On ground and in orbit microvibrations measurement comparison

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ABSTRACT

Since the 90's, the accuracy and the stability required for the Earth observation satellites instruments line of sight have increased. This is why the microvibrations generated by the mechanisms became a potential problem.

During the SPOT4 satellite project development, some work was performed to improve the knowledge of these phenomena. The first activity consisted of the quantification of torques and forces generated by the wheels and a frequency response functions (FRF) measurement on ground, suspended satellite. A microvibratory characterisation test bench was developed. The second way has been to develop an experiment called MICROMEDY as a technological passenger of the SPOT4 satellite to monitor the orbital microvibrations environment and structural behaviour.

This paper presents the on Ground tests, the orbital measurements and a comparison between the obtained results is made.

1. INTRODUCTION

The in board microvibrations preoccupation have been studied only since the beginning of the 90's. The accuracy and the stability required for the Earth observation satellites instruments line of sight lead imperatively to take into account the microvibrations.

Satellite being an isolated system, the mechanical energy produced by different moving equipments must be dissipated into this system. The mechanical disturbances are characterised by forces and torques that appear at the interface between the equipment and the satellite. These forces propagate through the structure to the sighting instruments. Among these disturbance sources we find the reaction wheels for the attitude control. In our case, the reaction wheels are based on the use of magnetic bearing for the rotor guidance. The disturbances proceed from several sources:
- A balancing lack creating an unbalance rotating force which magnitude is practically proportional to squared angular velocity.
- Spectrum lines in the radial axes current command provided by harmonics due to the radial control loop sensing.
- Bearing passive modes.

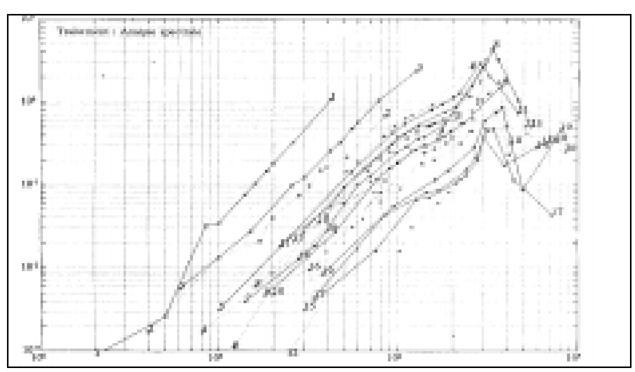
To improve the knowledge of these phenomena, CNES have begun works with the SPOT4 satellite development and also with a MIR experiment called CASTOR on the structural damping aspect.

2. WHEEL DISTURBANCES CHARACTERIZATION

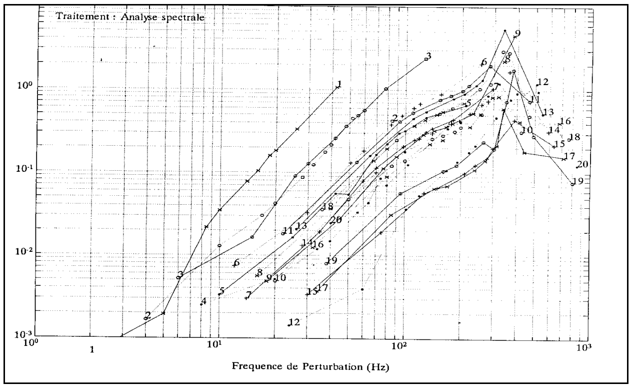
The first activity consisted of the measurement of torques and forces generated by the wheel. A microvibratory characterisation test bench was developed. The selected solution is based on the direct force measurement method. This principle lies on the measurement of the interface forces between the wheel and a dynamometric table for each of the 6 degrees of freedom. In order to obtain a measurement high accuracy (10^{-3} N) the test bench is installed on a large seismic block in order to be decoupled from the environment noise. The acceleration residual noise level is about 10^{-7} g.

The main characteristics of the test bench are:
- Specimen max. weight = 150 kg
- Force resolution = 10^{-3} N
- Torque resolution = some 10^{-4} Nm
- Frequency bandwidth = 0.2 Hz to 400 Hz (according to the specimen weight).
- Measurement accuracy = 5 %

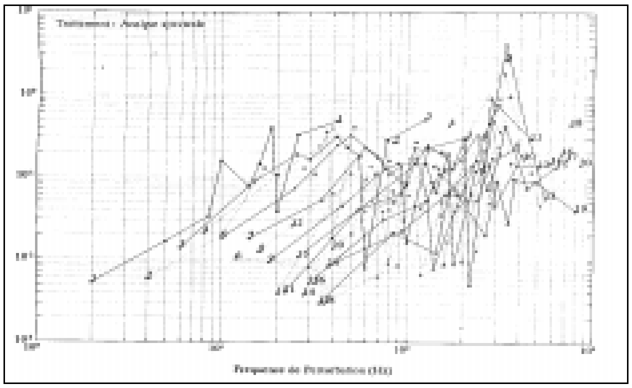
The characterisation tests consist in torques and forces measurements at different wheel rotating speed. In order to reach a high rotating velocity, the wheel is mounted in a vacuum chamber where the aerodynamic effects are negligible.



Harmonic forces along X axis



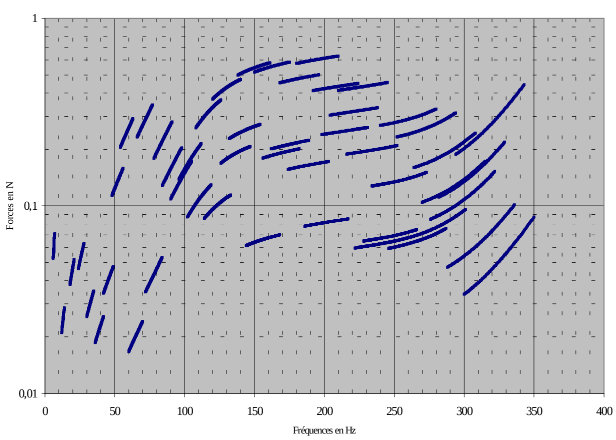
Harmonic forces along Y-axis



Harmonic forces along Z-axis

The three figures show that force amplitudes range from some 10^{-3} Newton to some Newton when the speed is about 40 Hz. We notice that there is a great number of harmonics (max. rank is 20). The Harmonics move in a large frequency bandwidth, then, they may excite structural modes and may generate high level microvibrations.

From these test results, microvibrations predictive model have been made to know the microvibratory behaviour of the susceptible equipment. The figure below shows the first 50 harmonics.



Harmonics level variation (6 < H1 < 7 Hz)

3. MICROMÉDY EXPERIMENT DESCRIPTION

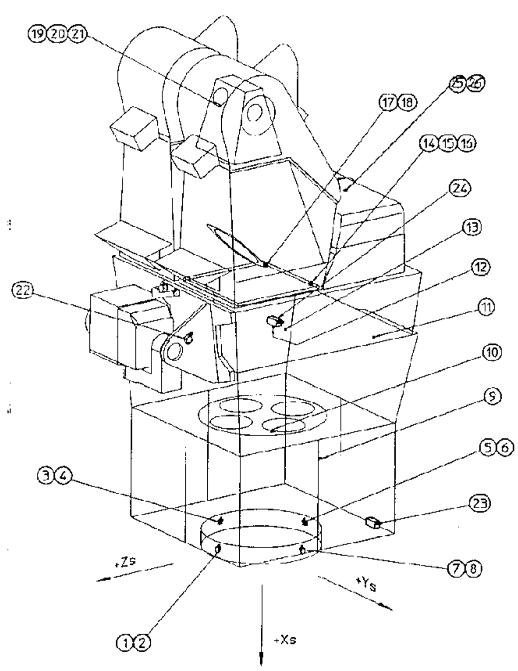
In orbit measurements were rare and more and more needed to improve ground simulations and test reliability. That’s why CNES decided to develop the MICROMEDY experiment. It is a part of PASTEC, a technological passenger of SPOT4.

3.1 The PASTEC payload

In 1989, CNES decided to set up a technological payload, PASTEC, on the SPOT4 satellite. A mission group selected seven experiments in various fields: CEDRE and THERME (material ageing), ERCOS and ERDOS (latch up phenomenon and dosimetry), SILLAGE (electrostatic discharges), MEDY and MICROMEDY (acceleration measurements). The development lasted about four years (from 1989 to 1992) and was headed by the Mechanical, Thermal and Energetic Division of CNES. The payload includes various transducers mounted on the satellite and their acquisition units, concentrated on a unique platform.

3.2 MICROMEDY hardware

The experiment consists in an electronic box, associated with ten very sensitive SEPTA A 878 ES pendular accelerometers, one BRUEL&KJAER 4390 piezoelectric accelerometer and one modified B&K 4810 mini-shaker. The figure below illustrates the transducers locations. This configuration is a result of compromises between the different objectives and the SPOT4 constraints. The microvibrations accelerometers are quite cumbersome, so available locations were difficult to find. For instance, it was first intended to set up accelerometers in the cameras (HRV) but the induced modifications were too important and costly. For the same reasons, the shaker had to be mounted in PASTEC.



22 : one accelerometer near the PASTEL telescope
23 : three accelerometers near the Xs reaction wheel
24 : three accelerometers near the tape recorder (EMS1)
25 : three accelerometers in the PASTEC payload
26 : one shaker in the PASTEC payload

In this paper, the analysis concerns the accelerometers that are located near the X wheel. These 3 accelerometers are : APF1X, APF2Y, and APF3Z.

4 – ON GROUND TESTS

The microvibrations test was performed at the end of 1997 on SPOT4 flight. The goal of these tests was to have a database for the comparison with the orbital tests and to estimate the predictive models.

The tested specimen was very close to the orbit configuration, except for some points: no solar arrays (impossible) empty tanks, one wall near the wheels missing, no superinsulation, on Ground instrumentation (a few kg).

The differences with the orbital configuration have been considered not critical for these measurements. Meanwhile, the empty tanks and the missing wall have certainly an impact on the FRFs measurement.

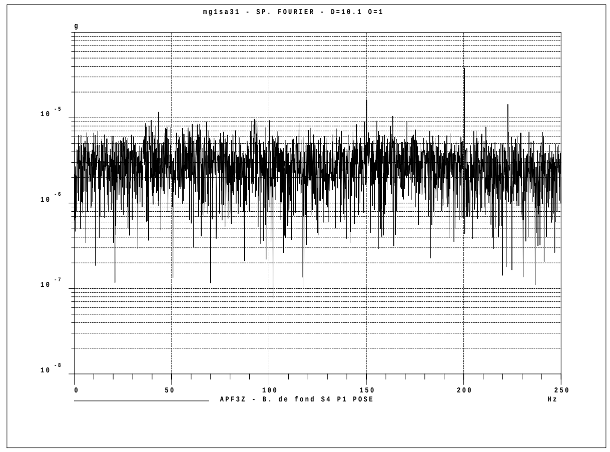
The satellite is suspended to a lifting tackle by four straps. The free-free configuration was simulated using a double suspension device.

SPOT4 during on ground tests

4.1 Ambient noise measurement .

channel	RMS Val.	Peak Val.	Aver. Lev PSD	Sp Lin 100Hz	Sp lin. 200Hz
APF1X	188 µg	750/ -742 µg	0.21×10^{-9} g^2/Hz	32 µg	10 µg
APF2Y	135 µg	532/ -539 µg	0.12×10^{-9} g^2/Hz	35 µg	6 µg
APF3Z	131 µg	487/ -504 µg	0.10×10^{-9} g^2/Hz	13 µg	33 µg

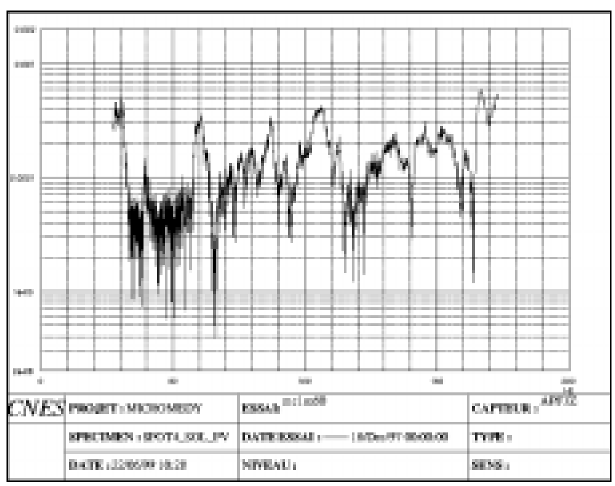
Ambient noise (acceleration) characteristics



Ambient noise (acceleration) spectrum

4.2 FRFs measurement

The transfer levels are low, but the global modes of the satellite are correctly identified. We note some peaks very close and very narrow near 30Hz. Two isolated pure modes at 60 and 85 Hz. They are visible on the 3 sensors. There are some peaks also near 110 Hz and a higher level near 160 Hz on the Z-axis.

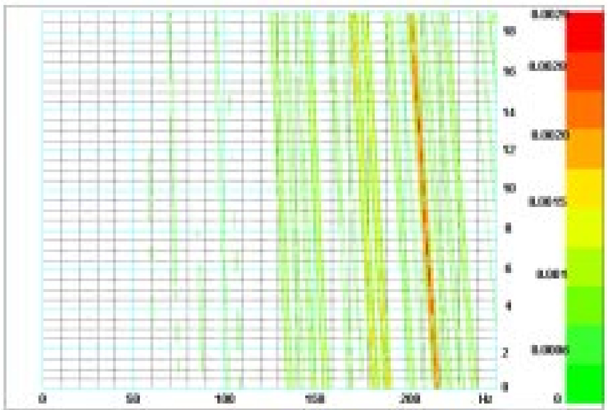


On ground FRF, APF3Z channel

4.3 Wheel effects measurement

The impacts of the three wheels have been separately measured. The rotating speed is set to dedicated value and then we let the wheel rotor decelerate only under the friction torque effect. This deceleration takes several minutes to go from 7 to 0.1 Hz. This time being incompatible with the Micromedy acquisition function the sweep are made around frequencies 7 Hz, 5 Hz, 3 Hz and 1 Hz.

The signals are unsteady and they are analysed thanks to a time-frequency method. We can precisely extract the wheel speed as a function of time and then track the corresponding harmonics during the sweep, filtering the noise. The figure below gives us an example of accelerations profile generated by the wheel. The amplified (by structural modes) harmonics during the speed sweep have a visible signature.



Acceleration profile – map

This table shows the maximum RMS level for the acceleration (mg rms) generated by each wheel. These values concern the accelerometers APF1X and APF3Z.

Speed	X wheel mg rms	Y wheel Mg rms	Z wheel mg rms
3 Hz	0.56 APF1X	0.42 APF1X	0.39 APF1X
5 Hz	1.55 APF1X	0.63 APF3Z	0.81 APF3Z
7 Hz	2.54 APF1X	1.06 APF3Z	1.2 APF3Z

We notice that the increase of the level is really a rotating velocity function.

The following table presents the more important spectrum lines measured with the 3 sensors located close to the « X-wheel ». The acceleration level are given for each functioning wheel.

Speed	X-wheel µg	Y-wheel µg	Z-wheel µg
3 Hz 1X	396 - H30	363 –H30	327 – H24
2Y	124 – H32	246 - H32	166 – H24
3Y	117 – H32	211 – H32	199 – H27
5 Hz 1X	976 – H30	338 – H32	585 – H13
2Y	512 – H30	322 – H32	306 – H 20
3Z	634 – H32	618 – H32	371 – H25
7 Hz 1X	2073 – H32	1039 – H9	862 – H28
2Y	659 – H25	548 – H32	627 – H25
3Z	1508 – H32	841 – H23	686 – H25

The comparison between the harmonic rank of these maxima and the high levels of the radial forces model show that the same harmonics have the highest levels.

5 – IN ORBIT MEASUREMENT

The satellite is in nominal configuration: deployed and controlled solar array, SPOT heliosynchronous orbit, in board system in nominal mode. The differences with the on ground operating conditions are:

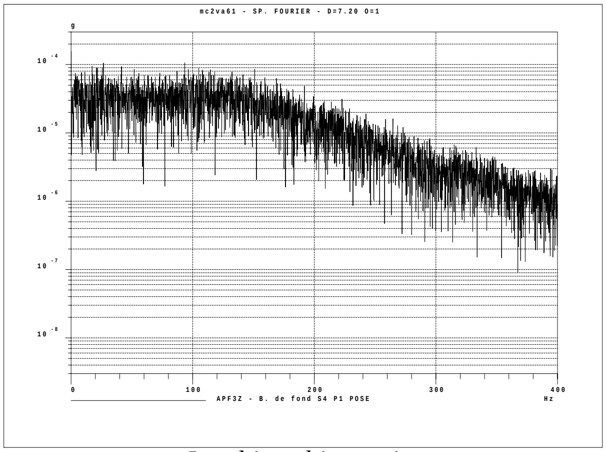
- All mechanisms are in operational mode,
- Attitude and orbit control system operational,
- Thermal environment controlled,
- Radiations effects on the electronics,
- For the structure: ultra-vacuum, no gravity.

Note: The accelerations measured with the APF1X sensor have to be taken cautiously. The time signature shape seems to show that the sensor or its electronics is defective.

5.1 Ambient noise measurement

In nominal rate the three wheels rotate with a low speed. There are 3 harmonics series very close one to the other. This phenomenon can be assimilated to a large broad band noise which the average level is depending to the location of the accelerometer (structural modes effects). It is impossible to separate this noise from the noise coming from transducers and electronics. The signal to noise ratio is about –10 dB.

Channel	Aver. Level Spectrum	Aver. level PSD	Rms noise
APF1X	23 µg	1.9×10^{-9} g^2/Hz	522 µg
APF2Y	22 µg	1.6×10^{-9} g^2/Hz	489 µg
APF3Z	9 µg	0.26×10^{-9} g^2/Hz	198 µg



In orbit ambient noise

The resulting overall noise is higher than the on ground ambient noise. Effectively, all the disturbances sources are in functioning mode.

5.2 FRFs measurement

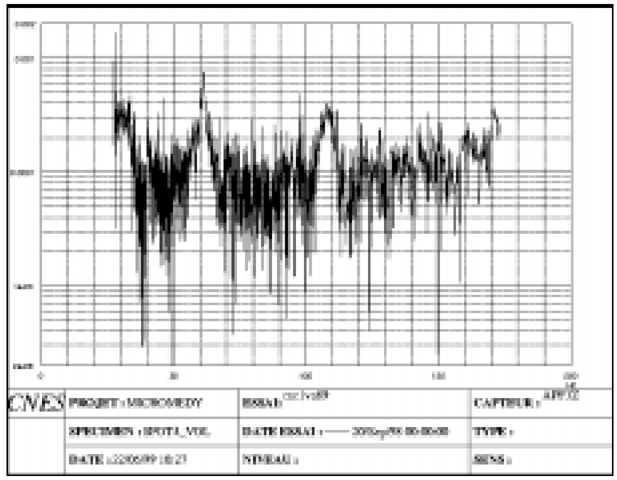
Several peaks appear in FRFs spectra. They are the wheel harmonics located at the same frequency than the shaker excitation frequency. In these conditions, only some behaviour changing can be analysed.

We note two very narrow peaks near 33 Hz similar to those seen near 30 Hz in the on ground tests. The level is lightly higher on the APF2Y channel (500 for 400 µg/N), lightly lower for the APF3Z channel (400 for 500 µg/N).

On the APF3Z channel, a mode is seen near 40 Hz. This is one of the first lateral modes of the satellite (not well excited). It is + 0.5 Hz shifted and its magnitude moves from 100 to 300 µg/N.

The satellite longitudinal mode appears near 61 Hz on the APF2Y channel ; it was near 60 Hz in ground configuration. This mode was not visible on the APF2Y channel (ground). The associated levels have highly increased, ratio 2 or 3: 750 for 350 µg/N on the APF3Z channel, 300 for 100 (ground noise) µg/N on the APF2Y channel. The mode shape (narrow peak) shows that the damping factor of this mode has decreased.

Near 85 Hz, one peak (visible on ground FRF) has disappeared on the APF3Z channel. The behaviour inside the 100-120 Hz broadband has changed. The modal signature is not the same. On the APF2Ychannel, some peaks have disappeared or their magnitudes have decreased. On the APF3Z channel, we see frequencies shift of about 2.5 Hz. The levels are the same. After, we can note a +3 Hz frequency shift for peak located near 140 Hz on the APF2Y channel; the level is the same.



In orbit FRF, APF3Z channel

The orbit FRF is noisier than the ground FRF. An explanation is the harmonic signature of the rotating wheels.

5.3 Xs wheel at high speed

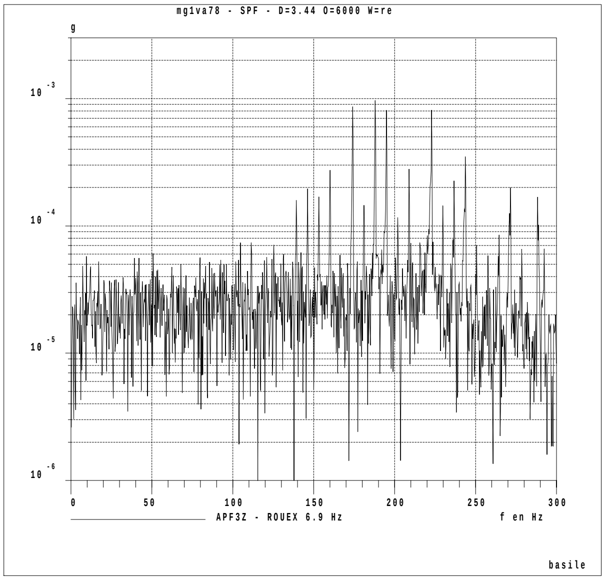
To do better comparison with on ground measurement and to have some informations for the SPOT5 satellite, the AOCS instructions have been temporarily modified and the X-wheel have been set to specific speed: 7 Hz and 5 Hz. The speeds have moved between 6.79 Hz and 6.36 Hz then between 4.928 Hz and 4.953 Hz during measurement.

The orbit/ground comparison can be made only with the two speed sweeps of the X-wheel. The wheel speed identification and the extraction of the harmonics is made with the same method used for the on ground sweeps analysis.

	X-wheel 6.9 Hz µg	X-wheel 4.9 Hz µg
APF1X	319 –H19	574 –H30
APF2Y	615– H25	705 – H14
APF3Z	1199 – H27	575 – H28

Higher level harmonics

Near the X-wheel the harmonic signature is correctly identified and the higher spectrum lines are included between 150 – 250 Hz. That corresponds with the harmonic ranks 25-35. Some peaks have a 1000 µg magnitude. Under 100 Hz, it is more difficult to see harmonics.



X-wheel speed: 6,91 Hz - APA3Z channel

The table below presents the highest acceleration levels for ground and orbit measurement. The X-wheel speed is about 7 Hz. The first number is the harmonic rank and the second is the acceleration level in µg.

On ground Tests			In orbit tests		
APF1X H / µg	APF2Y H /µg	APF3Z H / µg	APF1X H / µg	APF2Y H / µg	APF3Z H / µg
6/ 99	6/ 48	6/ 54	3/ 189	12/ 219	21/ 264
9/ 278	9/ 60	9/ 93	9/ 233	19/ 285	25/ 1065
11/ 345	11/ 107	11/ 104	12/ 167	21/ 527	27/ 1199
13/ 375	13/ 160	13/ 224	13/ 207	21/ 279	28/ 1005
19/ 109	19/ 33	19/ 36	17 /206	22/ 566	30/ 237
20/ 865	20/ 370	20/ 399	19/ 319	25/ 615	30/ 320
23/ 1080	23/ 249	23/ 651	20/ 284	27/ 475	30/ 345
24/ 79	24/ 23	24/ 101	21/ 225	27/ 209	32/ 1014
25/ 617	25/ 659	25/ 458	23/ 192	28/ 366	34/ 280
32/ 2073	32/ 250	32/ 1508	25/ 231	30/ 215	35/ 474

In comparison with on ground tests, we notice that the low frequency harmonics (H6 – H9) have practically disappeared, when the greater ranks harmonic appear.

It seems that the orbit levels are lower than the ground levels. Meanwhile, we have to take into account the wheel functioning point and the structure modal shift. In flight, the coincidences are not so good because of the wheel speed is higher and because of the decrease of the structural damping.

For the high rank harmonic, it is difficult to analyse the measured levels. The structure modal shift, the ground/ flight speed difference and the functioning point shift due to the gravity effect not allow a direct comparison of the two spectra.

The comparison between the ground wheel characterisation and the flight generated acceleration gives the same harmonic signature. Harmonics H9, H13, H20, H23, H25, H28, H30, H32 are the higher. The FRF between the X-wheel and the accelerometers position has not been evaluated. So, this FRF and the rigidity of the wheel support can explain the difference between the ground harmonic level and the level measured in flight

6 - CONCLUSION

The performances of MICROMEDY are very good, except for the probable failure of one channel and the lack of resolution in the low frequency range. A large amount of in orbit data is now available and the flight vibratory environment is better known.

Concerning the structure, we can say that the structure has roughly the same behaviouron ground and in orbit. However, in orbit, frequencies are slightly higher and damping ratios lower.

Concerning the wheels, the harmonic signature is practically the same in orbit or on ground. The harmonic content is very important; we can identify the 40^{th} harmonic rank. The level of each harmonic may be different to the one characterised on ground. The structure modal shift and the launch vibrations (unbalance modification) impact on the harmonic level.

The model based on the wheel characterisation seems to correlate the predictive levels and the realised measurement.

The maximum measured levels are about 1 mg near the X-wheel. The noise level generated by the nominal speed rotating of the wheels induces a raising of the ambient noise at low frequencies. We can note that the wheels in nominal state generate 0.1 micron disturbances on the X-wheel location and 0.3 micron (estimate) disturbances on a point located in the payload when the wheel is rotating at high speed.

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