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T-50 Horizontal-directional axis flight control law design and trajectory gain Research on aircraft dynamics under change

A Study on the Flight Control Law and the Dynamic Characteristic about Variation of Feedback Gains of T-50 Lateral-Directional Axis

Kim Jong Sup', the yellow bottle door, the River Spirit himself

(Chong-sup Kim, Byung-moon Hwang, and Young-shin Kang)

Abstract : The T-50 advanced trainer aircraft combines advanced aerodynamic features and a fly-by-wire flight control system in order to produce a stability and highly maneuverability. The flight control system both longitudinal and lateral-directional axes to achieve performance enhancements and improve stability. The T-50 employs the RSS concept in order to improve the aerodynamic performance in longitudinal axis and the longitudinal control laws employ the dynamic inversion with proportional-plus-integral control method. And, lateral-directional control laws employ the blended roll system both beta-betadot feedback and simple roll rate feedback with proportional control method in order to guarantez aircraft stability. This paper details the design process of developing lateral-directional control laws, utilizing the requirement of MIL-F-8785C and MIL-F-9490D. And, this paper propose the analysis of aircraft characteristics such as dutch-roll mode, roll mode, spiral mode, gain and phase margin about gains for lateral-directional inner loop feedback.

Keywords : RSS (Relaxed Static Stability), FLCS (Flight Control System), FBW (Flight-By-Wire)

I. Introduction

Most military aircraft currently being developed have air power characteristics and destabilize the aircraft statically to improve maneuverability The application of the stable mitigation concept designed to be universal c. In addition, the stability and maneuverability of unstable designed aircraft With highly developed digital control technology to guarantee One electric flight control system (digital Fly-By-Wire flight control The adoption of system)is essential. Therefore, FBW (Fly-By-Wire) ratio -Flight control law design of the row control system is the entire flight area(flight envelope) In order to ensure excellent maneuverability on the target aircraft It is a task that imposes proper stability and maneuverability. Aircraft The control law is designed through the following process. First Aerodynamics, From a database consisting of propulsion, weight, and hinge moments Perform the trim process to calculate the equilibrium state, and to each trim condition After obtaining a linearization model of the standing aircraft, the aircraft model Design control laws using linear analysis. In the all-flight area Nonlinear 6-degree of freedom simulay after scheduling control laws Verify and supplement control laws through Sean. Finally Maneuverability of aircraft by Handling Quality Simulator (HQS) After the verification of the ability, the control law design work is terminated c. Design requirements that apply to the design of such flight control laws There has been a lot of research on the condition[1-4]. But manned Interpretatively and accurately the piloted aircraft's piloted performance The formulation of the predicted design requirements is the pilot's control load(pilot workload) given flight mission, by-environment and joe at the time of flight It is very difficult because it depends on the state of the engaged person. Thus The advanced flight control system varies depending on the pilot's flight mission The ultimate goal is to provide the optimal flight control mode This is.

In this paper, control using horizontal-directional design concepts The design technique of the gain was described in the U.S. military standard The control gain was realized using the defined requirements c. In addition, the transverse-directional axis of the aircraft according to the change in orbital gain Dong was analyzed. For this study, the T-50 Higher training machine was used Using an iterabase, the control performance requirements are MIL-F- Dutch mode described in 8785C and MIL-STD-1797A (dutch-roll mode), roll mode, spiral mode Requirements for mode and stability margin [5-7].

II. T-50 Horizontal-directional axis control law Design

1. Horizontal-directional axis control

law T-50 Horizontal-directional axis flight control law is sliding angle-sliding angle Figure (8-B)Using the control technique of the ulceration structure, the ulceration gain design. However, when maneuvering on the vertical axis in an asymmetric armed shape, the foot In order to eliminate the phenomenon of raw roll movement, such as vertical axis maneuvers Roll angle speed in areas where small roll control input or roll angle speed is created Roll axis pilot command gain by relatively increasing the trajectory gain and The control law of the simple roll angular velocity trajectory structure using the same It was applied in part to the horizontal axis[8].

Fig. 1 represents the horizontal-directional axis jether law structure. Aircraft The horizontal axis and the directional axis movement are connected to each other(coupling).

* Corresponding Author Paper received

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Kim Jong-sup, Hwang Byung-moon : Korea Aerospace Industry Co., Ltd

(robocskim@koreaaero.co.kr / hwangbm@koreaaero.co.kr)

Young-Shin Kang : Korea Aerospace Research Institute(kangys@kari.re.kr)

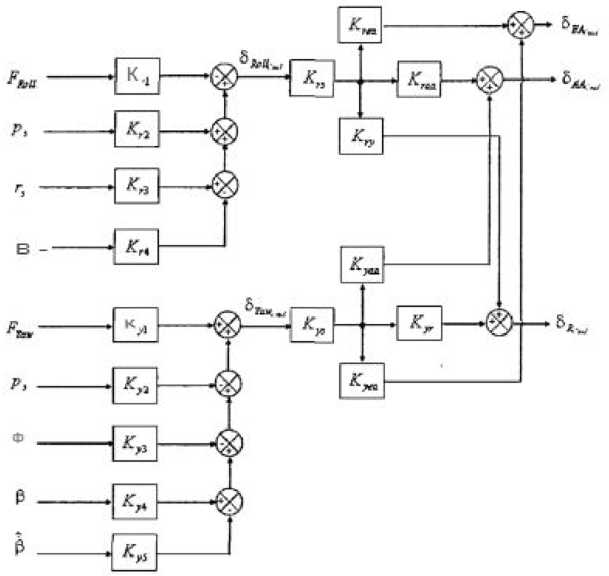

Figure 1. Horizontal-directional axis control law.

Fig. 1. Blended roll system in lateral-directional control law.

Therefore, in order for the aircraft to make a coordinated turn The required YAW angular velocity should occur, so playgirl The rudder must be operated correspondingly when the furon is operated. Therefore, aviation through control surface blending Separating the horizontal-directional axis so that the giga can be balanced Added control gain(ARI : Aileron Rudder Interconnection)for It has been.

Horizontal axis control uses pleperons and horizontal tail wings. Joe The command by the operator's control is roll command tilt(roll command gradient)is converted to roll rate(roll rate) and used. Departure of aircraft and linkage by roll Maximum roll angle turning dynamic to prevent coupling pressure, horizontal tail deflection and receiving Limited by sound angle. Therefore, during cruise flight and takeoff and landing The maximum roll angle speed is reduced by the above three variables. The horizontal axis trajectory variable is the roll mode time(roll mode time). constant) or roll angle to enhance the stability coefficient Lp This roll angle speed is relative to the stability axis For one roll. This means that the aircraft has a stable axis or wind axis If you do not roll against the (wind axis), you will receive it when flying horizontally The sound angle appears as a slide angle as you roll, which is undesirable This is because there is no linkage phenomenon. In addition, roll angle speed and yaw Reduce the impact of structural static phenomena on the right angle velocity ulceration loop In order to remove the structural linkage phenomenon, use a filter.

Directional axis control uses vertical tail wings. Rudder of the pilot Commands are slipped by rudder command gradient It is then converted to an angle command, preventing the phenomenon of deviation from the high angle of reception In order to reduce its size as the speed of the roll angle increases > The direction axis rotation variable is roll angle speed, slide angle and slide angle Unique frequency of dutch roll mode mainly as speed and is used for the augmentation of the attenuation rate.

T-50 Transversal-directional axis gain is slip angle-Slip angle speed trajectory It is designed by applying a structure, and in some areas, simple roll angle speed Follows the ulcerative structure. In this paper, the flight stage bracket A is compared to the flight stage bracket A. Slide angle-Slide angle speed trajectory control technique is used to control the sliding angle of the slide angle. Introduce techniques for calculating benefits[10,11].

1.1 Horizontal axis control gain design

For simplification of equations in horizontal-directional axis equations of motion Assuming Y = Y, = Ys, = Ys, = 0, the equation of motion is It can be expressed as (1)to (3) [9].

$$\dot{p} = LgB + Lpp + Lpr + L_{\delta_{Roll}}\delta_{Roll} \quad (1)$$

$$\dot{r} = Ng8 + Nap + N,r + N_{\delta_{Yaw}}\delta_{Yaw} \quad (2)$$

$$B = -R + 3\frac{V}{u_0}, \text{ where } R = r - \sin\phi\cos 0 \frac{}{u_0} \quad (3)$$

Fig. In the block diagram of I, the roll control command is expressed as (4) can.

$$\delta_{Roll_{Cmd}} = -K\text{-}LFRou + K\text{-}2p + K\text{-}3 - \quad (4)$$

Consider steady-state response (6Bou = 6Ro) and obtain feedback Assume that there is no roll order of the pilot (Fnod = 0)if (1) And (4)can be expressed as (5).

$$p = (Lp + K2Ls)p + (Lp + Ka1s)r + (L3 - KnLa)3 \quad (5)$$

(5)To remove the roll by yaw angle speed and slip angle For Kn, K.If n is obtained, it is equal to (6).

$$K_{r3} = -\frac{L_r}{L_{\delta_{Roll}}}, \quad K4 = \frac{L_\beta}{L_{\delta_{Roll}}} \quad (6)$$

Assuming the hydraulic operator as the primary delay filter, the table as shown in (7) It can be current. (4)Roll by yaw angle speed and slip angle There is no pilot roll input, assuming that there is no pilot roll input, substituting in (7) If written in the form of a high matrix, it is equal to (8).

$$\dot{\delta}_{Roll} = -w_A\delta_{Roll} + w_A\delta_{Roll_{Cmd}} \quad (7)$$

$$\begin{bmatrix} \dot{p} \\ \dot{\delta}_{Roll} \end{bmatrix} = \begin{bmatrix} L_p & L_{\delta_{Roll}} \\ w_A K_{r2} & -w_A \end{bmatrix} \begin{bmatrix} p \\ \delta_{Roll} \end{bmatrix} \quad (8)$$

(8)The two waves of the characteristic equation of the roll mode frequency (u4) and Peruf Define the frequency (w2) of the hydraulic operator mode and compare the coefficients If you obtain K gain, it is equal to (9).

$$K2 = \frac{'+ Lp)@n\ @A)}{L_{\delta_{Roll}}\omega_A} \quad (9)$$

Engineered Ka, K4 gain by yaw angle speed and skid Assume that the roll component by each has been erased, (1)and (4)in Steady state condition for maximum roll command (6nol = 6пы)P = 0, If you solve the equation by applying Fhot = p = pM"), then Kp (10)can be obtained as follows.

$$K_{r1} = \frac{p_{ss}^{Mox}}{F_{Roll}^{Max}}\left(K_{r2} + \frac{L_p}{L_{\delta_{Roll}}}\right) \quad (10)$$

The roll axis gain obtained above is the roll control input, such as the roll start This is applied in areas where there is a lot of demand or roll angle speed, avoid The roll control input is required to be small, such as the stroke motion, or the roll angle speed is - Small area in K.,and K.p is the same as the speed schedule Apply. This is when starting a pure vertical axis in an asymmetric armed shape Replace K2 to eliminate roll-off Simple roll angular velocity trajectory using the same as Ka by increasing to It is the result of applying some of the control techniques of the structure to the horizontal axis[8].

1.2 Directional axis control gain design

Fig. In the block diagram of 1, the Yow control command is shown as (11)Table It can be current.

$$\delta_{Yaw_{Cmd}} = K_{y1}F_{Yaw} - K_{y2}p - K_{y3}\phi + K_{y4}\beta - K_{y5}\dot{\beta} \quad (11)$$

Consider steady-state response (6y= 6y) and get feedback In order to assume that there is no pilot's Yow command (Fyxm = 0)ha And, (2), (3) and (11)can be expressed as (12)if solved using There are.

$$3- \cos\theta\cos\phi - Np + Kon + Kan - N \cos\theta\,\phi$$
$$- (Np + + (24 + KaN38 - N,R \quad (12)$$

(12) Roll angle speed and roll to consider only the direction axis movement If Knp, Kn0 for erasing the term for the posture angle is obtained (13) and the same.

$$K32 = \frac{\frac{\cos\theta\cos\phi}{u_0} - Np}{N_{\delta_{Yaw}}}, \quad Kg3 = -\frac{Ncos0\ 'ug}{N_{\delta_{Yaw}}}\frac{180}{\pi} \quad (13)$$

Assuming the right pressure operator as the primary delay filter (14) as shown in the table It can be current.

$$\dot{\delta}_{Yaw} = -\omega_A\delta_{Yaw} + \omega_A\delta_{Yaw_{Cmd}} \quad (14)$$

(11) The roll angle speed and roll posture angle terms are erased, and the pilot Assuming that there is no YOW input, it is arranged by substituting in (14). If you express the organized expression in matrix form using (12)and (3) Equal to 15

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & \omega_A K_{y5} & 1 \end{bmatrix}\begin{bmatrix} \dot{R} \\ \dot{\beta} \\ \dot{\delta}_{Yaw} \end{bmatrix} = \begin{bmatrix} N, & N3 & R \\ -1 & \frac{r_\beta}{u_0} & 0 \\ 0 & - & w,1 \end{bmatrix}\begin{bmatrix} \\ \beta \\ \delta_{Yaw} \end{bmatrix} \quad (15)$$

Dutch roll mode(CDn, Wpn)and hydraulic operation in the characteristic equation of (15) Define the frequency(@A) of the ki mode and compare the coefficients K K, obtain the gain is equal to 16.

$$K_{y1} = \frac{\omega_{D}^{2}\omega_B - N\frac{Y_\beta}{u_0}\omega_A - N_\beta\omega_A}{N.A} \quad (16)$$

$$K_{y5} = \frac{2\zeta_{DR}\omega_{DR}\omega_B - N_r\frac{Y_\beta}{u_0} + N_r\omega_A + \frac{Y_\beta}{u_0}\omega_A - N_\beta}{--A}$$

$$\text{where} = -N - \frac{Y_i}{u_0} + A - 2Cpn\ DR$$

Engineered <Gain by roll angle speed, roll posture The yaw component has been erased by the angle and slide angle speed - (2)and (11)to determine the normal condition for the maximum Yew order Applying (y = = 0, = = 8M) By solving the equation, Kb can be obtained as (17).

$$K_{y1} = \frac{-\beta_{ss}^{Max}}{Fy_{o}^{;}}\left(K_{y4} + \frac{N_\beta}{N_{\delta_{Yaw}}}\right) \quad (17)$$

1.3 Horizontal-directional axis control surface Composite control gain design Fig. The moment generated by the control surface in the block diagram of 1 is From 18 to 24 is the same.

$$L_{\delta_{RR}} = K.,\ (K14, + + K.,L4,) \quad (18)$$
$$N_{\delta_{Roll}} = K_{rs}\left(K_{rea}N_{\delta_{EA}} + K_{raa}N_{\delta_{AA}} + K_{ry}N_{\delta_R}\right) \quad (19)$$
$$L_{\delta_{Yaw}} = K_{ys}\left(K_{yea}L_{\delta_{EA}} + K_{yaa}L_{\delta_{AA}} + K_{yr}L_{\delta_R}\right) \quad (20)$$
$$N_{\delta_{Yaw}} = K_{ys}\left(K_{yea}N_{\delta_{EA}} + K_{yaa}N_{\delta_{AA}} + K_{yr}N_{\delta_R}\right) \quad (21)$$

Roll Split Ratio to obtain ARI gain Let's apply as shown in (22).

$$\frac{Ar}{A_{raa}} = DEAPDAA- func(M, Alt, cx)\backslash \quad (22)$$

N = La = 0 La to separate the horizontal axis and the directional axis Assuming that, (22)is assigned to (19)and organized as (23) Kp can be obtained.

$$K_{ry} = -\frac{DEAPDAA\ N3 + \frac{N_{\delta_{AA}}}{}K_{raa}}{N_{\delta_R}} \quad (23)$$

In addition, the asymmetric displacement of the horizontal tail wing by Yow command Assuming that it does not occur, solving (20), K is equal to (24 This can be obtained.

$$K_{yaa} = -\frac{L_{\delta_R}}{L_{\delta_{AA}}}K_{yr} \quad (24)$$

Assuming Knn= Kn = 1 in (23), (24), Knp, Kn can be obtained.

Kn K can be determined by applying a control force requirement. The control force requirement is a function of dynamic pressure, (18)and (19) by (25) Can be obtained as.

$$K_{rs} = \frac{func\_q)}{K_{rea}L_{\delta_{EA}} + K_{raa}L_{\delta_{AA}} + K_{ry}L_{\delta_R}}$$
$$K_{ys} = \frac{\_func(\bar{q})}{K_{yea}N_{\delta_{EA}} + K_{yaa}N_{\delta_{AA}} + K_{yr}N_{\delta_R}} \quad (25)$$

2. Horizontal-directional axis control law Design procedure

When the design procedure of the horizontal-directional axis control law is established, the following This can be expressed briefly.

①(26)Line the design goal of the horizontal-directional axis control law as shown Determine. The design goals are maximum roll angle speed, slip angle displacement, Dutch Roll mode is the unique frequency and attenuation ratio, and the roll mode phase number.

$$p_{ss},\ \beta_{ss},\ \omega_{DR},\ \zeta_{DR},\ \tau_R \tag{26}$$

② Use the gain design formula obtained in section 2.1 according to the design goals By setting the initial gain value.

(3)Higher Order System(HOS) with initial gain value Maximum Likelihood Estimation LOES: Low Order Equivalent Calculate System).

④ Eigenvalues of spiral mode from equivalent low-order systems(Eigen- value) is the design goal (Aar <) Until reduced to less than 1 The er gain is modified to calculate repeatedly, and a separate optimization process is performed It doesn't go through.

3. Design Requirements

Specified in U.S. military standards MIL-F-8785C and MIL-STD-1797A The design requirements for the horizontal-directional axis were applied. table 1 shows Dutch roll mode and stability margin requirements In addition, table 2 indicates the role mode awards and spiral requirements Give [5-7].

The requirements defined in Tables 1 and 2 do not include a controller Dynamic characteristics were defined for the aircraft. But includes a controller The FBW aircraft is made to improve control characteristics Higher order, which contains a number of filters and integrators within the phraseology system. Therefore, to apply the requirements of table 1 and 2 It should be determined by equivalence with the equivalence low difference system. In this paper Does not cover the details regarding the equivalent low-order technique.

Table 1. Dutch Roll mode requirements (category A).

Table1. Requirement of minimum dutch-roll frequency and damping(category A).

Level	Dutch Roll Mode			Margin	
	ζ_{DR}	$\zeta_{DR}\omega_{DR}$ (rad/sec)	ω_{DR} (rad/sec)	G.M	P.M
1	0.19	0.35	1.0	LGM > 6 dB HGM > 6 dB	Φ > 45°
2	0.02	0.05	0.4	-	-
3	0.005	-	0.4	-	-

Table 2. Roll mode time and Time to Bank requirements (category A).

Table2. Requirement of maximum roll mode time constant and minimum time to doublet amplitude(category A).

Level	TR Max(sec)	T2min(sec)
1	1.0	12
2	1.4	8
3	10	4

III. Control gain design and Analysis

1. Selection of test areas and items

In this paper, Fig. Test area as shown in 2 Height M0.8@10kft, M0.95@10kft and M1.05@10kft에서 Receiving angle Horizontal-directional axis for 9 areas by 0°, 2.5° and 5° The control gain was designed by applying the control law design procedure. That And Fig. Horizontal-directional axis trajectory in the all-flight area shown in 2 Horizontal-directional shaft dynamics and stability of the aircraft due to changes in gain The degree of slack was analyzed.

2. Horizontal-directional axis control Law Model

This paper describes the air power database of the T-50 Higher training aircraft used. To improve the stability of the transverse-directional axis of the aircraft, The sliding angle-sliding angle acceleration ulceration technique presented in section 2.1 The horizontal-directional axis control law was designed by applying. Mean Aerodynamic Chord (MAC) For aircraft located at 34.66% of the nonlinear equation of motion The result of calculating the trim conditions using table 3 is the same as table 3, each Obtain an approximate linearized fluid-dimensional aerodynamic coefficient under trim conditions It is the same as table 4, and Lg has a negative large value. This is C,a measure of lateral stability, has a negative large value Aircraft that do not contain a controller should not be on the horizontal axis It can be seen that it is determined[9].

3. Control gain design and linear analysis

results Set design goals for the test area and design in section 2.1

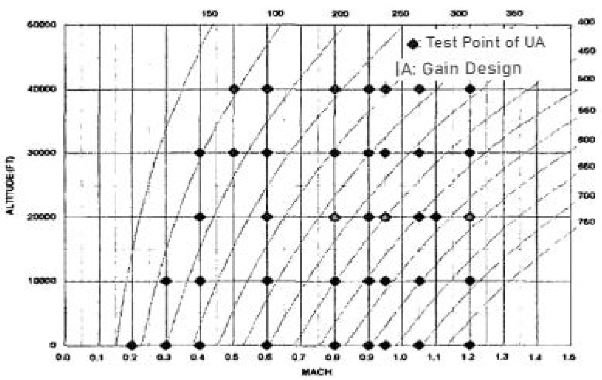

Figure 2. Test area.

Fig. 2. Test points.

Table 3. 1-g horizontal trim results.

Table 3. Result of 1-g wing level trim.

Case	Altitude (kft)	Mach	AoA (deg)	VCAS (knots)	HT (deg)	Thrust (%)
1	20	0.8	0	373	-1.417	63.8
2	20	0.8	2.5	373	1.279	69.4
3	20	0.8	5	373	4.081	85.6
4	20	0.95	0	449	-1.05	80.9
5	20	0.95	2.5	449	1.39	99.5
6	20	0.95	5	449	3.88	119.6
7	20	1.2	0	578	-1.51	125.9
8	20	1.2	2.5	578	-0.27	130.0
9	20	1.2	5	578	1.07	130

Table 4. Aircraft aerodynamic characteristics for the transverse-directional axis. Table4. A/C property of lateral-directional axis.

Case	L_p (sec1)	L, (see2)	L_r (sec-3)	L6AA (sec2)	L6EA (see)	LoR (sec2)	Number (sec1)	N (sec")	N (sec4)	$N_{\delta AA}$ (sec")	$N_{\delta EA}$ (sec^{-2})	$N_{\delta R}$ (sec2)	Y_p (ft/sec)	Y_β (fl/sec2)	Y. (fl/sec)	YSAA (fl/sec2)	YEA (fl/sec2)	YR (ft/sec2)
1	-3.38	-39.8	0.99	-81.9	-30.9	17.9	-0.071	11.1	-0.47	-3.86	-7.41	-8.01	-0.0000	-0.242	-0.9933	0.025	0.045	0.062
2	-3.37	-49.9	1.56	-80.1	-30.9	16.5	0.003	12.1	-0.53	-0.64	-5.79	-8.65	0.0001	-0.241	-0.9929	0.030	0.056	0.060
3	-3.41	-66.5	2.09	-81.3	-33.3	17.0	0.070	14.2	-0.63	3.06	-4.00	-9.25	0.0004	-C.229	-0.9926	0.037	0.052	0.059
4	-4.06	-23.9	1.21	-87.8	-34.8	12.3	-0.092	19.5	-0.58	-4.36	-11.18	-6.37	0.0000	-C.321	-0.9933	0.037	0.059	0.037
5	-4.04	-55.8	1.87	-74.3	-38.8	13.4	-0.005	18.5	-0.63	-0.93	-9.27	-7.03	0.0002	-C.310	-0.9931	0.036	0.070	0.038
6	-3.97	-85.6	2.54	-64.7	-42.8	12.9	0.077	21.8	-0.75	2.33	-7.05	-7.47	0.0005	-C.304	-0.9929	0.035	0.073	0.036
7	-6.39	-85.9	1.30	-36.6	-94.4	13.5	-0.165	17.9	-0.82	-4.29	-9.12	-6.63	-0.0000	-C.343	-0.9946	0.029	0.033	0.030
8	-6.41	-89.4	1.97	-38.4	-83.8	12.5	0.011	32.6	-0.89	-2.84	-7.61	-6.96	0.0001	-C.395	-0.9944	0.037	0.045	0.026
9	-6.37	-99.3	270	-39.5	-82.6	13.2	0.182	42.3	-1.04	-1.16	-3.32	-7.54	0.0004	-C.428	-0.9940	0.040	0.044	0.024

Table 5. Optimization results of gain for the horizontal-directional axis.

Table 5. Gain optimization of lateral-directional axis.

Case	Desired					Gain Optimization																
						Roll Axis Gain				Yaw Axis Gain					Blended Gain							
	ω_{DR} (rad/sec)	ζ_{DR}	τ_R (see)	p_{ss} (dps)	β_{ss} (deg)	Kл	K_{r2}	Ki3	K_{r4}	K_{y1}	K_{y2}	K_{y3}	K_{y4}	K_{y5}	K_{rs}	K_y	K_{rea}	K_{raa}	K_{ry}	Ky	Kycя	K_{yr}
1	4.63	0.6	0.287	200	6	0.034	0.0008	0.0097	0.155	2.001	0.014	0.0022	-0.64	0.501	1	1	0.25	1	-0.53	0	0	1
2	4.63	0.6	0.288	194	6	0.038	0.0009	0.0170	0.218	1.861	0.004	0.0024	-0.48	0.453	1	1	0.25	1	-0.17	0	0	1
3	4.63	0.6	0.285	178	6	0.040	0.0010	0.0242	0.308	1.752	-0.003	0.0027	-0.23	0.405	1	1	0.25	1	0.14	0	0	1
4	5.09	0.55	0.241	200	4	0.034	0.0007	0.0102	0.026	3.050	0.019	0.0029	-0.02	0.580	1	1	0.40	1	-1.38	0	0	1
5	5.09	0.55	0.241	187	4	0.042	0.0008	0.0191	0.074	2.774	0.005	0.0029	-0.18	0.529	1	1	0.40	1	-0.62	0	0	1
6	5.09	0.55	0.245	176	4	0.049	0.0010	0.0308	0.135	2.627	-0.006	0.0032	0.27	0.465	1	1	0.40	1	-0.06	0	0	1
7	5.87	0.5	0.154	145	2	0.063	0.0006	0.0127	0.194	3.887	0.029	0.0032	-1.22	0.623	1	1	0.50	1	-1.33	0	0	1
8	5.87	0.5	0.153	135	2	0.070	0.0007	0.0214	0.223	3.722	0.002	0.0033	0.91	0.476	1	1	0.50	1	-0.96	0	0	1
9	5.87	0.5	0.175	110	2	0.075	0.0008	0.0315	0.266	4.609	-0.021	0.0035	1.00	0.357	1	1	0.50	1	-0.37	0	0	1

Table 6.Interpretation results for the horizontal-directional axis.

Table6. Result of lateral-directional linear analysis.

Case	Dutch Roll Mode		Roll Mode	Spiral Mode	Cost	Stability Margin						Level Requirement
						Asym. HT		Asym. TEF		Rudder		
	ω_{DR} (rad/sec)	ζ_{DR}	τ_R (sec)	Root (l/sec)		G.M (dB)	P.M (deg)	G.M (dB)	P.M (deg)	G.M (dB)	P.M (deg)	
1	4.57685	0.53816	0.39992	-0.01113	3.02	62.11	N/A	49.80	N/A	23.57	68.87	Yes
2	4.57591	0.54145	0.37887	-0.01058	2.97	59.72	N/A	51.57	N/A	24.14	73.18	Yes
3	4.56874	0.56220	0.38875	-0.00699	2.98	59.41	N/A	39.25	N/A	24.62	80.04	Yes
4	5.14233	0.54535	0.34008	-0.00845	3.83	54.94	N/A	50.15	N/A	23.61	81.83	Yes
5	5.10959	0.52953	0.35617	-0.00818	3.81	51.26	N/A	52.52	N/A	24.13	82.29	Yes
6	5.15202	0.55229	0.36356	-0.00223	3.50	49.27	N/A	38.93	N/A	24.82	92.12	Yes
7	5.78315	0.45034	0.25435	-0.00639	2.96	51.67	N/A	52.67	N/A	22.05	69.45	Yes
8	6.23605	0.53057	0.26137	-0.00506	3.51	48.86	N/A	51.07	N/A	24.72	99.18	Yes
9	6.80412	0.41398	0.26991	0.00067	3.22	49.79	N/A	51.89	N/A	27.67	118.29	Yes

N/A : A gain or phase margin does not exist at this flight condition.

The result of calculating the control gain is the same as table 5. Current, T-50 steering The cotton composite control law has ARI(kry) for aircraft balance rotation - Asymmetric horizontal tail wings are used to share the score and roll orders. The gain (krea) is reflected. Thus, Ke and Ku gain is not considered, and Kraa, K, and benefits phase It is reflected in the number 1. Sliding angle-With sliding angle speed ulcer structure When calculating the control gain, the roll angular velocity trajectory gain (Ka) is the horizontal axis It is designed to be relatively small(1/10)than the pilot gain(Ki). Like this Due to problems with one design technique, pure in non-blue armed shape When performing pitch maneuvers, molar movement occurs. These problems

To solve the horizontal axis control law, as in F-16, roll angle speed Relatively increase the ulceration gain, roll axis pilot gain (Ka) Step applying the roll angle velocity ulceration gain (Kz) to the same gain The net roll angular velocity ulceration structure was applied to some areas. Km Gain M0.8 that represents the roll control ratio of the horizontal tail wing At speeds below 25%,at speeds above M 1.05 and above 50%, M0.8 The transition region between M1.05 and M1.05 was linearly connected. This is to increase roll control, and on the one hand, high Avoid applying to the main gain during roll operation in subsonic and transonic areas It is to reduce the dimension.

Sliding angle-Horizontal room designed with sliding angle acceleration convection technique Linear analysis was performed to evaluate the direction axis control gain. Verification items include gain margin, phase margin, dutch mode attenuation ratio and high Design requirements for Eugene frequency, role mode number, and spiral mode The satisfaction of the conditions was interpreted.

Table 6 shows the results of horizontal-directional axis linear analysis. Linear As a result of the analysis, when the gain designed in table 5 is applied, table Dutch Roll Mode, Roll mode, and Spiral mode presented in 1 and 2 You can see that everyone is satisfied with the rescue. Thus, the T-50 The stability of the aircraft by applying control laws and it is possible to improve the steering performance.

IV. Impact analysis of changes in ulcerative gain

1. Horizontal-directional axis dynamic characteristics according to changes in ulceration gain

The test area is Fig. Selected for the T-50 all-flight area as shown in figure 2 The aircraft shape is a representative shape of CAT (category) 1 F0(clean) shape was selected. Changes in ulcerative gain Horizontal-directional to interpret aircraft dynamics and stability slack - Linear analysis was performed on the axis. Ulceration through linear analysis ·Impact on gain margin due to changes in gain - Analysis was performed. Also equivalent depending on the change in ulcerative gain Dutch roll determined by the equivalent system · Mode attenuation ratio and natural frequency, role mode time series, Spiral mode The impact on was analyzed. The range of changes in ulcerative gain is Set from 50% to 150%, and the change is increased by 25% was. The meaning of 100%here is optimized without increment It's a gain. To determine the impact of altitude and mach water Fixed altitude and changed mach number.

As a result of linear analysis, many effects on horizontal-directional axis motion The ulceration gain on the horizontal axis is the roll angle speed and yaw angle speed It is a gain, and the direction axis is a slide angle and slide angle speed gain c. In this paper, the sliding angle and sliding angle at an altitude of 20kft The results of the analysis of the figure were shown representative.

1.1 Slip angle ulcer gain

Slip angle ulceration gain affects Dutch roll mode intrinsic frequency

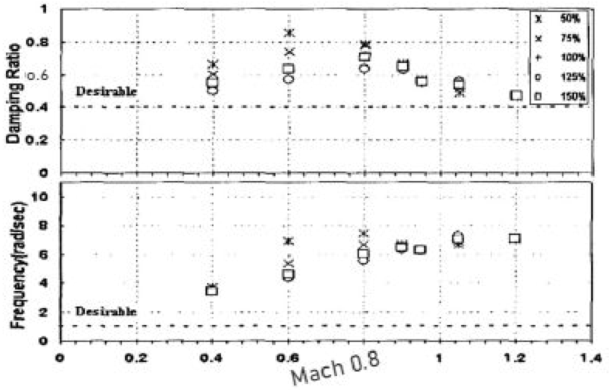

Figure 3. Dutch roll mode according to the change in direction axis slide angle return gain Attenuation ratio and frequency.

Fig. 3. Dutch-roll mode damping and frequency with variation of beta feedback gain in yaw axis.

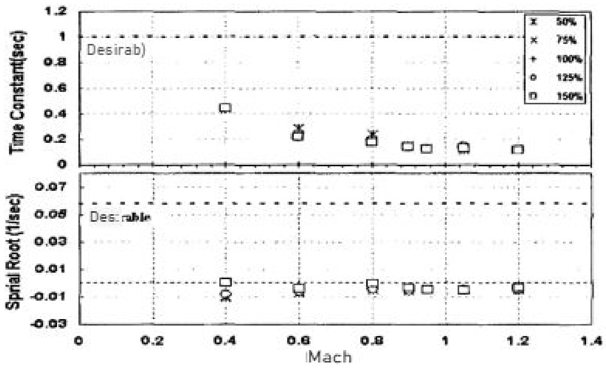

Figure 4. Roll mode visibility according to change in direction axis slip angle return gain Can and Spiral mode muscle.

Fig. 4. Roll mode time constant and spiral mode root with variation of beta feedback gain in yaw axis.

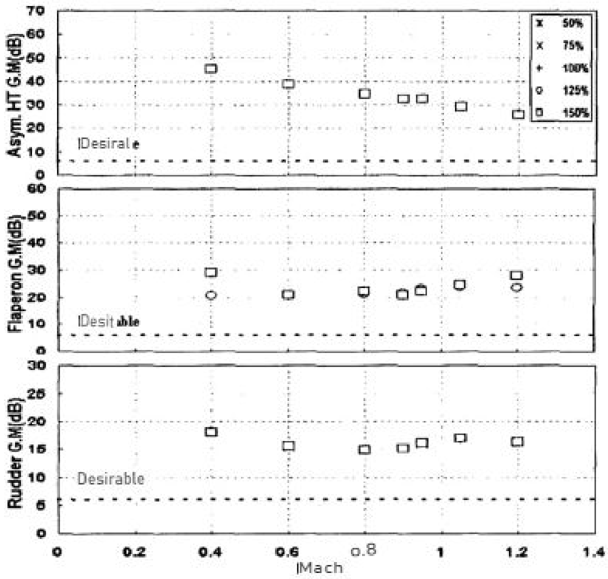

Figure 5. Stability margin according to the change in direction axis slide angle return gain.

Fig. 5. Stability margin with variation of beta feedback gain in yaw axis.

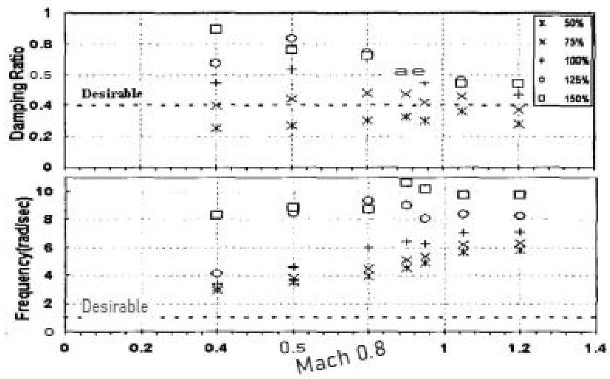

Figure 6. The Dutch according to the change in the direction axis sliding angle speed return gain Mode attenuation ratio and frequency.

Fig. 6. Dutch-roll mode damping and frequency with variation of betadot feedback gain in yaw axis.

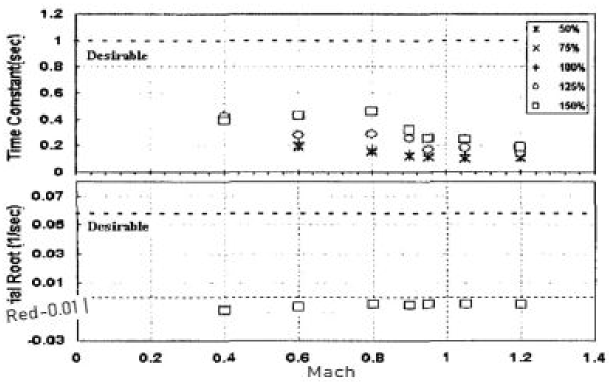

Figure 7. Roll mode according to change in direction axis sliding angle speed return gain Current number and spiral mode muscle.

Fig. 7. Roll mode time constant and spiral mode root with variation of betadot feedback gain in yaw axis.

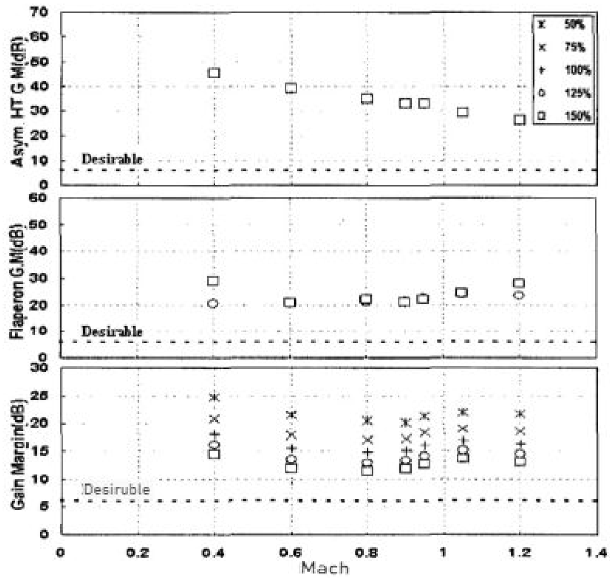

Figure 8. Stability according to change in direction axis sliding angle speed return gain Slack.

Fig. 8. Stability margin with variation of betadot feedback gain in yaw axis.

The stability of the rudder has also had a lot of impact on the slack. Fig3 is the Dutch mode according to the change in the slip angle trajectory gain Shows changes in attenuation ratio and natural frequency. Changes in ulcerative gain For Dutch roll mode attenuation ratio tends to depend on altitude and speed The sex was the same, but the width of the change was different. Altitude can increase The rock has a tendency to increase in width, and at the same altitude, AH There was a large change in the sound velocity area. And ulceration gains can be reduced Rock attenuation ratio showed a tendency to increase. Stools of ulcerative gain The natural frequency of the Dutch for the times tends to vary depending on the altitude It was the same, but the tendency was different depending on the speed. In the low-altitude area, the change in ulcer gain was large. At the same altitude, the more the gain decreases in the subsonic region, the more Dutch Roll intrinsic frequency showed a tendency to increase, transonic speed and In the supersonic region, there was a tendency to decrease.

Fig. 4, 5 is the role mode award number according to the change in the ulcer gain, spa Imho mode muscle and stability also indicate slack. Almost no impact You can see that it's not crazy.

1.2 Sliding angle speed ulcer gain

Slip angle speed trajectory gain Dutch mode and vertical tail wing Stability also had a lot of impact on slack. Fig. 6 is a dutch roll according to the change in the sliding angle speed ulcer gain It shows the mode attenuation ratio and the natural vibration return change. of ulcerative gain For changes, the Dutch roll mode attenuation ratio and natural frequency are high And the tendency according to speed was the same. Ulceration at the same height As the gain decreases, the attenuation ratio and natural frequency tend to decrease Indicated last name. Also, if excessively reduce the gain, persimmon Icebee was not satisfied with the requirements. Also, the natural frequency is bin The change was greater when the return income was increased than when it was reduced.

Fig. 7 is the role mode award number and spa according to the change in ulceration gain Imho indicates a change in the muscle of the mode. vs. changes in ulcer gain The role mode awards tend to vary depending on altitude and speed indicated. The higher the altitude, the more the change in the ulceration gain The smaller the impact, the lower the ulcer gain at the same altitude The number of hours became smaller. However, at high altitude, there is a certain tendency Did not have. Sliding angle speed trajectory gain is in spiral mode has little effect.

Fig. 8 is the stability margin of the aircraft according to the change in the trajectory gain appears. The gain margin is the same as the change in ulceration gain Showed a tendency. If the ulceration gain decreases at the same altitude The gain margin increased.

2. Example of gain accuracy calibration for Dutch Roll mode

The sliding angle-sliding angle velocity ulceration structure presented in this paper is Under the premise that the aircraft model obtained from the wind tunnel test is accurate It is a useful technique. However, aircraft models obtained from wind tunnel tests There is an error with the actual aircraft. If there is an error in aviation The control gain designed for the aircraft model is the pilot performance and stability of the aircraft will not be able to satisfy. These errors are linear and nonlinear The actual flight test with the aircraft movement predicted by the type interpretation Aircraft mod by comparing the aircraft movement that appears as you perform Dell can be calibrated, and there are two calibration methods. Calibrate the aircraft model based on the results of the flight test and make it linear. How to optimize the gain through the seat There is another way to have direct control while performing flight tests There is a method of gain tuning. The latter room The law uses the Flight Control Test Panel(FCTP) during flight testing By adjusting the gain, you can get the desired aircraft response c. In this paper, inaccuracies in aircraft models during flight tests Unwanted aircraft movement caused by gain of precision Provide a way to improve through calibration.

This section describes inaccuracies in the horizontal-directional axis aircraft model The resulting Dutch mode kinetic characteristics were analyzed. Dutch Roll mode mainly appears as a combination of slide angle and yaw movement As mainly removes and approximates the roll movement. Thus CC and G,with an error in, and a steer with a horizontal-directional axis Nonlinear analysis using force (roll-yaw doublet) was performed. Rain

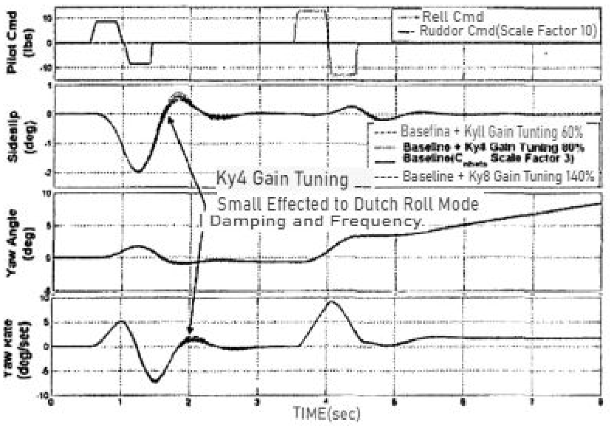

Figure 9. Nonlinear analysis of the adjustment of the direction axis sliding angle return gain Results(M0.6@20kft).

Fig. 9. Nonlinear analysis with beta feedback gain tuning in directional axis.(M0.6@20kft).

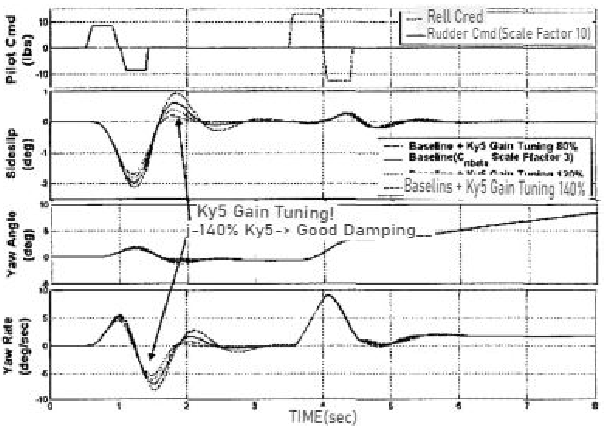

Figure 10. Nonlinear adjustment of direction axis sliding angular velocity return gain Interpretation results(M0.6@20kft).

Fig. 10. Nonlinear analysis with beta-dot feedback gain tuning in directional axis.(M0.6@20kft).

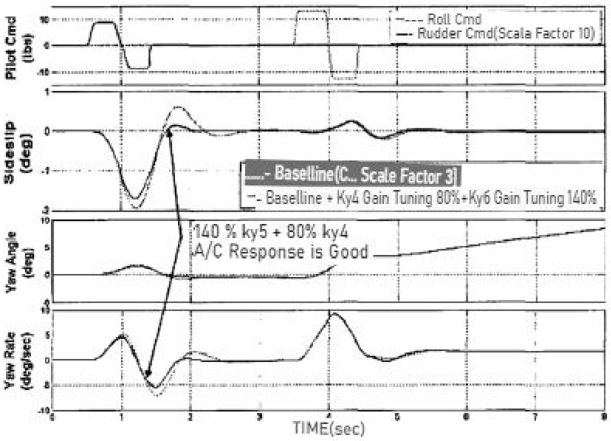

Figure 11. On the adjustment of the direction axis sliding angle and sliding angle speed return gain Nonlinear Analysis results for (M0.6@20kft).

Fig. 11. Nonlinear analysis with beta and beta-dot feedback gain tuning in directional axis.(M0.6@20kft).

As a result of linear analysis, the change in G is much in the aircraft direction axis movement Affected. If you increase G, Dutch mode unique frequency Showed a tendency to increase and decrease the C_{n_r}, C_{y_r} attenuation ratio. and and has little effect on changes in C I knew. This is relative to the value of Np, as shown in table 4 It is consistent with the conclusion that it has a large value.

Figs 9, 10, and 11 are for aircraft models with errors in G Go to the horizontal-directional axis while precision calibration of the control gain Nonlinear interpretation through roll-yaw doublet This is the result to be performed. Inaccuracies in horizontal-directional axis aircraft models In order to simulate the aerodynamic coefficient G2, an error of +200% is artificial Aircraft models that have been raised and do not contain errors Optimized control of the aircraft by using the dock mode luck Dong was observed. And slip to correct model error The rum angle and slip angle velocity trajectory gain were precisely calibrated. Aircraft The judgment criteria for the response are the Dutch mode attenuation ratio and the natural frequency. Judge whether you are bowed.

Fig 9, 10 and As can be seen in 11, the term in which the error exists Dutch mode attenuation when applying designed gain to air models It can be seen that the response characteristics are inadequate due to the decrease in rain.

Fig. 9 Is the result of attuning the K gain, which is the slip angle ulcer gain c. Kn, the amount of change in gain was 60%, 80%, 100% and 140% c. Analysis results, the ulcerative gain is the Dutch roll mode attenuation ratio and high It had little effect on Eugene frequency. Linear analysis results and If the attenuation ratio and natural frequency increase as the gain decreases Showed incense.

Fig. 10 Kp, which is the sliding angle speed ultracold gain, modulated gain The result is. The varying amounts of Kp benefits are 80%, 100%, 120% and 140% was followed by. As a result of the analysis, the K gain is the Dutch mode attenuation ratio and It has had a lot of impact on the intrinsic frequency. As a result of linear analysis As the gain increases, the attenuation ratio and natural frequency tend to increase Showed castle.

Fig. 11 is the result of coordinating Kn and gain. Kp Gain The Dutch mode is set to 80% and the Kp gain is set to 140% Precision calibration of the gain by increasing the attenuation ratio and natural frequency, Proper Dutch roll mode response characteristics were obtained. Linear Interpretation As you can see from the results, the sliding angle speed increase the gain of the ulcer By letting, the attenuation ratio and the natural frequency can be increased, but aviation The stability of the group can be reduced and become statically unstable Therefore, the gain is the appropriate range of the sliding angle speed ulceration gain It should be calibrated within. Precision gains in real-world flight tests When coordinated, the terms according to the change in orbital gain through linear analysis Pre-determine the range of gain adjustment by interpreting the air stability It should be.

V. Conclusion

The T-50 higher training machine guarantees stability and high mobility performance The harm control law is applied. Horizontal-directional axis flight control Law The structure is skid angle-Skid speed track structure and simple angular speed bin The ring structure is mixed.

In this paper, we use the slip angle-slip angle velocity ulceration structure System of flight control laws by presenting the design procedure of control gain We were able to build an enemy database. Also of ulcerative gain Analysis of the effect of changes on aircraft transverse-axial motion c. These results can be used during flight tests Against unwanted aircraft movement due to errors in aircraft models Thus, the control gain regulator to have the appropriate aircraft motion characteristics The law has been presented, and the results can be summarized as follows. Roll

① angle speed and yaw angle speed trajectory in the horizontal axis trajectory gain The sliding angle and sliding angle speed trajectory in the gain, direction axis trajectory gain The change in the score had a lot of effect on the horizontal-directional axis movement.

② Roll angular velocity trajectory gain applied to the horizontal axis is roll mode The inside of the temporal and asymmetric horizontal tail wings and asymmetric flaperon The degree had somewhat much effect on the slack. 3 The yaw angular velocity trajectory gain applied to the horizontal axis is spa Had somewhat much effect on the ical mode. But aircraft stable Nor did it affect the slack.

④ The sliding angle orbital gain applied to the directional axis is Dutch Had a lot of influence on the mode. But the aircraft stability is also on the slack Did not affect.

⑤ The sliding angle speed trajectory applied to the directional axis is more It has the most influence on Chirole mode, and the number of hours of roll mode And the stability of the vertical tail wing also had a lot of effect on the slack.

In this paper, horizontal-directional axis control law design procedure and control By presenting a gain adjustment technique, when developing the next aircraft Not only can you shorten the design period consumed, but you can also fly In the event of an error in the aircraft model during the test, appropriate detoxification Trial and error in aircraft development by presenting the technique of performing the definition It is expected that the five can be reduced.

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Xi Arc

p	Roll rate	$K1$	Roll command gain
r	Yaw rate	K_a	Stability axis roll rate feedback gain
β	Sideslip angle	K_{r3}	Stability axis yaw rate feedback gain
ϕ	Bank angle	K_{r4}	Beta feedback gain in roll axis
θ	Pitch attitude angle	K_{y1}	Yaw command gan
$\dot{p}$	Roll acceleration	K_{y2}	Stability axis roll rate feedback gain in yaw axis
$\dot{r}$	Yaw acceleration	K_{y3}	Roll attitude gain
$\dot{\beta}$	Rate of change of sideslip angle	K_{y4}	Beta feedback gain in yaw axis
g	Acceleration of gravity	K_{y5}	Beta-dot feedback gain
u_0	Forward velocity along x axis	K_{rs}	Roll scaling gain
$\bar{q}$	Dynamic pressure	K_{raa}	Differential flap gain.(splitratio)
L_β	Rolling moment about x with sideslip	K_{rea}	Aileron-to-tail inte.connect gain
L_p	Rolling moment about x with roll rate	K_{ry}	Aileron-to-rudder interconnect gain
L_r	Rolling moment about x with yaw rate	K_{ys}	Yaw scaling gain
$L_{\delta_{Ea}}$	Rolling moment about x with Asym. HT	K_{yaa}	Rudder-to-aileron interconnect gain

$L_{\delta_{AA}}$	Rolling moment about x with Aileron
L_{δ_R}	Rolling moment about x with Rudder
N	Yawing moment about z with sideslip
N	Yawing moment about z with roll rate
.N	Yawing moment about z with yaw rate
N_S	Yawing moment about z with Asym. HT
$N_{\delta_{AA}}$	Yawing moment about z with Rudder
N_{6S}	Yawing moment about z with yaw deflection
Y_β	Ys-force with sideslip
$Y_{\cdot}$	Ys-force with roll rate
Y_r	Ys-force with yaw rate
$Y_{\delta_{EA}}$	Ys-force with Asym. HT
$Y_{\delta_{AA}}$	Ys-force with Aileron
Y_{δ_R}	Ys-force with Rudder
K_{ycn}	Rudder-to-tail interconnect gain
K_{yr}	Rudder gain.(split ratio)
F_{Rol}	Roll control force
F_{Yaw}	Yaw control force
6nollgu	Roll command in roll axis
$\delta_{Yaw_{Cmd}}$	Yaw command in yaw axis
$\delta_{EA_{Cmd}}$	Differential elevator command deflection
$\delta_{AA_{Cmd}}$	Differential Aileron command deflection
6Row	Rudder command deflection
ω_R	Rollmode frequency(rad/sec)
@pr	Dutch-roll mode frequency(rad/sec)
ζ_{DR}	Dutch-roll mode damping ratio
ω_A	Actuator model frequency(rad/sec)

Kim Jong Sup

2000 Korea University of Technology and Education Control Machinery Graduated from the Department of Engineering. 2002 Hanyang University University Won Master of Electrical and Electronic Control Instrumentation Engineering, 2002 Year-Present Korea Aerospace Industry Co., Ltd. T / A-50 Flight Control team. The Law of Flight Control is of interest * Design and analysis, high angle control law System, system modeling.

Yellow Bottle Door

Graduated from the Department of Electronics, Gyeongbuk University in 1984. one thousand nine hundred eighty seven Master of East Graduate School. 1986-Present Korea Port T/A-50 Flight Control Team Team of Communist Co., Ltd. Chapter. System Design and Interpretation, Control BIPSIC design.

River Young Mountain

Graduated from Inha University Aeronautical Engineering in 1992. 1994, Seoul National University, Department of Aeronautics and Astronautics Sa. 1994-2004 Korea Aerospace Industry Flight Dynamics Team. 2004-Present Korea Airlines State-of-the-art Smart drone technology development Project Only. Areas of interest are Manned and Muin aircraft Control law design, guidance and navigation control.