# SARM A SOLAR ARRAY ROTATION MECHANISM

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**ABSTRACT**

The ADM-Aeolus (Atmospheric Dynamics Mission) satellite will make global wind-profile observations from a Sun-synchronous dawn-dusk orbit of 400 km altitude and shall provide information to advance our understanding of atmospheric dynamics and climate processes to improve weather forecasting. The orientation of the satellite and its orbit dictate that, after full wing deployment, both Solar Array (SA) wings need to be rotated over 45°.

To achieve this rotation a dedicated Solar Array Rotation Mechanism (SARM) has been developed. The design is based on a standard Dutch Space solar array panel hinge and the Multi-purpose Holddown and Release Mechanism (MHRM). The MHRM activates the hinge after the full deployment of the wing and the hinge mechanism provides the required actuation torque for the rotation and locks the SA wing in its final configuration.

The main design challenges of the SARM have been to provide sufficient stiffness and to keep the retarding torque of the cable harness as low as possible.

The cable harness is the main contributor to the retarding torque of a solar array hinge line. The hinge springs must provide sufficient actuation torque to overcome this retarding torque. The required safety margin on the actuation results in a significant contribution to the deployment shock. A low retarding torque of the harness has been achieved by placing it around a cylinder. The cable harness is now flat and has a significant length which results in minimal normal bending of the cable. The cylinder itself has many functions; fixation and guidance of the cable harness, main load path and interface to the hinge mechanism and the spacecraft.

An engineering model has been made to investigate if the retarding torque is sufficiently low and a finite element model of the SARM has shown that the required stiffness could be met.

As one wing has to rotate 45° clockwise and the other 45° counter clockwise, two mirror image SARM units are required. The standard hinge could have been used for both SARM units as is, however, the available volume, mass restrictions, stiffness and deployment shock requirements demanded a significant redesign, which resulted in two individual designs for both SARM units.

The SARM has been successfully qualified and after some minor alterations two flight units have been produced, subjected to acceptance testing, and delivered to the customer. The AMD-Aeolus satellite is scheduled for launch in 2011.

## 1. INTRODUCTION

The ADM-Aeolus (Atmospheric Dynamics Mission) satellite will make global wind-profile observations from a Sun-synchronous dawn-dusk orbit of 400 km understanding of atmospheric dynamics and climate processes to improve weather forecasting. AMD-Aeolus carries a continuously operated lidar instrument (ALADIN), which emits laser pulses towards the atmosphere. The orientation of the satellite and its orbit dictate that, after full wing deployment, the Solar Array (SA) wings need to be rotated over 45° to achieve their final configuration.

To achieve this rotation over 45° a dedicated Solar Array Rotation Mechanism (SARM, Fig. 1) has been developed, built and tested. The design has been based on a standard Dutch Space solar panel hinge (Fig. 2) and the Multi-purpose Holddown and Release Mechanism [1] (MHRM, Fig. 3). The MHRM releases the hinge after the full deployment of the wing. The hinge mechanism provides the required torque for the rotation and locks the SA wing in its final configuration.

This paper describes the development, design and qualification of the SARM.

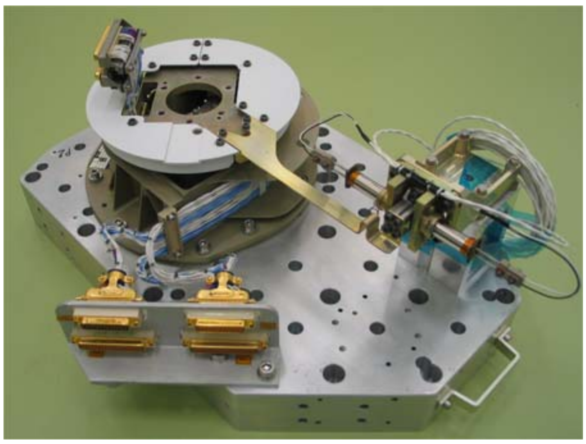

*Figure 1. The SARM assembly on an interface plate*

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## 2. REQUIREMENTS

The main requirements of the SARM are listed here:

- It shall provide a 45° rotation and locking in the 45° rotated position of the SA wing after full deployment.
- The mass of the assembly shall be less than 3.5kg.
- The deployed frequency of the SA wing including the SARM shall be higher than 0.2 Hz.
- The maximum deployment torque induced on the spacecraft interface shall be less than 40Nm
- The deployment actuator shall provide actuation torques/forces, which are at least 2 times the combined worst case resistance torques/forces predicted, while applying a safety factor of 1.5, i.e. the motorization ratio must be ≥ 3.
- Redundant micro switches are required to detect positive locking of the SARM. This requirement was introduced late in the program.

## 3. DESIGN APPROACH

The original approach was to keep it simple and cost effective. It was chosen to use the space qualified MHRM for activation after full solar array wing deployment and a FRED type standard solar panel hinge for the rotation as baseline for the development of the SARM

**FRED panel hinge**

The FRED panel hinge consists of 2 identical brackets which are normally attached between 2 SA panels, 2 springs to supply the motorization torque, 2 latches to lock the hinge and 2 synchro cable pulleys. The pulleys are part of the synchronisation system of the SA wing.

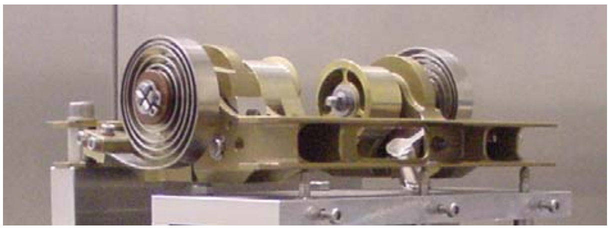

*Figure 2. The FRED panel hinge*

The FRED panel hinge rotates over 180˚, has a stiffness of 3626 Nm/rad around the rotation axis and is capable of transferring loads well over 500 Nm. The springs supply a torque of 1480 Nmm, this means that the maximum retarding torque of the hinge including harness is limited to 439 Nmm because the spring adjustment margin of 163 Nmm and the motorization ratio of 3 have to be taken into account.

**Multipurpose Hold-down and Release Mechanism**

The hold-down and release function of the SARM is provided by a MHRM. The main parts are the space craft (S/C) interface bracket, 2 thermal knives (one prime and one redundant) and a "Reel" cable element which includes a Dyneema hold-down cable.

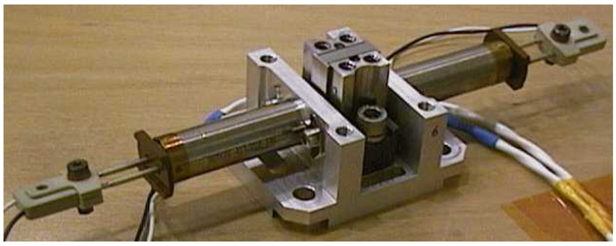

*Figure 3. MHRM*

**Feasibility study of preliminary design**

The main design challenges of the SARM have been to provide sufficient stiffness (the loads on the SARM are well below the load capability of the FRED hinge panel) and to keep the retarding torque of the cable harness as low as possible.

Dunkerley's Equation shows that the stiffness of the SARM has to be over 2000 Nm/rad in order to meet the SA deployed frequency requirement. A stiffness of 2000 Nm/rad is considered achievable because the stiffness of the baseline FRED hinge is high (3626 Nm/rad) and the number of parts/connections in the stiffness path of the SARM is minimal (2 parts only; the root hinge interface bracket and the SARM housing).

The maximum deployment torque induced moment on the S/C has to be less than 40 Nm. The deployment of the SA wing is damped by an eddy current damper. The SARM has no damper and therefore the motorization torque of the SARM, which has to be 3 times the retarding torque of the SARM, must be limited as much as possible. The retarding torque of the SARM is determined by the hinge and the cable harness. As the hinge design has been already established, the cable harness design must be optimized to limit its retarding torque.

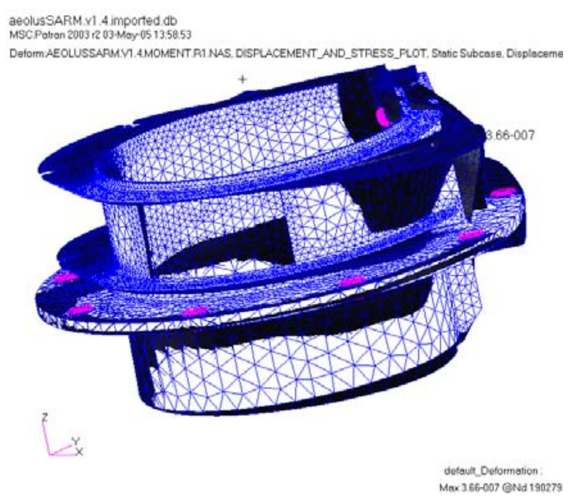


*Figure 4. SARM housing FEM*

Both the stiffness and the retarding torque of the SARM were checked on the preliminary, engineering model. A conservative stiffness assessment, using NASTRAN finite element models (Fig. 4 and Fig. 5), showed a stiffness of 2717 Nm/rad.

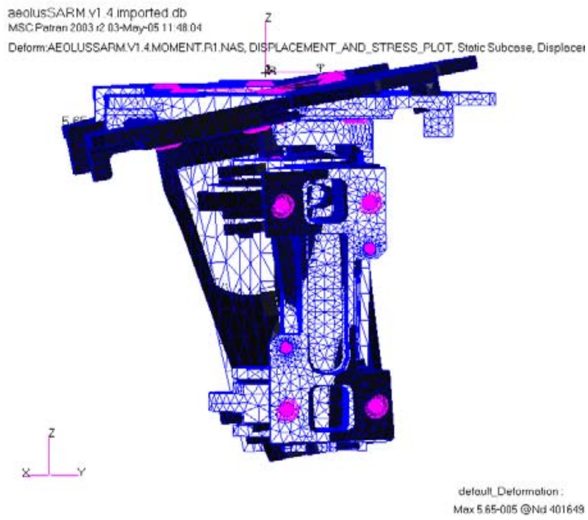


*Figure 5. Root hinge IF bracket and hinge FEM*

The retarding torque investigation with the engineering model showed that the cable harness stayed within a radius of 125 mm and had a retarding torque of 133 Nmm at ambient conditions. Fig. 6 shows the engineering model in a 45˚ position at which the cable harness is maximal deformed. The engineering model used an unmodified FRED hinge and cable harness which was not fully representative. Based on the results of the engineering test, the retarding torque of the SARM at cold conditions was assessed to be approximately 280Nmm, which is well below the identified maximum of 439Nmm.

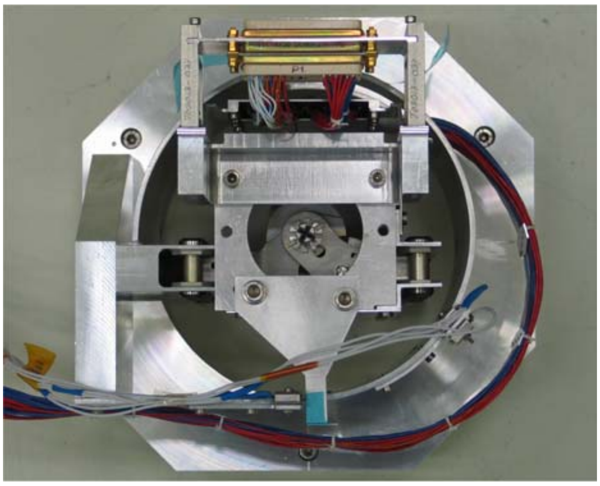

*Figure 6. SARM engineering model*

Both the FEM results and the Engineering test results showed that the SARM design is feasible from a stiffness and retarding torque perspective.

## 4. DESIGN

After confirmation of the feasibility of the concept the design has been further elaborated resulting in the design described hereafter. The main SARM parts are:

- The housing
- The cable harness and connectors
- The modified FRED panel hinge
- The root hinge IF bracket
- The MHRM and MHRM lever
- The thermal protection cover

Figure 7 shows the SA root hinge connected to the root hinge IF bracket via a thermal washer. The modified FRED hinge connects this IF bracket with the housing and the housing is the interface with the spacecraft. Another interface is with the MHRM lever to the release mechanism. The lever is stiff in radial direction, but flexible in both the other directions (Fig. 1).

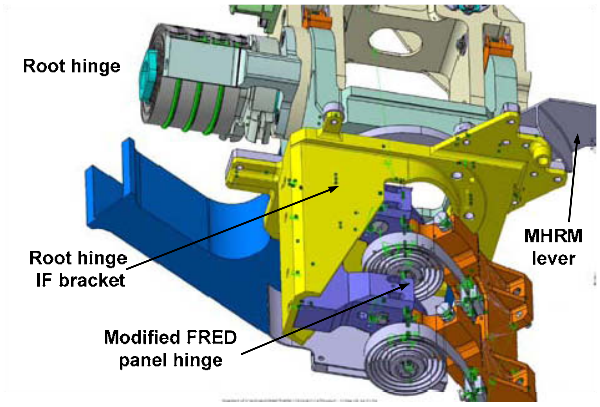


*Figure 7. Interface to the Solar Array and MHRM*

The original FRED panel hinge has been adapted in the final design. The length of the bracket has been modified so that the complete SARM complies with the specified available envelope. Furthermore, as shown in figure 8, the synchro cable pulleys have been omitted, and one spring has been replaced. The remainder of the parts (a.o. bearings, axis, latches and cams) are identical to the fully qualified FRED panel hinge.

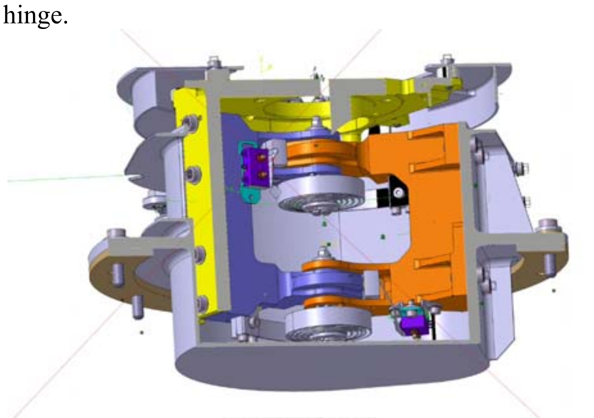

*Figure 8. SARM clockwise*

As one wing has to rotate 45° clockwise and the other 45° counter clockwise, two mirror image SARM units have been required (Fig. 8 and Fig. 9).

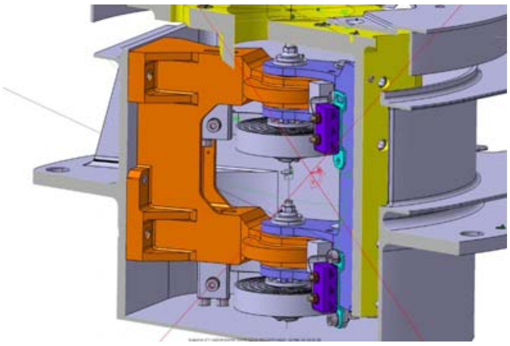

*Figure 9. SARM counter clockwise*

As discussed earlier, the reduction of the retarding torque of the cable harness is needed to minimize the deployment shock. The low retarding torque of the harness is achieved by placing it around a cylinder. The cable harness is now flat and has a significant length which results in minimal normal bending of the cable. This is quite different from the SA root hinge, in which the cable harness is a round bundle and subject to torsion bending.

The cylindrical housing of the SARM has, besides fixation and guidance of the cable harness, also another function: main load path and interface to the hinge mechanism and the spacecraft. Fig. 10 shows that the cable harness of the qualification model (QM) in the 45˚ position protrudes outside the flanges. The shape of the QM harness is somewhat different compared to the engineering model harness shape, on which the flanges of the QM housing were designed. This meant that after the qualification program the flanges of the flight models had to be extended (Fig. 11).

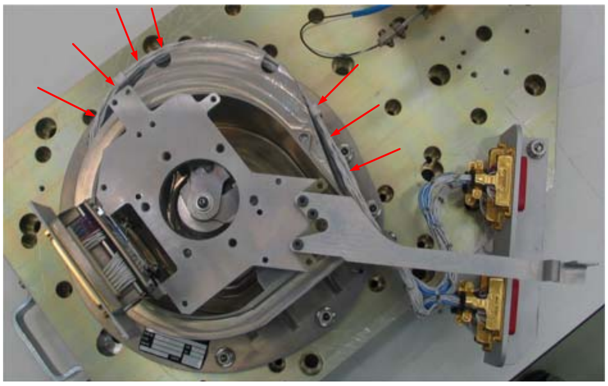

*Figure 10. Cable harness of the QM*

Special tooling has been designed for unlatching of the FRED solar array hinges. This standard tooling could not be used to unlatch the SARM. The QM has been used to develop the un-latching tools. Especially the un-latching tool for the lower latches of both SARM's needed quite some redesign from the standard un-latching tools of the FRED hinge. In the standard application of the FRED panel hinge, the latches are easy to access, whereas in the SARM they are quite difficult to access.

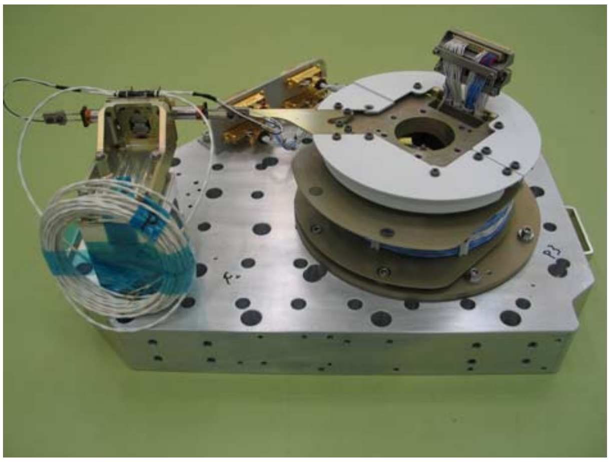

*Figure 11. FM SARM clockwise*

The preliminary engineering model design did not include micro switches. Late introduction required adaptation of various brackets and the levers of the switches itself had to be designed. The lever of the micro switch connects to the latch of the hinge. When the hinge locks, the latch is displaced relatively to the micro switch, the circuit opens and the locking of the hinge is confirmed. Both latches are monitored by individual micro switches, introducing the required redundancy. Three different levers for each micro switch type (2 types), have been produced and functionally tested before the best lever design has been selected (Fig. 12).

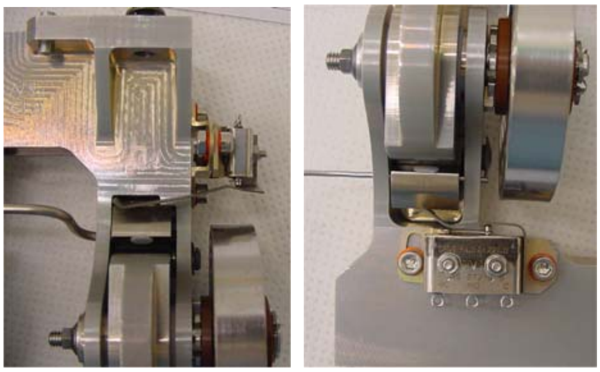

*Figure 12. Micro switches and levers*

## 5. TESTING

The following qualification tests have been performed on the SARM assembly:

- Mass measurements
- Fitcheck
- Continuity and insulation test
- Alignment

- Stiffness
- Functional performance test
- Retarding/actuation torque test
- Proofload
- MHRM release and deployment latch up test
- Life test
- Vibration test
- Shock test

Some of the qualification tests and flight model test results are discussed here.

**Mass measurement**
The QM mass (3.4 kg) meets the requirement of 3.5 kg; however some minor design changes to the housing introduced some additional mass, resulting in a mass of 3.5 kg for the flight models.

**Fit check & Continuity and insulation tests**
No major issues showed up. Pass/fail criteria on the cable harness, micro switches and the thermal knives of the MHRM are all met.

**Alignment tests**
The alignment verification in stowed and deployed condition has been included because:

- In the stowed condition of the SA wing, misalignment of the SARM might cause unintended IF loads on the S/C or wing.
- Any misalignment of the SARM may result in a deployed wing which does not meet the specified alignment requirements.

Two inclinometers are used; one inclinometer is used as a reference (Fig. 13). All alignment measurements are well within the required alignment angles.

**Stiffness tests**
The 2717 Nm/rad around the X-axis prediction with the conservative finite element model turned out to be a good prediction. The measurement in deployed position (Fig. 13) showed for the –X FM and + X FM respectively: 3240 Nm/rad and 3200 Nm/rad.

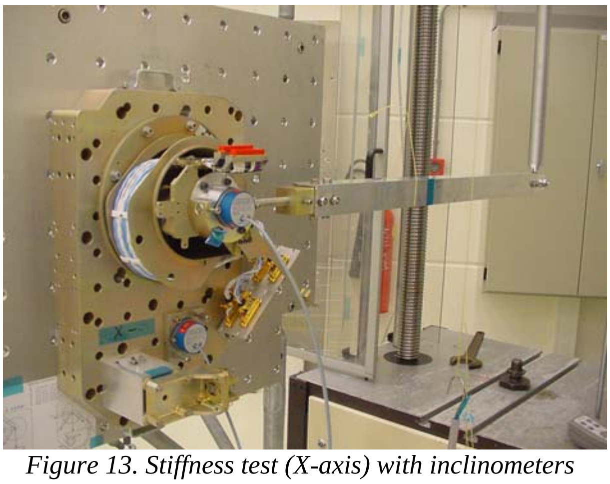

*Figure 13. Stiffness test (X-axis) with inclinometers*

The achieved stiffness, considering the fact that the baseline FRED hinge had a stiffness of 3626 Nm/rad, this means that the housing and the root hinge IF bracket stiffness are well over 50000 Nm/rad. All other stiffness requirements are also met and the hysteresis values are within the acceptance limits.

**Retarding / actuation torque tests**
The deployment / stowage movement is executed by means of the Aerotech Inc. stepper motor. The QM retarding torque results are given in Tab. 1.

| Temperature [°C] | Retarding torque [Nmm] | Condition |
|---|---|---|
| + 23 | 158 | ambient |
| + 55 | 146 | vacuum |
| - 23.5 | 309 | vacuum |
| - 45 | 361 | vacuum |

*Table 1. QM retarding torques*

The actuation torque of the QM model in deployed situation is 920 Nmm. This means that the motorization torque is 2.977 for the QM. In order to achieve a motorization ratio > 3 for the flight models, the actuation torque requirement is set to be > 930 Nmm and < 1100 Nmm. Both flight models fulfil the actuation torque requirement and the retarding torque tests on the flight models showed that both models met the retarding torques requirement at ambient conditions.

**MHRM release and deployment latch-up tests**
During the MHRM release tests a moment of inertia (MOI) simulator is attached, including a potmeter to monitor the deployment angle (Fig. 14). The simulator represents the moment of inertia around the X-axis of the deployed wing and also the torsional stiffness of this wing. The weight of the MOI simulator and the moving parts of the SARM have a "zero-g compensation".

Positive release of the MHRM and positive latching of the hinge at the end of deployment are achieved. Deployment shocks of MHRM release (Tab. 2) are in line with the calculated (hot case) deployment shock of 30.5 Nm. This figure is based on eq. 1.

$$M = \sqrt{(2 \cdot E \cdot K)} \quad (1)$$

With:
M = Moment on SARM
E = Kinetic energy of the wing
K = Rotation stiffness of the wing and SARM

| Test model | QM | +X FM | -X FM |
|---|---|---|---|
| Deployment time [sec] | 1.78 | 2.05 | 1.92 |
| Max. Moment [Nm] | 30.52 | 29.30 | 30.91 |
| Frequency [Hz] | 2.44 | 2.38 | 2.38 |
| Deployment switch | NA | Ok. | Ok. |

*Table 2. MHRM release and deployment shock results*

*Figure 14. MHRM release and deployment latch-up*

The stiffness of the MOI is higher than the rotational stiffness of the wing (2.4 Hz for the MOI simulator including SARM versus 2.168 Hz of the deployed wing without SARM), which explains why the shocks given in Tab. 2 (ambient temperature) are similar to the calculated (hot case) deployment shock.

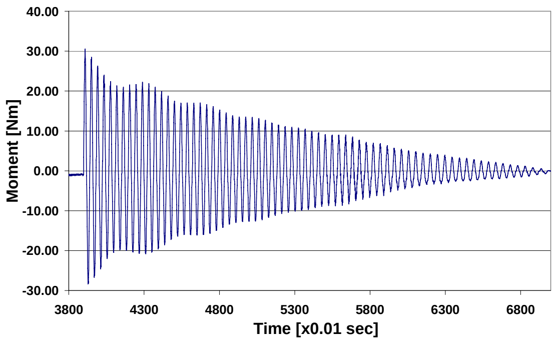


*Figure 15. QM SARM deployment shocks*

**Life test**

The life test has been performed by repeating the following sequence 150 times using the MHRM release and deployment latch-up test set-up (Fig. 14):

- Install unlatching pins
- Stow hinge
- Remove unlatching pins
- Hand release, allowing free rotation and latching

After the life test the inspection showed no degradation and the requirements of the consecutive measurements, functional performance and alignment are met and therefore the life test is successful.

**Vibration tests**

The sine and random vibration tests have been performed on 80 kN shaker at IABG Ottobrunn. A dummy weight of 3 kg with 9 accelerometers is added at the root hinge interface to represent the mass of the root hinge and part of the extension arm of the SA (Fig. 16). Both the sine vibration and random vibration tests have been performed in 3 directions and quasi static inputs up to 20 g are applied.

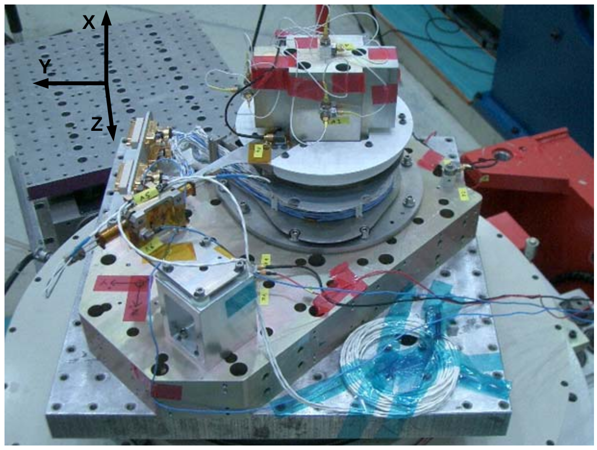


*Figure 16. QM SARM with dummy mass*

During the sine vibration tests it became clear that the SARM did not behave linear. The Y-runs show that the frequency of the mode of the dummy mass on the SARM below 100 Hz shifts due to variations in the input levels: 0.2 g input gives 36.6 Hz; 1.0 g input gives 64.3 Hz. This non linearity is also observed during the Z-runs. The non linearity is caused by the play in the SARM; this is indicated by the abrupt drop of the response in Fig. 17. At the lower frequencies the amplitude of the shaker is large enough to excite he dummy mass during a low level run, but at the higher frequencies the amplitude becomes smaller than the play in the SARM and the dummy mass can not be excited anymore. When the input levels increase also the amplitude of the shaker increases and the dummy mass can be excited at higher frequencies.

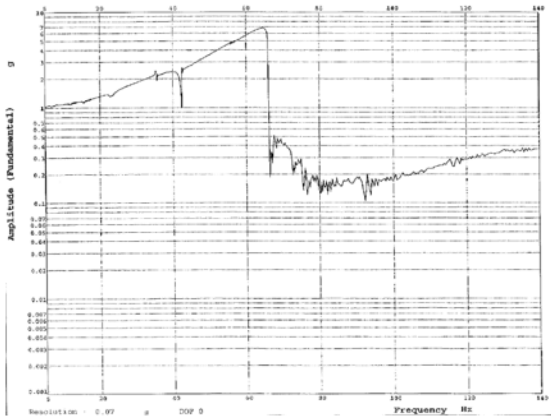

*Figure 17. QM sine vibration run*

To protect the SARM from excessive loads during the sine vibration and random vibration is the maximum allowable acceleration of the dummy mass COG is limited to 25 g in the X, Y and Z-Axis. This meant that for both the sine vibration and the random vibration notching of the input is to be applied and a request for deviation was issued and accepted.

All test levels as agreed during the test review meetings are met. MHRM release, alignment, stiffness and torque measurements performed after the shock test indicate no degradation of the SARM.

**Shock tests**

Prior to the shock test on the SARM QM, shock test are performed on a thick vibration adaptor plate (shock test dummy) to access how accurate these levels could be met (Fig. 18). The qualification shock on the SARM is one single shock perpendicular introduced (along X-axis) on the shock table. The required shock response spectrum (SRS) is given in Tab. 3.

| Frequency [Hz] | Qualification SRS [g] |
|---|---|
| 25 | 25 |
| 1500 | 2000 |
| 10000 | 2000 |

*Table 3. SRS levels*

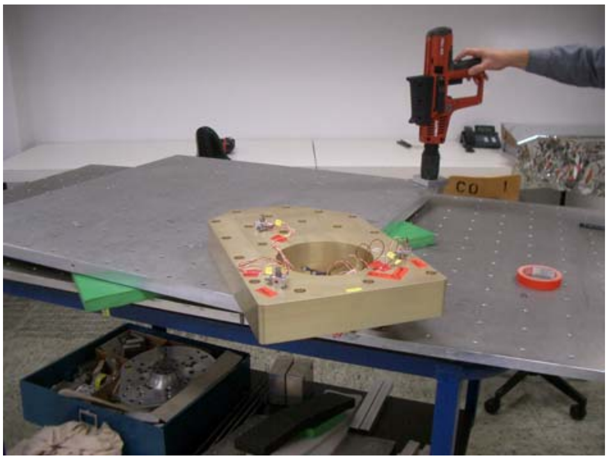

*Figure 18. Shock test preparation with dummy*

The dummy test results showed that the required SRS levels can be met between 200 Hz and 2000Hz and will have a significant overshoot above 2000 Hz. The results below 200 Hz are discarded because in general in the lower frequencies (for pyro shocks even up to 400 Hz) the SRS plots are not considered a reliable representation. The overshoot above 2000 Hz is not considered a problem, based on shock tests performed on a holddown and release mechanism which also includes thermal knives [2]. A significant overshoot between 200 Hz and 1000 Hz might cause a problem and should be avoided. Therefore, a relaxation of the requirements is agreed with the customer.

The shock response spectrum levels at the SARM location during the S/C shock test, factored by 2, should be covered by the SARM shock test. This is achieved for all 3 axes (see Fig. 19 for the X-axis SRS results).

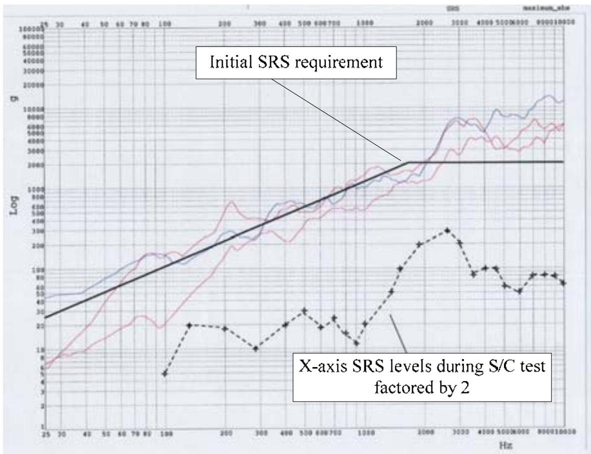


*Figure 19. X-axis shock test results*

The shock tests are considered successful because the MHRM release, alignment, stiffness and torque measurements performed after the shock test indicate no degradation of the SARM.

## 6. CONCLUSIONS

The SARM has been developed and successfully qualified. However, the objective of keeping it simple and cost effective has not been met. Various requirements and available volume proved to be incompatible with this objective. Both flight models have been built and both have passed successfully their acceptance tests.

## 7. ACKNOWLEDGEMENTS

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