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Controller Design for a Two-loop Missile Autopilot in Pitch Plane

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Abstract: ***This research work is an attempt towards achieving an approach for designing PI and PID controllers for a two loop missile autopilot system in pitch plain. A two loop autopilot configuration has been chosen which is characterized by a dynamics involving non-minimum phase zero. A systematic methodology for linear design in frequency domain of lateral autopilot for a class of guided missiles has been carried out. The present work utilizes the autopilot configuration with one accelerometer and one rate gyro. The configuration in pitch plain for the two loop autopilot system has been illustrated. The present work includes a study on plant uncertainties.***

Keywords: PI Controller, PID Controller, T&E Tuning Method, Ziegler–Nichols (ZN) tuning method, Kharitonov's Method

Introduction

Autopilot is an automatic control mechanism for keeping the spacecraft in desired flight path. An autopilot in a missile is a close loop system and it is a minor loop inside the main guidance loop. If the missile carries accelerometer and rate gyros to provide additional feedback into the missile servos to modify the missile motion then the missile control system is usually called an autopilot. When the autopilot controls the motion in the pitch and the yaw plane, they are called lateral autopilot. The lateral autopilot of a guided missile is a servo system delivering lateral acceleration according to the demand from the guidance computer. For aerodynamically controlled skid to turn missile the autopilot activates to move the control surface suitably for orienting the missile body with respect to flight path. This action generates angle of attack and consequently lateral acceleration for steering the missile in desired path. A guided missile is one which receives steering commands from the guided system to improve its accuracy. Guided action for guided missile may be defined may be defined as the process of gathering information concerning the flight of a missile towards a target and utilizing this information to develop maneuvering commands to the control system of the missile Guidance system functions by comparing the actual path of the missile with the desired path and providing commands to the control system which will result in maneuvering the missile to its desired path. Guidance system actually gives command to the autopilot to activate the controls to achieve the correction necessary. The autopilot responses to guided system demand by deflecting the control surfaces of the missile for aerodynamic controlled missiles. The deflection in control surface produces change in missile angle of incidence. If the incidence angle is changed, the forces acting on the missile body changes and it results in change in missile acceleration. The two loop autopilot system uses two loops to feedback information of missile motion to the forward path of the autopilot. One loop is involved with body rate information which is feedback using one rate gyro. The other is the missile acceleration, sensed using accelerometer and provides the main feedback.

Mathematical Modeling of Autopilot system

- **Classical Two Loop Auto pilot Configuration**

  The dynamics of the missile is described in terms of aerodynamic derivatives in semi-non-dimensional form. The relevant missile equations in pitch plain are expressed below:

  $\dot{w} = z_w w + (u + z_q)q + z_\eta \eta;$

  $\dot{q} = m_w w + m_q q + m_\eta \eta$

  And $f_z = z_w w + z_q q + z_\eta \eta$

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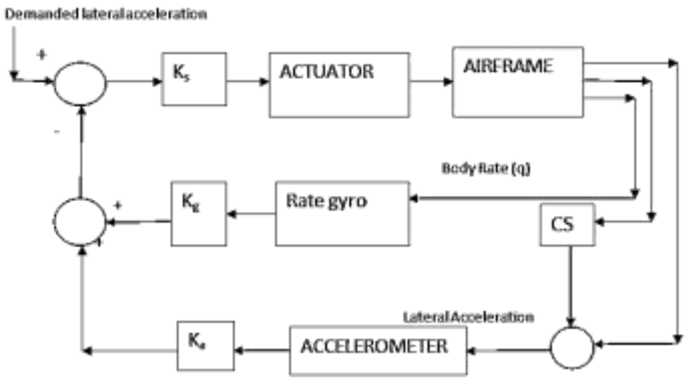

Fig. Classical two loop autopilot configuration

The developed design methodology has been tested for two flight conditions. The two loop autopilot configuration has been presented and the autopilot performance has been evaluated.

- **Lateral Autopilot with one Accelerometer and one Rate Gyro**

  Lateral autopilot in pitch plain with one accelerometer and one rate gyro is a modified form of what is described in yaw plane and uses identical terminology and convention and assumes the accelerometer to be at center of gravity of the missile. This configuration has two distinct loops called the body rate or inner loop and the outer or flight path rate demand loop. The mappings of signals or parameters are expressed as follows:

  $f_{zd} \triangleq \frac{f'_{zd}}{k_a}$; $\frac{k_p}{u} \triangleq \frac{k_a}{k_g}$

  $k_q = -k_g k_s$ where k_g and k_s are positive quantities and k_q is negative in pitch and where

  $$T_a = \frac{m_\eta}{m_w z_\eta - z_w m_\eta} \quad ; \quad \omega_b^2 = -m_w u$$

  $$k_b = \frac{m_w z_\eta - z_w m_\eta}{\omega_b^2} = \frac{m_\eta}{T_a \omega_b^2} \sigma^2 = \frac{z_\eta T_a}{u m_\eta}$$

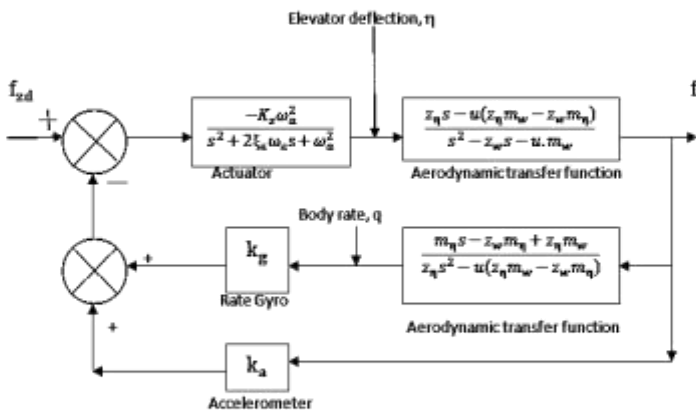

Fig. Lateral autopilot with one accelerometer and one rate gyro

- **Flight path rate demand autopilot in pitch plane utilizes conventional PI controller**

  Ziegler–Nichols tuning method is a heuristic method of tuning PI, PID controllers. There are two methods called Ziegler-Nichols tuning rules: the first method and the second method. A brief description of these two methods will be given in the following subsections with their relevancy in designing tuning constants of the two loop lateral autopilot of tail controlled missile in pitch plane. The block diagram of designed control system using PI controller has been presented.

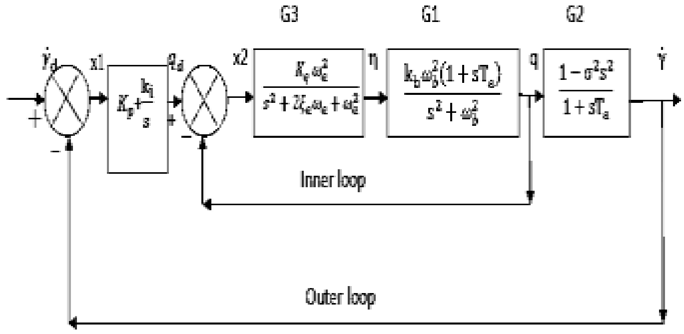

Fig. Flight path rate demand autopilot in pitch plane utilizes conventional PI controller

- **Flight path rate demand autopilot in pitch plane using conventional PID controller**

  The design procedure for determining the tuning constants of PID controller using conventional Ziegler-Nichols design technique has been utilized. A brief idea about the design technique along with determination of ultimate gain & corresponding ultimate time period has already been explained for the two operating conditions. There are three tuning constants in a PID controller, namely proportional gain (K_P), integral gain (K_i) and derivative gain (K_d). By the knowledge of these gains, reset time (T_i) and rate time (T_d) is obtained.

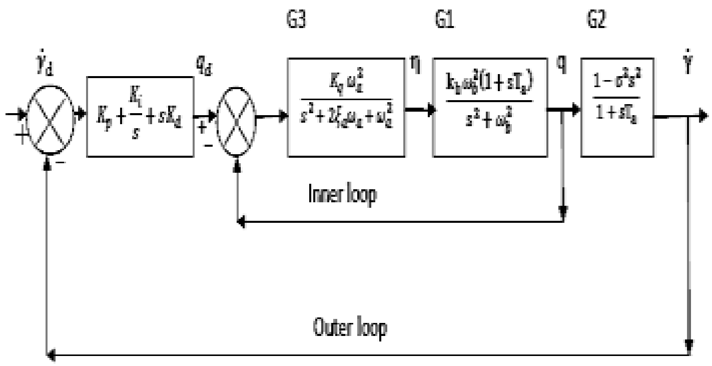

Fig. Flight path rate demand autopilot in pitch plane using conventional PID controller

- **Disturbance Rejection Capability of the Designed Control System**

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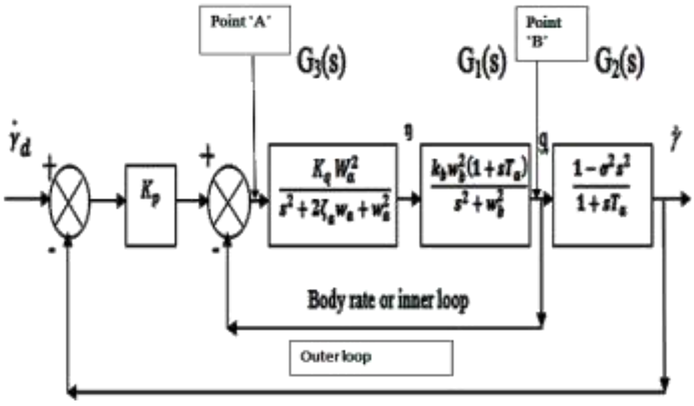

Fig. Disturbance Rejection Process

Result & Analysis

- **Comparison on the performances of PI controllers based on ZN design technique and T&E tuning method**

Table: Critical Gain Margin & Critical Phase Margin

Method	K_p	K_i	Critical gain margin (dB)	critical phase margin (deg)	Data set
Z-N closed loop tuning	7.52	94	6.27 (opening point x1)	27.1 (opening point x2)	1
T&E tuning	5.1	36.5	9.39 (opening point x2)	41.3 (opening point x2)	1
Z-N closed loop tuning	29.8	297.73	6.3 (opening point x1)	25.6 (opening point x1)	2
T&E tuning	24	47	8.21 (opening point x2)	45.5 (opening point x2)	2

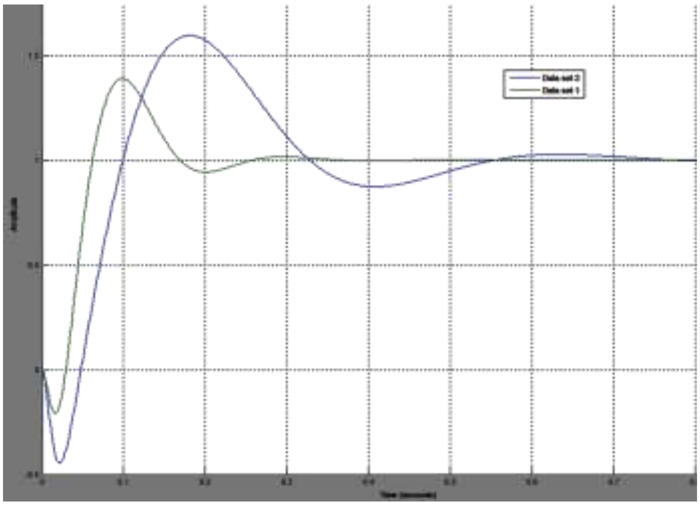

Fig. Step responses of flight path rate demand autopilot in pitch plane using ZN tuning method PI controller for two operating conditions

- **Comparison on the performances of PID controller based on ZN design technique and T&E tuning method**

Table: A comparison on the performance of ZN closed loop tuning and E&T tuning method for the design of PID controller

Specifications	Data set	ZN closed loop tuning	Trial & Error (T & E)	Improved by E&T Tuning
Maximum overshoot %	1	50.8	1.26	49.54
	2	Unstable	0.87	Makes the system response stable
Settling time (sec)	1	0.246	0.086	0.16
	2	Unstable	0.14	Makes the system response stable

Table: Critical Gain Margin & Critical Phase Margin

Method	K_p	K_i	K_d	Critical gain margin (dB)	critical phase margin (deg)	Case
Z-N closed loop tuning	9.93	206.87	0.12	1.77 (by opening loop at point X2)	29.3 (by opening loop at point X2)	1
T&E	7.2	50	0.05	5.39 (by opening loop at point X2)	36.9 (by opening loop at point X2)	1
Z-N closed loop tuning	39.3	655.5	0.58	System becomes unstable		2
T&E	32	60	0.06	5.89 (by opening loop at point X2)	37 (by opening loop at point X2)	2

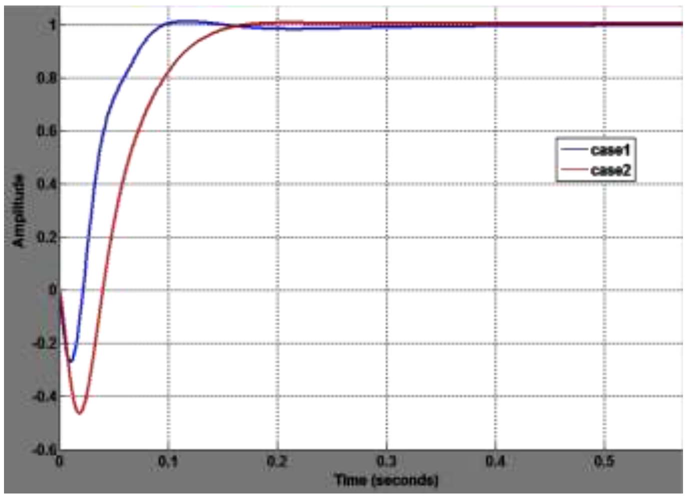

Fig. Step responses of flight path rate demand autopilot in pitch plane using ZN tuning method PI controller for two operating conditions

- **Study on the Uncertainty of System Parameters of PI Controlled Autopilot by Kharitonov's Method**

An interval is the family of all polynomials,

$$P(S) = a_n S^n + a_{n-1} S^{n-1} + a_{n-2} S^{n-2} + \cdots + a_1 S^1 + a_0$$

Where each coefficient $a_i \in R$ can take any value in the specified intervals, $l_i \leq a_i \leq u_i$.
It is also assumed that the leading coefficient cannot be zero, i.e. $0 \notin [l_i, u_i]$.
l_i *and* u_i are lower and upper specified ranges respectively of the corresponding coefficient.

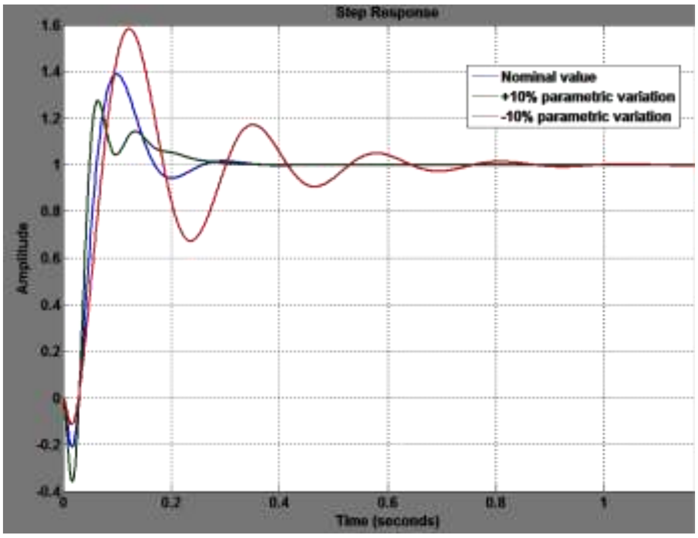

Fig. Study on the Uncertainty of System Parameters of PI Controlled Autopilot by Kharitonov's Method

- **Disturbance Rejection Capability of the Designed Control System**

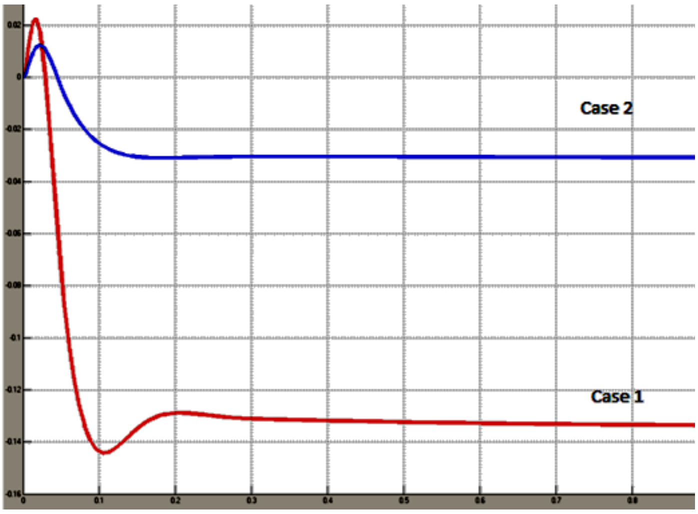

Fig. Two Loop Lateral Auto pilot without Controller

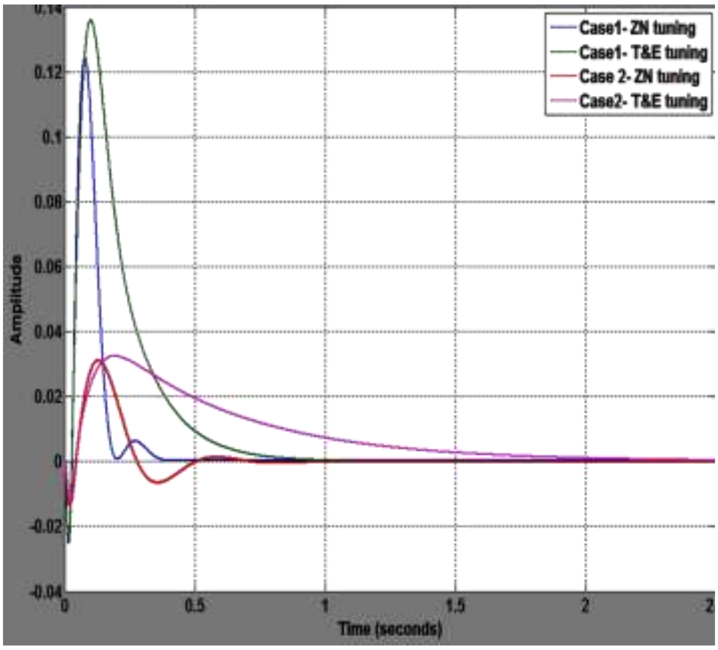

Fig. Two Loop Lateral Auto pilot with Controller

Conclusion

Complete attenuation of external disturbance is not possible by using a proportional controller. However, its elimination is possible by using conventional PI & PID controller employing in the plant in place of proportional controller, principally because of their integral control actions. Time taken for the system to eradicate the effect of external disturbance completely, is not the same for the system using the PI or the PID controller whose tuning constants are formed on the basis of different tuning methods. Peak values in response to external disturbance, before it completely settles down to zero, are dissimilar for different tuning strategies of PI and PID controller. This conclusion is also equally true for both the operating conditions (case1 & case2). The system which has competency to eliminate the effect of disturbance with minimum peak along with shortest possible time is said to be the best system while considering the effect of outdoor disturbance on plant dynamics. It has been seen that system having better input tracking ability offers better disturbance rejection capability.

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