Deployment Simulation for the Side Panels of A Spacecraft Solar Array

B. Lakshmi Narayana[1], H. N. Suresha Kumar[2], G. Nagesh[3] and B. S. Nataraju[4 *]
[1,2,3]Engineer, Spacecraft Mechanisms Group, ISRO Satellite Centre, Bangalore, India
[4] Head, Dynamics & Analysis Division, Spacecraft Mechanisms Group, ISRO Satellite Centre, Bangalore, India
[*] Email: - nataraj@isac.gov.in

Abstract

The solar array of INSAT-3A spacecraft is configured to have a yoke, three main panels and two side panels. The yoke is connected to the satellite through Solar Array Drive Assembly (SADA). The yoke and three main panels are deployed during primary deployment. The two side panels, which are of the same size as the first panel and kept folded on either side of first panel, are deployed during secondary deployment. The deployment of side panels and their subsequent locking produces reactive torque at SADA. This rotates the entire solar array during deployment and also after latch-up. The rotation of the array is about the pitch axis, overcoming the detent torque and friction torque at SADA. The extent of rotation during and after deployment depends on the magnitude of the detent torque and friction torque in SADA. Using the software ADAMS, numerical studies have been carried out simulating the on-orbit deployment of side panels. The spacecraft is considered to be in free-free condition. The objective of this study is to predict the deployment time, latch-up velocity, SADA rotation during and after deployment and body rates of spacecraft about pitch axis. This paper presents the details of the study. A comparison of analysis results with the on-orbit observations has also been provided.

Keywords: Deployment mechanism, Solar panel deployment, Spacecraft Body rates, ADAMS, Simulation

1 Introduction

The deployment of solar array or any other appendage is a mission critical activity in any satellite life. The influence of deployment of the solar array on the satellite is required to be studied. Once the array latches up, the satellite can have disturbance resulting in attitude change. Thus it is necessary to study the dynamics of the deployment. Several papers are available on this topic in the literature. Nataraju and Vidyasagar [1,2] studied the deployment dynamics of solar array having yoke and three panels. The detailed mathematical models for ground and on-orbit deployment have been discussed. Sathyanarayan et al [3] discussed on the deployment results only and its subsequent improvements by carrying out high-speed measurement. Balaji et al[4] proposed a matrix approach for handling of deployment of n-panel system for ground and on-orbit applications.The equations of motion have been formulated using Lagrange's method in all the above references. Lakshmi narayana et al [5] discussed deployment dynamics using ADAMS. In all these references deployment dynamics of yoke and three panels are discussed. However, the current paper discusses the influence of dynamics of side panel deployment on spacecraft and the already deployed main solar array.

The solar array of INSAT-3A is having a yoke, three main panels and two side panels. The yoke is connected to the satellite through SADA. The yoke and three main panels SP01, SP02 and SP03 are deployed during primary deployment. The two side panels SP04 and SP05 which are kept folded on the either side of SP01 are deployed during secondary deployment through a separate pyro. The two side panels get locked once they open up by 180 deg. relative to SP01. The deployment of side panels and their subsequent locking produces reactive torque at SADA. This reactive torque can rotate the entire solar array during deployment of side panels and also after their latch-up. The rotation of the array is about the pitch axis, overcoming the detent torque and friction torque of SADA. The extent of rotation during and after deployment of side panels depends on the magnitude of the detent torque and friction torque.

Numerical simulation of deployment is necessary in the present case, since a ground deployment test for the side panels in their on-orbit configuration is not possible on ground. Hence the mathematical simulation of deployment assumes greater significance.

Numerical studies have been carried out, using the software ADAMS [6], simulating the on-orbit deployment of side panels. The mass and inertia of the spacecraft subsequent to primary deployment of array have been considered. Measured characteristics of detent torque and friction torque at SADA have been incorporated with appropriate modifications for the on-orbit case. The inertia of the deploying side panels about hinge axis, the measured torsion spring characteristics, the harness characteristics, the friction characteristics, the initial velocity by snubbers etc have been modelled. The deployment time and latch-up velocity for the side panels, the resulting disturbances on the spacecraft and possible rotation of SADA due to deployment of side panels have been estimated [7]. The details of simulation studies have been discussed in the following.

2 Details of Modelling

A schematic of the spacecraft with the main solar panels deployed and two side panels stowed is shown in Fig. (1). The axis of rotation of two side panels and SADA axis are parallel to pitch axis of the spacecraft. A schematic of the side panels during deployment has been shown in Fig. (2). The energy for deployment is provided by preloaded torsion springs mounted along the hinge axis.

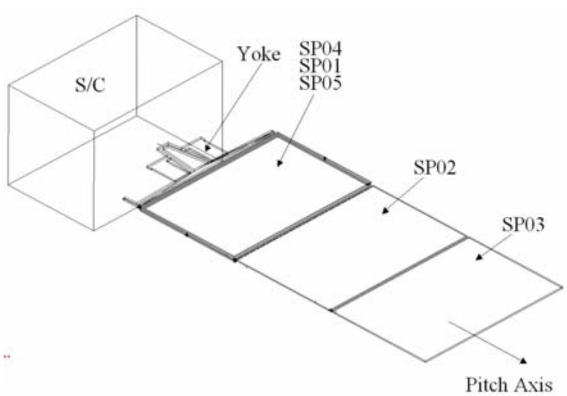

Figure 1 Side panels in stowed mode

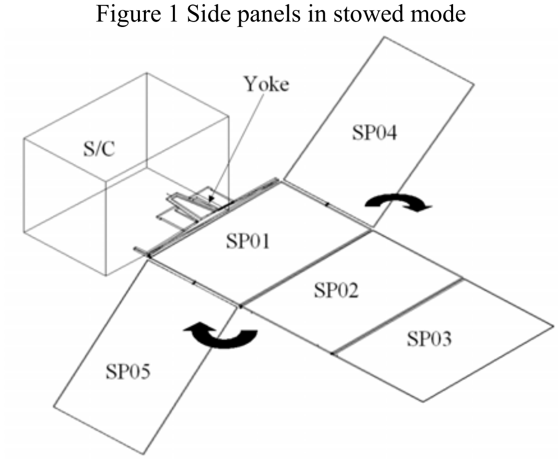

Figure 2. Side panels during deployment

To facilitate mathematical modelling, the torsion springs with measured stiffness characteristics have been defined at the requisite locations [8]. The mass and inertia properties of spacecraft and panels are derived from the hardware. The power and signal cables coming from the side panels and jumping over to the main panel across hinge axis, constitute the electrical harness. The torque characteristic of the harness is an important factor, influencing the deployment. This varies as a function of opening angle of the side panels and its measured data exhibits an aiding/resisting torque characteristics as indicated in Fig (3) below. These measured harness characteristics are fit with a polynomial expression and incorporated into the mathematical model.

Pre loaded snubbers are provided on SP01, SP04 and SP05 to enhance the stowed natural frequency of the stack and also to limit the amplitude of vibration. Eight such snubbers are located along the periphery at regular intervals. These snubbers provide an initial push force to the deploying panel and act for a very short interval of time of approximately 60 milli seconds. 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 loose contact. A typical characteristic of snubber force variation with time is shown in Fig. (4)

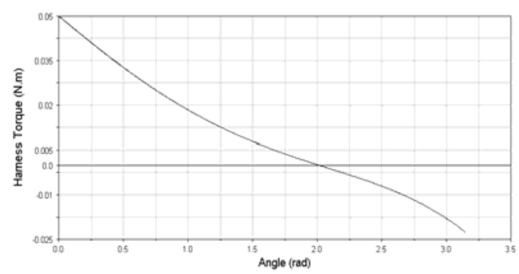

Figure 3 Variation Of Harness Torque With Angle Of Opening

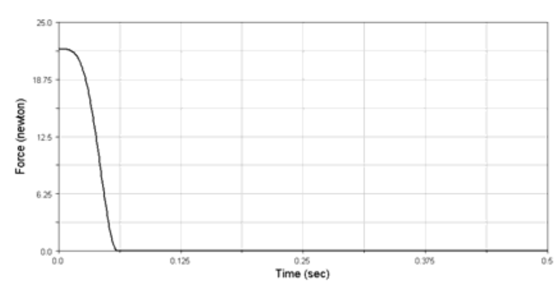

Figure 4 Variation of Snubber Force with Time

The measured detent torque is a function of SADA rotation angle and varies as a sine function. The peak amplitude has a range of 1.12 to 1.68 N.m. The variation is rapid with each cycle getting completed in 0.03 deg of SADA rotation. The friction torque during ground measurements has been found to be 2.8 Nm. For on-orbit conditions the friction torque would be lower. Hence a value of 1.4 N.m (50% of ground measured value) has been assumed for on-orbit simulation and is modeled to vary over a range of 1.4 to 2.8 Nm. The detent torque acts over and above this friction torque. The total resisting torque which is the sum of detent torque and friction torque can be expressed as

$$T = a + b\sin\left\{\frac{K\pi}{180}\theta\right\} \quad \text{N.m}$$

where,

a = Friction torque (varies from 1.4 to 2.8 Nm)

b = Peak detent torque (varies from 1.12 to 1.68 Nm)

$K = \dfrac{360}{0.03} = 12000$

θ = SADA rotation in deg.

A typical variation of total resisting torque with friction torque of 1.4 Nm and peak detent torque of 1.12 Nm acting over and above the friction torque in a sinusoidal manner has been represented in Fig. (5). A smaller step size of 0.001 sec has been used in the analysis to model the very rapid variation of detent torque.

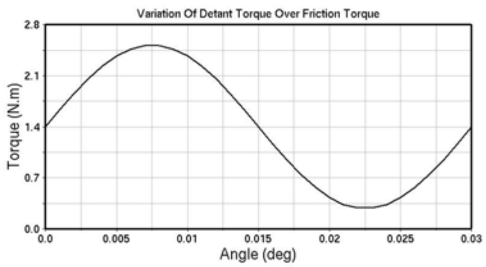

Figure 5. Variation of detent torque with SADA rotation

From the analysis of similar sized solar panels, it has been observed that the panels are stiff and the consideration of flexibility of the panels will have a very marginal influence on the deployment dynamics. There is also a good match between observed values of ground testing of main solar array and the mathematical model considering the panels rigid. Hence the panels are assumed to be rigid for the present analysis.

3 Results and Discussions

Four different cases have been studied with extreme values of 1.4 and 2.8 N.m for the friction torque and 1.12 and 1.68 N.m for peak detent torque. The analysis has been carried out modelling a free-free spacecraft with appropriate inertia values. The results of analysis are presented in following.

3.1 Case study 1

Total friction torque

$$T = 1.4 + 1.12\sin\left\{\frac{K\pi}{180}\theta\right\} \quad \text{N.m}$$

Results of study are presented in Table 1 below.

Table 1: Results of Case study 3.1

Deployment Time(sec)	Hinge	Deployment Angle (deg)	Latchup Vel. (r/s)
18.8	SP01-SP04	180	0.33
19.2	SP01-SP05	180	0.33
Array rotation about pitch axis during deployment (deg)			-13.0
Array rotation about pitch axis after latching (deg)			38.1
Final position of the array from starting position (deg)			25.1
The maximum pitch rate of spacecraft at the time of latching (deg/sec)			0.69
Time taken for array rotation after locking of side panels (sec)			14.7

The variation of angle of opening of side panels and SADA rotation with time is presented in Fig. 6. It can be observed from the Fig. (6) that the SP04 takes 18.8 sec to deploy. The corresponding time for SP05 is 19.2 sec. SP05 takes more time to deploy, as it is heavier. SADA is stationary up to 16 sec and starts rotating as the reactive toques produced by the deploying panels exceeds the detent torque. SADA rotates by 13.0 deg during deployment of side panels. The rotation of SADA gets reversed after locking of the side panels. SADA continues to rotate after locking of the panels and comes to rest after rotating 25.1 deg from its nominal position. The resultant angular momentum changes in direction after locking of panels. This change in direction of angular momentum reverses the SADA rotation.

Angular velocity of panels and SADA are presented in Fig.(7). The initial sudden rise in angular velocity of Side Panels is due to the push force provided by the snubbers. This is a rapidly varying force and becomes zero within a short time approximately 60 milli sec, once the snubbers lose contact. The change in slope of velocity curves is due to rotation of SADA. The velocity of Side Panels becomes zero as the hinges get locked.

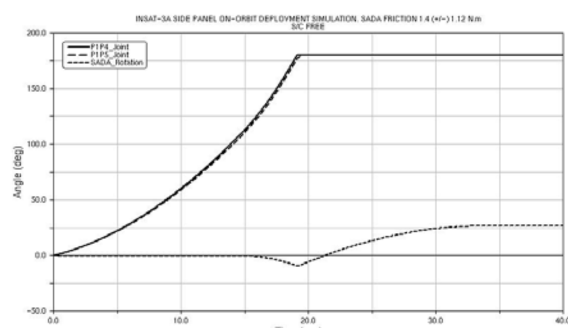

Figure 6. Variation of Angle of opening of Side Panels and SADA rotation with time.

The deployment of side panels and resulting SADA rotation produces disturbing torque on spacecraft. This induces spacecraft body rates about pitch axis as the spacecraft is free-free. The variation of pitch rate with time is shown in Fig. (8). The sudden rise in pitch rate soon after initiation of deployment is due to snubber forces. The change in slope is due to SADA rotation. The two side panels don't latch at the same instant of time. The kink in the pitch rate plot is due to the non-simultaneous locking of side panels. The maximum pitch rate for the spacecraft is 0.69 deg/sec.The solar array position at the time of locking of side panels is shown in Fig(9). After locking of side panels the array continues to rotate about the spacecraft pitch axis and final position is shown in Fig(10) .

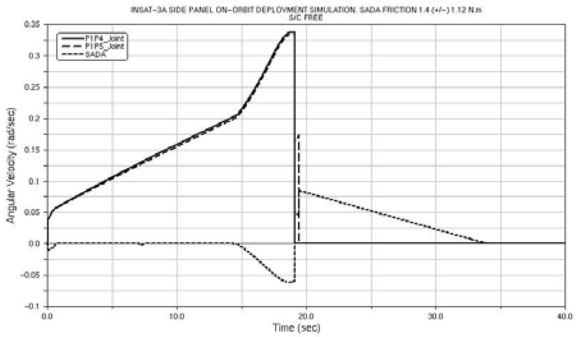

Figure 7. Variation of Angular velocity of Side Panels and SADA with time.

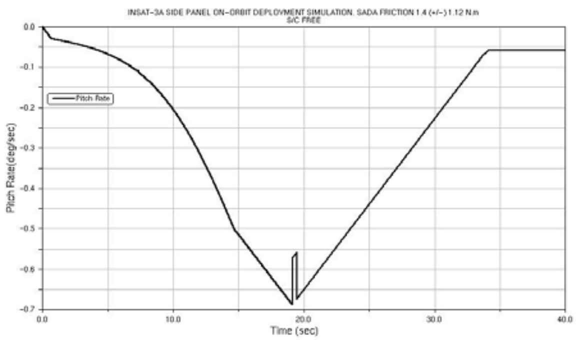

Figure 8. Variation of Spacecraft pitch rate with time

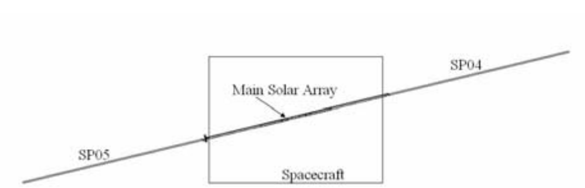

Figure 9. Solar array position at the time of locking of side panels.

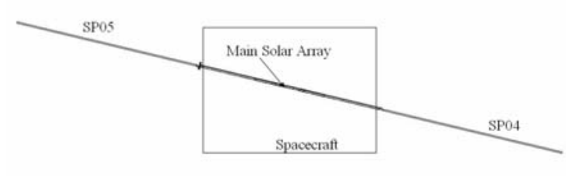

Figure 10. Final position of solar array.

3.2 Case study 2

Total friction torque

$$T = 1.4 + 1.68\sin\left\{\frac{K\pi}{180}\theta\right\} \quad \text{N.m}$$

Results of the analysis for this case have been presented in Table 2 below. The variation of angle of opening of side panels and SADA rotation with time is presented in Fig. (11).

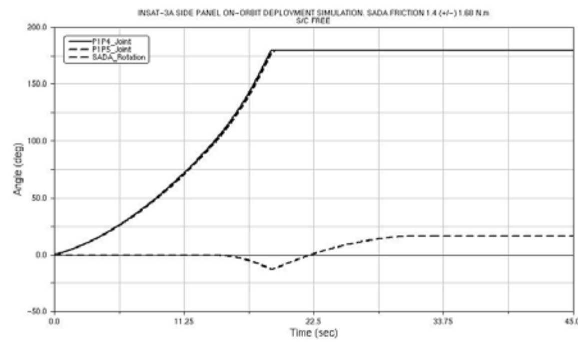

Figure 11. Variation of Angle of opening of Side Panels and SADA rotation with respect to time.

Table 2: Results of Case study 3.2

Deployment Time (sec)	Hinge	Deployment Angle (deg)	Latchup Vel. (r/s)
18.9	SP01-SP04	180	0.36
19.1	SP01-SP05	180	0.36
Array rotation about pitch axis during deployment (deg)			-12.6
Array rotation about pitch axis after latching (deg)			29.3
Final position of the array from starting position (deg)			16.7
The maximum pitch rate of spacecraft at the time of latching (deg/sec)			0.64
Time taken for array rotation after locking of side panels (sec)			14.4 sec

The results of this case are similar to the Case 3.1. SADA rotation during deployment of side panels and after locking of side panels is 0.4 deg less compared to the previous case as the SADA resistance is more in this case. Angular velocity of panels and SADA are presented in Fig. (12)

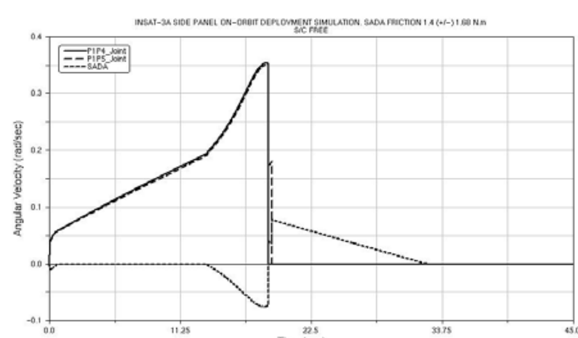

Figure 12. Variation of Angular velocity of Side Panels and SADA with time.

The solar array has come to rest 0.2 sec earlier compared to the earlier case. The variation of pitch rate with time is shown in Fig. (13). The variation of pitch rate is also similar to the previous case. The maximum pitch rate the spacecraft experiences is 0.64 deg/sec.

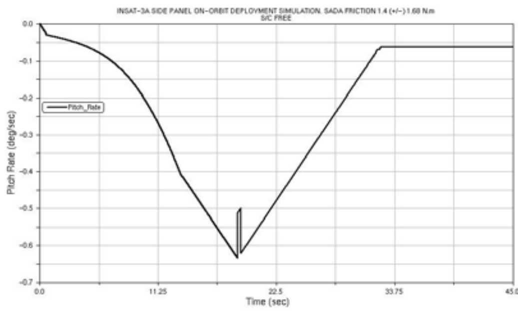

Figure 13. Variation of Spacecraft pitch rate with time

3.3 Case study 3

Total friction torque

$$T = 2.8 + 1.12\sin\left\{\frac{K\pi}{180}\theta\right\} \quad \text{N.m}$$

The results of the analysis are presented in Table 3

Table 3: Results of Case study 3.3

Deployment Time (sec)	Hinge	Deployment Angle (deg)	Latchup Vel. (r/s)
19.9	SP01-SP04	180	0.26
20.4	SP01-SP05	180	0.26
Array rotation about pitch axis during deployment (deg)			0.0
Array rotation about pitch axis after latching (deg)			28.9
Final position of the array from starting position (deg)			28.9
The maximum pitch rate of spacecraft at the time of latching (deg/sec)			0.85
Time taken for array rotation after locking of side panels (sec)			8.9

The variation of angle of opening of side panels and SADA rotation with time is presented in Fig. (14).

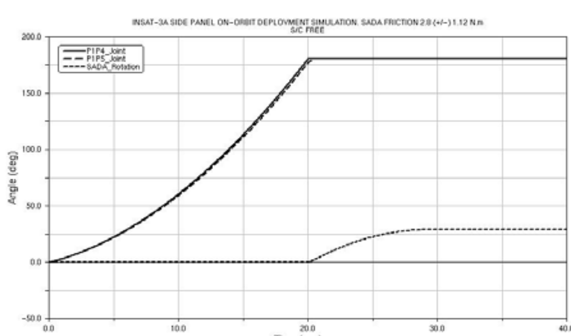

Figure 14. Variation of Angle of opening of Side Panels and SADA rotation with time.

It can be observed from the Fig. (14) that the SP04 takes 19.9 sec to deploy. The corresponding time for SP05 is 20.4 sec. SADA does not rotate in this case during deployment as the reactive torque produced due to deployment is smaller than the SADA friction. It can be observed that the deployment time in this case more than deployment time seen in Case 3.1 and Case 3.2. The latch-up of side panels occurs when the relative angular movement between side panels and SP01 is 180.0 deg. This would be achieved in case3.1 and 3.2 early since the main array also rotates during deployment. Whereas, in the present case, main array is not observed to rotate during deployment and hence the deployment time would be relatively longer. SADA starts rotating after the locking of side panels as the reactive torques produced due to locking is more than SADA friction. SADA rotates by 28.9 deg and comes to rest in 8.9 sec after locking of side panels. Angular velocity of panels and SADA are presented in Fig. (15).

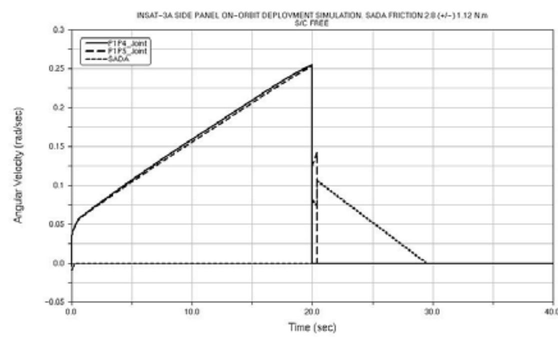

Figure 15. Variation of Angular velocity of Side Panels and SADA with respect to time.

There is no change in the slope of velocity curves as the SADA is not rotating during deployment of side panels. The variation of pitch rate with time is shown in Fig. (16).

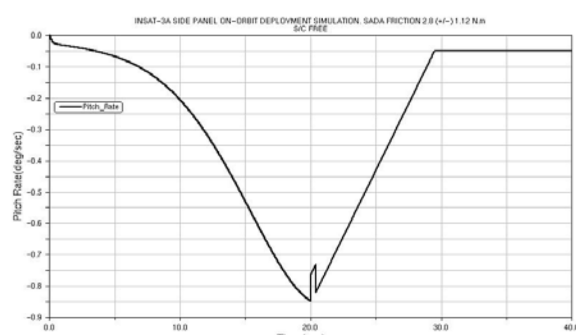

Figure 16. Variation of Spacecraft pitch rate with time

No sharp change in the slope of the pitch rate curve is seen as observed in case 3.1 and 3.2 during deployment of side panels since the SADA is not rotating during side panels deployment. The maximum pitch rate of the spacecraft is likely to be 0.85 deg/sec.

3.4 Case study 4

Total friction torque (Nm)

$$T = 2.8 + 1.68 \sin\left\{\frac{K\pi}{180}\theta\right\} \quad \text{N.m}$$

The results of analysis for this case are presented in Table 4

Table 4: Results of Case 3.4

Deployment Time (sec)	Hinge	Deployment Angle (deg)	Latchup Vel. (r/s)
19.9	SP01-SP04	180	0.26
20.4	SP01-SP05	180	0.26
Array rotation about pitch axis during deployment (deg)			0.0
Array rotation about pitch axis after latching (deg)			29.8
Final position of the array from starting position (deg)			29.8
The maximum pitch rate of spacecraft at the time of latching (deg/sec)			0.85
Time taken for array rotation after locking of side panels (sec)			9.1

The results of the analysis for this case are similar to Case 3.3. The variation of angle of opening of side panels and SADA rotation with time is presented in Fig. (17).

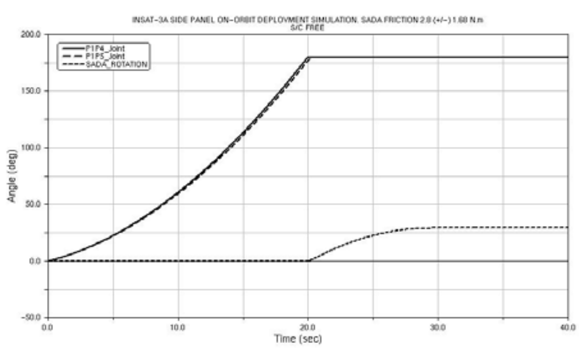

Figure 17. Variation of Angle of opening of Side Panels and SADA rotation with time

The deployment time of side panels in this case is same as in Case 3.3 as SADA in not rotating during deployment of side panels. SADA rotates by 29.8 deg after locking of side panels and comes to rest after 9.1 sec after locking of side panels. The main array will occupy a final position 29.8 deg from initial position.

The velocity of side panels and SADA and Spacecraft pitch rate variation with time is shown in Fig. (18) and Fig. (19) and are similar to Case 3.3. The spacecraft will experience 0.85 deg/sec body rate about pitch axis.

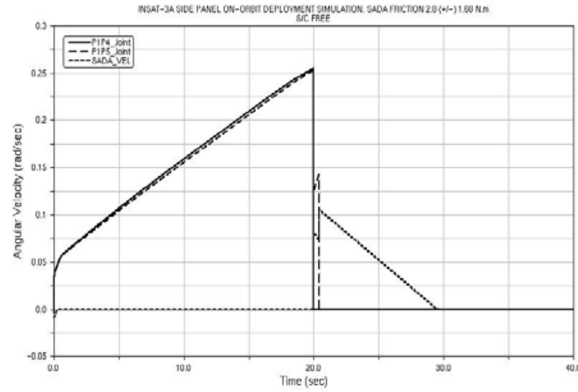

Figure 18. Variation of Angular velocity of Side Panels and SADA with respect to time.

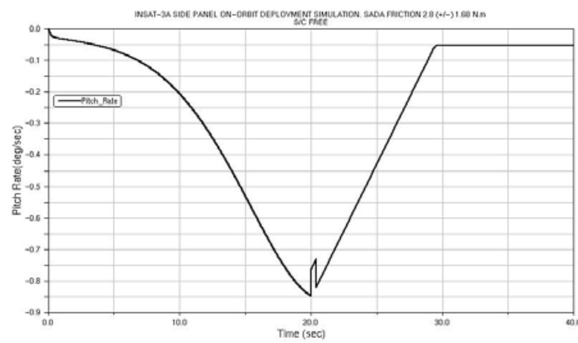

Figure 19. Variation of Spacecraft pitch rate with time

3.5 Observations during on-orbit deployment of side panels

Predictions for the on-orbit deployment characteristics of side panels were carried out based on the results of above case studies and also using the updated spacecraft mass properties data at the time of deployment. The range for predicted deployment time was determined accounting for variations in all the input parameters used for analysis and hence a wider band for deployment time was projected.

The on-orbit deployment of side panels was carried out successfully on 15th April 2003. The Table 5 below presents a comparison of predictions against actual on-orbit observations [9].

Table 5: Comparison of predicted and on-orbit observed deployment characteristics

Parameter	Predicted from analysis	Actual on-orbit observation
Deployment Time for SP04 (sec)	18.8 to 21.2	19.9
Deployment Time for SP05 (sec)	19.2 to 21.6	21.2
Rotation of solar array about pitch axis (deg)	16 to 30	~ 35
Spacecraft pitch rate at the time of latch-up (deg/sec)	0.69 to 0.85	0.78

The Fig. (20) presents a plot of spacecraft body rates during on-orbit deployment of side panels The Bottom curve shows the pitch rate variation of the spacecraft. The FFT analysis of spacecraft body rates immediately after deployment of side panels, indicate the first two frequencies of the full solar array of 0.27 Hz and 0.88 Hz. However the individual panel frequencies will be higher than 0.88 Hz. Since these are relatively higher frequencies, our earlier assumption of rigid solar panel model for deployment analysis is justified. The influence of panel flexibility on the deployment dynamics is not significant.

Fig. (21) presents the microswitch status plots, which provide details regarding on-orbit deployment time for the side panels.

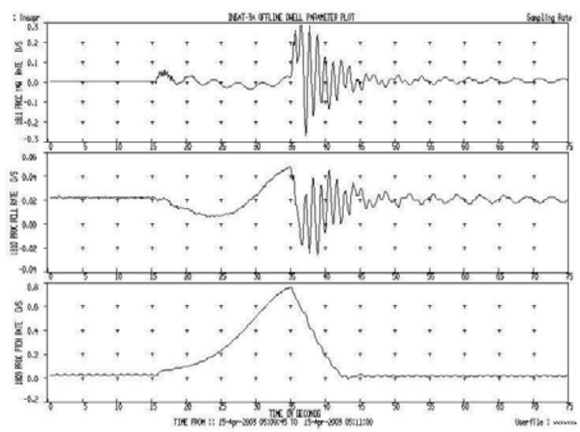

Figure 20 Plot of spacecraft body rates during on-orbit deployment of side panels

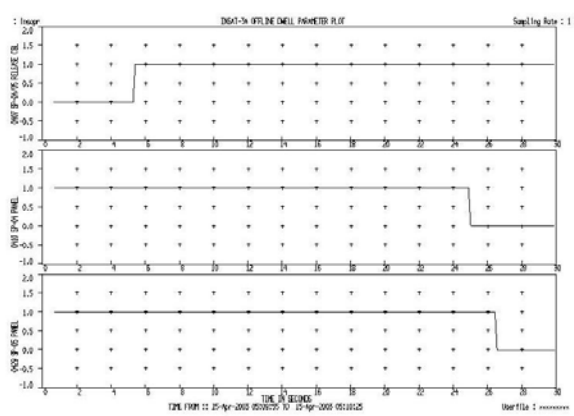

Figure 21 Microswitch status indications during on-orbit deployment of side panels

A good match between the numerical predictions and the actual on-orbit data can be observed from Table 5. The analysis results for spacecraft pitch rate during deployment exhibits a kink indicating a differential latching of the two side panels. The same is not observable in the on-orbit pitch rate plot. However, the microswitch data (Fig. (21)) confirms the differential latching and the same may not have been captured by spacecraft pitch rate due to sampling rate and data processing limitations. However the shape of the curve of pitch rate is similar to predicted curve.

Subsequent to on-orbit deployment of side panels, simulation studies were carried out to further match the on-orbit observations. It was attempted to determine the SADA friction values that would simulate the observed solar array rotation about pitch axis of 35 deg. A constant component of friction of value 2.4 Nm and the variable component of 1.3 Nm (maximum value) was found to simulate a solar array rotation of 35.35 deg. However, it should be noted that, it is one of the possible set of values among the different combinations possible.

4 Conclusions

- On-orbit deployment of side panels has been simulated using ADAMS software to determine SADA rotation during and after deployment of side panels, spacecraft body rate about pitch axis due to deployment, deployment time and latch up velocity of side panels.

- The present analysis gets significance since a ground test cannot be carried out simulating the on-orbit deployment of side panels with main panels deployed and spacecraft in free-free condition. The deployment characteristics need to be determined through numerical studies only.

- The deployment dynamics study takes into account the measured hardware characteristics like harness torque, push force from inter panel snubbers, resisting torque at SADA, mass & inertia of side panels, the deployment torsion spring & friction torque characteristics etc.

- Analysis has been carried out for four extreme values of SADA friction considering the variation in measured SADA friction data. The predictions for the on-orbit deployment characteristics were made based on the results of above study.

- A good comparison between the numerical predictions and the actual on-orbit data has been observed.

- One of the likely values of the friction and detent torque at SADA has been found out to get the pitch rotation observed in orbit.

Acknowledgements

The authors would like to thank Sri N. C. Bhat, Group Director, Spacecraft Mechanisms Group, ISRO Satellite Centre for his encouragement and support towards this work. The authors would also like to thank Sri. P. M. Varghese, IISU, VSSC, Trivandrum for providing details regarding friction and detent torque at SADA. Thanks are also due to Dr. P. S. Nair, Dy.Director, MSA, ISAC and Dr. K. N. Shankara, Director ISAC for their encouragement. The authors wish to thank all SMG colleagues for providing necessary data, guidance and support.

References

[1] B. S. Nataraju and A. Vidyasagar, "Effect of flexibility of closed control loops on deployment dynamics of accordian type of deployable solar arrays", National Conference on Machines and Mechanisms, February 19-21, 1985, Indian Institute of Science, Bangalore.

[2] B. S. Nataraju and A. Vidyasagar, "Deployment dynamics of accordian type of deployable solar arrays considering flexibility of closed control loops", 38th Congress of the International Astronautical Federation, October 10-17, 1987, Brighton, United Kingdom.

[3] M. N. Sathyanarayan, et al., "INSAT-2A and 2B Deployment mechanisms", Proceedings of 28th Aerospace Mechanisms Symposium, Cleveland, Ohio, May 18-20, 1994, pp 17-34

[4] K. Balaji, BS Nataraju and HN Suresha kumar, "Matrix approach to deployment dynamics of an n-panel solar array", Proc. Instn. Mech. Engrs Vol. 217 Part K: Journal of Multi-body Dynamics, 2003, pp 15-27.

[5] B. Lakshminarayana, HN suresha kumar and BS Nataraju, "Accordion deployemnt simulation of solar array using ADAMS", Paper presented at the 3rd National Seminar on Aerospace Related Mechanisms, DRDL, Hyderabad, June 1999.

[6] "Using ADAMS/View", & "Using ADAMS/Solver", Mechanical Dynamics Inc., Ann Arbor, Michigan, 1997.

[7] B. Lakshmi Narayana, H. N. Suresha Kumar and B. S. Nataraju, "A Note on INSAT-3A On-Orbit Deplyoment Simulation of Side Panels". Internal Note SMG, ISRO Satellite Centre, Bangalore, March 2003.

[8] SMG Team, "Design Review Document on Modifications in Deployment Mechanisms", Doc.No:. ISRO-ISAC-INSAT-3A-RR-0260, July 2002.

[9] SMG Team, "On-Orbit Performance of INSAT-3A Deployment Mechanisms" Doc.No:. ISRO-ISAC-INSAT-3A-PR-0390, June 2003.