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The stabilisation system

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Abstract. The attitude stabilisation of *Aryabhata* was accomplished by spinning it about its axis of maximum moment of inertia. The spin stabilisation ensures satisfactory thermal control, uniform power generation through the body mounted solar panels and the scan capability for the scientific payloads. To bring down the nutation of the spinning spacecraft to a value well within the specified limits, a fluid-in-tube damper was also provided.

The design philosophy, specifications, details and the dynamics of such a system are presented in this paper along with the qualification and performance evaluation tests of the components and subsystems. Also, the in-orbit performance of the stabisation system is discussed.

Keywords. Satellite stabilisation; attitude control; spin-stabilisation; spin-up system.

1. Introduction

It is well-known that the gyroscopic stiffness provided by spinning a spacecraft about its axis of maximum moment of inertia gives sufficient stability to its attitude against environmental forces arising from aerodynamic, magnetic and solar radiation effects. In addition, spin stabilisation helps in proper thermal control and ensures uniform power generation from the body-mounted solar panels. Further, it enables the onboard scientific experiments to observe both in the pointed and scan modes along and perpendicular to the spin axis respectively. With these considerations in mind, it was decided to employ a simple spin-up mechanism using cold gas jets for stabilising *Aryabhata*. As wide tolerances for the spin rate were accepted by the scientific experiments, a simple blow-down mode was considered feasible. Further, a fluid-in-tube type of nutation damper was employed to damp out the initial coning of the satellite resulting from the disturbances during the separation of the satellite from the rocket. As no specific pointing requirements were projected, attitude orientation capability was not incorporated; however, slow drift in the spin axis orientation was considered desirable for large space coverage.

2. Design philosophy

The higher limit on the spin rate was fixed at 90 rev/min based on telemetry and attitude reconstruction considerations.

A list of symbols appears at the end of the paper.

The spin decay which is mainly caused by the magnetic drag, has been calculated for two cases.

(i) The best case assuming the thin structural shell as a sphere and the rest of the conducting mass as a cylinder, for which the time constant of the spin rate decay worked out to be about 276 days.
(ii) The worst case with entire conducting weight taken as a thin spherical shell for which the time constant worked out to be 31.2 days. However, a similar Soviet satellite, Inter-Cosmos 106, launched into a similar orbit, had a spin decay time constant of only 22.3 days which was assumed for the worst case estimate from gas storage considerations for the designed operational life of 6 months.

After injection into orbit, the satellite has to be spun from zero to 90 rev/min. For subsequent spin-ups (from 15 to 90 rev/min), less gas energy is required compared to the initial spin-up. To standardise the system and considering the size of the available gas bottles, it was decided to have similar spin-up units. Further, it was decided to utilise two units for the initial spin-up operation as gas bottles with storing capacity of 1 kg were available. The spin rate increase is given by

$$W = M\ l\ I_{sp}/I_{zz}. \tag{1}$$

For dry air I_{sp}=60 s; also l=0.95 m; M=mass of the gas in each bottle=1 kg.

The specifications of the stabilisation system were:

spin rate	10-90 rev/min
half cone angle	less than 0.1°
dynamic unbalance	less than 0.1°
transverse velocity at the separation	less than 21°/s
moment of inertia about spin axis, I_{zz}	98.5 kg m^2 (flight-1 model)
spin decay time constant	22.3 days (worst case)
operational life of the satellite	6 months.

3. Design details

3.1. *Spin-up system*

Figure 1 shows the schematic layout of the spin-up system. The six spin-up blocks, each consisting of a gas bottle, a charge valve and a pyro valve, were connected to a common manifold. The manifold was connected to a pair of nozzles, thus connecting each spin-up block to the same nozzles. The specifications of the various components are given in table 1.

The various components were assembled through mechanical connections and welded joints with a stainless steel pipe of 4 mm inner diameter and 6 mm outer diameter.

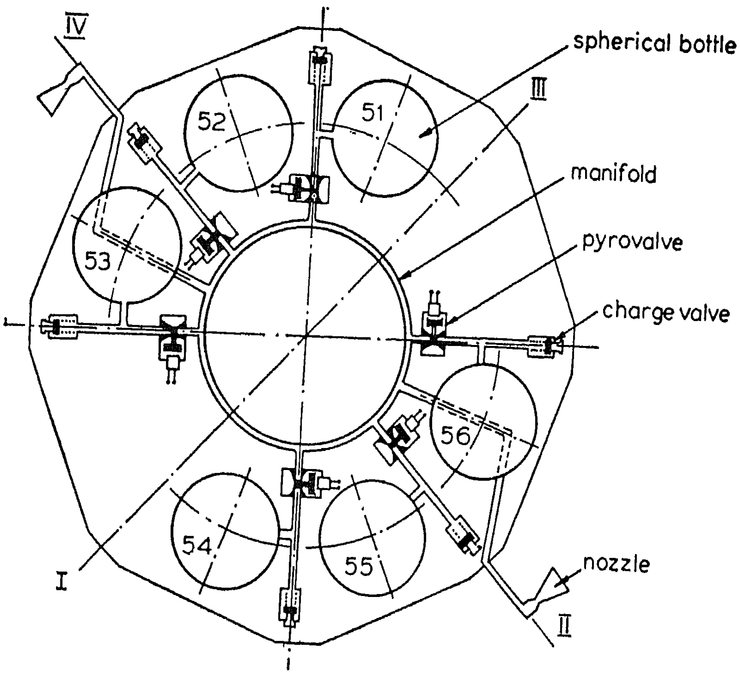

Figure 1. Principal pneumatic scheme of the spin-up system

Table 1. Specifications of the components

(i) *Gas bottles*	
Shape	spherical
Material	titanium alloy
Volume	3.5 litres (nominal)
Weight	3.5 kg
Maximum working pressure	250 kg/cm^2
Burst pressure	1000 kg/cm^2
Operational life	5 years at 250 kg/cm^2
(ii) *Pyro valves*	
Testing pressure	330 kg/cm^2
Firing current	3.0 to 0.4 A
Non-firing current	20 mA
Resistance	1.2 to 1.6 ohms
(iii) *Charge valves*	
Operational pressure	250 kg/cm^2
Cracking pressure	0.25 kg/cm^2
(iv) *Nozzles*	
Maximum working pressure	250 kg/cm^2
Throat diameter	1 mm
Exit diameter	3 mm
Inlet cone angle	90°
Exit cone angle	25°
Efficiency	95%

3.2. Electrical circuits

The pyrocharges get ignited when a minimum current of 0.4 A is passed through for at least 10 ms. For redundancy, each pyrovalve was fitted with two such pyrocharges, connected in parallel.

Figure 2 shows the electrical circuit used for firing the pyrovalves. Each pyro valve, in series with a 9.1 ohm, 6.5 W resistor, was connected to the 22–28 V battery supply through two normally open relays connected in parallel. A minimum of 1.5 A current was passed for 250 ms on command. A guard command, called spin arm command, was provided to safeguard against spurious commands. The spin commands are to be operated within 40 s of the spin arm command. The complete status of the spin-up system was telemetered to the ground.

4. Analysis of spin dynamics

Considering the satellite as a rigid body, with body fixed principal moment of inertia axes X, Y, Z, rotating with velocity W_x, W_y and W_z respectively, the equations of motion are given by

$$I_{xx} W_x + (I_{zz} - I_{yy}) W_y W_z = T_x; \tag{2}$$

$$I_{yy} W_y + (I_{xx} - I_{zz}) W_x W_z = T_y; \tag{3}$$

$$I_{zz} W_z + (I_{yy} - I_{xx}) W_x W_y = T_z. \tag{4}$$

In the absence of torques, the transverse velocity for rotationally symmetric body is given as

$$W_x = W_T \cos \Omega\, t, \tag{5}$$

$$W_y = W_T \sin \Omega\, t, \tag{6}$$

where $\Omega = [I_{zz}/(I_{xx} I_{yy})^{1/2} - 1]\, W_z$ and W_T = initial transverse velocity.

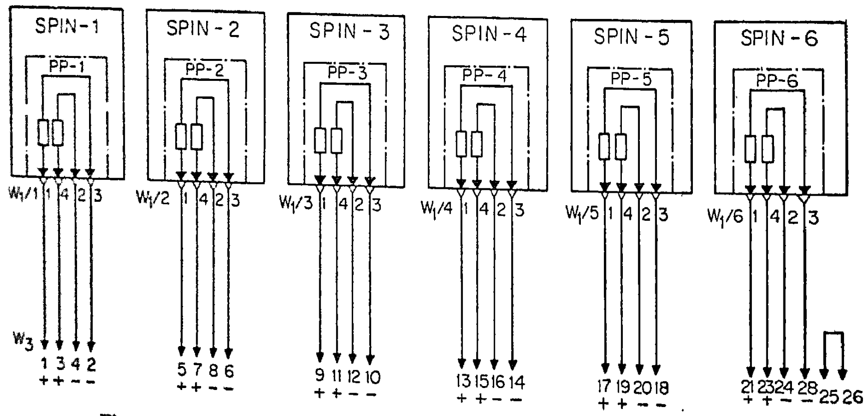

Figure 2. Electrical circuit of the spin-up system

This transverse velocity results in coning of the spin axis about the total angular momentum vector. The coning angle is given by

$$\tan \nu = [(I_{xx} I_{yy})^{1/2}/I_{zz} W_z] W_T. \tag{7}$$

In the absence of any internal dissipation in the body, the body would be stable when spinning about its axis of maximum or minimum moment of inertia. But the inherent internal dissipation in the body (i.e., structural, fuel sloshing or any moving part in the satellite) makes the spinning about the axis of maximum moment of inertia a criterion for stability.

In the blow-down mode, the thrust as a function of time is

$$F = C_1 A_t P_0 \left[1 + \frac{(k-1)}{2V} A_t (R_0 T_0 g k)^{1/2} \left(\frac{2}{k+1} \right)^{\frac{1}{2}, \frac{k+1}{k-1}} t \right]^{-2k/k-1},$$

where $$C_1 = \left[k \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}} \left(\frac{2}{k-1} \right) \left\{ 1 - \left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} \right\}^{1/2} + \epsilon P_2/P_1 \right].$$

Equations (2) to (4) are programmed on a computer taking into consideration the various misalignment torques. The misalignment torques will result in additional transverse velocity apart from separation disturbances. For the allowable limit of 10% increase in transverse velocity because of misalignments over the initial separation velocity, the allowable tolerances were $\leqslant 5\%$ in case of maximum differential thrust for two nozzles and 1° for angular misalignment of the nozzles.

Since the dynamic unbalance had to be limited to 0·1° in terms of principal axes, the cross products of inertia had to be

$$I_{xz}, I_{yz} \leqslant 0{\cdot}0012\, (I_{zz} - I_{xx}).$$

This was ensured by dynamically balancing the satellite using a vertical dynamic balancing machine.

5. Nutation damper

Figure 3 shows a sketch of the fluid-in-tube nutation damper which was a fibreglass toroidal hollow tube, partially filled with silicone oil. The damper was fixed to the top structural plate through eight supporting lugs.

The silicone oil moves in the damper with constant angular velocity till the nutation angle decays to a residual value. This results in the dissipation of the transverse energy at a constant rate and hence the coning angle decays. The residual coning is governed by frictional drag and acceleration torques due to coning. When these two are equal, further dissipation takes place at a very slow rate, the flow being laminar. The residual coning angle is given by (Rogers 1959)

$$\nu_{res} = \tan^{-1} \left(\frac{C_f A r^2 (1 - I_{xx}/I_{zz})^2}{4 R_p a_t \sin n/2} \right).$$

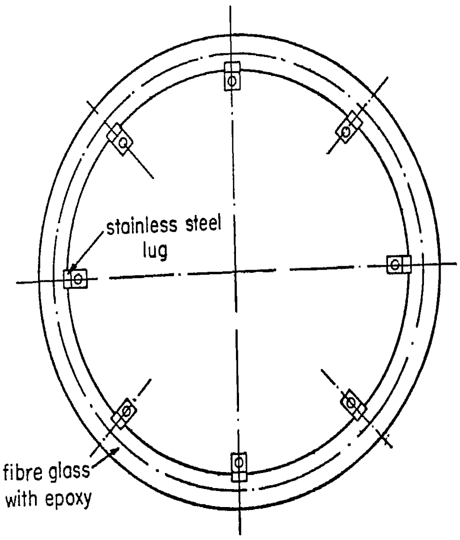

Figure 3. Nutation damper

For the nutation damper in *Aryabhata*, the residual coning angle of the satellite was 26 min. The time for the coning angle to decay from the initial value ν_i to the final value ν_f was 1·2 min based on the formula

$$t = \frac{1 - \cos \nu_i / \cos \nu_f}{\frac{1}{2} C_f A \rho r^3 I_{zz} W_z (1/I_{xx} - 1/I_{zz})^2},$$

with W_s=90 rev/min and ν_i=1·2°.

6. Qualification

The system was subjected to various qualification and performance evaluation tests at component and subsystem level for different models of the satellite as listed below.

(i) The vibration test was carried out on the spin-up system along all the three axes and subsequently tested for leaks for various qualifying and developmental models. Six models were tested for leak in atmosphere and vacuum using a helium leak detector to ensure leakproofness. One model was stored in pressurized condition in vacuum for 6 months and then tested for leak etc., to ensure stability in the vacuum condition.

(ii) The thrust impulse was determined for the five models in vacuum chambers.

(iii) The gas bottles were qualified to store gas for 5 years at 250 kg/cm^2 pressure. The temperature cycles from -10°C to $+$ 50°C were simulated and their effect on leakage was studied.

(iv) Pyro valves were qualified to operate at temperatures ranging from $-$ 50°C to $+$50°C and pressures upto 300 kg/cm^2; leakage was found to be less than 1×10^{-5} Torr litre per second.

(v) The charge valves were qualified to have a nominal life of 6 months under pressures of 250 kg/cm^2, temperatures $-40°C$ to $+50°C$. The leak rate was less than $1{\cdot}75 \times 10^{-3}$ is torr litres per second.

(vi) Totally 22 nozzles were tested in vacuum using a thrust measuring equipment with 2% accuracy. Only the pairs of nozzles whose differential thrust was less than 1% were fitted in the system.

(vii) The nutation damper was qualified against vibration by testing for leak before and after the vibration. The bonding of the stainless steel lugs with fibreglass was also qualified for temperature cycling, vacuum and vibration specifications.

(viii) The performance of the damper was evaluated on a 3-axis air bearing. The coning decay time of 1.2 min and the residual coning angle of less than 0.1° was estimated from this data.

(ix) Independent electrical tests were conducted on the spin-up system for checking the electrical connections, continuity, insulation resistance, etc. An 'autonomous test console' was made to test the system and the continuity of the pyro charges, ensuring non-firing of the charges during the tests.

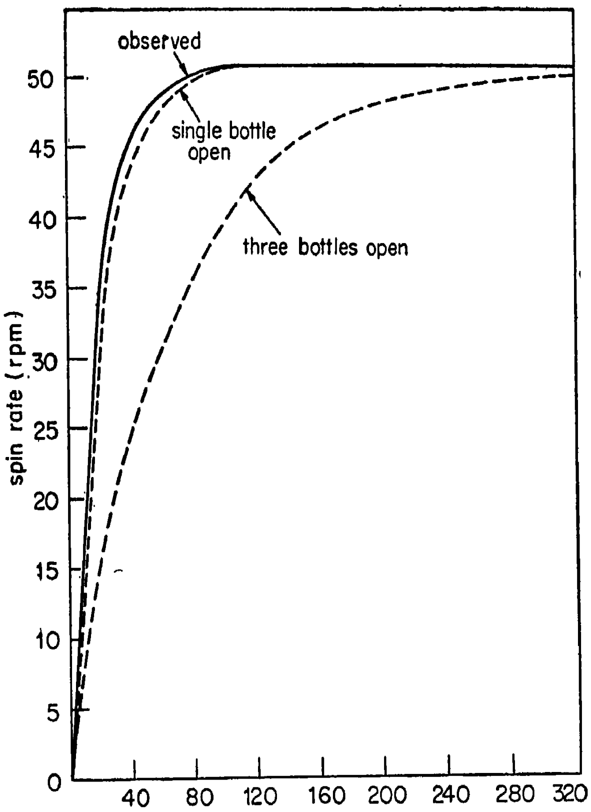

Figure 4. Spin build-up curve for *Aryabhata*

(x) All these independent tests were conducted on all models of the satellite. In addition, complex tests were conducted with prototype and flight model to ensure proper interface with the telecommand parameters, telemetry monitoring and sensor inputs. A special test was conducted to fire the pyrovalves in the prototype model. The complex tests were repeated at the USSR Cosmodrome.

(xi) The flight model of the spin-up system was tested for leaks at the Cosmodrome and charged with dry air as per the requirements.

7. Performance in the orbit

Soon after launching, it was observed that the satellite did not spin as per the design and the spin command was, therefore, given to fire gas bottle 2 in the 45th orbit. The spacecraft attained the spin rate of 50.3 rev/min which was very close to the predicted value. The spin build-up analysis (figure 4) showed that the first two gas bottles did not get emptied and the simulation studies indicated that the malfunction of a relay in the pyrovalve circuit was a cause of the initial spin failure.

The actual spin decay was found to be much lower than that calculated for the worst case and the spin decay time constant was found to be about 154 days (figure 5).

It was extrapolated using sun sensor data that the residual coning angle attained a value less than 0.05°.

8. Conclusions

The spin-up system has functioned satisfactorily with spin rate as calculated. The spin decay has been found to be much slower than that observed for a similar Soviet spacecraft Cosmos 106 and the estimated operational life of the satellite of 6 months is thereby extended to beyond two years. The residual coning angle is very close to the designed value of less than 0.1°.

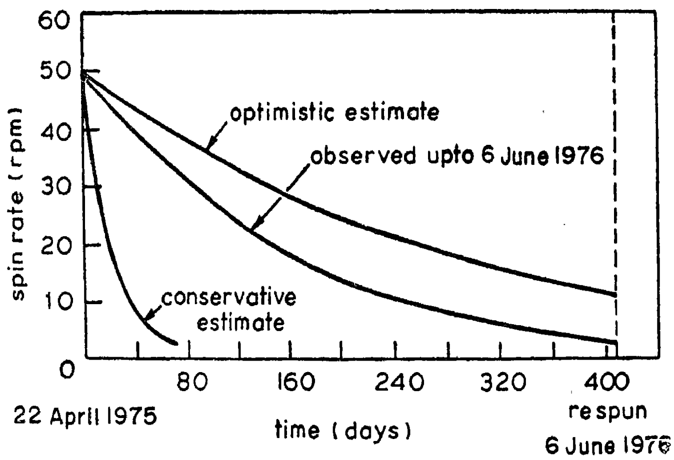

Figure 5. Spin decay curve for *Aryabhata*

Acknowledgement

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List of symbols

A	wetted area of the tube (m^2)
A_t	throat area (m^2)
a_t	cross-sectional area of the tube (m^2)
C_f	drag coefficient
g	gravitational constant (9.81 m/s^2)
I_{sp}	specific impulse of the gas (s)
I_{xx}, I_{yy}	moments of inertia about transverse axes (kg m^2)
I_{zz}	moment of inertia about spin axis (kg m^2)
k	specific heat ratio for the gas
l	arm length (m)
M	mass of the gas (kg)
n	angle of fluid column filled
P_0	initial gas pressure (kg/m^2)
P_1	inlet pressure at nozzles (kg/m^2)
R_0	gas constant
r	radius of the damper tube (m)
R_p	mounting distance of tube plane
T_0	initial temperature (K)
V	volume of gas bottles (m^3)
W	angular velocity (rad/s)
ϵ	expansion ratio
ν	coning angle
ρ	density of the fluid (kg/m^3)

Reference

Rogers E E 1959 US Naval Ordinance Test Std. Rep. No. 10 P 565