A New Force Measurement Device for Spacecraft Testing

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A new Force Measurement Device (FMD) has been used during the sine-vibration testing of ESA's Rosetta spacecraft, to measure directly the forces and moments at the spacecraft/launch-vehicle interface. It proved extremely useful in ensuring that the test levels required by the launcher authorities were strictly applied, and that the tests were executed safely. The FMD's output was also valuable for the validation of the finite-element model. The use of this new device, which is simple to set up and requires just six instrumentation channels, is therefore highly recommended in conducting future spacecraft qualification and acceptance vibration tests.

Introduction

The Structural and Thermal Model (STM) of the Rosetta scientific spacecraft was successfully tested at ESTEC in Noordwijk (NL) between December 1999 and May 2000. During the sine vibration tests, a technique known as 'primary notching' was applied, which involves reducing the input level so that the dynamic interface forces do not exceed the static interface forces corresponding to the quasi-static design loads defined by the launcher authorities. This, by definition, is a very delicate operation: on the one hand, any structural failure must be avoided, but on the other adequate qualification must be achieved in order to be acceptable to the launcher authorities.

Generally, the level of notching is determined by a combination of test results and analysis predictions. This method has two major drawbacks, because it relies on a finite-element model (FEM):

– The accuracy of the interface forces depends on the quality of the model and on the measurement-point plan: a poorly representative FEM, inadequate instrumentation or an error in the methodology can result in a wrong estimate of the interface forces and thus in a wrong notched input, which could lead to structural damage or to a too low, and thus inadequate, qualification input.
– The final acceptation of the qualification has to be confirmed once the FEM is correlated, which means well after the qualification test campaign.

In Rosetta's case, a new Force Measurement Device (FMD) was used, which measures the forces and moments directly at the test-specimen interface. This allows the primary notching to be performed with very good safety, and also allows one to be sure that adequate loads have been applied during the qualification campaign.

The Force Measurement Device (FMD)

The FMD has been developed for ESA by Ingemansson Technology AB (Sweden) under an ESTEC contract. It consists of two rings connected by eight piezoelectric Kistler Z14976 force links, as shown in Figure 1. Each force link measures the dynamic forces in the three directions (Fig. 2), and the two rings correspond to a 1194mm-diameter spacecraft interface.

The measured values are weighed, combined, and reduced to three forces and three moments in an electronic circuit contained in the Signal Processing Unit (SPU). These six output channels are available for either data acquisition or for vibration level control.

Apart from the functioning of the system itself, the stiffness of the device is of particular concern since the impact of its presence on the test specimen needs to be as small as possible. The FMD's stiffness was first assessed by finite-element analysis, and then tests were performed on a single transducer. Finally, the complete device was tested at ESTEC with the structural and thermal model of the Olympus spacecraft (mass 1200 kg and centre of gravity at ~1.7 m) in early 1996 (Fig. 3).

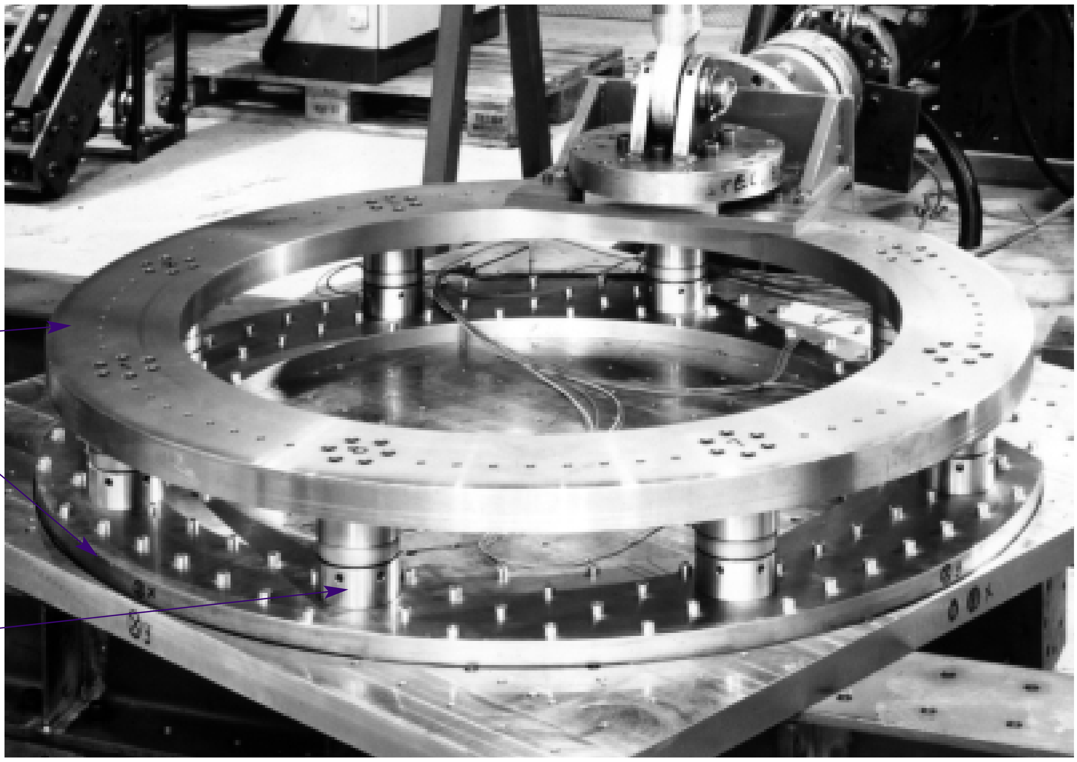

Figure 1. The new Force Measurement Device (FMD)

The main characteristics of the FMD:

Frequency measurement range:	up to 100 Hz at high level and ~300 Hz at low level
Force measurement range:	up to 800 kN axially and up to 200 kN laterally
Moment measurement range:	up to 260 kNm in bending and up to 130 kNm in torsion
Typical measurement error:	1 to 4%
Axial stiffness:	9.55×10^9 N/m
Bending stiffness	2.73×10^9 Nm/rad
Overall mass:	494 kg.

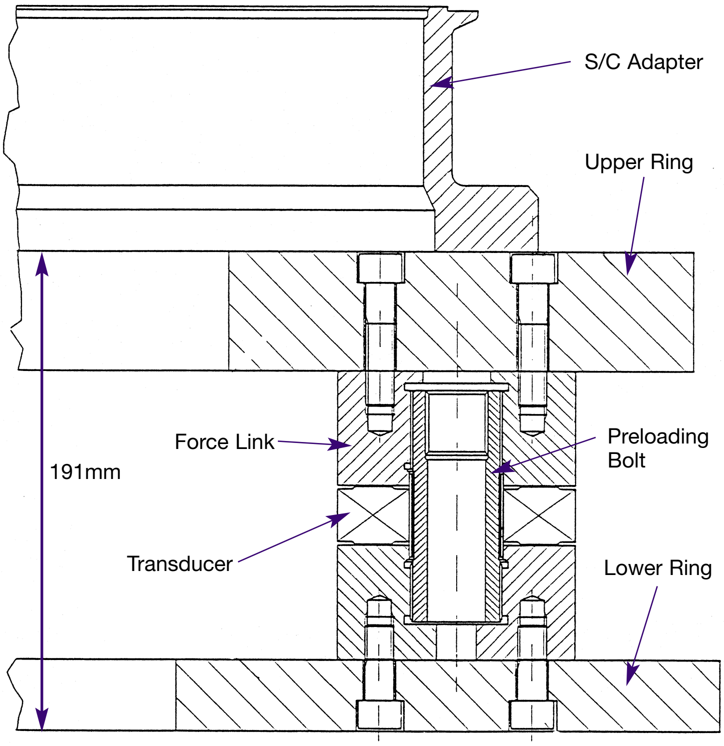

Figure 2. Cutaway of the force link

The Olympus spacecraft was submitted to low-level sweeps up to 2000 Hz and to high sine-vibration levels up to 100 Hz, with and without the FMD. Comparison of the low-level runs showed that the axial fundamental frequency shifted from 46.2 to 45.9 Hz (-0.5%), and the lateral one from 14.7 to 14.6 Hz (-0.6%). For other modes, the frequency shift was less than 3%.

The FMD has subsequently been made available as a regular testing tool at the ESTEC Test Centre.

FMD's application in the Rosetta STM test campaign

Before starting the qualification of the Rosetta STM, the multi-shaker table was submitted to an acceptance test, which also provided the opportunity to verify the good functioning of the FMD. The test set-up consisted of the slip-table, FMD, load spreader, and a 2085 kg dummy specimen. The aim with the load spreader was to increase the load capability of the slip-table. The interface forces and moments were measured with the FMD, as well as computed.

The FMD measurements and the calculations matched very well. For the first resonance, the measured and calculated bending moments agreed to within 1%, and the measured lateral force at low frequency corresponded to the rigid body mass above the FMD times the acceleration input also to within 1%. The cross-talk appeared to be very small, being typically less than 4%. Finally, a maximum overturning moment of 203 kN.m was applied to the table. The FMD was submitted to a maximum bending moment of 183 kN.m and a maximum lateral force of 47 kN.

Before performing the Rosetta test campaign, the effects of the FMD's flexibility were analysed. As the frequency shift proved acceptable, it was decided to use this device. For the lateral excitation, the configuration was very similar to that used with the dummy spacecraft, with load spreader, FMD and the Rosetta adaptor. In the axial direction, the load spreader was no longer needed and was therefore removed, as shown in Figure 4.

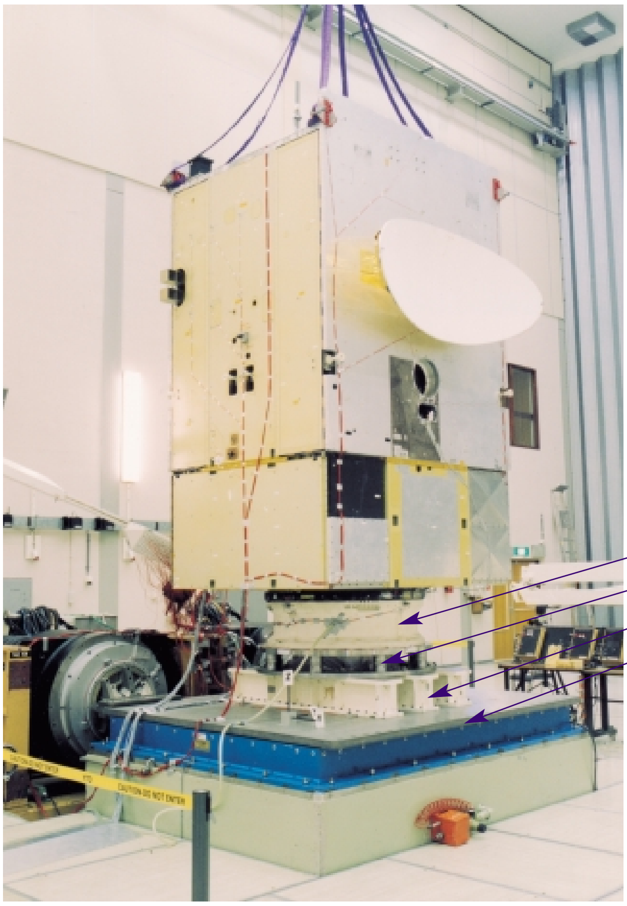

Figure 3. The Olympus STM mounted on the Force Measurement Device (FMD)

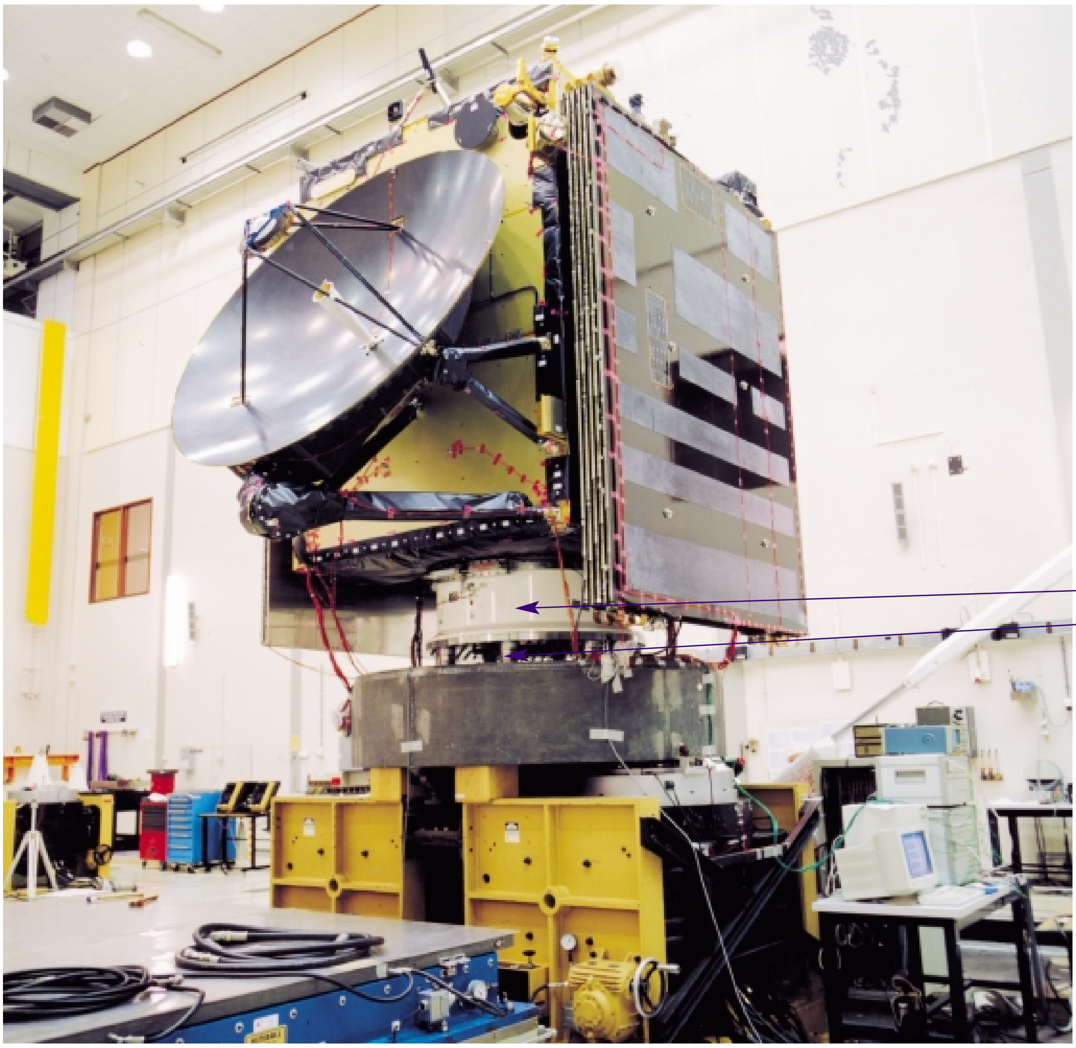

Figure 4. Rosetta STM mounted on the Force Measurement Device (FMD) for axial sine vibration testing

The mass and dynamic properties of the Rosetta STM were as follows:

Mass:	3058 kg
CoG:	1.18 m
1st bending modes:	16.3 Hz in X and 16.5 Hz in Y
2nd bending modes:	32.5 Hz in X and 31.8 Hz in Y
1st axial modes:	37.1 Hz and 40.4 Hz in Z.

The FMD was used during the sine vibration tests to measure the interface forces and moments. An automatic notching procedure was established, comparing the FMD outputs directly to the thresholds. The shaker control system accepted this unusual input without problems. The target levels were met with a limited error of typically 6%. The FMD-achieved auto-notched levels were in good agreement with those estimated by more traditional methods, i.e. use of strain gauges and accelerometer measurements in combination with model predictions. The final notched input was always based on the FMD data, since it was considered more accurate and more reliable. The FMD was also used for secondary notching of response levels on the lower tank.

Low-level sine sweeps were performed up to 200 Hz. The FMD did not show any disturbing resonances in this frequency band. The maximum bending moment applied at FMD level was 125 kN.m, the maximum axial force 106 kN, and the maximum lateral force 65 kN, which is at least a factor 2 below the FMD's limit. The outputs of the FMD were of particular interest because the shaker had difficulty in applying a smooth input at the main resonances. The spiky readout would have made determination of the resulting interface forces very difficult without the actual FMD measurements.

The FMD also provided very valuable data for the finite-element-model correlation, in two respects:
– to tune the major modes dictated by the primary structure, without being disturbed by the local modes that often affect the calculation of modal masses and of model correlation criteria
– to determine that the FEM used for the Launcher Coupled Dynamic Analysis (LCDA) is representative at the spacecraft/launcher vehicle interface, thereby increasing confidence in the LCDA predictions; moreover, this can easily be done without the use of such model correlation criteria as the Modal Acceptance Criterion (MAC) or Cross-Orthogonality Check (CoC).

Conclusions

The Force Measurement Device was used for the first time in the qualification testing of the Rosetta spacecraft. Its major advantages can be summarised as follows:
– Direct measurement of interface forces and moments.
– Immediately validates the qualification of the main modes, whatever the quality of the FEM.
– High accuracy of the interface-force measurements.
– High stiffness resulting in limited frequency shift.
– Can be used for auto-notching.
– Provides useful data for the FEM correlation.
– Very good linearity and low cross-talk.
– Uses only six measurement channels.
– Easy to implement in a test set-up.

Some points worthy of attention were also highlighted during the Rosetta test campaign:
– In general, an extra load spreader is required between the slip-table and the FMD (depends on the particular slip-table).
– The use of an additional load spreader and of the FMD increases the overturning moment on the slip-table (additional mass and higher CoG).
– Currently only available for a 1194 mm diameter spacecraft interface, but the technology can easily be applied to other interface diameters.

All in all, the new Force Measurement Device has been demonstrated to be useful, reliable, and practical:
– Useful, because the notched levels could be determined and applied with good confidence so as to ensure adequate safety during testing, and because it was also possible to confirm to the launcher authorities that the qualification loads were indeed reached during these tests. Moreover, the data are valuable for the test validation of mathematical models.
– Reliable, because high stiffness and accuracy have been shown.
– Practical, because its implementation in the test set-up is simple, and because it requires only six measurement channels.

The use of the FMD device is therefore highly recommended in the vibration qualification and acceptance testing of all spacecraft.

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