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Launch Stabilisation System for Vertical Launch of a Missile

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ABSTRACT

The launch platform stabilisation control system is a roll-pitch stabilised platform for the vertical launch of a missile from a naval ship. Stabilisation of the launch platform is achieved with the help of embedded controllers and electro-hydraulic servo control system. The launch platform is stabilised wrt true horizontal with a 2-axis (roll and pitch) stabilisation system consisting of a gimbal and a set of three high-pressure servo hydraulic actuators. The control system uses rate gyro and tilt sensor feedbacks for stabilising the platform. This paper outlines the details of the launch platform stabilisation control system, results of digital simulation, and the performance during sea trials.

Keywords: Launch stabilisation system, launch platform, stabilised vertical launch system, SVLS, missile launching, control system, controller design

NOMENCLATURE

x_v	Servovalve spool position
K_{vl}	Steady state gain of valve
ω_v	First-order corner frequency of valve
I	Input current to servovalve (A)
Kq_1	Flow constant-cap side
Kq_2	Flow constant-rod side
C_{ip}	Internal or cross port leakage coefficient of piston
V_1, V_2	Volume of oil contained in cap-side and rod-side chambers of the piston, respectively
x_p	Displacement of piston in the cylinder
C_{ep}	External leakage coefficient
A_1	Cross-sectional area of cap-side chamber of cylinder
A_2	Cross-sectional area of rod-side chamber of cylinder
β_e	Equivalent bulk modulus of oil
J	Inertia of the system
B	Viscous damping of the system
M	Mass of the system
R	Distance of centre of mass from the gimbal
d_{1g}, d_{2g}	Distance from the axis of rotation and from the actuator piston (roll and pitch)
θ	Tilt of the platform

1. INTRODUCTION

The weapon system is a state-of-the-art electro-hydraulically stabilised vertical launch system (SVLS) for the vertical launch of a missile. This complex and innovative system, without any parallel in the

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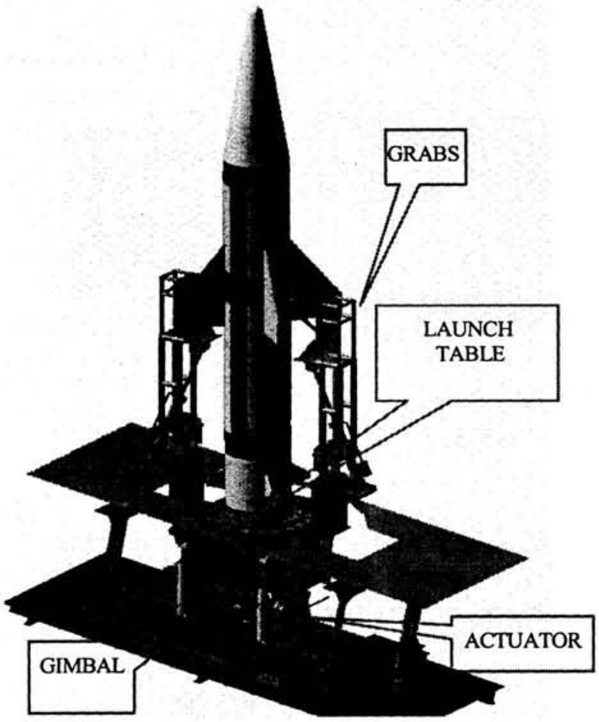

Figure 1. Model of missile stabilisation platform

world, has been indigenously developed from concept to realisation through exemplary collaborative development between Prog AD (DRDO) and Larsen & Tourbo Ltd, with valuable suggestions and input from the Indian Navy (Fig. 1). State-of-the-art concurrent engineering techniques such as 3-D solid modelling, finite element analysis methods, and advanced control simulation techniques were employed for the development to ensure successful realisation of the system without hard prototype route.

The challenge for such a launch stabilisation system is to stabilise a high inertia, large mass imbalance (inverted pendulum) on a hydraulically-driven platform having low stiffness and damping.

The system configuration involved a 2-axis gimbal and a set of three high-pressure servo hydraulic actuators to provide correcting (balancing) moments. Flow to the three hydraulic actuators was controlled by servovalves, which were, in turn, controlled by an embedded controller. The launch platform was free to rotate about roll and pitch axes constrained by end limits.

The missile was clamped onto the platform using an innovative clamping device at the base. A backup support system was provided in the form of a pair of grabs pivoted on the stabilised launch basket and reaching above the missile centre of gravity. Just prior to lift-off, the grabs were opened hydraulically.

The launch stabilisation control system has to maintain the platform position horizontal within specified accuracy and roll-pitch rates. Additionally, the system was to compensate for the disturbances such as wind force, etc.

Figure 2 gives the orientation of the piston actuators. Orientation of the actuators was in such a way that two of these (2nd and 3rd) compensated for pure roll motion and all the three together compensated for pitch motion.

The perpendicular distance between the actuator centreline and the roll and pitch axes passing through the gimbal centre were designated as d_{1g} and d_{2g} (as shown in Fig. 2) .

2. SYSTEM MODELLING

The system was divided into two independent control models about roll and pitch axes for carrying out linear analysis and controller design. The basic assumptions are:

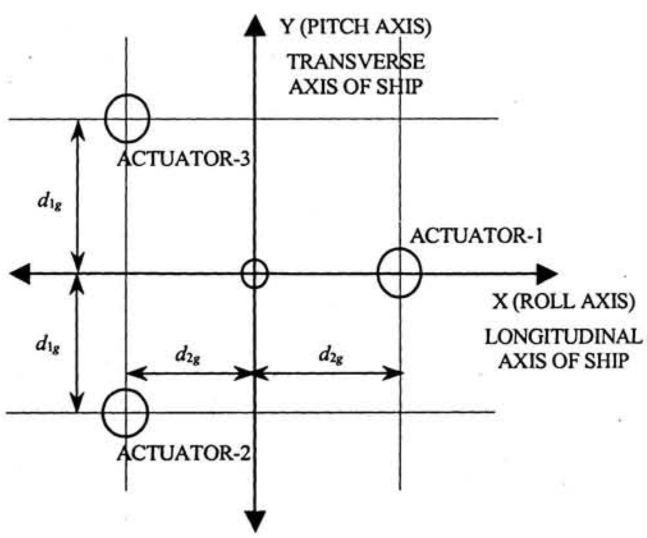

Figure 2. Geometry of hydraulic actuators

- Roll and pitch motions can be controlled independently.
- All the three hydraulic actuators are similar in construction
- The platform is perfectly rigid and its motion relative to the ship is described by pure rotation about the 2-gimbal axes.
- The cross-coupling effects of roll and pitch axes are considered negligible.

The hydraulic system was a high-pressure and high-flow rate system. The powerpack comprised variable delivery pumps with horsepower limiters and an accumulator bank for providing peak oil flows. A classical linearised as well as simulation model[1] of the hydraulic system was used for modelling the plant. The destabilising moment was supported by the cap-side and the rod-side pressures, respectively of the actuators located on either side of the gimbal.

A two-stage servovalve, with both electrical and mechanical feedbacks was used on each actuator in the system. The servovalve was characterised by its current gain, flow gain and the first-order corner frequency. The pressure at the servovalve inlet was kept constant, which was achieved by a supply-side accumulator and a pressure reducer. A conservative value of oil compressibility was considered taking partial air entrapment in the system. Internal and external leakage coefficients were used to model the leakage and damping created by the leakage across the actuator piston and the servovalve spool position.

3. FEEDBACK ELEMENTS

The roll and pitch rate feedbacks were taken from a rate gyro sensor. Absolute roll and pitch angle feedbacks were sensed with a tilt sensor. Pressure transducers were used for providing pressure feedback across the control ports of the servovalve connected to cap-end and rod-end of the actuators.

4. DISTURBANCE LEVELS & ACTUATOR SIZING

The system was expected to operate at sea state 4. However, the system was designed to operate under roll-pitch amplitudes and frequencies exceeding the stipulations as per DOD-STD-1399 for ship motion parameters. The wind-load under operating conditions was computed from the ship velocity and wind speed data.

The launcher subsystems were designed to withstand the missile thrust during operations and in abort conditions.

5. SYSTEM MODEL

Figure 3 shows the simplified block diagram of the roll/pitch plant for a small amplitude tilt.

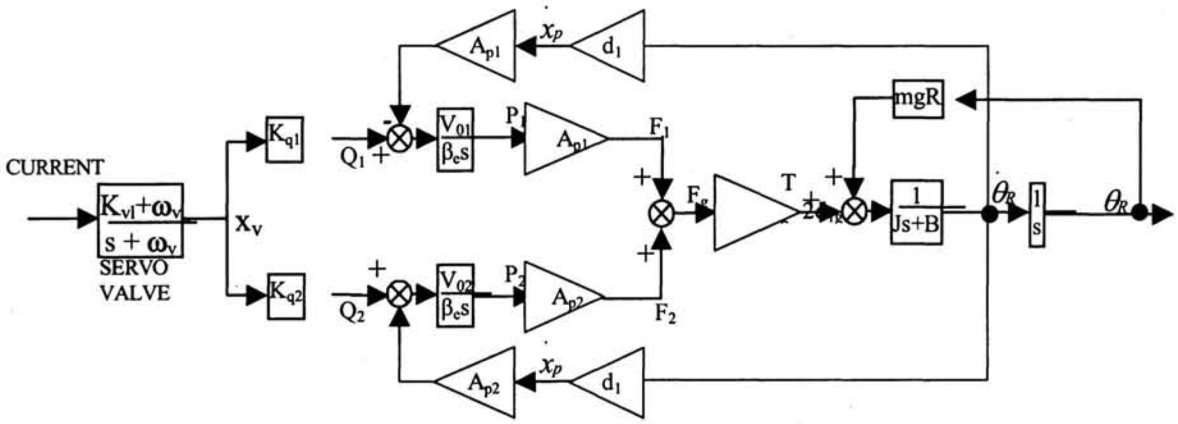

Figure 3. Block diagram of system plant

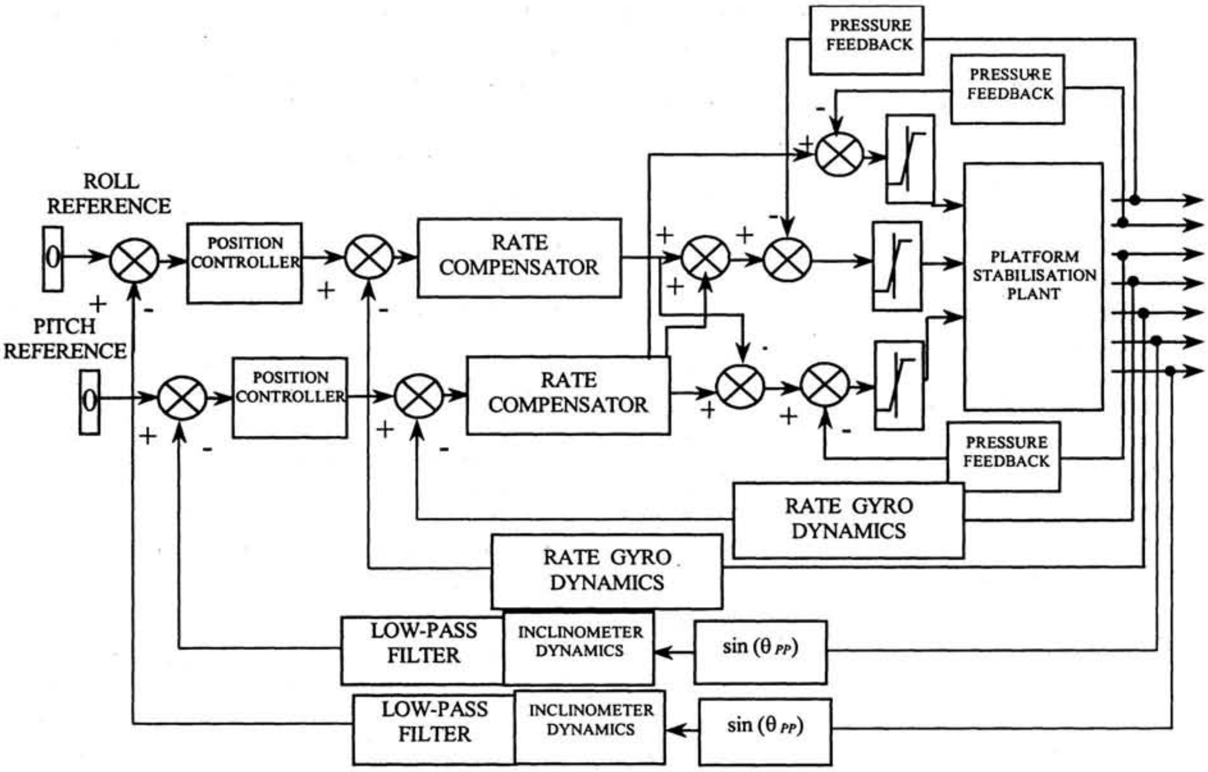

Figure 4. Block diagram of platform stabilisation control system model

The system model is given in Eqn. (1)

$$x = Ax + Bu$$
$$y = Cx \tag{1}$$

Let angle of tilt (roll or pitch) $\theta = x_1$ and $\theta = x_2$, then the above state space equation becomes Eqn. (2) and Eqn. (3).

$$\begin{bmatrix} \dot{x}_v \\ \dot{p}_1 \\ \dot{p}_2 \\ \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -\omega_v & 0 & 0 & 0 & 0 \\ kq_1\beta_e/V_1 & -(C_{ip}+C_{ep})\beta_e/V_1 & C_{ip}\beta_e/V_1 & -A_1 d_{1g}\beta_e/V_1 & 0 \\ kq_2\beta_e/V_2 & C_{ip}\beta_e/V_2 & -(C_{ip}-C_{ep})\beta_e/V2 & -A_2 d_{1g}\beta_e/V_2 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 2A_1 d_{1g}/J & -2A2d_{1g}/J & -MgR/J & -B/J \end{bmatrix} \begin{bmatrix} x_v \\ p_1 \\ p_2 \\ x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} k_{v1}\omega_v \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} i \tag{2}$$

$$\theta = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_v \\ p_1 \\ p_2 \\ x_1 \\ x_2 \end{bmatrix} \tag{3}$$

5.1 Roll Plant Model

The transfer function from the input current to the platform roll position is given below:

$$\frac{\theta_r(s)}{I(s)} = \frac{1.056 \times 10^6}{s(s+94.24)(s^2+0.0082s+229.99)}$$

5.2 Pitch Plant Model

The transfer function from the input current to the platform roll position is given by Eqn. (4) as

$$\frac{\theta_p(s)}{I(s)} = \frac{1.05085 \times 10^6}{s(s+94.24)(s^2+0.0082s+471.67)} \tag{4}$$

6. CONTROL SYSTEM MODEL

The block diagram of the platform stabilisation control system model is given in Fig. 4.

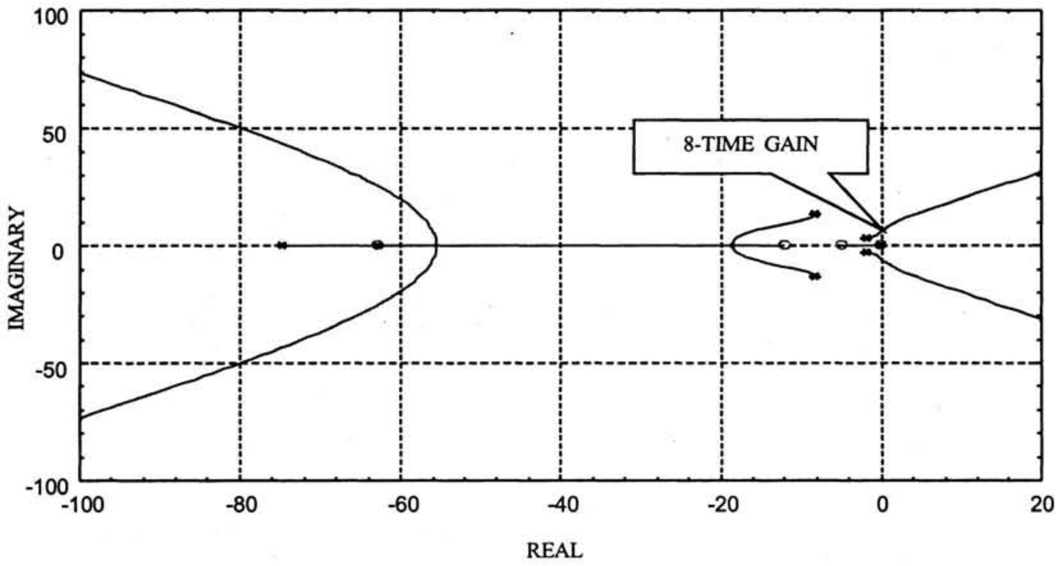

Figure 5. Root locus of the roll system with controllers

6.1 Roll Controller Design

The roll plant shows a very low damping. To increase the system damping, dynamic pressure feedback was incorporated into the control strategy. The feedback transfer function is given in Eqn. (5)

$$G_{pfb} = \frac{4.11\times10^{-11}s}{0.7s+1} \quad (5)$$

With this feedback, the transfer function of the roll plant is given in Eqn. (6).

$$\frac{\theta_r(s)}{I(s)} = \frac{1.063\times10^{6}}{s(s+74.003)(s^2+20.27s+263.87)} \quad (6)$$

The root locus of the roll control system is given in Fig. 5.

6.2 Pitch Controller Design

The pitch plant shows a very low damping. To increase the system damping, dynamic pressure feedback was incorporated into the control

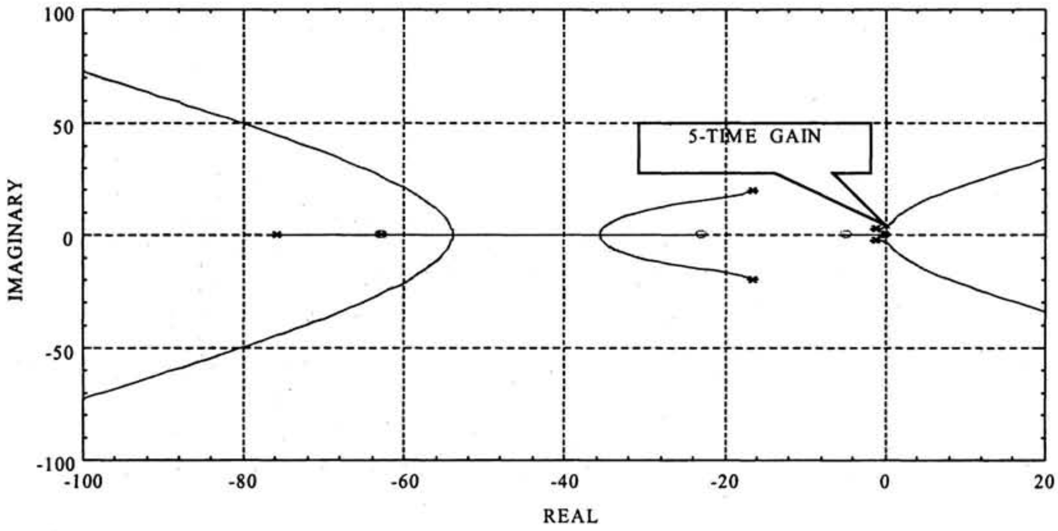

Figure 6. Root locus of the pitch system with controllers

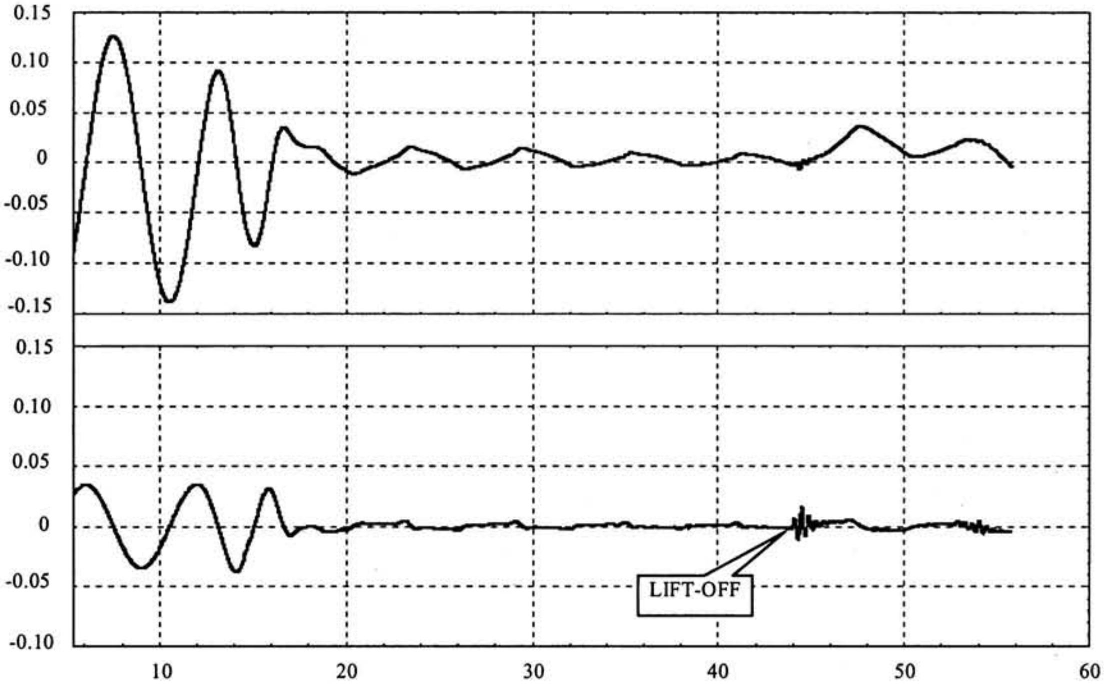

Figure 7. System response (roll of 7 °, pitch of 3 ° and period 6 s)

strategy. The feedback transfer function is given in Eqn. (7).

$$G_{pfb} = \frac{4.11\times10^{-11}s}{0.7s+1} \quad (7)$$

With this feedback, the transfer function of the pitch plant is given in the following Eqn. (8).

$$\frac{\theta_p(s)}{I(s)} = \frac{1.864\times10^6}{s(s+75.22)(s^2+35.2s+691.2)} \quad (8)$$

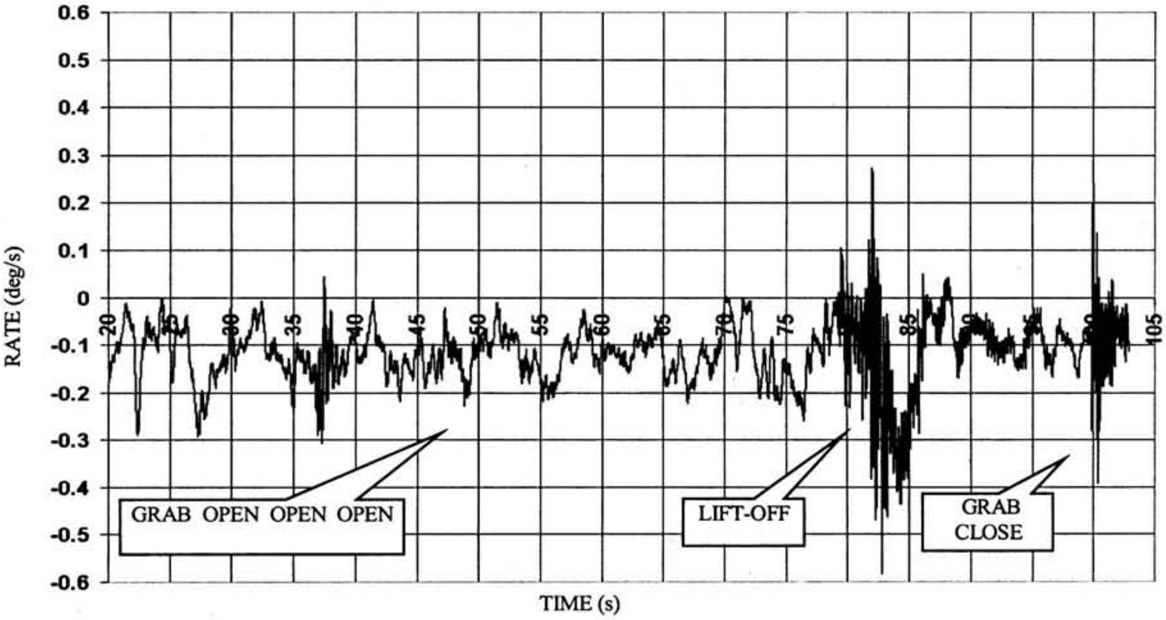

Figure 8. Inertial navigation sensor reading during the trials: Roll rate before and after firing

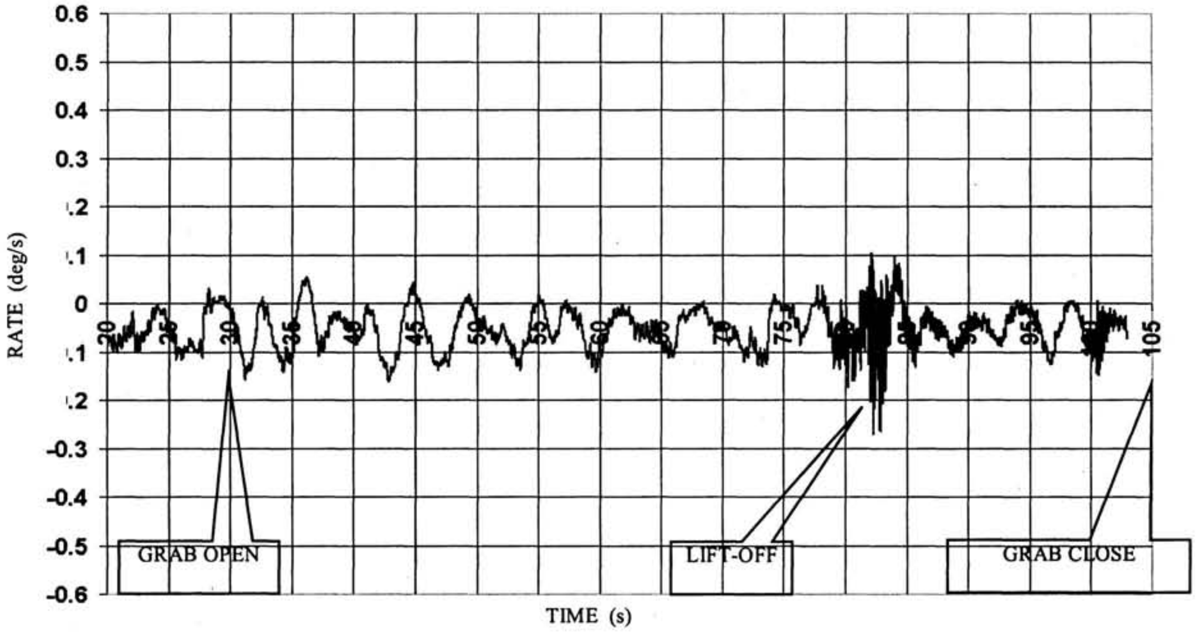

Figure 9. Inertial navigation sensor reading during the trials: Pitch rate before and after firing

The root locus of the pitch control system is given in Fig. 6.

7. SIMULATION

Digital simulation was carried out for the system incorporating various system nonlinearities and considering the effects of ship roll and pitch, wind torque, ship acceleration, etc and the result is shown in Fig. 7.

8. SEA TRIALS

Figures 8 and 9 show the data captured from an inertial navigation sensor mounted on the platform, during firing trials from the designated ship.

9. SUMMARY

The results of the firing trials were as predicted during the digital simulation. The controller was robust and its design adequately catered for disturbance rejection, so that the noise during firing thrust and other disturbances did not cause any instability to the system. The slight disturbance, which was observed during the rocket motor firing, was well within the specified limits.

REFERENCES

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2. P1703 Platform stabilisation control simulation report. Larsen & Toubro Ltd, Mumbai.