# MICRO VIBRATION IMPROVEMENT OF A STEPPER ACTUATED MECHANISM

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## ABSTRACT

A two axis X-Band Antenna Pointing Mechanism (APM) was developed by Astrium/KARI and flown on Kompsat-3 as downlink equipment. A second set of identical equipment will be flown on an identical follow-on space craft.
The APM is a compact two axis pointing mechanism with an integrated Hold-down and Release Mechanism. The azimuth range is un-limited while the elevation range is 130deg. The System is equipped with Contactless X-Band Rotary Joints for RF Signal transfer. The rotational motion is executed by two identical stepper motors with harmonic drive gears acting to an external spur gear and controlled by an Astrium provided Stepper control electronic.

*Figure 1: APM Assembly*

## 1. Introduction

Though the system was optimised for minimised µ-jitter, in-orbit data of the first set of mechanism under real 0 g and S/C I/F stiffness conditions showed the necessity for further improvements in view micro vibration attenuation on payload level. Further considerations have to be taken to reduce the micro jitter emitted by the APM in order to avoid impact to the payload on the follow-on mission.
Previous tests and analysis showed that the main contribution to the micro jitter was resulting from the stepper motor detent torque. The micro vibration contribution due to motor micro-stepping was negligible as the related frequency of fundamental harmonic was already out of the range of interest.
The proposed jitter reduction measures had to be finished latest within a time frame of one year, since the mechanism H/W was already delivered to the S/C. Furthermore the Jitter mitigation measures should interfere with the existing interfaces and mechanism envelope.
The activities for modification included a Design phase, a Bread Board phase and a FM H/W modification phase.

## 2. Analytical Approach

As the actuator is the main contributor to the micro jitter a Matlab Simulink analysis was performed to characterise the effects of different design improvement ideas. The goal was to improve the payload line of sight (LOS) error on system level, affected by the operation of the APM.
The Matlab model included a steady state model of the X-Band Antenna and the space craft (S/C) as well as a jitter source model of the actuator. The jitter model of the actuator was correlated with an actuator jitter characterisation measurement. Changing parameters of the model corresponding to FM H/W modification showed strong impact on the LOS.
Finally four solutions showing the highest jitter reduction potential were selected for a detailed investigation:

- Modification of control electronic
- Modification of actuator link I/F between actuator output pinion and spur gear)
- Modification of in plane APM I/F Stiffness to S/C
- Modification of out of plane APM I/F Stiffness to S/C

The line of sight jitter analysis result for the x-direction of the optical payload is shown below.

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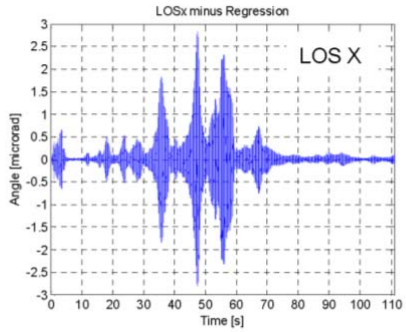


*Figure 2: Initial LOS micro vibration*

The next figure shows the improvement in the LOS in the x-direction with the selected actuator link modification

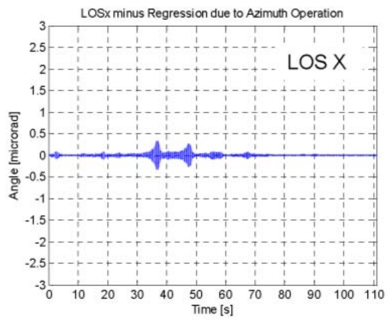


*Figure 3: Improved LOS micro vibration*

A trade off for the four options at the end of the analysis phase showed that the actuator link was the preferred solution. The main drivers for the decision are shown below:

- The impact to the schedule was acceptable
- Existing H/W can be easily modified
- Verification can be performed at minimized effort
- No change of Interfaces or envelope

## 3. Preliminary design phase

With the decision to modify the actuator link, an existing design idea from Astrium came into focus. The idea was to de-couple micro jitter from the S/C via reduced torsional stiffness of the gear wheel mounted on the actuator output shaft.

The design for the actuator link employs a preloaded split pinion assembly at the actuator output. The lower part of the pinion is fixed to the output shaft while the upper part of the pinion is in free rotation and loaded by four springs against the mating spur gear wheel for backlash free engagement.

*Figure 4: Original FM design of APM actuator link which was planned to be modified*

On basis of the analysis results, a soft element was planned to be introduced into the actuator link. For this purpose, the upper half and the pretension springs were removed from the existing split pinion solution and the lower part was planned to be equipped with a torsional flexible element to reduce torsional stiffness.

By principle this can be achieved in various ways. One design idea leads to a solution with an elastic silicone ring in the gear wheel plane. For this design a silicone ring was used to connect the actuator output shaft to the toothed outer part. The silicone ring works as decoupling element and provides some basic damping.

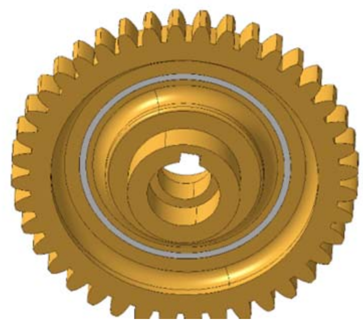

*Figure 5: GW with silicon ring*

In the second solution a design with spring blades machined into the gear wheel plane was proposed. This design uses four cantilever arms to attach the actuator output shaft to the gear wheel teeth.

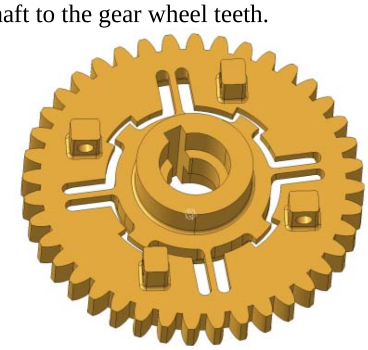

*Figure 6: GW with spring blades*

A FEM was used to estimate the optimum between stresses in the spring blade and its stiffness. Modelling a detailed Nastran 3D model with tetrahedron elements was used to identify the maximum stresses in the pinion due to the applied load.

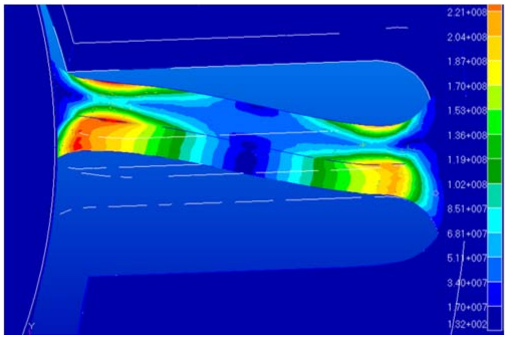


*Figure 7: FEM stress in spring blade*

The maximum load was defined by the actuator output torque. Allowed stress levels were defined by the rupture allowable of the pinion material including a margin of 1.5.

## 4. Bread Board (BB) phase

As both designs had no heritage it was decide to check the feasibility of the two design solution in a BB phase. The BB verification was split in two subtasks.
The first part was the selection of a proper material for the silicone ring.
The criteria for the selection were the stiffness, the gluing characteristics and the rupture force.
For a first selection check, pull tests with longitudinal samples were performed. The samples were made in a way that the gap length was identical to the gap in the FM gear wheel.

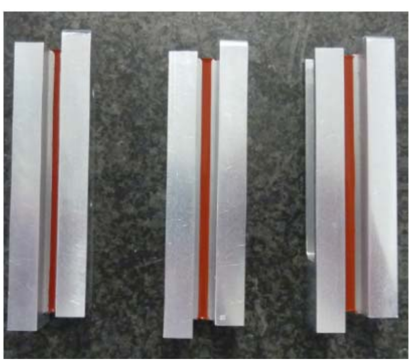

*Figure 8: Longitudinal shear samples*

The upper figure shows different gap widths used to check the stiffness of the gap. A typical rupture characteristic is shown in the figure below. One observation was that the failure mode was always a rupture in the synthetic material and not at the bonding I/F to the aluminium. The figure below shows a typical failure mode of the synthetic material. The failure begins at the one end of the sample a leads to the interlaminar rupture of the adhesive.


*Figure 9: Failure mode of she3ar samples*

The best solutions were achieved with RTV-S961 and a gap dimension of 1mm.

The next step after the gap dimensioning and the material definition was the preparation of rotational samples to check the rotational stiffness and the adhesion forces. One sample was manufactured with a RTV-S961 ring and one with the machined spring blades By design, excessive plastic deformation of the spring blades was avoided by hard end stops in the gear pinion.

*Figure 10: Rotational samples*

During each stiffness test the samples were fixed to a Kistler torque sensor and the torque over angle was measured. The maximum input torque was limited to available actuator output torque. Both samples survived the test.

### 4.1. BB H/W verification phase

For testing purposes a BB model comprising of a simplified base bracket as support structure with FM identical slip ring, bearing and gear stage was prepared. An angled yoke structure was used to simulate the eccentricity of the azimuth actuator position.

*Figure 11: APM Bread Board model*

Used test equipment was a Kistler table with a Kistler amplifier and a Matlab XPC. Data acquisition was done with the XPC. The APM BB was attached by a stiff adapter to the Kistler table.
Initial micro vibration tests on an APM FM actuator and gear stage were conducted. These first tests showed that the BB model disturbances generated by the actuator detent torque were consistent with the FM model jitter performance.
For a next test step the APM BB was assembled including the silicone ring design respectively the flex blade design in the gear pinion in order to verify the µ- jitter performance on APM level. With each assembly a series of various angular velocities, acceleration profiles and sample mission were performed to identify the µ-jitter characteristics.

*Figure 12: GW with silicone ring*

*Figure 13: GW with spring blades*

The measured time data of the forces and torques were processed with Matlab following a FFT-analysis and a standard deviation analysis. Jitter test results of each velocity for all three test series had been compared in their frequency spectra and in the standard deviation.

During test, the silicone ring bonding failed in the I/F to the gear wheel close to the end of the jitter test. This is in deviation to the above described linear samples, where the silicon always failed under load in the silicon material, but not in the gluing are.
A second drawback for the silicon ring design was that the stiffness of the silicon material behaved strongly non-linearity over temperature.

Comparing the BB jitter test results for all three configurations:

- Gear stage as is
- Spring Blade
- Silicone Ring

The following results can be summarised:

- The silicone ring shows the biggest jitter reduction, however the motor detent torque is still measurable in this configuration.

- For the Spring Blade design the attenuation is lower, however the material issues (gluing, aging, stiffness temperature dependency) coming up for the Silicon ring design pose a significant drawback to this design, so that the blade spring design was adopted for flight as the optimised low risk/short schedule solution.

Next figure shows the I/F forces in the x-, y- and z-axis at the Kistler table for the operation of the BB APM azimuth stage actuator for all three configurations.

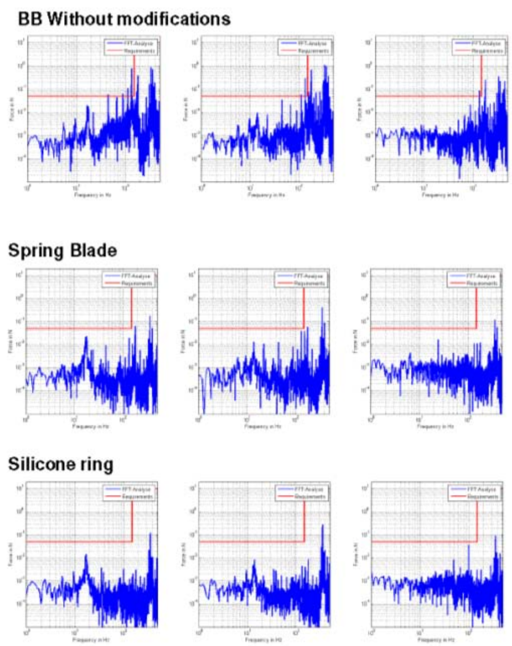


*Figure 14: Micro Jitter disturbance forces*

The read curve in each plot represents the required jitter level from the customer specification.

## 5. FM H/W phase

As the verification of the spring blade design at BB level was successfully passed, the decision was taken to start the modification of the FM H/W.
An initial Jitter test was performed with the FM APM. This jitter test was performed to characterize the APM after it was received back from the customer at Astrium GmbH Friedrichshafen.
In a next step the FM APM the gear wheel assembly was modified and equipped with spring blades in the same way as the BB gear wheel.
Finally the gear wheel was fixed to the actuator output shaft and the APM assembly was successfully finished.

### 5.1. FM H/W verification phase

A reduced test campaign was performed for the verification workmanship and to qualify the implemented design changes. This campaign was similar to the nominal APM acceptance test campaign but with modified load levels.

These activities were performed after FM modification to verify the APM:

- Jitter Test
  - Measurement of forces and moments (6 DoF) in- and out of plane at the APM I/F
- Reduced Vibration Test
  - In plane vibration test at acceptance level
- Reduced TV Test
  - Two temperature cycles with APM operation at hot and cold and HRM release.
- Performance Test
  - Verification of APM operation range for azimuth and elevation axis

Environmental and jitter tests were performed under control of Astrium GmbH at the Astrium facility in Friedrichshafen.


*Figure 15: Jitter test setup for APM*

All tests had been performed successfully according to the test procedures. Comparison of the results from the environmental tests showed a good correlation with the previous tests performed during the FM acceptance test phase.
As can be seen in the below tables, which show the comparisons of the peak values for a rotation velocity of 1deg/sec in place off all other velocity measurements, the modification led to a strong attenuation of the jitter forces and moments.

| **Fx-Axis** | **Income Test [N]** | **Post env. Test [N]** |
|---|---|---|
| 44,4 | 0,5338 | 0,0009 |
| 66,6 | 0,5163 | 0,0103 |
| 88,8 | 1,7830 | 0,0121 |
| 111,1 | 0,2979 | 0,0116 |
| 133,3 | 0,0944 | 0,0176 |

*Table 1: Comparison peak jitter force in x-direction*

| Fy-Axis | Income Test [N] | Post env. Test [N] |
|---|---|---|
| 22,2 | 0,0662 | 0,0515 |
| 44,4 | 0,9459 | 0,0195 |
| 66,6 | 0,0598 | 0,0219 |
| 88,8 | 0,7781 | 0,0125 |
| 111,1 | 0,2292 | 0,0191 |
| 133,3 | 0,5632 | 0,0257 |

*Table 2: Comparison peak jitter force in y-direction*

| Fz-Axis | Income Test [N] | Post env. Test [N] |
|---|---|---|
| 44,4 | 0,0239 | 0,0030 |
| 66,6 | 0,0307 | 0,0065 |
| 133,3 | 0,0629 | 0,0138 |

*Table 3: Comparison peak jitter force in z-direction*

| Mx-Axis | Income Test [Nm] | Post env. Test [Nm] |
|---|---|---|
| 44,4 | 0,4950 | 0,0102 |
| 66,6 | 0,0433 | 0,0116 |
| 88,8 | 0,3544 | 0,0047 |
| 111,1 | 0,0536 | 0,0085 |
| 133,3 | 0,1842 | 0,0138 |
| 177,7 | 0,1423 | 0,0865 |

*Table 4: Comparison peak jitter moments in x-direction*

| My-Axis | Income Test [Nm] | Post env. Test [Nm] |
|---|---|---|
| 22,2 | 0,0123 | 0,0014 |
| 44,4 | 0,1369 | 0,0009 |
| 66,6 | 0,1898 | 0,0040 |
| 88,8 | 0,3353 | 0,0025 |
| 111,1 | 0,0129 | 0,0024 |
| 133,3 | 0,0169 | 0,0023 |

*Table 5: Comparison peak jitter moments in y-direction*

| Mz-Axis | Income Test [Nm] | Post env. Test [Nm] |
|---|---|---|
| 22,2 | 0,0192 | 0,0143 |
| 44,4 | 0,1368 | 0,0027 |
| 88,8 | 0,0396 | 0,0006 |
| 111,1 | 0,0067 | 0,0009 |
| 133,3 | 0,05332 | 0,01117 |

*Table 6: Comparison peak jitter moments in z-direction*

The next table shows a comparison of the standard deviations for a jitter results with an input rotation velocity of 1deg/sec. This method was identified as an efficient way for micro jitter comparison next to the comparisons of the main peak values.

| Value | Income Test [N or Nm] | Post env. Test [N or Nm] |
|---|---|---|
| Fx | 1,42059 | 0.0540492 |
| Fy | 1,40796 | 0.110181 |
| Fz | 0,49579 | 0.114395 |
| Mx | 0,702293 | 0.0354312 |
| My | 0,384875 | 0.0172587 |
| Mz | 0,179196 | 0.0358221 |

*Table 7: Comparison of the standard deviation of the jitter test results between the incoming and outgoing test*

The comparison of the results showed a high attenuation (e.g. 96% for Fx at 1deg/sec) similar to the comparison of the peak values.

## 6. Summary / Lessons Learnt

During the activity performed on Astrium GmbH site, it was shown that the prediction of micro jitter improvement measures by analysis are possible, especially if initial characterisation measurement results of components can be fed into the analytical model. In this context, the analytical model shall describe the main source for the jitter which is in our case generated by actuation of the stepper motor.
Further results are that with a silicone ring an additional jitter attenuation could be included if the material ageing, bonding and stiffness issues could be solved.

With the chosen solution which is the spring blade design, a strong reduction of emitted µ-jitter disturbances could be achieved but there are still some peaks observed in the actuator stepping frequency especially when this frequency is next to APM Eigenfrequency. On the other hand, the spring blade design provides a very reliable technical solution and a solution which can easily be implemented even into existing H/W.

The results achieved verified the activities on S/C System level at KARI premises.

## 7. Acknowledgements

We would like to thank KARI for supporting the activities.