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AN IMPROVED METHODOLOGY FOR LINEAR DESIGN OF LATERAL AUTOPILOT INCOMPLETE STATE FEEDBACK CONTROLLER USING POLE PLACEMENT METHOD

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ABSTRACT

In this paper a systematic methodology for linear design of lateral autopilot has been proposed and investigated. The objective of this methodology is to obtain the parameters from a set of parametric equations, performance measurement and the characteristic of the plant and the available actuator. The methods for a kind of design situation has been shown and illustrated with examples. In this work a pole placement method for designing a linear missile autopilot system is presented. A procedure for the choice of proper closed-loop pole location has been done which assures desired transient performance. For specified stability margins some control over the missile body rate, peak fin deflection and fin rate can be achieved. State vector feedback control provides the freedom to choose close loop poles satisfying the desired transient response. The autopilot system considered is a forth order plant. Two pairs of complex poles have been chosen to dictate the closed loop performance. An adequate separation between them can assure that the non-dominant poles have negligible effects on the system performance. This study provides a design methodology for lateral autopilots applying incomplete state feedback using pole placement technique. An incomplete state feedback controller has been designed to eliminate the need for an observer system. From this design desired stability margins with different speed of responses has been achieved which might be utilized a choice of autopilot speed of response.

Keywords: Autopilot, Kharitnov's thorem, Incomplete state feedback controller, Speed of responses.

1. INTRODUCTION

In this paper a unified set of design formulae has been developed with appropriate level of approximations which are valid for a class of missiles and different autopilot configurations. This paper presents design relations for two loop autopilots. This is done by deriving a set of reasonably accurate expressions for evaluating the autopilot performance in the frequency domain. These expressions are represented in a suitable form for appreciating the effects of variations of important design parameters. For tactical guided missiles lateral autopilots [1] are servo systems delivering lateral acceleration according to the demand from

the guidance computer. For aerodynamically controlled skid to turn missiles, the autopilot activates the actuator to move the control surface suitably for orienting the missile body with respect to the flight path. The objective of this paper is to develop a systematic methodology for the design of autopilot for a class of guided missile. Few authors recognize that autopilot design path may vary widely depending on the situation.

A systematic methodology for linear design of lateral autopilot has been proposed in this paper. The objective of this methodology is to obtain the parameters from a set of parametric equations, performance measurement and the characteristic of the plant and the available actuator. The methods for a kind of design situation has been shown and illustrated with examples. [1]

A pole placement method for designing a linear missile autopilot system is presented in this article. A procedure for the choice of proper closed-loop pole location has been done which assures desired transient performance. For specified stability margins some control over the missile body rate, peak fin deflection and fin rate can be achieved. An incomplete state feedback controller has been designed to eliminate the need for an observer system. From this design we can achieve desired stability margins with different speed of responses might be utilized a choice of autopilot speed of response. [2]

The missile autopilot design using linear parameter varying control techniques has been taken from the paper [3]. The controller provides exponential stability guarantee and performance bound in terms of the missile plant. A systematic gain scheduling approach is one of the most popular nonlinear control design techniques which have been widely used in the fields ranging from aerospace and process control.

In the paper [5] we can find a θ-D design technique of nonlinear missile autopilot. A variety of Hα techniques to develop tactical missile autopilots robust to the presence of parametric variations have been analyzed in [6,10]. The Routh Hurwitz and Kharitnov's Criterion is discussed in the book Modern Control Engineering. [7,8,9].

A systematic methodology for linear design of lateral autopilot has been proposed in this paper. The objective of this methodology is to obtain the parameters from a set of parametric equations, performance measurement and the characteristic of the plant and the available actuator.

The set of formulae usually derived are not obtainable to a unified design technique. In this paper we are using only one type of design problem.

- **Design Problem**

Given missile parameters:

Actuator: natural frequency (ω_a), damping ratio (ξ_a).

Airframe and environment: t_a, m_η, σ^2, ω_b.

- **Design Specification:**

Critical gain margin $\geq$ GM (a specified value of gain margin)

Critical phase margin $\geq$ PM (a specified value of phase margin)

Design Objective: To obtain the control gains (K_p, K_q) for the maximum possible Gain Crossover Frequency (GCF).

The main contribution of the paper is: (i) t o study the forth order autopilot missile, (ii) Pole placement method for designing incomplete state feedback controller for linear missile autopilot system and (iii) to use the using Kharitnov's method to obtain the range of some variables.

2. DESIGN PARAMETER OF AN AUTOPILOT

The following figure depicts the block diagram of a two loop missile autopilot in pitch plane [1]. The missile state model is based upon the two loop configuration. Where, G1(s) and G2(s) are aerodynamic transfer function and G3(s) represents the second order actuator.

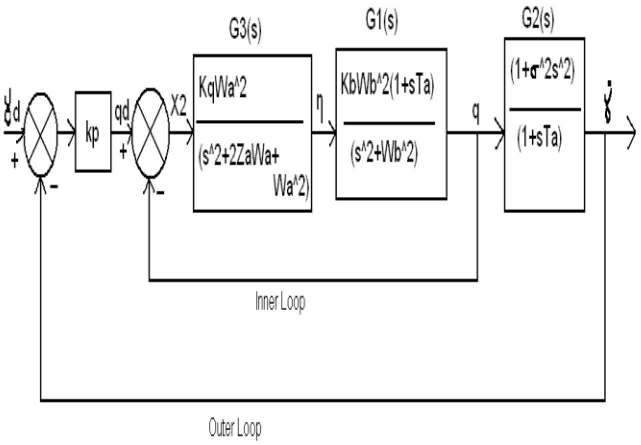


Fig.1. Block diagram of two loop missile autopilot in pitch plane

TABLE 1: Parameters identification-

Parameters	Name of the parameters
Kb	Airframe aerodynamic gain,sec-1.
Mp	Peak overshoot.
Kp	Lateral autopilot control gain outer loop.
q	Missile body rate in pitch, rad/sec.
qd	Missile body rate demanded in pitch, rad/sec.
Kq	Fin servo gain, sec-1.
ta	Incidence lags of airframe, sec.
Ks	Forward path gain is state feedback design
η	Elevator deflection, rad.
$\dot{\eta}$	Elevator deflection rate, rad/sec.
$\dot{\gamma}$	Missile flight path rate, rad/sec.
ξa	Damping ratio of actuator.
σ	A quantity whose inverse determines the location
$\dot{\gamma}_d$	Missile flight path rate demanded, rad/sec.
ωa	Natural frequency of oscillation of Actuator, rad/sec.
ωb	Weathercock frequency, rad/sec.
γd	Missile flight path demanded, rad.

3. AUTOPILOT SYSTEM DESIGN PARAMETERS

The autopilot system design parameters for the missile have been given in this table. Both the design situations are of problem above mentioned and two loop autopilot configuration is considered.

TABLE 2: Values of the Parameters

t_a	ω_b	σ^2	m_η	ω_a	ξ_a	K_b	U	K_p	K_q
2.85 sec	5.6 rad/sec	0.00142 s^2	-12.84 s^{-2}	180 rad/sec	0.6	-0.1437 sec-1	3000 m/s	9.1	1.72

For case 1 we get-

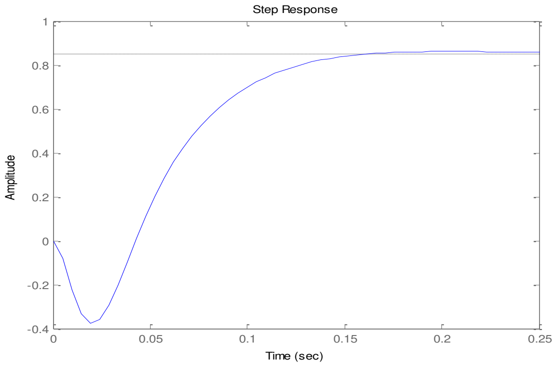
$$G_1(S)=\frac{K_b{\omega_b}^2(1+St_a)}{S^2+{\omega_b}^2}=\frac{-(12.8433S+4.506432)}{(S^2+31.36)}$$

$$G_2(S)=\frac{(1-\sigma^2S^2)}{(1+St_a)}=\frac{(1-0.00142S^2)}{(1+2.85S)}$$

$$G_3(S)=\frac{K_q{\omega_a}^2}{(S^2+2\xi_a\omega_aS+{\omega_a}^2)}=\frac{-55728}{S^2+216S+32400}$$

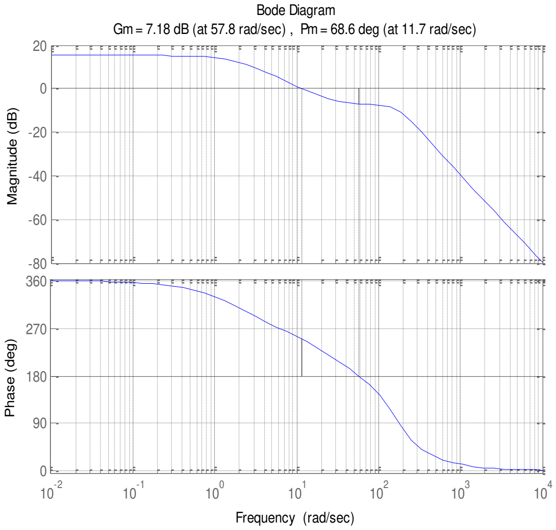
Frequency domain -

- **Time response-**



Discussion- Due to the presence of non minimum phase zero, the plots have been dripped in the negative Y axis.

- **Bode plot-**



Discussion-

TABLE 3: Frequency domain Analysis of Missile Autopilot in Different Cases-

	Case 1
GM(Gain margin)	2.2868
PM(Phase margin)	68.6272
GCF(Gain Crossover Frequency)	57.8352
PCF(Phase Crossover Frequency)	11.7378

4. POLES ASSIGNMENT

The pole-placement technique for the augmented plant model has been utilized to find the state feedback and integral gains in the absence of the observer. Denoting the chosen closed-loop pole locations as

S 1,2 = – a ± jb (dominant poles),

S 3,4= –c ± jd (faster poles), the desired characteristic equation is

$$S^4 + d_3S^3 + d_2S^2 + d_1S + d_0=0$$

[from the equation 1+G(S)H(S)=0]

Where,

$$d_3=(2a+2c)$$

$$d_2=(a^2+b^2+c^2+d^2+4ac)$$

$$d_1=(2a^2c+2b^2c+2ac^2+2ad^2)$$

$$d_0=(a^2+b^2)(c^2+d^2)$$

Steps for determination of closed loop poles-

Find a and c from the equation for the known value of actuator damping ratio ξa and natural frequency ωa.

Compute b using the equation for chosen value of peak overshoot Mp.

Select a suitable value for d.

$$a = \frac{\xi_a \omega_a}{6} = 18$$

$$c = \frac{5\xi_a \omega_a}{6} = 90$$

$$b = \frac{-\Pi \xi_a \omega_a}{6\ln(M_p)} = 18.8759$$

$$d = 10$$

By putting the values of a,b,c,d we can get d3,d2,d1 and d0 as

$$d_3 = (2a + 2c) = 216$$

$$d_2 = (a^2 + b^2 + c^2 + d^2 + 4ac) = 1.5360 \times 10^4$$

$$d_1 = (2a^2 c + 2b^2 c + 2ac^2 + 2ad^2) = 4.7166 \times 10^5$$

$$d_0 = (a^2 + b^2)(c^2 + d^2) = 5.5786 \times 10^6$$

$$\mathrm{k}_1 = \frac{(\mathrm{d}_0 - \omega a^2 b^2)\,\mathrm{t}_\mathrm{a}\sigma^2 - (d_1 - 2\xi_a\omega_a\omega_b{}^2)\sigma^2 + (d_2 - \omega_a{}^2 - \omega_b{}^2)}{\mathrm{K}_s\mathrm{K}_q\omega_a{}^2 t_a(1+\sigma^2\omega_b{}^2)}$$

$$k_2 = 0$$

$$k_3 = \frac{(d_1 - 2\xi_a\omega_a\omega_b{}^2)}{K_s K_q K_b \omega_a{}^2\omega_b{}^2 t_a}$$

$$k_4 = \frac{(\mathrm{d}_0 - \omega_a{}^2\omega_b{}^2)\,t_a - (d_1 - 2\xi_a\omega_a\omega_b{}^2) - (d_2 - \omega_a{}^2 - \omega_b{}^2)t_a\omega_b{}^2}{\mathrm{K}_s\mathrm{K}_q\mathrm{K}_b\omega_a{}^2\omega_b{}^2 t_a(1+\sigma^2\omega_b{}^2)}$$

Once the state feedback control gains are known for a given set of aerodynamic data and actuator dynamics, the GM and PM of the designed autopilot can be evaluated by opening the autopilot loop in pitch plane using the resulting open loop transfer function-

$$\mathrm{G(S)} = \frac{(\mathrm{c}_2\mathrm{S}^2 + \mathrm{c}_1\mathrm{S} + \mathrm{c}_0)}{(\mathrm{S}^2 + \xi_\mathrm{a}\omega_\mathrm{a}\mathrm{S} + \omega_\mathrm{a}{}^2)(\mathrm{S}^2 + \omega_\mathrm{b}{}^2)}$$

Where,

$$\mathrm{c}_0 = \omega_a{}^2\omega_b{}^2\,(\kappa_1\mathrm{K}_s\mathrm{K}_q + \kappa_3\mathrm{K}_s\mathrm{K}_q\mathrm{K}_b + \kappa_4\mathrm{K}_s\mathrm{K}_q\mathrm{K}_b),$$

$$\mathrm{c}_1 = \mathrm{k}_3\mathrm{K}_\mathrm{s}\mathrm{K}_\mathrm{q}\mathrm{K}_\mathrm{b}\omega_a{}^2\omega_\mathrm{b}{}^2 t_a,$$

$$c_2 = (k_1 K_s K_q \omega_a{}^2 - k_4 K_s K_q K_b \omega_a{}^2\omega_b{}^2\sigma^2)$$

Bode plot-

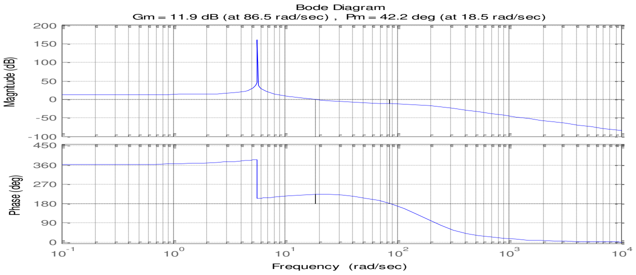


TABLE: 5 Frequency Domain Analysis of Incomplete State Feedback Controller-

4. CONCLUSION

The controller gains computed using exact formulae are valid for a class of cruciform tail-controlled missiles where the controlled variable is the lateral acceleration. A procedure for selection of autopilot closed loop poles has been developed, which can satisfy Gm and Pm specifications for a given set of autopilot system parameters.

The incomplete SVF controller without fin-rate feedback eliminates the need for an observer system to provide estimation for the unavailable $\dot{\eta}$. The numerical example illustrated that a cost-effective design with a slower actuator might be achieved for the specified operating point using a modified SVF controller without implementation of fin position feedback. It is interesting to note that a closed loop actuator with feedback gain k1 produces a reduced speed of response in the closed-loop.

The gain crossover frequency of the incomplete SVF controller is greater than the GCF of the complete one.

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