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Hardware-in-the-loop Simulation For TR-I Rocket Roll Control System

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Abstract

A test rocket, designated as TR-I was launched to acquire engineering design data for H-II, Japanese next generation satellite launcher, which has been under development by National Space Development Agency of Japan (NASDA).

A simple roll control system has been installed to the TR-I in order to maintain roll angle and roll rate within a limitation during the flight for assuring complete downlink of the telemetery system and for simulating flight condition of the H-II.

In this paper, majar components of the roll control system, such as Electronics Package (E-PACK), Inertial Sensor Package (ISP), Solid Motor Roll Control unit (SMRC) and their hardware-in-the-loop (HWIL) simulation will be discussed, reffering to the actual flight data.

Introduction

NASDA has been developing H-II launch vehicle which is capable of launching a two-ton class geostationary satellite, and the first flight is planned in 1992.

The TR-I is a single staged solid fueled rocket with two dummies of Solid Rocket Booster (SRB) on both sides, designed as a quarter scaled vehicle of H-II to keep the aerodynamic similarity except for the tail fins of TR-I. The configuration and characteristics of TR-I are shown in Fig.1 and Table 1 respectively.

The flight profile of TR-I is illustrated in Fig.2.

The development of TR-I started in 1986, and test flight has been successfully done already.

Missions of TR-I are :

(i) to obtain the engineering data which is unobtainable by ground tests or computer simulation such as aerodynamic load, aerodynamic heating, acoustic noise and vibration. These engineering data will be supplied to the H-II vehicle designing, and

(ii) to confirm the separation method of SRBs. In TR-I, explosive separation devices and separation motors are automatically activated when the axial acceleration rate comes down less than 0.1G during the burnout of main motor.

From the mission requirements that the antenna of an onbord SHF (14.86GHz) telemetry system should look down ground receiving station directly to satisfy its sharp directivity and also the roll rate should be kept small at the SRBs separation, which is predicted to occur during 45-54 seconds into the flight, following technological reqiurements are placed for the roll control system of TR-I;

(1) Roll angle should be maintained whithin ±40 degrees for 70 seconds after lift-off.

(2) Roll rate during 45-54 second must be kept within ±5 deg/sec.

The pitch and yaw attitudes are fin stabirized instead of being actively controled as in H-II.

Before the flight test, the roll control system was tested through the hardware-in-the-loop simulation.

The Roll Control System

The function of each component of the roll control system consisted of E-PACK, ISP and four SMRCs as shown in Fig.3 is as follows.

E-PACK is a 16-bit microprocessor digital control unit which execute control logic programs, generates roll control commond signals and flight sequence signals, processing the angular rate and angular increment data from the ISP.

ISP has three rate-integration gyros to measure airframe angular rates in three-axes and airframe angular increment in roll. But pitch and yaw angular rates are being monitored only.

SMRC unit, with a solid gas generator and a Hot Gas Valve (HGV) as shown in Fig 4, is attached on far end of each tail fin to produce the roll control moment, switching the hot gas flow by HGV in accordance with the actuations chart shown on Table 2. Block diagram of the roll control system is shown in Fig 5. Switching lines of roll control moment on the phase plane of roll angle error and roll rate, are designed to be categorized into three regions according to the magnitude of the roll angular error as shown in Fig 6, to minimize angular rate in the limit cycle and settling time during the angle control phase.

These regions are;

(Ⅰ) $\Phi_L \leq |\Phi\varepsilon|$
(Ⅱ) $\Phi_c < |\Phi\varepsilon| < \Phi_L$
(Ⅲ) $|\Phi\varepsilon| \leq \Phi_c$

Where

$\Phi\varepsilon$: roll angle error
Φ_c : gain switching angle
Φ_L : limit angle

Region (Ⅰ) is the saturation mode where switching line is parallel to the angle axis due to the saturation of the gyro signal.

Region (Ⅱ) is the angle control mode. Here, angular rate control is emphasized, to reduce the rate feedback gain, Kr.

Region (Ⅲ) is the angular rate control mode, where the rate feedback gain Kr is designed to be large.

In addition, the dead band △ and the rate feedback gain Kr are calculated with the time delay, thrust level of SMRC and moment of inertia of the airframe. After 40 seconds into the flight, two of four SMRC HGVs are maintained in the neutral position to reduce the control moment, as to match the reduced aerodynamic pressure then.

The minor cycle of the E-PACK control logic program is 10 msec, which is much faster than the rising time of SMRC thrust (150 msec maximum as shown in Fig.7), therefore, E-PACK can pick up some partial thrust as samples during the rising and also falling transition time periods so that the system functions seemingly as a linear control system.

Hardware-in-the-loop Simulation

Purpose

The purpose of the HWIL simulation is to prove the performances of the roll control system of TR-I. In the HWIL simulation, the following three points were mainly examined.

(1) Confirm and prove the values of control parameters such as Δ, Kr, Φ_L and Φc which are derived from the digital simulation.
(2) Estimate the integrated angular error of the control system in actual flight, simulating the flight parameters as close as possible to the actual planned flight.
(3) Debug the control logic programs of E-PACK, and check the hardware interface, such as electrical and mechanical matching.

Method

The configuration of HWIL simulation is shown in Fig.8. The onboard hardware used there are E-PACK, ISP and SMRCs. The characteristics of the hybrid computer are shown in Table 3, with the simulation flow diagram in Fig.9.

Receiving control forces from SMRCs, the hybird computer calculates the flight trajectory, roll angle and roll rate to actuate the rate table.

The basic equations used in the simulation are;

$$F_x = T - QSC_A$$
$$F_y = -QSC_{N\beta}\beta$$
$$F_z = -QSC_{N\alpha}\alpha$$
$$L = QSd(C_{L\delta}\delta + C_{Lp}pd/2V) + QS_s d_s C_{L\alpha s}\alpha_s$$
$$M = QSd((Xcg-Xcp)C_{N\alpha}\alpha + C_{Mq}q/2V)$$
$$N = QSd(-(Xcg-Xcp)C_{N\beta}\beta + C_{Nr}r/2V)$$

Where

- F_x, F_Y, F_Z : normal forces along the X,Y,Z axes
- L, M, N : moments about the X,Y,Z axes
- T : thrust of the main motor
- V : rocket velocity
- Q : dynamic pressure
- S : rocket reference area
- S_s : SRB reference area
- d : rocket reference length
- d_s : SRB reference length
- Xcg : center of gravity location on the X axis
- Xcp : center of pressure location on the X axis
- α_s : total misalignment angle of SRBs'
- δ : total misalignment angle of fins'
- α : angle of attack
- β : sideslip angle
- p,q,r : rocket angular rates about the X,Y,Z axes
- C_A : aerodynamic coefficient for normal forces along the X axis
- $C_{N\alpha}, C_{N\beta}$: aerodynamic derivatives for normal forces along the x axis
- $C_{L\delta}$: aerodynamic derivatives for moment along the X axis
- C_{Lp}, C_{Mq}, C_{Nr} : aerodynamic derivatives for damping moments along the X,Y,Z axes

Because of the limitation on SMRC test stand capability, only one actual SMRC unit is used in the simulation, being activated by cold nitrogen gas instead of solid fueled hot gas. Then hot gas SMRC thrust is calculated by the hybrid computer, remaining three SMRC units are mathematically modeled in the computer.

ISP is mounted on the rate table which is required over 5 Hz response in order to simulate the roll motion of the airframe.

Control equations and frequency response of the rate table are shown in Fig.10 and Fig.11 respectively.

Parameters which cause roll disturbance, such as the installation misalignment of tail fins, SRBs and the off-set of SMRCs are independently taken into calculation in the simulation. But the other parameters such as thrust vector off-set and

Simulation Results

Simulation results are shown in Fig.12. The major items observed there are:

(1) The maximum angle error is 8.3 degrees at 6.2 seconds after launch, when completely satisfies the requirements.
(2) The roll rate of the rocket between 45 to 54 seconds after launch where SRBs might be jettisoned is 1 deg/sec, which also completely satisfies the requirements.
(3) The electrical interface among components are normal.

Flight Test Results

Simulation and flight test results are shown in Fig.13 and Fig.14, respectively. There are some interesting observations between these results. they are :

(1) The actual roll angle in flight is larger than the simulation result from the lift-off until 6 seconds after launch.
The angles of attack and bank, shown in Fig.15, was so large then that the induced roll moment could be caused by the angle of attack and aerodynamical asymmetry of the banked airframe.
(2) The roll angle changes around 27 seconds after launch.
The altitude of TR-I rocket at 27 seconds is about 10 km, and in this zone a strong wind was blowing. This is clearly observed video taped pictures. From these facts this change might be thought to be caused by the asymmetry of the wind shear.

misalignment coupling of the main motor, center of gravity off-set of the airframe, induced roll moment by pitch and yaw coupling, wind shear effect and so forth are so difficult to estimate in details that these parameters are equivalently calculated as a simulation margin. As for launching angle range, 78±3 degrees is used to predict the trajectory dispersion.

Conclusion

In this paper we described the roll control system of TR-I rocket and its HWIL simulation test. As the result of this simulation, we prove the validity of the angle control mode and the angular rate control mode for the roll control system under the expected circumstances. The simulation results was compared with actual flight data, and we got the good coincidence between them while the atomospheric effect is low. But data of roll disturbance factor described in the section of Simulation Method should be accumlated much more for the presice simulation and this will be our technological subjects in the future.

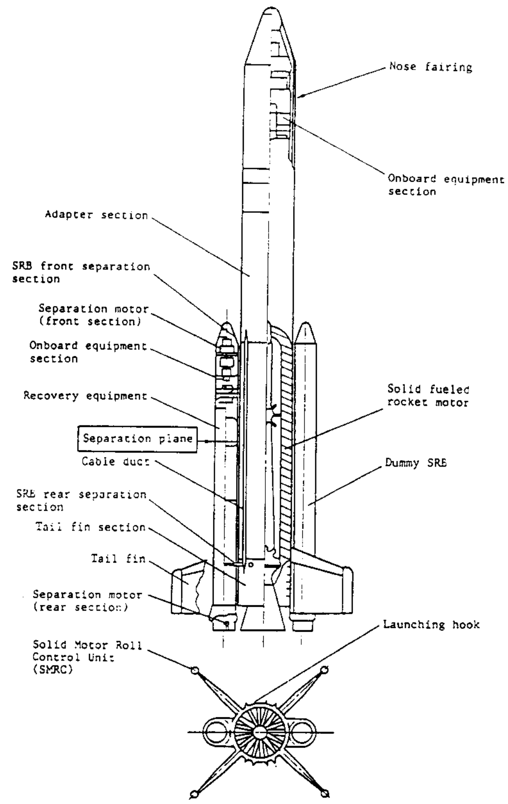


Fig. 1 Configuration of the TR-I rocket

Time (Second)	Event
X - 40	Start-up of the E-PACK timer
X - 15	Initial setting of the roll angle signal
X + 0	Ignition of the rocket motor
X + 6	Ignition of SMRC (Starting roll control)
X + 40	Stopping of two SMRC units
X + α	Separation of SRB (α = 50.1/sec nominal)
X + 61	Separation of the recovery section
X + 70	Stopping of roll control
X + β	Emission of beacon electromagnetic wave
X + γ	Land on the water

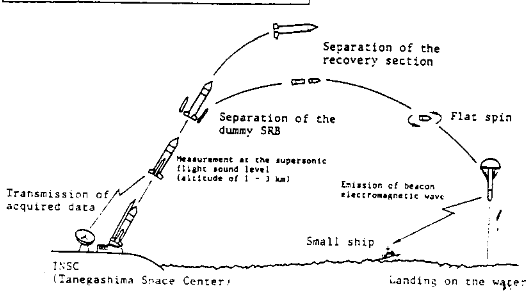


Fig. 2 Flight profile of the TR-I rocket

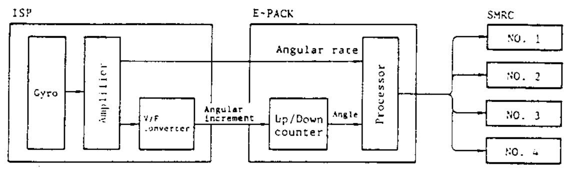


Fig. 3 Configuration of the roll control system

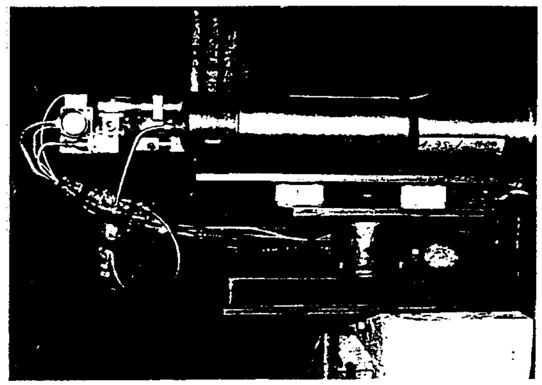


Fig. 4 Solid Motor Roll Control unit (SMRC)

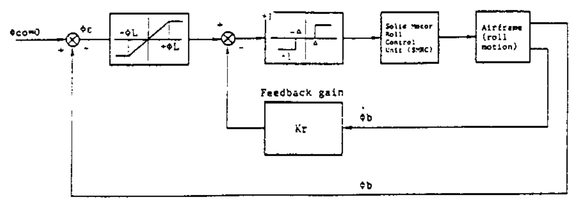
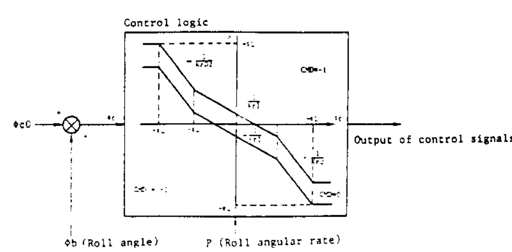


Fig. 5 Block diagram of the roll control system



Parameter Chart

Names	Symbol	Unit	Value
Gain 1	Kr1	s	3.0
Gain 2	Kr2	s	0.2
Dead band		degree	5.0
Gain switching angle	ϕ_c	degree	5.0
Limit angle	ϕ_L	degree	9.0
Limit angular rate	$\dot{\phi}_L$	deg/sec.	(19.0)

Fig. 6 Control switching line

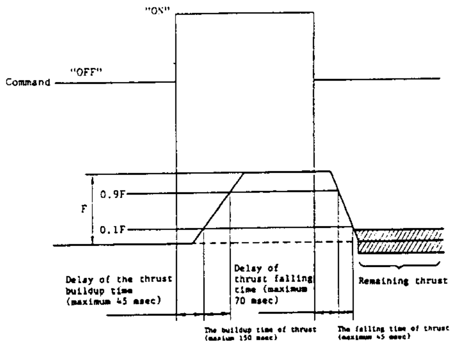


Fig. 7 Mathematical model of SMRC

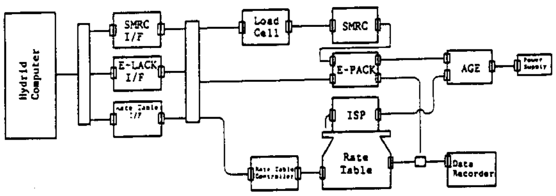


Fig. 8 Configuration of hardware in the loop simulation

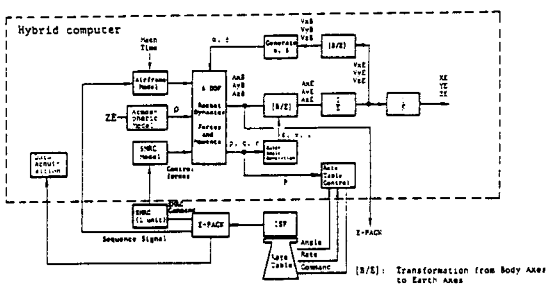


Fig. 9 Simulation flow diagram

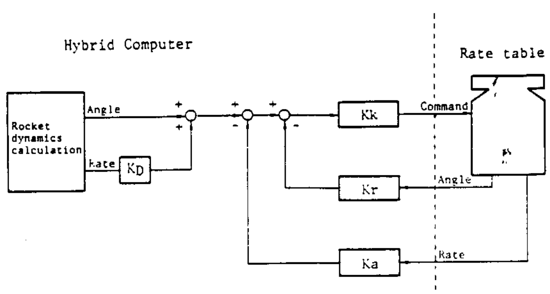
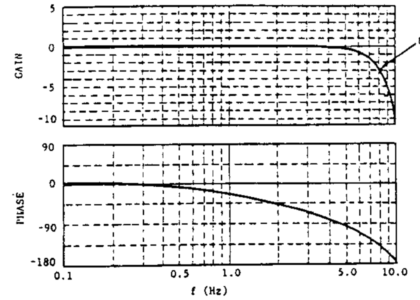


Fig. 10 Block diagram for rate table control



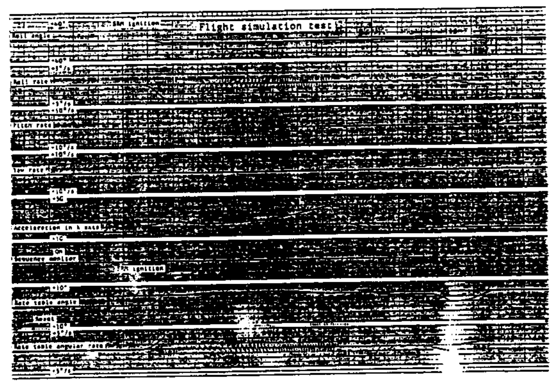
Test conditions

KK = 1.05
KR = 0.025

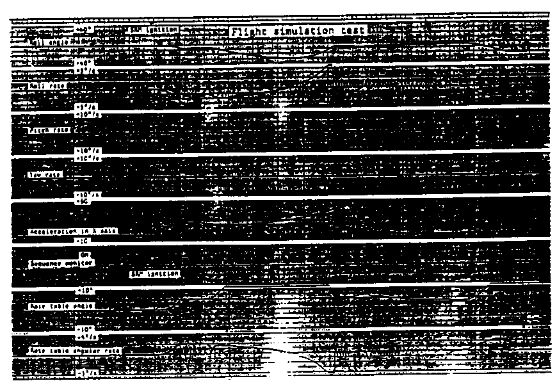
Test results

W (Hz)	GAIN (dB)	PHASE (deg)
0.1	0.00	1.-
0.2	0.03	5.2
0.3	0.04	-1.3
0.5	0.04	-6.2
0.7	0.04	-16.3
1.0	0.03	-21.7
2.0	-0.15	-43.4
3.0	-0.35	-68.3
5.0	-0.25	-93.1
7.0	-1.22	-125.5
10.0	-9.15	-172.0

Fig. 11 Rate table frequency response characteristics



Nominal thrust, nominal launching angle



Minimum thrust, minimum launching angle

Fig. 12 Flight simulation test results

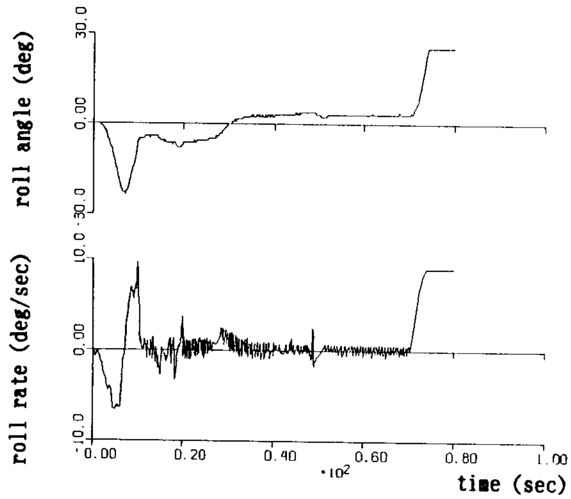


Fig13. Flight Test Results

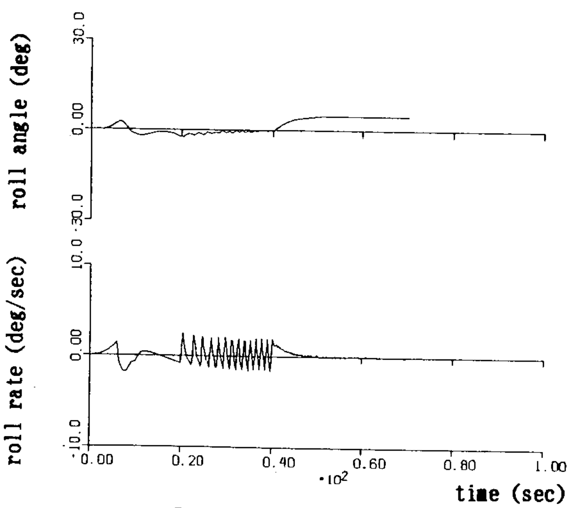


Fig.14 Simulation Results

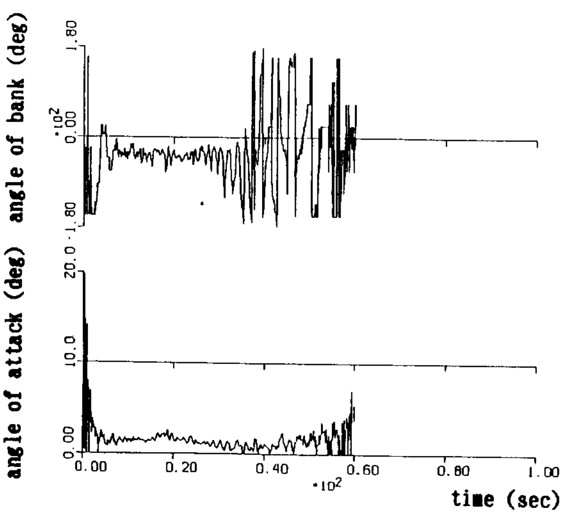


Fig.15 Flight Data

TABLE 1 Specification

Item			Specification*	Remarks
Overall length			14 meters	
Diameter			1.1 meters	Representative diameter of the core rocket
Gross load			12 tons	
Rocket motor	Propellant		Solid propellant	
	Total weight		8 tons	
	Propellant weight		7 tons	
	Buring character-istics	Initial thrust	62 tons	Sea level
		Specific impulse	272 seconds	Under vacuum
		Total burning time	50 seconds	
Fairing	Overall length		3.6 meters	
	Diameter		1.1 meters	
Dummy SRB	The number of loading		2	
	Overall length		7 meters	
	Diameter		0.5 meter	
	Weight		500 kg (per unit)	

*: Approximate value

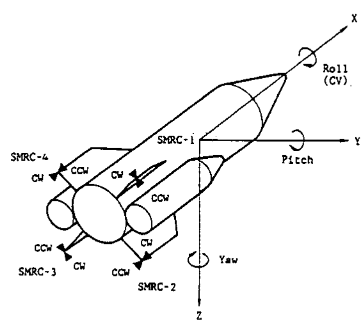


TABLE 2 Combination of SMRC's actuations

Time after lift-off	Hot gas valve (HGV) / Control signals (CMD)	SMRC-1		SMRC-2		SMRC-3		SMRC-4	
		CW	CCW	CW	CCW	CW	CCW	CW	CCW
6" - 40"	+1	ON	OFF	ON	OFF	ON	OFF	ON	OFF
	0	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
	-1	OFF	ON	OFF	ON	OFF	ON	OFF	ON
40" - 70"	+1	ON	OFF	OFF	OFF	ON	OFF	OFF	OFF
	0	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
	-1	OFF	ON	OFF	OFF	OFF	ON	OFF	OFF
70" -	0	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF

TABLE 3 Characteristics of Hybrid computer

Item	Type	Specification,	
Digital part	Gould Co. CONCEPT 32/97	Basic word length:	32 bits
		Main storage:	4 MB
		Execution cycle:	300 ns
		OS:	MPX - 32
Analog part	EAI Co. SIMSTAR	Integrator:	30
		Multiplier:	32
		3-input adder:	12
		Adder:	80
		SIN/COS:	6 per each
		Comparator:	12
		External input/output:	32 ch per each