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Implementation and validation of autopilot design for vertical missile systems

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Abstract. high nonlinearity and deficiency in control at boost-phase due to high angle of attack during maneuver and low velocity in the vertical launched missile. The necessity of high maneuverability and vertical launching require thrust vector control additional to aerodynamic control. effectively increasing the alertness of the missile against air defense threats by using That mixture usage of aerodynamic and thrust vector controls. Critical design of guidance and control is difficult and critical due to requirement and the rapidly changing dynamics of this type of missiles. The aim of this paper is to design autopilot with aerodynamics surfaces(fin)and thrust vector control by system characteristics reflection. by using Missile Lebadev Program (MLP) the model is developed based on the configuration of operating missile. Two control systems are aimed, which usages the command trajectory result optimization and the pitch rate controller which tracks real-time guidance command. The guidance and control strategy are developed through an actuation systems and autopilot design in the two channels pitch and roll based on the poles assignment technique. The investigation of the performance of pitch autopilot and its ability to reject disturbances due to cross-coupling between pitch and roll channels showed that, the pitch channel can reject disturbances within average time 3.5 sec.

Nomenclature

α	Angle of attack.	c_{x0ru}	Drag coefficient of actuation system.
β	Sideslip angle.	$c_{xru}^{\delta^2}$	Induce drag coefficient of actuation system.
θ	Trajectory inclination angle.	M	Missile mass.
ϑ	Pitch angle.	D_M	Missile diameter.
ξ	Damping ration.	v_M	Missile velocity
τ	Time constant.	M	Mach number.
γ	Missile roll angle.	I_z	Moment of inertia on z-axis.
δ_p	Deflection Pitch actuator.	ϕ_T	Efficiency for corrosion actuator.
x_a	Drag aerodynamic force.	S_M	Cross-sectional area of the missile.
q_{ru}	Dynamic pressure of actuation	ρ	Air density.
S_m	Cross-sectional area of actuation	x_{cg}	Missile center of gravity.
c_{yru}	Lift coefficient	x_{cp}	Missile center of pressure.
x_{cpru}	Center of pressure of actuation system.	x_B	Higher order derivative.

g	Gravity acceleration	M_z^{α}	Pitching moment coefficient.
x_B	Higher order derivative.	Y_a	Aerodynamic lift force due to actuation.

Introduction

Missile categories is classes into two section: tactical and strategic missiles, tactical one track short range maneuvering and stationary target where it's guidance and control more critical [1,2]. where for long range and knowing target strategic one is used. strategic and tactical missiles are operate in exo,endo-atmospheric conditions respectively. Due to fast developing in warfare, higher turn rates and larger maneuverability envelopes while reduced storage values required for tactical missiles. Unusual missile control technology produced from high angle of attack maneuver regime and lateral acceleration capability increasing. Thrust vector control (TVC)and\or side jet technology is some advanced missiles combine classical control technology [3,18]. starting of the jet vane thrust control starting with V-2 missile and still up till now in thrust vector control technology.in the initial stage of launching, highely speed, the control stability requirement is seen by (TVC) system [4,26]. TVC system is make fast change in orientation of thrust vector and add necessary lateral force to make fast change in flight path. jet vane system is conventional to many TVC systems like jet taps, secondary injection of liquid\gas into the nozzle gas flow and the flex nozzle [5,6]. tactical missiles due to small value torque, small space requirements, and the ability to control pitch, roll, and yaw simultaneously. Detecting of missile deviation from reference trajectory is one of guidance system tasks. And send signals to control system to error minimization. Maneuvering the missile quickly and efficiently as a result of these signals is the control systems task.by Cartesian system or polar system the missiles control system is carried out. Two signals are produced from angular error detector in the Cartesian system. Up-down and left-right which are applied to separate servos like rudder and elevators servo[7,8,21]. However, in polar coordinate system the usual method is to regard signal as a command to roll control through an angle (γ). The guided missile is controlled in Cartesian either aerodynamically by control surfaces or altering the thrust direction and/ or magnitude. The later method of control (TVC) is of interest in this thesis.

This control method does not depend on dynamically pressure of the atmosphere but defective motor burn out. It is the intentional change of the thrust vector in accordance with the control demand. Hence, changing the motion behavior of the missile due to moment and thrust force [4]. One of the most desirable reasons for using TVC is the vertical launch phase of all ballistic missiles whose total weight is well over 90% fuel to avoid dynamic loading[9,19,20].

As a conclusion guidance and control strategy works for minimizing the errors between actual trajectory and required trajectory (guidance constraints) in the powered flight with high penalty at impact point or shut-off/burn out velocity. Hence, there are two approaches for dealing with the sources of errors through guidance and control strategies design:

- To consider all sources of error except the inertial navigation errors. i.e., the actual trajectory as same as the measured trajectory and this can be achieved by using a very high sophisticated precise inertial navigation system[10,25].

- To consider all sources of error modeled as disturbances for the system and measurements errors. This deal to a problem of state estimation for obtaining actual trajectory states.

1. Thrust Vector Control & Speed Characteristics (TVC)

Thrust change with time is one of the most related characteristics of thrust vector control and Flight condition independently. But aerodynamics control depends on flight conditions like dynamics pressure velocity and altitude. The main design parameter knowing the capability of TVC and aerodynamically control during flight.TVC systems limited when the thrust deflection angle is maximum. Angle between missile center line and thrust line is thrust deflection angle. Related parameter to vane deflection angle is temperature, geometry, nozzle exhaust velocity, material and thickness. Design parameter like jet vane shape ,vane in nozzle placement exhaust Mach number is total deflect thrust angle etc[].maximum deflection of total thrust with TVC Technologies.90 degree launch angle ,4.5 Mach maximum velocity,not sustain motor after boost motor velocity decreases ,25000,28000 range and altitude,this all parameter to analyze trajectory and ballistic velocity[11,12,24].

2. Missile Flight Control

The automatic flight control systems for ballistic missiles encounter generally constraints:

- Effect of missile elasticity.
- Dynamic actuators properties and instrumentation.
- aerodynamic of airframe instability.
- Splashing of propellants(liquid) for missiles with engine.
- Contact with guidance.

The ballistic missile quality performance in powered phase flight is studied in two distinct, through related phases. Dynamics of motion around center of gravity (Autopilot \short period dynamics) and the center of gravity(cg) dynamics (Flight path control \long period dynamics) as mentioned before in chapter one. Fig.1.
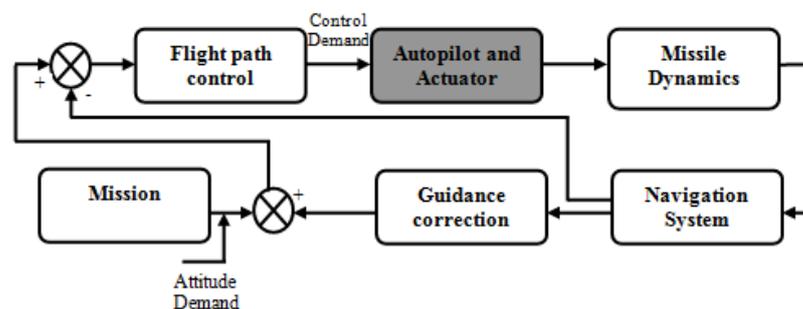

Fig.1 Ballistic Missile Flight Guidance and Control.

Aim of any autopilot system achieving stability and fast, well-damped response to input control command with insensitivity to external disturbances[13,14].

The major design problems arise because a missile is unstable aerodynamically; the inertia instrumentation effect and actuator introduce more complications.
 design of the autopilot, primarily, based on a linear dynamic model; making use of:

- Linear perturbation model from the nominal conditions.

Hence, the powerful techniques of linear analysis [7,8] are exploited most fully to synthesize the autopilot configuration that meets design requirements of the control problem.

3. Equation of Motions of Missile Dynamics

3.1. Missile Pitch Dynamic

- The axial force along x-axis in velocity coordinate system is given by:

$$F_x = T_x \cos\alpha \cos\beta + X_{aero} - mg\sin\theta = m\dot{V}_x \tag{1}$$

The perturbation of axial force equation is given by [11]:

$$m\frac{\partial \Delta V_x}{\partial t} = (T_x^{v_x} + X_{aero}^{V_x})\Delta V_x + (X_{aero}^{\alpha} - T_x.\alpha)\Delta\alpha - (mg\cos\theta)\Delta\theta + X_{aero}^{\delta_p} + x_B \tag{2}$$

- The lift force equation is given by:

$$F_y = T_y(\cos\gamma\sin\alpha + \cos\alpha\sin\gamma\sin\beta) + Y_{aero}\cos\gamma - Z_{aero}\sin\gamma$$
$$- X_{aero_{ru}}\sin\alpha + Y_{aero_{ru}}\cos\alpha - mg\cos\theta = mV_y\dot{\theta} \tag{3}$$

Where γ is the roll angle and it has approximately zero value. Therefore, considering also, small values for the side slip angle &the angle of attack we can simplify the above equation as follows:

$$F_y = mV_y\dot{\theta} = T_y\alpha + Y_{aero} - X_{aero_{ru}}\alpha + Y_{aero_{ru}} - mg\cos\theta \tag{4}$$

- The torque equation along missile z-axis
  The torque equation is function of aerodynamic coefficients, missile diameter, and cross-sectional area, also function of inertial moment about z-axis and static margin which defined as the difference between center of gravity and center of pressure of the missile[15,23].

  After applying the perturbation to torque equation, the final torque equation can be written as:

$$\Delta\ddot{\theta} + \Delta\ddot{\alpha} + a_{30}\Delta V_z + a_{31}\Delta\dot{\alpha} + a_{32}\Delta\alpha + a_{33}\Delta\dot{\theta} = a_{34}\Delta\delta_p \tag{5}$$

Then, the pitch plane transfer function of the missile dynamics obtained as:

$$w_\delta^\vartheta(s) = \frac{k_\delta^\vartheta(1 + T_1 s)}{(T_2^2 s^2 + 2\xi T_2 s + 1)(\tau s + 1)} = \frac{k_\delta^\vartheta(1 + T_1 s)}{A_1 s^3 + A_2 s^2 + A_3 s + A_4} \tag{6}$$

3.2. Missile Roll Dynamic

- The missile roll dynamics transfer function can be calculated as follows [11]:

$$I_x \ddot{\gamma} = M_x \quad ; \quad \omega_x = \dot{\gamma} \quad ; \quad M_x = m_x^{\omega_x} . \omega_x + m_x^{\delta} . \delta \tag{7}$$

$$\ddot{\gamma} = \frac{m_x^{\omega_x}}{I_x} \dot{\gamma} + \frac{m_x^{\delta}}{I_x} . \delta = c_1 \dot{\gamma} + c_2 . \delta \tag{8}$$

$$\ddot{\gamma} - c_1 \dot{\gamma} = c_2 . \delta \tag{9}$$

- The transfer function of missile roll channel dynamics can be written as:

$$w_\delta^\gamma = \frac{k_\delta^\gamma}{s(T_\gamma + 1)} = \frac{k_{99}}{s(T_9 s + 1)} \tag{10}$$

An open-loop simulation is performed, which means no autopilot is considered. The flight condition selected is $167.974 m/\sec$, $2.218 km$, 0.2 Mach, and -0.02^0 angle of attack at $t = 30 \sec$, and $462.278 m/\sec$, $10.749 km$, 3.0 Mach, and -0.0053^0 angle of attack at $t = 60 \sec$. The simulation of missile dynamics in pitch and roll planes at different times during the powered phase results in different parameters as shown in figs.2,3.
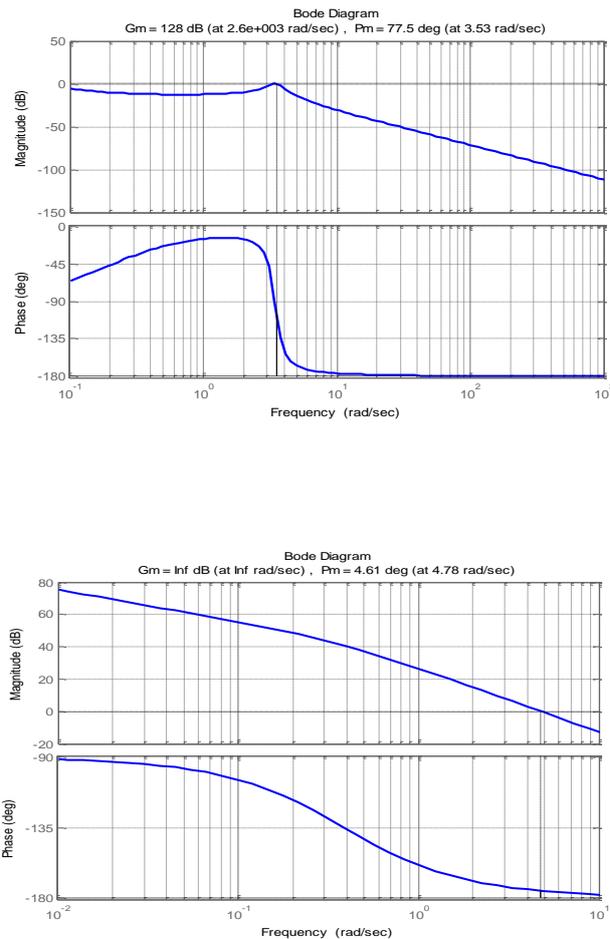
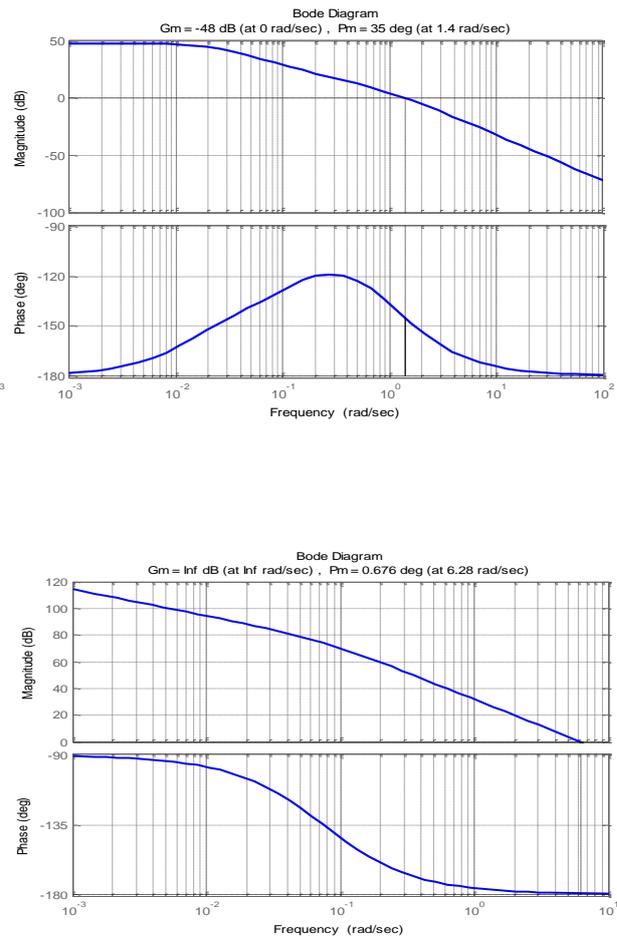

Fig.2 Frequency response of pitch dynamic   **Fig.3** Frequency response of roll dynamic

4. Actuation System Design

The design of most actuation systems is depend on the system requirements is that the actuation must deliver a specific moment to overcome the hinge/load moment For example, we must know what is the max deflection angles needed for the control demand?, max hinge moment for system design, maximum frequency or bandwidth of the system operations[11]. Depend on the requirements of the system as maximum deflection angle required about , max hinge moment about and the frequency about . Fig.4 shows the closed loop of actuation system design[16].
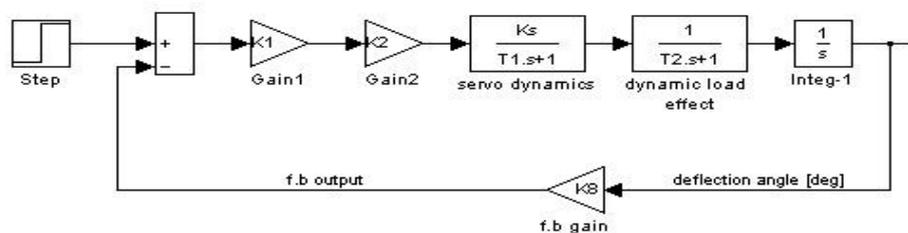

Fig.4 Closed loop of Actuation System

The actuation system closed loop transfer function can be written as:

$$w_{Ac}(s) = \frac{k_0}{As^3 + Bs^2 + Cs + 1}$$

(11)

Table .1 shows the actuation system Parameters:

Natural frequency	29.58 [r/s]
Settling time	0.16022 [sec]
Time constant	0.058 [sec]
Delay time	0.02 [sec]
Overshot	0.706%
Damping ration [ξ]	.844
Damping frequency [ω_d]	15.86[o/s]

5. Pitch Controller Design

The main problem for designing a controller involves careful choice of zero(s) and the pole(s) to modify the root locus or frequency response of the uncompensated system so that the performance required specifications are satisfied. the gain is Setting in the first step for adjusting the system to be

in satisfied performance. In many real cases, however, gain adjusting alone may not supply enough change of the system response to meet the required specifications. As in case, steady-state performance is improved by gain increasing but poor in stability will find or instability then cause necessary redesign for the system. In more real cases, compensation is basically a concession between relative stability & steady-state error[17,22]. Using the compromise design technique the controller transfer function can be written as:

$$w_{pc}(s) = \frac{k_{33}(1 + T_{33}s)}{(T_{11}s^2 + T_{22}s + 1)} \tag{12}$$

Where $k_{33}, T_{33}, T_{11}, T_{22}$ represents the proportional sensitivity gain of gyro and controller, and time constants of the pitch controller respectively.

The derivative time is the time interval at which the rate actions development the effect of proportional control (PI) action. Fig.5 shows the general shape of the pitch channel autopilot.
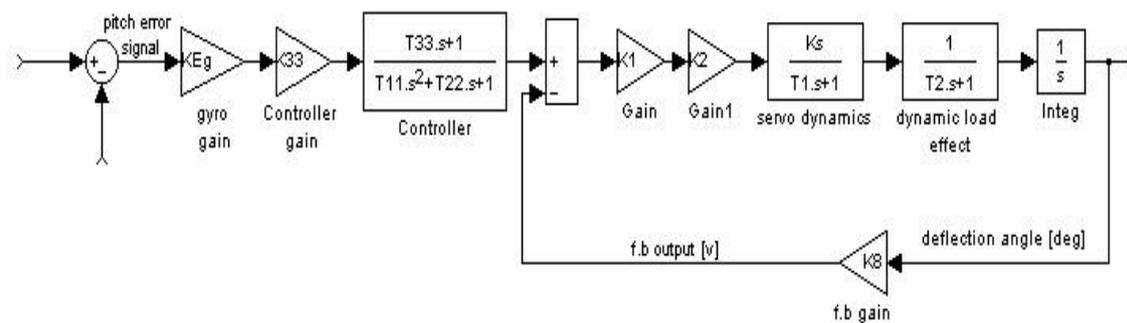

Fig .5 Pitch Channel Autopilot.

The pitch autopilot design open loop transfer function can be written as:

$$w_{g}^{\delta}(s) = \frac{k_{g}^{\delta}(T_{33}s + 1)}{(T_{11}s^2 + T_{22}s + 1)(As^3 + Bs^2 + Cs + 1)} \tag{13}$$

Then the calculation of the optimum gain of pitch channel autopilot can be calculated by:

$$k_{g\,opt} = k_{g}^{\delta} = \frac{\vartheta_{o/p}}{\delta_{fb\ o/p}} \tag{14}$$

6. Stability Analysis of Pitch Channel

Stability of linear closed loop is achieved by closed loop poles location in frequency domain. Location of pole in right half of frequency domain mean that the system is unstable with time increasing gives us rise to dominant mode, increasing in transient response monotonically or oscillate with increasing amplitude elastic an unstable system.to overcome the unstable in the system we must redesign the open loop transfer function yields to satisfactory relative stability and a high velocity error coefficient. Law frequency required large gain near the cross over frequency .in high frequency the gain should be decreased rapidly as soon as possible to minimize the effect of noise [3]. The autopilot especially the controller is designed to stabilize the channel and satisfy the performance requirements. This

autopilot is investigated all over the envelope of missile operation or guidance. Fig.6 shows the Missile pitch channel stability.
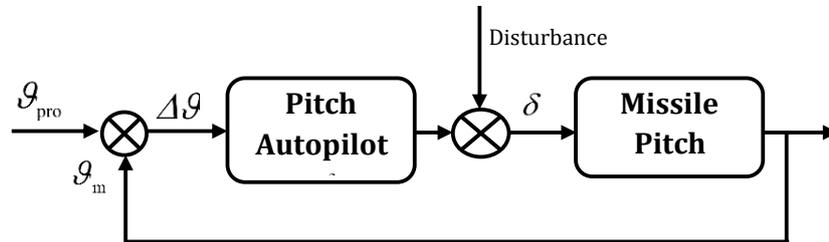

Fig.6. Missile pitch channel stability

For this analysis, the frequency response of the compensated pitch channel represented in gain margin, phase margin, and bandwidth in addition to time response characteristics are summarized in Table.2 and fig.7.

Table.2 Pitch Channel Characteristics

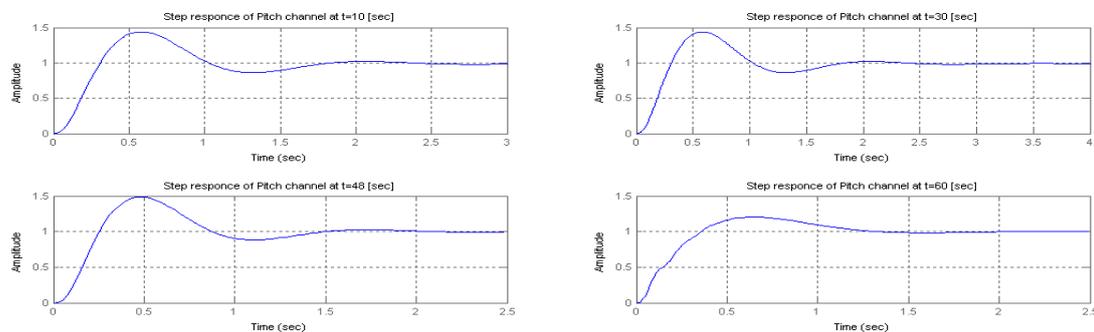| Time [sec]	Gain margin [dB]	Phase margin [deg]	Corner frequency [r/sec]	Settling time [sec]	Overshot [%]	Rise Time [sec]
10	13.756	49.489	4.9906	2.1	28	0.22
30	13.198	59.114	6.5491	1.9	30	0.23
48	12.490	49.814	5.5024	1.8	25	0.25
60	13.850	56.902	4.8534	1.5	20	0.32

Fig.7 Step Response of Missile Pitch Channel

Using the tradeoff design procedure the roll controller transfer function, which is in the form of PID, can be written as follows:

$$\frac{\delta(s)}{\gamma(s)} = w_\gamma^\delta(s) = \frac{k_{22}(T_4 s + 1)}{(T_5 s^2 + T_6 s + 1)} + \frac{k_4}{(T_7 s + 1)} \tag{15}$$

Then, the general form of the roll controller can be written as:

$$w_\gamma^\delta(s) = \frac{k_{55}(T_{44} s + 1)(T_{55} s + 1)}{(T_5 s^2 + T_6 s + 1)(T_7 s + 1)} \tag{16}$$

Where $k_{55}, T_{44}, T_{55}, T_{5,6,7}$ represents the proportional sensitivity gain, and time constants of the roll controller respectively.

These times are function of control and aerodynamic derivatives which is a function of flight trajectory. Fig.8 shows the general dynamical diagram of the roll autopilot with missile roll dynamics.
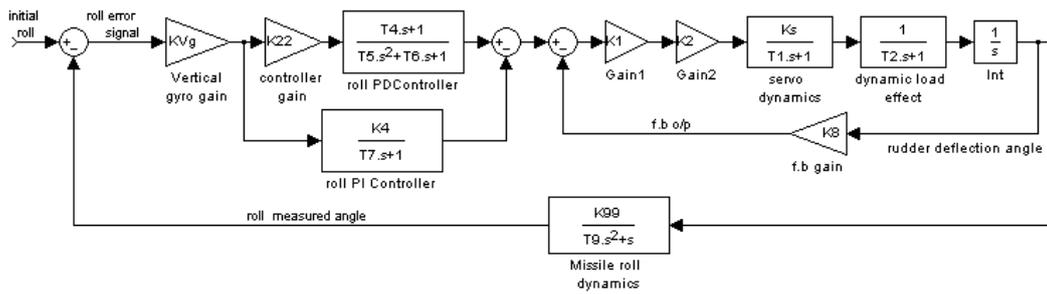

Fig .8 Dynamical diagram of Roll Autopilot with Missile Roll Dynamics

7. Cross coupling effect between roll and pitch channels

One of the lateral autopilot objectives is it reduce the cross coupling between pitch and yaw motions [13]. If the missile has two axes of symmetry and there is no roll rate then, there will be no cross coupling between pitch and yaw motion. Many missiles are allowed to roll freely and this rolling produces acceleration in and axes causing coupling in pitch, yaw and coupling moment in pitch, yaw, and angular motion in the other plane as the moment of inertia about the roll axis.

These cross coupling effects can be regarded as disturbances to which the closed loop system should be considerably less sensitive than the open loop [16,17]. Thus, a rate gyro is utilized to reduce this cross coupling. That is, the rolling can be considered as a disturbance effect on the pitch channel control and has to be rejected through the autopilot design.

Fig.9 shows the effect of roll channel upon the pitch channel through cross coupling between them.
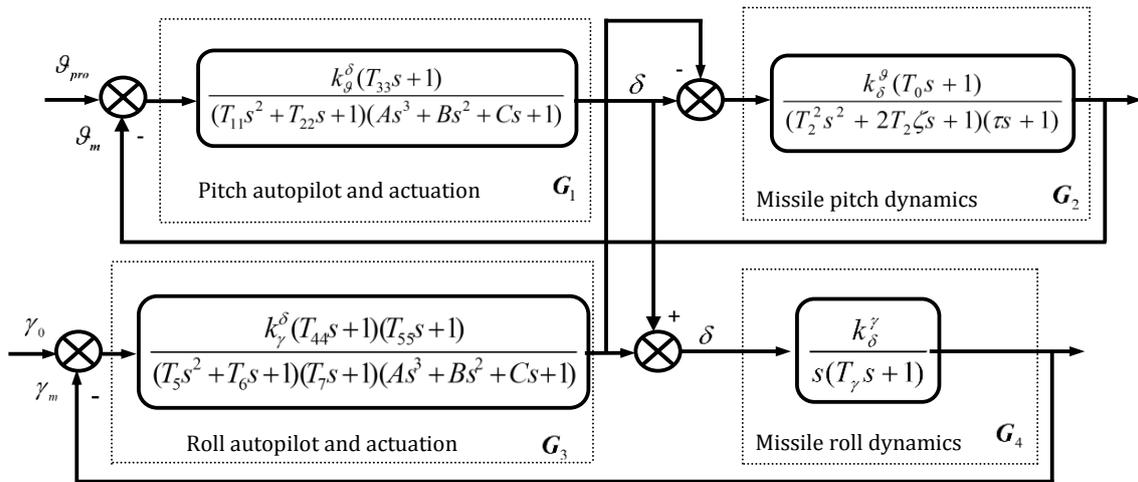
Fig.9 Effect of Roll Motion upon Pitch Channel

To obtain the response of pitch channel to roll disturbance, the above figure is modified to fig.10.
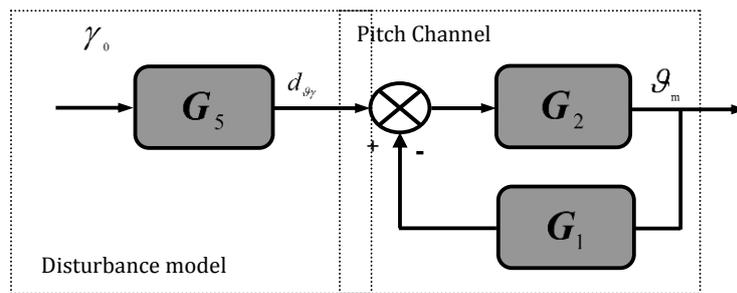

Fig.10. Response of Pitch to Roll Motion Disturbance

The contribution of the open loop transfer function due to roll disturbance to the output of pitch channel is represented by:

$$\mathrm{G}_6 = \frac{\vartheta_m}{\gamma_0} = \frac{\mathrm{G}_2\mathrm{G}_5}{1+\mathrm{G}_1\mathrm{G}_2} \tag{17}$$

To investigate the performance of pitch autopilot and its ability to reject the disturbance due to cross coupling, a step input is applied to the roll channel to examine its contribution at the output of the pitch channel as shown in fig.11.
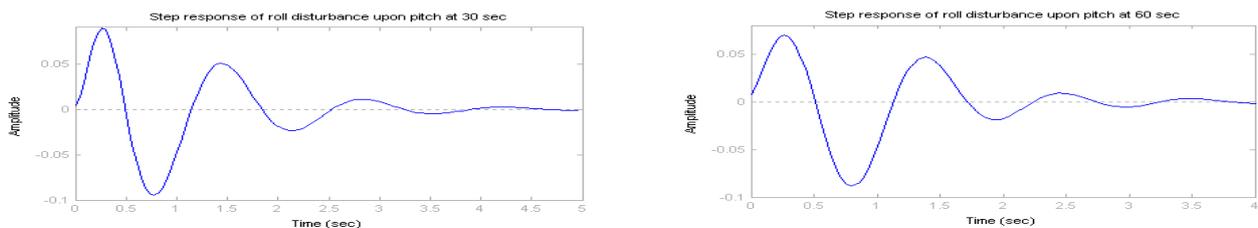

Fig.11 Step Response due to Roll Disturbances upon Pitch Channel

Conclusion

The analysis carried out in this paper, indicates that the missile maneuver is mainly restricted in the pitch plane and consequently the analysis is performed for the pitch and roll dynamics. The results show that, the missile dynamic motion in pitch and roll are unstable. Generally stability of missile is achieved by designing autopilot system to control dynamic motion around center of gravity also reasonable fast and well damped response for control request.

The problems of design arise due to the aerodynamic instability and the delay effects of instrumentation and actuators. The autopilot consists of four channels: pitch, roll, yaw, and lateral. The main problem for designing a controller involves careful choice of pole(s) and zeros(s) in order to alter the root locus or frequency response of the uncompensated system. From the analysis of pitch and roll channel we found that, with autopilot the performance of the missile is improved all over the time of flight with gain margin and phase margin in the limits and settling time not increased about . The investigation of the performance of pitch autopilot and its ability to reject disturbances due to cross-coupling between pitch and roll channels showed that, the pitch channel can reject disturbances in average .

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