Development and Testing of a High Compact Stepper Motor Mechanism

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Abstract

The Laboratory for Atmospheric and Space Physics (LASP) has developed for the Mars Atmosphere and Volatile EvolutioN (MAVEN) mission an Imaging Ultraviolet Spectrometer (IUVS) instrument. A grating flip mechanism (GFM), inside the IUVS instrument, is based on a highly compact and innovative stepper motor solution to drive an optic in two precise, bi-stable positions. Rotation angle between positions was 90°. This paper discusses major design restrictions, unique design characteristics and lessons learned from the development up through environmental and performance testing.

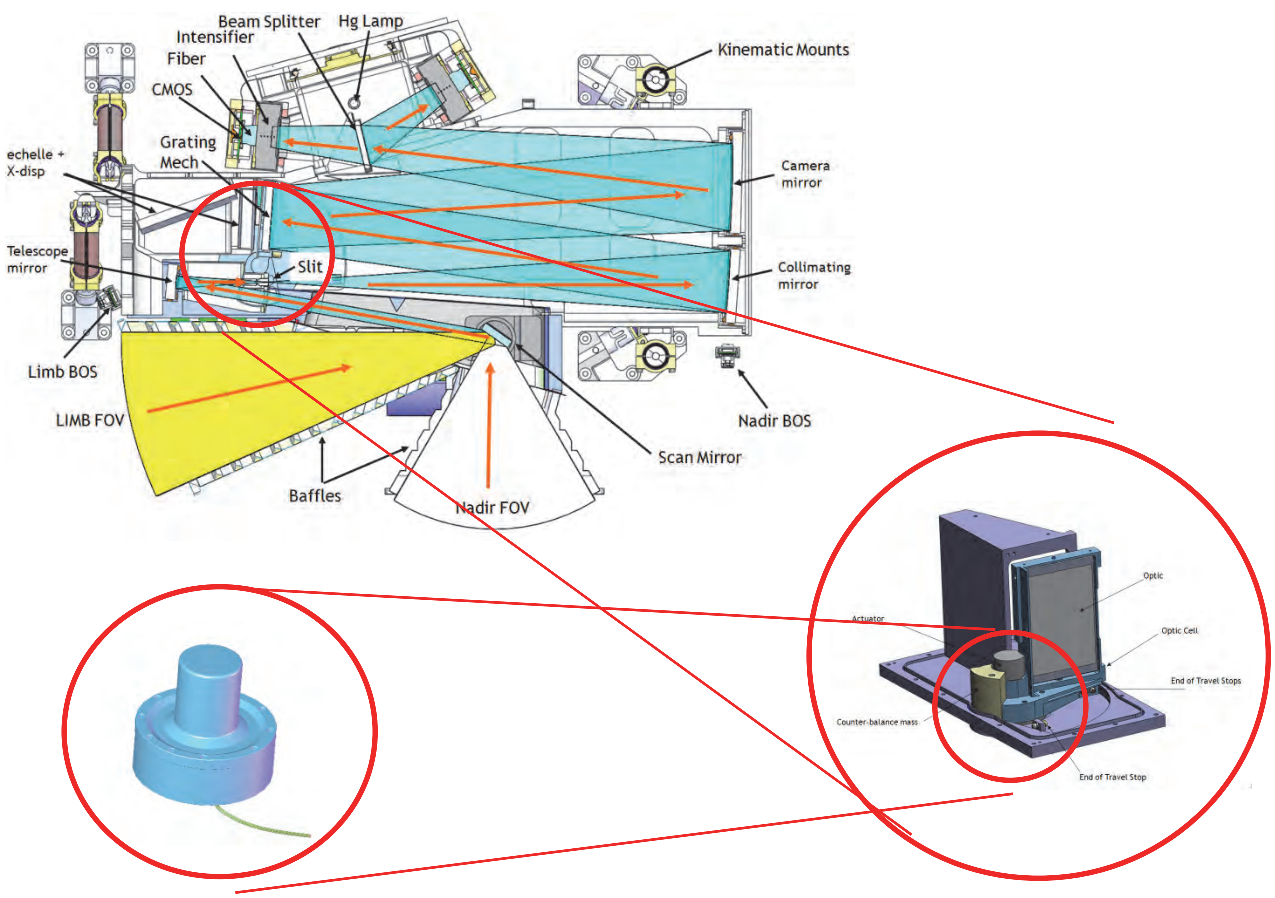

Figure 1. IUVS mechanism overview

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Introduction

Function of the GFM consists of turning a grating assembly inside two hard end stops. The position accuracy defines the systemic grating position. Very restrictive geometrical boundary conditions limited the degree of freedom for an actuator solution – especially with respect to axial length and diameter for the actuator. Standard components or “of the shelf” products were not applicable.

Low weight, high rigidity and functional safety were fundamental design criteria. The long-term cleanliness of the grating represents a systemically size for the spectroscope. To keep the probability and the various ways of grating surface contamination in a very low level, an effective design strategy had to meet all these criteria. This risk mitigation was the key point in the complete design concept. A much more compact construction had to be developed.

Mounted on the cover was the grating assembly with the counter balance mass. The rotation angle was 90°. Two hard end stops on both sides limit the rotation angle. Electrical limit switches detect both end positions. To facilitate the bi-stable positioning we added a flexible coupling between cover and planetary gear shaft. Our purpose was to turn the grating assembly very smoothly in to the end positions. A torque preload should hold the grating in the end position under unenergized conditions via detent torque. Motorization was done by a special modified hybrid stepper motor size VSS 25.200.0,1-X from Phytron.

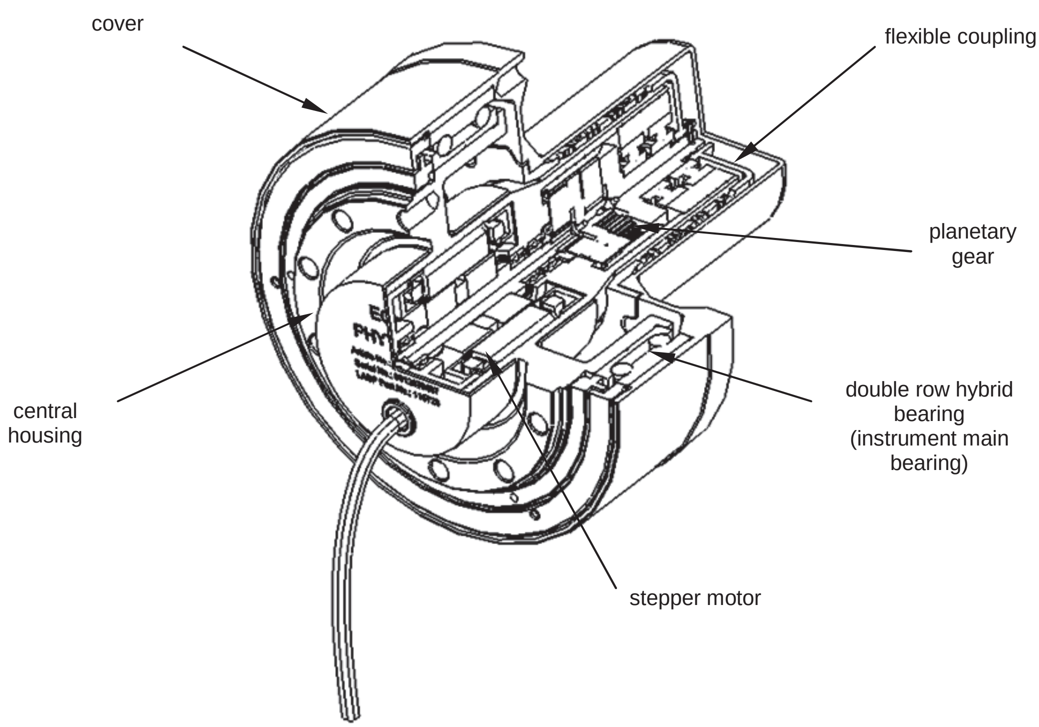

Figure 2. Integrated stepper motor mechanism

Main Functional Requirements

Thermal Constraints

The operating temperature range from -10°C (safety range -30°C) up to +40°C creates some different friction characteristics. Each lubricated bearing needs a little higher torque under cold conditions.

At begin of the project it was not possible to calculate the friction characteristic for the double row instrument bearing. Equivalent data were not available from the manufacturer. Due to the special construction, quality criteria, preload and specified materials, no similar bearing was usable for a representative friction test at that time.

36 balls in each bearing race, 72 balls in total. 144 wet lubricated single contact points creates a higher friction uncertainty. Torque loss with affects to the functional safety was a critical issue. Agglomeration effects during long time storage were an additional uncertainty. Other bearings in the mechanism and the lubrication inside the planetary gear increase the complex of friction problems. The thermal characteristic influences all parameters. These are well known effects.

On the other hand, the stepper motor, driven by a constant voltage driver, must create enough torque to overcome all static and dynamical friction parameters. The integrated 2-stage planetary gear with a ratio of 49:1 increases the available stepper motor torque.

Friction Torque Separation

To minimize the thermal induced torque reduction and uncertainty we try to split the consequences over the time. For a better understanding we must describe the process, to drive the grating assembly in to a hard end stop, in more detail. The stepper motor with 200 steps per revolution (=1.8°/full step) operates normally with a small magnetically load angle, depending on the torque load.

The planetary gear have a backlash of 35 arcmin and the very exact calculated and qualified flexible stiffness of the coupling allows us to drive with 4 motor full steps in the hard end stop. So, if we turn out of the end stop we can use the:

- stepper motor magnetic load angle
- planetary gear backlash
- flexible coupling stiffness

for a friction torque separation. If we turn the grating assembly out of the torque preloaded end position, the motor must not overcome all friction parameters at same time. In the first milliseconds, the complete motor torque is only necessary to overcome the motor internal friction torque (bearings, detent torque). Motor shaft began to turn.

The planetary gear is now positive preloaded due to the flexible coupling and began to turn with a much lower friction torque as normally required. The backlash reduces the coupling preload slowly and absorbed some vibrations (function like a damper). Some milliseconds later the planetary gear began to turn.

In a third step on the time line, motor and planetary gears were turning; the flexible coupling was used as a torque peak damper to overcome the friction torque of the instrument bearing. At -10°C, we need 34 mA and at -30°C only 37 mA starting current. So the engineering teams from LASP and Phytron played with the characteristic and performance of different design elements to create friction risk mitigation.

To drive in a hard end stop is from a friction and torque point of view not so critical due to the lower dynamical friction values. The worst case was to drive out of a hard end stop.

Final Concept Approach

Flexible Titanium Coupling
To get enough safety margins in the flexible coupling design, following the wisdom "expect the unexpected", we start with some different designs.

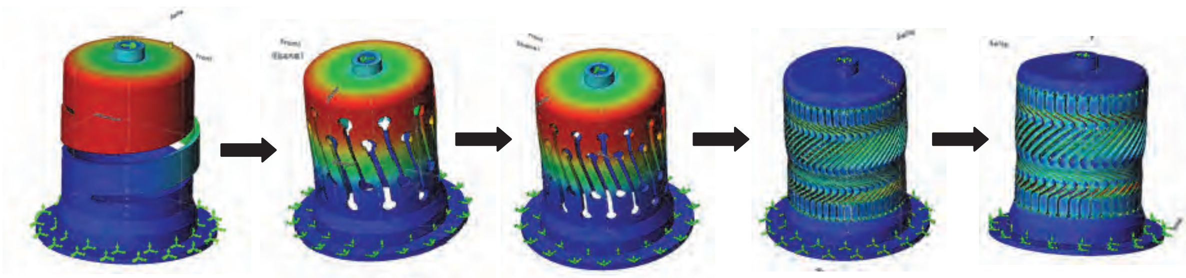

Figure 3. Evolution steps flexible coupling

Nearly 30 different models were calculated to find an optimal flexure structure. The stiffness was defined and the dimensions very hard restricted. Material stress reduction and the radial and axial dimensional changes were limited, too. We could reduce the internal stress from 724 MPa down to 54 MPa (= ~8%). Both parties recalculated the final FEM model. LASP with ANSYS, Phytron used COSMOS. The results correlated in the stress and dimensional changes very exact.

To reduce any risk in the later assembling and test phase, we decided to produce three different flexure structures in the couplings. So, three versions were manufactured and tested respective to the torsional stiffness. Calculated and final measured stiffness values were different. Similar results were found in [1].

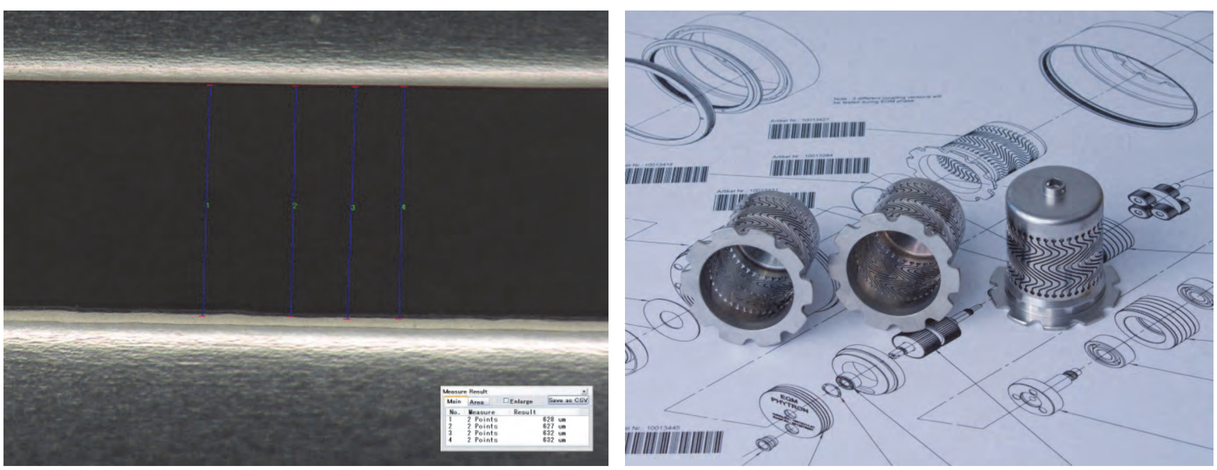

Figure 4. Structure of flexible couplings

Intensive studies of comparable flexible structures, which were used in other mechanisms e.g., titanium butterfly pivots [2] and their final tested characteristics, creates a higher confidence level for our design approach.

Central Housing Structure

The only constructive way to be able to press many requirements in a small space was to use a well coordinated conceptual design in hybrid joining technology. The central housing used all the advantages of the accuracy of CNC machines. At the same time, it represents the basic structure without soft joints.

To achieve excellent out gassing properties, the cover envelops the entire internal structure on 3 sides. Desorbing products will be dissipated controlled in one direction.

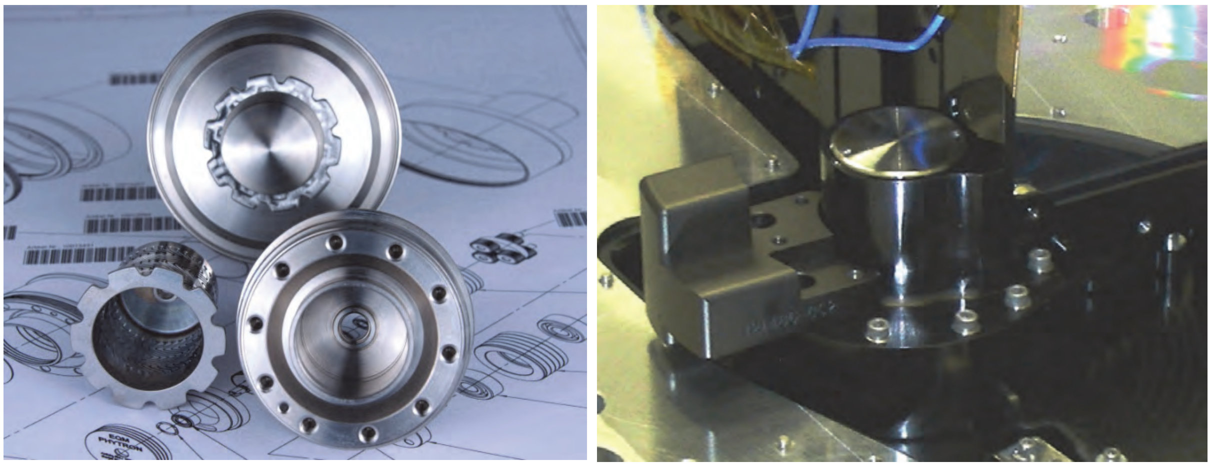

Figure 5. Main structural titanium parts and complete mechanism

Final Grating Flip Stepper Motor

To obtain detailed performance data from each assembly phase, several tiered test sequences have been defined. The performance data were therefore known at any time. The irreversibility of some assembly processes requires a precise line of action with parts which must absolutely comply with the requirements.

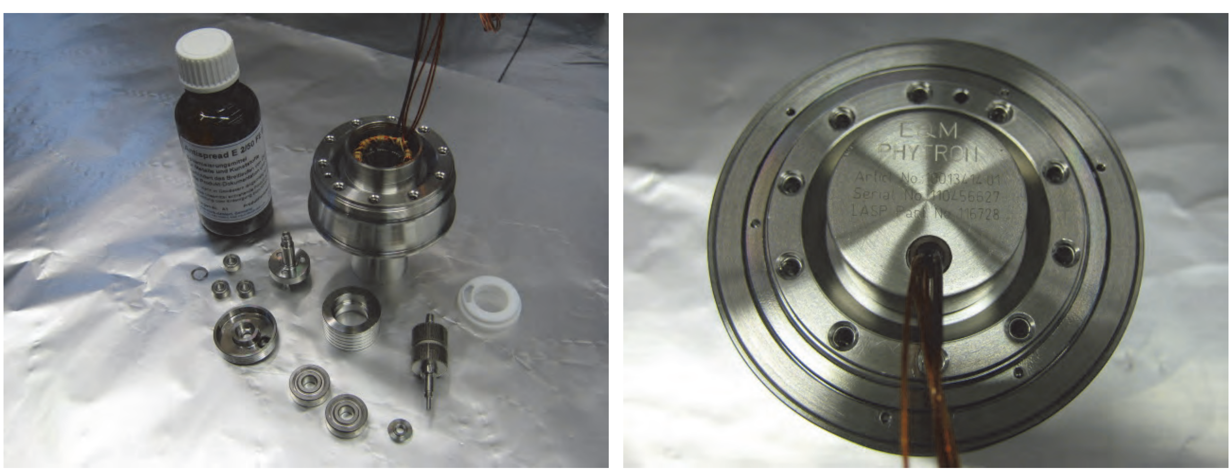

Figure 6. Final tested motor assembly

The complete unit can be connected with the IUVS instrument structure via 10 internal threads. Heli coil inserts prevent a fretting between the materials. The cover contents similar threads for the grating flip mechanism. Both mounting points are very close together. The stiffness of the large instrument hybrid ball bearing dominates the overall stiffness.

Figure 7. Final tested motor assembly

The flexible coupling separates two mechanical oscillating systems. One system is defined by the stepper motor, the planetary gear, and the upper part of the coupling. Vibration source is represented by the stepper motor. Second system is defined with inertias of the grating flip mechanism, the instrument ball bearing and the cover. Static and dynamic friction inside ball bearings and gears can have far-reaching repercussions on the damping properties.

Main Test Results

Outgassing Test Results

A residual gas analyzer (RGA) was used to measure the volatile impurities in the assembled actuator at +40°C. Results of the test indicate the actuator is suitable for the strict requirements of a FUV optical instrument – i.e. virtually indistinguishable from a clean vacuum chamber.

Vibration Testing

The EQU actuator was assembled in to the GFM life test unit (LTU) and subjected to the corresponding qual-level vibration environment. Test levels included sine burst to 17 Gs and random vibe to over 10 Gs rms per axis. Following the testing the actuator performed smoothly and passed all post-test inspections.

Life Testing

Following the vibration testing the LTU was subjected to a thermally controlled vacuum life test which included over 6,000 cycles at a range of temperatures. The actuator met all operational criteria from -30° C to +40°C and passed the life test successfully.

Optical Repeatability Testing

The LTU was driven into the hard stop over 200 times, and the optical orientation of the grating was measured each time using an autocollimator. The position repeatability was measured at less than 10 arc-sec, which meets the mechanism requirements.

Conclusions and Recommendations

1. A sequence of several manufacturing processes reduces the coupling stiffness in a range of approx 40%. Result of different material properties and the unpredictable behavior in the rim zone. Our strategy, to create 3 different coupling versions, was very helpful at the end. Real tests were highly recommended in an early project phase.

2. Trust-based cooperation between the design teams at a very early stage of the project is the basis of innovative products.

3. The distribution of the entire starting friction in several temporally separated events represents an efficient way.

4. Adjusting rings made of titanium with fine threads creates difficult problems during assembling. Very precise inspection and deburring under the microscope is necessary.

5. The characteristic of both mechanical oscillating systems must match exactly together. Meant with “match” is naturally “out off-tune”. At worst case, the system creates resonance or bouncing effects. In a complete representative "plug and play" system test, the performance characteristics should be verified in an early project phase. Alternative settings shall be provided in the degrees of freedom of control electronics or software intelligence.

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