DYNAMIC MODELLING OF THE BEPI-COLOMBO SEPARATION SYSTEM

Perturbation Analysis of Mass Properties and Spring Design for Module Separation

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ABSTRACT

The Bepi-Colombo mission is ESA's cornerstone mission to Mercury due to be launched in 2014. The spacecraft is a composite of three modules that will be separated after the long duration cruise stage of the mission is complete (~6 years).

The MTM (Mercury Transfer Module) is the first module to be separated from the MCSA (Mercury Composite Spacecraft - A). The separation occurs when Pyrotechnic bolts are fired, allowing the separation springs to push the two modules apart (Z direction). It is essential that the acceleration is kept to a minimum so that spacecraft appendages are not damaged. A minimum separation velocity and perturbation (roll, pitch, spin and translations in X and Y) is required to:

a) avoid collisions
b) protect vulnerable spacecraft components from high temperatures until sufficient module distance has been achieved

The separation system uses unguided springs in order to reduce weight. The effects on module rotation of these unguided springs needs to be understood as the springs protrude through the high temperature insulation. This insulation could be damaged by uncontrolled rotation of the modules causing the springs to clash with the insulation during the separation event. The separation dynamics are further complicated by the umbilical connectors that are de-mated during the separation event. These connectors have relatively high de-mate friction for a small portion of the separation travel that has to be managed to reduce accelerations and perturbations.

The model is constructed using ADAMS™, a multi-body simulation tool, and utilises ADAMS Insight™ which is a stochastic tool used for Monte-Carlo and sensitivity analysis.

This paper presents the modelling of the separation system, contact modelling and stochastic analysis. This paper discusses the lessons learned and the conclusions drawn from the modelling activity.

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1. BUILDING THE MULTI-BODY DYNAMIC MODEL

EADS Astrium in Stevenage has heritage in designing separation systems having developed the SPELDA and DELTA II launch vehicle separation systems. These systems separated the payload from the booster just after orbit insertion. The mathematical modelling applied to develop these designs was much simpler, being less sensitive from a perturbation perspective, due to the fact that the boosters were much heavier than the payload. Essentially, the separation event was modelled as if the booster was grounded. For the Bepi-Colombo mission the separation modules would have similar mass properties leading to a much higher degree of interaction during the separation event. This fact together with the implementation of unconstrained springs to save weight (both DELTA II and SPELDA used guided springs) meant that a much more detailed mathematical model was required.

To build the dynamic model a number of parameters are required for each module:

1) Mass
2) Inertia in all planes
3) CoG location
4) Spring characteristics (stiffness and preload)
5) Spring locations
6) Allowable spring clearance
7) Umbilical connector characteristics
8) Umbilical connector positions

Some of the parameters are straight forward to model but both the spring and the umbilical connectors behaviour are more difficult.

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1.1. Modelling the Separation Springs

As discussed previously the separation springs are not guided during the separation in order to reduce system weight. A normal compression spring has axial stiffness as well as lateral stiffness. The axial stiffness is essentially linear over the compression stroke, but the lateral stiffness increases as the spring is compressed. Therefore, during separation, the extension of the spring reduces its lateral stiffness. The springs in the model are fixed onto one module (as they would be in the flight) but allowed to deflect laterally as the modules separate, see Figure 1.1-1.

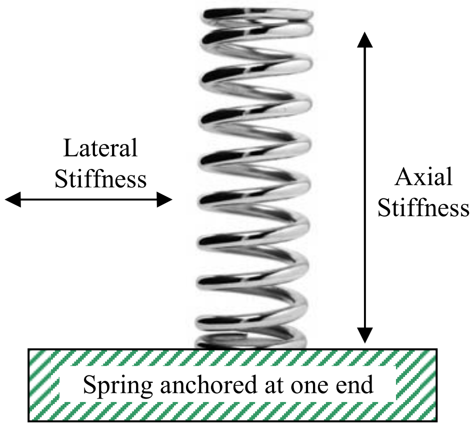

Figure 1.1-1, Spring Characteristics

As the spring reaches the end of its travel it separates from one of the modules. The interaction between the spring and the module is complex at this interface. In the model the spring relies on friction to stay in place otherwise it would try and slide across the separation plane as soon as any perturbation occurred. In order for the spring to separate at the end of its travel contact modeling is used. A contact model models the interaction of colliding bodies. In this case the spring is colliding with the module and the energy is transferred to the module due to the stiffness of the contact. This contact model along with the friction recreates the real-life behavior of the spring, IE:

1) Spring stays in contact (without sliding) with the module whilst a positive preload exists.
2) Spring separates from module when preload = 0
3) Contact stiffness and exponent (the amount of energy transferred in the contact) does not contribute to module separation. IE Coefficient of restitution <1.

1.2. Modelling the umbilical connectors

During module separation four connectors that provide inter-module power and data connectivity are also de-mated. The connectors are equipped with their own de-mate spring and are often described as “zero-force” connectors. In reality this is not the case.
A similar connector was used on the Cassini Huygens mission. During development of the connectors, the de-mate forces were measured, with the force vs. distance plot reproduced below.

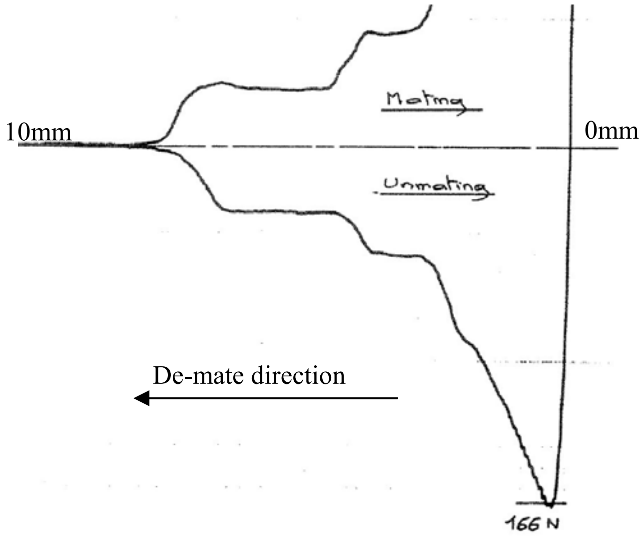

Figure 1.2-1, Connector de-mate force measurement

The plot shown in Figure 1.2-1 shows the typical characteristics of connector de-mate forces. A force of 166N is required to start the de-mate process. This pull force rapidly reduces over the first 4mm of extraction whereupon a plateau is reached. This plateau is pure friction, being constant with respect to position. Another reduced plateau is then reached where friction is evident until the connector/pins are fully extracted and the force is reduced to zero. Any implementation of a de-mate spring will not fully follow this complex de-mate curve as the spring will follow Hooke’s law leading to excess energy. See Figure 1.2-2 below.

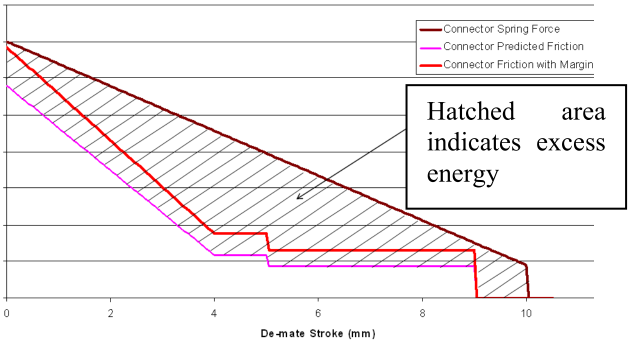

Figure 1.2-2, Connector De-mate Spring and Zero Force Spring Implementation

In order to ensure that there is sufficient force to overcome connector friction for the whole of the de-mate stroke then excess energy is produced as shown by the hatched area in See Figure 1.2-2. The effect of this excess energy is an increase in module accelerations.

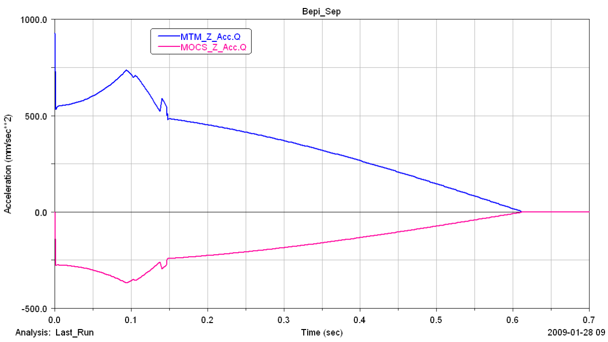

Figure 1.2-3, The effect of Excess Connector Energy Effect on Module Accelerations

Figure 1.2-3 is a prediction of module accelerations from the MBD (multi-body dynamic) analysis tool. The effect of the connector "zero force" springs can clearly be seen as two peaks at the start of separation. These high accelerations are of concern as they result in loading of the module appendages and could lead to a structural failure.

1.3. Modelling the Spring Clearances

As the Bepi-Colombo mission operates close to the Sun a high level of thermal protection is required. Once the separation has occurred then the void left by the springs needs to be covered to stop solar energy penetrating the module. These DTCs (Deployable Thermal Covers) have a finite spring clearance size decided by the layout of the spacecraft. It is vitally important that the separation springs do not snag on these covers as the separation occurs. The multi-body dynamic model has been used to size the DTCs.

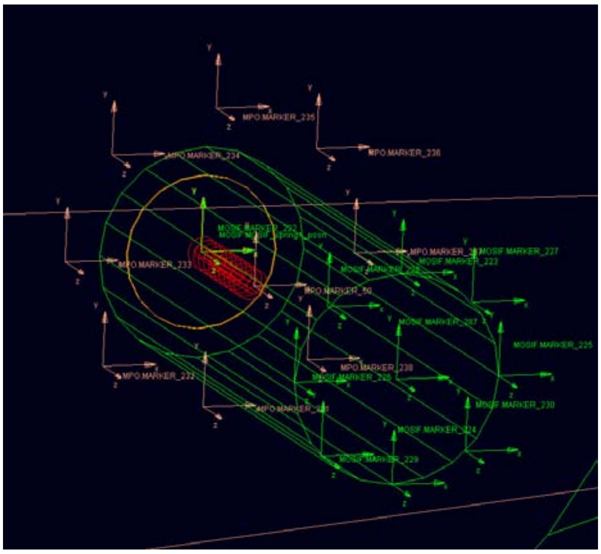

Figure 1.3-1, Monitoring of DTC clearance during separation

In Figure 1.3-1 a view of the MBD model is presented. 8 Markers (x,y,z arrows) are arranged around the end point of the spring (shown as green cylinder) and 8 further markers are distributed on the opposite module to mark out the position of the DTC aperture. The positions of these markers are monitored throughout the separation event producing a graph reproduced in Figure 1.3-2 below.

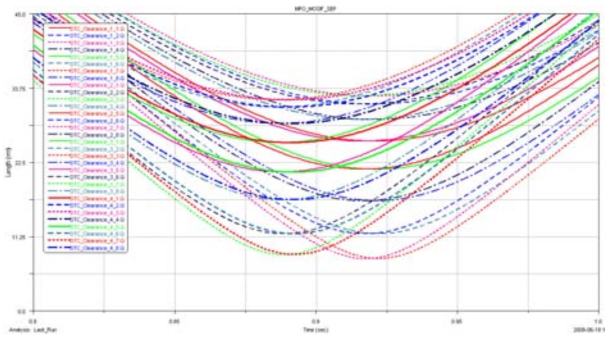

Figure 1.3-2, Graph showing closest approach of spring and DTC aperture

The closest approach is captured and the marker can be easily identified. Using this technique, the aperture size of the DTC can be determined without over-sizing due to unknowns. This will effectively reduce the DTC aperture size and help maintain thermal protection to the spacecraft even if the DTC failed as the aperture size will be minimized.

2. STOCHASTIC (MONTE-CARLO) ANALYSIS

As with every complex system there is an element of uncertainty in the actual value of the spacecraft and component key parameters. Inevitably the mass properties (mass, inertia and CoG position) of the system will fluctuate during the development process; there will be tolerances in the FM build with respect to spring position and orientation; the separation spring preloads and stiffnesses will have some variability along with the connector characteristics.

Traditionally a complex system was designed for the worst case, but this leads to over-design. For example, worst case mass from an acceleration point of view occurs when the modules are lightest. But worst case minimum velocities occur when the modules are heaviest. The system is too complex to design for one case.

Stochastic analysis has been used to design the Bepi-Colombo separation systems. Each variable is given a tolerance and a likelihood of occurring. Some skewing of this probability is also used for some parameters. For example, it is highly unlikely that the separation springs will become stiffer over time, but creep may mean that some of the preload is lost, skewing the probability in one direction. Others parameters like CoG position are just as likely to be 10mm out any direction so are not skewed.

3. RESULTS FROM MONTE-CARLO ANALYSIS

	Units	Mean	Standard Deviation	Variance	Min	Max	Requirement	Units
MTM_ZVel	mm/s	218.0	5.08	25.84	204.38	228.82		mm/s
Stack_ZVel	mm/s	-108.6	3.18	10.08	-115.98	-102.42		mm/s
Combined Sep Vel	mm/s	326.6	3.61	13.00	319.83	333.73	>300mm/s	mm/s
MTM_Roll	deg/s	-0.021	0.011	0.000	-0.044	0.002	<1 °/s	°/s
MTM_Pitch	deg/s	-0.098	0.045	0.002	-0.186	-0.001	<1 °/s	°/s
Stack_Roll	deg/s	-0.021	0.009	0.000	-0.042	-0.005	<1 °/s	°/s
Stack_Pitch	deg/s	-0.100	0.047	0.002	-0.192	0.002	<1 °/s	°/s
MOCS_Z_Accelaration	mm/s/s	-372.8	11.40	130.06	-396.8	-347.32	<300mm/s/s	mm/s^2
MTM_Z_Acceleration	mm/s/s	939.8	29.85	891.03	864.02	1002.95	<500mm/s/s	mm/s^2
MTM_LAT_X_Vel	mm/s	-0.3	1.13	1.28	-3.41	2.91		mm/s
MTM_LAT_Y_Vel	mm/s	0.9	0.87	0.75	-0.88	3.22		mm/s
MOCS_LAT_X_Vel	mm/s	0.1	0.57	0.33	-1.35	1.74		mm/s
MOCS_LAT_Y_Vel	mm/s	-0.4	0.43	0.18	-1.59	0.47		mm/s

The MBD (multi-body dynamics) model generated includes 65 independent variables that have been given tolerances, a probability of occurrence and skew to accurately predict the range of velocities, perturbations and accelerations during the separation. For such a complex system a high number of runs (>1000) need to be ran automatically in order to provide enough accuracy. If each run takes ten minutes then the analysis will be complete in 7 days! In order to keep run times low the number of independent variables needs to be controlled. Some sensitivity analysis is intended to justify omission of some variables from the study, which are not contributing significantly to the separation perturbations.

4. CONCLUSIONS

The use of the MBD tool coupled with the stochastic tool has enabled a much better understanding of the module separation event that would not be possible with a 2D spreadsheet approach. The effect of the umbilical connectors modelling; the lateral spring stiffness modelling and the DTC clearance monitoring will provide knowledge that will in the end lead to a more tailored design of the separation system, reducing mass and increasing likelihood of a successful separation. The stochastic tool has allowed sensitivity analysis to be performed quickly, leading to better understanding of the key drivers in the system. Overall, closer study of such perturbations has allowed for greater optimisation in terms of separation margins, particularly through better understanding of the time-variant force components like the umbilical connectors. In terms of validating mechanical clearances during separation, it has also been beneficial to mitigate such a risk by analysis.

5. FURTHER WORK

In order to increase the accuracy of the separation system some further work has been identified.

5.1. Spring lateral Stiffness

A more realistic separation spring is to be added to the model where the lateral stiffness changes with spring extension. The MBD model only allows for linear stiffness in its flexible body models so a custom model needs to be created to capture such effects.