Chapter 7

TiungSAT-1 MOMENTUM WHEEL COMMISSIONING

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INTRODUCTION

In the nominal Attitude Determination & Control System (ADCS) configuration, TiungSAT-1 is stabilised to nadir (earth) pointing by a 6m gravity gradient boom and further control is achieved through 3-axis magnetorquers. This configuration can produce a pointing accuracy of ±3° for the spacecraft in its earth-imaging role. As an experiment, TiungSAT-1 is also fitted with a pitch momentum wheel that will be able to provide an enhanced pointing accuracy of ±1° with inherent roll and yaw stiffness.

By definition, a momentum wheel is nominally spinning at a particular rate and changes speed, i.e. angular momentum, as a means of providing control over the spacecraft attitude (Wertz 1978). However, it firstly needs to be started up from rest and also since this particular wheel is an experiment on TiungSAT-1, there may arise a need to stop it spinning.

This simulation-based study investigates the feasibility and performance of a proposed strategy for starting up the wheel and stopping it in an emergency. It basically involves *tricking* the wheel controller to start-up or slow down the wheel through instructing initial pitch demands. The momentum wheel control system is a proportional plus integral controller as can be seen in the SIMULINK system block diagram in Figure 1 and described in the paper by Norhizam (1997).

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The two momentum wheel modes, i.e. on and off, can be associated with the spacecraft's two stability modes, namely the non-spinning Yaw-freeze-mode and the BBQ-mode respectively. The spacecraft is safe in the BBQ-mode with the wheel at rest, but as discussed later, the spacecraft needs to be in the Yaw-freeze-mode in using the momentum wheel. In both stability modes, the spacecraft nominal attitude remains nadir pointing.

However, in the Yaw-freeze-mode there is a concern that the spacecraft may have the potential to experience temperatures of up to 100°C and down to -40°C since the spacecraft is not distributing the solar heating effect uniformly through the spacecraft. In particular, the adhesive used for the solar panels can only withstand operating temperatures of up to 100°C (Redux 1997). This is an extreme possibility that will require the spacecraft to respin.

The simulations were done primarily using the TiungSAT-1 ADCS Simulation Program developed by Hashida (1997). Some modification to the C-program had to be made to implement the wheel start-up and stopping strategies. Of particular interest is the time taken to complete the operations which is more appropriately related to the number of orbits in this study. The simulation block diagram is shown in Figure 2.

TiungSAT-1 was originally planned for a sun-synchronous orbit at 98° inclination and altitude of 670 km, whereby the nominal orbital period can be taken as 98 minutes.

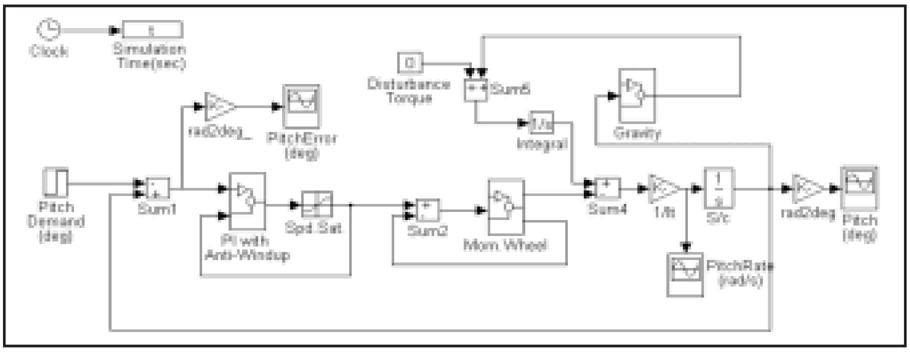

Figure 1. Momentum wheel pitch control system.

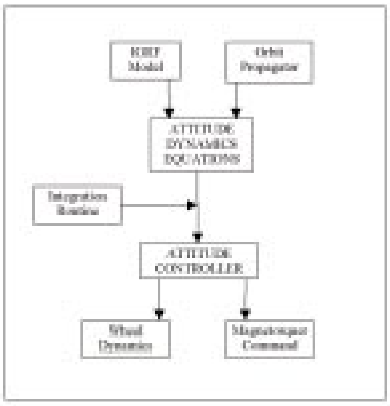

Figure 2. Simulation block diagram.

Functional Description

The momentum wheel is a flywheel designed to operate at a biased non-zero momentum. It provides a variable momentum storage capability about its rotation axis and is usually fixed in the spacecraft (Chetty 1991).

A momentum wheel stabilisation system is used to maintain the attitude by momentum exchange between the spacecraft and the wheel. As a torque acts on the spacecraft along one axis, the momentum wheel reacts, absorbing the torque and maintaining the attitude, i.e. the wheel spin rate increases or decreases to maintain a constant attitude (Wertz 1978).

The angular momentum produced by this action is given by the equation: $h = I \times \Omega$, where I is the wheel moment of inertia about its rotational axis, i.e. pitch axis, and Ω is the wheel angular velocity or spin rate (or more conveniently referred to in this document as wheel speed). The single momentum wheel on TiungSAT-1 will provide three-axes stabilisation with the two axes in the orbit plane, i.e. roll and yaw, being held in their position by gyroscopic effect of the momentum wheel (passive stabilisation). An active attitude control about the third axis, i.e. pitch, which is orthogonal to the orbit plane, is obtained by increasing or decreasing the momentum.

Secular torques acting on the spacecraft cause the momentum wheel speed to either increase or decrease and in time this speed change will accumulate until the wheel speed moves outside operational constraints. A momentum exchange or dumping using the three-axis magnetorquers must then be employed to restore the momentum wheel speed to its nominal operating value. This process can be called *momentum wheel desaturation*. Desaturation of the wheel speed and realignment of roll/yaw error will be performed by the magnetorquer.

System Description

In construction, the wheel consists of a housing containing a flywheel, bearing assembly and electric drive motor. There is also the essential electronics for driving the wheel and, controlling and measuring the wheel speed. A brushless dry lubricated DC drive motor is used. Wheel speed control is implemented by a proportional-integral closed loop digital control system through pulse-width modulation using speed feedback information measured from Hall effect sensors. Nominally the wheel will be spinning at 2500 rpm in the satellite orbital direction and constrained within 2000 and 3000 rpm.

The wheel moment of inertia is 7×10^{-4} kgm^2. Torque is then provided together with the wheel spin acceleration which is defined to be 50 rpm/s maximum. The maximum rated torque to the spacecraft is specified at 4mNm. This limit is in view of the possible bending of the tip mass boom due to spacecraft rotational motion. Estimated lifetime is about 10 years but, from discussions, optimum performance can only be expected for the first 2 years of operation.

In maintaining nadir pointing, the wheel speed is modulated in response to only pitch error signal (coarse roll and yaw requirements should have already been acquired initially through magnetorquers). The momentum wheel will be commanded through the CAN bus by the on-board computer (OBC) which also executes the attitude determination and digital control routines.

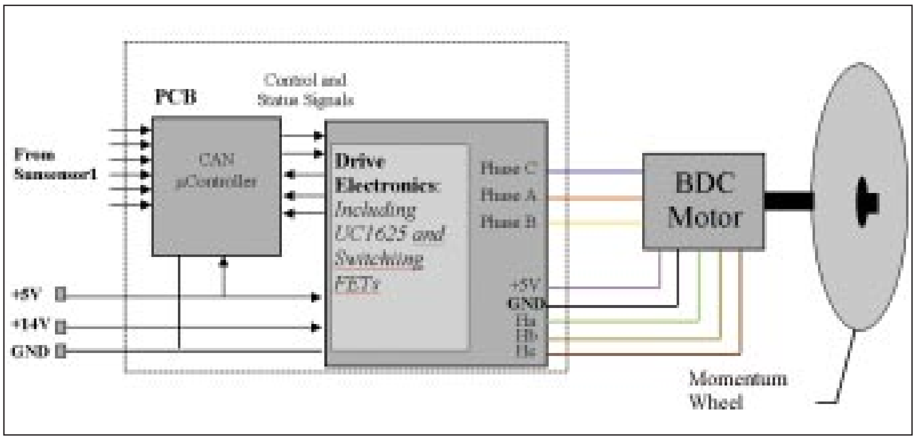

Figure 3. Momentum wheel system

MOMENTUM WHEEL START-UP

A Case for Yaw-Freeze

The nominal BBQ-mode is characterised by a periodic 10 minutes z-spin for maintaining a favourable temperature distribution which produces a z-directed angular momentum. The nadir-pointing requirement also means that the spacecraft is effectively rotating in pitch with an approximately 100 minutes cycle and this produces an angular momentum along the orbit normal.

Spinning the momentum wheel will produce an additional angular momentum to the spacecraft body. If the wheel is suddenly spun up to its nominal speed, the large momentum produced together with the existing momentum due to the nominal rotational motions will result in a very disturbed and unstable motion as illustrated in Figure 4. This simulation shows the pitch wheel being switched on almost instantaneously to run at its nominal 2500 rpm following a stable BBQ-mode. Hence, this shows that the z-spin needs to be stopped, i.e. the Yaw-freeze-mode needs to be acquired, before the momentum wheel is commissioned.

Wheel Start-Up Techniques

It has been shown in the previous section that the wheel can only be engaged after stopping the spacecraft z-spin and acquiring a stable attitude. This can be achieved by appropriate firings of the magnetorquer to slow down the spin and eventually stopping it. The wheel start-up may then be carried out with particular attention not to introduce a sudden change in angular momentum that can potentially topple the spacecraft. Several studies had been conducted on the operation for starting up the momentum wheel (Aorpimai 1997 & Hashida 1996). The methods suggested are briefly described below as Method 1 & 2 respectively. Method 3 is suggested here as another way of commissioning the wheel through pitch command and magnetorquer firings. In all three

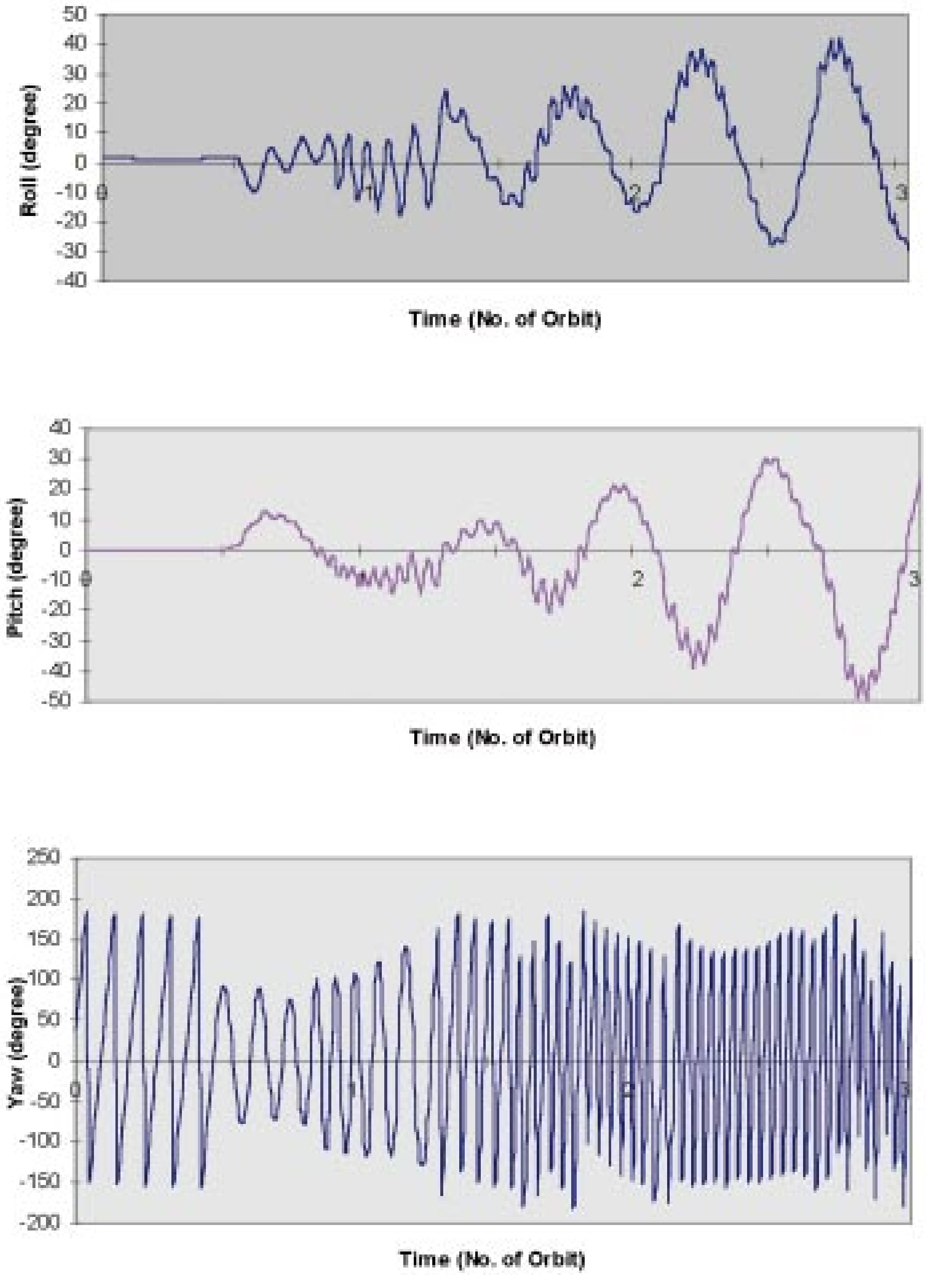

Figure 4. Spacecraft attitude behaviour due to sudden wheel start-up in BBQ-mode. The spacecraft can be seen to be in a stable BBQ-mode within the first half orbit before the wheel is suddenly switched on to spin up to 2500 rpm (nominal).

methods Yaw-freeze must first be assumed before any wheel start-up manoeuvres are made:
Method 1: The wheel is spun to its nominal speed in steps of 2 or even 4 with the application of magnetorquers for damping out the attitude disturbances produced by the wheel start-up (Aorpimai 1997).

Method 2: Hodgart's Deadbeat Manoeuvre which involves sequential increase of wheel speed which can inherently cancel out the unwanted angular momentum produced by start-up (Hashida 1996).

Method 3: The magnetorquer control is switched off at the start. This is followed by an initial positive pitch demand to the wheel which will effectively increase the wheel speed. The momentum wheel will continue to speed up to its nominal value in achieving the demanded pitch.

The next step in Method 3, the preferred method, is to get the spacecraft back to nadir pointing but maintaining the wheel nominal speed at the end of it. This involves the application of magnetorquers to damp out the disturbances produced. There are two possible options to this as described below:
Option A: The momentum wheel controller is left continuously in a closed loop operation. When the wheel nominal is reached the magnetorquer is switched on to maintain this speed. The spacecraft is brought back to a nadir-pointing attitude by the wheel together with gravity assistance (see Figure 5).

Option B: As soon as the nominal wheel speed is reached, the wheel controller is switched to open loop mode to keep it coasting at the nominal. The natural gravity gradient effect will cause the spacecraft to rotate back towards nadir pointing. To stop libration in this motion the magnetorquer control is then switched on to maintain a Yaw-freeze attitude. The full wheel controller is switched back on after the spacecraft is stable. This option noticeably involves more instructions (see Figure 6).

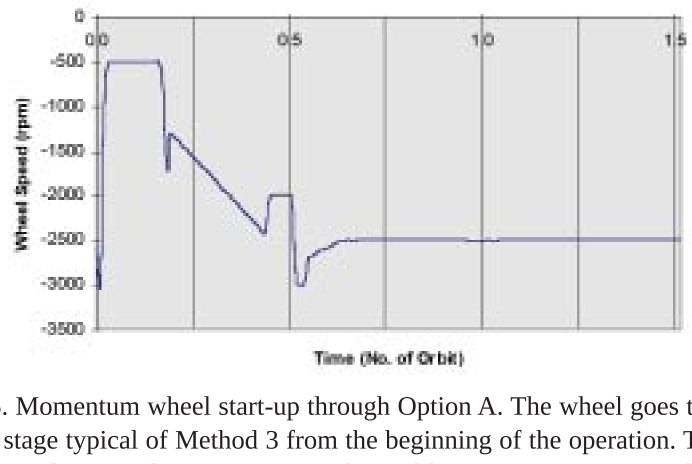

Figure 5. Momentum wheel start-up through Option A. The wheel goes through a transient stage typical of Method 3 from the beginning of the operation. The wheel saturates to its lower and upper operational speed limits, i.e. 2000 rpm and 3000 rpm, respectively, before stabilising at the nominal (after 0.65 orbit in this example).

Figure 6. Momentum wheel start-up through Option B. This option as characterised by the plot gets the wheel to start coasting at the nominal speed faster than Option A, however, they both complete wheel start-up at nearly the same time.

Success of Wheel Start-up

Figure 7 and 8 are the simulation results of the spacecraft attitude for *Option A* and *Option B*, respectively. Both show very small residual disturbances and the pitch has managed to stabilise at nadir pointing. There do not seem to be any significant differences in the attitude behaviour between both options.

The magnetorquer firings also look to be acceptable and of similar degree for both options as shown in Figure 9 and 10.

Factors Affecting Wheel Start-up Time

Different initial pitch demands were tested for both options, ranging from 10° to 25°. This is noting a safety limit of 30° in order to avoid a possible upside down topple. The time taken for each option to complete the wheel start-up is characterised by the spacecraft attitude becoming stable and the wheel spinning at nominal. *Option A* is found to be dominated by the time required for the wheel to reach nominal whereas *Option B* is dominated by time required for the pitch to stabilise.

Table 1 and 2 show the time performances of each option in terms of number of orbits. Although there are some differences in the time taken between the two options in completing the operation, they are not significant as both take less than one orbit. The possibility of different performances with regard to the orbital position where the operation starts is not investigated in detail as it does not appear to be significant as proven in the wheel stop case.

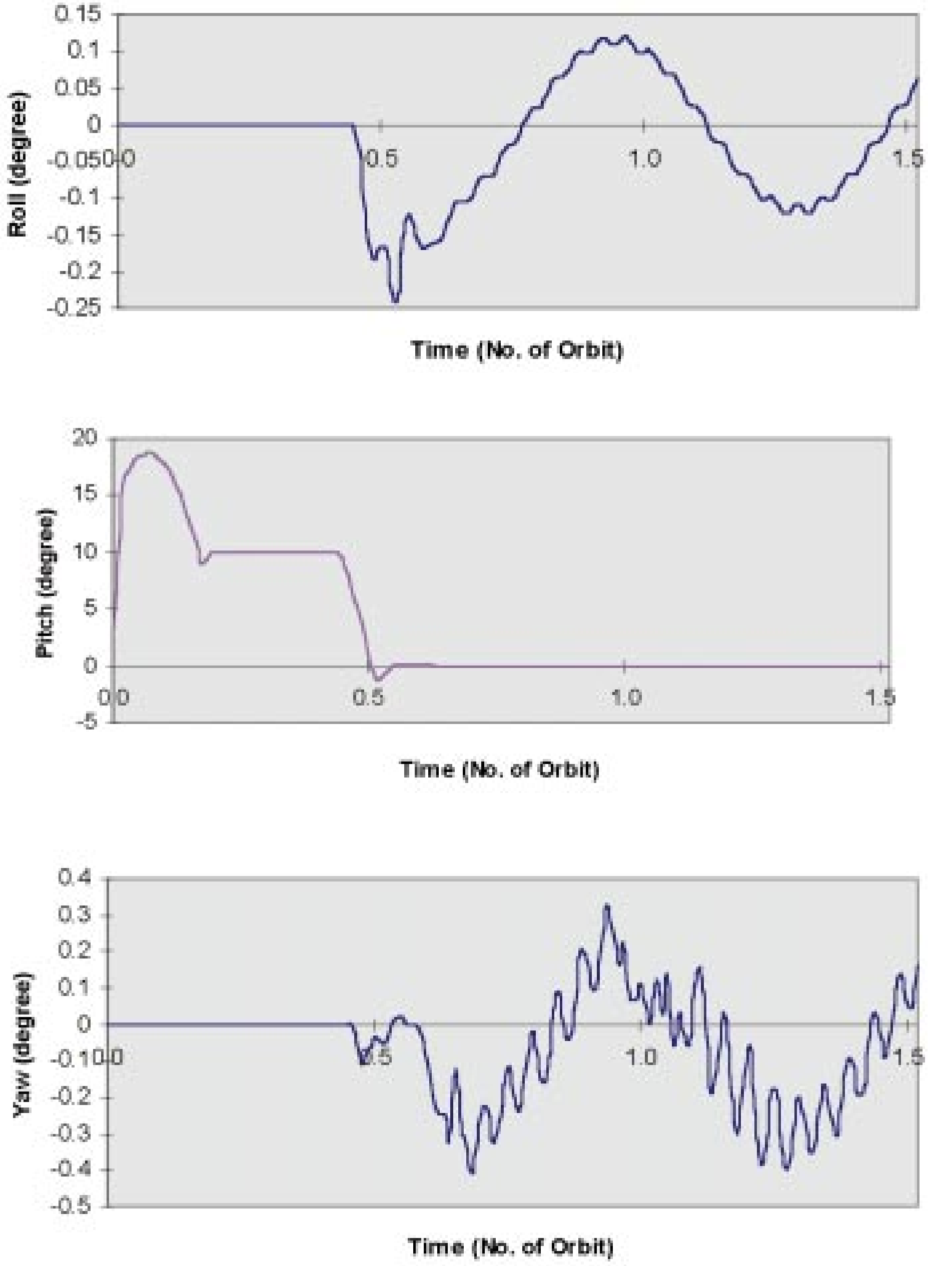

Figure 7. Spacecraft attitude behaviour for Option A wheel start-up operation. Characteristically roll and yaw show a very small, hence acceptable, nutation effect after wheel start-up. In this example, the pitch overshoots within the safety limits of ±30° then attains the demanded 10° attitude and continues to rotate to nadir pointing through gravity assistance and momentum wheel. Here everything stabilises just after half an orbit.

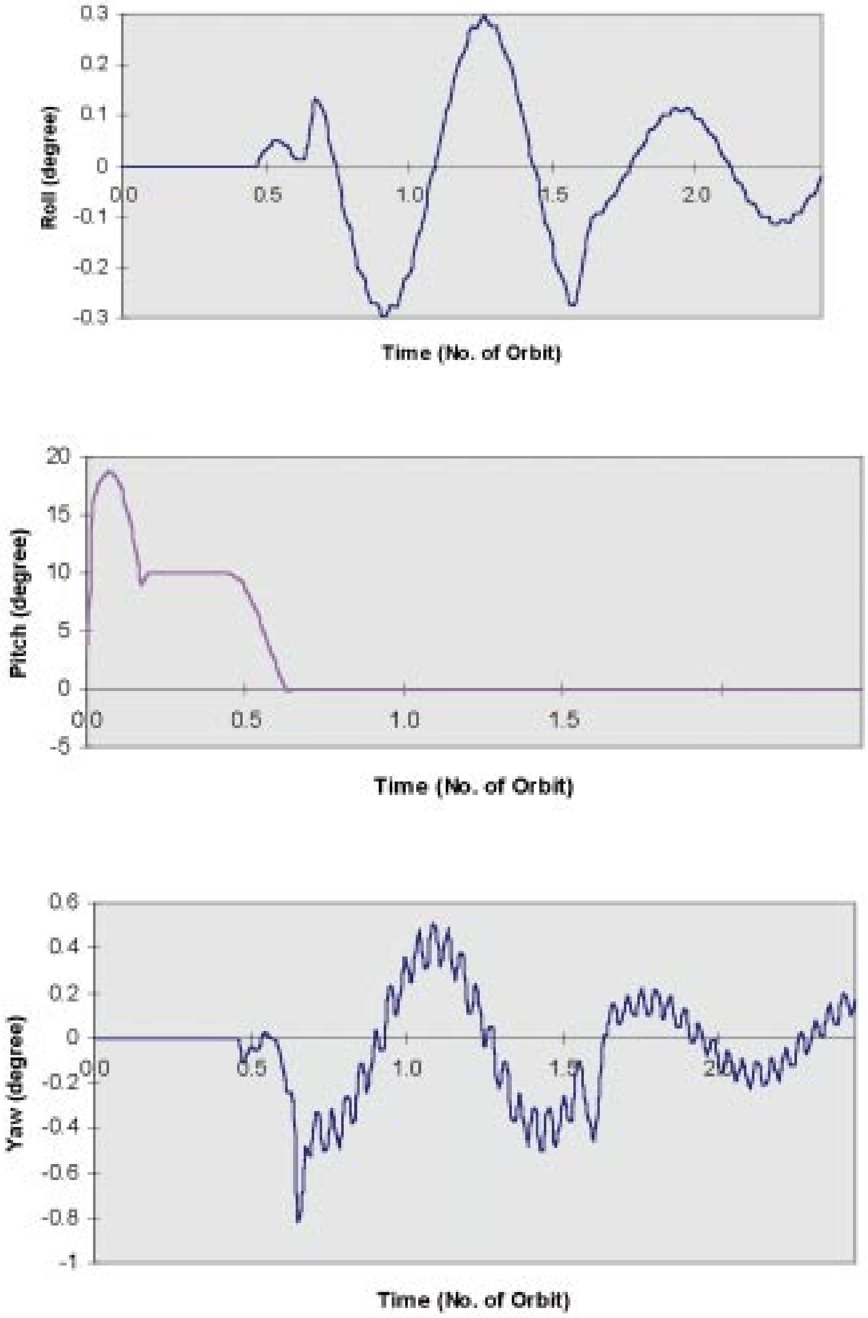

Figure 8. Spacecraft attitude behaviour for Option B wheel start-up operation. The attitude behaviour is similar to that of Option A except that it takes slightly longer to complete, i.e. 20 minutes for a 10° initial pitch demand.

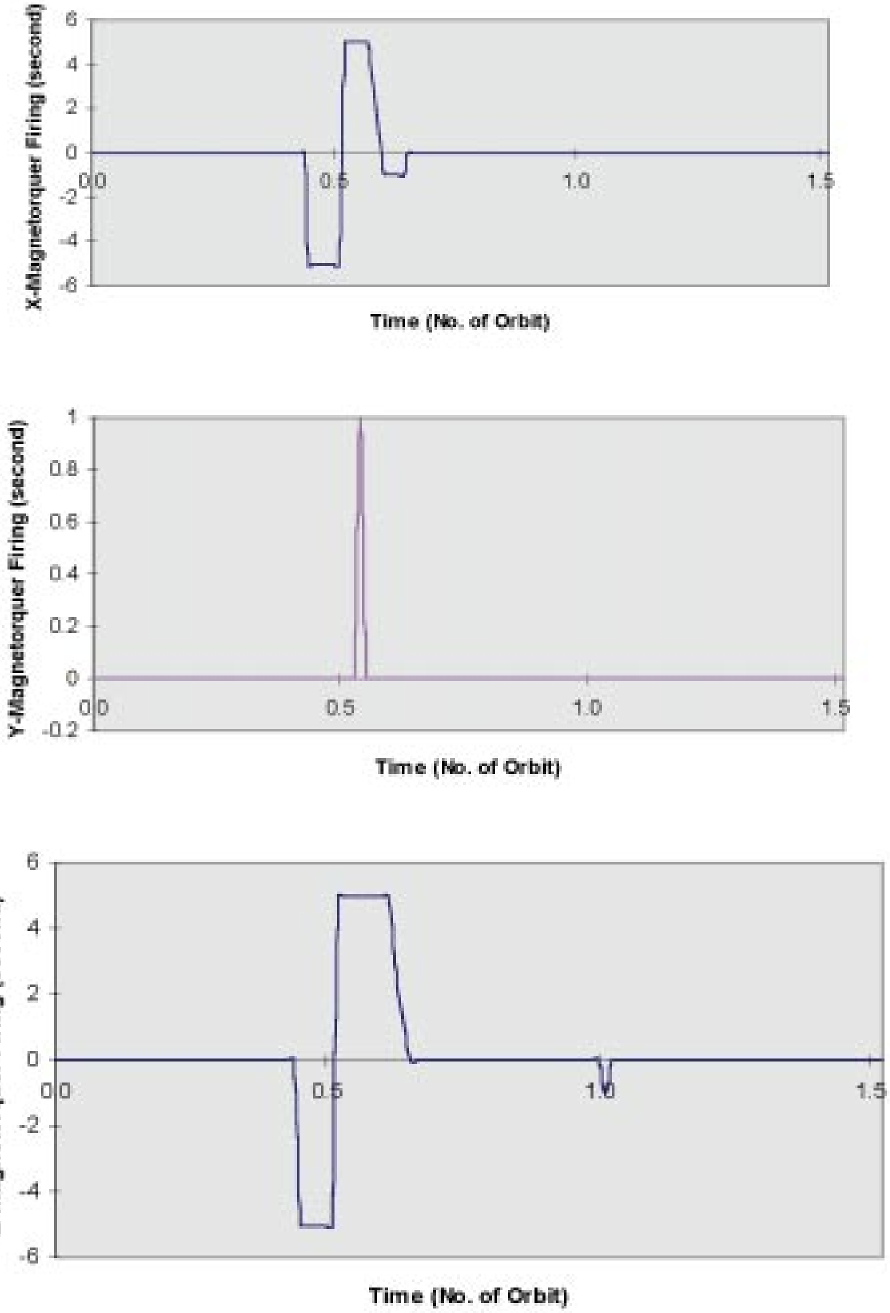

Figure 9. Magnetorquer firings for Option A wheel start-up operation. Rigorous firings of magnetorquers to maintain the wheel speed at nominal as part of the operation are not shown to be necessary.

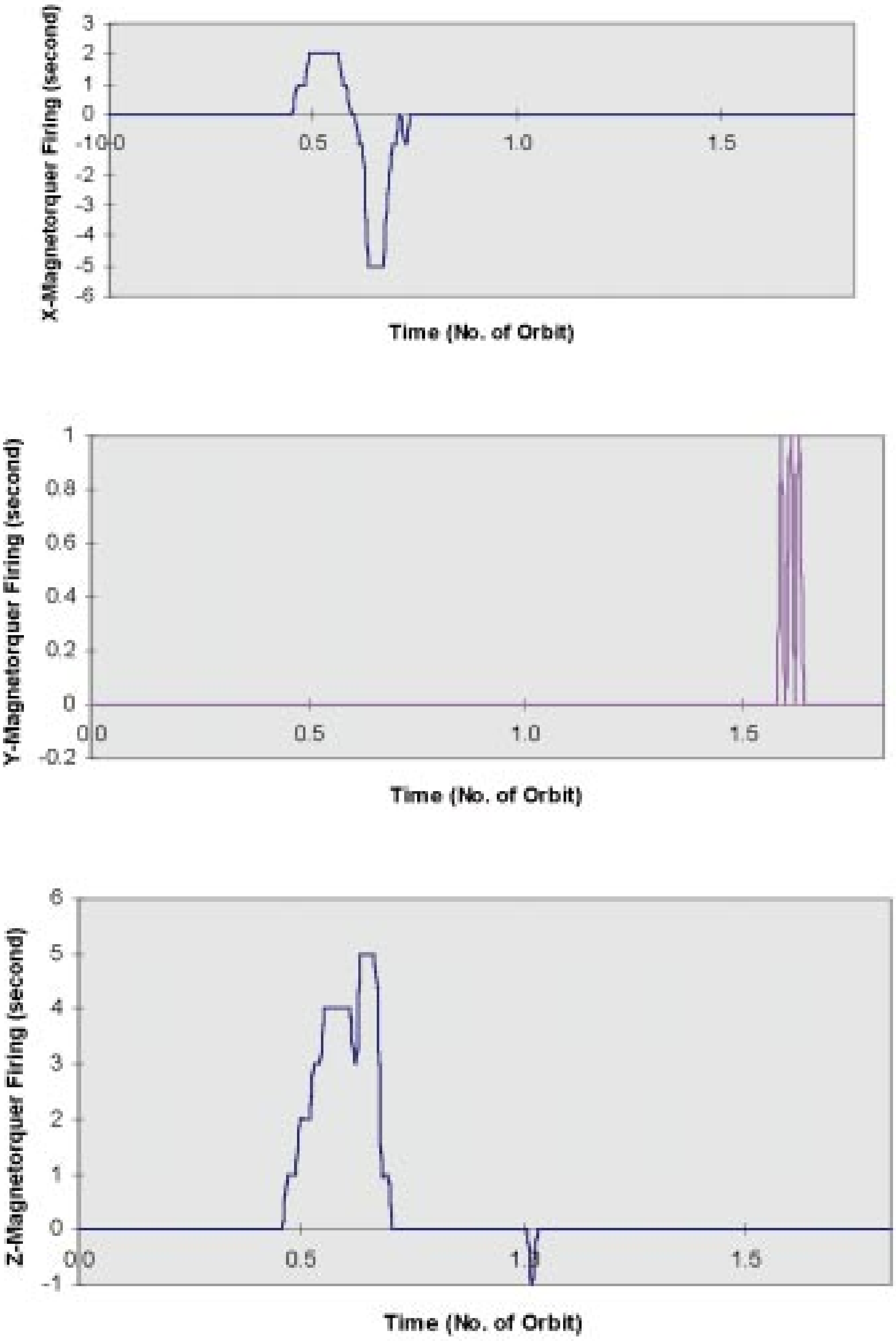

Figure 10. Magnetorquer firings for Option B wheel start-up operation. Again typical of Method 3, rigorous firings of magnetorquers are not required.

Table1. *Option A* wheel start-up performance.

Initial Pitch Demand	No. of Orbit Required (98 minutes/orbit)
10^0	0.64
15^0	0.6
20^0	0.54
25^0	0.59

Table 2. *Option B* wheel start-up performance.

Initial Pitch Demand	No. of Orbit Required (98 minutes/orbit)
10^0	0.62
15^0	0.52
20^0	0.48
25^0	0.46

Comparison of Wheel Start-up Techniques

The different techniques can be compared qualitatively as shown in Table 3. The "power budget" (does not indicate real quantities) reflects the amount of magnetorquer firings required to complete the operation and the "complexity" represents the operational timings involved and the level of software reconfiguration.

Table 3. Qualitative comparison of wheel start-up techniques.

Technique	Duration Required	Power Budget	Complexity
Method 1	Long	High	Low
Method 2	Short	Low	High
Method 3	Medium	Medium	Medium

SATELLITE SPIN RECOVERY

Strategy for Spin Recovery and Wheel Stop

The momentum wheel has first to be stopped before firing the magnetorquers to respin the spacecraft. Similar to starting the wheel, stopping it cannot be done instantaneously as this can cause the spacecraft to topple due to the sudden momentum dump. An operation devised for the spacecraft spin recovery suggests the following three stages which assumes an initially perfect nadir pointing attitude:

Stage 1 - Demanding an initial negative pitch attitude which effectively slows down the wheel.

Stage 2 - Stopping the wheel after a steady minimum wheel speed is reached.

Stage 3 - Magnetorquer firings to respin the spacecraft.

Wheel Stop (Stage 1)

A preliminary simulation study using SIMULINK was done to understand and reflect the feasibility of the spin recovery strategy. This was sufficiently done by the implementation of Stage 1 that shows the time required for the momentum wheel to reach a steady minimum speed from the onset of the operation.

The momentum wheel designed and constructed for TiungSAT-1 has demonstrated linearity down to 150 rpm. However, to increase level of confidence a minimum wheel speed of 500 rpm is in fact used.

The characteristic pitch overshoot as expected from this second order system is a concern. In order to avoid a divergent pitch condition that will topple the spacecraft upside down, as mentioned earlier, a safety limit of ±30 degrees for pitch is adopted.

The wheel continues to decelerate in the attempt to acquire the demanded pitch by acting upon the pitch error signal as part of the closed-loop controller which has been described in a TTT Project Report (Norhizam 1997). This allows the wheel to slow down to its specified minimum speed before being totally switched off.

The preliminary results in Table 4 show that the wheel can be stopped faster with larger initial pitch demands. The corresponding maximum pitch overshoots appear to be within the safety limit.

Table 4. Stage 1 performance for different pitch demands.

Initial Pitch Demand (deg)	Time Taken for Wheel Speed to Minimise (sec)	Max. Pitch Overshoot (deg)
10	2800	±15
15	1950	±19
20	1550	±23
25	1400	±27.5

A more risky case of considering a minimum speed of 250 rpm was also investigated. For a 25 degree initial pitch demand, the wheel takes 1500 seconds to reach minimum speed with a ±25.5 degree overshoot. Although there is a slight difference in this case, it does not indicate a significant improvement in performance.

Success of Spin Recovery

The whole spin recovery operation through all the three stages was simulated. Simulation results (represented by Figures 11 and 12) show that the spacecraft manages to settle down to a stable BBQ-mode with the yaw spin rate at about 0.6° /sec. Figure 13 shows the wheel successfully slowing down and continues to be at rest. Figure 14 shows a series of magnetorquer firings which coincide with the start of the spacecraft respin.

Factors Affecting Recovery Time

Simulations were done for a range of initial pitch demands, with ground initiation from Kuala Lumpur and Guildford. The different orbital positions and directions of motion can affect the time required to complete the wheel stop operation due to its relation to the varying levels of Earth's magnetic field which governs the magnetorquer performance (Hashida 1997). However, although results (Table 5 and 6) do show some differences, they are not deemed to be significant.

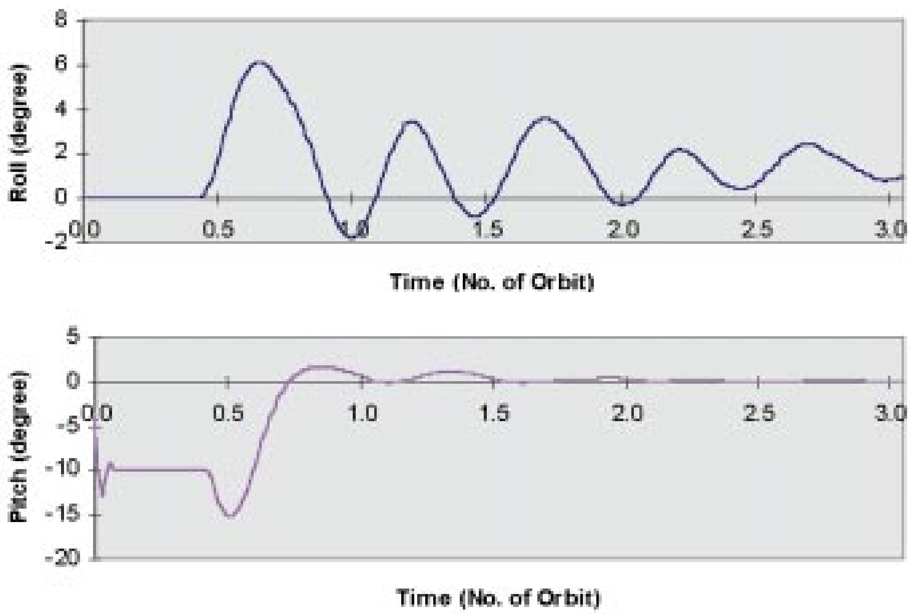

Figure 11. Roll and pitch during spacecraft spin recovery operation. Roll becomes stable corresponding to pitch manoeuvres (after about 0.7 orbit in this example). After command is given to start the operation, the pitch overshoots a little before attaining the -10° demand and further overshoots (still within safety limits) when the wheel is switched off, i.e. Stage 2. Then the pitch starts to level off to nadir pointing as the magnetorquers take over to respin the spacecraft.

In all cases spin recovery is achieved after less than one orbit from the time the command is received from the ground. Surprisingly, although the wheel can be stopped faster with larger pitch demands, there is no net effect on the total recovery time. This is because the yaw spin recovery takes up a longer time. It can be slightly faster when the ground command is sent from Guildford at the corresponding satellite orbital direction as shown in Table 6.

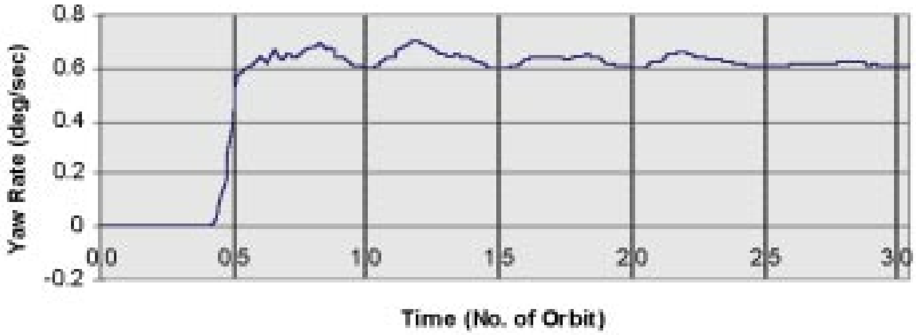

Figure 12. Yaw spin during spacecraft spin recovery operation. BBQ-mode has been reacquired through magnetorquer firings, i.e. Stage 3, typically after half an orbit which is characterised by the 0.6°/sec yaw rate.

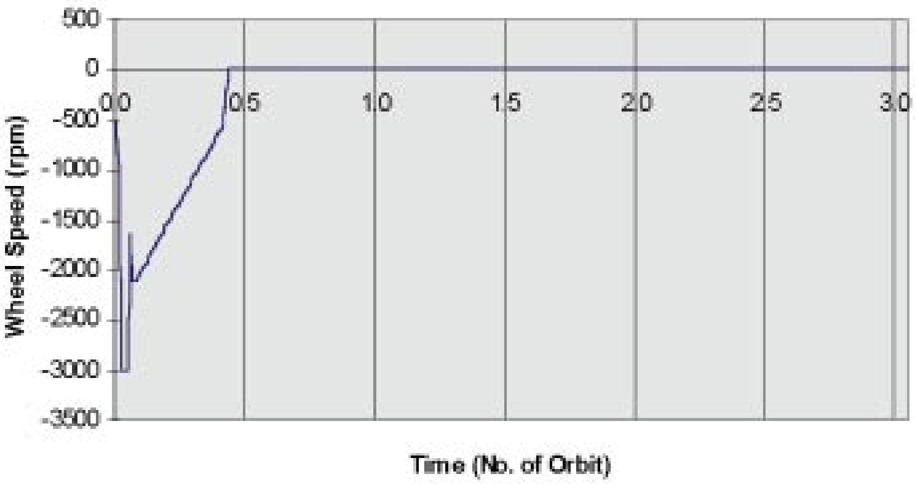

Figure 13. Momentum wheel stop for spacecraft spin recovery. From the nominal speed of 2500 rpm, the wheel goes through some transients and saturation (at 3000 rpm). On reaching the minimum emergency limit of 500 rpm and where pitch must also have stabilised at the demand, the wheel is then switched off.

Table 5. Spin recovery with ground command from Kuala Lumpur.

Initial Pitch Demand	Orbital Motion	No. of Orbit Required
-10^{o}	Descending	0.55
	Ascending	0.5
-15^{o}	Descending	0.55
	Ascending	0.5
-20^{o}	Descending	0.55
	Ascending	0.5
-25^{o}	Descending	0.55
	Ascending	0.5

Table 6. Spin recovery with ground command from Guildford.

Initial Pitch Demand	Orbital Motion	No. of Orbit Required
-10^{o}	Descending	0.6
	Ascending	0.8
-15^{o}	Descending	0.6
	Ascending	0.35
-20^{o}	Descending	0.5
	Ascending	0.35
-25^{o}	Descending	0.3
	Ascending	0.35

CONCLUSIONS

Simulation results of the ADCS for TiungSAT-1 shows that its pitch momentum wheel can be successfully started up to its nominal 2500 rpm from rest in the Yaw-freeze-mode and in the contrary, can be slowed down to rest from spinning to recover the BBQ-mode. Both operations favourably take less than one orbit to complete, irrespective of the operational parameters which are the initial pitch demand, orbital position and direction of motion.

The strategy proposed here is to use the technique of *tricking* the wheel through an initial pitch demand that will start-up or slow down its speed together with the application of magnetorquers and the assistance of gravity gradient. Pitch demands are restricted by overshoots that must not exceed ±30°, which is the chosen pitch safety limits.

The wheel start-up technique proposed here reflects a safer approach as compared to the other options available, hence recommended. The two possible options within this approach, i.e. *Option A* and *Option B,* which vary in terms of the way the magnetorquers are utilised as described in Section 4.2, do not show significant differences in performance, however, *Option A* is preferred as it is less complex to implement.

Kuala Lumpur or Guildford results show that the operation can be achieved fastest (within safety limits of pitch) by instructing a -25° initial pitch demand from Guildford

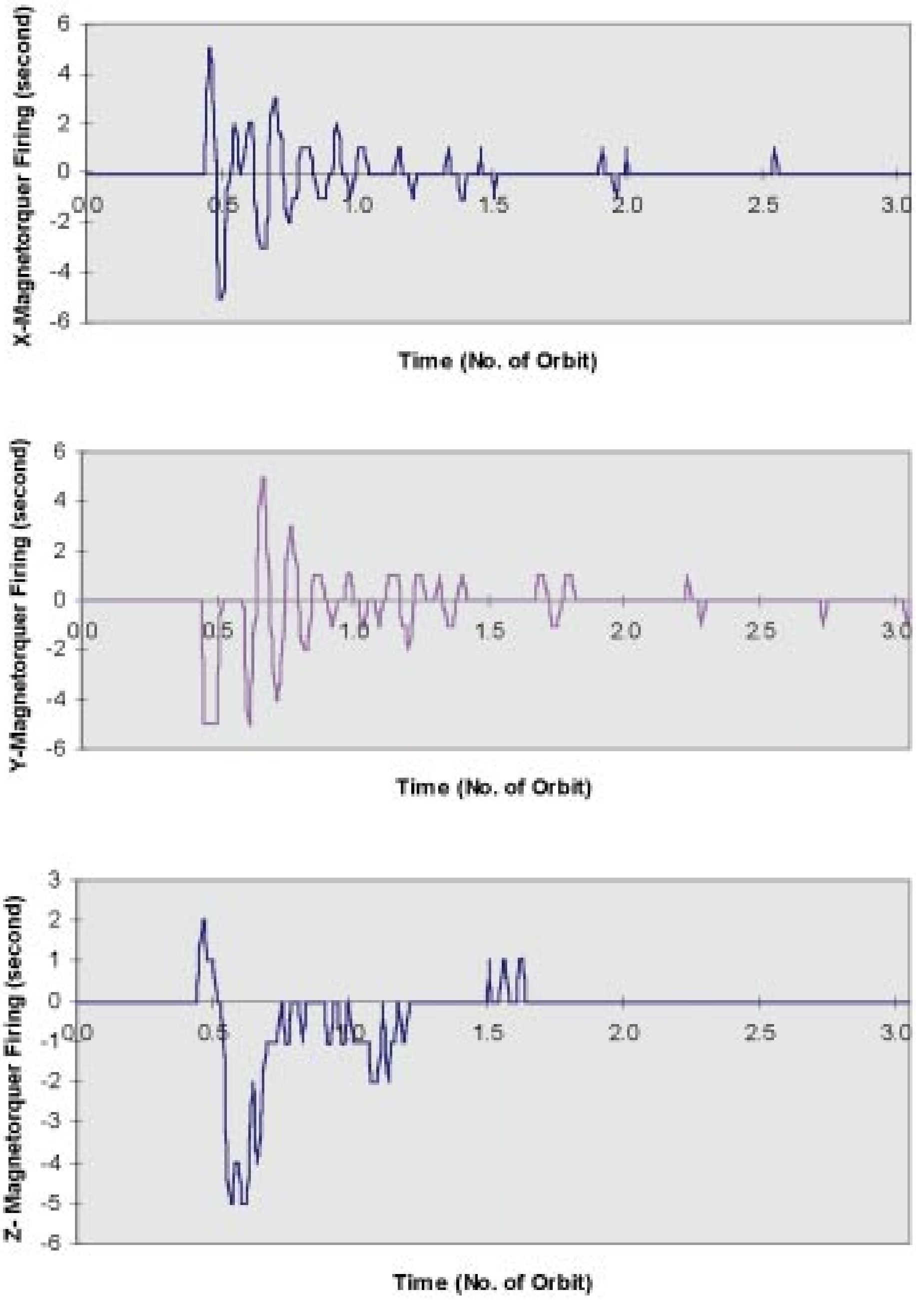

Figure 14. Magnetorquer firings for spacecraft spin recovery. Firings start just before half an orbit which is when the wheel is completely switched off. More firings are involved compared to the wheel start-up operation but still not too demanding, hence acceptable.

in the descending mode. However, this is only marginally faster than the average, which can be taken as 0.5 orbit.

There is no significant difference in level of success for the wheel stop operation and spin recovery to be instructed from either Kuala Lumpur or Guildford.

As a precaution, although the wheel start-up and stopping have been shown to be successfully achievable through simulations, there are still risks involved and thus it is advisable to limit this mode of operation as much as possible. It will definitely be interesting to see how it is going to work out in orbit once TiungSAT-1 is launched.

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