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Micro vibration analysis concerning optical instruments of Herschel spacecraft

1 INTRODUCTION

Micro vibrations are a critical criterion for the optical instruments of Herschel scientific spacecraft. They generate disturbing accelerations on bolometers and the optical equipments, and an increase in temperature at the CVV module. Therefore, it is important to foresee the consequences of micro vibrations during the whole life of the spacecraft.

The aim of this analysis is to evaluate the level of those micro vibrations :
- At the center of gravity of each optical instrument ;
- And at one central point of the CVV.

The main sources of perturbation identified on the Herschel spacecraft are the reaction wheels used to adjust the orientation of Herschel. The chosen wheels are TELDIX 25 Nms (they are well-known due to the experience gained with SkyBridge program).
This study deals with the effects of one single wheel which turns in the range from 0 to 3600 rpm (0-60 Hz).
The configuration taken into account corresponds to the launch configuration, in which Helium tanks are full. Further studies should be carried out to know the response of the satellite when the tanks are empty.
The given specification for the optical instruments is to keep the acceleration level of these instruments under 10 µg.

2 MODELLING AND ANALYSIS

2.1 Numerical modelling

This micro vibration analysis is based on :

- A finite element model to predict the transfer function between the disturbance point and the instrument localization ;
- A model of the disturbance source.

The finite element model is the one used at the end of the proposal period which was completed with the physical model of the cryostat. Nodes which represent the optical equipments are the nodes : 48044, 48054, 48064 located at the center of gravity. of each instrument. The chosen node to study the CVV is the 50710 which has a central position on the shell of the CVV.
The node 12166 represents the reaction wheel.

2.2 NASTRAN analysis

The NASTRAN analysis is a free-free modal analysis (normalized on the generalized mass) of Herschel spacecraft. Modes between 0 and 100 Hz have been taken into account for this study because they can influence the response from 0 to 60 Hz.
The output file contains the disturbing source displacements and the disturbed equipment displacements on each mode. These results are stored in a PUNCH file and are used for micro vibration calculation.

2.3 Micro vibration analysis

µVision is a software developed by CNES and is specific to micro vibrations. The results were checked with NASTRAN which is well-known in mechanical analysis.
The needed inputs to micro vibration calculations are :

- PUNCH file from NASTRAN analysis ;
- Perturbing source definition : type (reaction wheel, magnetic wheel…), frequency, number of harmonics, excitation level, excitation type and direction of this excitation ;
- Modal damping assumptions. They are estimated thanks to tests experience, and have been reduced in order to match with the worst case ; hence we fixed this value at 0.005 for each mode.

The type of the wheel is a TELDIX 25 Nms ;

2.3.1 Hypothesis :

The wheel is characterized by a static unbalance equal to 1 g.cm (1.10-5 kg.m). This unbalance causes a radial force :

$$F = Us * w^2$$

with Us = unbalance mass * radial distance of this mass

The dynamic unbalance can range from 10 to 20 g.cm². However, it is impossible to use these values with µVision software : equivalent unbalances have to be estimated. Those equivalent unbalances are expressed in kg.m which permit to reach the same level of excitation than with dynamic unbalances. We used the curves given in annex (cf. annex 1) to determine those values. Only the 3 first harmonics were taken into account ; the higher harmonics are negligible. Those curves were translated to obtain a stress equal to 1.4 N at 60 Hz which corresponds to the effect of the static unbalance for the first harmonic. Thus, the equivalent unbalances are :

- 5.625 10-7 kg.m for the second harmonic ;
- 1.67 10-8 kg.m for the third harmonic.

This wheel has also one non-integer harmonic due to bearing-driven disturbances and especially to the balls : this harmonic has a frequency equal to 0.59 * f0. According to other studies, the equivalent unbalance has been estimated to 2.487 10-6 kg.m.
Nota : The second and third harmonics are also negligible in comparison with the fundamental level : 99 % of the maximal displacement is explained by the first harmonic. Other harmonics explain few smaller maxima (cf. annex 2).
A linear sum has been done with all these harmonics in order to consider maximal values of displacement and acceleration.
Only the radial forces are modeled, because axial forces are negligible.
Calculations were carried out successively with excitation along X, Y and Z axes. A rotating effort in the planes XY, XZ and YZ corresponds to a combination of these efforts, and thus the response to this rotating disturbance is between the responses of excitations along the two axes of the plane considered separately (cf. annex 3).

3 RESULTS

According to these hypothesis, this analysis shows that :

- The maximal acceleration of the optical equipments reaches 7.7 mg along the Z axis, at a frequency equal to 60 Hz, when disturbance is along the radial axis Z ;
- The global accelerations level is around 5 mg at many different frequencies from 29 Hz to 60 Hz (cf. annex 4) ;
- The maximal acceleration of the CVV, less damped than the focal plane, reaches 42 mg.

These results have a linear dependence towards damping assumptions and towards the amplitude of the excitation. It should be interesting to know more exactly which damping assumptions we could attribute to each mode (we decided to put 0.005 on each mode ; an other hypothesis estimates that 0.02 is also realistic. This would permit to divide the level of acceleration by 4).
As a conclusion, those accelerations are very different from the specification of 10 µg. However, a simple calculus shows that this kind of wheel turning at 36.3 Hz (one of the mode of the structure), generates an associated effort of 0.521 N ; if the structure is considered as a rigid body, this force creates an acceleration equal to :

$$\gamma = 0.521 / (3023 * g) = 17.5\ \mu g$$

(3023 kg is the mass of Herschel satellite)

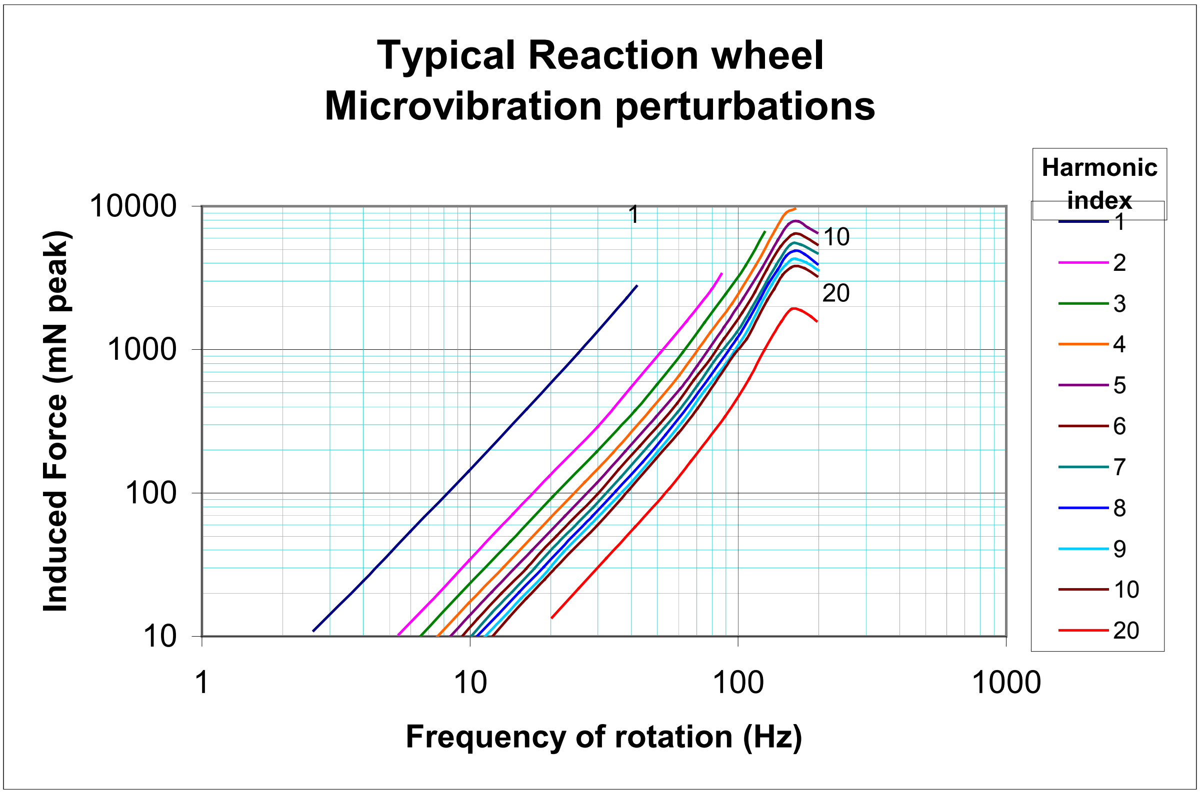
Thus, the acceleration without structure amplification already exceeds the specification. Consequently, it is not surprising that a structural mode generates an acceleration 500 times higher than the specification.

This analysis shows that it seems difficult to be compliant with the specification of 10 µg. It should be necessary to try to re-evaluate this specification and in a same time, to improve the model and our knowledge of the reaction wheel.

To reach the specification of 10 µg (if this requirement is really justified), it could be possible to support the optical equipments with passive damping devices (an active control of the damping is excluded because this solution is not certified yet). An other solution could be either to change the wheels or to modify the support of these wheels That last idea would imply to reflect about a semi rigid support. Although this solution may be in contradiction with the own aim of the wheel, we could think that the micro vibrations problem does not happen in the same range of time than the problem of the attitude control.

Annex 1

This curve gives the induced force of a reaction wheel on magnetic bearings, which is different from the one used in herschel and in this analysis. It has been used only to determine the ratio between the harmonics.



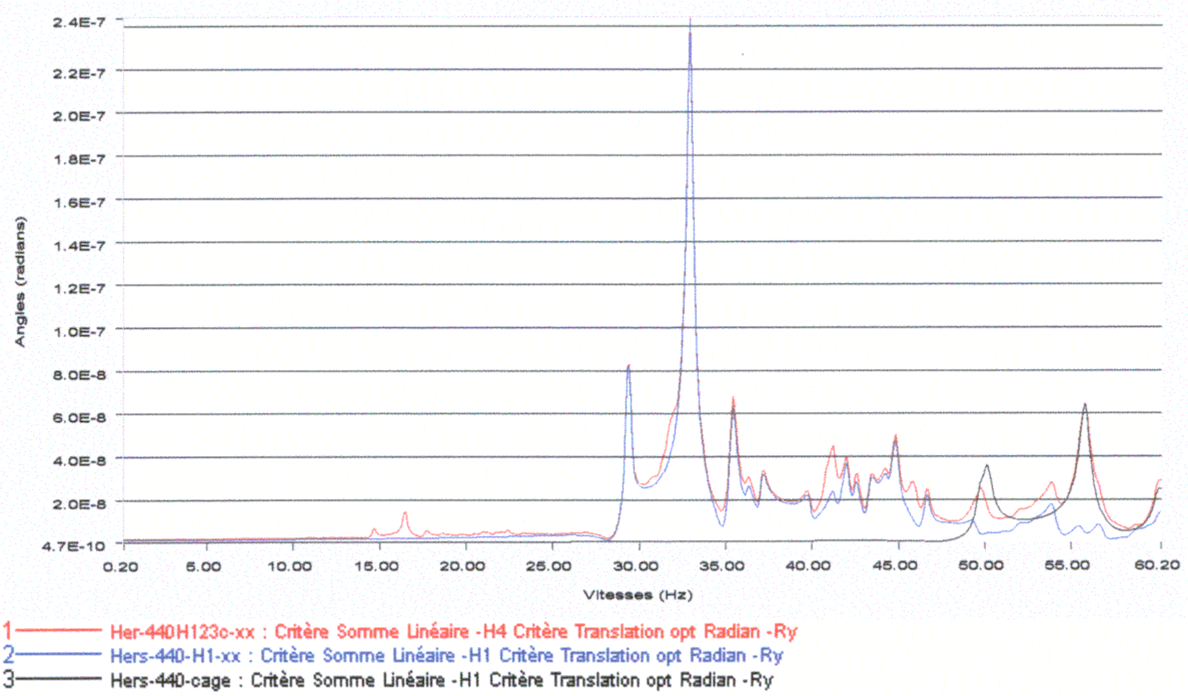
Annex 2

Date: 10-07-2001

Dossier FSD: c:\µVISION\Herschel2.fsd\Herschel2.fsd

Commentaire

Participation des harmoniques dans la réponse :
Courbe 1 en rouge : réponse avec toutes les harmoniques (l'harmonique 2 entraîne les pics autour de 17 Hz)
Courbe 2 en bleu : participation de l'harmonique 1
Courbe 3 en noir : participation du mode de cage



Explanation :

The response to the three harmonics (red curve) is mainly due to the disturbance corresponding to the fundamental level (harmonic 1) : the blue curve, associated to the harmonic 1, is similar to the red one and justifies more than 99 % of the maximum value. The peaks located around 17 Hz are the consequence of the second harmonic : they are the image of the major peak (2.5 10-7 m) at a frequence divided by 2. The response due to the third harmonic is not visible. And the black curve which represents the effects of the bearing-driven disturbances, focuses on the fact that this non-integer harmonic generate minor peaks at a frequence divided by 0.59 in comparison with the main peaks.

Annex 3

Explanation :
The red curve shows the excitation due to a revolving effort in the plane XY. This response is a combination of a sinusoidal disturbance along the axis X only (blue curve) and of a sinusoidal disturbance along the axis Y only. The two excitations along X and Y envelop the revovling excitation and thus, they correspond to the worst case.

Annex 4

Nœud de sortie	Instrument optique 1 (Nœud 48044)								
Axe d'excitation	X			Y			Z		
Axe des déplacements	x	y	z	x	y	z	x	y	z
Déplacement maximum (m)	1.48E-07	2.36E-07	4.50E-07	8.26E-08	5.00E-07	1.78E-07	5.45E-07	3.48E-07	9.33E-07
Fréquence du déplacement max (Hz)	59.4	32.9	29.3	42	44.8	42.5	59.4	36.2	36.3
Accélération associée au déplacement max (g)	0.00210148	0.001028	0.00155467	0.00058637	0.00403847	0.00129386	0.00773856	0.00183522	0.0049475
Accélératin maximale si différente (g)	0	0	0.00267126	0.00072764	0	0.00136846	0	0.00218885	0.00727272
Déplacement associé (m)			1.85E-07	5.87E-08		1.10E-07		2.71E-07	5.02E-07
Fréquence associée (Hz)			59.9	55.5		55.6		44.8	60
Accélération maximale (g)	0.00210148	0.001028	0.00267126	0.00072764	0.00403847	0.00136846	0.00773856	0.00218885	0.00727272
Nœud de sortie	Instrument optique 2 (nœud 48054)								
Axe d'excitation	X			Y			Z		
Axe des déplacements	x	y	z	x	y	z	x	y	z
Déplacement maximum (m)	1.09E-07	6.41E-07	4.31E-07	8.54E-08	5.11E-07	1.63E-07	4.95E-07	6.42E-07	8.22E-07
Fréquence du déplacement max (Hz)	60	35.3	29.3	42.4	44.8	29.4	53.5	43.3	36.3
Accélération associée au déplacement max (g)	0.00157914	0.00321439	0.00148903	0.00061785	0.00412732	0.00056699	0.00570169	0.00484397	0.00435889
Accélératin maximale si différente (g)	0	0.00344802	0	0.00472658	0	0.00093186	0	0	0
Déplacement associé (m)		2.38E-07		3.34E-07		1.27E-07			
Fréquence associée (Hz)		60		59.3		42.7			
Accélération maximale (g)	0.00157914	0.00344802	0.00148903	0.00472658	0.00412732	0.00093186	0.00570169	0.00484397	0.00435889
Nœud de sortie	Instrument optique 3 (nœud 48064)								
Axe d'excitation	X			Y			Z		
Axe des déplacements	x	y	z	x	y	z	x	y	z
Déplacement maximum (m)	1.31E-07	2.95E-07	4.41E-07	1.58E-07	5.45E-07	2.72E-07	4.06E-07	3.08E-07	8.96E-07
Fréquence du déplacement max (Hz)	59.5	35.4	29.3	44.8	44.9	35.4	59.4	36.2	36.3
Accélération associée au déplacement max (g)	0.00186636	0.00148771	0.00152358	0.00127616	0.0044216	0.00137172	0.00576487	0.00162427	0.00475129
Accélératin maximale si différente (g)	0	0.0016226	0.00340456	0	0	0.00157914	0	0.00247154	0.00496921
Déplacement associé (m)		1.12E-07	2.35E-07			1.09E-07		3.06E-07	3.43E-07
Fréquence associée (Hz)		60	60			60		44.8	60
Accélération maximale (g)	0.00186636	0.0016226	0.00340456	0.00127616	0.0044216	0.00157914	0.00576487	0.00247154	0.00496921
Nœud de sortie	Point du CVV (Nœud 50710)								
Axe d'excitation	X			Y			Z		
Axe des déplacements	x	y	z	x	y	z	x	y	z
Déplacement maximum (m)	8.24E-08	1.07E-07		4.67E-08	1.01E-07		2.99E-06	2.48E-07	
Fréquence du déplacement max (Hz)	59.8	43.3		55.8	43.3		59.4	43.4	
Accélération associée au déplacement max (g)	0.00118582	0.00080733	0	0.00058516	0.00076206	0	0.04245558	0.00187984	0
Accélératin maximale si différente (g)	0	0.00092989	0	0	0.00079247	0	0	0	0
Déplacement associé (m)		6.44E-08			5.47E-08				
Fréquence associée (Hz)		59.9			60				
Accélération maximale (g)	0.00118582	0.00092989	0.00318675	0.00058516	0.00079247	0.00127829	0.04245558	0.00187984	0.00138084
Accélération maximale des instruments optiques (g)	0.00773856								
Accélération maximale du point sur le CVV (g)	0.04245558								

Valeur issue de Nastran :
accélération de 0.22ms² pour un echelon d'ampliude unité à 60.0Hz (or à cette fréquence l'excitation a une amplitude de 1.421)

Valeur issue de Nastran :
accélération de 0.26ms² pour un echelon d'ampliude unité à 43.9Hz (or à cette fréquence l'excitation a une amplitude de 0.760)

Valeur issue de Nastran :
accélération de 0.26ms² pour un echelon d'ampliude unité à 36.3Hz (or à cette fréquence l'excitation a une amplitude de 0.521)