EXOMARS MSA. “TEST HDRM” DEVELOPMENT FOR SEPARATION PERFORMANCE VERIFICATION

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ABSTRACT

Among the technological goals of the Exomars Mission, of high importance was the development of the technology needed for landing payload on Martian surface. Indeed the mission launched in 2016 foresees the release of a Entry Descent and Landing Demonstrator Module (EDM) from the Trace Gas Orbiter about 1.5 million km away from planet surface with the target to land within an area of 50 km diameter. The spin-eject separation mechanism shall be therefore capable to deliver very precise deployment performance being the EDM not able to adjust its flying trajectory.

To verify the capacity of the MSA to fulfil such a challenging target, dedicated development tests campaign has been defined, at component, single mechanism and mechanisms assembly levels, which includes a large number of mechanism separations within a reduced timeframe. Moreover it has been deemed necessary to verify the effect on the separation performance of the high preload used to mate the three separation interface and, finally, for full scale separation test it was required to precisely set the separation time and the time scatter among the three nodes of the MSA.

It was therefore not possible to use the HDRM implemented in the MSA design but a special “Test HDRM” had to be developed and characterised with the goal of guaranteeing the possibility of a correct preload application and having a tuneable and repeatable release time. At the same time the “Test HDRM” had to be extremely reliable and to allow for short reset time. The purpose of this paper is to present the activities performed for the development of the “Test HDRM” including the verification and characterisation testing. Moreover an overview of the tests and test setups in which these HDRM are used is reported as well.

1. INTRODUCTION

1.1. Mission description

The Exomars programme is based on two missions both led by ESA, which launches are foreseen in 2016 and 2018 respectively.

For the former mission ESA will supply a spacecraft composite made by a Mars Orbiter (TGO) carrying an Entry, descent and landing Demonstrator Module (EDM), which mass is about 600 kg, whereas the latter foresees a rover which will drill into the Martian surface trying to detect traces of organic molecules.

The objectives of the 2016 mission are summarised in the following:
- entry, descent and landing of a payload on the Mars surface,
- investigation of the Martian atmospheric gases and their sources,
- supply of communications capability for present and future missions (2018-20).

1.2. MSA main Requirements

RUAG space has been entitled with the responsibility to develop the Main Separation Assembly (MSA) which is the subsystem connecting the EDM with the TGO. The MSA shall assure the mechanical and functional connection between the EDM and the TGO, include provisions for hoisting and handling of the Spacecraft Composite and enable the separation of the two modules when commanded providing the EDM an axial velocity and rotational speed within a defined window. This guarantees a safe release and a precise landing on a specific area on Mars.

Beside the structural requirements, i.e. the ability to safely connect the two modules, a set of requirements has been defined concerning the separation function. Structural requirements are expressed in terms of first lateral and axial eigenfrequencies of the EDM mounted on the TGO and capacity of withstand without plastic deformation or rupture the loads generated by the EDM subjected to specified quasi static accelerations, whereas for separation function MSA shall guarantee:
- An EDM axial velocity relative to TGO greater than 0.3 m/s,
- A tolerance on the axial velocity of the EDM (including degraded separation conditions) smaller than ± 15 mm/s,
- A lateral absolute velocity of the EDM smaller than 11 mm/s,
- A spin velocity of the EDM between 2.5 rpm and 3.0 rpm,
- A rotational velocity ratio of the EDM smaller than 3.6°, where rotational velocity ratio is defined as:

\[
\tan^{-1}\left(\frac{\omega_{\text{lat}}}{\omega_{\text{spin}}}ight)
\]

(1)

Such an accuracy about the deployment performance is required since the EDM release from the TGO will occur three days before reaching the Mars atmosphere whereas the targeted landing area is of 50 km diameter and no trajectory adjustment is possible after separation. Moreover MSA mass shall be limited to 41 kg and functionality guaranteed in the range -65°C – +40°C.
2. MSA DEVELOPMENT AND VERIFICATION

2.1. MSA Design description

During the design and development of the Exomars Main Separation Assembly (MSA) the experience relevant to the realization of the Spinup and Ejection Device (SED) for ESA Huygens Project has been taken into account.

The Exomars Main Separation Assembly (MSA) is built by the following components:

- a TGO-EDM adapter, made of machined aluminium alloy brackets connected with CFRP struts, which provides the interface with the TGO Central Tube upper I/F.
- three Main Separation Mechanisms (MSM) keeping TGO and EDM connected during launch and cruise phases and able to deliver the required separation performances when commanded.

Each MSM is constituted by two main structural parts, the OIF (Orbiter Module Interface Fitting) and the DIF (Descent Module Interface Fitting) which are bolted to the TGO-EDM adapter and to the EDM respectively.

OIF and DIF are connected together via three precision conical studs (forming the Separation Surface) which transfer the axial and transverse loads as well as the bending and torsional moments. The mating surfaces have special surface treatments in order to reduce stiction, friction coefficient and the risk of fretting during launch and are preloaded by means of a Hold Down and Release Device (HDRD). The HDRD is based on a non-explosive actuator, including a Separation Nut, able to provide the required release capability once separation signal is given, which engages the Release Element connected to the separation stud securing the OIF and the DIF during the launch and the cruise phases. A load cell is installed between the DIF and the separation stud in order to precisely assess the preload during integration and to check it before launch.

In order to facilitate the separation stud release from the separation nut and to avoid mechanical interferences along the DIF separation path, a retracting spring helps in extracting the separation stud from its engaged position and secures it after the release.

For what concern the separation function, the Rail Unit connected to the OIF, and the Roller Unit, connected to the DIF, provide guidance during the early phases of the separation until the final release speed is achieved. The separation force is given by one Separation Spring acting between the OIF and the DIF.

OIF and DIF are equipped with brackets hoisting the electrical connectors which are separated during the EDM release. These brackets can be dismounted from MSM to allow for connectors/harness check without disassembling the entire MSA from EDM and feature shutters that protect the connector elements after separation.

2.2. Verification flow

MSA qualification has been reached through a full Proto flight model (PFM) approach by applying test levels and durations defined for qualification models.

Whereas the structural performance has been verified by means of dedicated test on PFM for the separation performance, a flight like functional model (FuMo) of the three MSM has been used in junction with final separation test on PFM. Moreover separation tests have
been performed at single MSM level of PFM as well. This approach is justified by the fact that the MSA components responsible for the structural behaviour are different from those which drive the separation performance, i.e. the parts constituting the guiding system.

The test philosophy relevant to separation performance verification was developed to reduce as much as possible the test duration by exploiting the “waiting time” for NEA refurbishment to perform the full scale separation test which was executed using flight like Fu.Mo. MSM equipped with dummy HDRM. Indeed the Fu.Mo. MSM, procured together with the PFM, have been used for the full scale separation test campaign to prove that the required separation performance are delivered not only in ideal conditions but also taking into account degradation of some parameters. Moreover test results have been used to validate the FE analysis model by which the EDM separation performances in flight are computed. By considering several different configurations obtained with variation of the input parameters and consequently the corresponding calculated EDM dynamic, an “end to end” analysis can be finalised.

Test Campaign on PFM MSM, instead, was focused on verification of the MSM separation performance before and after application of the environmental loads. In Figure 4 the complete MSA test flow is presented.

3. "TEST HDRM" DEVELOPMENT

From the needs described in the previous section the following requirements for "Test HDRM" has been defined:
- Withstand a preload of at least 60 kN,
- Guarantee a release time smaller than 40 ms and a release time repeatability of 1.5 ms (standard deviation) when the preload is set to 60 kN,
- Be ready for release after an activation is performed within 1 hour and without dismounting it from MSM OIF,
- Be mountable on MSM OIF by using the interfaces
- Use the mounting interface defined for the flight separation nut,
- Allow mounting of the flight separation stud by using a release element with similar shape as flight separation nut to check that no risk of separation stud jamming occurs,
- Have a mass smaller than 12 kg,

To fulfill the requirements a “Test HDRM“ has been developed which consists of an electro-mechanical device based on a release element hold in place by three segments. The release element is screwed to the separation stud and the each of the three segments is constrained within a piston via two cylindrical rollers. By axially moving the piston the rollers are driven within grooves machined in the segments allowing their radial movement and therefore disengaging the release element.

Piston movement is obtained by means of a spring actuated lever system held in place before release by an electromagnet.

The electromagnet is fitted on a preloaded spring as well to guarantee a quick and repeatable release of the lever.
Once the electromagnet is unpowered the lever moves laterally because of the spring force and therefore the piston within release unit can translate and disengage the segments which constrain the release element.

To reset the “Test HDRM” the separation element shall be brought back into the separation unit. At the same time the leverage shall be put in contact with the powered magnet, so that the segments within the release unit can hold the release element in a stable position. Moreover the preload of the springs acting on lever and electromagnet can be adjusted for performance optimization during the “Test HDRM” development phase.

The magnet is powered via an electronic ground support equipment (EGSE) which can control up to three HDRMs and trigger them with delays which can be individually programmed.

For this purpose the EGSE contains three digital timers which provide a programmable turn-off/on delay each. After the trigger button has been pressed the digital timer produces a signal with a time delay equal to the specified value. The output signal of each timer is used to control a power stage that switches the current through the HDRMs.

The digital timers and the internal circuitry are supplied by mains power whereas the actuator power is provided by an external PSU to allow testing different types of actuators at different voltages. The same EGSE has been therefore used for either the test with “Test HDRM” and the test with flight like separation nut.

For safety reasons the actuator circuit is fully isolated from the main power circuit. The “Test HDRM” has been developed through a prototype mechanism which has been modified during the development to improve the mechanism handling characteristics. The prototype HDRM and the final design are presented in the pictures below in which one of the two structural frames has been removed to show the internal parts.

No main modification has been required during the development neither on the release unit nor on the electromagnet unit. The only improvement involved the magnet force, and consequently its dimensions, and the spring driving the lever unit which has been reduced in dimensions and weight.

Indeed during the “Test HDRM” development phase it has been recognised that the force to be provided by the spring acting on level unit required for HDRM activation was much smaller than expected. This impacted the counter force provided by the electromagnet as well. Moreover a damper on the electromagnet have been added to reduce the shock due to “Test HDRM” activation.

The mechanism in the final design have been used either for test at single MSM level and for full scale MSA separation test as shown in the following.
4. "TEST HDRM" PERFORMANCE VERIFICATION

Before using the "Test HDRM" for the performance verification at single MSM and complete MSA levels some preliminary test have been performed aimed at verification of the capability of the “Test HDRM" to either withstand the target preload and guarantee the required release time and release time repeatability. The test have been executed on the prototype "Test HDRM" and then repeated on the three mechanisms used to reproduce the separation nut function during the full scale separation test.

The set-up used for the characterisation test is depicted in the following picture.

![Figure 10: "Test HDRM" characterisation test set-up](image)

The “Test HDRM", which is shown in the picture in the hybrid configuration used to check the final design but with the prototype frame, has been fitted with a dummy separation interface which hosts the full bolt catcher assembly.

Several sensors have been installed on the set-up to guarantee complete monitoring of the “Test HDRM" behaviour.

In particular the following components have been instrumented:
- Bolt catcher (accelerometer)
- Electromagnet spring (accelerometer)
- Separation IF – OIF side (accelerometer)
- Separation stud (load washer for preload measure)
- “Test HDRM” EGSE (voltmeter on electromagnet power line).

Each signal has been acquired at 20kHz.

Of great interest have been the measurements of separation stud force in comparison with the activation signal, i.e. the interruption of the electromagnet power supply.

Beside “Test HDRM“ overall design concept check, during the development test campaign, the sensitivity of release time to the force generated by the springs acting on lever and electromagnet units have been investigated with the aim of reducing as much as possible the time scatter between activation signal and separation stud preload release in case of repeated activations.

For each test configuration, i.e. short or long lever spring assembly, big or small electromagnet and lever/electromagnet springs force, at least 5 repeats have been performed for a total of more than 60 tests.

Typical curves for separation stud preload and magnet and bolt catcher accelerations in comparison with activation signal are reported in the figure below.

The voltage curve shows that EGSE is able to activate the mechanism, i.e. reducing the electromagnet supply voltage to zero in a very short time, i.e. less than 0.1 ms (point A in Figure 12).

Once the supply voltage is switched off the magnet force decreases as well and the electromagnet spring pull it away from the counterpart.

The magnetic force reduction is such that the magnet movement occurs after about 1 ms (point B).

![Figure 12: Magnet acceleration](image)

The shock which occurs 6 ms after the activation signal is given (point C) is the hit of bar on which the magnet is mounted against the supporting frame.

Once the electromagnet releases the lever unit the piston within the separation unit moves and the segments are disengaged.

The radial movement of the segments releases the preload of the separation stud.
From the separation stud preload curve it can be seen that the phenomenon described above starts about 21 ms after the “Test HDRM” is activated (point \( A \)). The total time needed for preload release is about 3 ms (point \( C \)).

Bolt catcher accelerometer provides similar information as the other sensors. Additionally it can be seen that the hit of the separation stud against the bolt catcher housing occurs about 6 ms after preload full release (point \( E \)).

Even though the bolt catcher functionality was not a parameter to be verified by “Test HDRM” development test campaign, being bolt catcher design practically identical to MSA flight component, such development test allowed to check that no jamming occurred at bolt catcher level.

In the frame of the test campaign the mechanism has been tested up to a separation stud preload of 73 kN. Moreover it shall be highlighted that the resettable time between two following test (i.e. including tightening of the separation stud and bolt catcher remounting) has been kept below 30 min.

After validation of the “Test HDRM” final design, the three mechanism for MSA functional tests have been procured. The three mechanism have been tested to verify that expected performance are delivered in terms of repeatability of single “Test HDRM” and among the three units. Each mechanism, instrumented as per test executed during the development phase, has been tested at least 5 times. From supply voltage, loads washer and accelerometers signal the characteristically times described in points \( A \) to \( E \) have been extracted and average values and standard deviations computed. A summary of the statistics for each mechanism is reported in the table below in which the times corresponding to points \( A \) and \( C \) only are reported.

Times are measured starting from electromagnet supply voltage interruption (point \( A \)).

<table>
<thead>
<tr>
<th>HDRM</th>
<th>Preload (kN)</th>
<th>Magnet activation (ms)</th>
<th>Preload release (ms)</th>
<th>Number of releases</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSM 1</td>
<td>62.2</td>
<td>1.7</td>
<td>24.2</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>4.9</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>MSM 2</td>
<td>62.0</td>
<td>0.6</td>
<td>26.6</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>6.1</td>
<td>0.1</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>MSM 3</td>
<td>60.6</td>
<td>0.7</td>
<td>27.6</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>6.5</td>
<td>0.2</td>
<td>0.9</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Test HDRM performance summary

From table results it can be seen that from point of view of repeatability the “Test HDRM” are all very close and match the requirement asking for a standard deviation smaller of the preload release time smaller than 1.5 ms. The small difference in average preload release time is not an issue since it can be compensated by the HDRM EGSE by specifying a different activation time for each mechanism.

At the end of the validation and characterisation phases the “Test HDRM” have been released for the use in the MSA functional test campaign.

5. MSA SEPARATION PERFORMANCE VERIFICATION

Two types of test have been performed during MSA separation performance test campaign. At single MSM level, for each of the three mechanisms the energy released, including contribution of separation spring, separable connector and flight HDRM, has been verified whereas at MSA level a full scale separation test has been performed. Details about test campaign set-up and findings can be found in [1].

5.1. MSM energy measurement

The test setup consists of a jig in which the DIF is mounted on an I/F plate moving along theoretical helix to prevent any contact between MSM rollers and rail. The separation speed can be tuned by connecting the DIF mounting I/F plate with a wagon on which a dummy mass is installed. Alternatively a static test can be performed as well.

By measuring the force acting between OIF and DIF
(via three tri-axial load cells on which the plate supporting the OIF is mounted) and the DIF stroke (via a laser transducer) it is possible to compute the energy released during the separation.

During MSA development a large number of tests has been performed by using the “Test HDRM” whereas for qualification test a flight like separation nut has been installed to verify the correct spring energy to be set to have the required amount of energy released to the EDM.

Moreover “Test HDRM” has been used for test set-up repeatability verification.

The flight models of MSM have been subjected to static and dynamic test to verify that functional performance were not influenced by environmental test campaign.

No significant variations have been found with the only exception of a small energy loss which was anyway due to contact between the separation stud and the components within the bolt catcher linked to the tolerance chain of these parts. As a consequence the MSM design was modified to guarantee a frictionless stud movement.

An important outcome of the test was that the energy released in flight configuration, i.e. with flight like HDRM and separable connector, was 0.7 J per MSM smaller than the elastic energy stored in the separation spring because of HDRM and separable connector dynamic losses.

From “Test HDRM” point of view it has been interesting to see that, compared to flight HDRM the measured energy was about 0.9 J per MSM higher since in case of “Test HDRM” the preload is released by an additional spring assembly to which additional elastic energy is associated.

5.2. MSA full scale separation test

For the MSA full scale separation test a fully representative, in terms of mass and inertia, dummy EDM has been used, which performance have been measured via two couples of high speed camera able to read the tri-dimensional position of 20 targets designed on target panels fitted on it. Based on marker position over time the EDM dummy centre of gravity trajectory and its translational and rotational velocities have been computed. The no gravity conditions have been simulated via a pneumatic offloading device mounted on top of a 7 m high steel truss structure, able to guarantee an almost constant offloading force over 0.4 meters measurement stroke.

Several different configurations have been tested and the corresponding test reproduced by analysis to correlate the calculation parameters used in separation performance prediction software.

With the correlated virtual model it has been therefore proved that MSA is able to fulfil the separation requirements in flight conditions and considering the possible disturbances, e.g. activation delay on the three mechanisms or spread of mass and inertia of TGO due to uncertainties in fuel consumption prediction.

On the basis of analysis results and of the final mass and inertia measurements at satellite level the spring energy of the three MSM will be defined.

6. CONCLUSIONS

In order to meet the demanding separation requirements of the Main Separation Mechanism developed for the Exomars mission an high numbers of mechanism activations at MSM and MSA levels have been deemed necessary. To optimize the test campaign not only from performance point of view but also in terms of schedule and cost a “Test HDRM” has been developed and validated. The “Test HDRM” has been successfully used in the whole MSA test campaign being a key factor in the fulfilment of the project targets.

7. Acknowledgments

RUAG wants to thank the all the supplier of Test HDRM and the GSE used during the test campaign for their support.

8. References