MICRO-VIBRATION MEASUREMENTS ON THERMALLY LOADED MULTI-LAYER INSULATION SAMPLES

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OVERVIEW

Some scientific missions require to an extreme extent the absence of any on-board micro-vibration. Planned missions to be named to this respect are GOCE and MICROSCOPE. Their missions demand for extremely low micro-vibration environment on orbit.

Based on evidence from ongoing missions, multi-layer insulation (MLI) type thermal control blankets have been identified as a structural element of spacecrafts which might deform under temperature variations as caused by varying thermal irradiation on orbit. Any such deformation exerts tiny forces which may cause small reactions resulting in micro-vibrations, in particular by exciting the spacecraft eigenmodes.

In close collaboration of CNES and IABG, the set-up for the experimental determination of micro-vibration events of MLI under thermal loads, which already was used within the scope of the GOCE project, has been improved, as well as the procedures have been refined with respect to the MICROSCOPE project.

In this paper, the improvements and the experience of these micro-vibration measurements will be presented and the conclusions which may be drawn on the choice of MLI will be discussed.

1. INTRODUCTION

The MICROSCOPE (**MICRO**-**S**atellite à trainée **C**ompensée pour l'**O**bservation du **P**rincipe d'**E**quivalence) is the third microsatellite of the CNES Myriade program. It is dedicated to test the Equivalence Principle with an accuracy of one hundred better than the one obtained with experiments realized on Earth.

The Equivalence Principle is the fundamental postulate of Einstein's General Theory of Relativity and states that physical laws in a reference frame being in free fall in a gravitational field are equivalent to the physical laws in an inertial reference frame.

The MICROSCOPE satellite (see Fig. 1) is scheduled for launch end of 2010 and shall be placed in a polar Sun synchronous orbit at 790 km. The satellite has a mass of 200 kg with dimensions of 0.9 m x 0.9 m x 1.3 m. The main payload, the T-SAGE instrument, consists of two independent differential accelerometers which shall measure the acceleration on board of the spacecraft with an accuracy better than 10^{-12} m/s^2.

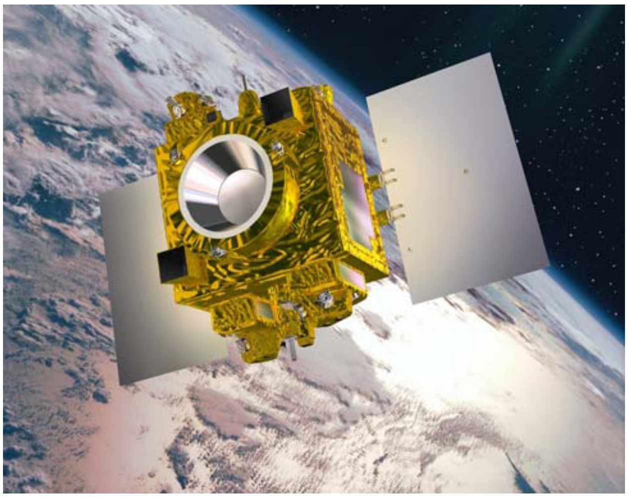

FIG. 1: MICROSCOPE spacecraft, picture © CNES 2006

Based on the experience from previous gravity missions like CHAMP and GRACE, the MICROSCOPE spacecraft will be specifically designed to meet very high requirements with respect to its own micro-gravity environment. Unintented micro-vibrations have to be avoided as far as possible in order to minimize the amount of non-gravitational forces which need to be measured or compensated.

As a consequence, the spacecraft is built with no moving parts and with fixed solar wings. However, thermal control blankets had to be retained in the design though they are considered as a potential source for micro-vibrations when being thermally loaded. Micro-vibrations caused by MLI type thermal control blankets may occur since the MLI might deform under temperature variations as caused by varying solar irradiation in orbit due to thermal expansion or compression. In effect, the MICROSCOPE spacecraft will be operated in inertial and spinning modes, and different aspect angles with respect to Sun or Earth will induce temperature variations of the external layer of the MLI up to 130°C. Accordingly, MLI samples of different composition had to be investigated to determine the layout with the least risk to produce micro-vibrations.

In a close collaboration of CNES Toulouse and IABG, the test procedures initially used for the GOCE MLI investigations were improved and finally tests to measure the micro-vibrations of thermal control blanket samples under transient thermal irradiation were performed. The effects to be measured which had to be observed challenged the measurements down to the detection limit in the range of some tens of micro-g.

2. OBJECTIVES AND TEST SAMPLES

The objective of the experimental investigation was to measure the micro-vibrations induced by thermal cycling of four different MLI layouts in order to find the optimum choice of MLI for the MICROSCOPE spacecraft with respect to minimize the risk of micro-perturbations. The design of the four MLI types investigated was already based on previous experimental results. Tab. 1 shows the main characteristics of the MLI samples.

Sample	**External layer**
Sample 1	**PCBE white paint** x 25µm Kapton x VDA both sides
Sample 2	**PCBE white paint** x 12,7µm Kapton x VDA both side x 3P adhesive x NOMEX
Sample 3	**MAPATOX K** 5µm x 50µm Kapton x VDA internal side
Sample 4	**MAPATOX K** 5µm x 50µm Kapton x VDA internal side x A528 adhesive x NOMEX

TAB 1. MLI sample characteristics

The main difference between these MLI samples was the material of the external layer. The inner layers, however, always were of standard type. The size of the samples was 0.54 m x 0.46 m. The mass of each of the MLI samples was in the range of 0.2 kg.

In order to meet the test objective, experimental evidence was required to establish a direct correlation between the visual observation of an MLI motion and the induced micro-vibrations. Once this correlation had been confirmed, the follow-up objective was to statistically assess the number of micro-vίbration events and their magnitude.

3. TEST LOGIC

Of course, a full-scale spacecraft test was neither very practicable nor considered useful at all. A much better approach was to perform a reduced scale test on the level of MLI samples for the following reasons:

a) Better customisation of the test set-up to the phenomena of interest and much easier suppression of any detrimental side effects.
b) Micro-vibrations much easier may be observed when the MLI samples under investigation involve a relatively high mass compared to the overall mass of the set-up. That is, compared to the spacecraft mass of 200 kg, a test set-up of about 4 kg requires 50 times less resolution for the vibration measurement equipment.
c) Existing test facilities may be used
d) Testing is possible at an early stage of the hardware development
e) Lower costs of a scaled down test.

However, the results of such a scaled down test have to be extrapolated to the spacecraft level.

Besides of these general considerations, the prerequisites concerning the test performance were as follows:

a) In order to have representative attachment of the MLI samples to a spacecraft structure, a typical spacecraft sidewall honeycomb panel was used. This implied three consequences:
   - it must be assured by test that the panel itself does not induce micro-vibration under thermal loads
   - it must be very low-frequency suspended to uncouple it dynamically from the environment
   - the dynamic behaviour of the suspended sidewall panel had to be characterized by a modal test.
b) When comparing the micro-vibration behaviour of four MIL samples, the applied thermal profiles had to be as identical as possible.
c) The background vibrations and the noise of the measurement chains had to be low enough to enable the detection of micro-vibration events in the range of 50 µg peak-peak.
d) The micro-vibration measurements and visual observation had to be synchronized.

The test approach was to expose the test samples to on-orbit environmental conditions in a thermal vacuum chamber and to irradiate the outer side of the thermal blankets. Then the micro-vibration had to be measured.

4. TEST CONDITIONS AND PROGRAM

Four different thermal profiles (test type 1 to 4) as indicated in Fig. 2 had to be applied to these samples each in a thermal vacuum chamber in order to investigate the effect of different temperature change rates. These thermal profiles varied in time between 25 min and 100 min, as well as in the temperature range of -50°C to 0° C and -60° to +70° as the maximum range, respectively. The minimum temperature was driven by the proven operation range of the accelerometers which did not allow going below -60 °C.

In order to achieve these profiles, active heating by an IR-rig and passive cooling by the chamber shroud was applied as follows:

a) The shroud temperature had to be established such that the temperature of the sidewall panel was at the MLI initial temperature with a tolerance of +/-5° and at the initial temperature and +20°/-0° all the time during a cycle.
b) The shroud temperature should enable the cooling of the MLI down to -60°C, respectively -50°C in order to achieve the required initial temperature for the thermal cycles.

c) The IR-rig had to enable the heating of the MLI surface up to +70°C at a maximum temperature change rate of 100° per 5 min (with 20% tolerance).
d) The minimum and the maximum temperatures of a cycle had to be achieved within a tolerance of +/-5°.
e) The irradiation of the IR-rig had to be uniform (to be checked by 5 TC on the MLI sample). The average of these 5 TC MLI temperature measurements was considered as the reference temperature.

The performance of the thermal cycling required vacuum environment. Each thermal profile and the related micro-vibration measurement had to be started at a vacuum better than 10^{-5} mbar. However, vacuum up to 10^{-3} mbar was considered acceptable for the micro-vibration measurement since the convection effect remains negligible.

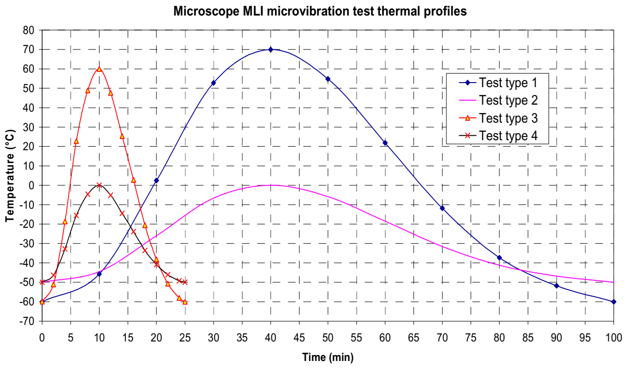

FIG. 2: Thermal profiles (MLI outer layer temperature)

It was foreseen to cycle the heating and the cooling of a sample several times as indicated in Tab. 2 in order to assess the repeatability of the MLI' behaviour and of the test results.

Test Phases	MLI test	Number of cycles	Total Duration (min)
Phase 1	Test type 3	3	75
Phase 2	Test type 1	2	200
Phase 3	Test type 2	1	100
Phase 4	Test type 4	2	50

TAB 2. Test runs per MLI sample

The required test recordings were specified as follows:

- 5 TC on each MLI sample
- 5 TC on the carrier panel (under the MLI)
- 4 high sensitive accelerometers on the carrier panel
- 1 accelerometer close to the suspension of the panel at the chamber interface
- Thermal conditions in the 2m TVA (vacuum pressure, shroud temperature, chamber temperature)
- Two video cameras inside the chamber (synchronized with the accelerometer data)

All accelerometer data were recorded in the time domain at a sample rate of 1 kHz with an intended analysis band-width of 300 Hz. The chamber ambient conditions and the TC's were recorded at a sample rate of 1 per 30 seconds.

5. TEST FACILITY AND SPECIFIC TEST INSTALLATIONS

5.1. The 2m Thermal Vacuum Facility (2m-TVA)

The test facility used for this test was the thermal vacuum chamber 2m-TVA of the space simulation department at IABG. The 2m-TVA is a horizontally positioned thermal vacuum chamber. The test facility is equipped with a cylindrically shaped and thermally controllable shroud with an internal diameter of 1.8 m and a length of 2.1 m. Its temperature can be adjusted from 77 K (LN2) to 423 K (GN2) and it is equipped with roughing pumps and two cryopumps to generate pressure lower than 10-5 mbar. The chamber's data acquisition system provides up to 500 measuring channels for thermocouples. For other measurements, special sealed feed-throughs are available, in particular up to four video cabinets and several BNC connectors for active IEPE accelerometers. The 2m-TVA is low-frequency supported on airbags and enables the uncoupling of the chamber from building vibrations (structure borne noise) above about 5 Hz. The isolation with respect to airborne noise mainly is achieved by the vacuum inside of the chamber.

However, the typical operation of such a chamber, despite its free-free support, is still far from being favourable for a micro-vibration test. The vibrations produced by the facility itself origination from the GN2 flow in the shroud, the valves of the cooling control system, and the running cryopumps are too high for such an investigation. Therefore, it was essential for this test to customize the set-up and the operation of the chamber such that acceptable results could be achieved.

Additionally for this specific test, the chamber was equipped with an IR-lamp array providing the required heating of the MLI samples.

5.2. Mechanical Set-Up

The MLI samples were fixed via 16 VELCROs to the sandwich composite panel. The size of the panel was 0.54 m x 0.46 m x 0.02 m. The mass of the panel was 3.8 kg plus 1.3 kg of measurement installations (accelerometers, connectors and about 1 m of cable lengths). This panel was low-frequency suspended to the rail system at the ceiling of the 2m-TVA such that the panel had an inclination of 10 degrees with respect to the vertical (see Fig. 3). The target frequency for all for all rigid-body modes was less than 2 Hz. In front of the panel an IR-lamp array was suspended with 3 x 2 IR lamps of 1 kW radiation power each.

The intention of this low-frequency suspension was to isolate the panel as efficiently as possible from its environment. Since in vacuum the suspension modes are nearly undamped, any activity of the chamber itself, like the cryopumping or the switching of magnetic valves, may excite the suspension modes up to some milli-g vibration amplitudes. Therefore, it was essential for the micro-vibration measurements to completely shut-down the 2m-TVA during the thermal cycling and the micro-vibration measurements. This measure was acceptable, since the required test conditions (shroud temperature and vacuum) could be established for about one hour without exceeding the specified limits. By this measure, the residual rigid-body vibrations of the carrier plate were reduced to less than 10 µg.

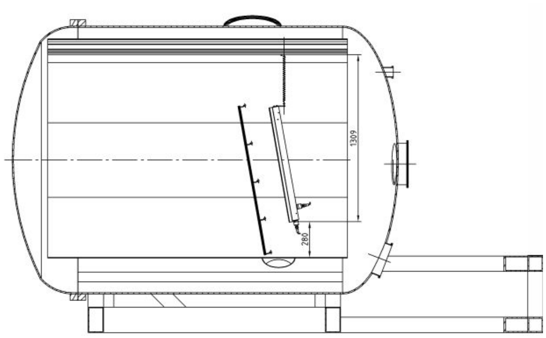

FIG. 3: Principle of the mechanical set-up in the 2m-TVA

5.3. Measurement Set-Up

For the measurement of the carrier plate accelerations, four seismic accelerometers with a sensitivity of 1V/g were used. These IEPE accelerometers may be used under vacuum and in a temperature range of -60°C to 120°C. Two sensors were installed normal to the carrier plate opposite to the side where the MLI sample was fixed, and one sensor was installed in each of the in-plane directions of the panel. Another sensor was placed close to the suspension rail system of the 2m-TVA monitoring any externally induced vibration of the chamber. The measurement points for the micro-vibration recording are shown in Fig. 4.

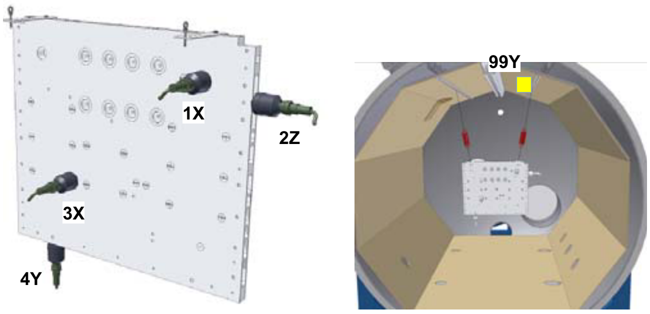

FIG. 4: Suspension and measurement system

For the signal conditioning and recording, the new data mechanical handling facility was used providing low-noise IEPE current supply, an AC cut-off frequency of 0.16 Hz, an A/D of 24 bit and a signal-to-noise ratio better than 105 dB. By these features, the background noise acceleration spectral density (ASD) of the measurement system itself was better than 10^{-7} g/√Hz.

For the measurement of the surface temperatures, each MLI sample was equipped with five and the panel also with five thermocouples. The recording of the TCs and of the chamber conditions was performed with the standard acquisition of the 2m-TVA using a sample rate of 1 sample in 30 seconds.

5.4. Vibration Behaviour of the Set-Up

Before starting any micro-vibration measurement on an MLI sample, the vibration behaviour of the panel itself was characterized by a modal check and background noise measurements. The frequency response functions of the panel as shown in Fig. 5 indicate panel elastic modes at about 200, 300 and 400 Hz. Also, all panel suspension modes were confirmed to be below 2.5 Hz.

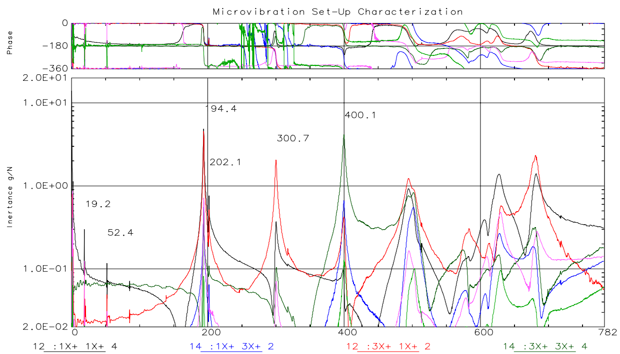

FIG. 5: Panel frequency response functions

The background ASD of all sensors on the panel, as well as at the 2m-TVA chamber rail are shown in Fig. 6. The relevant magnitude of the background noise only can be assessed, when the chamber is closed and in condition for the micro-vibration measurements. Otherwise, even sound pressure waves e.g. from speech will spoil the result due to the high sensitivity of the set-up to any excitation.

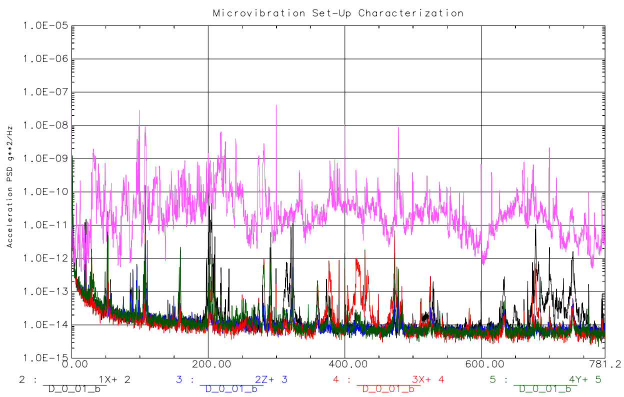

FIG. 6: Background noise ASD

The corresponding rms values of the background vibrations are: 3 … 10 µg (rms) for the panel responses and 250 µg (rms) for the rail response (magenta spectrum). Fig. 6 as well shows the dynamic uncoupling between the chamber and the suspended panel, even though further existing links between the panel and the chamber due to the cabling of the TCs and of the accelerometers existed. As it can be seen in Fig. 6, the noise floor of the measurement chain is far less than 10^{-6} g/√Hz.

Some tonal components appear in this ASD which have to be attributed to the panel modes responding to random excitation, and which are related to modes of the chamber and the suspension system itself, as well as to electrical disturbances produced by transformers of the environmental control system of the laboratory. Unfortunately, these transformers could not be switched off completely during the measurements. Nevertheless this background noise ASD was well acceptable for the micro-vibration measurements.

In order to characterize the thermal behaviour of the panel itself, one thermal cycle was performed on the panel and micro-vibration measurements were taken. The results indicate that some thermally induced micro-vibration events may be caused by the panel itself (i.e. without the MLI). However, the thermal cycling conditions were much worse for the panel (and the attached accelerometers) in this dry run than applied later in the MLI cycling. The conclusion was that only some few or even not any micro-vibration events caused by the panel may have interfered with those generated by the MLI samples in the subsequent MLI test.

These measurements also proved that it clearly can be distinguished between the micro-vibration events on the panel caused by the MLI and by events induced by the environment. In the latter case, the micro-vibration events on the chamber and the panel are closely related. Otherwise, the measurement point on the chamber will not respond at all. Fig. 7 clearly demonstrates this relationship.

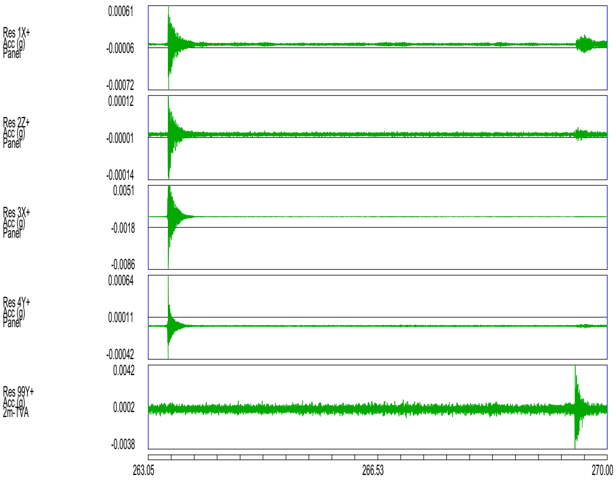

FIG. 7: Different response characteristics for micro-vibration events on the panel (left of the first four records) and originating from the exterior of the chamber (right of the last record). The typical acceleration response maxima are some 100 µg on the panel and 4 mg on the chamber.

Typically, all micro-vibration events resemble the decaying responses of a structure after impact force excitation. It has to be noted here, that when a micro-vibration event takes place, after the initial transient the panel will respond with its natural frequencies. In the case of Fig. 8, the main panel response is in its 400 Hz eigenmode.

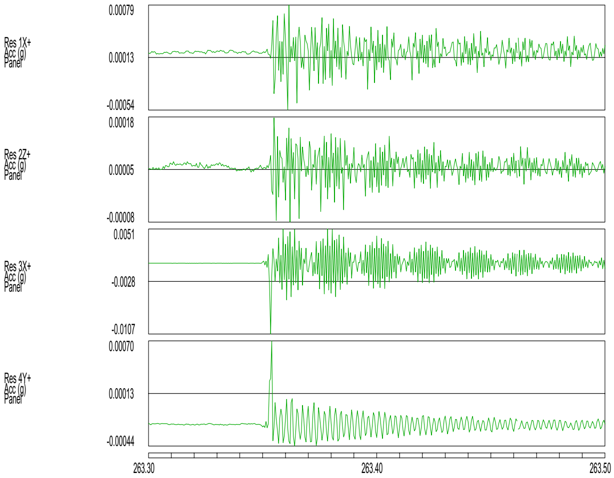

FIG. 8: Detailed view of panel micro-vibration response

Finally, after these initial investigations, the first MLI sample was installed in the 2m-TVA and the micro-vibration test sequence was started. Fig. 9 shows the completed set-up.

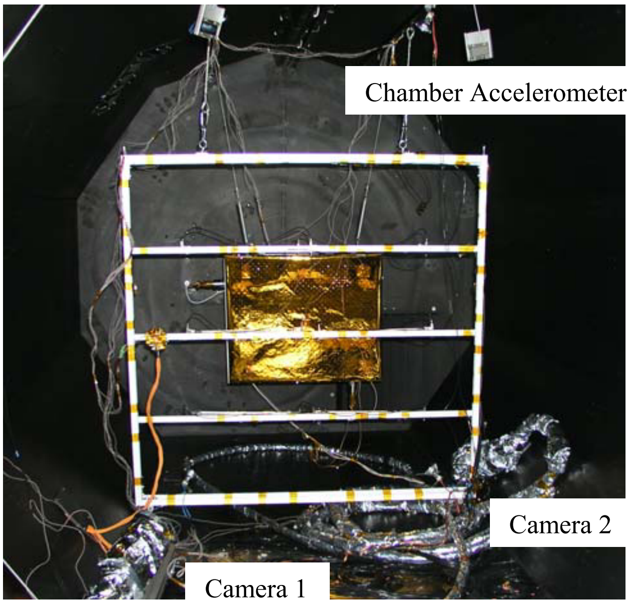

FIG. 9: Completed set-up

The behaviour of the MLI sample under the transient thermal load was recorded on video tape. The small video cameras may bee seen in Fig. 9 at the lower corners of the IR rig. Flat illumination with lamps and the reflections of the IR lamps by the test sample surface itself provided good means to observe motion of the MLI sample.

6. TEST RESULTS

The immediate results of the micro-vibration test were time-history recordings of the chamber conditions and the temperature of the sample blanket surface, as well as the video recording of the illuminated MLI sample. A typical record of the temperatures during three repetitions test type 3 is shown in Fig. 10. This shows that the temperature profiles were well reproduced during each cycle.

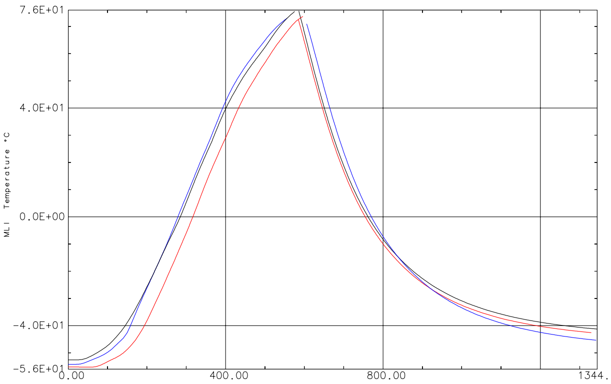

FIG. 10: MLI temperature cycles during test type 3

While the temperature profile during each heating phase was controlled actively, the cooling of the MLI was passive, i.e. was cooled by the heat radiation exchange with the cooled shroud (shroud temperature around -60° Celsius).

Typical time history records of the test conditions and the micro-vibration events are shown in Fig. 11 (heating phase) and Fig. 12 (cooling phase). These time history diagrams show from top to bottom: Chamber acceleration, 4 panel accelerations, MLI temperature, panel temperature and chamber pressure. The micro-vibration events of the MLI typically were in the range of some 100 µg and occurred during the heating phase more than during the cooling phases. In the periods of no temperature change at the maximum or the minimum temperature, no micro-vibration events were observed. The chamber conditions remained quite stable with pressure variations lees than some 10^{-5} mbar and the panel temperature did not change by more than 3 degrees during a cycle.

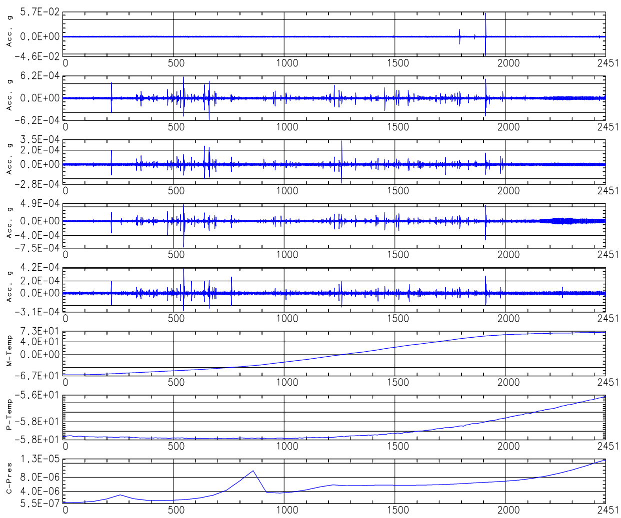

FIG. 11: Heating phase test type 1

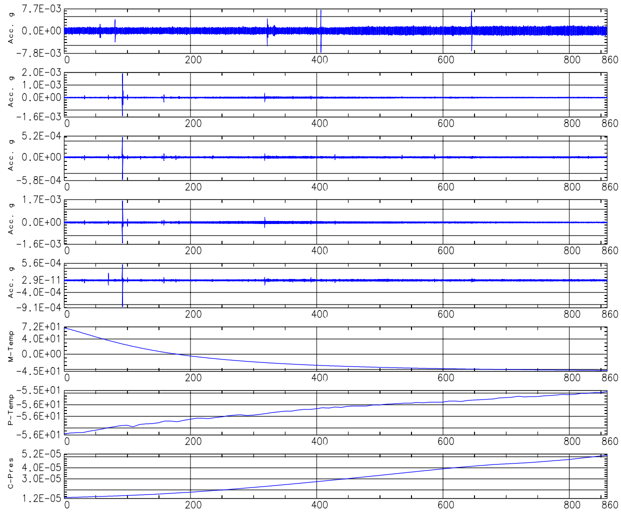

FIG. 12: Heating phase test type 1

The large difference in number of micro-vibration events of the test configuration shown in Fig. 11 and 12 was the case for all MLI type investigated. It was noticed that MLI sample 3 (TAB 1) produces less perturbations and with lower levels.

For visualizing the correlation between visible motions of the MLI and corresponding micro-vibrations events, much benefit was taken out of the new mechanical data handling which enables the fully synchronized recording and after test replay both of measurement data and of video data on one single screen. Fig. 13 shows a typical scene during data replay. This feature of the data handling facility facilitates the correlation of measurement data with visual observations and enables the off-line stream analysis of the data in the time and the frequency domain simultaneously.

FIG. 13: Off-line data analysis

The time-domain accelerations clearly show distinct peaks of some 0.05 to 2 mg which exceed the general noise floor of 0.05 mg (peak-peak). These micro-vibration events were often visually correlated to the motions of the MLI sample. Fig. 14 presents a typical micro-vibration event being initiated by the MLI sample motion. This event starts with a sudden increase of the acceleration with amplitudes of nearly 100 µg and has a duration of about 30 ms. This impact-like-event also excites modes of the carrier plate in this case at 400 Hz and at higher frequencies.

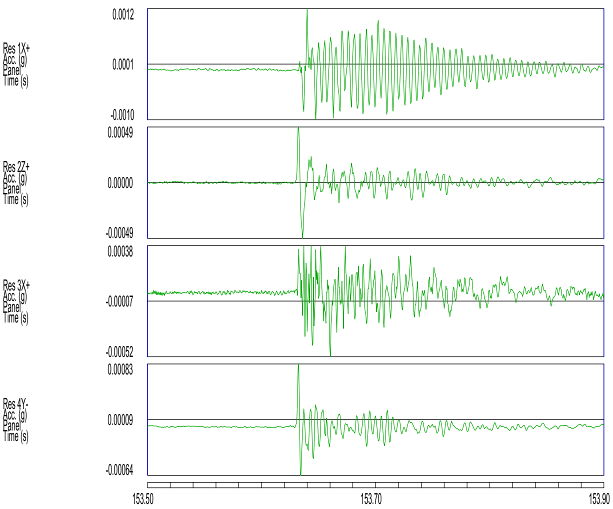

FIG. 14: Detailed view to a micro vibration event

Based on the counting and the classification of the events with respect to the acceleration magnitudes encountered, a clear assessment of the each MLI sample during each phase of the micro-vibration investigation was possible. Tab. 3 shows the result of the classification of micro-vibration events by maximum magnitude. The relative occurrence of micro-vibration events while comparing the different MLI samples (without disclosing the identification of the corresponding MLI type) is given in Fig. 15.

Test Run	Duration (s)	Events Classification <50 µg	<100 µg	<200 µg	<300 µg	<400 µg	<500 µg	>500 µg
S1_3_01h	555.2	26	46	29	13	9	6	10
S1_3_01c	757.8	30	39	14	6	8	5	5
S1_3_02h	574.9	21	26	16	4	4	1	4
S1_3_02c	743.4	25	27	11	5	4	4	7
S1_3_03h	595.2	9	26	9	5	5	0	4
S1_3_03c	734.9	18	28	13	6	3	4	6
S1_1_01h	2465.0	52	61	17	11	6	1	2
S1_1_01c	630.5	26	27	13	4	4	0	2
S1_1_02h	2425.1	50	52	24	6	4	3	2
S1_1_02c	752.9	32	18	10	6	1	2	1
S1_2_01h	2260.0	10	15	8	1	1	2	1
S1_2_02c	676.6	4	14	1	1	0	0	2
S1_4_01h	530.1	0	4	3	0	1	1	3
S1_4_01c	659.5	4	11	2	2	0	0	3

TAB 3. Micro-vibration statistics for one MLI sample

7. CONCLUSION

In general, the objectives of the micro-vibration test have been achieved. The operation of the 2m-TVA chamber and the installed measurements clearly allowed the correlation of the motion of the sample blankets to the measured micro-vibrations. In particular, the required resolution of the measurement chain in the range of some µg was achieved. On the basis of exerted environmental conditions and the measured micro-vibration events, the identification of the most favourable MLI lay-up was possible.

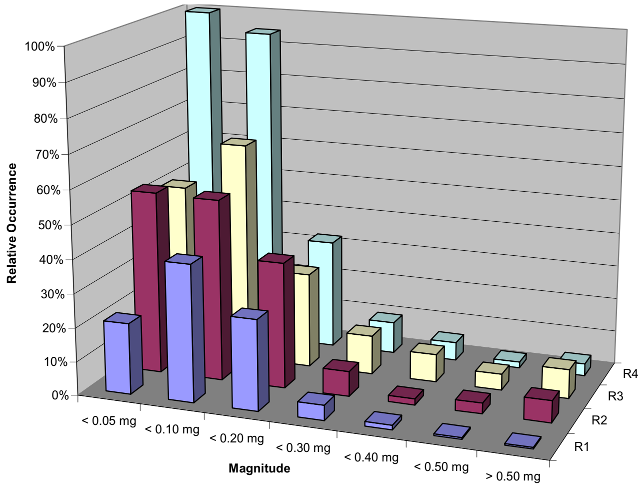

FIG. 15: Relative occurrence of micro-vibration events

Nevertheless, some improvements should be considered for future activities. First of all, the measurement of the micro-vibrations provides only a rough indication of the forces which a motion of the thermal control blanket may exert on a spacecraft. The set-up as presented here allows a good comparison on sample blanket level however, the extrapolation to the spacecraft seems difficult because of the quite different dynamic characteristics of the spacecraft compared to one single sidewall panel. Therefore, for analytical reasons, it would be more advantageous to know the excitation forces rather than the resulting micro-vibrations, because the vibrations depend on the dynamic characteristics of the specific set-up.

Although some significant progress has been made concerning the resolution of the micro-vibrations since the previous micro-vibration measurements for the GOCE MLI samples, further effort may be recommended for the suppression of background noise (the test chamber should be in a completely isolated room, and electrical interferences need to be even better suppressed), as well as the use of even higher resolving accelerometers, if available on the market.

ACKNOWLEDGEMENT

The authors like to thank CNES Toulouse for the kind permission to reproduce extracts from the test data and to present them in this paper.