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SPOT-4 solar array deployment - tests/analyses correlation

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Abstract

To validate the complex in-flight deployment of the new SPOT solar array, a mix of accurate simulations and ground tests was required. We describe in this paper the activities performed at MATRA MARCONI Space to predict the kinematics and dynamics of the deployment with special emphasis on the ground tests which were conducted to validate our prediction models. The successful in-flight deployment of a solar array of the same design has confirmed the validity of our analyses.

1 Introduction

For the new series of SPOT platforms, including the platform used for the SPOT4 satellite, a new type of solar array has been developed by Aérospatiale. This solar array uses a deployment technique which allows an unregulated, passive deployment for complex array configurations. The overall array configuration is shown in figure 1. It is made of a yoke connecting the spacecraft main body to an array made up of five solar panels. The body, the yoke and the panels are connected by a new type of hinge device, called ADELE, developed by Aérospatiale to provide both a driving torque for deployment and sufficient stiffness to hold the array in the deployed configuration. The driving torque at deployment is created by folded metal blades (the so-called Carpentier joints). When the ADELE is open an antibacklash system prevents the hinge from closing back. Three different types of ADELE hinges are used for a total of six hinges (A1 to A6) needed for deployment; they differ only by the value of their driving torque. The total energy provided by one ADELE during deployment varies between 0.96 and 2.4 Joule.

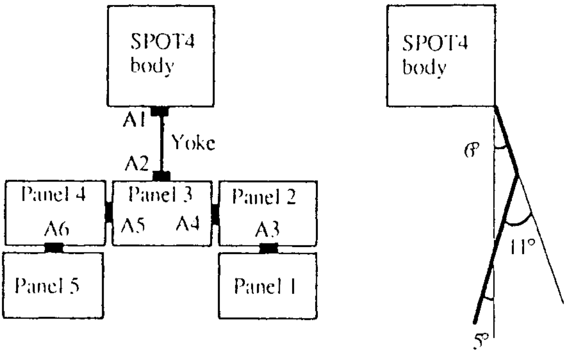

Figure 1 - Solar array configuration

The deployment is performed in two steps (see figure 2). The first step, called primary deployment, is initiated immediately after launcher separation in order to allow the use of thrusters which are located under the array in launch configuration. This 2-D deployment is used to deploy the yoke, a stack of four panels attached together (panels 2 to 5) and panel 1. Then a three-axis stabilisation is performed which has the advantage to damp the solar array flexible modes which were excited during primary deployment. The second step, called secondary deployment, follows with the deployment of the last four panels in 3-D after which the spacecraft is again three-axis stabilised. During both deployments, the spacecraft attitude control system is turned off to avoid extra disturbances that could be created by the thrusters.

This solar array deployment cannot be tested on the ground: the spin rates conditions (at launcher separation) of the primary deployment cannot be reproduced and the 3-D secondary deployment cannot be performed because of the complexity of the gravity compensation device which would be required. In addition, the aerodynamic forces would create torques on the hinges which would not be negligible compared to the ADELE driving torque. Extensive analyses and simulations are therefore required.

MATRA MARCONI Space, as prime contractor of the SPOT series of platforms, developed accurate simulation tools to predict the in-flight deployment kinematics and dynamics of the solar array attached to the platform. These analyses are presented in [1].

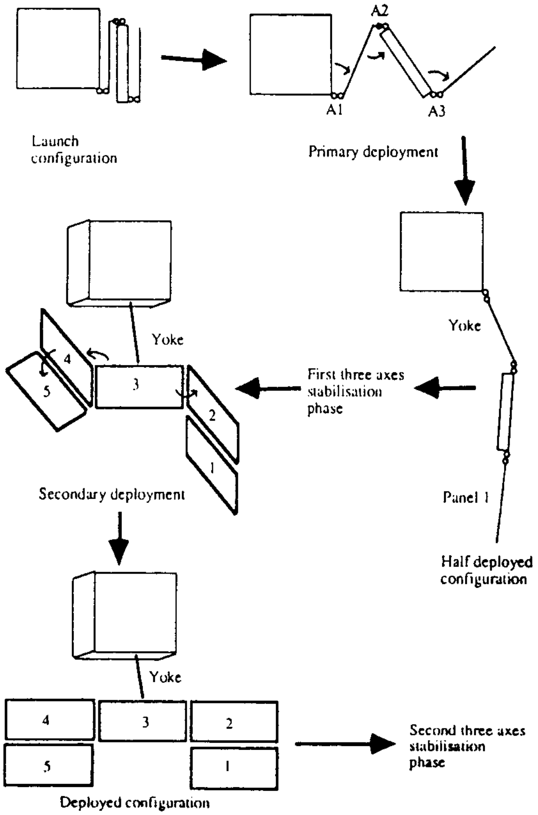

Figure 2 - Deployment sequence

2 Deployment dynamics validation approach

Given the large number of parameters involved, a large set of simulations was required to fully validate the deployment sequence (duration of both primary and secondary deployment, torque margin, contact margin with the structure, forces and torques generated in the structure) and its interaction with the spacecraft attitude control system (induced spacecraft angular rates, S/C stabilisation duration after each deployment). Failure cases were also analysed. This process led to a satisfactory validation of the deployment.

However, as explained in [1], the simulation results showed unexpected levels of forces in the hinges at locking. Extensive analyses performed by MATRA MARCONI Space, CNES and Aérospatiale allowed to explain these phenomena. It appeared that a combination of some geometric features (yoke shape, solar array cant angle) and of the high non-linearity of the ADELE torque profile around 180 deg could explain the relatively large amount of energy transferred to the high frequency mass modes (above 10 Hz) of the yoke which were responsible for the high level forces found by simulation.

Nevertheless, given the criticity of the solar array deployment and the potential impact of these predicted forces, it was decided to perform a complementary validation by ground tests. The geometry of the solar array deployment is such that only a test representative of the primary deployment could be envisaged. Given the solar array size, it appeared also that the complete primary deployment configuration could not be tested on available test facilities because of limitations in the available test benches size; it, therefore, had to be reduced to a two-body deployment (see test configuration below).

At the same time, the test had to validate the simulator, named DYGEST, used for most of the actual deployment simulations and analyses. DYGEST (presented in [1]) is an ad-hoc simulation tool, specifically developed at MATRA MARCONI Space for the deployment analyses and it appeared that it could not be adapted to another deployment configuration such as the ground test configuration. Since the validation could only be assessed through successful comparison of test results with corresponding predictions by simulation, intermediate steps had to be introduced in the DYGEST validation process. This has been done using the DYNAMICA software.

DYNAMICA is an automatic generator of dynamic simulation programs developed at MATRA MARCONI Space (see [2] for a more complete description of DYNAMICA). Using symbolic computation techniques, it derives the equations of motion of any given system of interconnected rigid or flexible bodies and translates them into an highly optimised FORTRAN code, directly suitable for simulations or usable as dynamic kernel in any user simulation environment. The particular kinematics of the ADELE hinge has been introduced in DYNAMICA, allowing the generation of simulators of the in-flight deployment and of the test configuration.

Figure 3 shows the deployment validation approach using ground tests and the DYGEST and DYNAMICA software. It shows how DYGEST has been indirectly validated by the ground deployment tests. First a perfect correlation has been demonstrated between the DYGEST simulation results and results coming from the simulator generated by DYNAMICA. Second, the correlation between test results and predictions given by the test simulator generated by DYNAMICA validated at once both the ground test simulator and the flight deployment simulator generated by DYNAMICA, since the dynamic kernels of both simulators were generated the same way and the other models such as the ADELE torque profile were exactly identical.

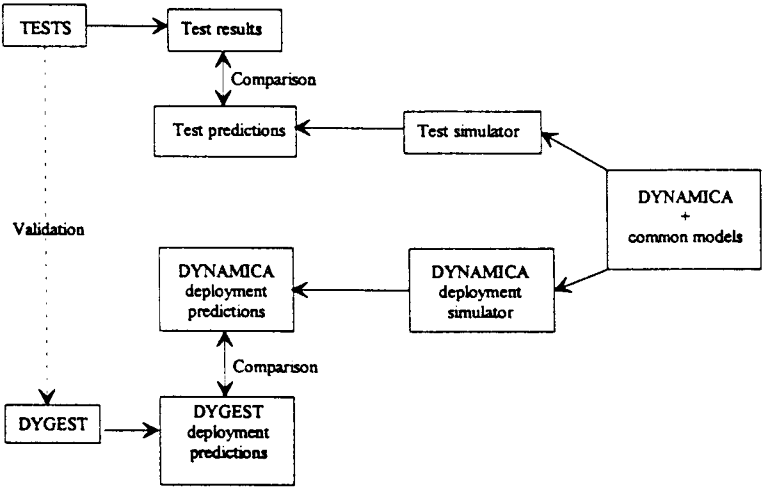

Figure 3 - Simulator validation approach

3 Ground deployment test configuration

Two major objectives were given for the implementation of the ground deployment tests: they should be as representative as possible of flight conditions and they should provide maximum observability of the kinematics and dynamics parameters.

Tests representativity of in-flight behaviour was obtained by:

- the use of the yoke flight model which links the platform to the solar array,

- two flight-model ADELEs at each extremity of the yoke including the electrical cables used to carry the solar array current,

- the use of a mock-up array stack as representative as possible of the real array mass-inertia characteristics,

- two, especially designed and manufactured, air bearing devices to provide a 0g environment to the deployment,

- the minimisation of disturbing torques and forces due to the test bench by using a flat granite table.

The observability of the major physical parameters is provided by:

- video-acquisition of the deployment kinematics ,

- accurate measurement of accelerations and forces/torques at selected points of the solar array model,

- high-frequency acquisition of the relevant parameters with an overall bandwidth (hardware plus software) larger than 500 Hz.

In addition, schedule constraints led to the reuse, as far as possible of existing test equipment. The full tests were conducted over a period of four months in 1994.

3.1 Test bench description

The deployment test bench was made of four main elements: a flat granite table, the solar array model, the measurement acquisition tools and the data acquisition and processing electronics.

A large flat granite table is available at MATRA MARCONI Space in Toulouse. It lays on an aseismic floor and has dimensions of 3.2 by 9.6 meter. Before the deployment tests, the flatness was checked and showed that there was in fact a tilt of +310 μm/m along the table length and - 42 μm/m along the table width.

The solar array model was made up of several different mechanical parts as shown in figure 4:

- a socket simulating the S/C platform. This part is fixed on the aseismic floor and has a very high stiffness,

- the first ADELE (AE) with a set of 9 flexible cables normally used to carry the solar cells current. The axis of this joint is adjusted to be perpendicular to the table with an accuracy better than 0.05 degree,

- the flight model of the yoke,

- the second ADELE (AB) almost identical to the first joint with an arrangement of the flexible cables as close as possible to the flight configuration,

- the simulated arrays stack with dimensions and mass constrained by the table size and the maximum load of each air bearing cushion. It is made of a steel beam and additional adjustable masses. Its total weight is about 55 kg.

- the two air bearing cushions. They have been designed and manufactured by BERTIN under a CNES contract. Each cushion is made of a baseplate sliding on the table and a mechanical payload articulated together through a knee joint. The payload up and down motion is controlled by a feedback system which maintains a constant vertical force using compressed air. The feedback control software is running on a dedicated PC computer and the compressed air is provided by a high pressure bottle mounted on the cushion. Three force sensors, one control valve and some pneumatic services complete this device which weighs about 11 kg.

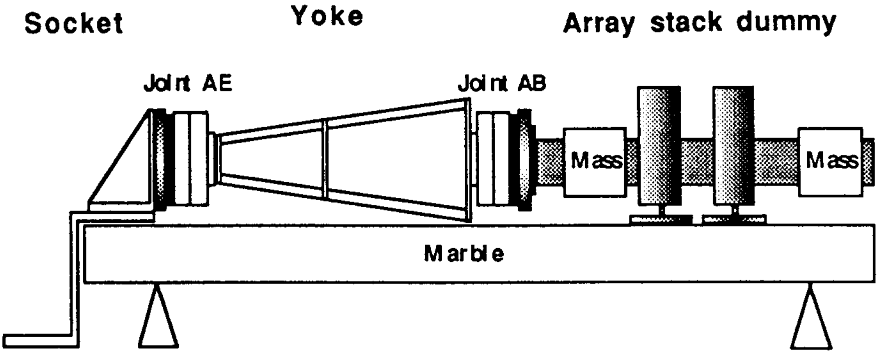

Figure 4 - The solar array test model

Several data acquisition sensors were used concurrently during the tests:

- horizontal position sensors: a no-contact measurement technology was used. The system was made of four infra-red diodes distributed on the solar array model (see figure 5) with a camera placed at four meters above the table giving for each diode two analogue signals corresponding to the coordinates of the diode in the horizontal plane. The camera field of view was 4 x 6 meters and the accuracy in position was better than 2 cm with a scanning rate of 8 kHz.

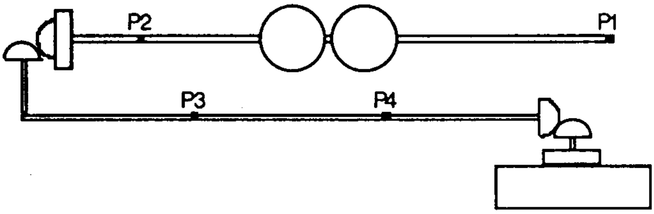

Figure 5 - Horizontal position sensors layout

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- vertical position sensors: two height sensors (based on LVDT technology) were installed on the air bearing cushions to verify that feedback control maintained the solar array model into the allowed vertical limits of ± 7 mm.

- accelerometers : four sets of two-axis accelerometers were installed as shown on figure 6. Three of them were fixed on the ADELE cylinders to measure high-frequency phenomena. The accelerometers had a full scale of ± 10 m/s^2.

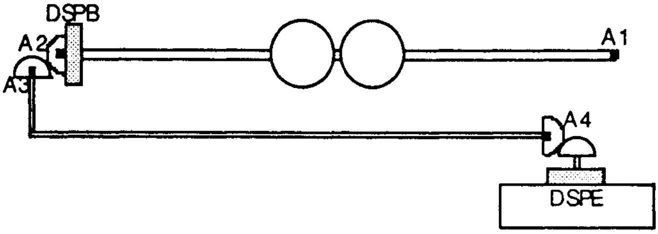

Figure 6 - Accelerometers and force sensors layout

- force and torque sensors: two sophisticated strain-gauge sensors, DSPE and DSPB, were installed close to each ADELE, as indicated on figure 6. They provided measurements at 1 kHz with an anti-aliasing filter over a full scale indicated in the following table for each axis.

	X axis	Y axis	Z axis
Full scale force (N)	1000	350	1000
Full scale torque (Nm)	60	250	60

To be representative of the flight model, we had the constraint to only use, to carry the acquisition sensors signals, the flexible flat cables that are implemented on the solar array to carry the current generated by the solar cells. The use of other cables could have caused unwanted forces and torques during deployment. Consequently we used flight quality cables geometrically arranged like on the actual solar array.

For the data acquisition and processing electronics, a VME bus architecture was selected with two processing units:

- a dedicated CPU running under VxWorks to acquire the signals at 1 kHz

- a SUN/Solaris CPU for test monitoring, data recording and post processing.

3.2 Sequence of tests

After test bench integration, 32 different test cases were performed successfully covering the following configurations:

- partial deployments until locking of each ADELE,

- nominal deployments including normal and repeatability tests,

- failure simulation by reduction of the ADELE energy,

- worst case simulations of a spinning satellite with an initial impulse to the array adding energy of 0.2 J, 0.45 J and 0.77 J,

- ADELE characterisation performed in static and dynamic modes, including especially observation and monitoring of the successive bucklings and unbucklings of the ADELE Carpentier joints.

Because of the low-level driving torques of the ADELE, careful balancing of the solar array model was required to avoid introducing disturbing forces and torques. Problems were initially experienced when balancing the solar array. When balanced in the folded configuration, small misalignments amplified the vertical motion of the array as soon as deployment started and the air cushions feedback control sent quickly the devices to the limits of the vertical range. The problem was solved by balancing the solar array model in the half deployed configuration of figure 7 which presented the lowest yoke torques which could be compensated manually by setting the force set point of air cushion device.

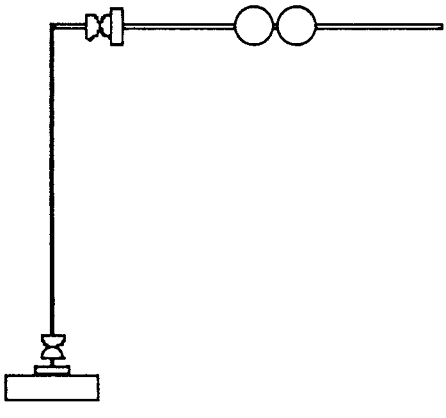

Figure 7 - Test set-up balancing configuration

4 Correlation of tests results with simulations

4.1 Test predictions

The dynamic representation of the solar array model used for simulations is shown on figure 8. The two air bearing devices are modelled as external torques acting on the array stack dummy. The light but non negligible table mean slopes are also modelled.

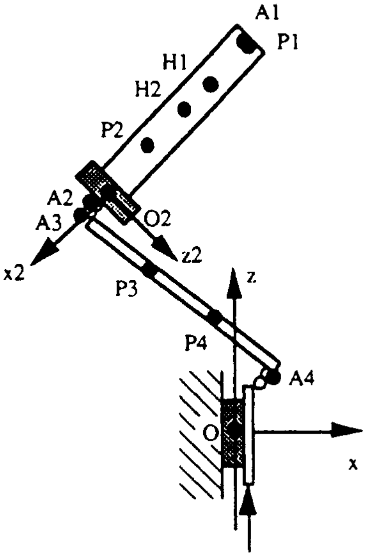

Figure 8 - Dynamic model of the test configuration

Preliminary simulations were performed to assess the feasibility of the test, especially in terms of representativity with respect to the actual in-flight primary deployment. These simulations demonstrated that the representativity was very good with respect to all the deployment main characteristics, in particular the order of hinge locking and the efforts (torques and forces) at the hinges.

Sensitivity analyses were also performed in order to identify the main parameters and to evaluate the achievable accuracy on the results. These analyses contributed therefore to the test bench definition (e.g. required sensor bandwidth and resolution). One of the main identified point was the balancing of the test dummy which had indeed to be very good in order to avoid disturbing efforts in the yoke and too large variations of the air cushions vertical positions; as described above, this was one of the main difficulties encountered during test set-up. These analyses also proved that the test table slopes were in fact favourable since, by increasing the available system energy, the generated efforts at the hinges were closer to the flight predictions than without any slope.

The tests themselves and therefore the associated simulation activities have been divided in two parts, named below the intermediate tests and the final tests.

The intermediate tests have been performed on a simplified configuration: a single ADELE, a rigid mass/inertia dummy and a single air bearing device. The modelled and measured ADELE torque profiles are shown on figure 9.

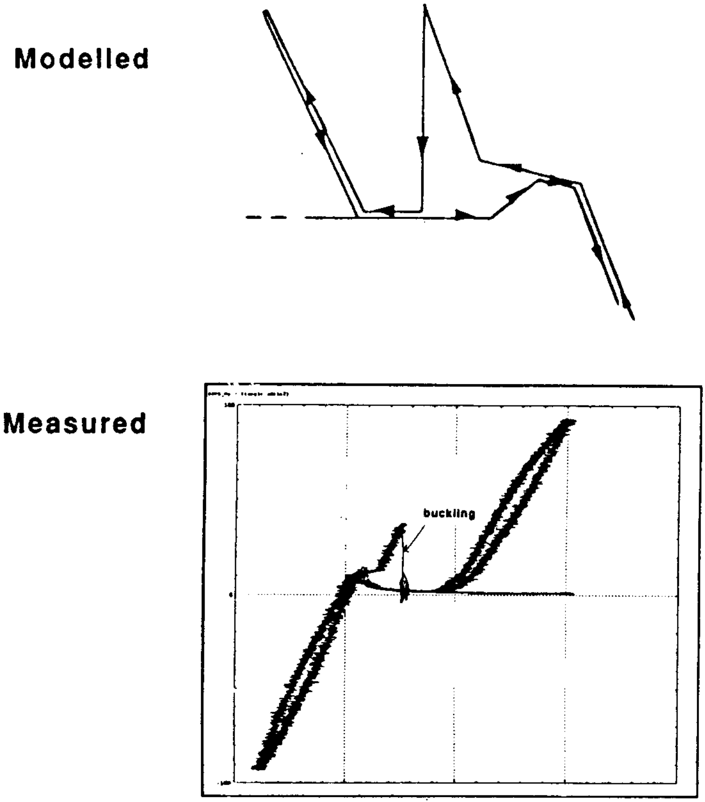

Figure 9 - Modelled and measured ADELE torque profiles

The test results demonstrated that the ADELE modelling was globally correct (in terms of kinematics, energy, shape of the motor torque profile) but also showed unexpected results, mainly high frequency force peaks, very limited in time (less than 0.1 s) but reaching surprising levels (up to 1000 N). Thanks to the high quality measurements and to investigations using a video camera, it could be established that these force peaks coincided with the ADELE Carpentier joints bucklings and unbucklings, themselves responsible for a loosening of the hinge cylinders followed by an extremely fast tightening (cylinder translation) generating the forces.

The intermediate test results allowed also to correct some discrepancies in the numerical parameters of the torque profile model around 180 deg. These discrepancies could satisfactorily be explained by the fact that parts of the ADELE stiffness were not taken into account in the original model. This led to differences in the slopes of the models - therefore, for a given system energy, in the predicted maximum torques - and also in the hysteresis of the ADELE- therefore in the amount of dissipated energy during an unbuckling-buckling cycle.

The correction of the model allowed to predict with a high accuracy the torque at the hinge (maximum value, frequency, etc.) and the number of unbuckling-buckling cycles. The complex phenomena leading to the force peaks has however not been modelled since, being very reproducible, it could be predicted in association with each buckling or unbuckling.

The final test predictions consisted mainly in sensitivity analyses in order to establish success criteria with respect to the test results. According to these analysis and the intermediate test experience, an high confidence could be gained in the predictions of the kinematics, i.e. the hinge locking times. However, concerning the efforts, more uncertainties had to be taken into account since both ADELEs of the final configuration were not exactly identical (as in the actual solar array). Therefore, the updated model of the first ADELE could not be used as is for the second one. The main uncertainties of the predictions were therefore relative to the second ADELE model.

4.2 Final tests results analyses

As indicated before, many test series have been carried out, leading to a large amount of data; the analysis of the final test results focused on the following points:

- **deployment kinematics** (figure 10): with the horizontal position sensors, the evolution of the hinge angles during the deployment could be measured with a high accuracy. It showed, for both hinges, a nearly perfect correlation with the simulations, in the nominal cases as well as in the deployments with additional energy. This result reinforced the intermediate test conclusion: our modelling is very accurate with respect to the ADELE kinematics, the ADELE motor torque curve (up to locking), the electrical cables resistive torque and also the test table slope effect. As a side result, this strong correlation also proved that the simple air bearing device model used for the simulations was sufficient and that the transverse torques, due to the unavoidable residual unbalance of the test dummy and acting on the yoke and the ADELE, had no significant effect on the kinematics.

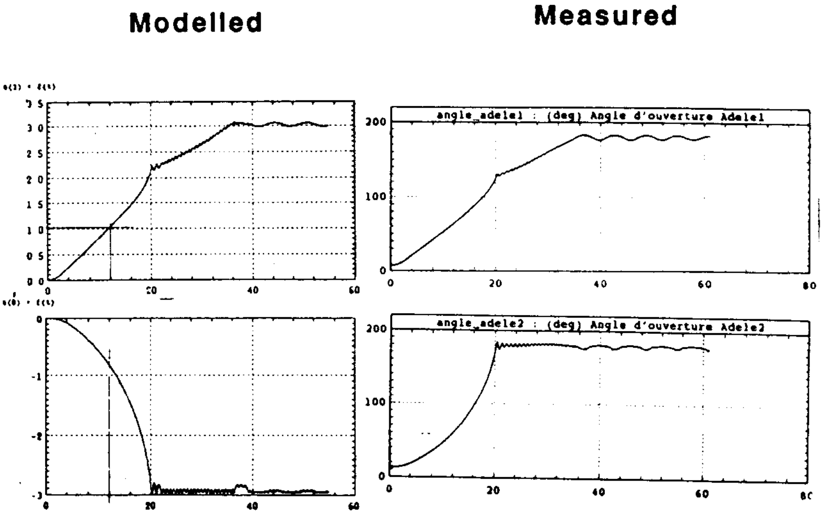

Figure 10 - Modelled and measured ADELE deployment angles

- **second ADELE characterisation:** the second ADELE was characterised during the final tests as the first one during the intermediate tests, i.e. alone with a simple inertia dummy. Similar results were found, in particular similar slope and hysteresis area errors with respect to the initial model which were due to mechanical stiffness not taken into account. Identical peak forces coinciding with hinge bucklings and unbucklings were also observed, leading to the conclusion that, as expected, all ADELEs had a similar dynamic behaviour. Other investigations allowed also to establish that some ADELE torque profile characteristics around 180 deg as well as the force peaks maximum were in fact slightly dependent on parameters such as the initial alignment of the hinge anti-backlash system or the level of external transverse torque acting on the hinge. All these phenomena, although not modelled, could be satisfactorily explained and anticipated on subsequent tests.

After the second ADELE characterisation, an excellent correlation, for both hinges, between test and simulation results was also shown for the torques about the vertical axis, as well in terms of level as in terms of frequency. In particular, the energy losses in the hinge hysteresis cycles were well represented leading to an exact prediction of the number of bucklings and unbucklings during deployment.

- **forces about X and Z**: two physical phenomena must be distinguished to explain these horizontal forces. First, according to the ADELE characterisation results, high peak forces corresponding to the hinge bucklings and unbucklings were expected but not observed. After investigation, it appeared that the yoke longitudinal stiffness was sufficiently lower than the ADELE one to filter the peaks. As a consequence, the peaks were much lower than in the ADELE characterisation configuration (one ADELE plus a rigid body).

Second, the horizontal forces due to a transfer of energy in the yoke longitudinal mass modes were expected. In fact, it appeared that the force frequencies (around 10 Hz) were correctly reproduced by simulation, confirming the excellent modelling of the yoke flexibility. However, the force levels were much smaller than predicted. This result could not be fully explained. It is nevertheless likely that it is a consequence of the hinge cylinder loosening during the buckling and unbuckling phases, leading to a different distribution of the energy in the yoke mass modes. However it showed that the simulations were giving an envelope of the tests results, even taking into account the buckling force peaks since the highest value measured in the final tests remained lower than the highest predicted value. Nevertheless, despite this favourable result, the maximum peaks were still expected to occur for the ADELEs connecting two rigid solar panels and therefore not connected to the flexible yoke (during the secondary deployment, for instance).

Finally, the test results, especially the updated ADELE models, were used for an update of the flight predictions, taking also into account the unmodelled force peaks. These new simulations were found to be very consistent with the original simulations and therefore did not lead us to reconsider the previous validation and qualification results of both the deployment and the mechanical design of the solar array.

5 Conclusion

The development and validation of the new SPOT solar array deployment has provided a rare opportunity to validate a complex deployment dynamics software using ground tests in a controlled configuration. All the basic modelling assumptions we had taken have been validated by the ground tests. The recent first flight deployment of a solar array of the same design has provided a further opportunity to check the accuracy of our predictions. The dynamics models and software described in this paper can be now confidently used to predict the deployment kinematics and dynamics of this type of solar array in new configurations.

Acknowledgements

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