Analytical Estimation and Experimental Validation of Acceleration at Spacecraft Solar Array Latch-up Considering Differential Latching

B. Lakshmi Narayana, Gaurav Sharma, G. Nagesh, C.D. Sridhara and R. Ranganath

Abstract Solar array deployment on-board a spacecraft is a mission critical activity. The torque margin over friction torque in the deployment hinge mechanism is an important parameter that ensures positive deployment. Higher torque margin results in higher latch-up moment that affects the design of panel substrates and hinges. Latch-up moment estimated earlier assumes simultaneous latching of hinges. However, in reality, hinges latch at different instants of time due to the presence of closed control loops which has been confirmed by on-orbit observations. The latch-up sequence of the panels influences the distribution of latch-up moments induced at the hinges. In this paper, a mathematical model for a solar array with a yoke two panel configuration is developed using ADAMS software which considers differential latching of hinges. The mathematical model includes the influence of panel flexibility, close control loops, harness, snubbers, ejectors and air drag. The acceleration and moment at latch-up are estimated as a function of time. Deployment time and acceleration at latch-up dictate the magnitude of latch-up moment at hinges and have been compared with experimental value obtained from accelerometer mounted on the outermost panel, during ground deployment test. The novelty in the present work is the formulation of a test validated methodology to analyse the deployment dynamics of a multi-panel solar array considering differential latching which has the potential to simulate the latching of solar array more accurately compared to previously adopted methods. It will be useful in carrying out deployment dynamics of futuristic solar arrays with larger number of panels.

Keywords Solar array · Dynamics · Differential latching · Acceleration

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1 Introduction

A typical solar array used in satellites consists of a yoke and one or more number of panels. It is kept stowed during launch and deployed in the orbit. The yoke and panels are interconnected by hinges. The deployment of solar array is extensively tested and verified on ground before deployment in the orbit. The ground deployment testing of a solar array consisting of a yoke and two panels is shown in Fig. 1, in stowed, partially deployed and fully deployed configurations.

The ground deployment of solar array is carried out by suspending the yoke and panels on overhead zero-g test set-up. The force in the overhead zero-'g' spring is adjusted to balance the weight of the yoke/panels so that the hinges do not experience load. The energy for the deployment is provided by preloaded torsion springs mounted at the hinges along the hinge lines. The Close Control Loops (CCL) provided between Yoke-Panel 1 and Panel 1-Panel 2 enable coordinated deployment ensuring that each panel opens up by a similar angle and latches near
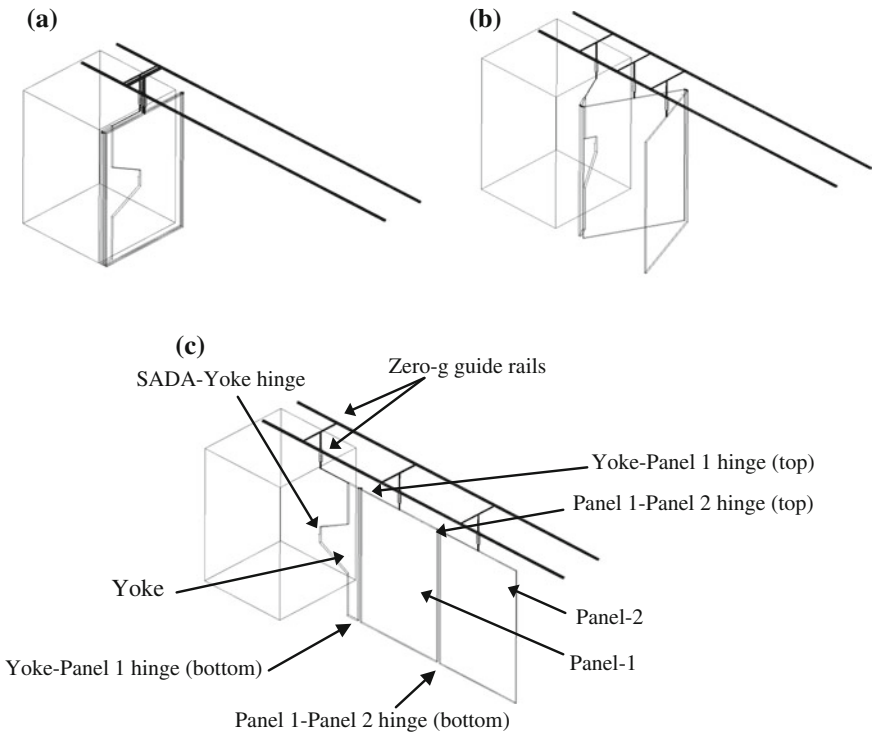

Fig. 1 Schematic of ground testing of solar array deployment. **a** Solar array (stowed). **b** Solar array (partially deployed). **c** Solar array (fully deployed)

simultaneously with respect to other panels (Fig. 6). This minimizes the inter panel latch up shock because the momentum gets countered between the successive joints due to change in the direction of rotation.

The latching of hinges produces latch-up shock at the hinges which needs to be estimated as it is an input for design of hinge mechanism and yoke/solar panel substrates. The dynamics of deploying solar array has been studied by many researchers in the past. Nataraju and Vidyasagar [1] formulated the deployment dynamics of a yoke and three panel configuration using Lagrange's method assuming the panels to be rigid. Subsequently, the latch up shock was estimated for the single solar panel by energy method [2]. Nagaraj et al. [3] studied the deployment dynamics of two flexible links with revolute joints undergoing locking. The flexibility was modeled by finite element method and locking was modeled by momentum balance method. The theoretical results were validated by experiments. The study on yoke and two panel configuration of solar array was extended for 'n' panels by Balaji et al. [4] using matrix approach. The authors also considered the effect of damper and air drag in the model. The energy transfer for each stage of locking for flexible links was addressed by Nagaraj et al. [5]. de Faria et al. [6] evaluated the latch-up force through transient dynamics for the Brazilian solar array. The link flexibility of multi-link flexible structures was modeled by Na and Kim [7] using Timoshenko beam theory and compared with the experimental results of two flexible links undergoing locking, as carried out by B.P. Nagaraj et al.

As observed from above survey, the latch-up moments at the hinges of a deploying appendage on spacecraft were either estimated by energy method or by transient dynamic analysis both of which assume simultaneous latching of hinges. The energy method assumes that the latch up kinetic energy is absorbed by the deployed solar array in the form of strain energy. The loading distribution is assumed triangular and the strain energy of the deployed array is calculated for unit angular acceleration which is then scaled up to obtain equivalent angular acceleration for the latch-up energy. The magnitude of loading is then the product of equivalent angular acceleration, mass per unit length of yoke/panel and distance along the yoke/panel. In transient dynamics, the velocity distribution of the solar array at latch-up is assumed triangular and is obtained from the rigid body dynamics. It is then taken as an initial condition for finite element model of deployed array to estimate the latch up moments at hinges. In actual scenario, latching takes place at different intervals of time due to flexibility of CCL wire ropes connecting yoke to first panel and first panel to second panel. The latch-up moment experienced by the hinges depends on the sequence of latching of the panels. Therefore, a model that predicts the latch-up moment at hinges considering differential latching would be more accurate compared to earlier methods.

In the present work, the deployment dynamics is carried out for solar array having a yoke-two panel configuration in a single software platform ADAMS considering differential latching of hinges. Mathematical modelling includes the influence of panel flexibility, close control loops, harness, snubbers, ejectors and air drag.

Simulations are carried out for ground and on-orbit conditions and acceleration/ moment at latch-up are estimated as a function of time. The time taken for array deployment and the acceleration at latch-up are indicative parameters that dictate the magnitude of latch-up moment. These have been measured in the test and used to validate the correctness of analytical estimates. The paper is organized as follows. Section 2 provides the details of modeling, Sect. 3 presents the results of analysis and test and Sect. 4 summarises the essential findings of the study.

2 Details of Modelling

2.1 Modelling of Yoke and Panels Flexibility

Based on the FFT of on orbit body rates at solar array latch-up of an earlier satellite, first bending natural frequency was observed to be 0.73 Hz. The geometry and flexibility parameters of yoke and panels were modeled to achieve 0.73 Hz using PATRAN finite element software. The modal neutral files generated for yoke and panels were imported to ADAMS/View. A revolute joint is created between yoke and ground. A torsion spring of known pre- rotational angle and stiffness is created along the axis of this joint. Panel-1 is positioned keeping the required gap between it and the yoke. Two rigid links are created between the Yoke and Panel-1 facilitating the creation of a revolute joint where the torsion spring is modeled. The procedure is repeated for other inter-panel hinges.

2.2 Modelling of Closed Control Loop (CCL)

A typical CCL used in solar array consists of a pre-tensioned wire rope passing over two pulleys mounted between the successive joints as shown in Fig. 2. The generalized coordinates are shown in Fig. 3.

In the absence of tension springs in CCLs for a given angle α of the yoke, the panel should rotate by angle α_P as given in Eq. 1 but due to tension spring the first
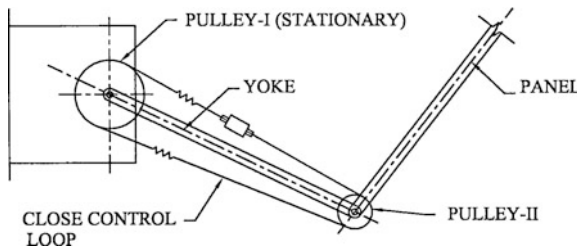

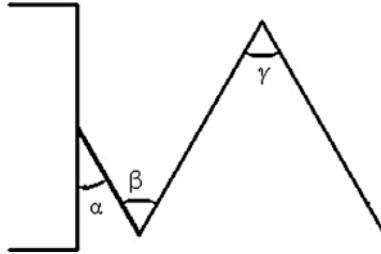**Fig. 2** Schematic of CCL connecting yoke and first panel

Fig. 3 Generalised coordinates

panel rotates by angle β which changes the length of CCL springs affecting the energy in the tension springs through which the torque between the joints gets adjusted.

$$\alpha_P = \frac{R_{PY}}{R_{P1}} \alpha \tag{1}$$

where, R_{PY} is the radius of yoke pulley and R_{P1} is the radius of panel-1 pulley. The feedback energy of the tension springs is calculated as ½ (difference in the angle of rotation)^2 (radius of pulley)^2 (spring stiffness). It is calculated as:

$$U_{C1} = \frac{1}{2} \left[\frac{R_{PY}}{R_{P1}} \alpha + \beta \right]^2 R_{P1}^2 (k_{C11} + k_{C12}) \tag{2a}$$

$$U_{C2} = \frac{1}{2} \left[\frac{R_{P2}}{R_{P3}} \alpha + \gamma \right]^2 R_{P3}^2 (k_{C21} + k_{C22}) \tag{2b}$$

where, R_{P1}–R_{P3} are the radii of pulleys 1–3, k_{Cij} are the equivalent stiffness values of CCL loop. Summation of potential energy U_{C1} and U_{C2} gives the total energy of tension springs. Taking $R_{PY}/R_{P1} = 2$ and R_{P1}–R_{P3} as R, the generalized force at various coordinates that have been modeled as external forces in ADAMS/View are given by:

$$\frac{-\partial U}{\partial \alpha} = -2(k_{C11} + k_{C12})R^2(2\alpha + \beta) \tag{3a}$$

$$\frac{-\partial U}{\partial \beta} = -(k_{C11} + k_{C12})R^2(2\alpha + \beta) - (k_{C21} + k_{C22})R^2(\beta + \gamma) \tag{3b}$$

$$\frac{-\partial U}{\partial \gamma} = -(k_{C21} + k_{C22})R^2(\beta + \gamma) \tag{3c}$$

2.3 Modelling of Harness and Snubbers/Ejectors

The power generated by solar cells bonded on to the solar panels is transmitted through power cables that extend from one panel to another and from innermost panel to yoke where they are connected to a solar array drive assembly. Measured torque characteristics of the harness are modeled using spline, as shown in Fig. 4. Preloaded snubbers are provided between yoke and spacecraft deck and between panels to enhance the stowed natural frequency of the stack and limit the amplitude of vibration during launch. They also provide initial push force to the deploying panel acting for a very short duration. These are also provided at hold down interfaces to provide initial push force for deployment of panels. This is represented in the mathematical model by a linearly varying force with maximum value at the start of deployment and reducing to zero (once the snubbers or ejectors loose contact). A typical snubber/ejector force variation with time is shown in Fig. 5.
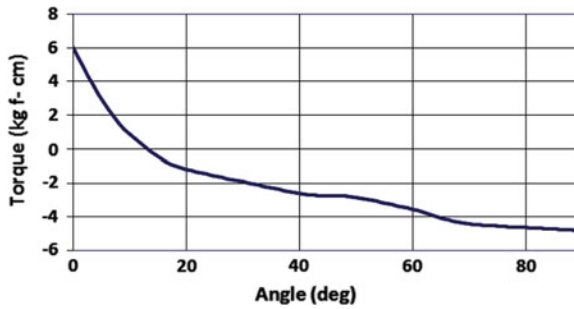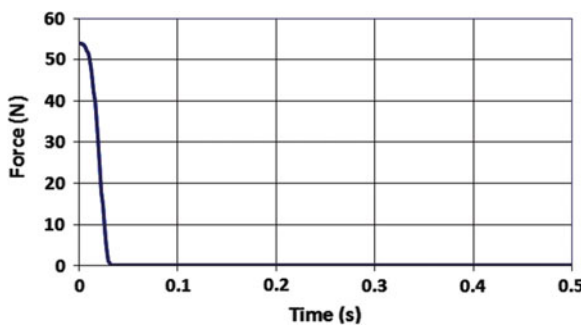
Fig. 4 Typical variation of harness torque

Fig. 5 Typical variation of snubber force

2.4 Modelling of Air Drag

Solar array deployment is carried out on ground to demonstrate the functional requirement of the mechanism. The presence of air drag in the laboratory offers resistance to the deploying panels. Mathematically, the drag force is given by:

$$F_D = \frac{1}{2} C_D \rho A V^2 \tag{4}$$

where, C_D = drag coefficient, ρ = density of air, A = projected area of each strip, V = linear velocity. The panels are divided into ten equal sized strips along the length and the linear velocity of each strip is estimated at each instant of time and the drag force is applied.

2.5 Modelling of Latching

Latching of hinges is modelled using BISTOP [8] function in ADAMS. BISTOP is a two sided impact function that provides resistive torque when the hinge rotates by a predefined angle (90° for SADA-yoke and 180° for inter panel hinges) as a function of angular velocity. This prevents further rotation of the hinges and each latching reduces the degrees of freedom by one. The BISTOP [8] function is defined by following parameters; x: Real variable that specifies the angular displacement to be used for force computation, $\dot{x}$: Real variable that communicates the angular velocity to BISTOP function, x1: Upper limit of x, x2: Lower limit of x, k: Non negative real variable that specifies the boundary surface interaction. In the present model it is hinge stiffness. Experimentally measured hinge stiffness for SADA-Yoke, Yoke-Panel 1 and Panel 1-Panel 2 are used as inputs, e: Positive variable that specifies the exponent of the force deformation characteristics, cmax: Non negative real variable that specifies the maximum damping coefficient, d: Positive variable that specifies penetration at which full damping is applied.

3 Results and Discussion

The simulation is carried out for ground and on orbit conditions. During simulation the torque provided by the BISTOP function are activated once the hinge moves by the predefined angle (90° for SADA-Yoke hinge and 180° for inter panel hinges). As the locking of hinges is not simultaneous, simulation is continued till all the hinges get locked. Locking torques are activated using simulation scripts. The results are presented in following sections.

3.1 Ground Simulation

Simulation provides the deployment time, latch-up velocity of panels, acceleration near Panel 1-Panel 2 hinge, and latch-up moments, during deployment and subsequent to latching. The latching time and peak moments are summarised in Table 1. The variation of angle of opening of yoke and panel joints with time is shown in Fig. 6 and the corresponding latch up moment plots for the hinges are shown in Fig. 7.

It is observed from analysis that SADA-Yoke latches first at 11.88 s, followed by latching of Panel 1-Panel 2 hinges at 12.0 s and final latching of Yoke-Panel 1 hinge at 12.01 s. This matches with the observed deployment time of 12.0 s on ground measurement. Peak moment of 95.0 N m was observed at SADA-Yoke hinge due to first latching whereas the latch-up moments at other two hinges are observed to be nearly equal as they latch nearly at the same time.

The linear acceleration at a point near Panel 1-Panel 2 hinge is measured, as shown in Fig. 8. The predicted and measured acceleration at this location is shown in Figs. 9 and 10 respectively.

It can be observed that the predicted peak acceleration is 0.68 g and matches well with measured acceleration of 0.7 g.

Table 1 Estimated latch-up moment at hinges for ground conditions

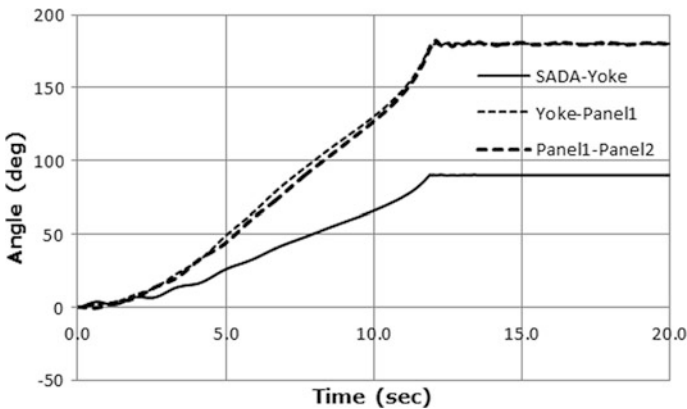|	SADA-Yoke	Yoke-Panel 1	Panel 1-Panel 2
Latching time (s)	11.88	12.01	12.0
Latch-up moment (N m)	95.0	30.0	27.0

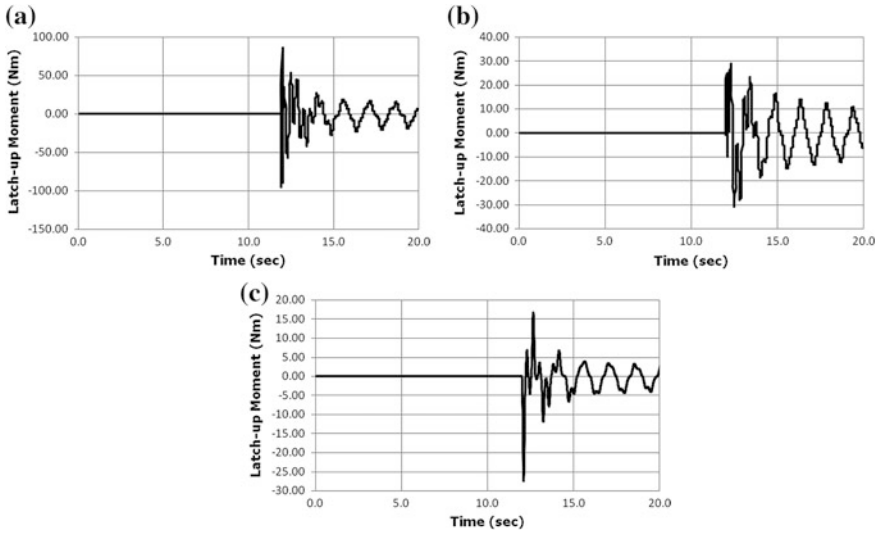**Fig. 6** Angle of opening of yoke and panels with time for ground conditions

Fig. 7 Variation of latch-up moment at different hinges for ground conditions. **a** Latch-up moment at SADA-Yoke. **b** Latch-up moment at Yoke-Panel 1. **c** Latch-up moment at Panel 1-Panel 2
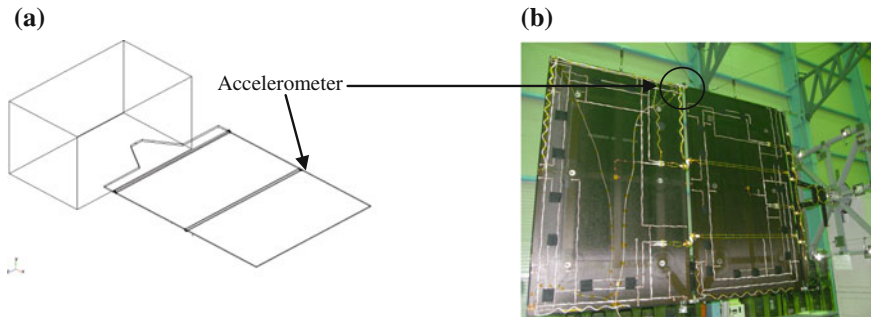

Fig. 8 a Accelerometer location. **b** Deployed solar array
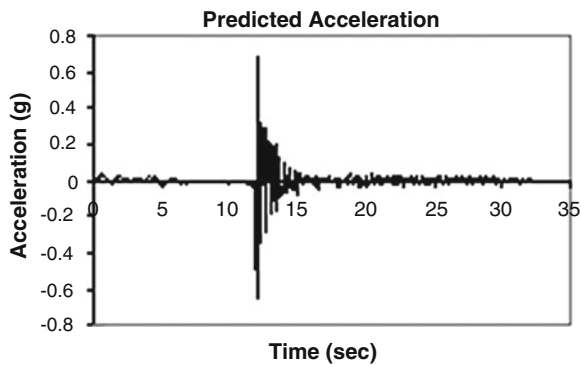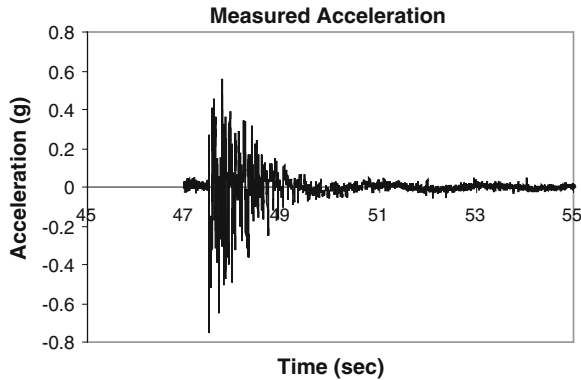

Fig. 9 Predicted acceleration versus time

Fig. 10 Measured acceleration versus time

3.2 On Orbit Simulation

Simulation studies are carried out for on-orbit conditions for estimating the deployment time and latch-up moment. The variation of angle of opening of yoke and panel joints with time is shown in Fig. 11. Latching time and peak latch up moments are presented in Table 2. Lesser co-efficient of friction compared to ground conditions, absence of air drag and effects of zero-g simulation hardware, results in faster on-orbit deployment and higher latch-up moments compared to ground conditions. It may be observed that the sequence of latching on-orbit is
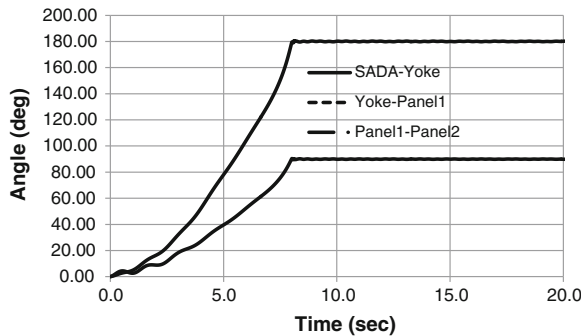

Fig. 11 Angle of opening of yoke and panels versus time for on-orbit conditions

Table 2 Estimated latch-up moment at hinges for on-orbit conditions

	SADA-Poke	Yoke-Panel 1	Panel 1-Panel 2
Latching time (s)	7.9	8.0	8.1
Latch-up moment (N m)	124	52.0	27.0

SADA-Yoke, Yoke-Panel 1 and Panel 1-Panel 2. The peak linear acceleration at a point near Panel 1-Panel 2 hinge is estimated as 1.48 g.

4 Conclusions

The dynamics of deploying solar array consisting of a Yoke and two Panels has been successfully carried out considering the influence of yoke and panel flexibility, close control loops, harness torque variation, snubber force, ejector force and air drag. During deployment, the array is a multibody dynamical system and after latch up, it behaves as a structure. Both these phases are modeled and analysed on a single software platform ADAMS seamlessly considering differential latching. Simulation results have been obtained in terms of deployment time, angle of opening, acceleration and latch-up moment, for ground and on-orbit conditions. The fidelity of simulations is validated on ground by comparing the measured deployment time and acceleration at latch-up with predicted values. The methodology developed provides an effective means to model the dynamics of deploying solar array more accurately compared to previous methods. This will be of immense use in the study of deployment dynamics of future spacecrafts where large number of panels would need to be deployed.

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