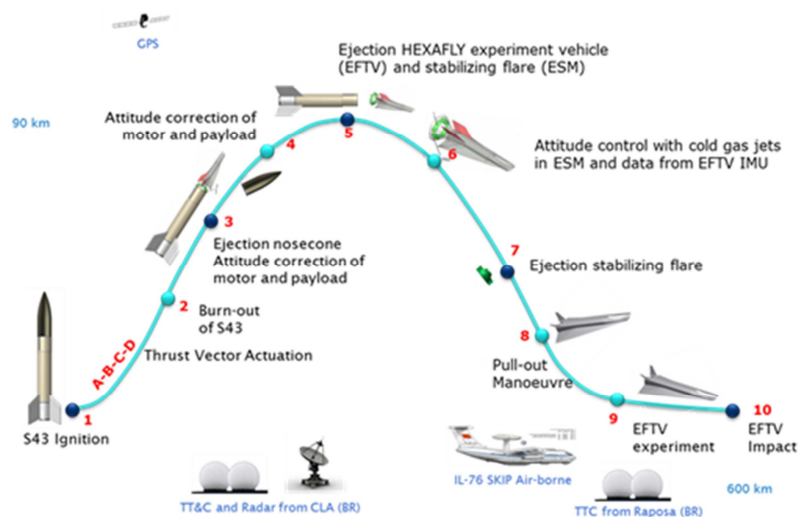


Fig 2. Mission profile

The most critical point of the trajectory is the pull-out manoeuvre, which needs an accurate control of the vehicle starting the glide at the targeted cruise point, while not breaking the Actuation System of the elevon due to high aerodynamic loads during the manoeuvre.

2. Actuation System functional architecture

The functional architecture of the servo-actuator subsystem is reported in Fig 3. It is composed of an electromechanical linear actuator activated by an Electronic Control Unit (ECU), using a linear position sensor as feedback signal. Through the ECU, the servo-actuator interacts with the Flight Control Computer (FCC), containing the GNC software, assuring the actuator rod to be positioned according to the GNC [6] reference signals. Some optional housekeeping data could be provided to the FCC in order to check the health status of the actuation function.

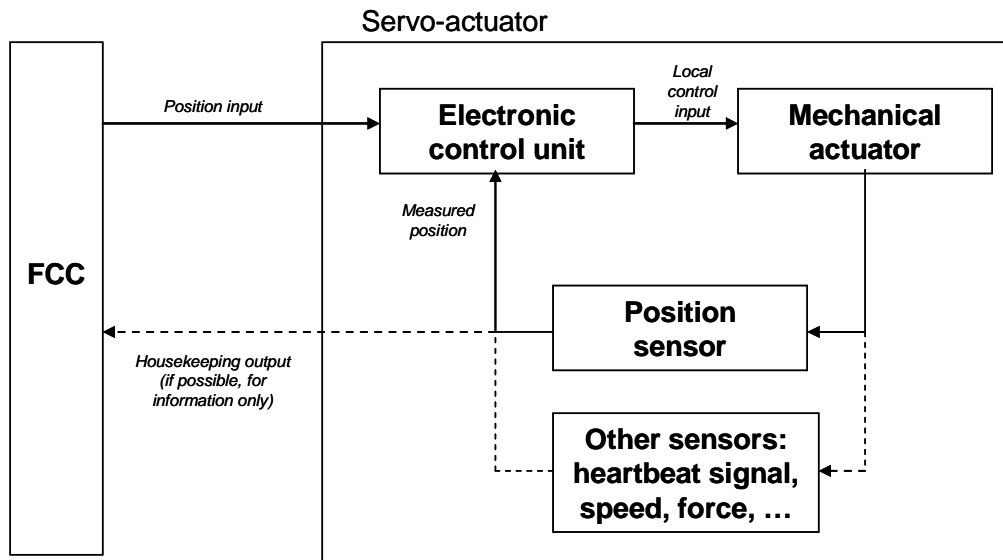


Fig 3. Servo-actuator functional architecture

3. Actuation System performance requirements

The performance requirements for the actuation system are obviously applicable to the final element of the actuation chain, i.e. to the elevons. These specifications have been derived from the preliminary flight mechanics/GNC analyses, briefly described hereafter.

Given the experimental breaking value of the Hinge Moment (HM^{break}) a trajectory optimization has been carried out with the goal of having the peak of the Hinge Moment (including the inertial effects) along the trajectory lower than the breaking value (reduced by a safety factor). The procedure then used a 3 DoF simulation model and its output was the reference glider trajectory, to be tracked by the Guidance laws. The objective of the optimization procedure was the minimization of Hinge Moment peak, subject to mission and vehicle constraints, in particular:

- the stability and trimability requirements;
- the mission requirements (high-efficiency levelled flight, no-fly zones and telemetry flying areas satisfied, etc.);

Further assessments, based on control laws analysis and synthesis, have provided some insights about the required ECU tracking linear performances (natural frequency, damping factor, latency time, etc.). As a matter of fact, the servo-actuator of the Actuation System must ensure the correct positioning of the elevons within specified tracking performances and be able to guarantee these performances despite disturbances and uncertainties that may affect the positioning accuracy (i.e. mechanical yokes, transducer accuracy and so on). The servo-actuator was then required to fulfil the following tracking requirements:

- Steady state error (bias) and static accuracy $\leq \pm 1^\circ$;
- Natural frequency ≥ 100 rad/s (16 Hz) (equivalent 1st order time constant ≤ 0.01 s);
- Damping factor ≈ 0.7 ;
- Latency ≤ 0.02 s;
- Dead zone and backlash $\leq \pm 0.1^\circ$.

In addition, the following dynamic requirements were defined:

- Maximal angular speed $\geq 20^\circ/\text{s}$
- Maximal angular acceleration $\geq 700^\circ/\text{s}^2$

As a next step, a Monte Carlo analysis was carried out using a complete 6 DoF simulation environment, including an approximated overall thermal and mechanical deformation model (affecting the torsion bar and elevon).

In this way, it was possible to define a set of requirements dependent on the occurrence probability related to the MC analysis. Therefore, in case it was found hard to fulfil the requirements related to maximal angular speed and angular acceleration, the Actuation System was required to satisfy at least the limitations reported in Tab. 1, accepting a given risk. Indeed, these limitations were provided as a function of different occurrence probabilities (coming from the same MC analysis):

Occurrence probability (in % of simulations)	Max angular speed (module) [deg/s]	Max angular acceleration (module) [deg/s ²]
90	9.91	446.68
95	10.66	489.1
99	12.26	559.92

Tab. 1 Maximum angular speed and acceleration statistics from preliminary Monte Carlo analysis

As explained earlier, during the re-entry and gliding phases of the flight when the servo-actuator is operating, the moment applied on the elevon + torsion bar + lever arm subsystem (due to aerodynamic, inertial and friction loads) should not exceed HM^{break} , which was set to 280 Nm on the basis of a preliminary analytical assessment of the CMC torsion bar mechanical strength by DLR.

As for the angular speed and angular acceleration requirements (see Tab. 1), in case it was found hard for the servo-actuator to withstand the longitudinal effort corresponding to 280 Nm, the servo-actuator was required to withstand at least the effort corresponding to the values reported in Tab. 2, accepting a given risk. Once again, these values were provided as a function of different occurrence probabilities.

Occurrence probability (in % of simulations)	Max hinge moment (module) [Nm]
90	202.79
95	226.47
99	260.29

Tab. 2 Maximum hinge moment statistics from preliminary Monte Carlo analysis

The mechanical strength of the CMC torsion bar was then enhanced by DLR up to nearly 330 Nm including a safety factor. This value clearly allows more possibilities and potentialities for the fulfilment of the mission and it will be taken into account for the refinement of GNC design and development during the subsequent phases of the project.

4. Actuation System mechanical design

The Actuation System has been designed by ONERA and DLR with respect to the GNC [6] performances requirements, preliminary provided by CIRA on the basis of FM/GNC analyses.

The Actuation System of each control surface is mainly composed of:

- a frame fixation composed of two metallic parts
- a linear actuator and its deported Electronic Control Unit (ECU)

- (iii) a metallic lever arm which transforms the linear motion of the actuator's rod as a rotational motion of the torsion bar
- (iv) a CMC torsion bar / elevon assembly with a metallic insert at the extremity of the bar for connection to the lever arm
- (v) a fuselage fixation composed of a ball bearing and a metallic plate
- (vi) a wing fixation composed of two metallic parts

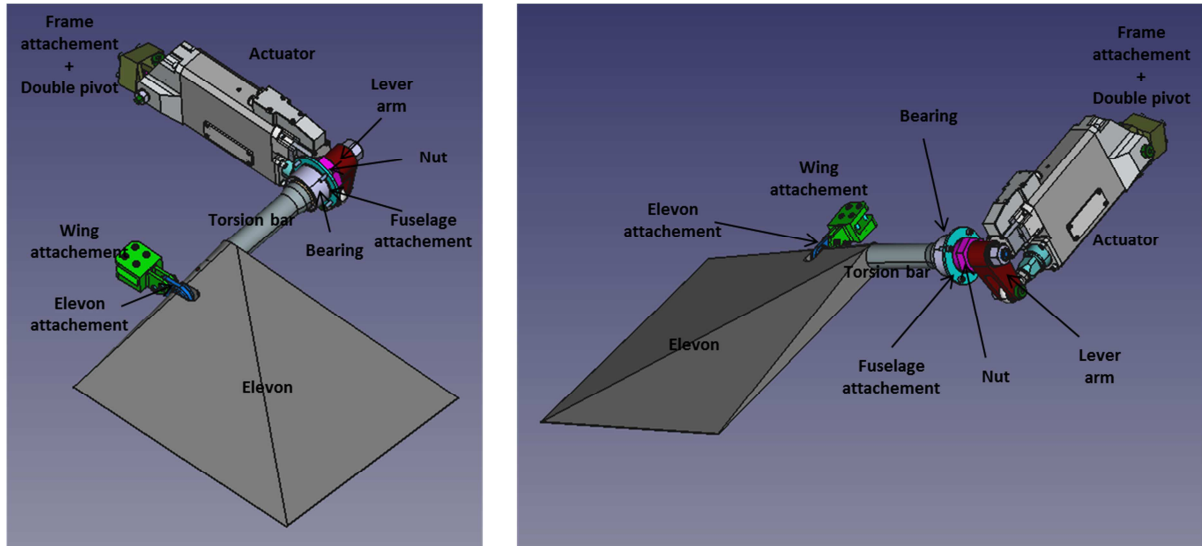


Fig 4. Actuation System

4.1. Frame fixation parts

The base of the actuator is fixed to the internal structure of the vehicle thanks to two parts (green and purple parts in Fig 5) forming a double pivot link. It was preferred to a single pivot link so as to prevent any blockage of kinematics due to thermo-mechanical deformations during the flight.

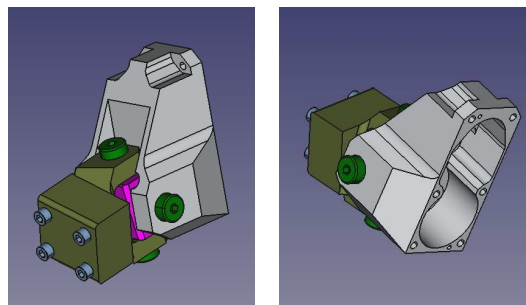


Fig 5. : Frame fixation parts

Those two parts are made with titanium material able to withstand high stress and high temperature at the interface with the internal structure while keeping a moderate mass density comparing to refractory steel material.

Those two parts are partly protected from internal thermal radiation thanks to the insulation jacket wrapping the actuator (see next section) so as to prevent any heating of the mechanical joints.

4.2. Actuator and ECU

The actuator is provided by the French firm ISP-Systems. It is a COTS linear servo-actuator customized to withstand vibrational g-loads, vacuum conditions, and high longitudinal load during the pull-out manoeuvre.

The actuator's rod is terminated by a 3 rotational DoF ball bearing so as to prevent any blockage of kinematics due to thermomechanical deformation of the vehicle.

The actuator is controlled by a deported Electronic Control Unit (ECU) located upstream in the vehicle. Electronic cards are encapsulated into a metallic box able to withstand vibrational g-loads and vacuum conditions.

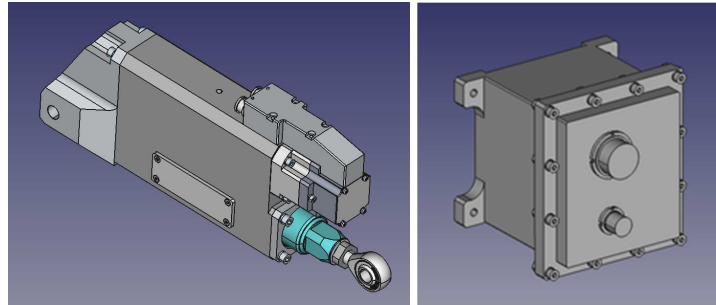


Fig 6. Linear actuator and its deported ECU

The actuator is protected from thermal radiation inside the vehicle thanks to a light flexible microporous thermal protection named Aeroguard® provided by the Belgium firm PROMAT. This thermal protection forms an insulation jacket wrapping the actuator and some other parts of the Actuation System (frame attachment parts, lever arm, fuselage fixation parts).



Fig 7. Actuator insulation jacket

4.3. Lever arm

The linear motion of the actuator's rod is converted into a rotational motion of the torsion bar thanks to a metallic lever arm. It is made with titanium material able to withstand high stress while keeping a moderate mass density comparing to steel material.

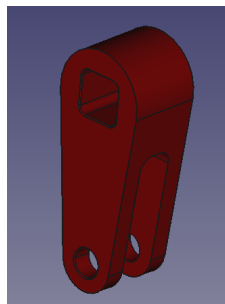


Fig 8. Lever arm

The lever arm is protected from thermal radiation inside the vehicle thanks to the insulation jacket wrapping the actuator (see previous section) so as to prevent any heating of the mechanical joints.

4.4. Elevon-torsion bar assembly

The control surface of the Actuation System is a CMC elevon rotating around its hinge line thanks to a CMC torsion bar passing through the base of the wing and the lateral fuselage and finally connecting to the lever arm activated by the actuator's rod. The elevon is also connected to the trailing edge of the wing thanks to a single pivot link.

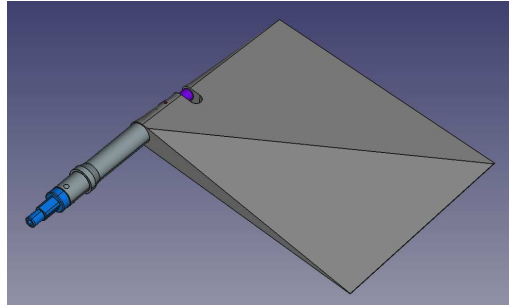


Fig 9. Elevon-torsion bar assembly

The torsion bar is terminated by a titanium insert so as to insure the mechanical connection with the titanium lever arm. This titanium insert is connected to the CMC torsion bar thanks to three bolts and ceramic glue at the interface between the inner CMC torsion bar and the titanium outer conical part.

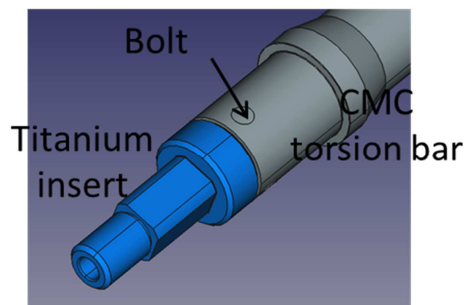


Fig 10. Titanium insert / CMC torsion bar connection

A small CMC cylinder aligned with the hinge line and a CMC bush around it (purple part in Fig 11) insure a pivot link with the wing fixation parts (see dedicated section).

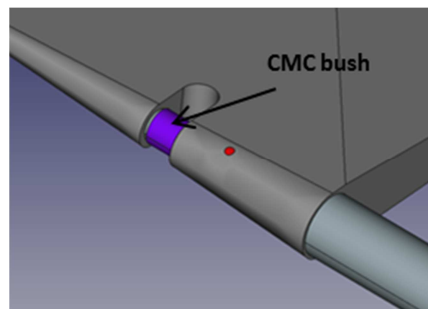


Fig 11. Connection with the wing

The C/C-SiC (CMC) material is produced at the DLR Institute of Structure and Design. The C/C-SiC material is characterized by the high thermal and chemical stability, hardness and abrasive wear resistance. The manufacturing process is based on the Liquid Silicon Infiltration process [7] [8] (LSI) and can be divided in three major steps:

- At the beginning the CFRP “green” bodies are made from commercial available 2D carbon fibres fabrics or fiber roving’s and phenolic resin via autoclave, hot-press or RTM process. At this stage, the material doesn’t differ from any conventional CFRP material. Here, a CFRP plate based on a 2D carbon fibres fabric and a CFRP bar based on a torsion optimised fiber laydown was used.
- In the second step, these green bodies are pyrolysed at temperatures above 900°C over a period of several days in inert gas atmosphere. The result is a highly porous C/C preform.

Between the second and the third step, the C/C preform bodies are machined such that the C/C torsion bar and the C/C elevon could be joined as one single part. The connection is realized by joining the two parts with a phenolic based resin.

- At the third process step, the complete torsion bar-elevon assembly is infiltrated with molten silicon. The porous C/C preform is infiltrated by capillary forces. In the same time during the infiltration process, the silicon reacts with the carbon matrix and carbon fibres and forms the SiC matrix at the contact areas. The siliconization process takes place in fine vacuum at temperatures above 1420°C.

At the end, the free silicon can be removed from the assembly during de-siliconization or mechanically. The final step is the machining of the elevon IF to the attachments.

The most critical properties of the assembly were the torsion bar mechanical strength (i.e. its breaking hinge moment) so as to allow the pull out manoeuvre, and the torsion bar stiffness so as to minimize the deviation between the ordered angular position of the elevon and its real position.

The CMC torsion bar, its titanium insert, and its CMC dummy interface with the elevon (see Fig 12) were tested on a bench so as to determine the stiffness and breaking torque of the assembly.

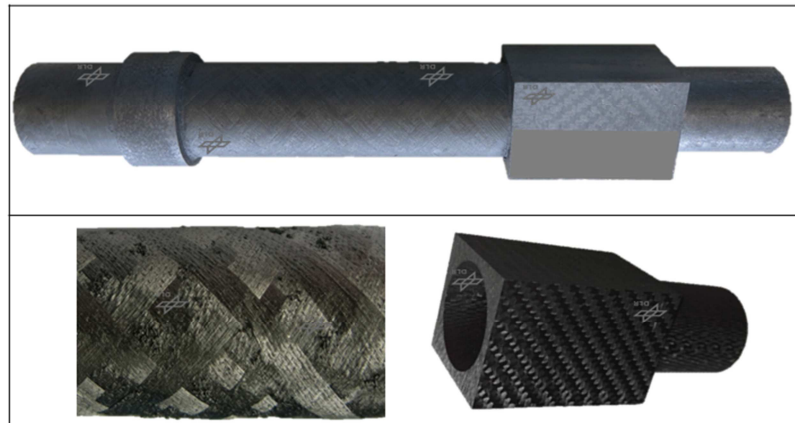


Fig 12. Test sample material after the second and final third production step

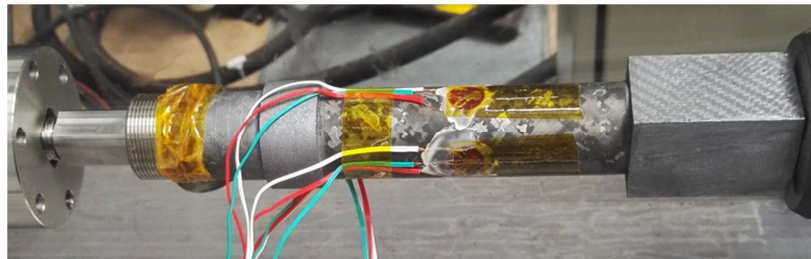


Fig 13. Final integrated test sample at the torque test bench (before testing)

The final tests showed that the CMC-titanium sample can withstand the nominal torque requirement of 280 Nm and even guaranty a maximum allowable torque of up to 330 Nm (including a safety factor) at the chosen torsion bar dimensions.

The stiffness of the sample (integrating the dummy interface with the elevon) was experimentally determined as nearly 10 000 Nm / rad.

The tests also showed the good dynamic behaviour of the sample under dynamic loads (50 Nm with a sinus overlay of +/-15 Nm at 10Hz) without any damages or modifications of the sample properties.

Those performances will be transmitted to the FM/GNC analysis for a future update of the trajectory profile using those potentialities.

4.5. Fuselage fixation parts

The CMC torsion bar is passing through the lateral fuselage thanks to a 3 rotational DoF ball bearing provided by the French firm SKF Aerospace. This ball bearing is a high temperature self-lubricated steel bearing able to work in vacuum and to withstand 250°C.

The inner ring of the ball bearing (gold part in Fig 10) is fixed to the torsion bar thanks to a big metallic nut (purple part in Fig 14) drilled around the torsion bar. The outer ring of the ball bearing

(grey part in Fig 14) is fixed to the lateral fuselage thanks to a metallic plate (blue part in Fig 14). Those two parts are made with titanium material able to withstand high stress and high temperature at the interface with the internal structure while keeping a moderate mass density comparing to refractory steel material.

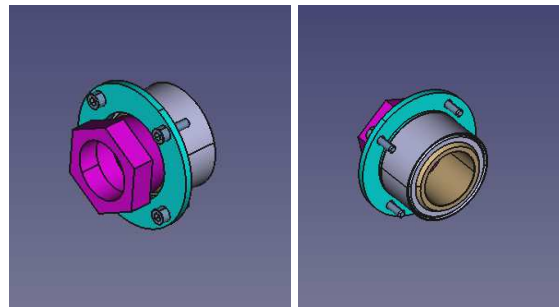


Fig 14. Fuselage fixation parts

Some hot air coming from the external flow could enter the cavity between the torsion bar and the wing panels and then potentially overheat the bearing via convective heat transfer (see Fig 15). It was shown by micro-aerothermodynamics that this would not occur [9]. As an extra insurance though, the cavity will be filled with a thermal protection named PROMAGLAF®-HTK provided by the Belgium firm PROMAT.

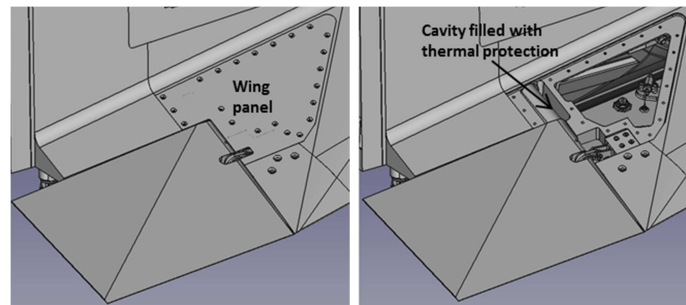


Fig 15. Thermal protection of ball bearing

4.6. Wing fixation parts

The elevon is connected to the wing thanks to two metallic parts (green and blue parts in Fig 16) forming a pivot link with the elevon thanks to a CMC bush (purple part in Fig 16) between the blue part and the small cylinder of the CMC elevon (see previous section).

Those two parts and the associated bolts and nuts are made with titanium material able to withstand high temperature and high thermo-mechanical stress.

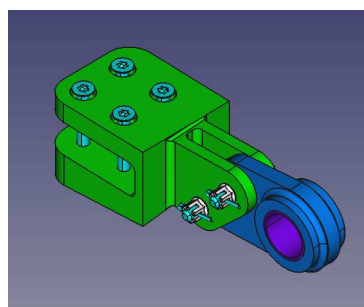


Fig 16. Wing fixation parts

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