

COMPARISON OF H-inf AND COEFFICIENT DIAGRAM METHOD IN AEROSPACE

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Abstract: The longitudinal control of the fighter with dual control surfaces is a typical MIMO control problem, where various modern control design techniques are employed. Although Coefficient Diagram Method (CDM) is proven effective in SISO or SIMO control design, the concrete procedure for MIMO design is not established yet. A trial design by CDM is made for this MIMO problem and the result is compared with the standard H-inf design. *Copyright © 2004 IFAC*

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1. INTRODUCTION

The classical control and modern control are mainly used in control design. However, there is a third approach generally called as algebraic design approach. The Coefficient Diagram Method (CDM) (Manabe, 1998, 2002b) is one of the algebraic design approaches, where the coefficient diagram is used instead of Bode diagram, and the sufficient condition for stability by Lipatov (Lipatov and Sokolov, 1978) constitutes its theoretical basis.

The purpose of this paper is to present one example of MIMO design by CDM and to make comparison with H-inf design. For this purpose, the problem is taken from the well-known example of the longitudinal control of a modern fighter in Robust Control Toolbox of MATLAB (Chiang and Safonov, 1994). The procedures for CDM MIMO design have not been established yet, and this paper is the continuation of the previous effort (Manabe, 2002a).

This paper is organized as follows: In Section 2, the basics of CDM are briefly explained. In Section 3, the mathematical model and the problem statement are presented. In Section 4, the decoupling controller is designed. In Section 5, feedback controllers are designed as SISO problems by CDM. In section 6, frequency responses and singular value plots are

shown. In Section 7, simulation results are shown. In Section 8, the comparison is made with the H-inf controller.

2. BASICS OF CDM

Some notations used in CDM is briefly explained. The characteristic polynomial $P(s)$ is given in the following form.

$$P(s) = a_n s^n + \dots + a_1 s + a_0 = \sum_{i=0}^n a_i s^i \quad (1)$$

The stability index γ_i , the equivalent time constant τ , and the stability limit γ_i^* are defined as follows.

$$\gamma_i = a_i^2 / (a_{i+1} a_{i-1}), \quad i = 1 \sim n-1, \quad (2)$$

$$\tau = a_1 / a_0, \quad (3)$$

$$\gamma_i^* = 1 / \gamma_{i+1} + 1 / \gamma_{i-1}, \quad (4)$$

γ_n and γ_0 are defined as ∞ .

The equivalent time constant of the i -th order τ_i is defined as follows;

$$\tau_i = a_{i+1} / a_i, \quad i = 1 \sim n-1. \quad (5)$$

Then the following relations are derived.

$$\tau_i = \tau_{i-1} / \gamma_i = \tau / (\gamma_i \dots \gamma_2 \gamma_1), \quad (6a)$$

$$a_i = \tau_{i-1} \dots \tau_1 \tau a_0 = a_0 \tau^i / (\gamma_{i-1} \gamma_{i-2}^2 \dots \gamma_2^{i-2} \gamma_1^{i-1}). \quad (6b)$$

The sufficient condition for stability (Lipatov and Sokolov, 1978) (Manabe, 1999) is given as

$$\gamma_i > 1.12\gamma_i^* \text{ for all } i = 2 \sim n-2. \quad (7)$$

In CDM, the following stability indices are recommended. These values are improvement of Kessler (1960) standard form.

$$\gamma_{n-1} = \dots = \gamma_3 = \gamma_2 = 2, \quad \gamma_1 = 2.5. \quad (8a)$$

For more relaxed form, with very small sacrifice of stability,

$$\begin{aligned} \gamma_i &> 1.5\gamma_i^*, \quad i = n-2 \sim 3, \\ \gamma_{n-1} &= \gamma_2 = 2, \quad \gamma_1 = 2.5. \end{aligned} \quad (8b)$$

In these cases, the step response has no overshoot, and the settling time is about $2.5 \sim 3\tau$.

3. MATHEMATICAL MODEL AND PROBLEM STATEMENT

The problem selected is the longitudinal control of a modern fighter, shown in Fig. 1 (Chiang and Safonov, 1994) (Safonov et al., 1981) (Safonov and Chiang, 1988). This aircraft is trimmed at 25000 ft and 0.9 Mach. The linear model in state space expression is given as follows, where the MATLAB type expression is adopted, such that vector $[2 \ 4 \ 5]^T$ is expressed as $[2; 4; 5]$.

$$\begin{aligned} [\dot{\delta V}; \dot{\alpha}; \dot{q}; \dot{\theta}; \dot{\delta}_e; \dot{\delta}_c] &= A_g [\delta V; \alpha; q; \theta; \delta_e; \delta_c] + B_g [u_e; u_c], \\ [\alpha; \theta] &= C_g [\delta V; \alpha; q; \theta; \delta_e; \delta_c] + D_g [u_e; u_c], \end{aligned}$$

$$A_g = \begin{bmatrix} -0.022567 & -36.617 & -18.897 & -32.090 & 3.2509 & -0.76257 \\ 9.2572e-5 & -1.8997 & 0.98312 & -7.2562e-4 & -0.17080 & -0.49652e-3 \\ 0.012338 & 11.720 & -2.6316 & 8.7582e-4 & -31.604 & 22.396 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -30 & 0 \\ 0 & 0 & 0 & 0 & 0 & -30 \end{bmatrix},$$

$$B_g = [0 \ 0; 0 \ 0; 0 \ 0; 0 \ 0; 30 \ 0; 0 \ 30],$$

$$C_g = [0 \ 1 \ 0 \ 0 \ 0; 0 \ 0 \ 0 \ 1 \ 0 \ 0], \quad D_g = [0 \ 0; 0 \ 0]. \quad (9)$$

The state variables are velocity deviation (δV), angle of attack (α), attitude rate (q), attitude angle (θ), elevon angle (δ_e), and canard angle (δ_c). The output variables are α and θ . The control input variables are elevon actuator input (u_e) and canard actuator input (u_c).

By the use the of two control inputs, the non-conventional precision flight path control becomes possible. Vertical translation mode keeps θ while varying α . Pitch pointing mode keeps both α and θ . Direct lift mode keeps α while varying θ . The stated objective of the control is interpreted as making α and θ to follow the respective commands (α_r and θ_r). The more precise design specification is given in singular value specification as follows;

(1) Robustness Spec.: -40 dB/decade roll-off and at least -20 dB at 100 rad/sec.

(2) Performance Spec.: Minimize the sensitivity function as much as possible.

These specifications will be interpreted in the terms

of CDM in the later section.

In order to make CDM MIMO design, the plant has to be expressed in a right polynomial matrix fraction (PMF). When actuator dynamics are moved to controller, the control inputs become δ_e and δ_c . Also q is replaced by $s\theta$, and δV is eliminated from the equation. The left PMF is given as follows;

$$A_u(s)[\alpha; \theta] = B_u(s)[\delta_e; \delta_c], \quad (10)$$

$$A_u(s) = \begin{bmatrix} a_{u11} & a_{u12} \\ a_{u21} & a_{u22} \end{bmatrix}, \quad B_u(s) = \begin{bmatrix} b_{u11} & b_{u12} \\ b_{u21} & b_{u22} \end{bmatrix},$$

$$a_{u11} = s + 1.9876,$$

$$a_{u12} = -0.0075030s^2 - 1.0029s + 0.00073219,$$

$$a_{u21} = -11.72s + 0.18730,$$

$$a_{u22} = s^3 + 2.6542s^2 + 0.29166s + 0.39591,$$

$$b_{u11} = 0.066325, \quad b_{u12} = -0.17300,$$

$$b_{u21} = -31.604s - 0.67310,$$

$$b_{u22} = 22.396s + 0.49600.$$

In order to make design easier, fictitious inputs δ_e^* and δ_c^* are introduced, such that

$$B_u(s)[\delta_e; \delta_c] = B_p(s)[\delta_e^*; \delta_c^*], \quad (11)$$

$$B_p(s) = \begin{bmatrix} b_{p11} & 0 \\ 0 & b_{p22} \end{bmatrix},$$

$$b_{p11} = b_{u12}, \quad b_{p22} = b_{u21}.$$

Then the following relation is derived.

$$[\delta_e; \delta_c] = E_1 [\delta_e^*; \delta_c^*], \quad (12)$$

$$E_1 = B_u^{-1}(s)B_p(s) = \begin{bmatrix} 0.97298 & 1.3730 \\ 1.3730 & 0.52638 \end{bmatrix} + \Delta(s).$$

In this equation $\Delta(s)$ can be neglected, because it is very small. Thus the plant model for CDM design is obtained as follows:

$$A_u(s)[\alpha; \theta] = B_p(s)[\delta_e^*; \delta_c^*]. \quad (13)$$

In order to convert it to right PMF, new variables α_1 and θ_1 are introduced such that

$$[\alpha; \theta] = B_p(s)[\alpha_1; \theta_1]. \quad (14)$$

Then Eq. (13) becomes

$$A_p(s)[\alpha_1; \theta_1] = [\delta_e^*; \delta_c^*], \quad (15)$$

$$A_p(s) = B_p^{-1}(s)A_u(s)B_p(s) = [a_{p11} \ a_{p12}; a_{p21} \ a_{p22}],$$

$$a_{p11} = a_{u11}, \quad a_{p12} = a_{u12}(b_{p22}/b_{p11})$$

$$= -1.3706s^3 - 182.23s^2 - 3.7681s + 0.0028487,$$

$$a_{p21} = a_{u21}(b_{p11}/b_{p22}) \square -0.064156, \quad a_{p22} = a_{u22}.$$

Eqs. (14)(15) constitute right PMF for CDM design. Because the outputs of the designed controller are δ_e^* and δ_c^* , the following conversion is necessary to obtain actual control inputs u_e and u_c .

$$[u_e; u_c] = E_1 [(s/30+1)\delta_e^*; (s/30+1)\delta_c^*]. \quad (16)$$

Because $B_p(s)$ is diagonal, design becomes much simpler.

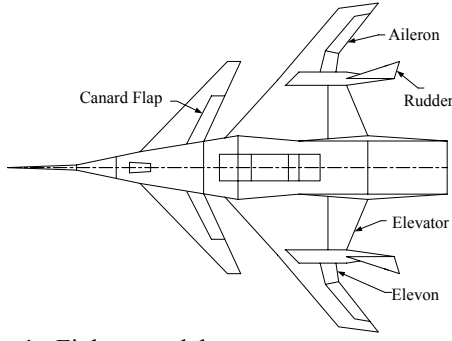


Fig. 1. Fighter model

4. DECOUPLING CONTROL DESIGN

The purpose of control is to make the outputs α and θ to follow the command α_r and θ_r . The specification given in terms of singular value can be interpreted as follows;

- (1) Each control channel should be independent and no interaction is expected.
- (2) Each channel should have the same characteristics.
- (3) The auxiliary sensitivity function of each channel should show -40 dB/decade roll-off and at least -20 dB at 100 rad/sec.

Usually the sensitivity function becomes larger when the interaction exists between two channels. Thus the minimization of sensitivity function makes the interaction the minimum. The singular value specification takes worse value between the two channels, and naturally each channel should show the same characteristics. In this situation, the two singular values take the same value and they are equal to the characteristics of each channel.

The controller equation is given as follows;

$$A_c(s)[\delta_c^*; \delta_e^*] = B_c(s)[\alpha_r - \alpha; \theta_r - \theta], \quad (17)$$

$$A_c(s) = A_c^*(s)A_c^{**}(s).$$

Because auxiliary sensitivity function $T(s)$ and sensitivity function $S(s)$ are of interest, so-called error system is adopted. In error system, reference numerator $B_a(s)$ is equal to feedback numerator $B_c(s)$. $A_c(s)$ is divided into two parts. $A_c^*(s)$ is a diagonal channel controller, and $A_c^{**}(s)$ is a decoupling controller, which makes $A_c^{**}(s)A_p(s)$ almost diagonal.

The closed loop response is given as follows;

$$[\alpha; \theta] = B_p(s)A^{-1}(s)B_c(s)[\alpha_r; \theta_r], \quad (18a)$$

$$A(s) = A_c^*(s)A_c^{**}(s)A_p(s) + B_c(s)B_p(s). \quad (18b)$$

$A_c^*(s)$, $B_p(s)$, and $B_c(s)$ are diagonal, and $A_c^{**}(s)A_p(s)$ is almost diagonal. Because $B_c(s)B_p(s)$ is very large and diagonal, $A(s)$ becomes practically diagonal. Thus the closed loop response is decoupled. Decoupling controller can be designed by

approximating $\text{adj}(A_p(s))$ at high order. The selected decoupling controller is as follows;

$$A_c^{**}(s) = \begin{bmatrix} s + 2.5642 & 1.3706s + 183.23 \\ 0.064156 & s + 1.9876 \end{bmatrix}. \quad (19)$$

Then

$$A_{cp}(s) = A_c^{**}(s)A_p(s) = [a_{cp11} \ a_{cp12}; a_{cp21} \ a_{cp22}], \quad (20)$$

$$a_{cp11} = s^2 + 4.5539s - 6.4798,$$

$$a_{cp12} = -3.3684s^2 + 43.985s + 72.55,$$

$$a_{cp21} = 0,$$

$$a_{cp22} = s^4 + 4.5539s^3 - 6.1882s^2$$

$$+ 0.73387s + 0.78709.$$

Thus

$$A(s) = A_c^*(s)A_{cp}(s) + B_c(s)B_p(s), \quad (21)$$

$$A_c^*(s) = [a_{c11}^* \ 0; 0 \ a_{c22}^*], \quad B_c(s) = [b_{c11} \ 0; 0 \ b_{c22}].$$

Design will be made on the basis that $A(s)$ is diagonal. Ordinary CDM design approach for SISO is applied.

5. FEEDBACK CONTROL DESIGN

From Eqs. (20)(21), the open loop transfer function for α control is given as follows;

$$G(s) = (b_{c11}b_{p11}) / a_{c11}^*a_{cp11}, \quad (22)$$

$$a_{cp11} = s^2 + 4.5539s - 6.4797, \quad b_{p11} = -0.17300,$$

$$a_{c11}^* = l_2s^2 + s, \quad b_{c11} = k_2s^2 + k_1s + k_0, \quad l_2 = 1/30.$$

Because the plant is the 2nd order and integral control is added, controller order must be 2. The actuator dynamics, $l_2 = 1/30$, is moved to controller transfer function. Design is made on the following basis.

$$\tau_2 = 0.045, \quad \gamma_2 = 4, \quad \gamma_1 = 2.5,$$

$$\tau = \gamma_2\gamma_1\tau_2 = 0.45. \quad (23)$$

The choice of $\gamma_2 = 4$ is to reduce the gain peak at the crossover frequency. The results are as follows;

$$k_2 = -122.88, \quad k_1 = -859.4, \quad k_0 = -1828.6,$$

$$l_2 = 1/30, \quad \gamma_i = [1.5549 \ 4 \ 2.5], \quad \tau = 0.45,$$

$$\omega_c = k_2(-0.17300) = 21.257. \quad (24)$$

The crossover frequency is denoted as ω_c . The selection of $\tau_2 = 0.045$ is to make ω_c around 20 rad/sec. The coefficient diagram is shown in Fig. 2a. The design can be carried out by constructing the coefficient diagram by hand, or by special CDM CAD (MSS, 2000).

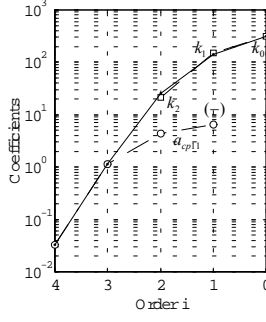
From Eqs. (20)(21), the open loop transfer function for θ control is given as follows;

$$G(s) = (b_{c22}b_{p22}) / a_{c22}^*a_{cp22}, \quad (25)$$

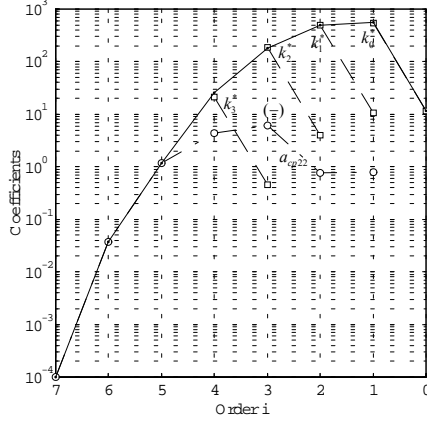
$$a_{cp22} = s^4 + 4.5539s^3 - 6.1882s^2$$

$$+ 0.73387s + 0.78709,$$

$$b_{p22} = -31.604s - 0.67310,$$



a. α control



b. θ control

Fig. 2. Coefficient diagram,

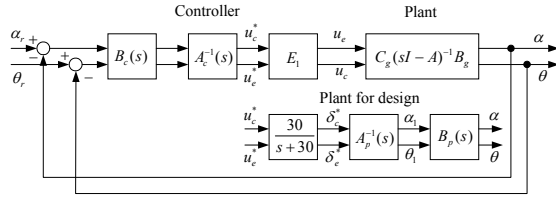


Fig. 3. Block diagram

$$a_{c22}^* = (l_2^*s + 1)(l_3^*s^2 + s),$$

$$b_{c22}^* = k_3^*s^3 + k_1^*s^2 + k_0^*s + k_0^*, \quad l_2^* = 1/30.$$

Because the plant is the 4th order and integral control is added, controller order must be 4. But because a_0 coefficient of characteristic polynomial is to be accepted as it is, controller order becomes 3. The actuator dynamics, $l_2^* = 1/30$, is moved to controller transfer function. Also $l_3^* = 0.003$ is pre-assigned Design is made on the following basis.

$$\tau_4 = 0.045, \quad \gamma_4 = 3.2, \quad \gamma_3 = \gamma_2 = 2.5,$$

$$\tau_1 = \gamma_4 \gamma_3 \gamma_2 \tau_4 = 0.9. \quad (26)$$

The results are as follows;

$$k_3^* = -0.68207, \quad k_2^* = -5.8683, \quad k_1^* = -15.651,$$

$$k_0^* = -17.197, \quad l_2^* = 1/30, \quad l_3^* = 0.003,$$

$$\gamma_i = [11.619 \quad 1.4248 \quad 3.2 \quad 2.5 \quad 2.5 \quad 53.257],$$

$$\tau_1 = 0.9, \quad \tau = 47.931,$$

$$\omega_c = k_3^*(-31.604) = 21.556. \quad (27)$$

The selection of $l_3^* = 0.003$ is for pseudo-

differentiation, and must be sufficiently small compared with $l_2^* = 1/30$. The coefficient diagram is shown in Fig. 2b. Due to the small zero in the plant, the coefficient of the 0-th order cannot be designed and has to be accepted as it is.

6. FREQUENCY RESPONSE

The frequency response and singular value plot of the closed-loop system will be sought. For the plant model, the original state-space model of Eq. (9) is used. The actuator dynamics in the designed controller are moved to the plant. The controller is given as follows;

$$A_c(s) [u_c^*; u_e^*] = B_c(s) [\alpha_r - \alpha; \theta_r - \theta], \quad (28a)$$

$$[u_e; u_c] = E_1 [u_c^*; u_e^*], \quad (28b)$$

$$E_1 = \begin{bmatrix} 0.97298 & 1.3730 \\ 1.3730 & 0.52638 \end{bmatrix}, \quad A_c(s) = A_c^*(s)A_c^{**}(s),$$

$$A_c^{**}(s) = \begin{bmatrix} s + 2.5642 & 1.3706s + 183.23 \\ 0.064156 & s + 1.9876 \end{bmatrix},$$

$$A_c^*(s) = [a_{c11}^* \quad 0; 0 \quad a_{c22}^*], \quad B_c(s) = [b_{c11}^* \quad 0; 0 \quad b_{c22}^*],$$

$$a_{c11}^* = s, \quad a_{c22}^* = l_3^*s^2 + s,$$

$$b_{c11}^* = k_2s^2 + k_1s + k_0, \quad b_{c22}^* = k_3^*s^3 + k_2^*s^2 + k_1^*s + k_0^*,$$

$$k_2 = -122.88, \quad k_1 = -859.4, \quad k_0 = -1826.6,$$

$$k_3^* = -0.68207, \quad k_2^* = -5.8683, \quad k_1^* = -15.651,$$

$$k_0^* = -17.197, \quad l_3^* = 0.003.$$

This is the 5th order controller. The above controller model expressed in left PFD is converted to state-space model by Poly-x (Kwakernaak and Sebek, 2000), and then combined with state-space model of the plant by MATLAB. The block diagram is shown in Fig. 3.

The sensitivity function $S(s)$ and auxiliary sensitivity function $T(s)$ are defined as follows;

$$[\alpha; \theta] = T(s)[\alpha_r; \theta_r], \quad (29a)$$

$$[\alpha_r - \alpha; \theta_r - \theta] = S(s)[\alpha_r; \theta_r], \quad (29b)$$

$$T(s) = [T_{11} \quad T_{12}; T_{21} \quad T_{22}],$$

$$S(s) = [S_{11} \quad S_{12}; S_{21} \quad S_{22}].$$

Naturally, the following relations hold.

$$T_{11} + S_{11} = T_{22} + S_{22} = 1,$$

$$T_{12} + S_{12} = T_{21} + S_{21} = 0. \quad (30)$$

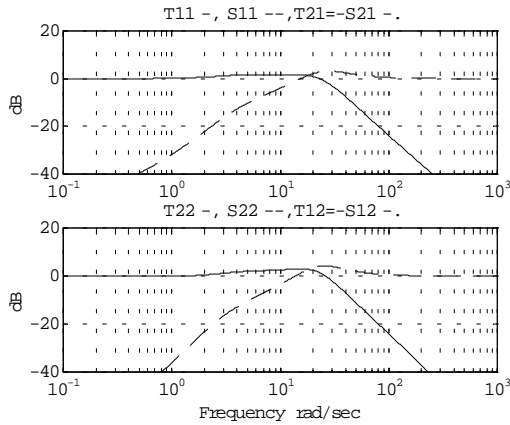
The frequency responses are shown in Fig. 4a. This shows that the cross-coupling terms are very small and invisible on the figures. The singular value plots are shown in Fig. 4b. They are almost identical with the frequency response. The achieved gamma value for the 8-th order H-inf controller in the Robust Control Toolbox is 16.8. The corresponding gamma value for this CDM 5th order controller is about 13 as read from Fig. 4b.

As a comparison, the results of a 3rd order controller without decoupling control are shown in Fig. 5

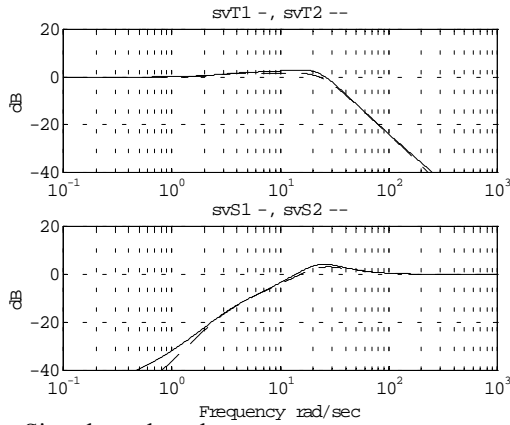
(Manabe, 2002a). The controller consists of one PI and one PID, and the parameters are as follows;

$$\begin{aligned} A_c^{**}(s) &= I, \\ k_2 &= 0, \quad k_1 = -86.705, \quad k_0 = -391.11, \\ k_3^* &= 0, \quad k_2^* = -0.47462, \quad k_1^* = -2.2315, \\ k_0^* &= -3.5669, \quad l_3^* = 0.003. \end{aligned} \quad (31)$$

The crossover frequency ω_c is 15 rad/sec. The gamma value is about 7 as read from Fig. 5b due to large interaction of T_{12} .



a. Sensitivity and auxiliary sensitivity function



b. Singular value plot

Fig. 4. CDM 5th order controller with decoupling control

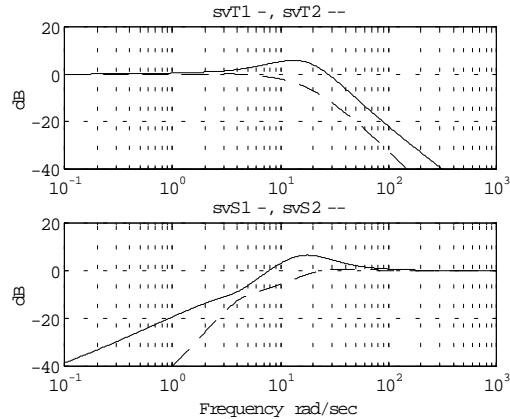


Fig. 5. CDM 3rd order controller without decoupling control, singular value plot

7. SIMULATION

Simulation is performed with the designed controller Eqs. (28a, b) and the exact fighter model Eq. (9). Two cases are shown. The first case, Fig. 6, is for α_r step command, and the second case, Fig. 7, is for θ_r step command. In both cases, the outputs follow the reference commands. The interaction is very small.

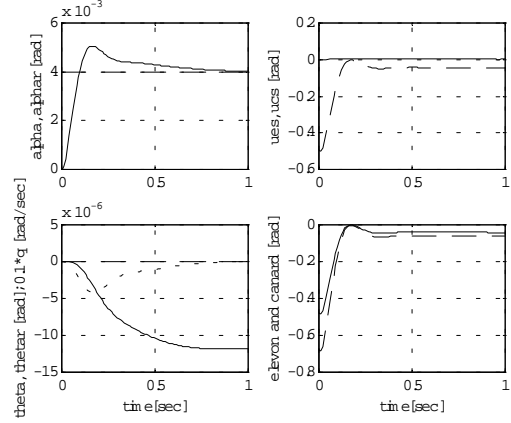


Fig. 6. α_r step command response

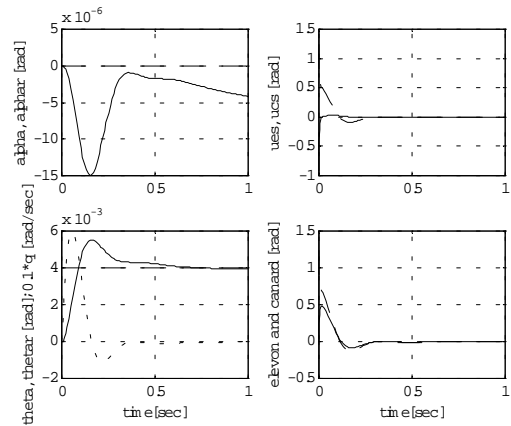


Fig. 7. θ_r step command response

8. COMPARISON WITH H-INF CONTROLLER

The controller designed in MATLAB Robust Control Toolbox is the 8th order. The frequency responses are shown in Fig. 8a, b. Both channels are almost decoupled. The gamma value is stated as 16.8.

The pole-zero analysis will be made in a manner as suggested by Kwakernaak (2002a, b). The plant has 6 poles and 1 zero.

Poles: $-0.25779, 0.68898 \pm j0.24880, -5.6757, -30, -30$. Zeros: -0.0020981 .

The H-inf controller has 8 poles and 6 zeros. Thus auxiliary sensitivity function $T(s)$ has 14 poles and 7 zeros, of which 5 poles and zeros are cancelled out, and remaining 9 poles and 2 zeros are effective.

Cancelled poles and zeros: $-0.020981, -0.25779, -5.6757, -30, -30$.

Poles: $-0.68980 \pm j0.24880, -22.705 \pm j18.444, -23.834 \pm j20.692, -95.031, -408.96, -2000$.

Zeros: $-0.60064 \pm j0.32068$.

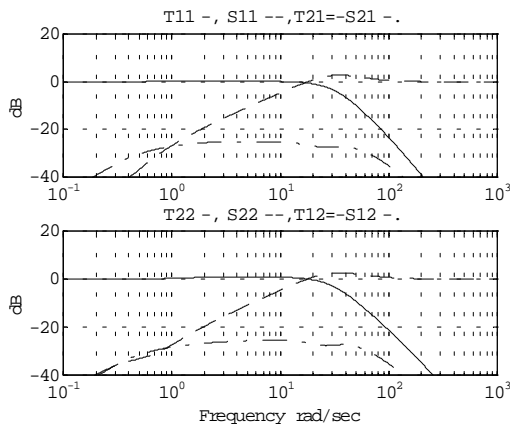
The CDM 5th order controller has 5 poles and 5 zeros. Thus $T(s)$ has 11 poles and 6 zeros.

Poles: -0.020902 , $-2.2393 \pm j1.4192$,
 $-3.3734 \pm j2.3409$, -4.4581 , $-11.758 \pm j19.484$,
 $-13.904 \pm j19.243$, -335.41 .

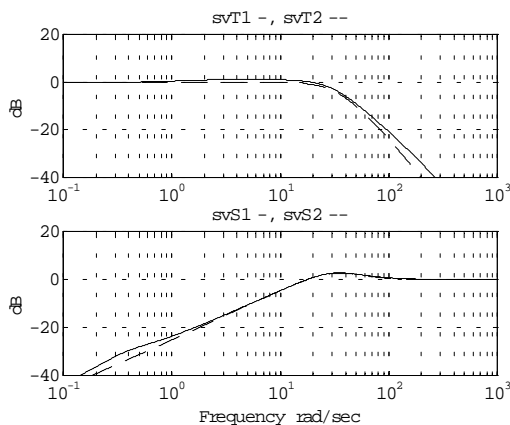
Zeros: -0.020981 , $-1.7787 \pm j1.3539$,
 $-3.4969 \pm j1.6237$, -5.0469 .

In H-inf controller, pole-zero cancel of actuator dynamics (-30, -30) is made. Such cancellation is unacceptable in usual design, because the effort of extending the frequency band beyond actuator dynamics tends to induce the problem of un-modeled dynamics.

In CDM 5th order controller, the actuator dynamics is not compensated, and the bandwidth is narrower. The gamma value is smaller (about 13), but attenuation at 100 rad/sec is -25 dB, much lower than specification.



a. Sensitivity and auxiliary sensitivity function



b. Singular value plot

Fig. 8 H-inf 8th Order controller

9. CONCLUSION

The major results of this paper are as follows:

(1) A controller is designed for the longitudinal control of a modern fighter with elevon and

canard by CDM.

- (2) The designed controller is a 5th order controller composed of one PID and one PIDA with decoupling capability. It achieves about 80% of gamma achieved by the H-inf 8-th order controller, but with better attenuation capability.
- (3) The 8-th order controller designed by H-inf contains pole-zero cancellation of actuator dynamics, which is usually not recommended in practical design
- (4) MIMO design by CDM is still at the developing stage. Further studies are keenly needed.

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