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Chapter 1

CHAELIE Aircraft

1.1 Aircraft Data

1.1.1 General Parameters

Wing area (m^2)	510	
Aspect ratio	7.0	
Chord, \bar{c} (m)	8.3	
Total related thrust (kN)	900	
C.G.	0.25 \bar{c}	
Pilot's location (m) (relative to e.g.)		
I_{X_p}	26.2	
I_{Z_p}	-3.05	
Weight (Kg)	Approach 250000	All other Flight Conditions 290000
Inertias ($Kg\ m^2$)		
I_{xx}	18.8E6	24.6E6
I_{yy}	41.35E6	45E6
I_{zz}	58E6	67.5E6
I_{xz}	1.2E6	1.32E6

1.1.2 Flight Conditions Parameters

Parameter	Flight Condition			
	1	2	3	4
Height (m)	S.L.	6100	6100	12200
Mach No	0.100	0.5	0.8	0.8
U_0 (m/s)	67	158	250	250
\bar{q} (Nm ²)	2810	8667	24420	9911
α_0 (degree)	8.5	6.8	0	4.6
γ_0 (degree)	0	0	0	0

1.1.3 Longitudinal Stability Derivatives

Stability Derivative	Flight Condition			
	1	2	3	4
X_u	-0.021	0.003	-0.0002	0.0002
X_w	0.122	0.078	0.026	0.039
X_{δ_r}	0.292	0.616	0.0	0.44
X_{δ_h}	3.88E-6	3.434E-6	3.434E-6	3.434E-6
Z_u	-0.2	-0.07	-0.09	-0.07
Z_w	-0.512	-0.433	-0.624	-0.317
Z_q	-1.9	-1.95	-3.04	-1.57
Z_{δ_r}	-1.96	-5.15	-8.05	-5.46
Z_{δ_h}	-1.69E-7	-1.5E-7	-1.5E-7	-1.5E-7
M_n	0.000036	0.00008	-0.00007	0.00006
M_w	-0.006	-0.006	-0.005	-0.003
$M_{\dot{w}}$	-0.0008	-0.0004	-0.0007	-0.0004
M_q	-0.357	-0.421	-0.668	-0.339
M_{δ_r}	-0.378	-1.09	-2.08	-1.16
M_{δ_h}	0.7E-7	0.67E-7	0.67E-7	0.67E-7

1.2 Equation of Motion in Longitudinal Mode

$$x = A x + B u, \quad A = A_1 \ A_2, \quad B = A_1 \ B, \quad y = C x, \quad u = \Delta \delta_e$$

$$A_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{1-Z_w} & 0 & 0 \\ 0 & \frac{M\dot{\omega}}{1-Z_w} & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad A_2 = \begin{bmatrix} X_u & X_w & 0 & -g \cos\theta_0 \\ Z_u & Z_w & U_0 + Z_q & -g \sin\theta_0 \\ M_u & M_w & M_q & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} X_{\delta e} & X_{\delta T} \\ Z_{\delta e} & Z_{\delta T} \\ M_{\delta e} & M_{\delta T} \\ 0 & 0 \end{bmatrix}, \quad x = \begin{bmatrix} \Delta u \\ \Delta w \\ \Delta q \\ \Delta \theta \end{bmatrix}$$

1.2.1 Flight Condition 1

$$A = \begin{bmatrix} -0.021 & 0.122 & 0 & -9.7022 \\ -0.2 & -0.512 & 65.1 & -1.45 \\ 1.96 & -0.0056 & -0.4091 & 0.0012 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0.292 & 3.88 \\ -1.96 & -1.69 \\ -0.3764 & 7.0135 \\ 0 & 0 \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

1.2.2 Flight Condition 2

$$A = \begin{bmatrix} 0.003 & 0.078 & 0 & -9.741 \\ -0.07 & -0.433 & 156.05 & -1.1615 \\ 1.08 & -0.0058 & -0.4834 & 4.6462 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0.616 & 3.434 \\ -5.15 & -1.57 \\ -1.0879 & 6.7063 \\ 0 & 0 \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

1.2.3 Flight Condition 3

$$A = \begin{bmatrix} -2 & 0.026 & 0 & -9.81 \\ -0.09 & -0.624 & 246.96 & 0 \\ -7 & -0.0046 & -0.8409 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 3.434 \\ -8.05 & -1.5 \\ -2.0744 & 6.7105 \\ 0 & 0 \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

1.2.4 Flight Condition 4

$$A = \begin{bmatrix} 2 & 0.039 & 0 & -9.7784 \\ -0.07 & -0.317 & 248.43 & -0.7868 \\ 8.8 & -0.0029 & -0.4384 & 3.147 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0.44 & 3.434 \\ -5.46 & -1.57 \\ -1.1578 & 6.7063 \\ 0 & 0 \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

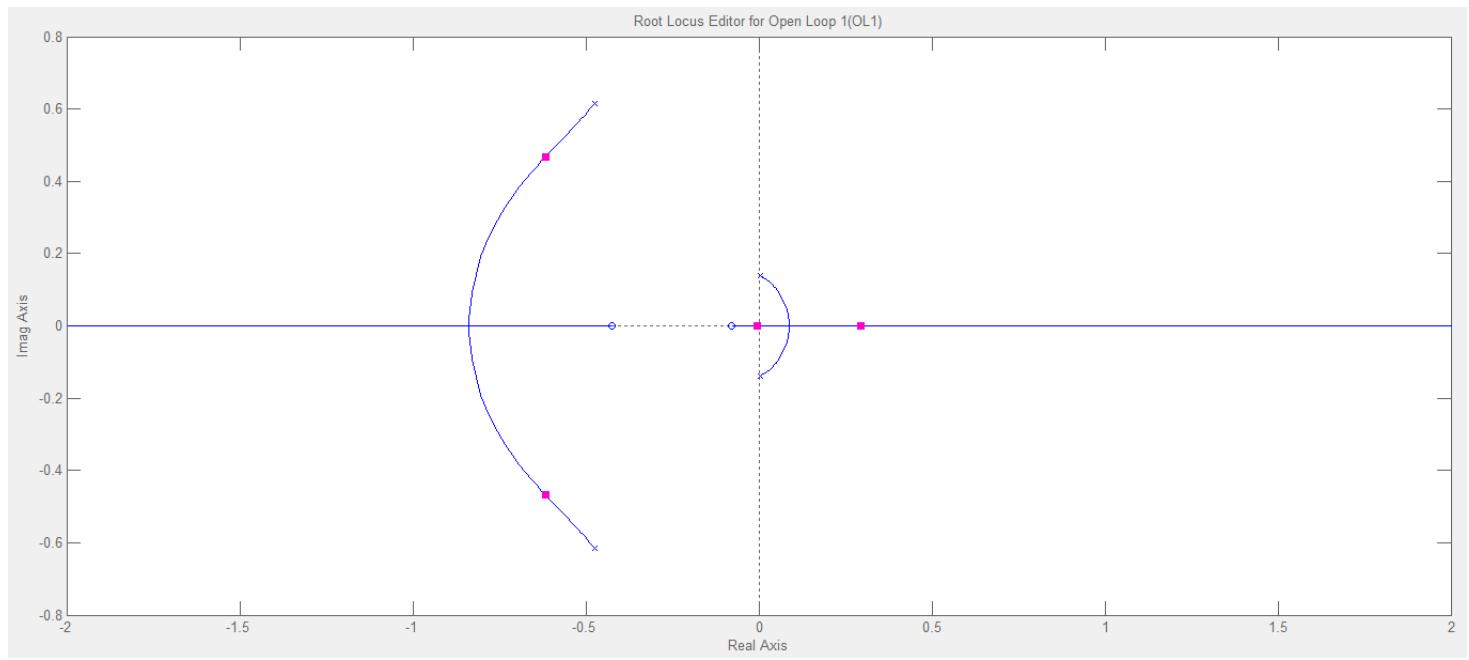
1.3 Transfer Function of $\frac{\theta}{\delta_e}$ in S and Z Domains

Flight Condition	S-Domain	Z-Domain	Sampling Time
1	$G(s) \frac{-0.3764s^2 - 0.1896s - 0.01269}{s^4 + 0.9421s^3 + 0.616s^2 + 0.01364s + 0.01165}$	$G(z) = \frac{-0.5646z^3 + 0.3215z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$T_s = 2.1$
2	$G(s) \frac{-1.088s^2 - 0.4377s - 0.00438}{s^4 + 0.9134s^3 + 1.121s^2 - 0.007947s + 0.004457}$	$G(z) = \frac{-1.378z^3 + 1.153z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$T_s = 2.16$
3	$G(s) \frac{-2.074s^2 - 1.258s - 0.005104}{s^4 + 1.465s^3 + 1.654s^2 + 0.002274s + 0.003986}$	$G(z) = \frac{-1.176z^3 + 0.9539z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$T_s = 1.36$
4	$G(s) \frac{-1.158s^2 - 0.3511s - 0.003009}{s^4 + 0.7552s^3 + 0.855s^2 - 0.001326s + 0.002242}$	$G(z) = \frac{-2.023z^3 + 1.822z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$T_s = 2.63$

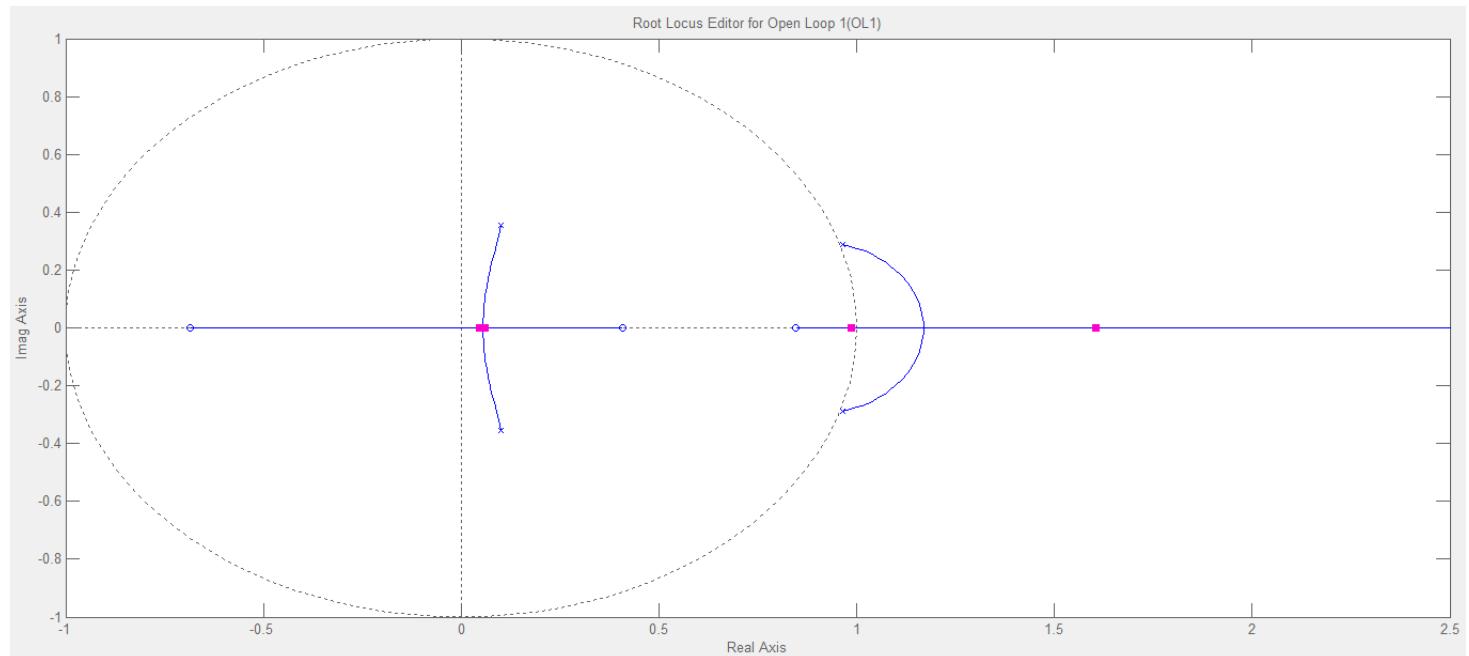
1.4 Root Locus

1.4.1 Flight Condition 1

S-Domain

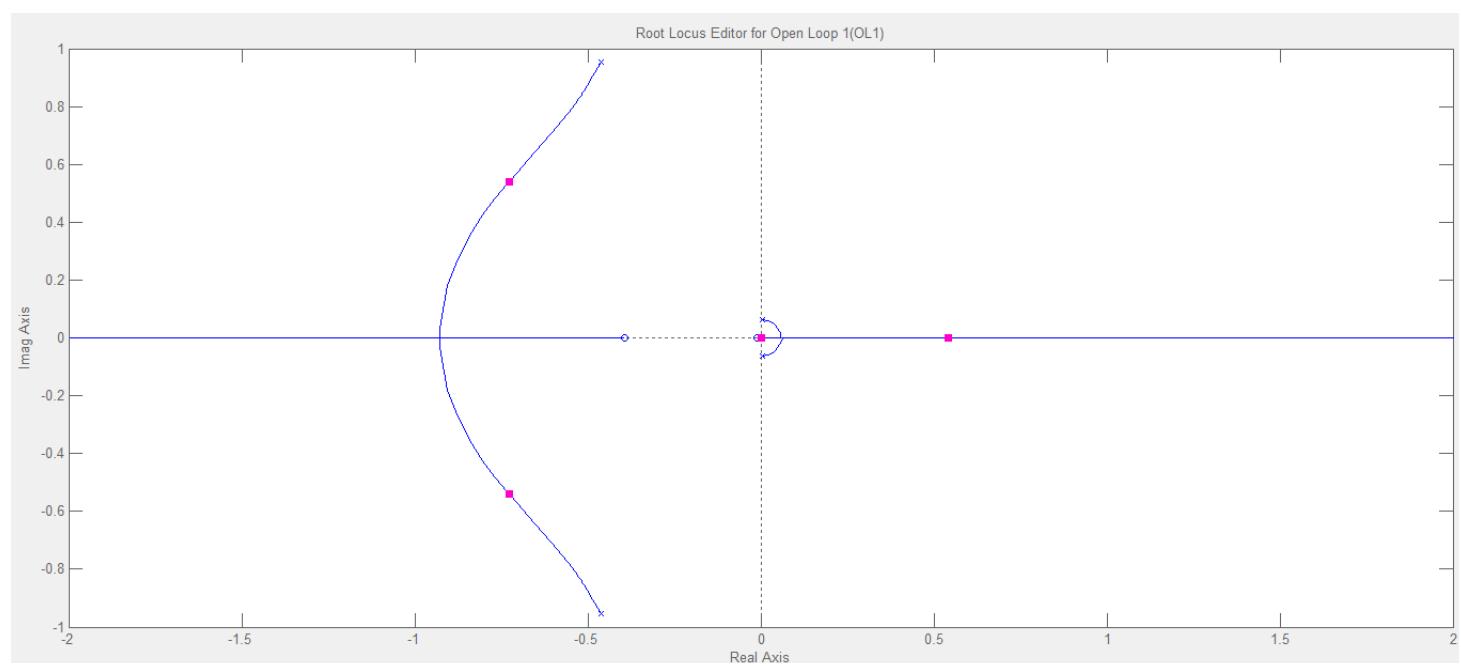


Z-Domain

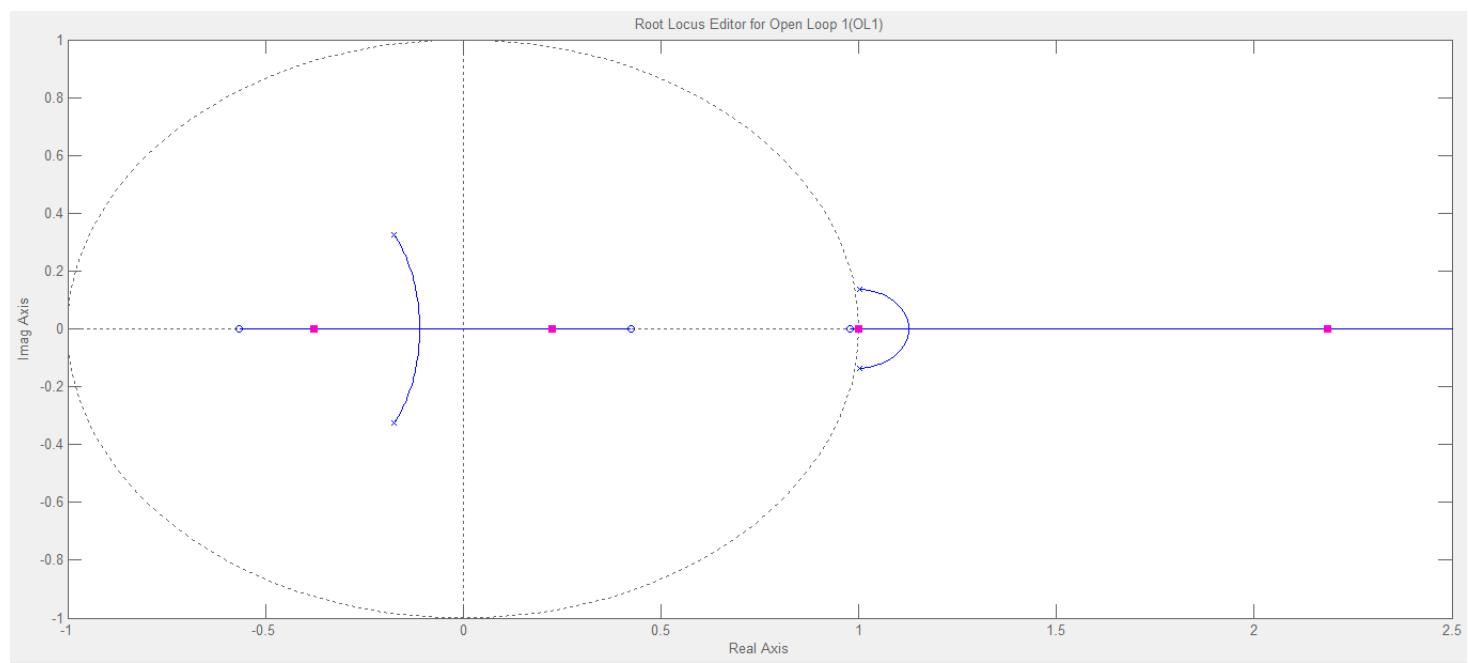


1.4.2 Flight Condition 2

S-Domain

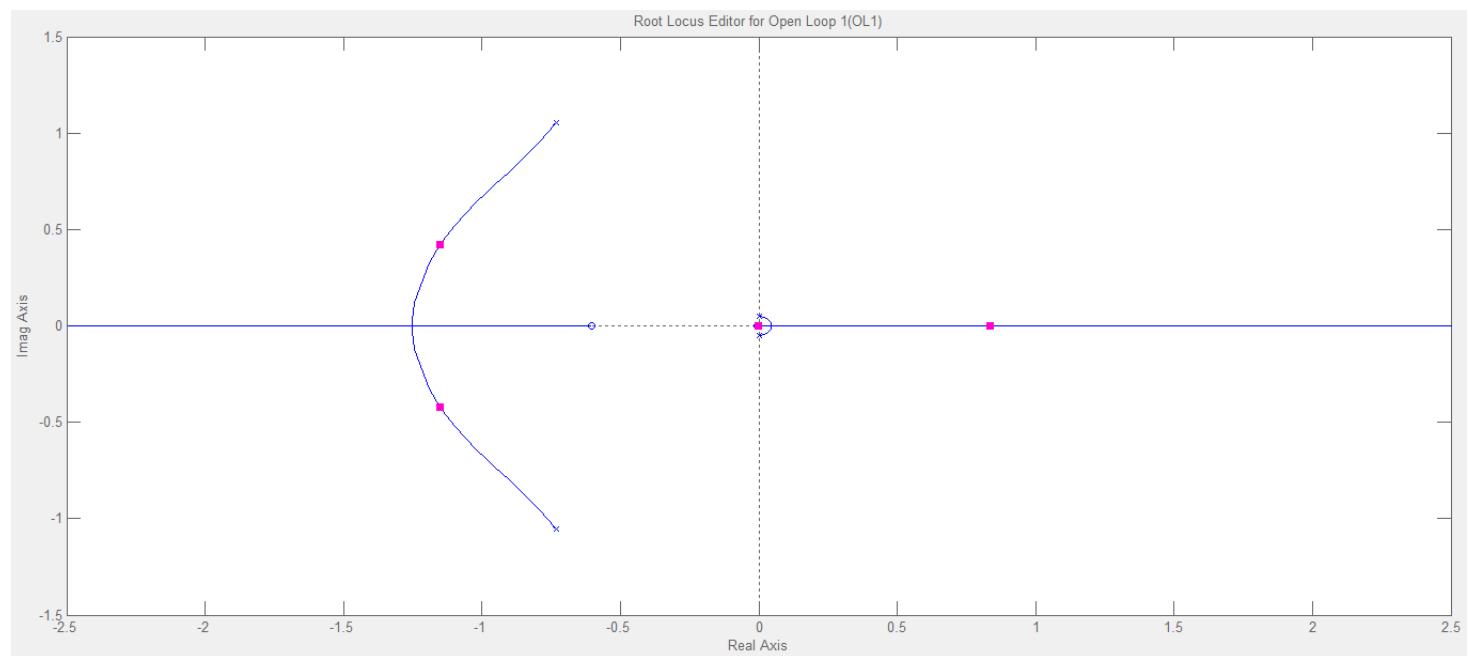


Z-Domain

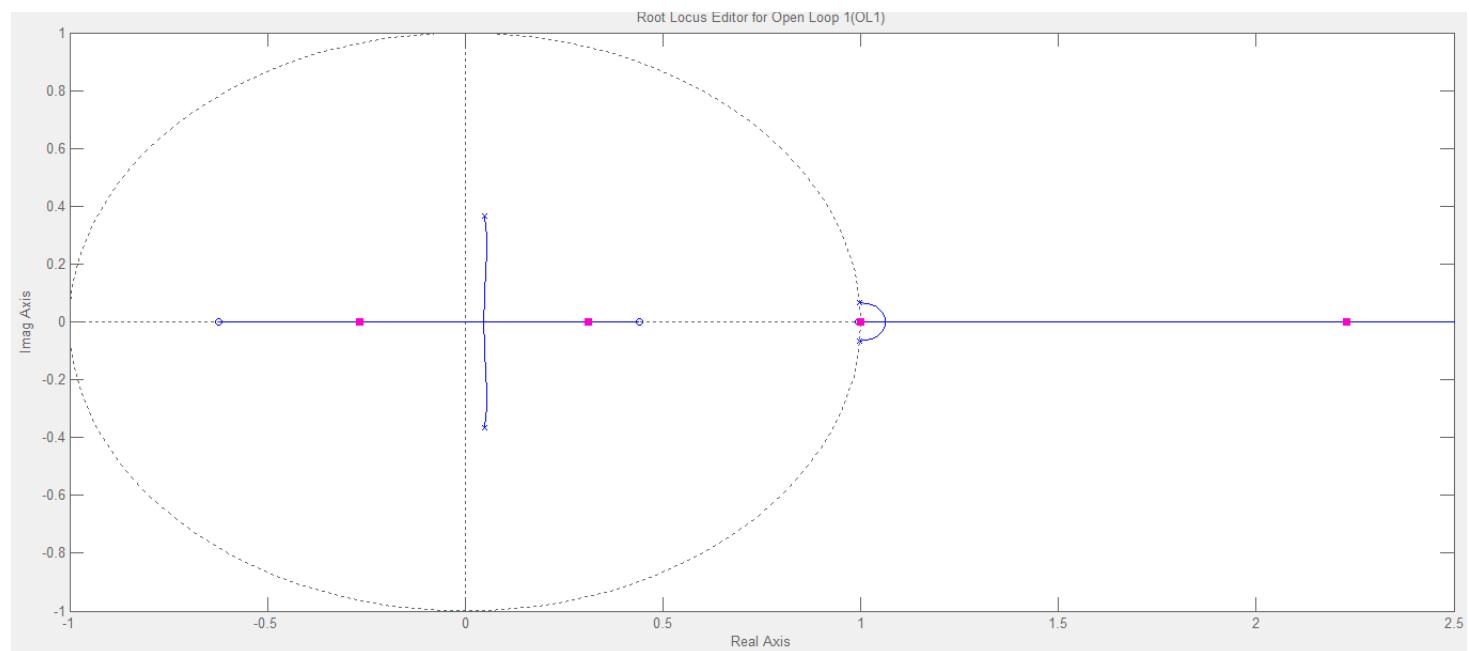


1.4.3 Flight Condition 3

S-Domain

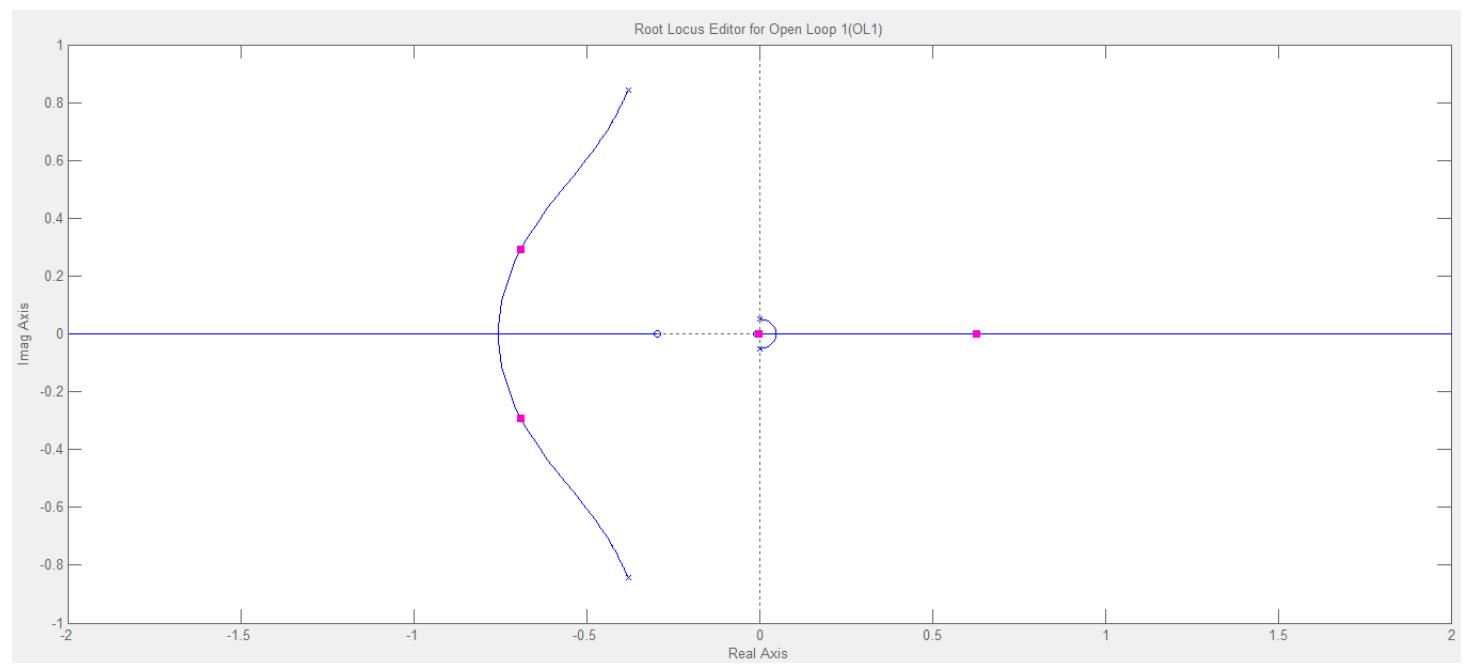


Z-Domain

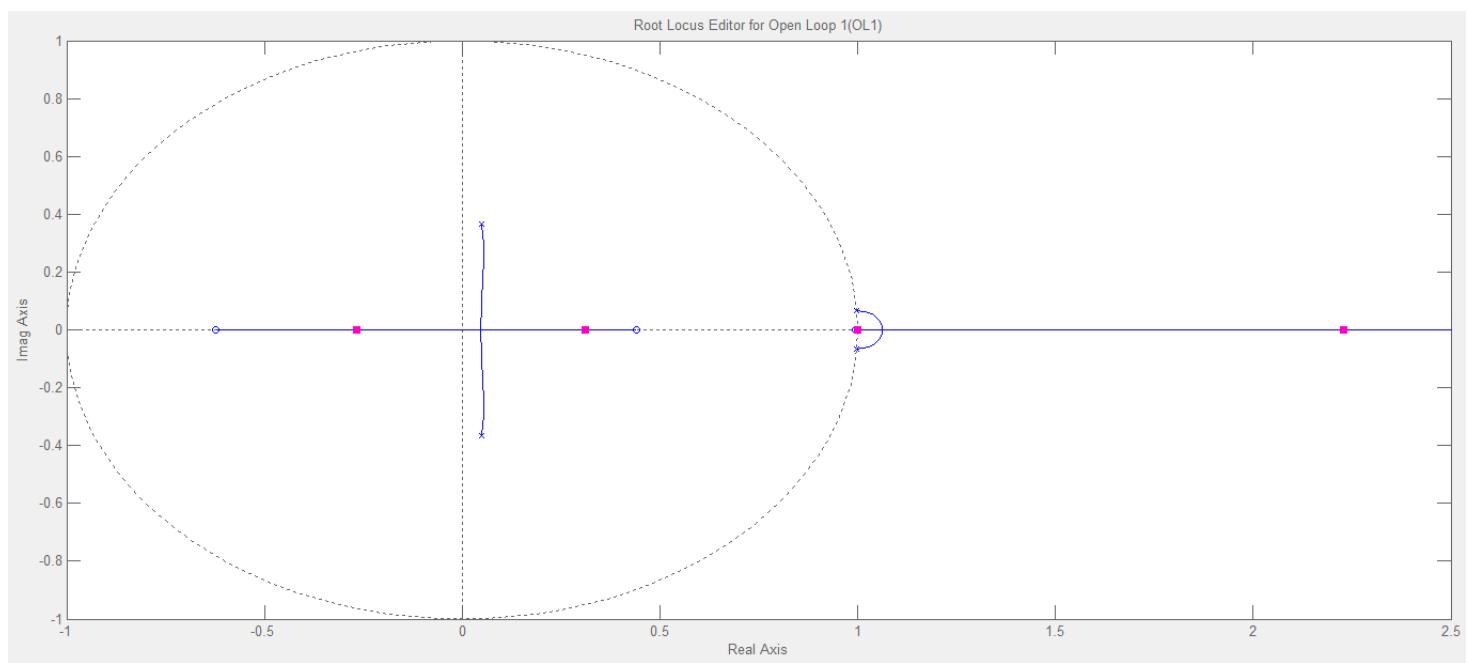


1.4.4 Flight Condition 4

S-Domain



Z-Domain



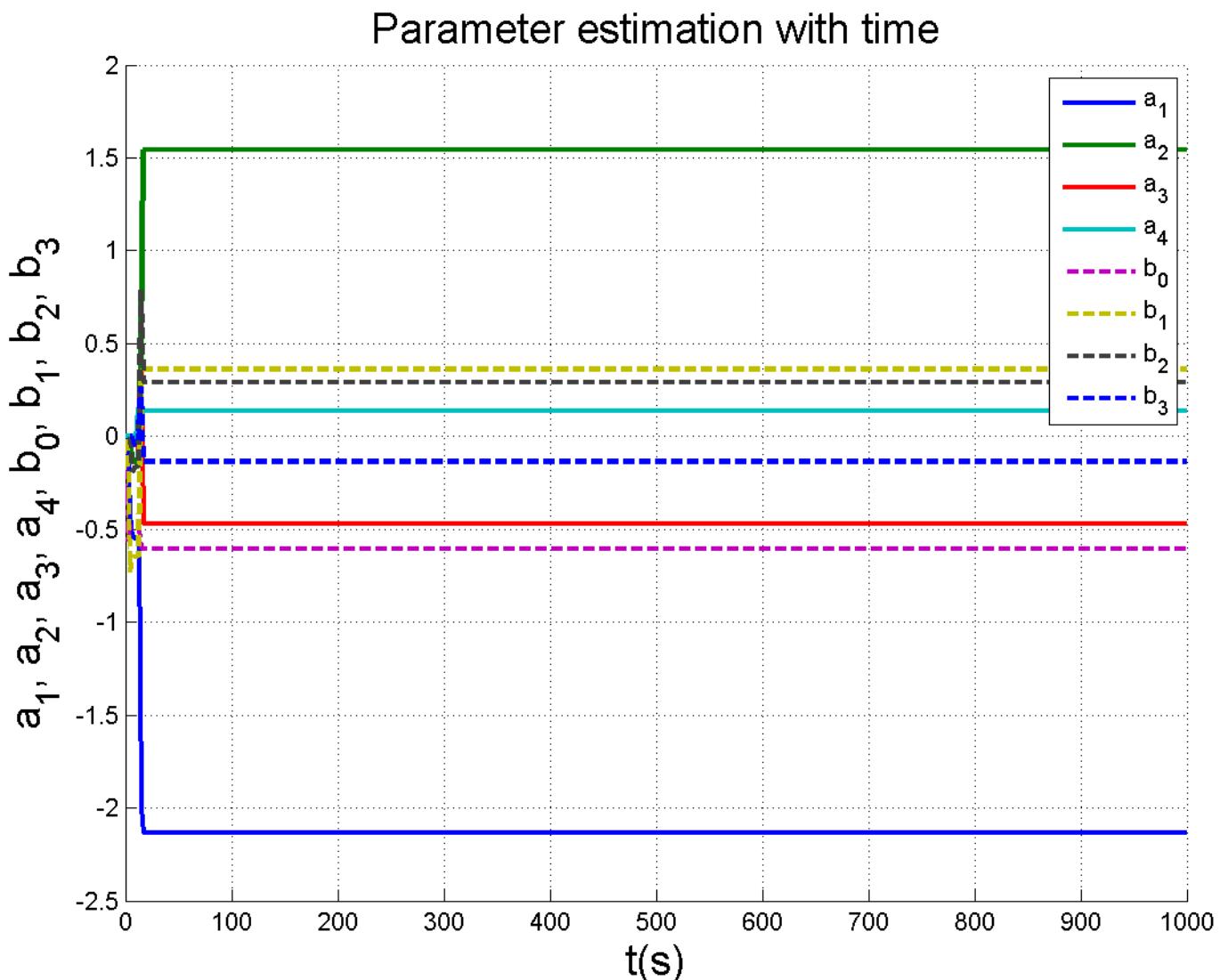
1.5 Parameter Estimation

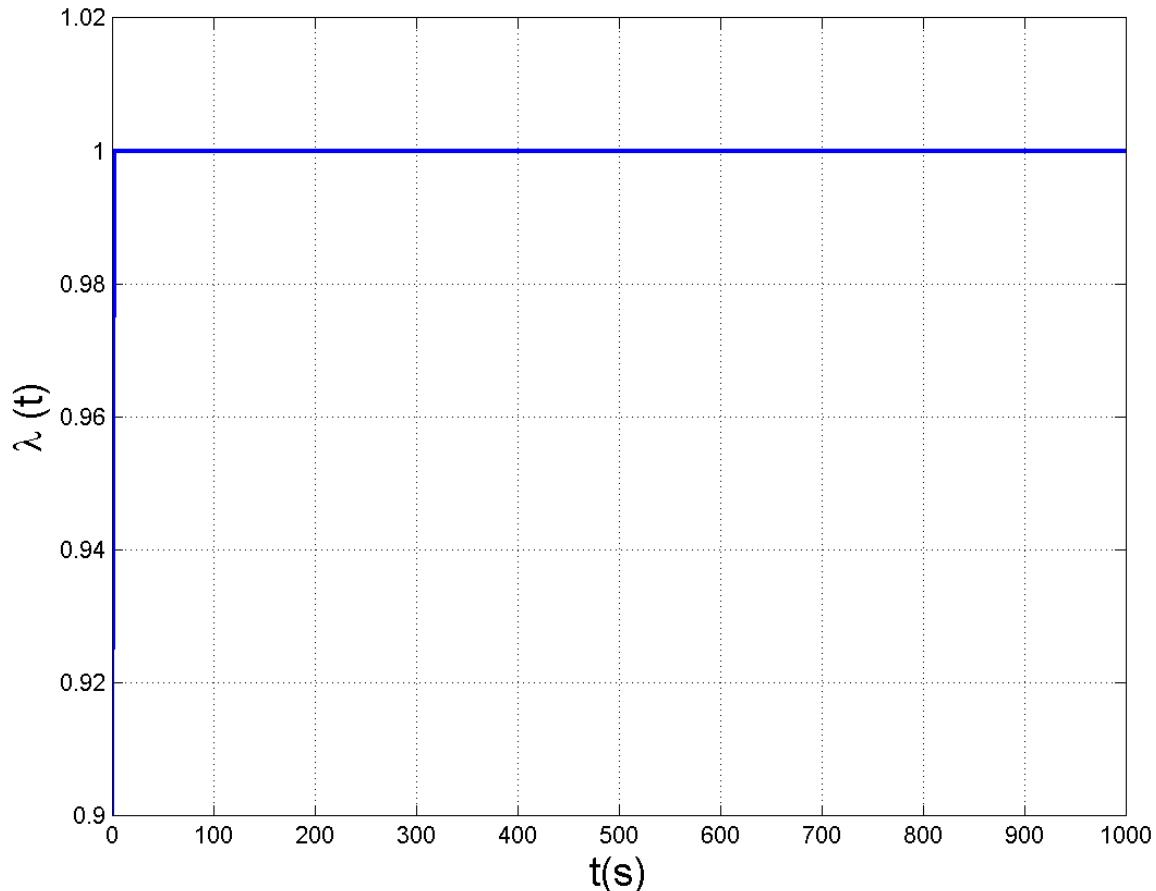
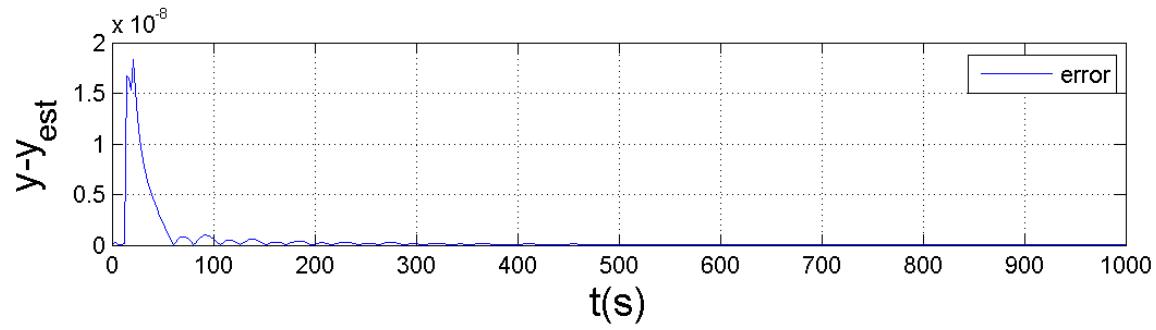
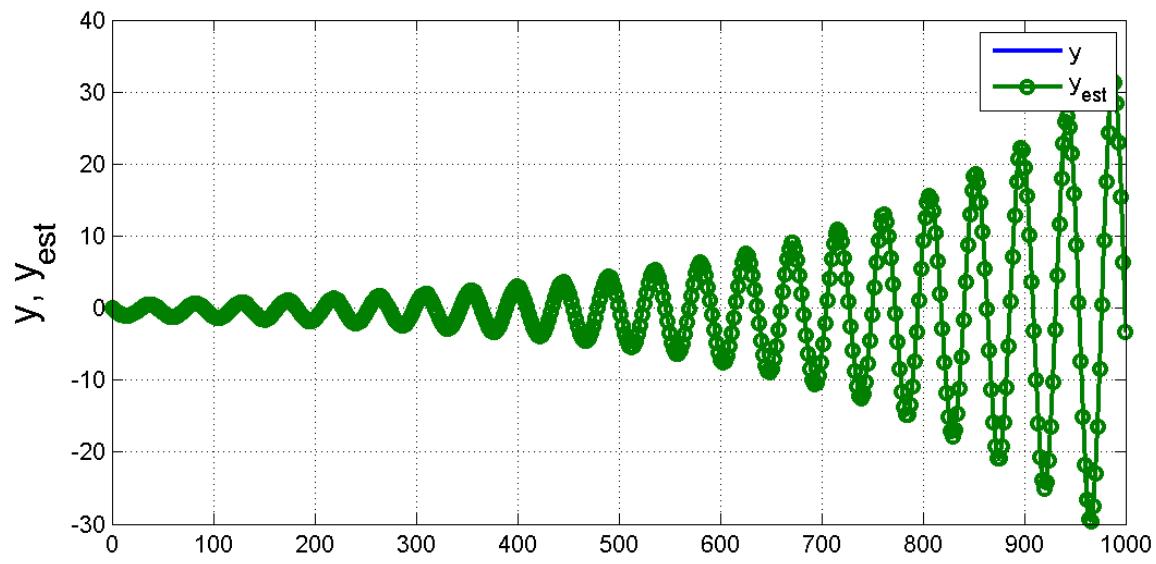
I use Recursive Least Square with Time Varying Forgetting Factor method as follow,

$$\begin{aligned}
 K(t) &= P(t-1)\phi(\lambda(t-1) + \phi'(t)P(t-1)\phi(t))^{-1} \\
 \epsilon(t) &= y(t) - \phi'(t)\theta(t-1) \\
 \theta(t) &= \theta(t-1) + K(t)\epsilon(t) \\
 P(t) &= (\lambda(t-1) - K(t)\phi')P(t-1) \\
 \lambda(t) &= 1 - \frac{1 - \phi'(t)K(t)\epsilon(t)^2}{\sigma^2(\epsilon)\mu(\epsilon)}
 \end{aligned}$$

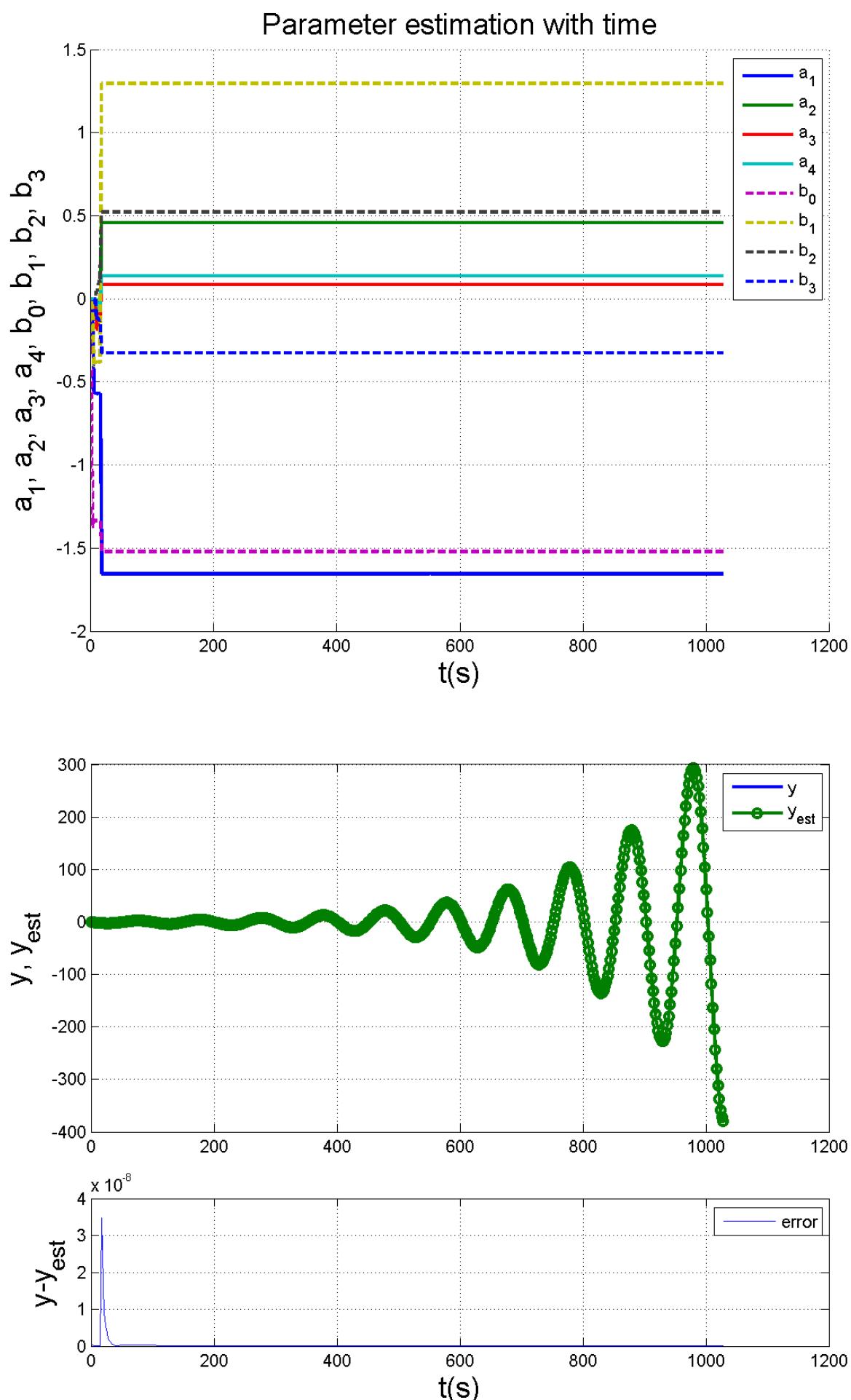
I use step input $u(s) = \frac{0.3}{s}$ for estimation

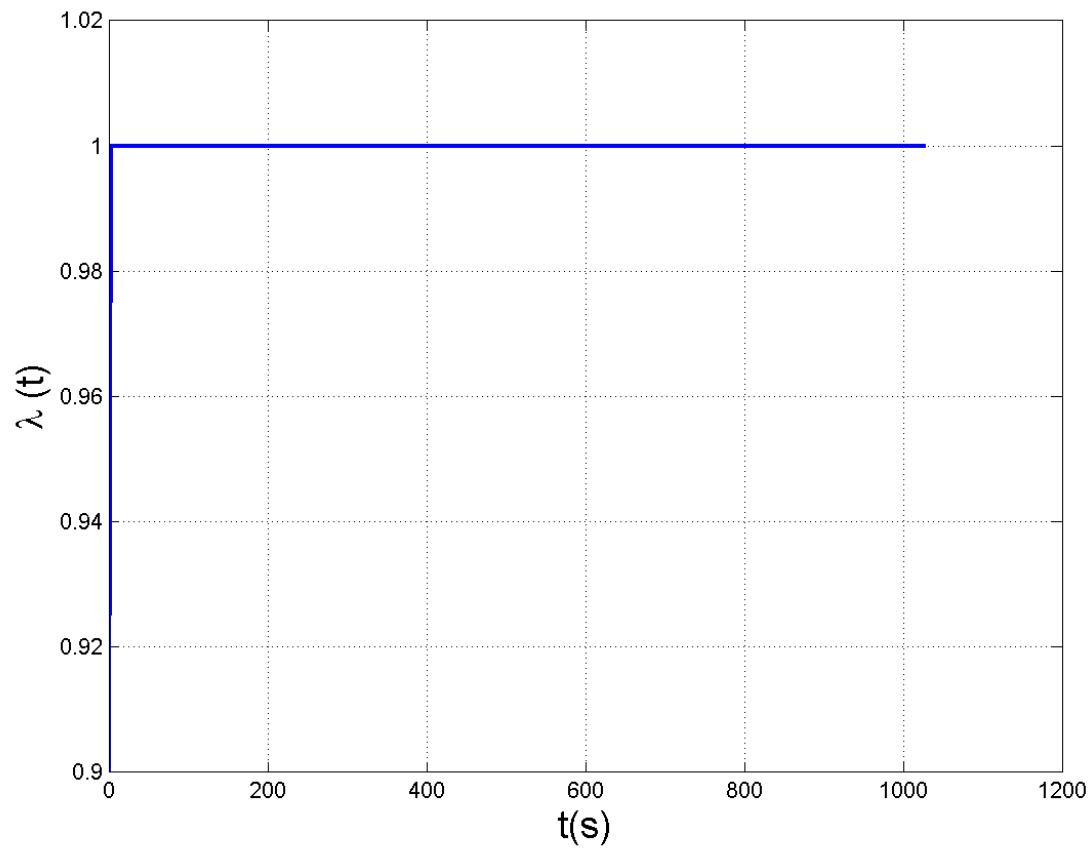
1.5.1 Flight Condition 1



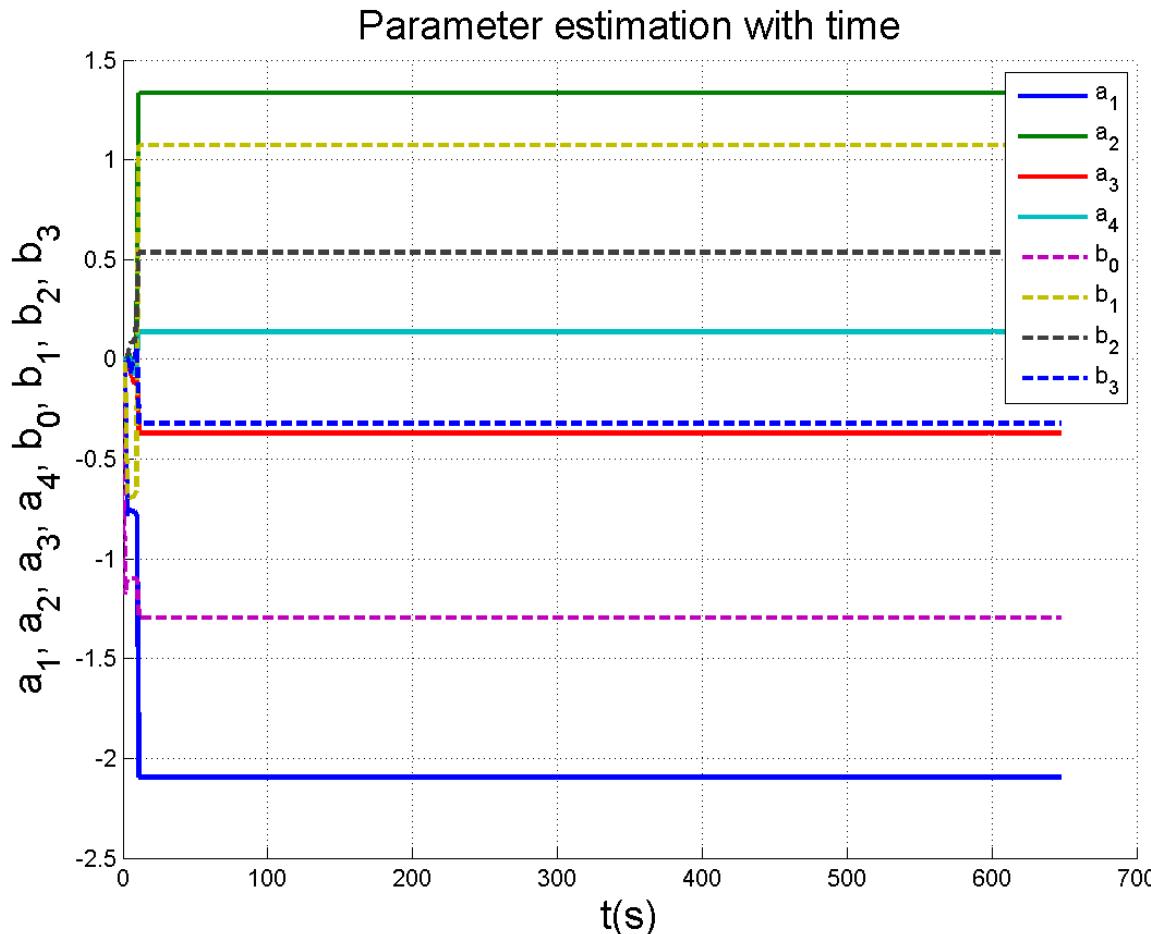


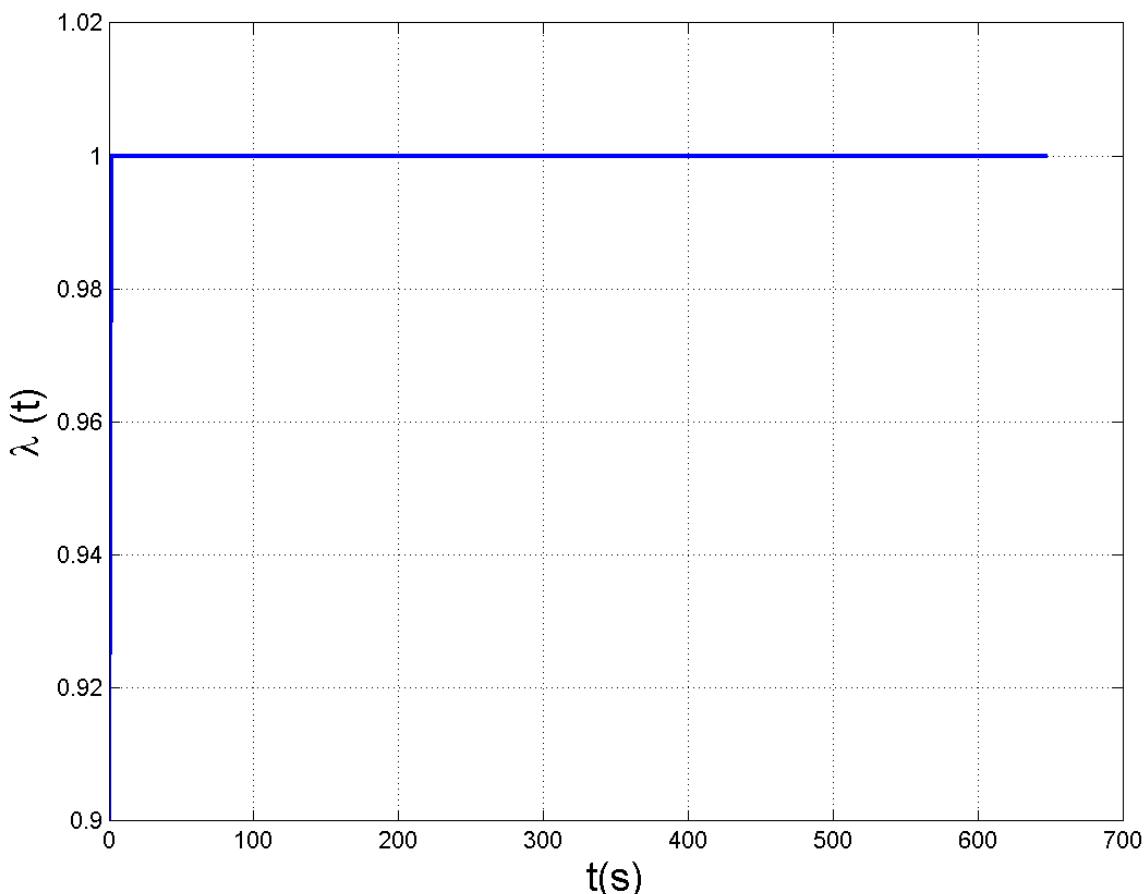
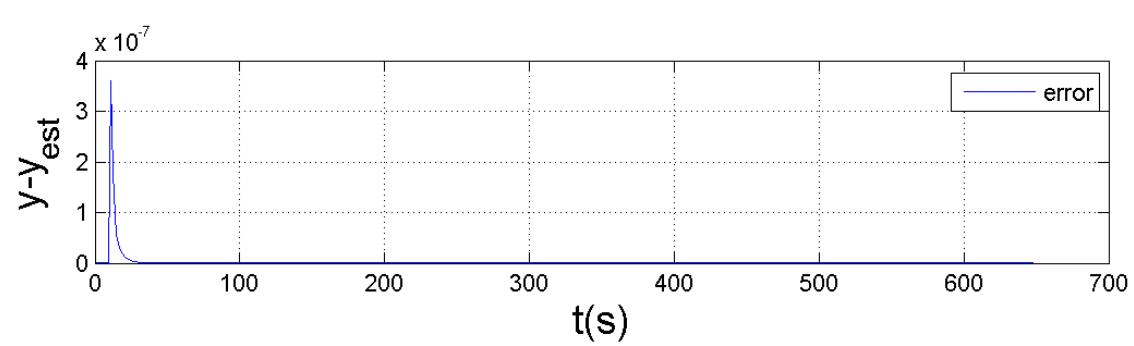
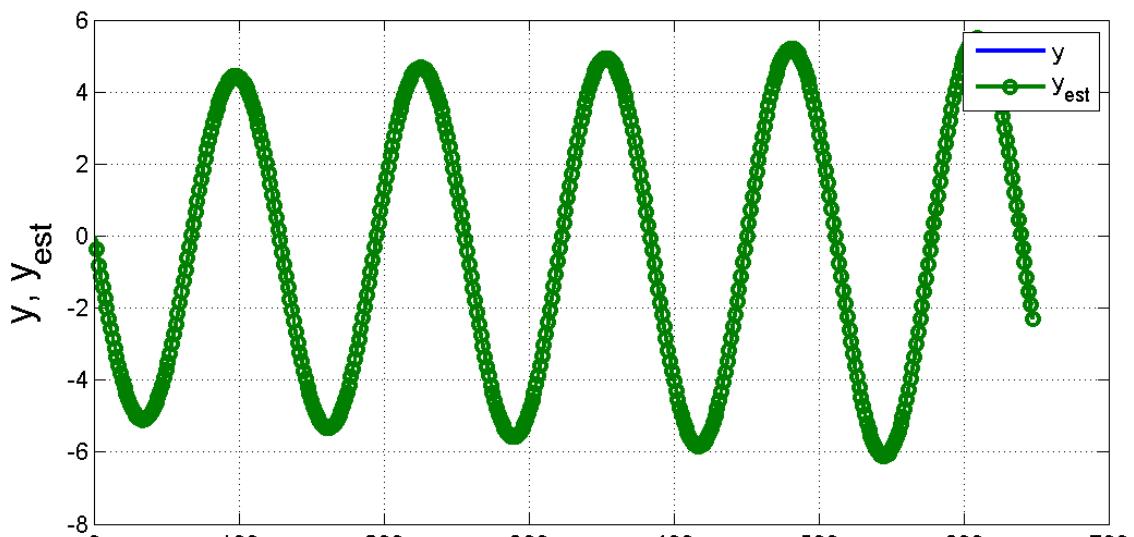
1.5.2 Flight Condition 2



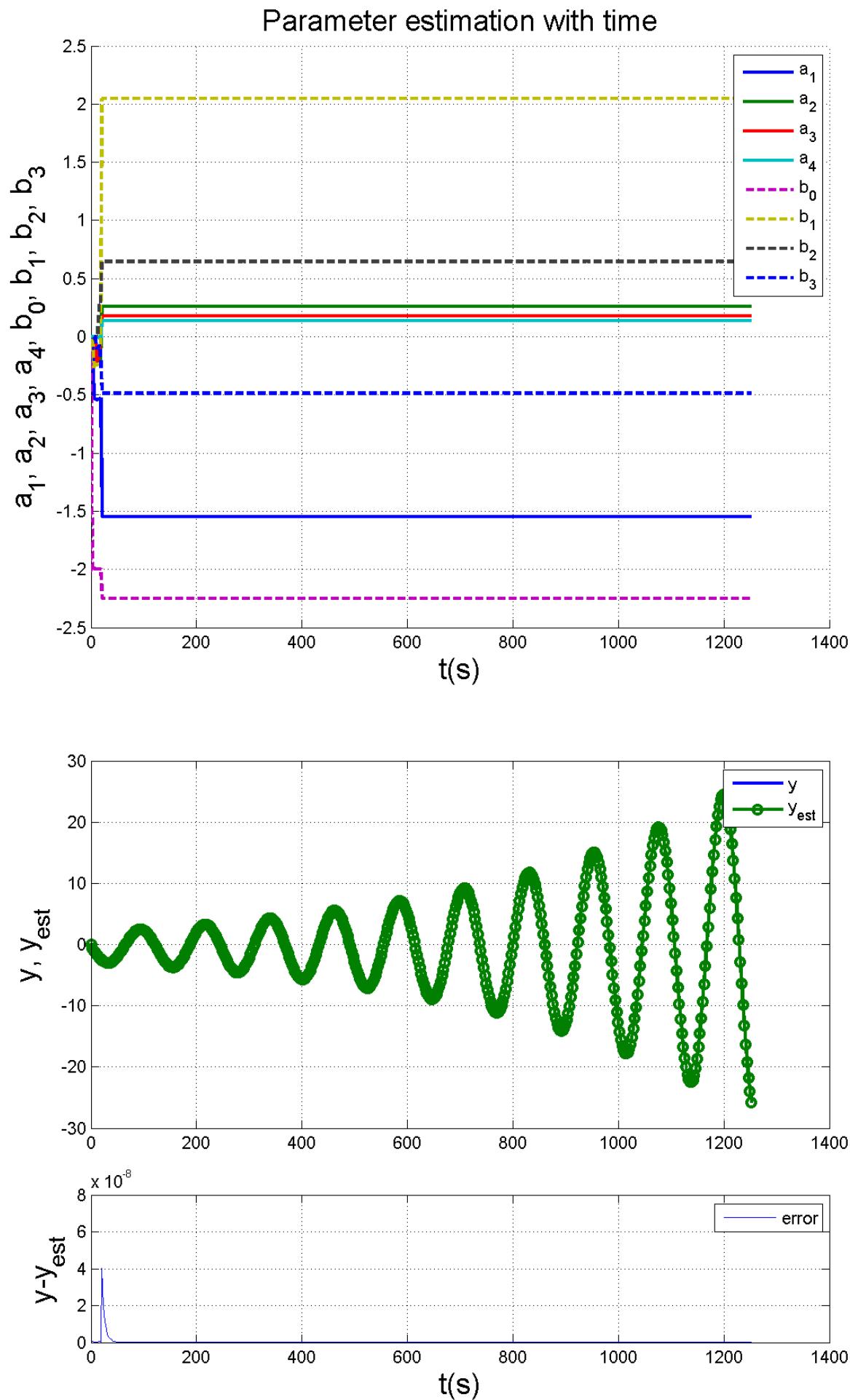


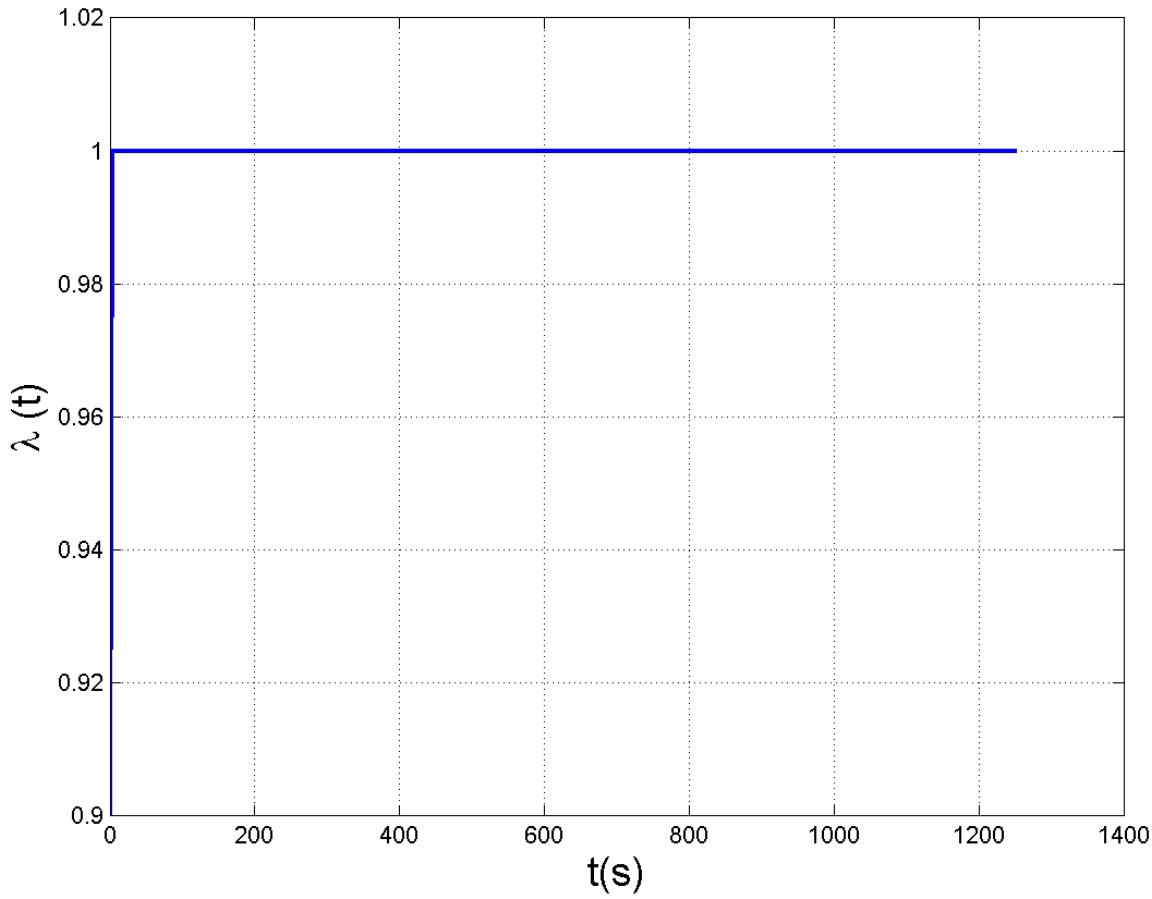
1.5.3 Flight Condition 3





1.5.4 Flight Condition 4





1.5.5 Results

Flight Condition	$G(z)$ Estimated
1	$G(z) = \frac{-0.5646z^3 + 0.3215z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$
2	$G(z) = \frac{-1.378z^3 + 1.153z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$
3	$G(z) = \frac{-1.176z^3 + 0.9539z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$
4	$G(z) = \frac{-2.023z^3 + 1.822z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$

NOTE

The Aircraft is unstable so it's hard to make time varying estimation, but I do it with controller.

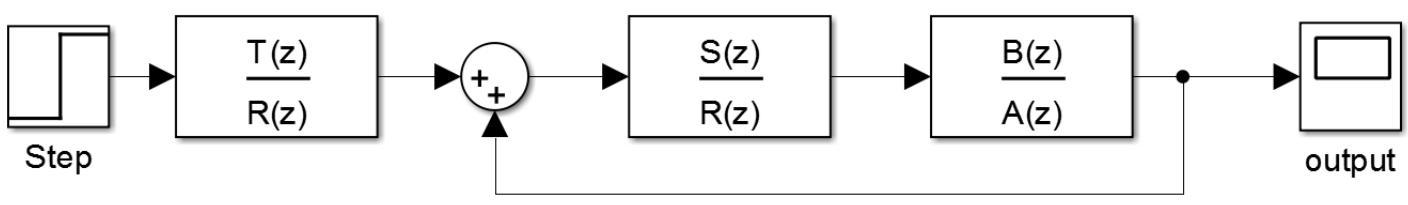
1.6 Indirect Self-Tuning Regulators

I used four scenarios to design indirect STR for this A/C under two different inputs, step input and square input with saturation on $\delta_e = \pm 20^\circ$.

I start the control action after $(2N, \text{where } N = \max(n_a, n_b + d + 1))$ to get a first estimate of system which want to be controlled

1.6.1 Indirect Self-Tuning Regulator Using Model Following Without Zero Cancellation For Step Input

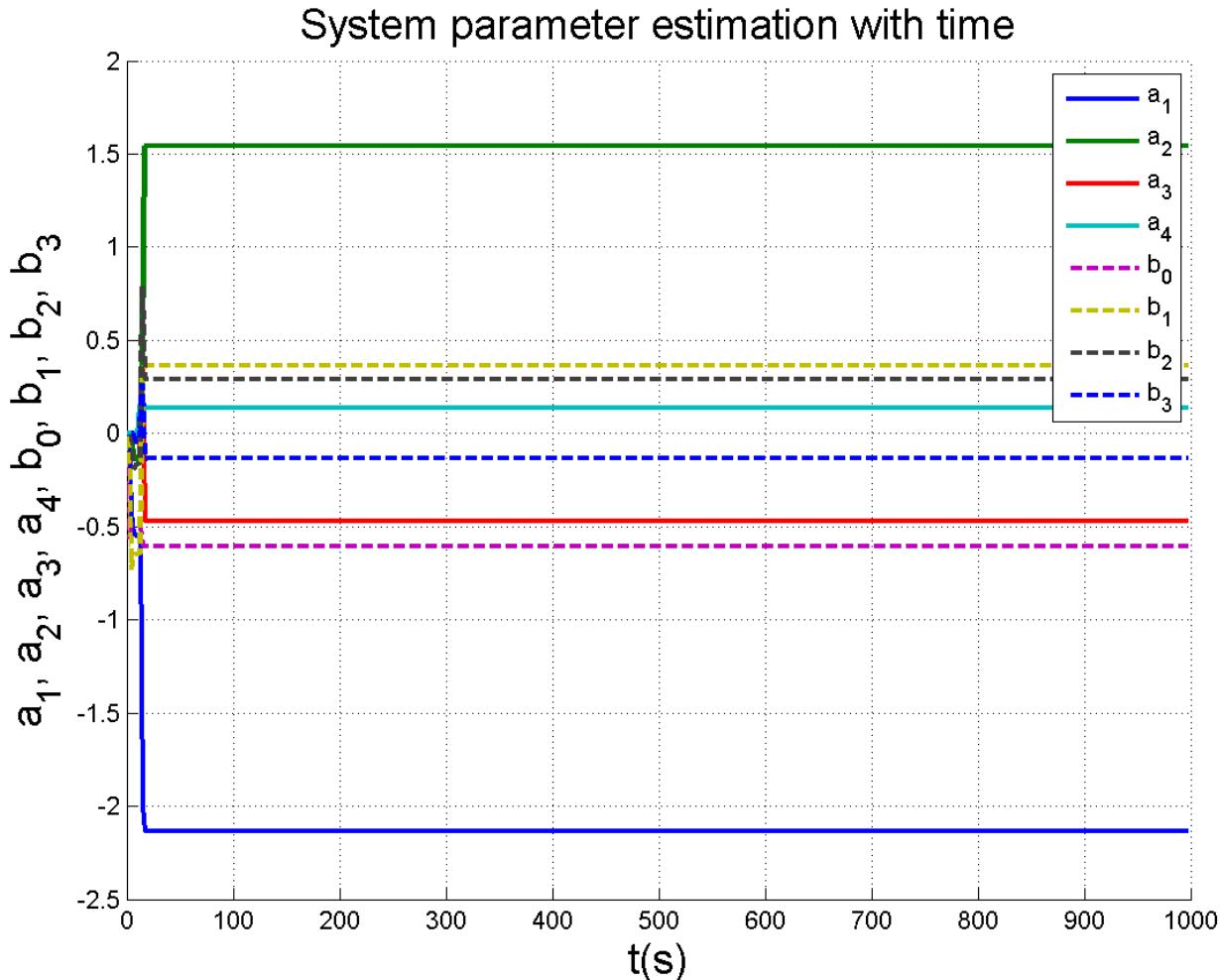
Controller Scheme

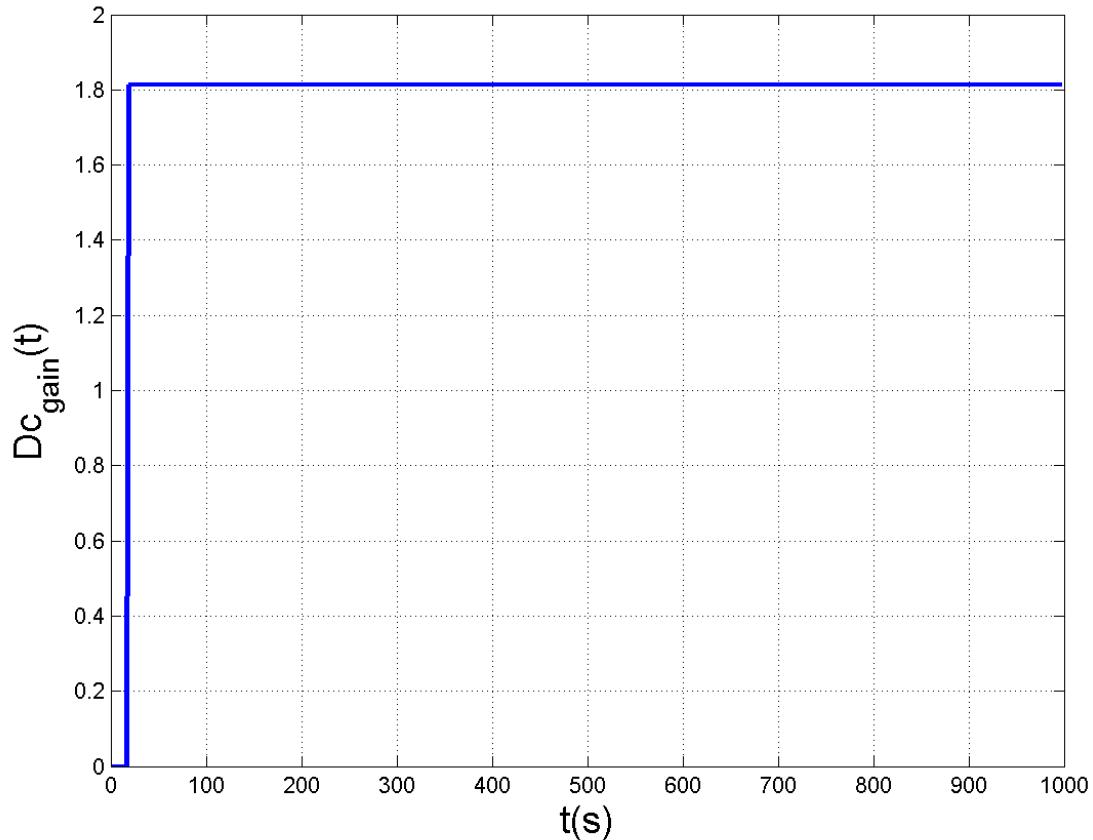
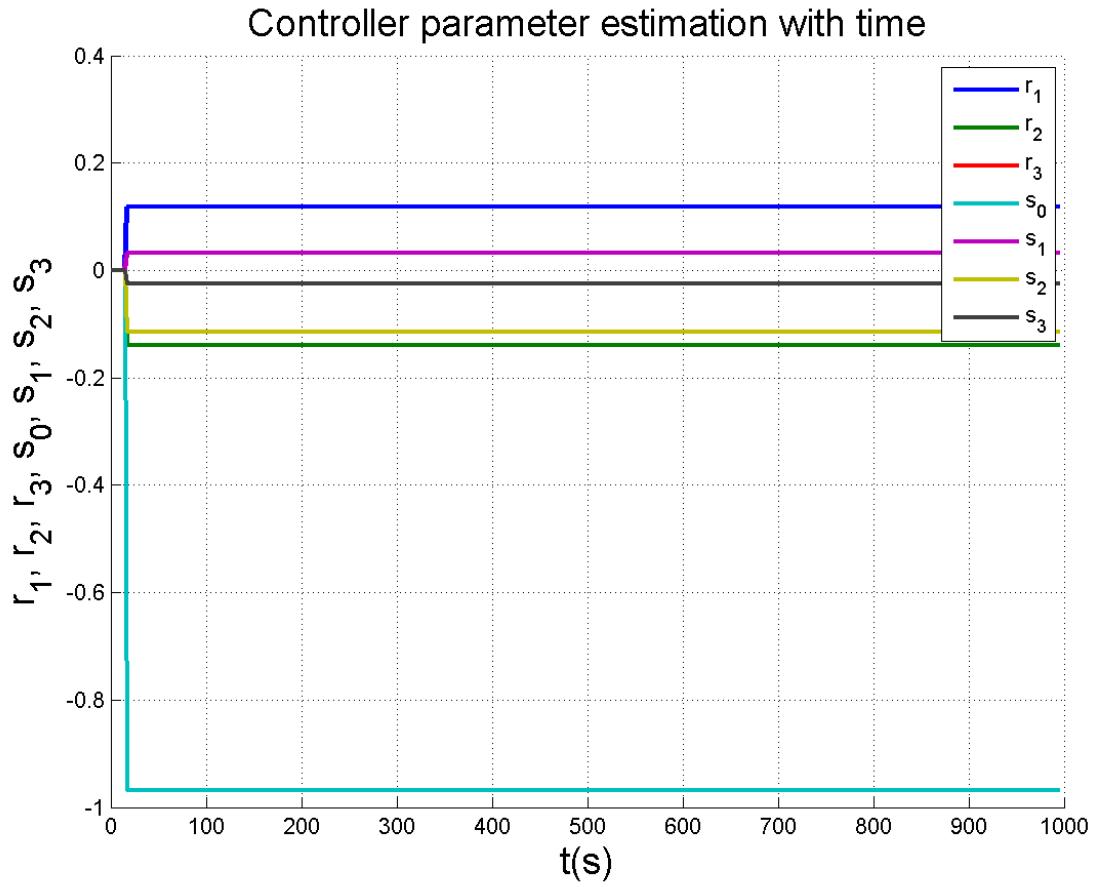


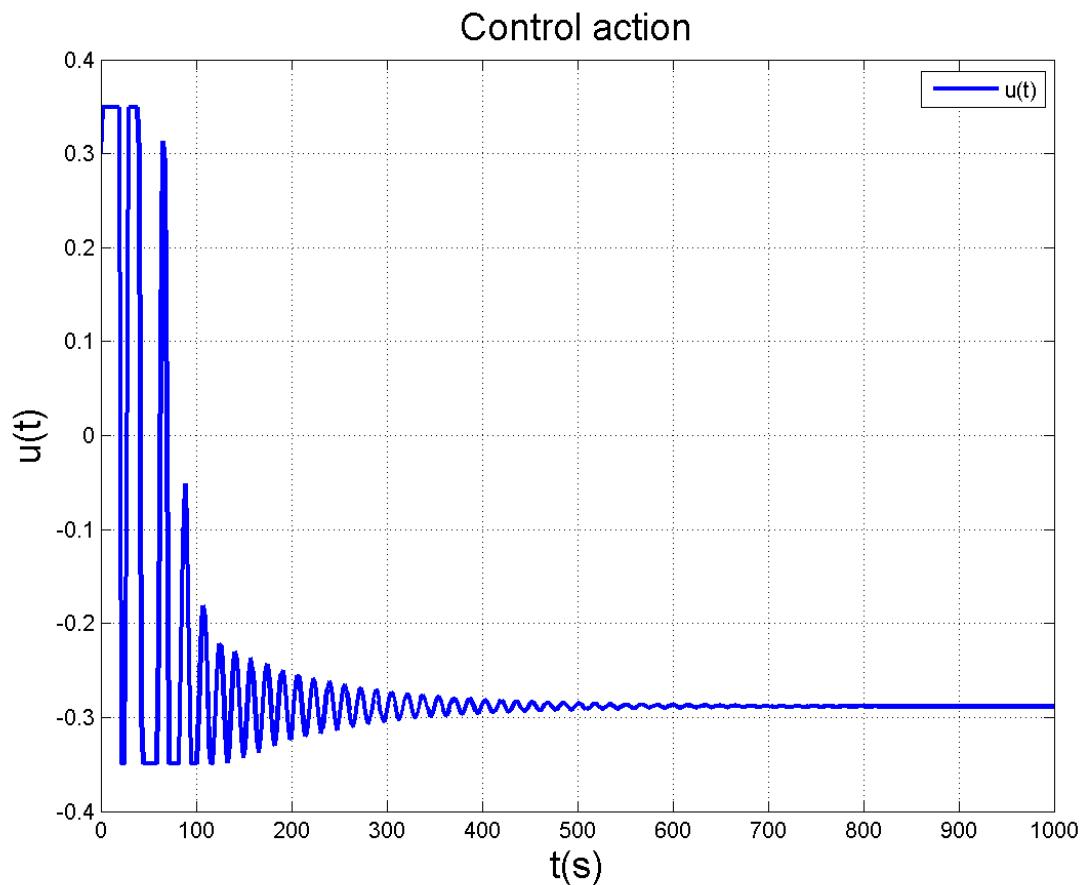
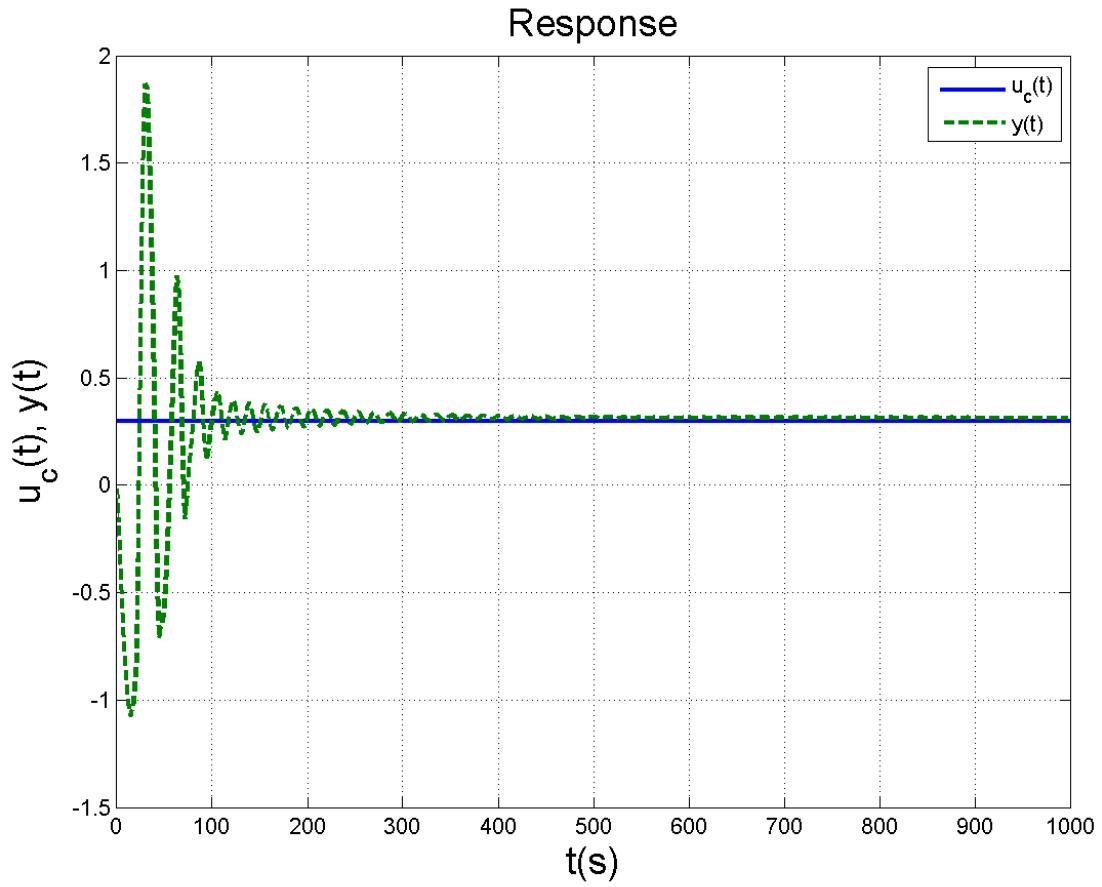
Required Poles in Z-Domain

Flight Condition	A_m	A_0
1	[0.48, 0.45]	[0.1, 0.1, 0.1, 0.1, 0.1]
2	[0.8, 0.8]	[0.02, 0.02, 0.02, 0.02, 0.02]
3	[0.7, 0.9]	[0.3, 0.3, 0.3, 0.3, 0.3]
4	[0.7, 0.55]	[0.24, 0.24, 0.24, 0.24, 0.24]

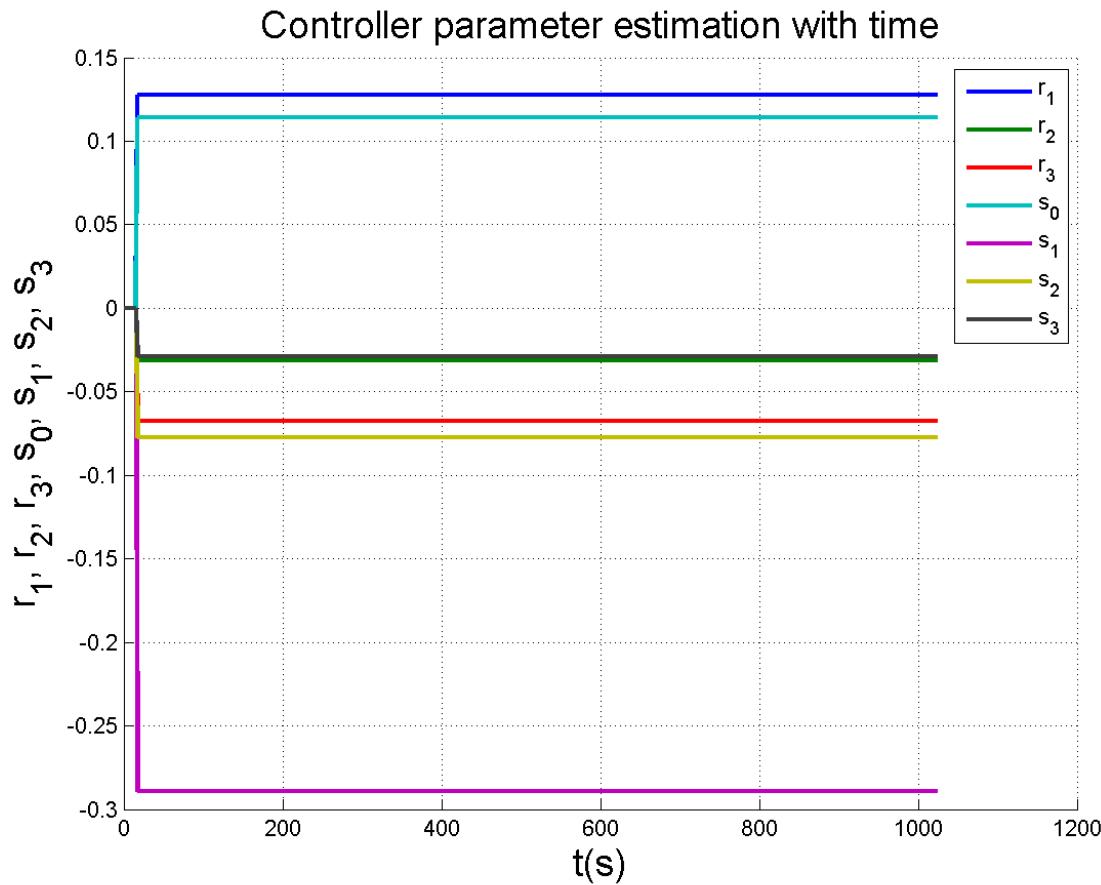
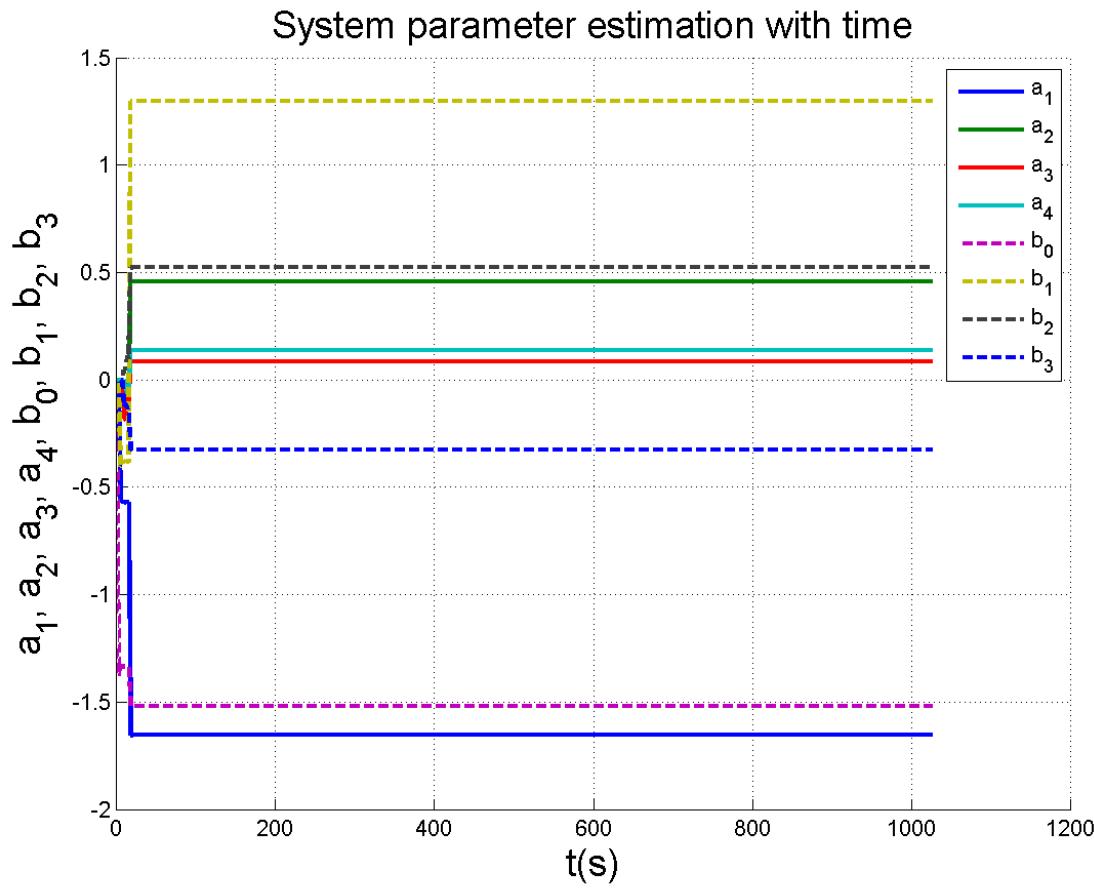
Flight Condition 1

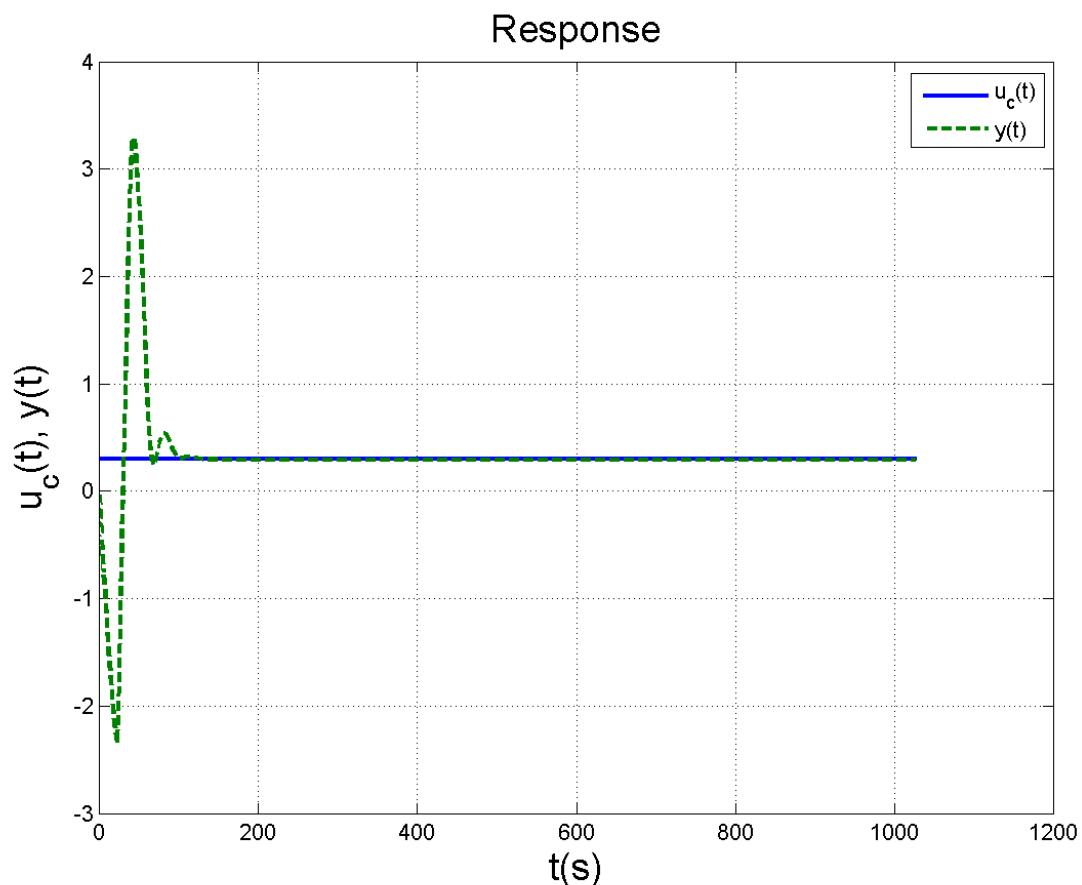
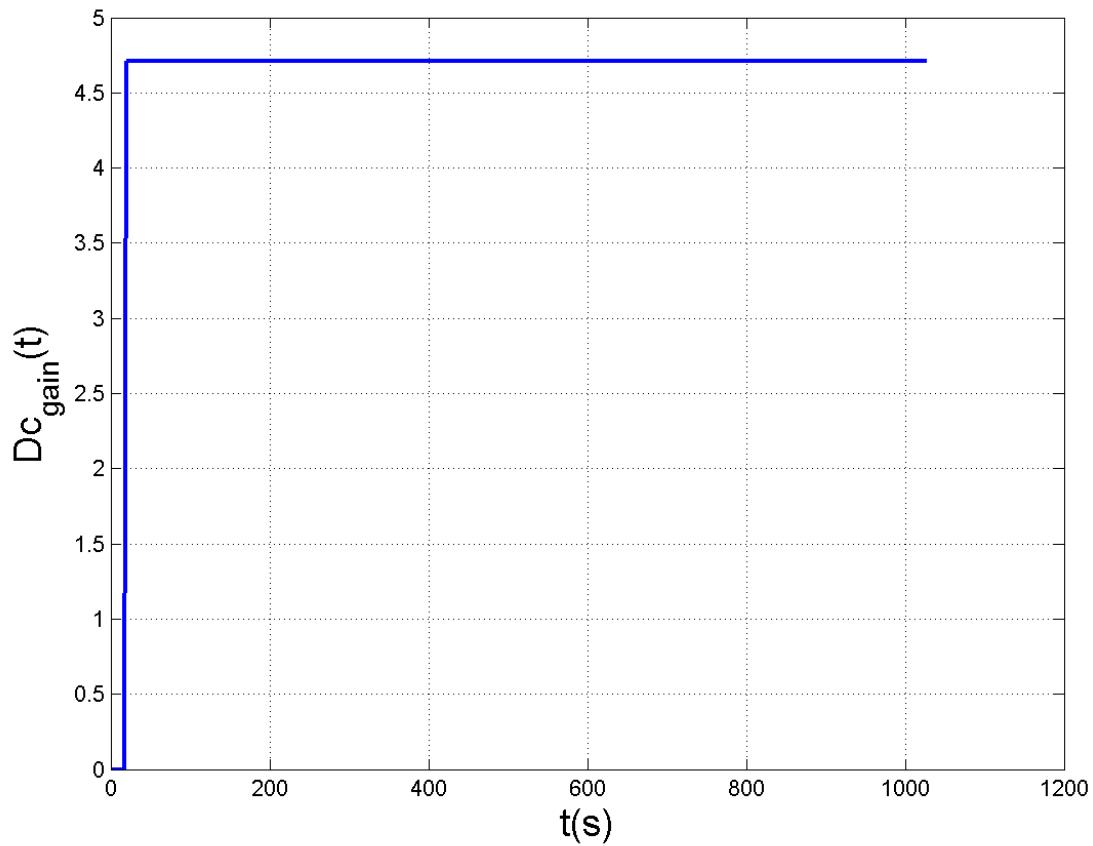


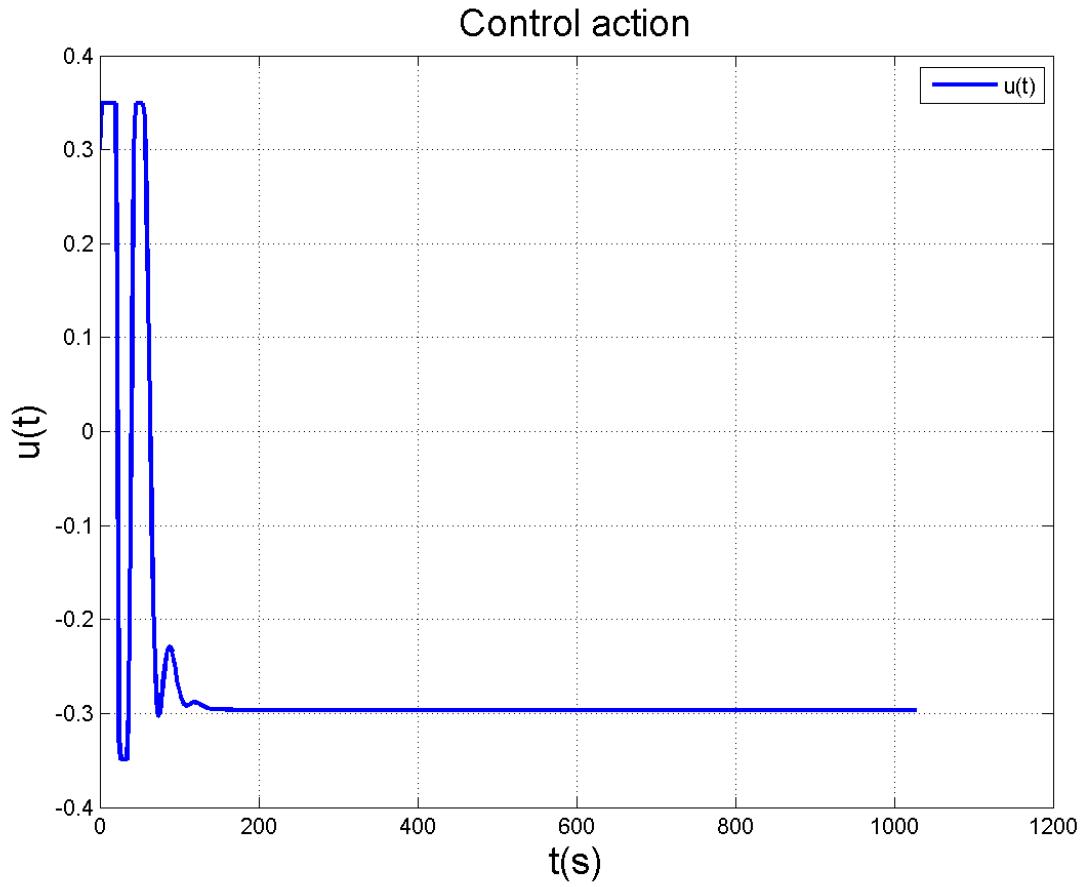




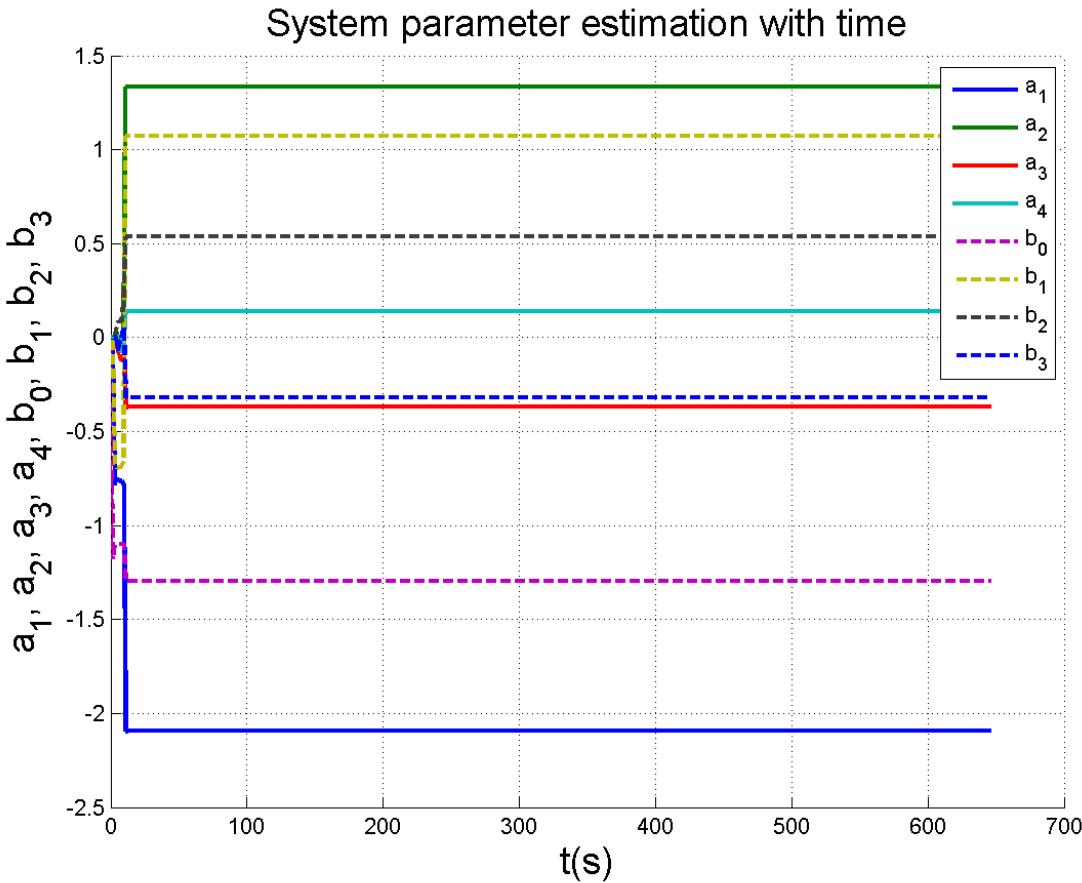
Flight Condition 2

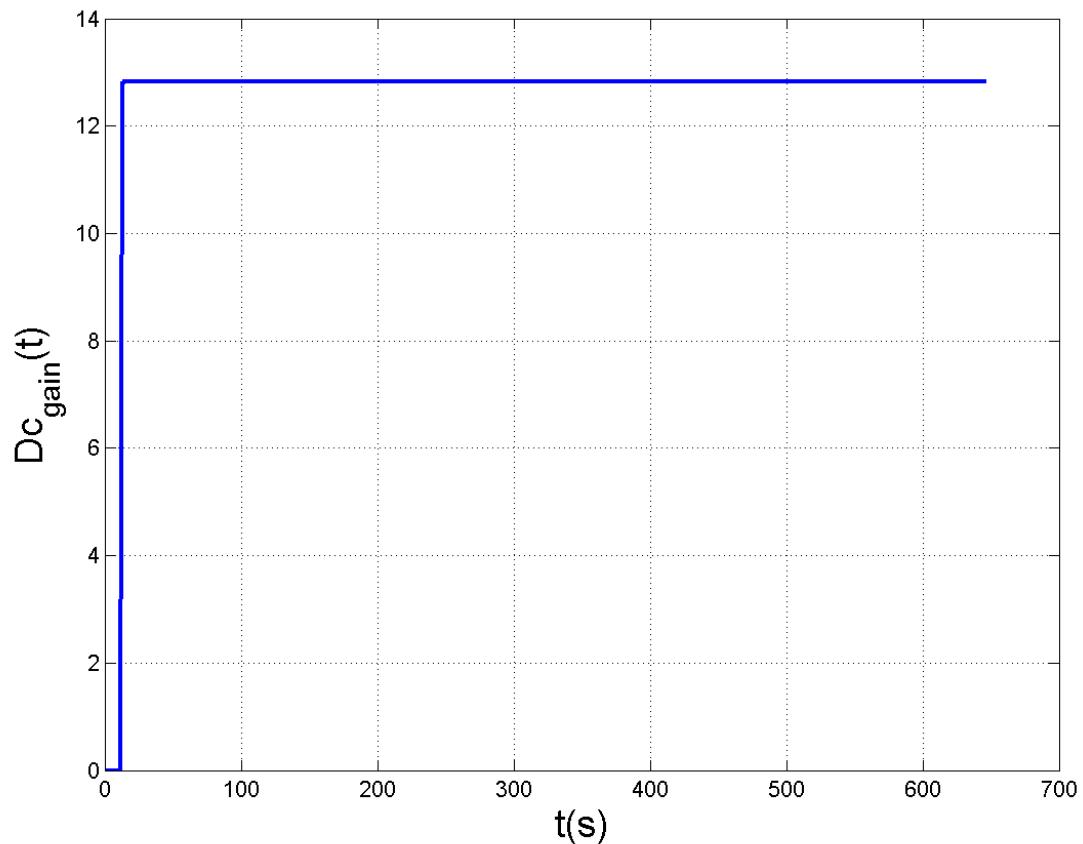
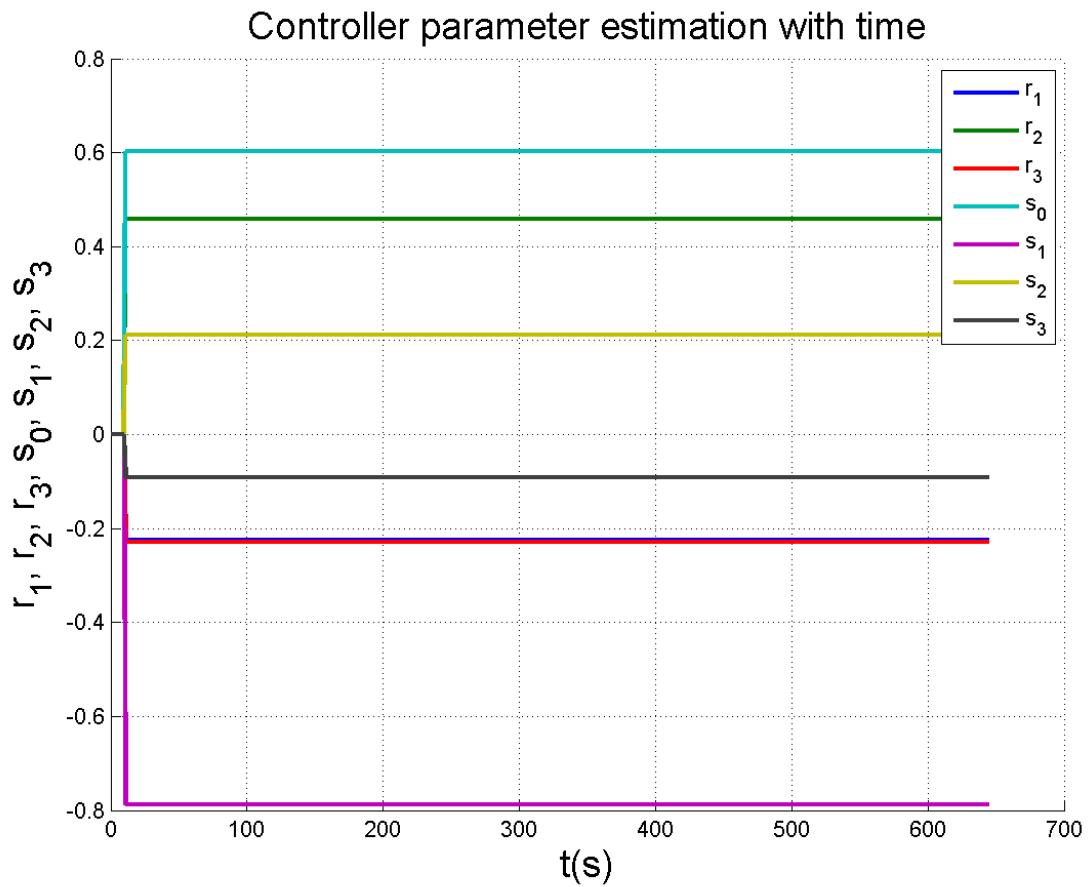


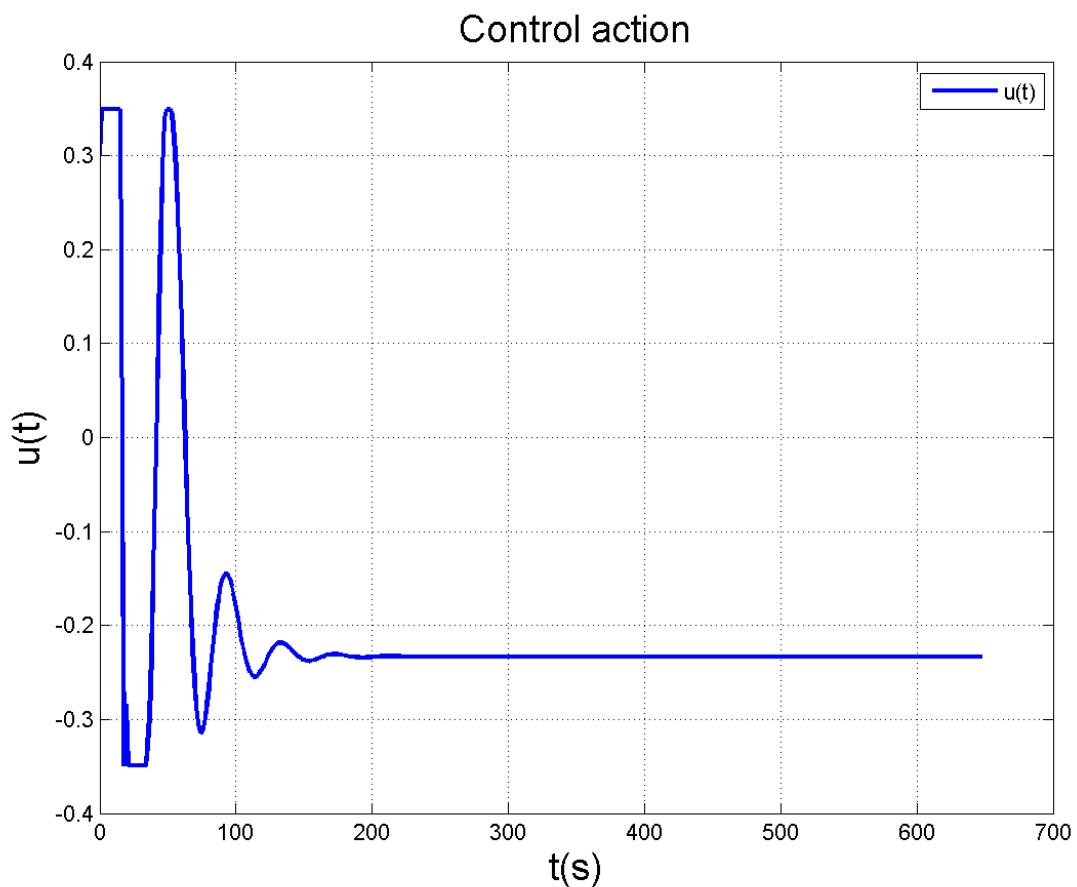
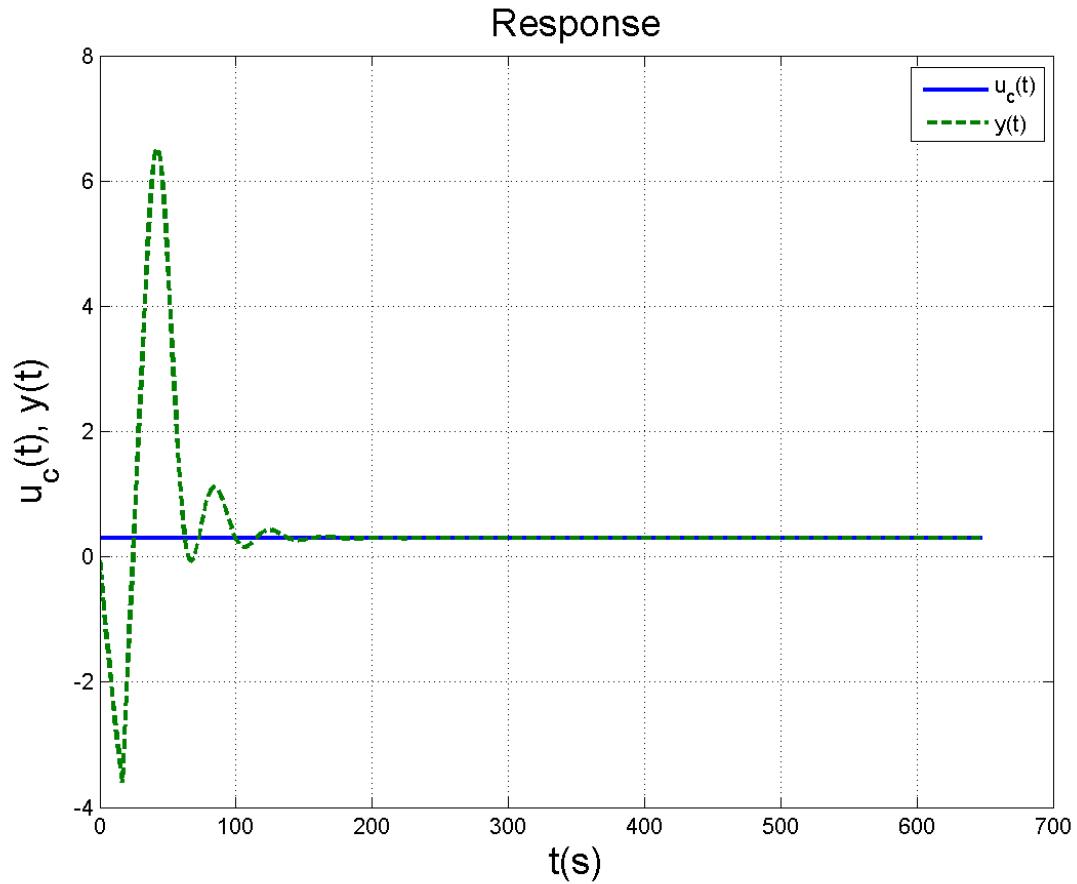




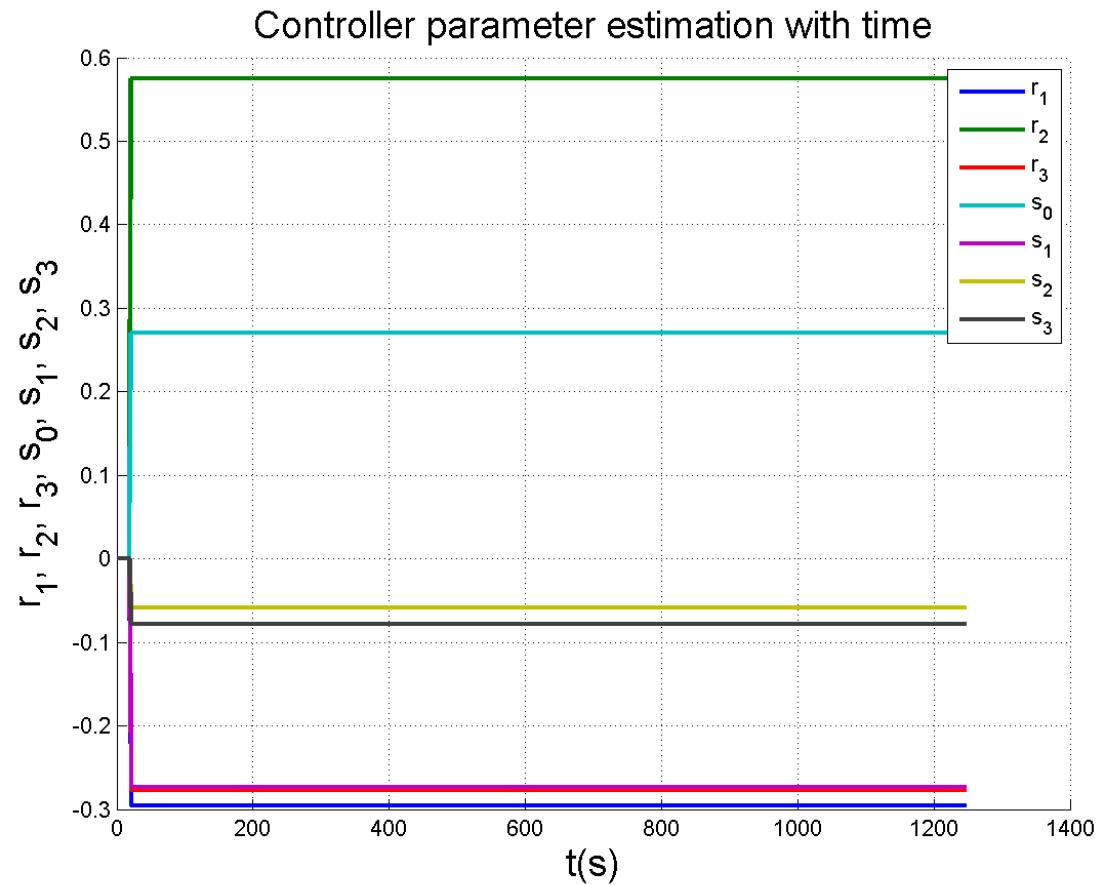
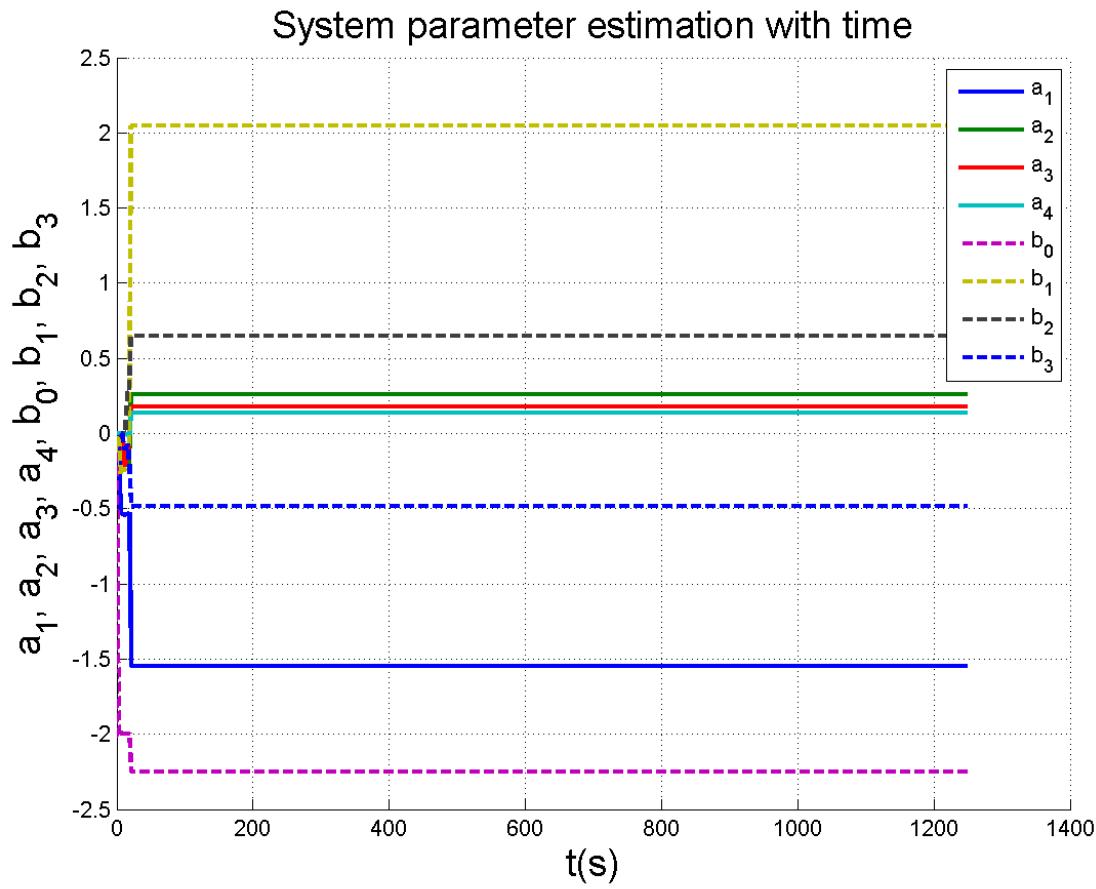
Flight Condition 3

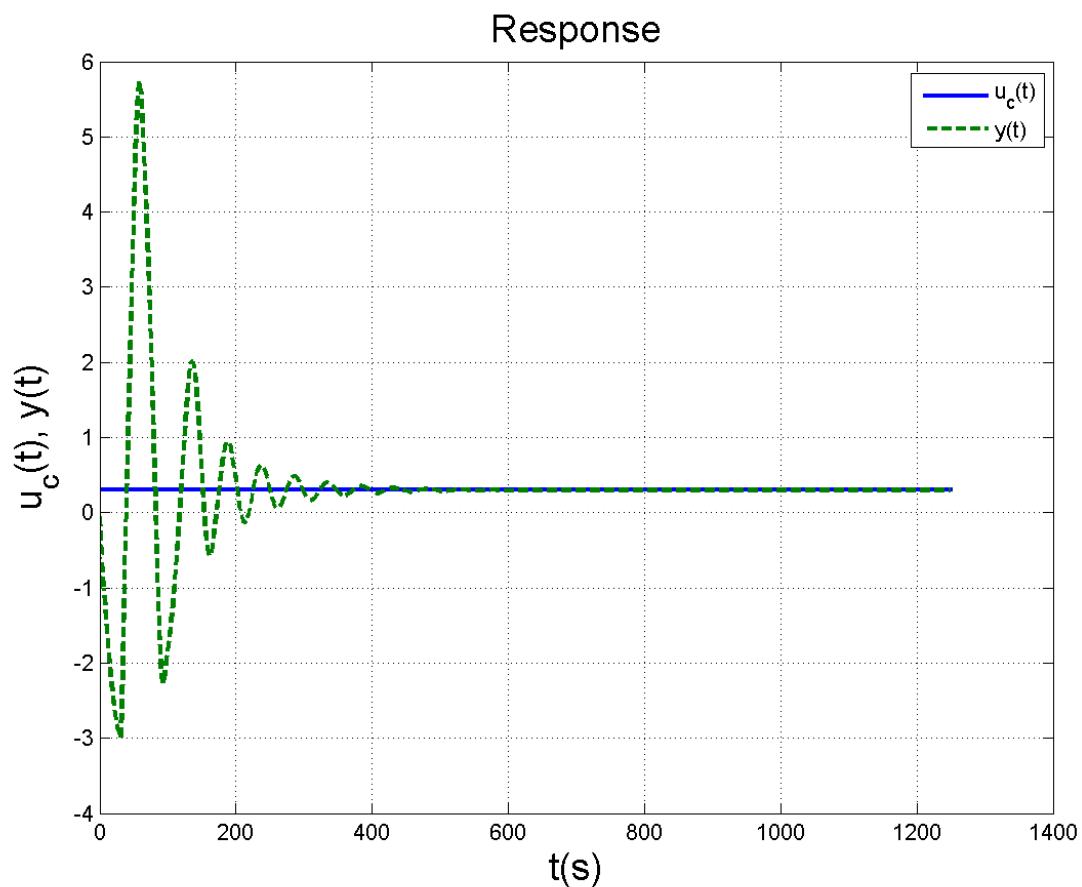
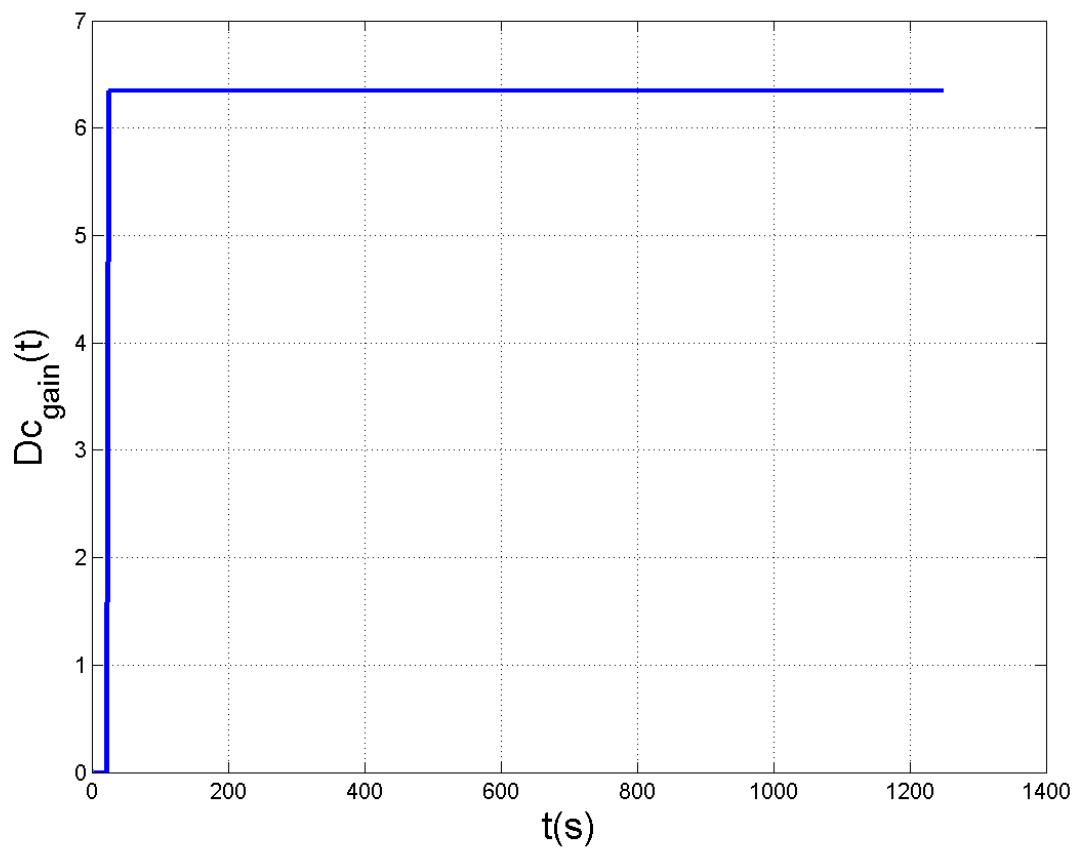


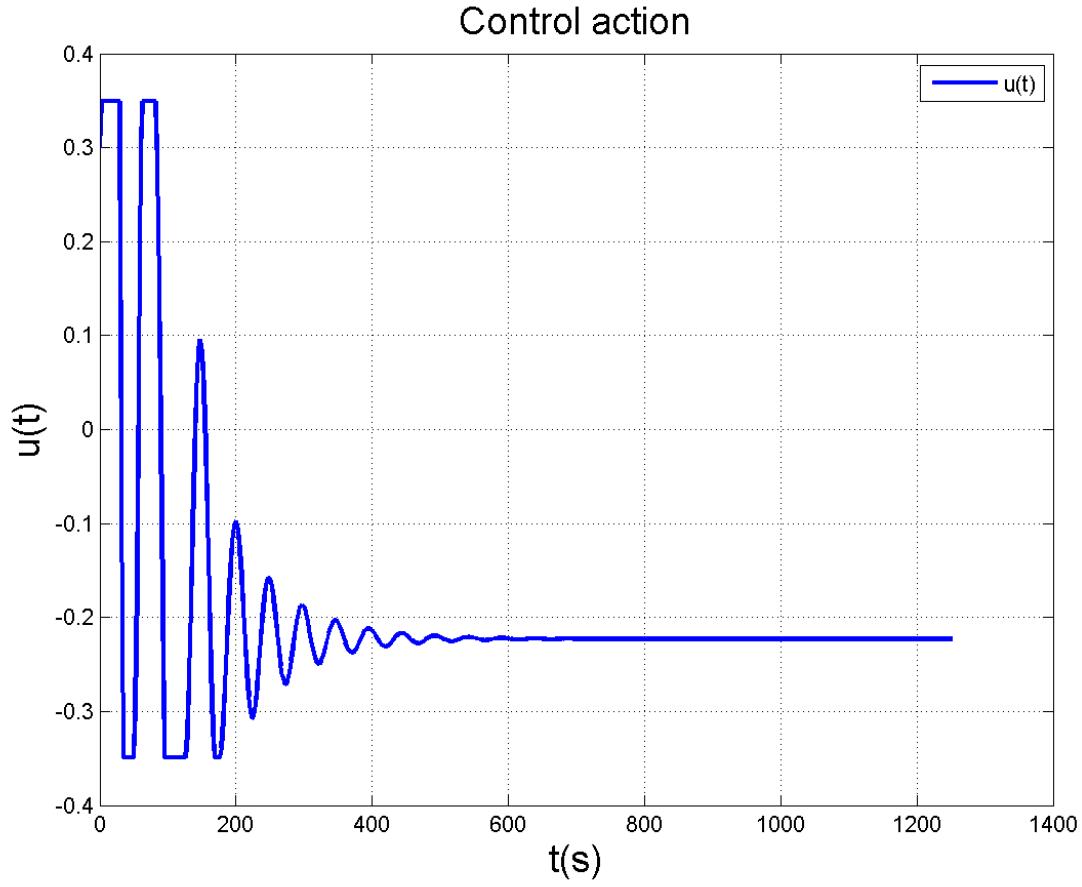




Flight Condition 4



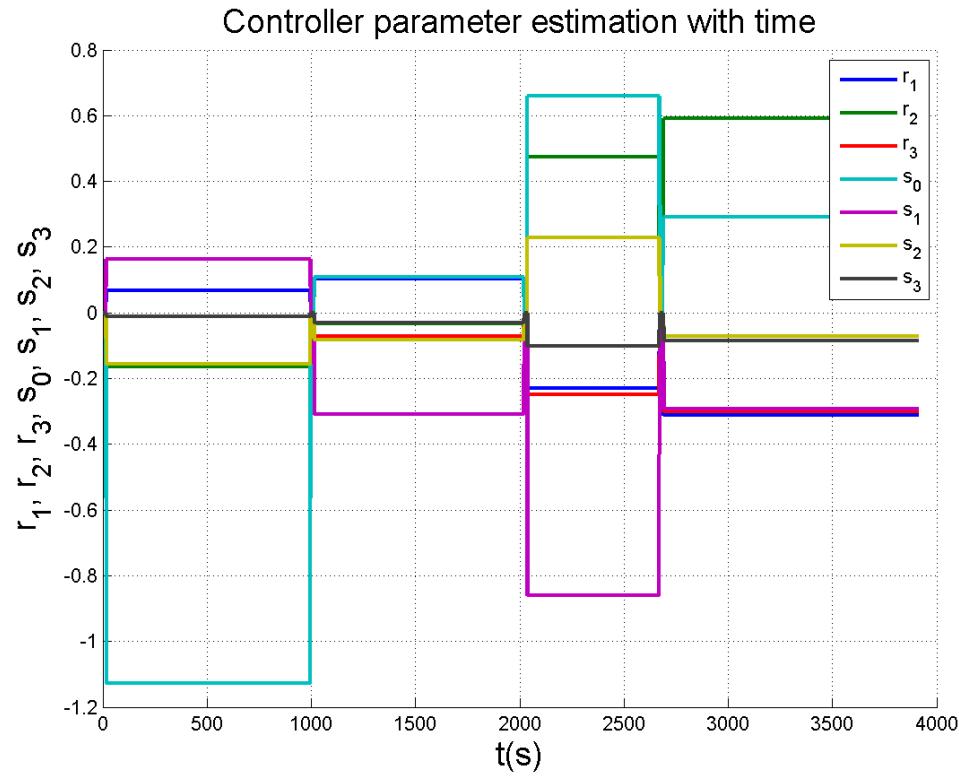
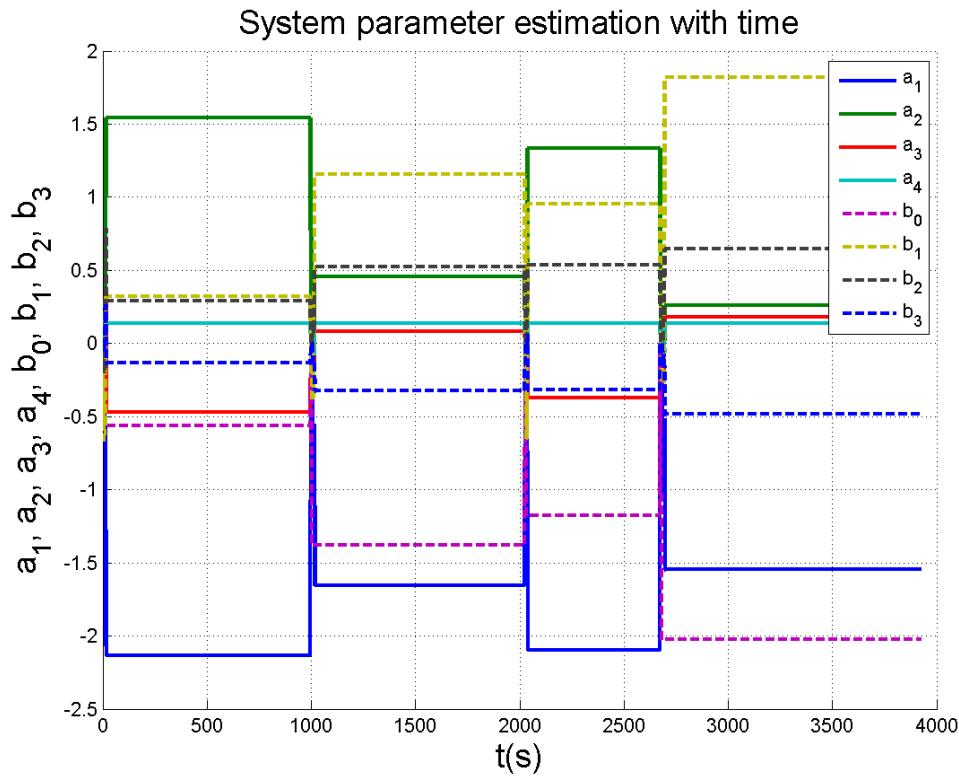


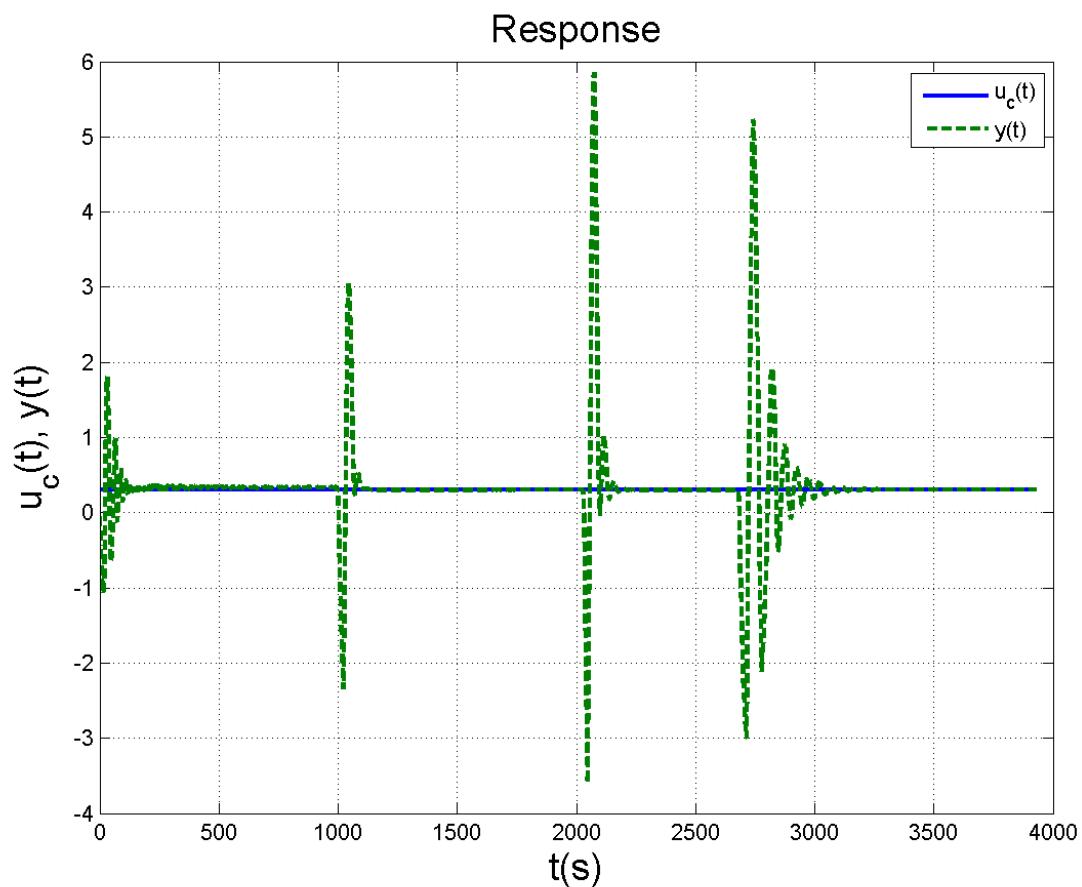
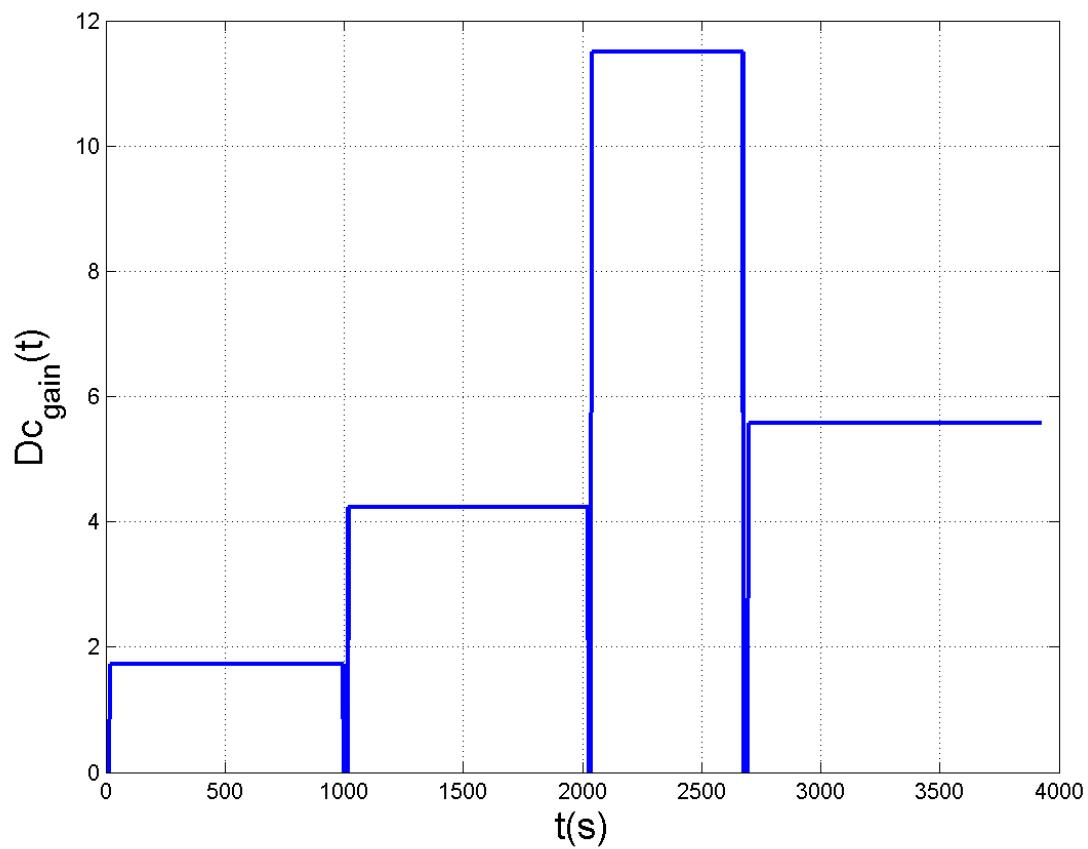


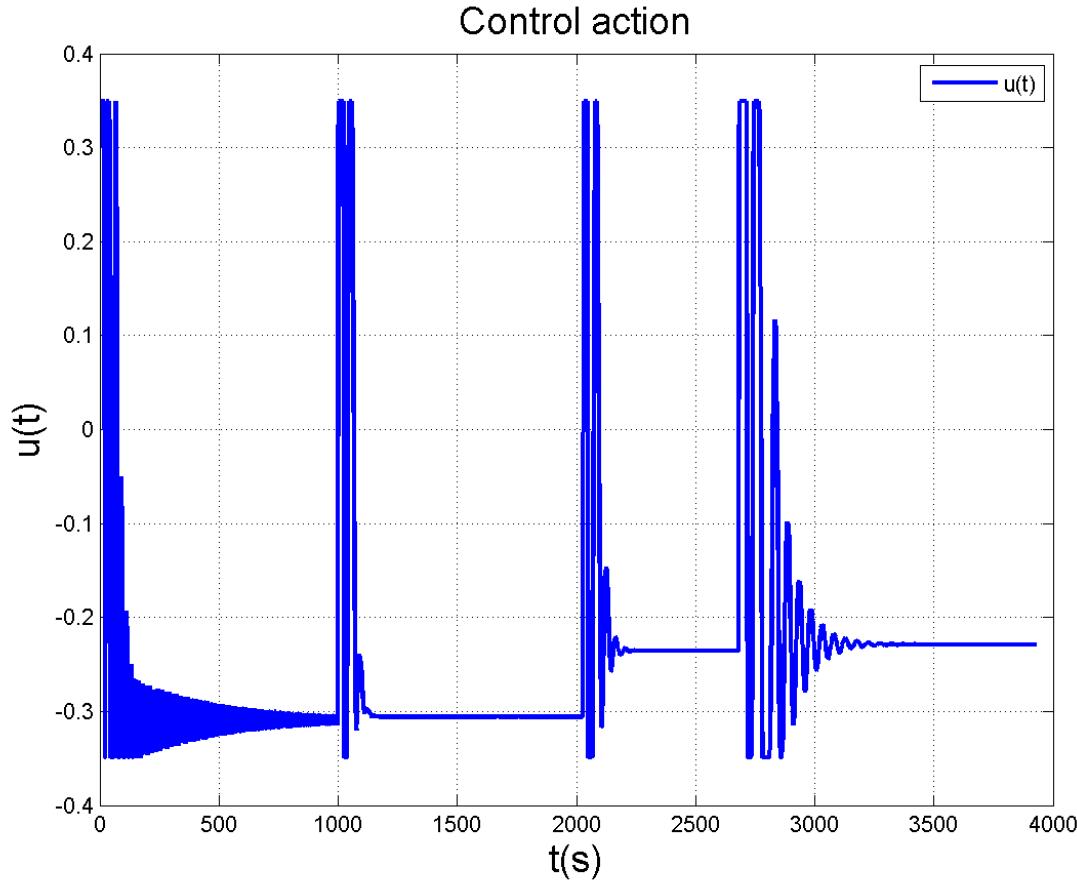
Results

Flight Condition	$G(z)$ Estimated	Feed Forward Controller	DC_{gain}
1	$G(z) = \frac{-0.6048z^3 + 0.3617z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$\frac{S}{R}(z) = \frac{-0.9676z^3 + 0.03209z^2 - 0.1145z - 0.02546}{z^3 + 0.1191z^2 - 0.14z - 0.02463}$	$\frac{T}{R}(z) = 1.814$
2	$G(z) = \frac{-1.522z^3 + 1.297z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$\frac{S}{R}(z) = \frac{0.1138z^3 - 0.2895z^2 - 0.07766z - 0.02899}{z^3 + 0.1279z^2 - 0.03137z - 0.06781}$	$\frac{T}{R}(z) = 4.707$
3	$G(z) = \frac{-1.295z^3 + 1.073z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$\frac{S}{R}(z) = \frac{0.6022z^3 - 0.7886z^2 + 0.2123z - 0.09237}{z^3 - 0.2245z^2 + 0.4573z - 0.2282}$	$\frac{T}{R}(z) = 12.82$
4	$G(z) = \frac{-2.25z^3 + 2.049z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$\frac{S}{R}(z) = \frac{0.2699z^3 - 0.2734z^2 - 0.05836z - 0.07783}{z^3 - 0.2951z^2 + 0.5753z - 0.2772}$	$\frac{T}{R}(z) = 6.348$

For All Flight Conditions Together







Results

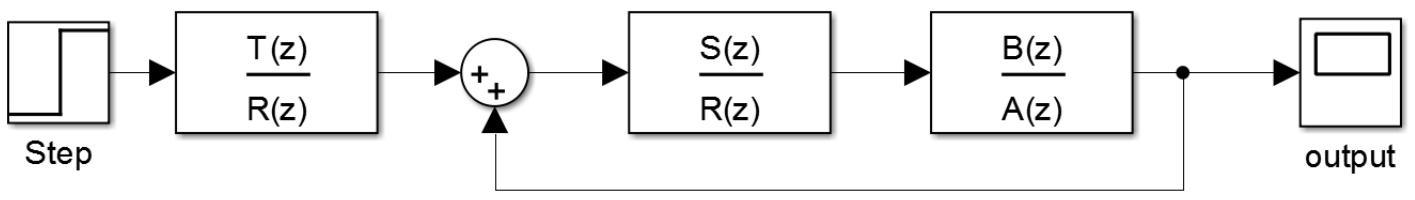
Flight Condition	$G(z)$ Estimated	Feed Forward Controller	DC_{gain}
1	$G(z) = \frac{-0.5646z^3 + 0.3215z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$\frac{S}{R}(z) = \frac{-1.128z^3 + 0.1626z^2 - 0.1567z - 0.01222}{z^3 + 0.06749z^2 - 0.1651z - 0.01184}$	$\frac{T}{R}(z) = 1.72$
2	$G(z) = \frac{-1.378z^3 + 1.153z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$\frac{S}{R}(z) = \frac{0.1076z^3 - 0.3084z^2 - 0.08262z - 0.03083}{z^3 + 0.1029z^2 - 0.03346z - 0.0721}$	$\frac{T}{R}(z) = 4.229$
3	$G(z) = \frac{-1.176z^3 + 0.9539z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$\frac{S}{R}(z) = \frac{0.6583z^3 - 0.8597z^2 + 0.2284z - 0.1011}{z^3 - 0.2304z^2 + 0.4738z - 0.2486}$	$\frac{T}{R}(z) = 11.5$
4	$G(z) = \frac{-2.023z^3 + 1.822z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$\frac{S}{R}(z) = \frac{0.2917z^3 - 0.2937z^2 - 0.07217z - 0.0848}{z^3 - 0.3125z^2 + 0.5914z - 0.3018}$	$\frac{T}{R}(z) = 5.579$

Comments

- The system parameter goes to its true values if i control all flight conditions together.
- There is a change in controller parameter between the controller of all flight conditions and the controller of each flight condition.

1.6.2 Indirect Self-Tuning Regulator Using Model Following With Zero Cancellation For Step Input

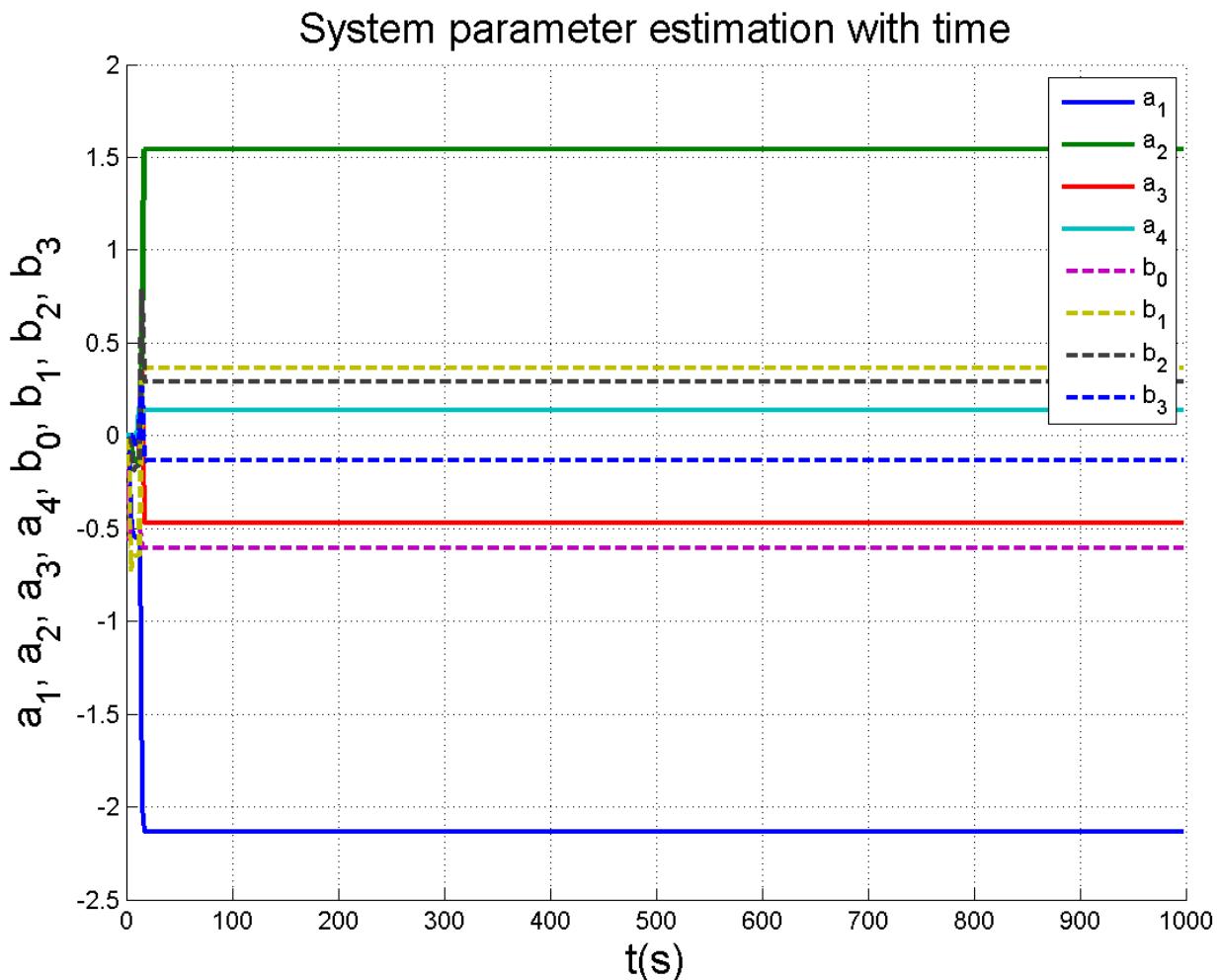
Controller Scheme

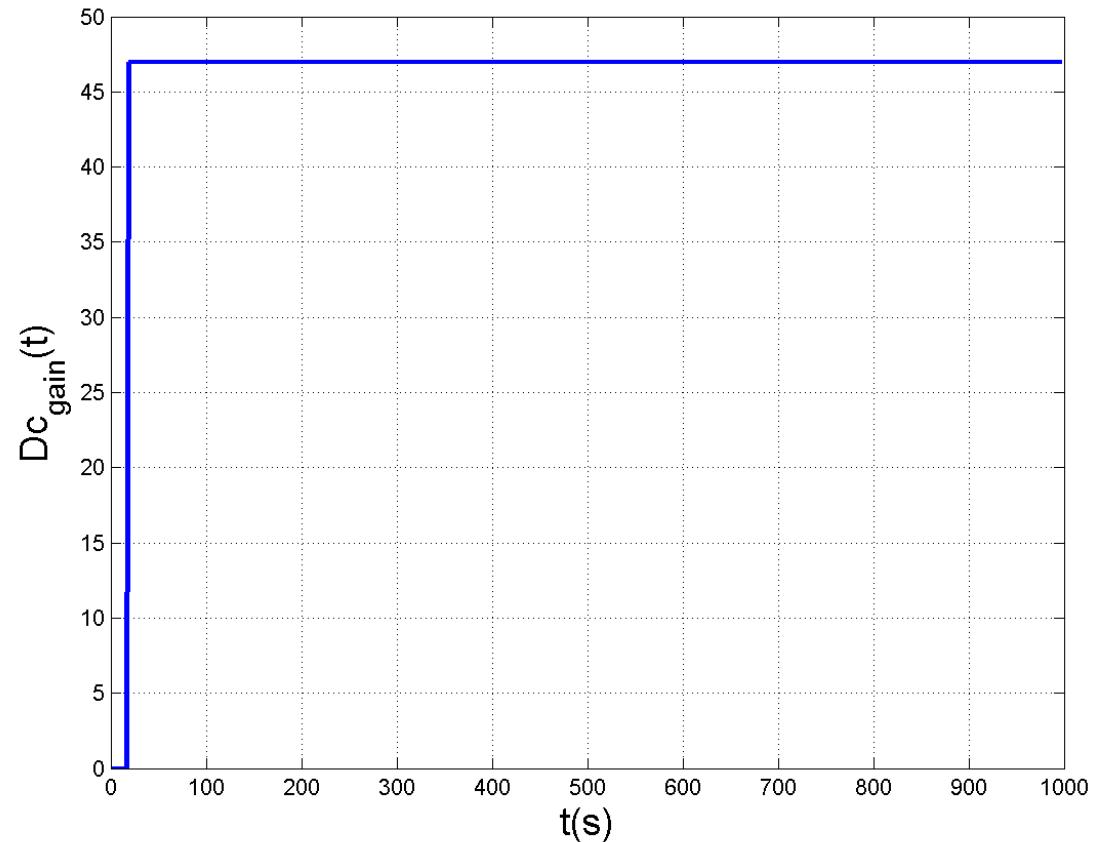
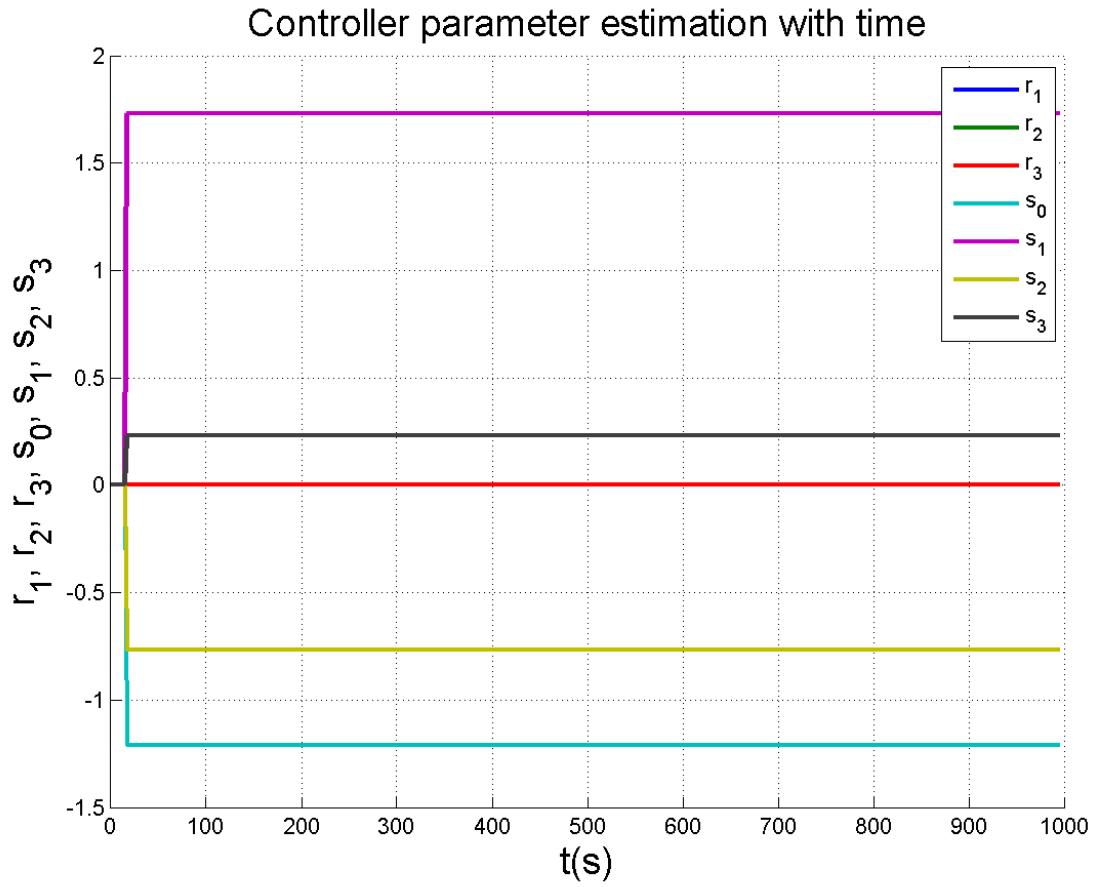


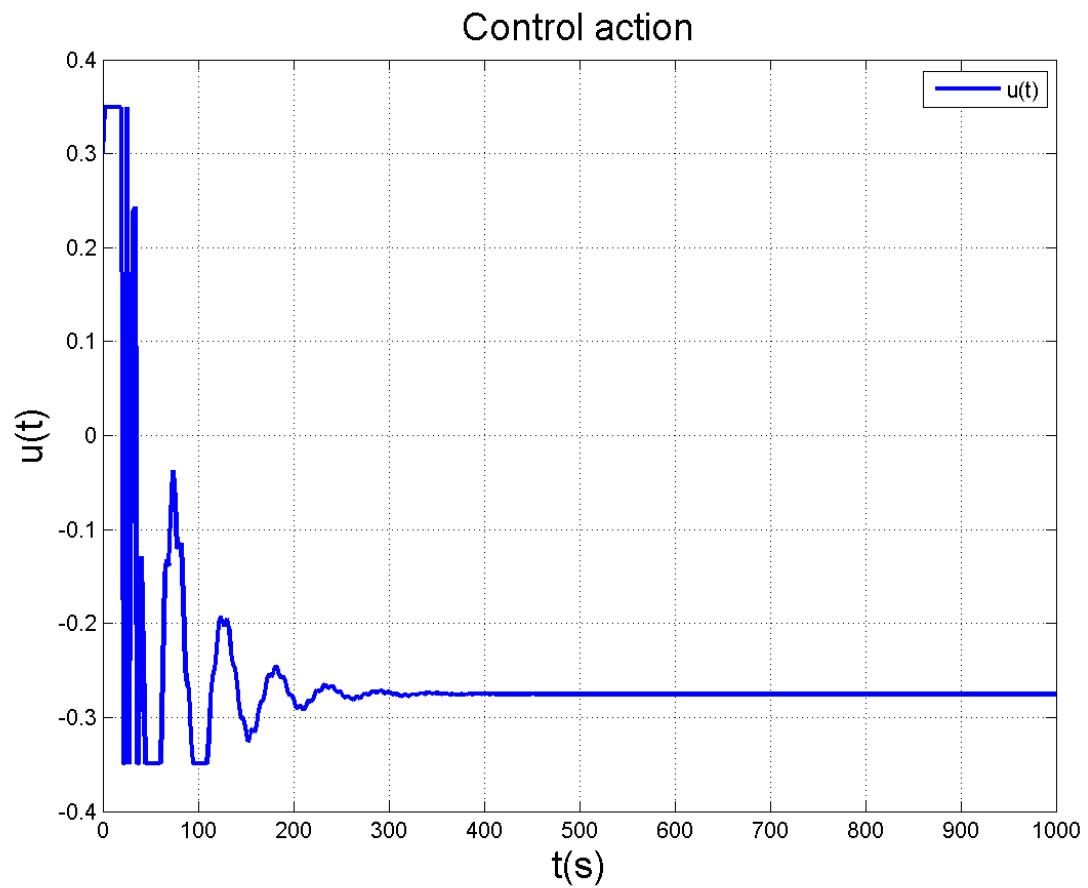
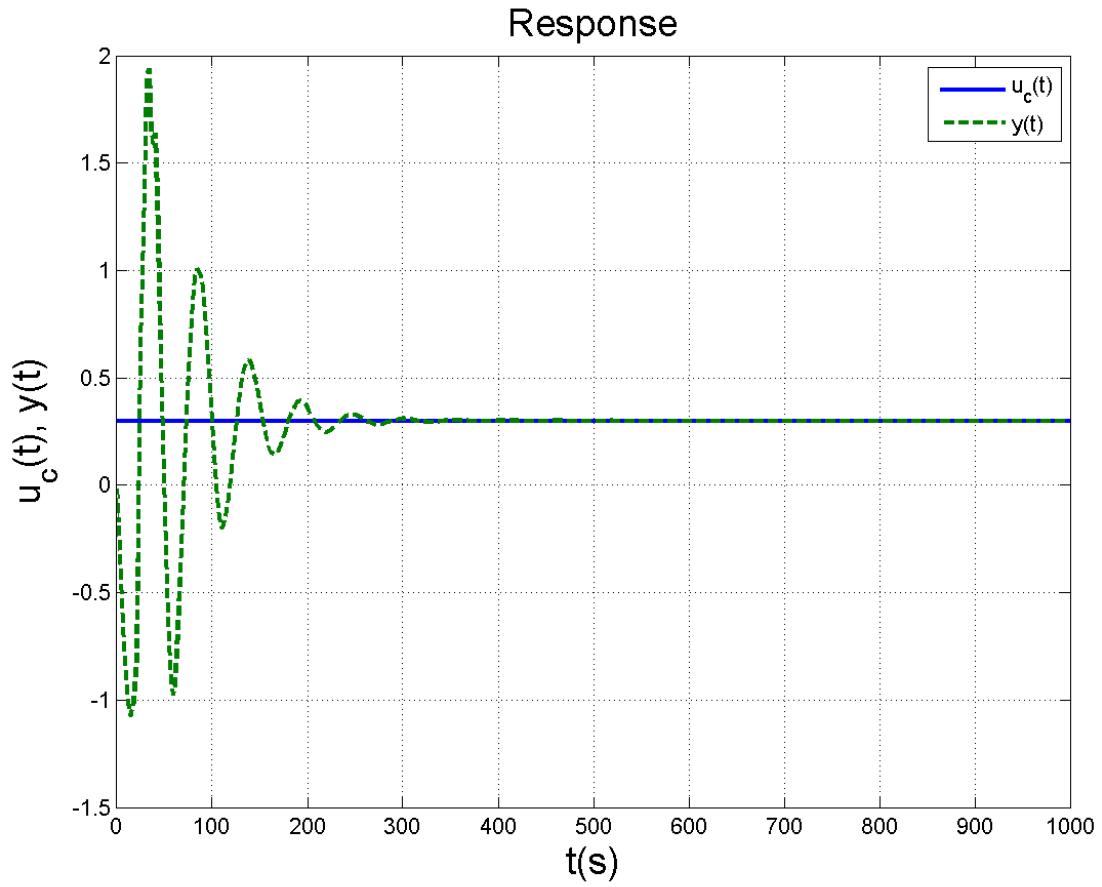
Required Poles in Z-Domain

Flight Condition	A_m	A_0
1	[0.692, 0.7]	[0.002, 0.002, 0.002, 0.002, 0.002]
2	[0.3, 0.5]	[0.02, 0.02, 0.02, 0.02, 0.02]
3	[0.665, 0.7]	[0.002, 0.002, 0.002, 0.002, 0.002]
4	[0.3, 0.2]	[0.1, 0.1, 0.1, 0.1, 0.1]

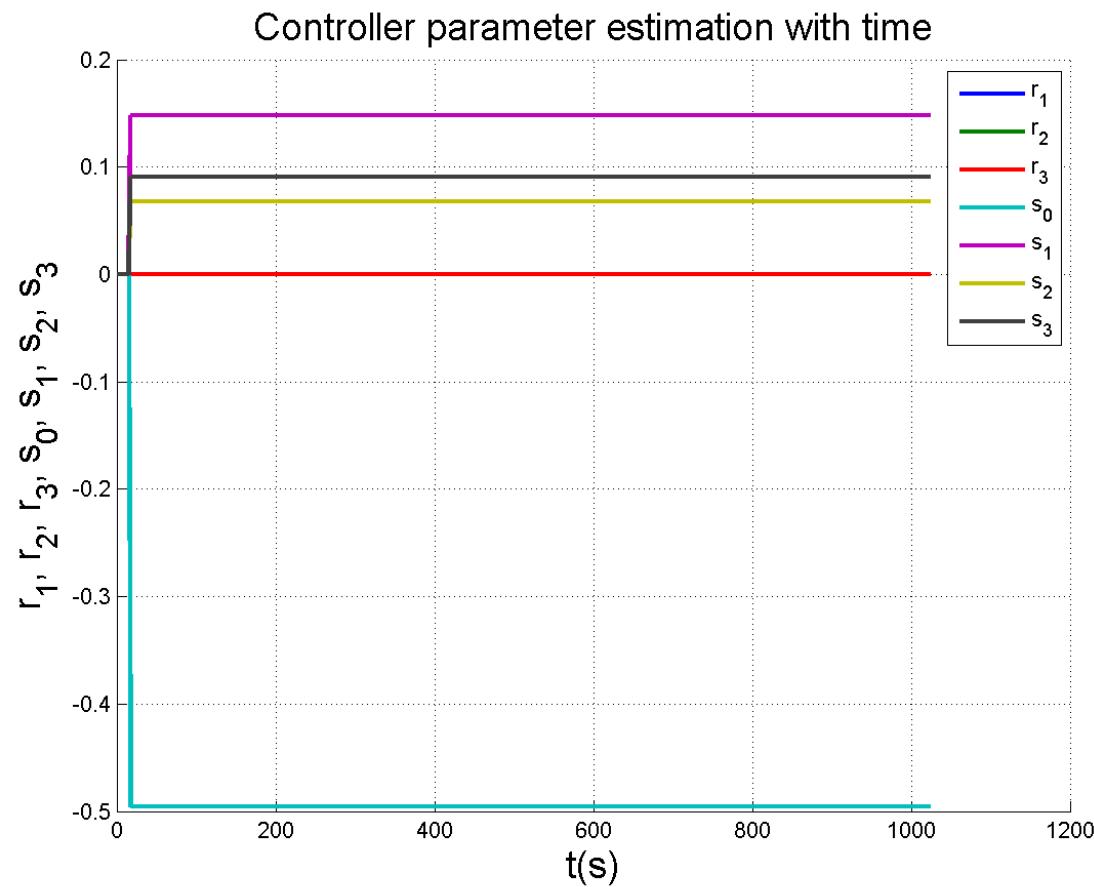
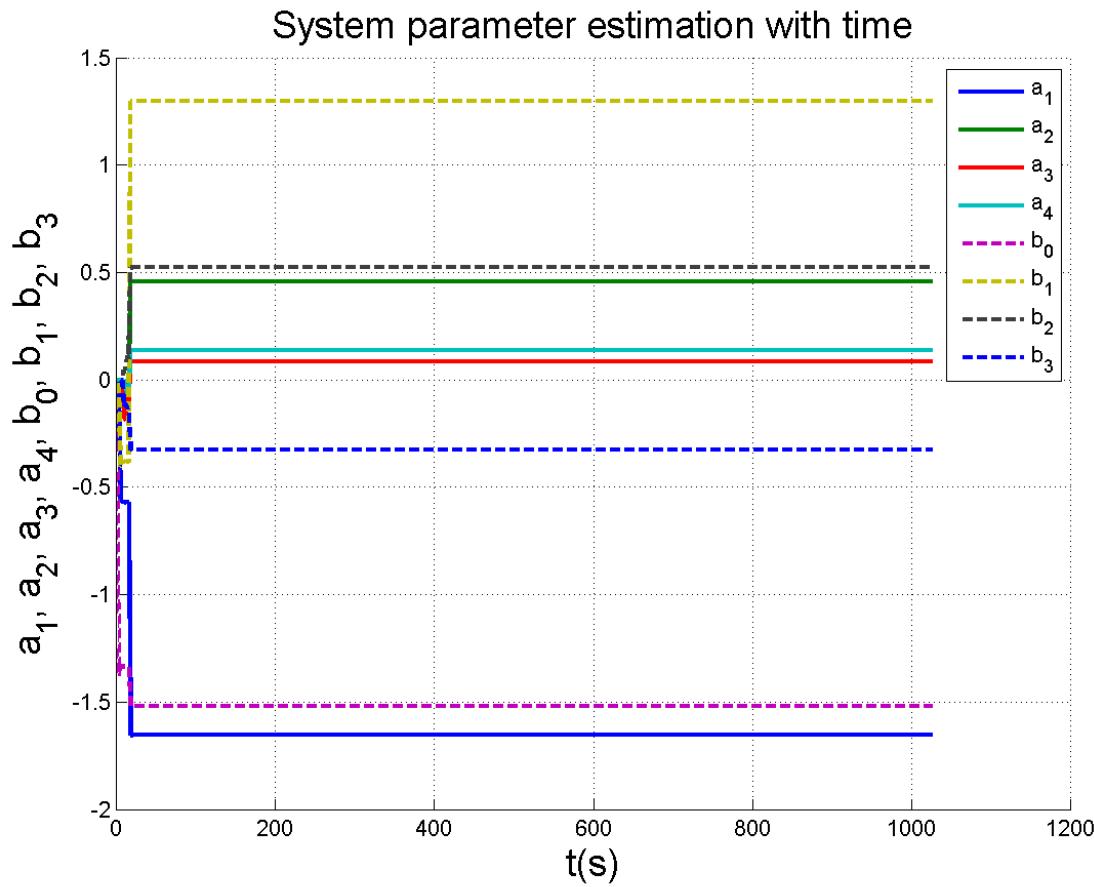
Flight Condition 1

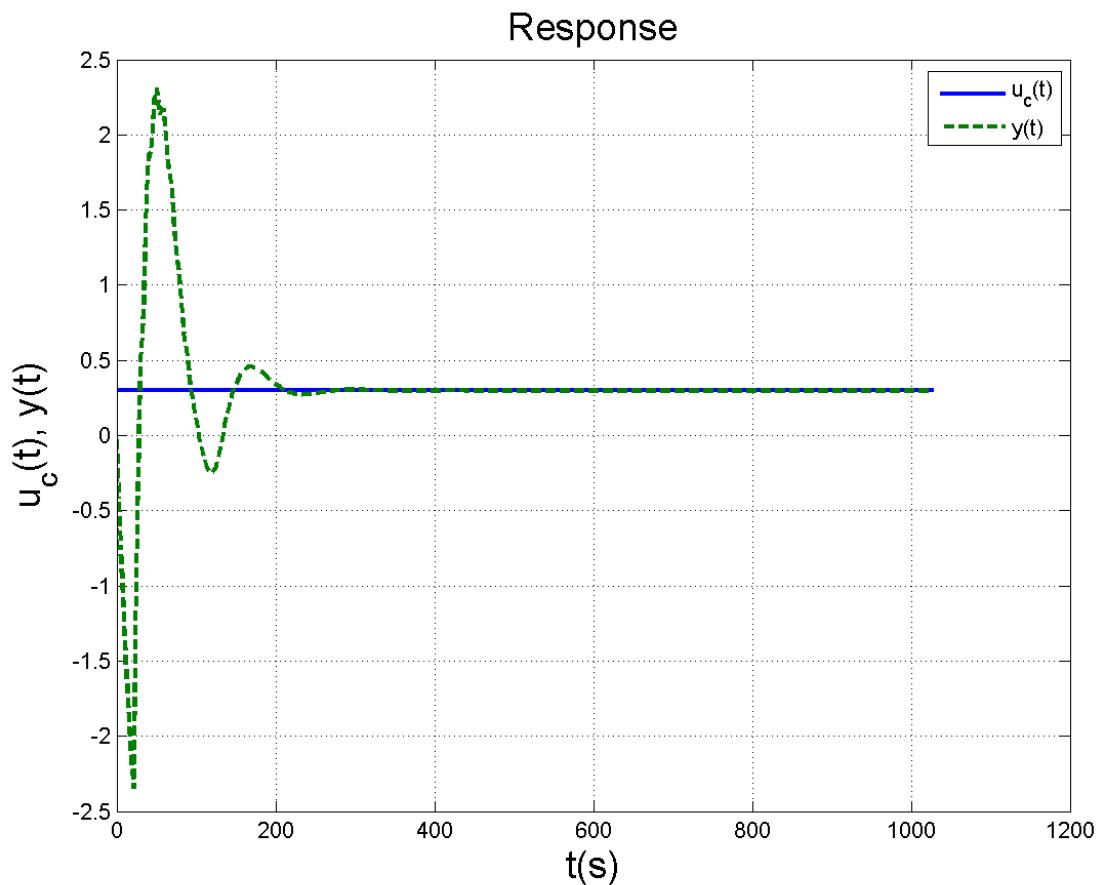
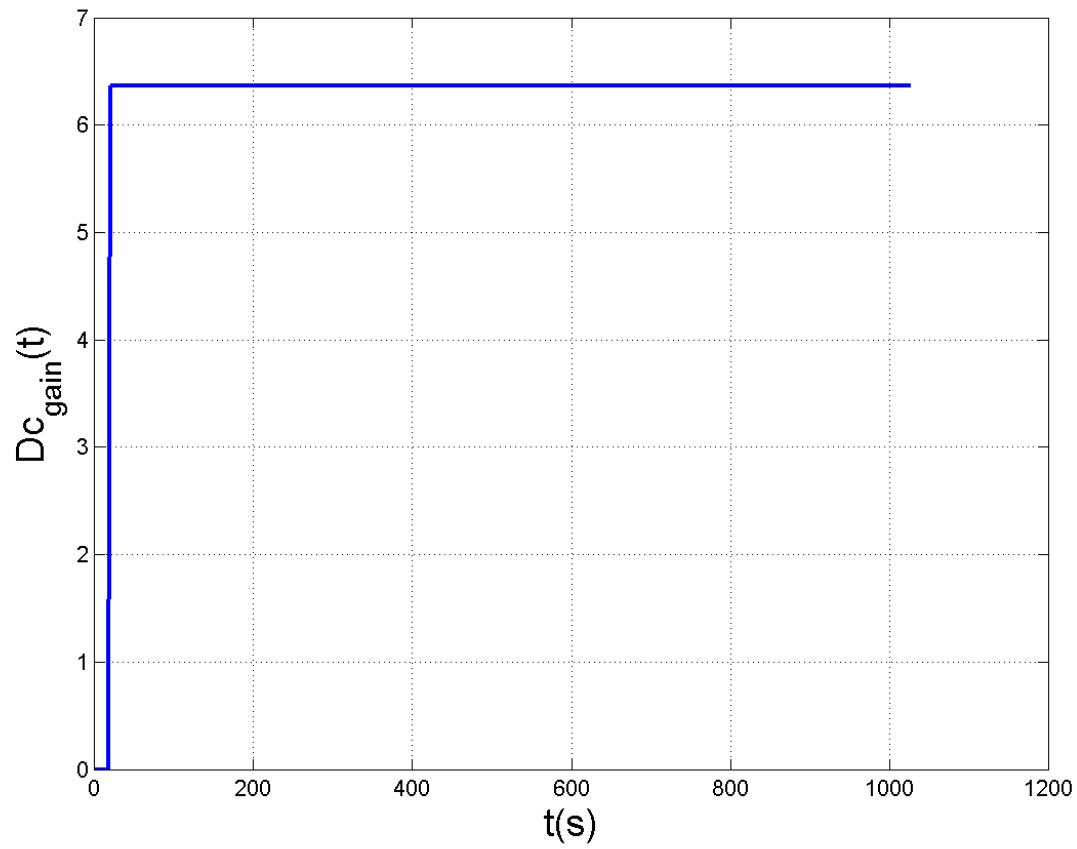


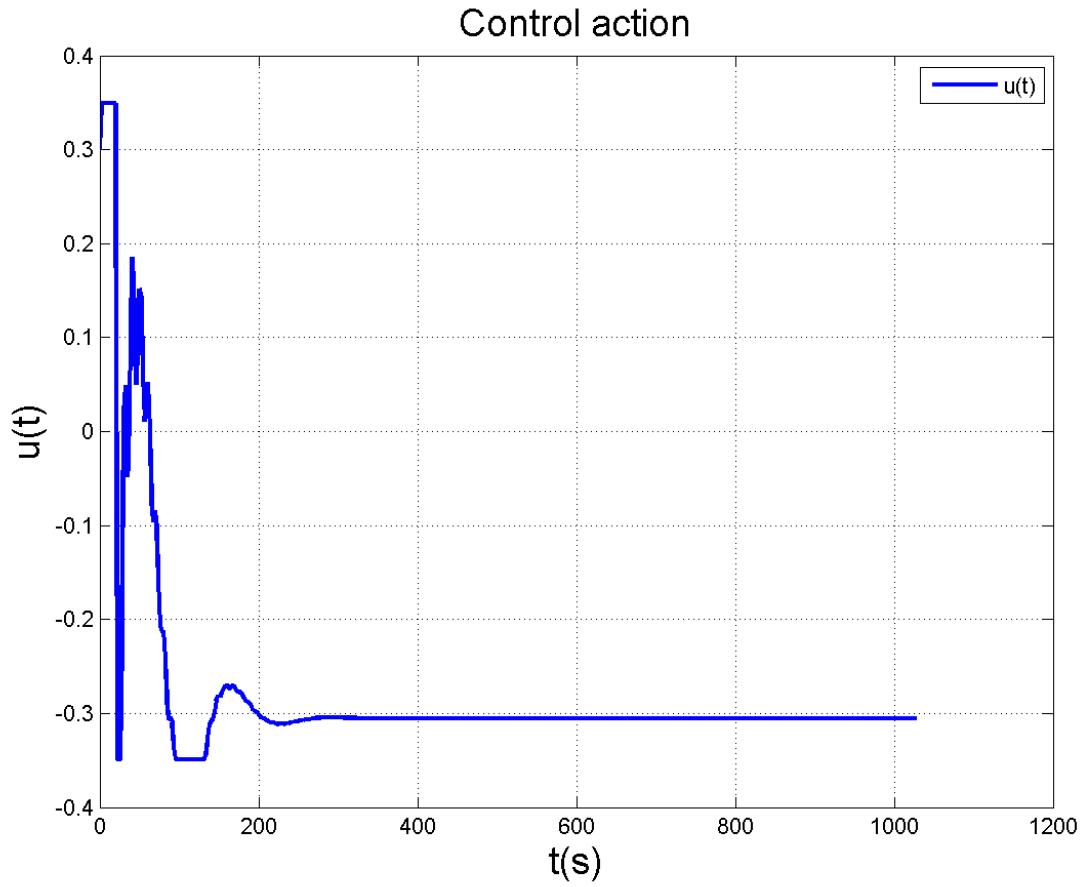




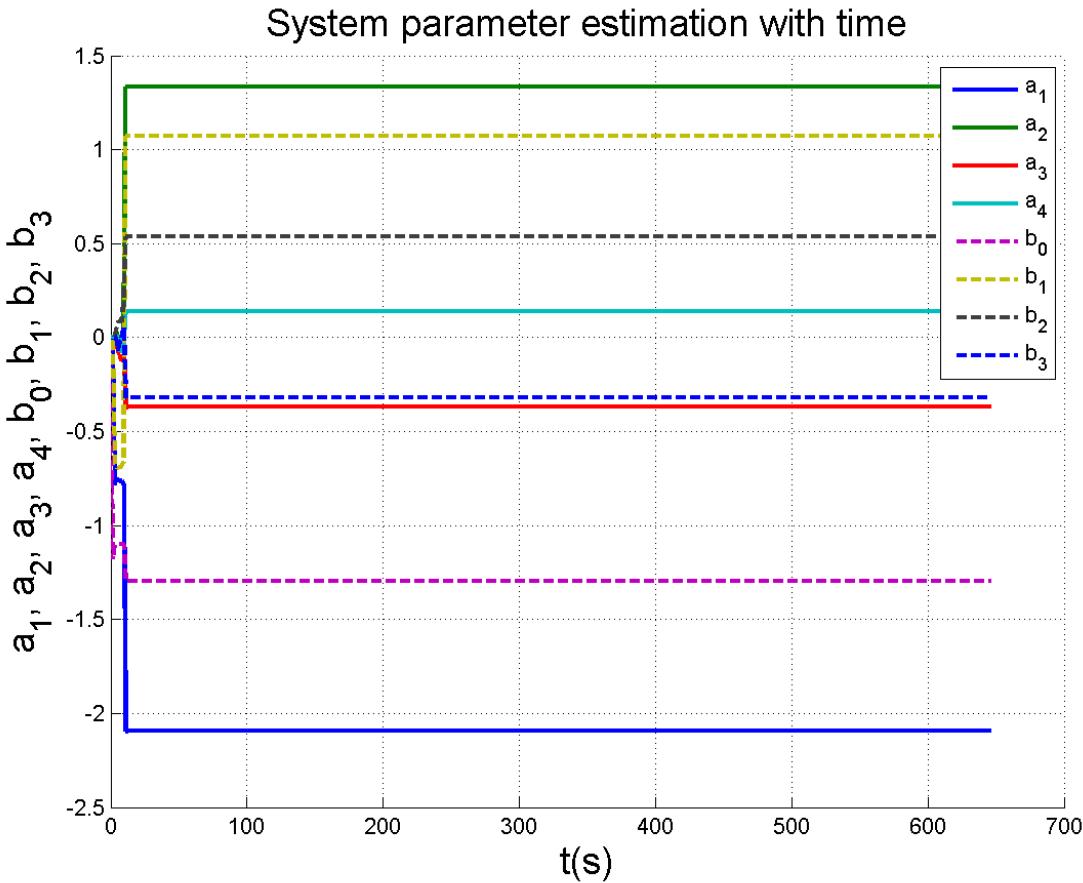
Flight Condition 2

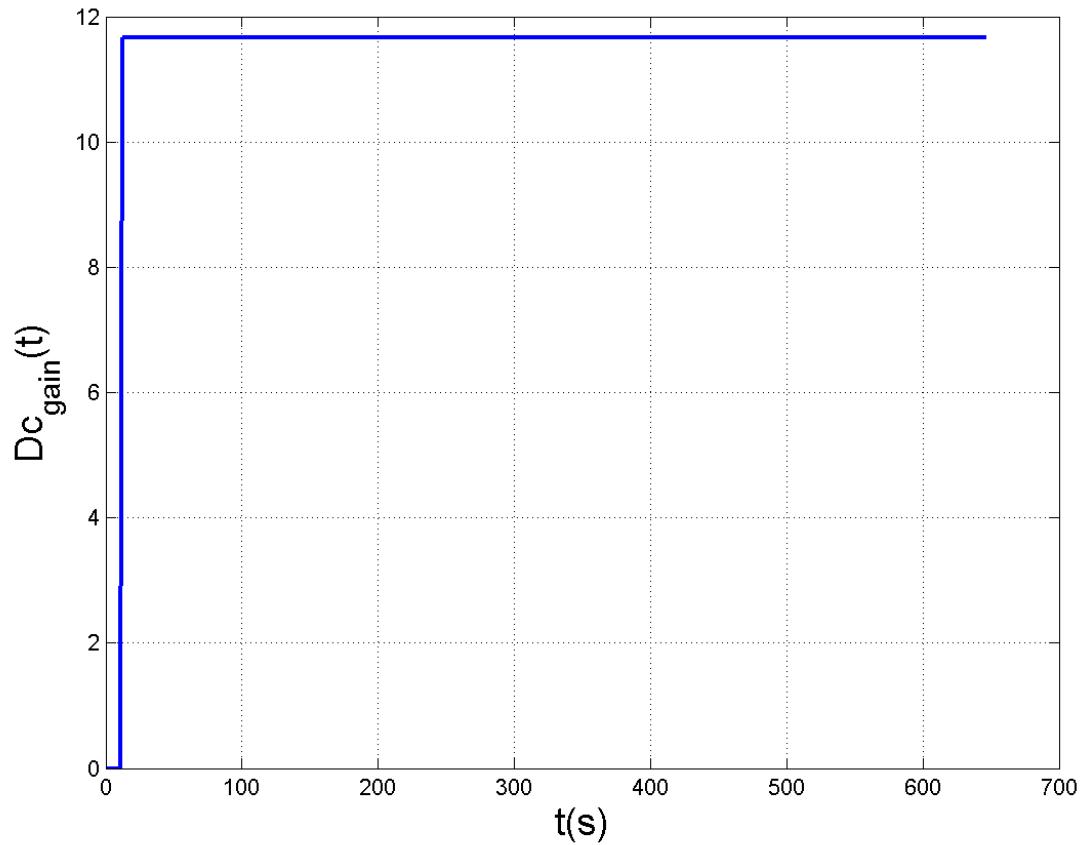
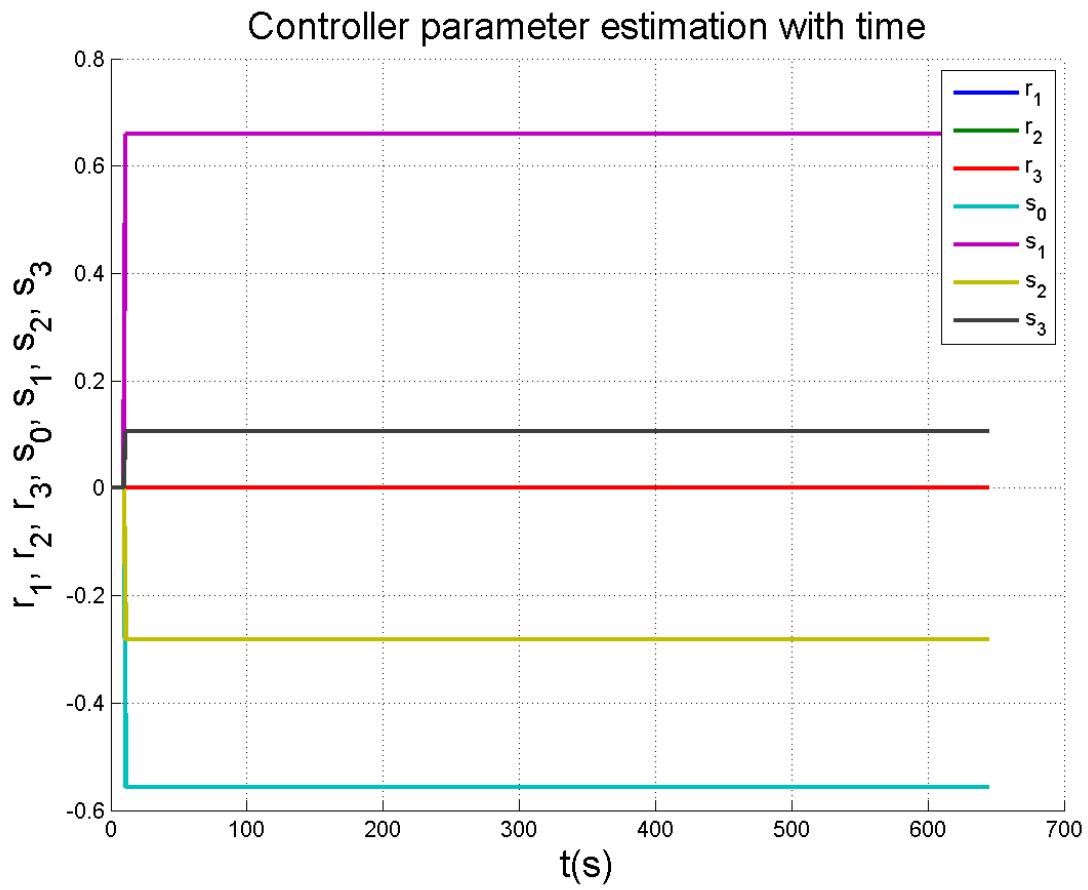


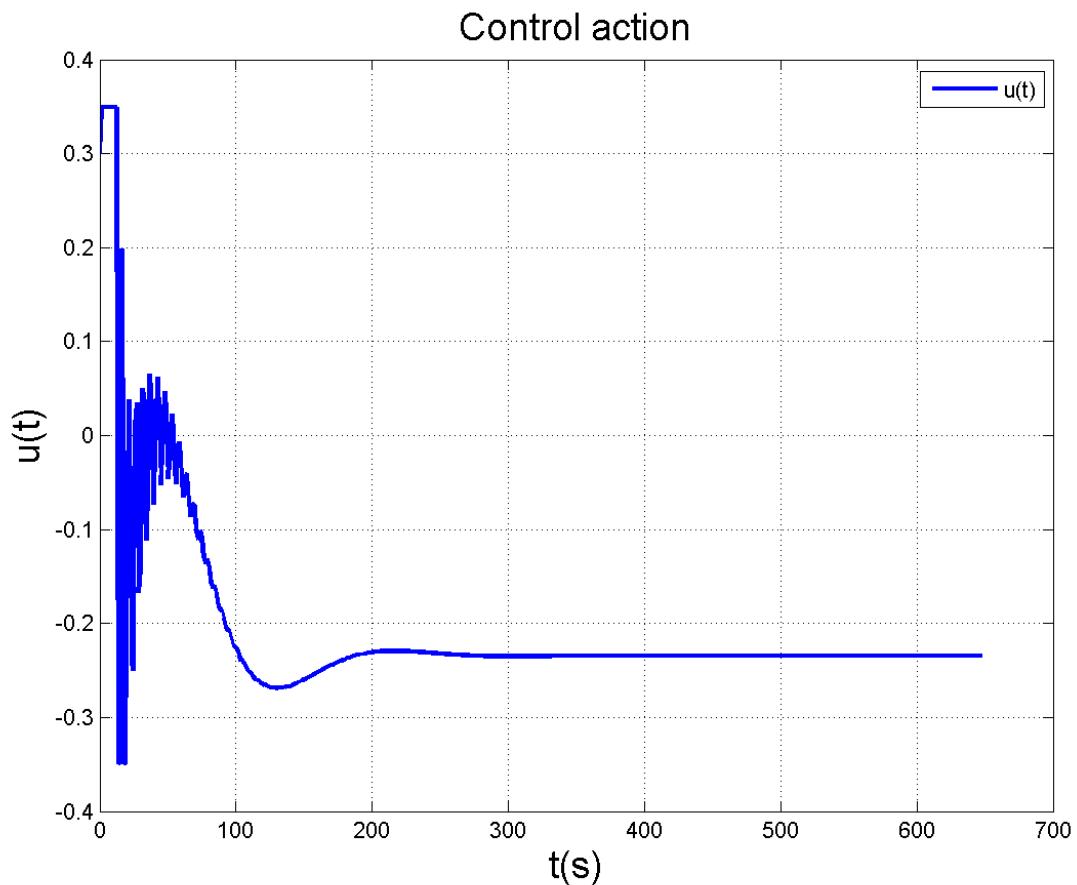
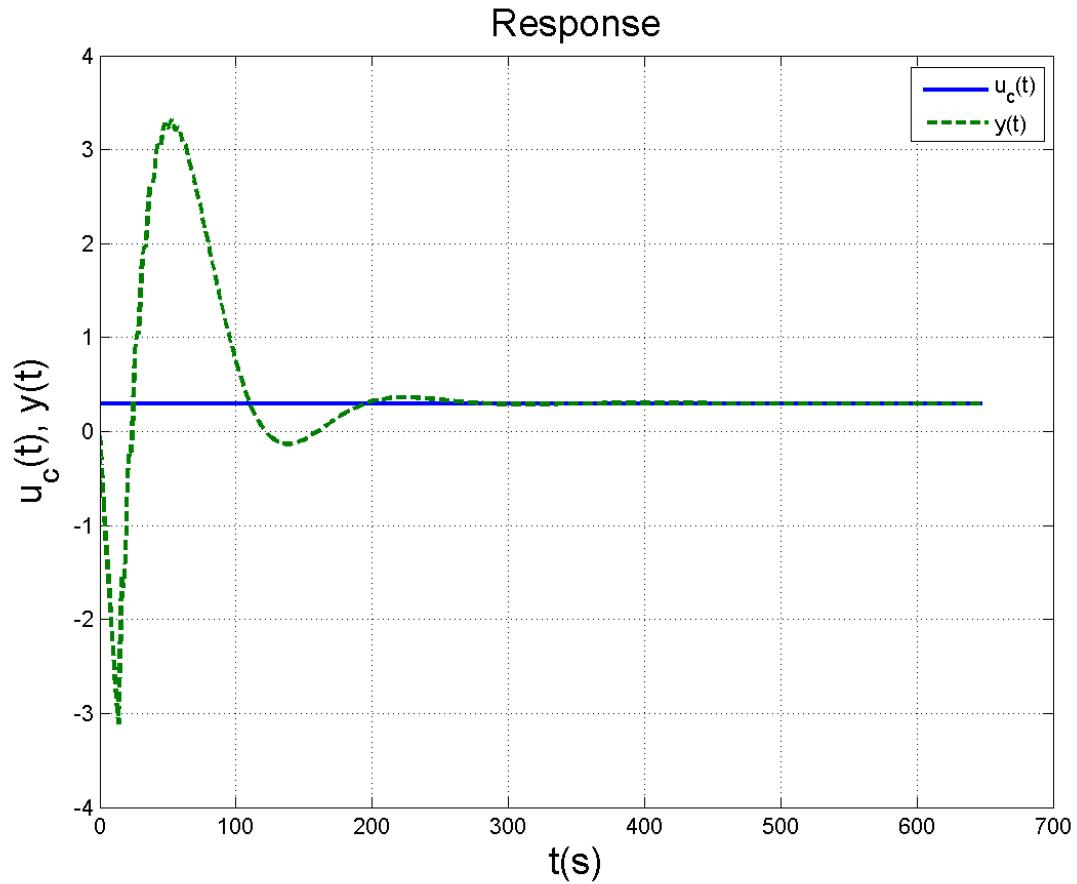




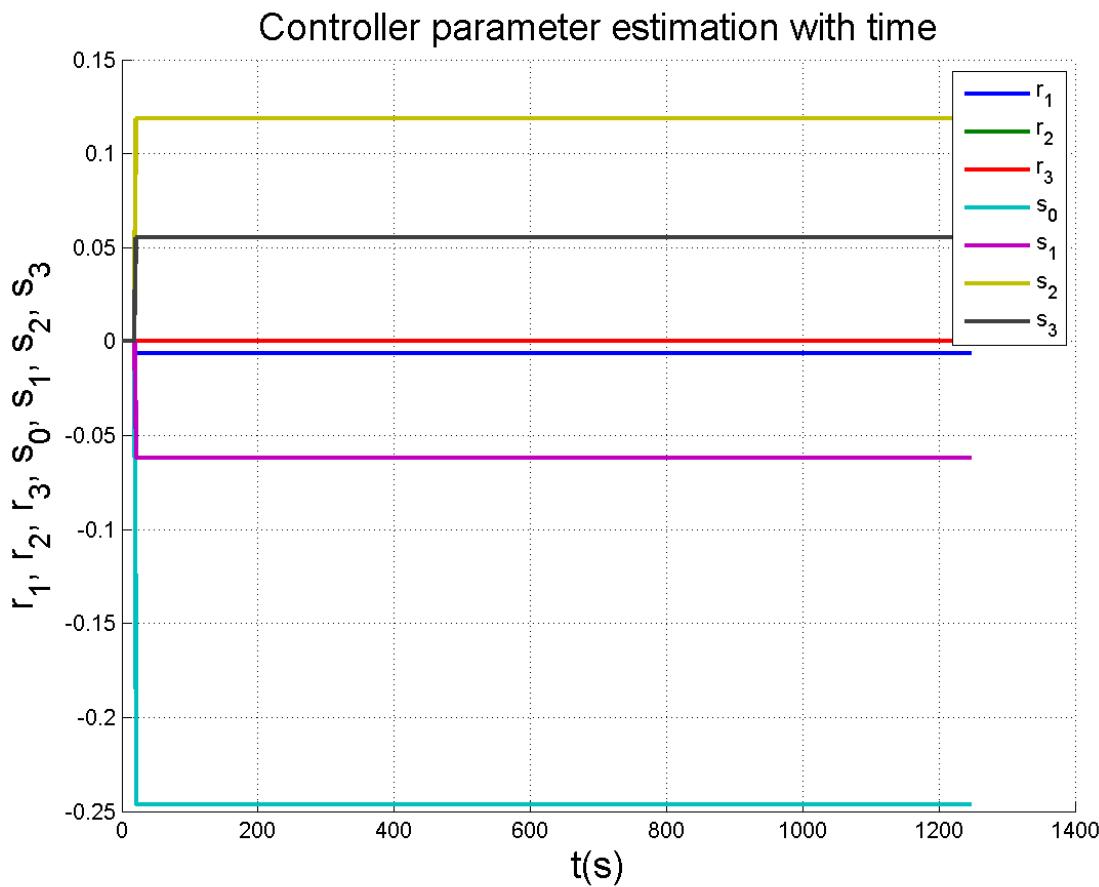
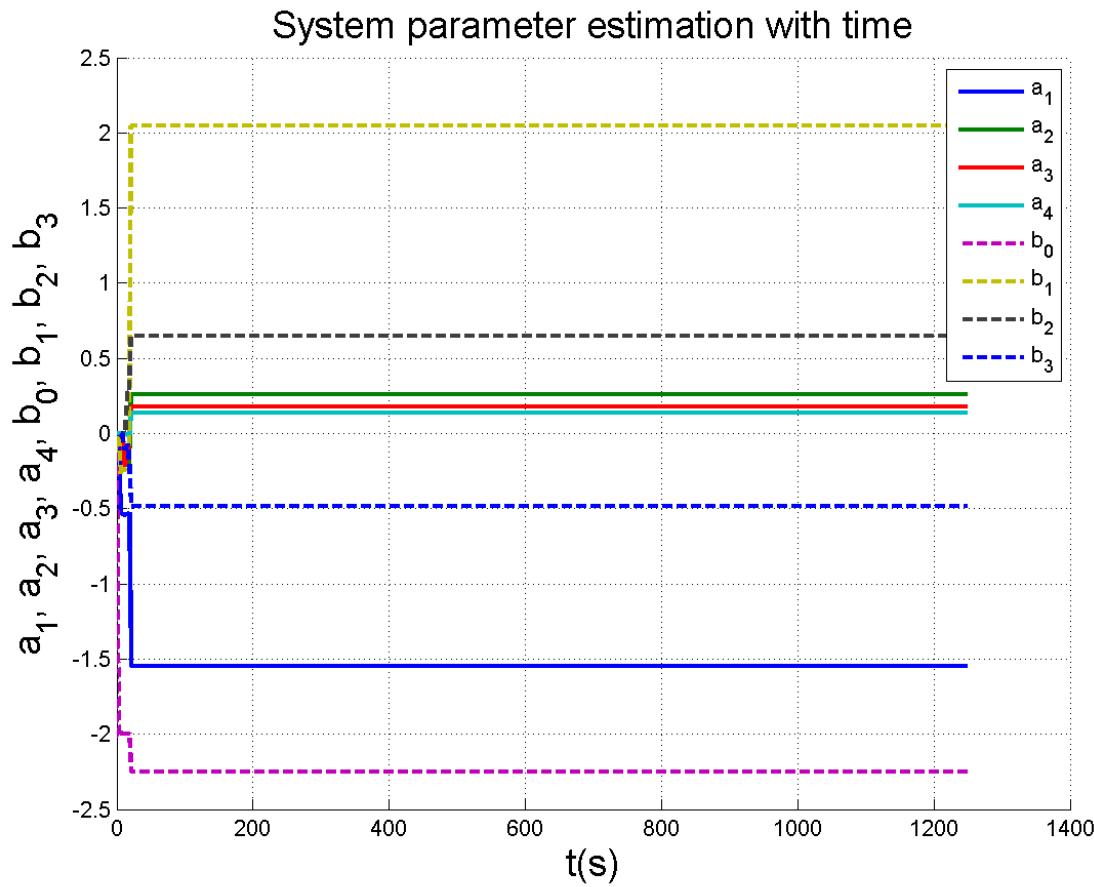
Flight Condition 3

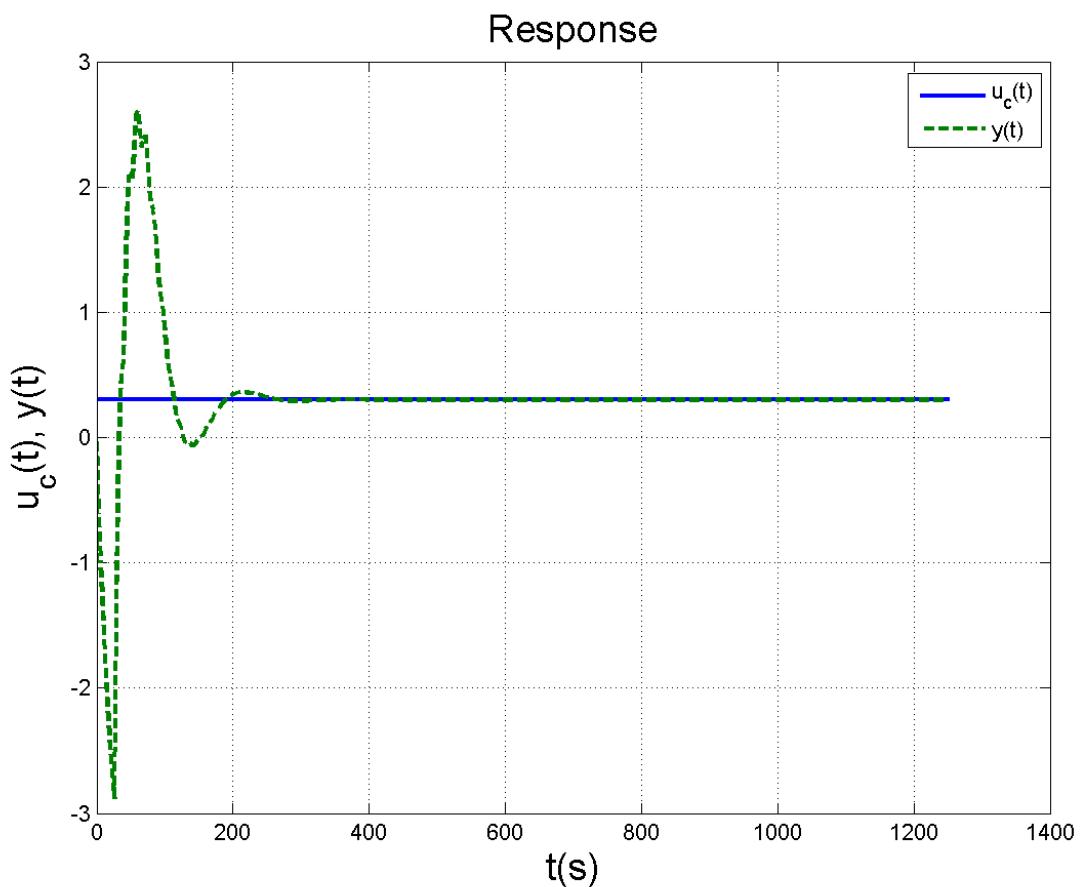
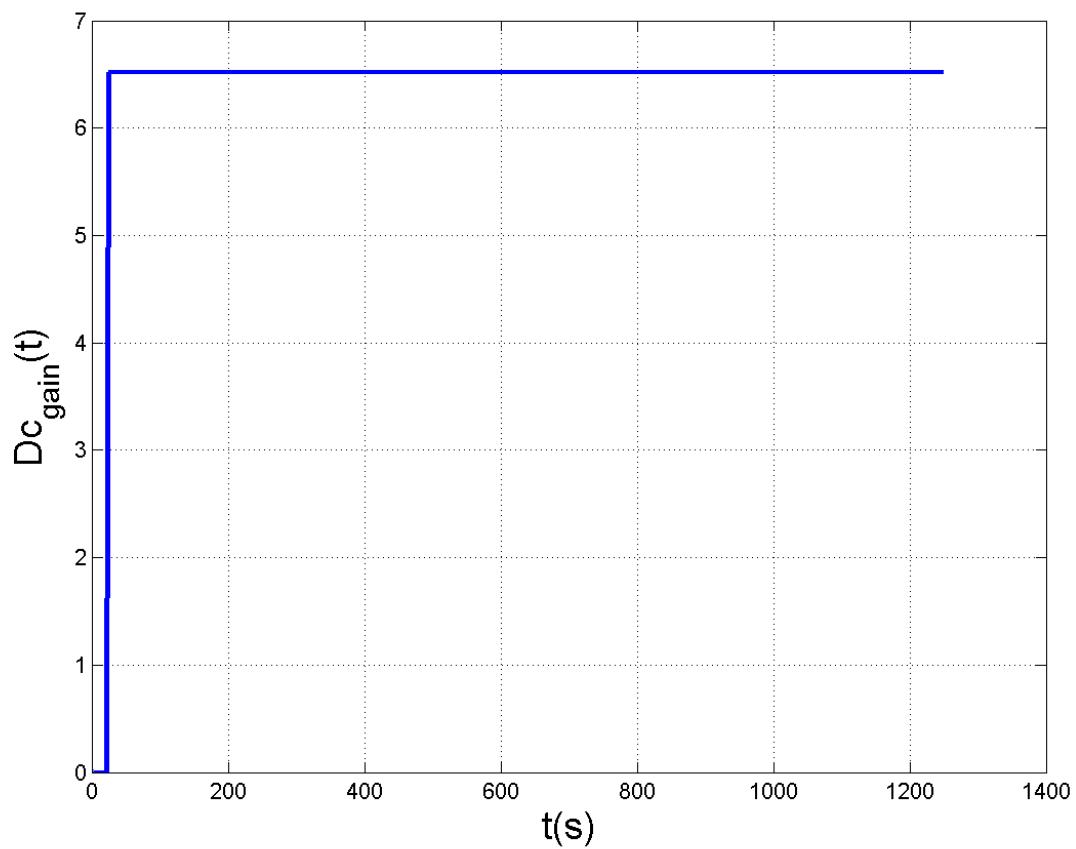


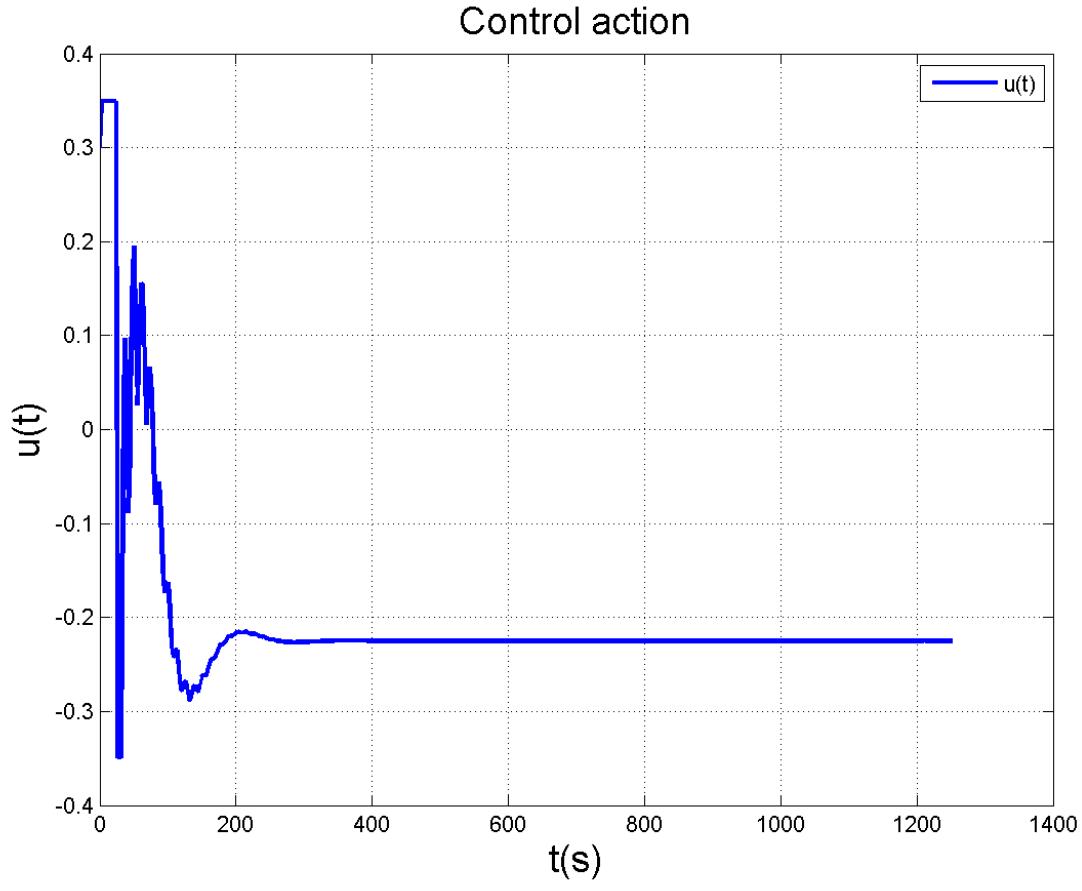




Flight Condition 4



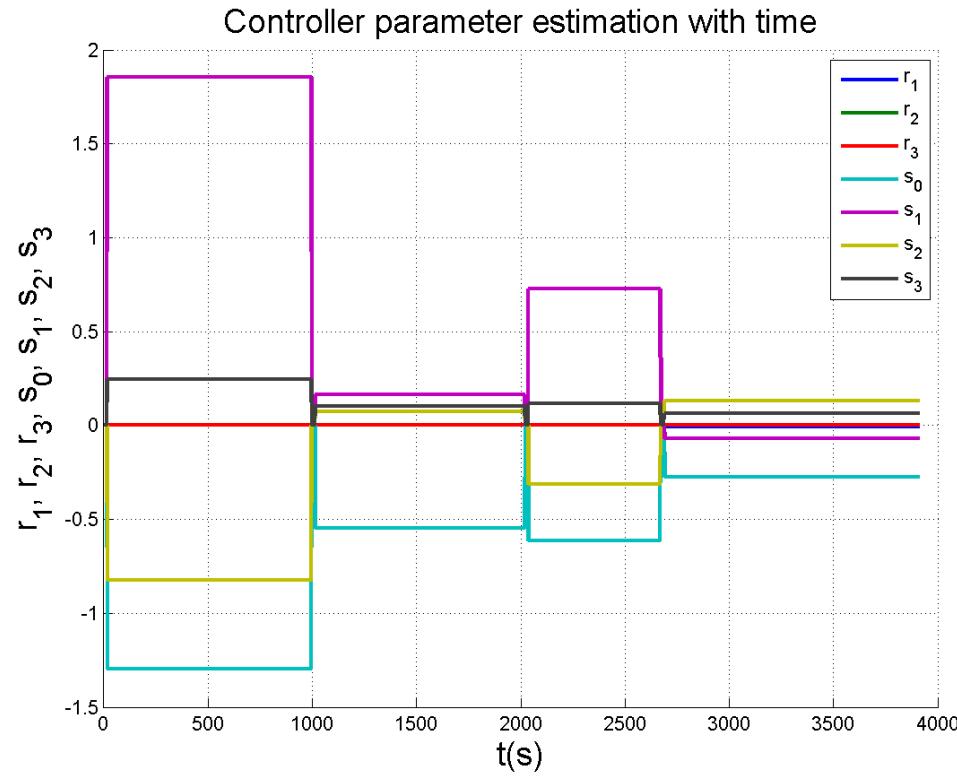
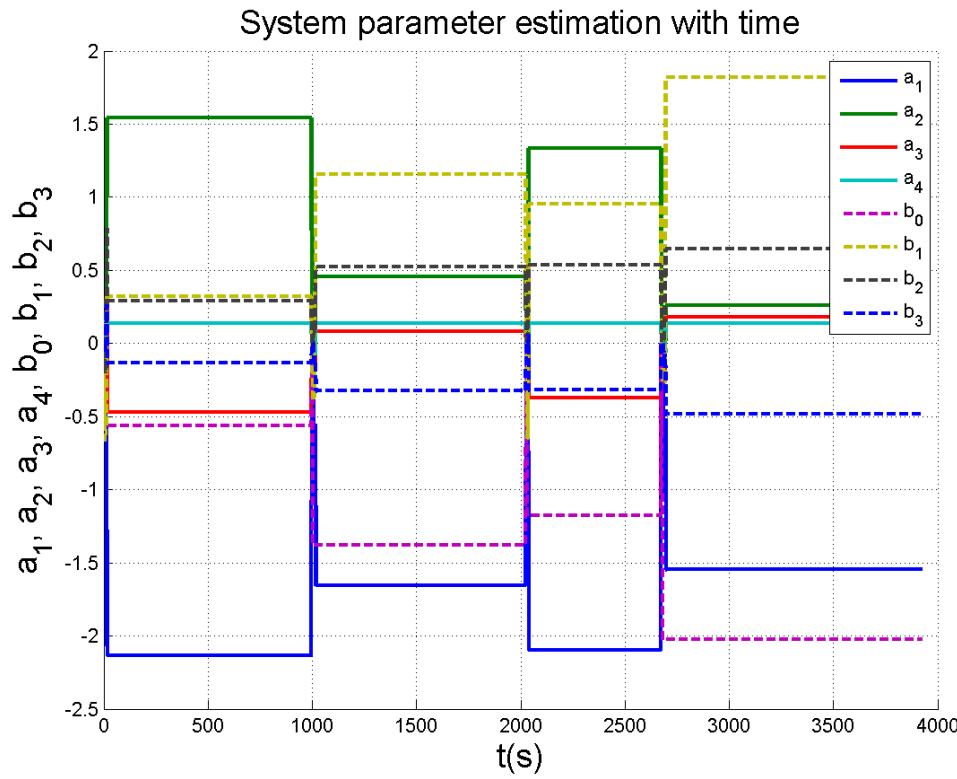


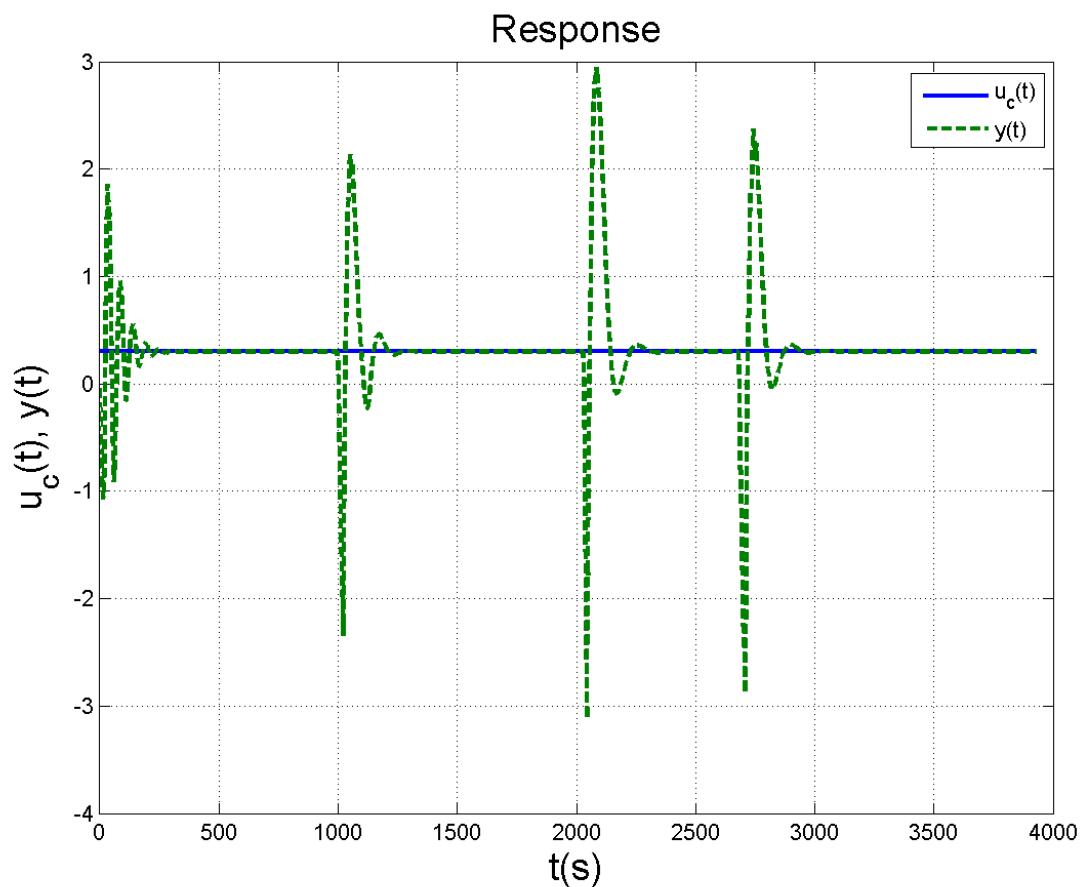
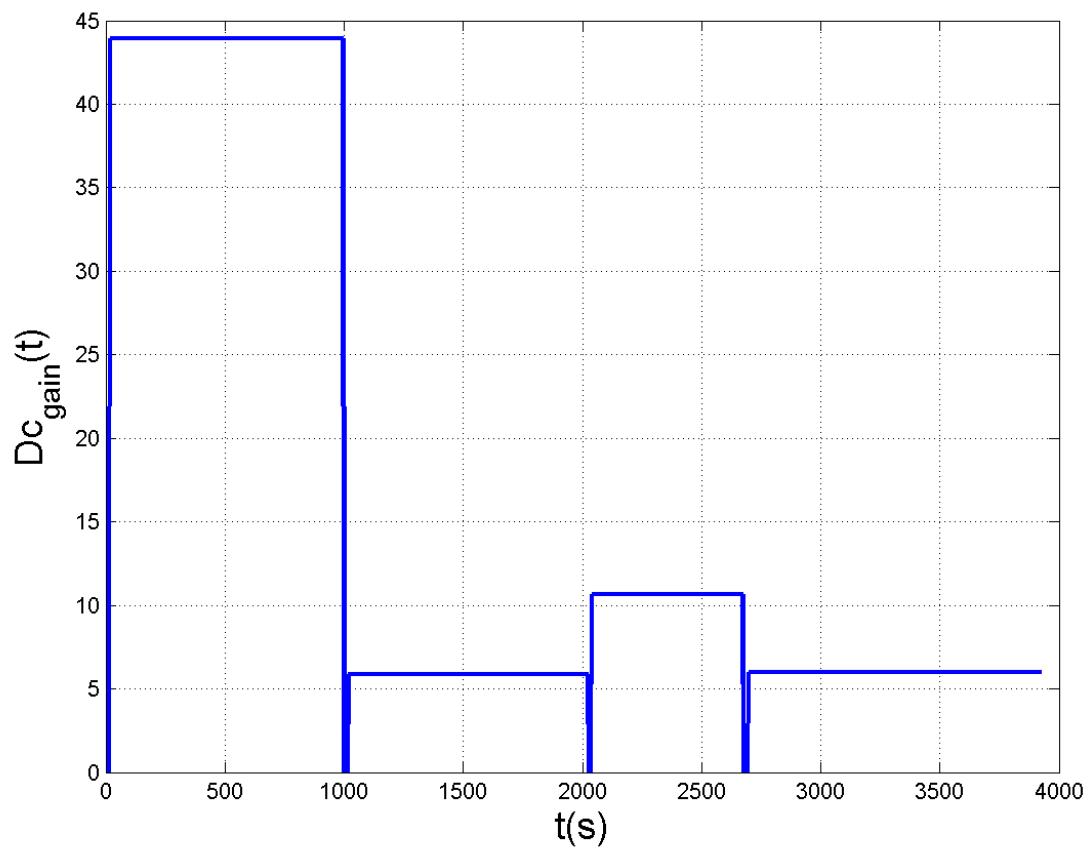


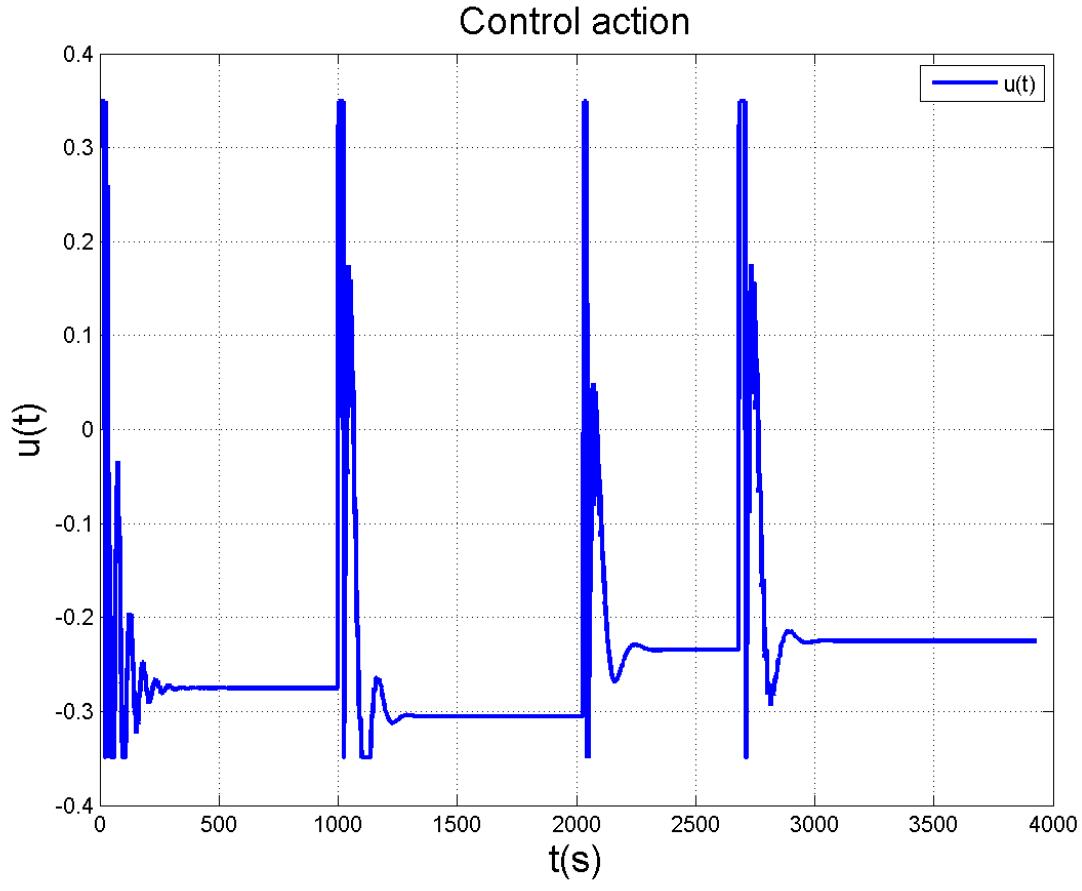
Results

Flight Condition	$G(z)$ Estimated	Feed Forward Controller	DC_{gain}
1	$G(z) = \frac{-0.6048z^3 + 0.3617z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$\frac{S}{R}(z) = \frac{-1.211z^3 + 1.73z^2 - 0.7676z + 0.2286}{z^3 - 2.801e-07z^2 + 2.802e-10z - 1.121e-13}$	$\frac{T}{R}(z) = 46.96$
2	$G(z) = \frac{-1.522z^3 + 1.297z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$\frac{S}{R}(z) = \frac{-0.4959z^3 + 0.1478z^2 + 0.06753z + 0.09092}{z^3 - 9.146e-05z^2 + 8.836e-07z - 3.452e-09}$	$\frac{T}{R}(z) = 6.363$
3	$G(z) = \frac{-1.295z^3 + 1.073z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$\frac{S}{R}(z) = \frac{-0.5561z^3 + 0.6602z^2 - 0.2826z + 0.1052}{z^3 - 2.732e-07z^2 + 2.731e-10z - 1.093e-13}$	$\frac{T}{R}(z) = 11.66$
4	$G(z) = \frac{-2.25z^3 + 2.049z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$\frac{S}{R}(z) = \frac{-0.2462z^3 - 0.06174z^2 + 0.1184z + 0.05538}{z^3 - 0.006598z^2 + 0.0002607z - 4.372e-06}$	$\frac{T}{R}(z) = 6.515$

For All Flight Conditions Together







Results

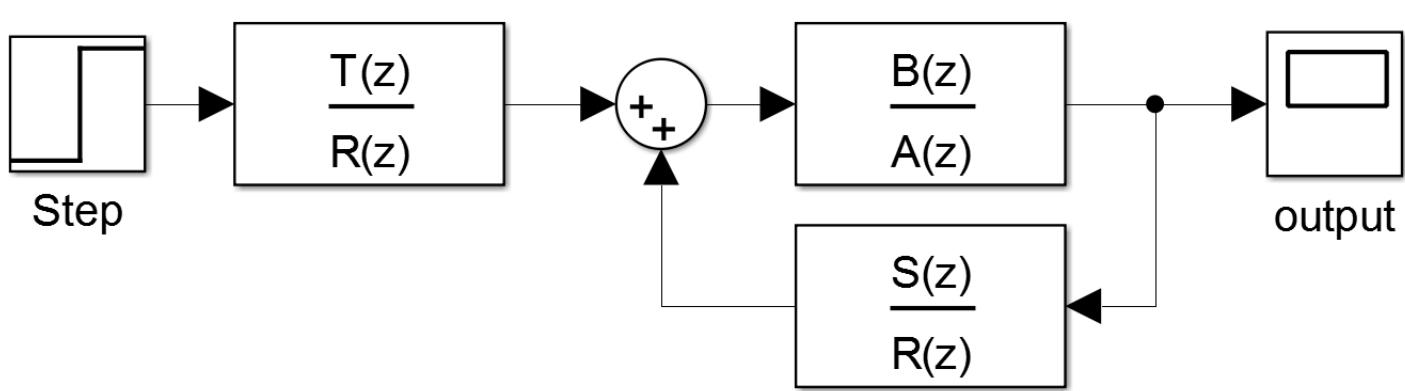
Flight Condition	$G(z)$ Estimated	Feed Forward Controller	DC_{gain}
1	$G(z) = \frac{-0.5646z^3 + 0.3215z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$\frac{S}{R}(z) = \frac{-1.297z^3 + 1.853z^2 - 0.8223z + 0.2449}{z^3 - 2.801e-07z^2 + 2.802e-10z - 1.121e-13}$	$\frac{T}{R}(z) = 43.91$
2	$G(z) = \frac{-1.378z^3 + 1.153z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$\frac{S}{R}(z) = \frac{-0.5478z^3 + 0.1633z^2 + 0.07459z + 0.1004}{z^3 - 9.146e-05z^2 + 8.836e-07z - 3.452e-09}$	$\frac{T}{R}(z) = 5.856$
3	$G(z) = \frac{-1.176z^3 + 0.9539z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$\frac{S}{R}(z) = \frac{-0.6125z^3 + 0.7272z^2 - 0.3113z + 0.1159}{z^3 - 2.732e-07z^2 + 2.731e-10z - 1.092e-13}$	$\frac{T}{R}(z) = 10.68$
4	$G(z) = \frac{-2.023z^3 + 1.822z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$\frac{S}{R}(z) = \frac{-0.274z^3 - 0.06869z^2 + 0.1317z + 0.06162}{z^3 - 0.006598z^2 + 0.0002607z - 4.372e-06}$	$\frac{T}{R}(z) = 5.957$

Comments

- The system parameter goes to its true values if i control all flight conditions together.
- There is a change in controller parameter between the controller of all flight conditions and the controller of each flight condition.

1.6.3 Indirect Self-Tuning Regulator Using Model Following Without Zero Cancellation For Step Input

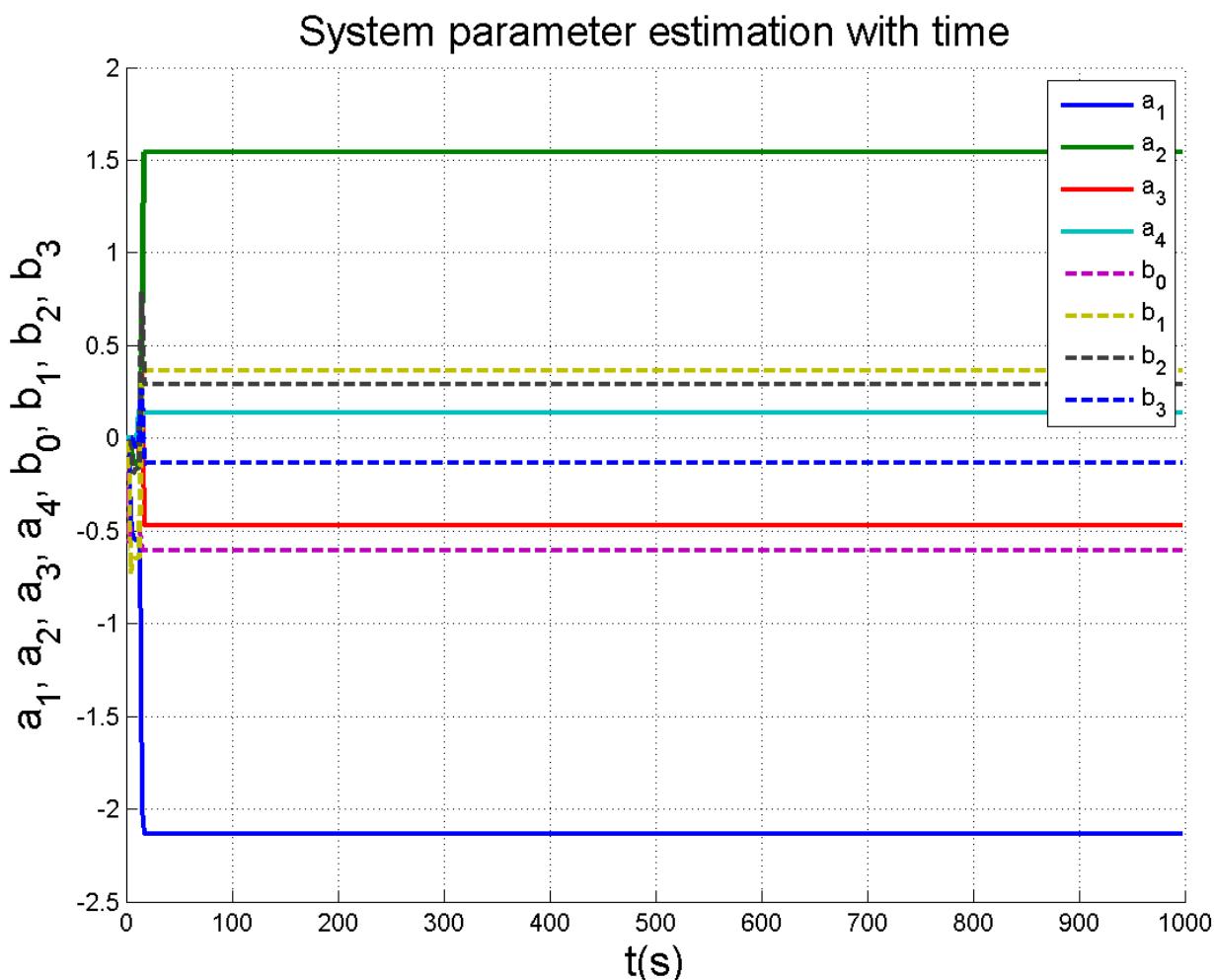
Controller Scheme

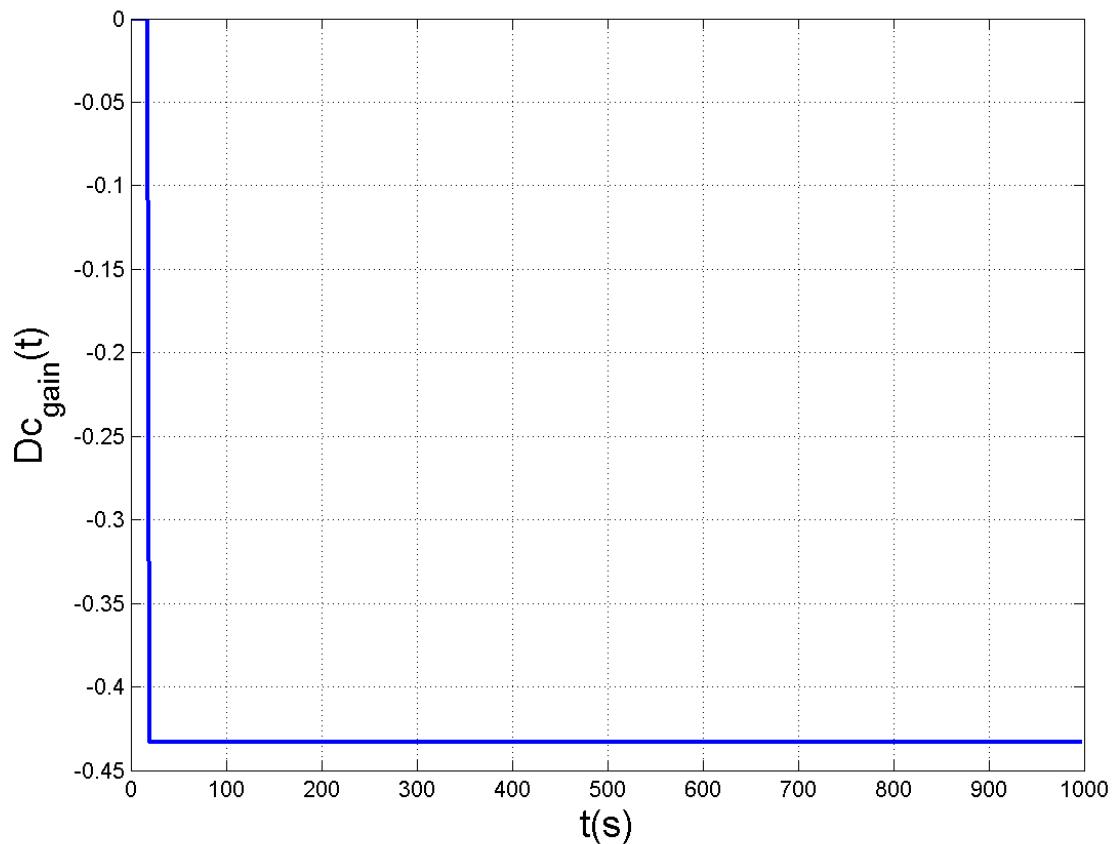
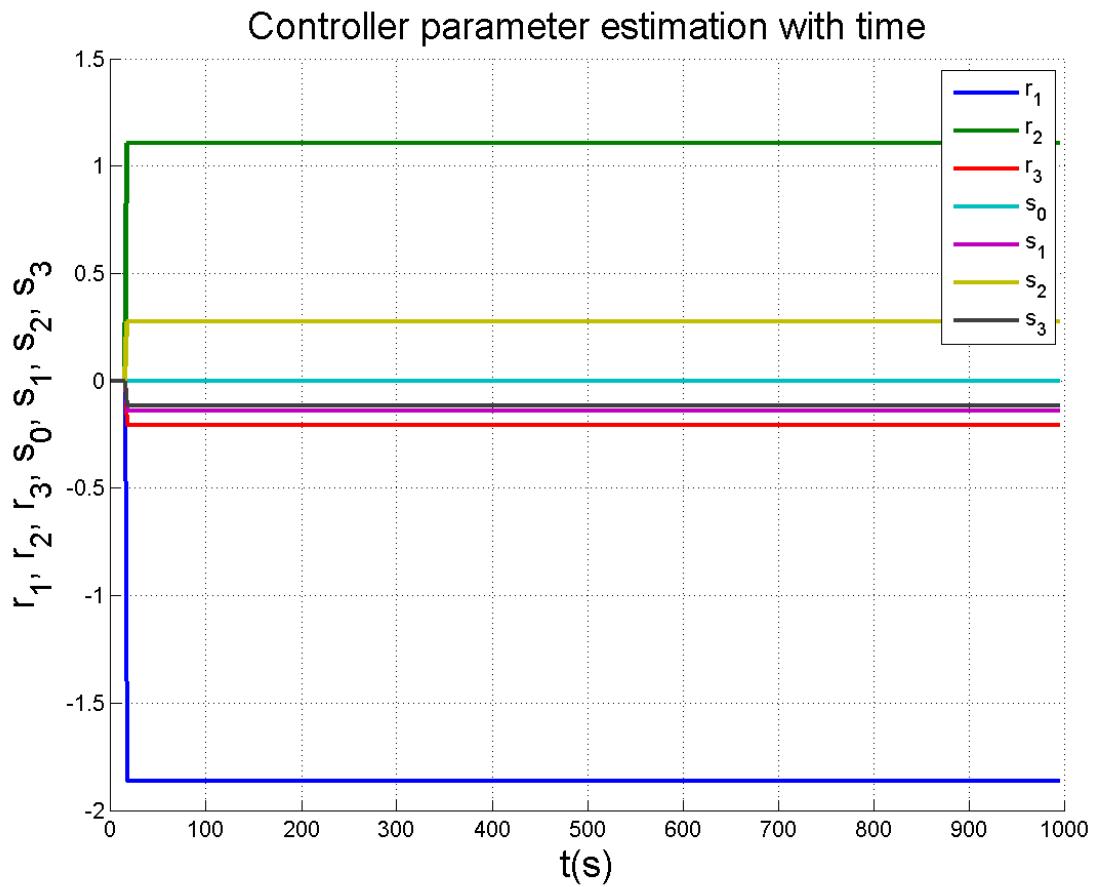


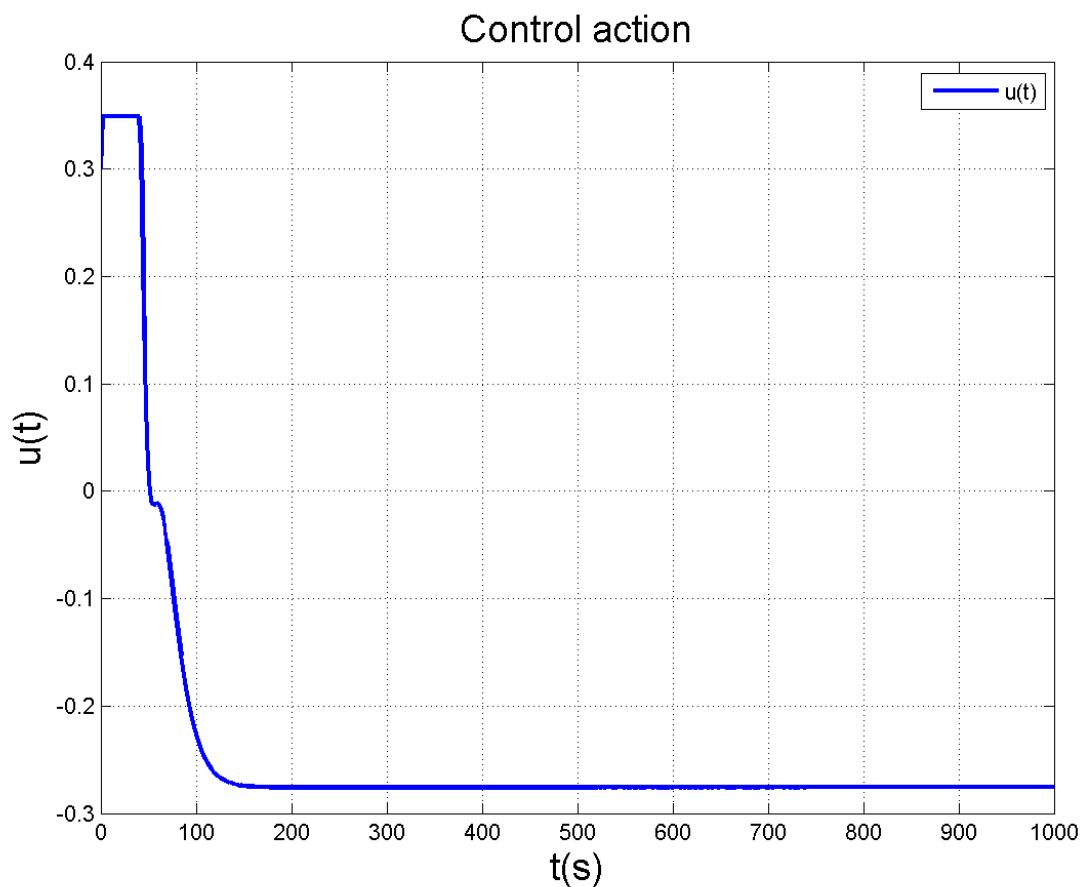
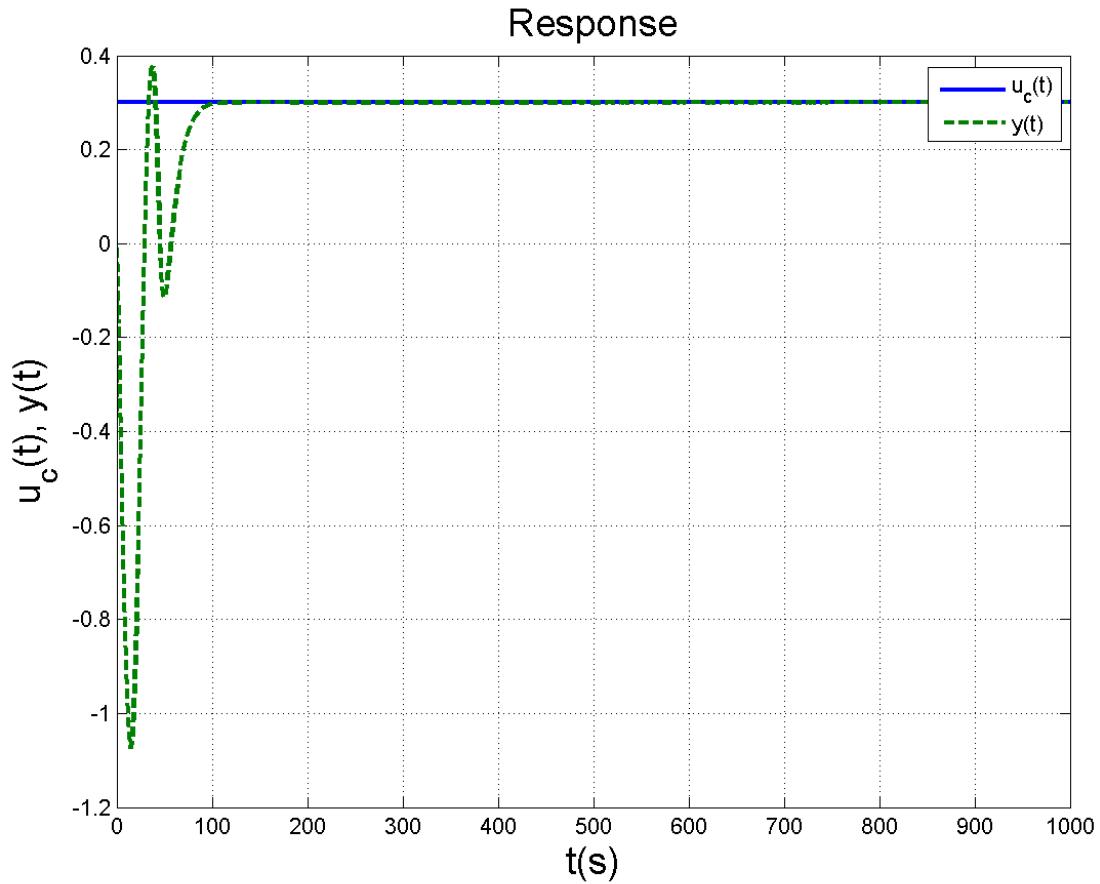
Required Poles in Z-Domain

Flight Condition	A_m	A_0
1	[0.85, 0.75]	[0.4, 0.4, 0.4, 0.4, 0.8]
2	[0.8, 0.8]	[0.2, 0.2, 0.2, 0.2, 0.2]
3	[0.95, 0.88]	[0.2, 0.2, 0.2, 0.2, 0.2]
4	[0.6, 0.85]	[0.2, 0.2, 0.2, 0.2, 0.2]

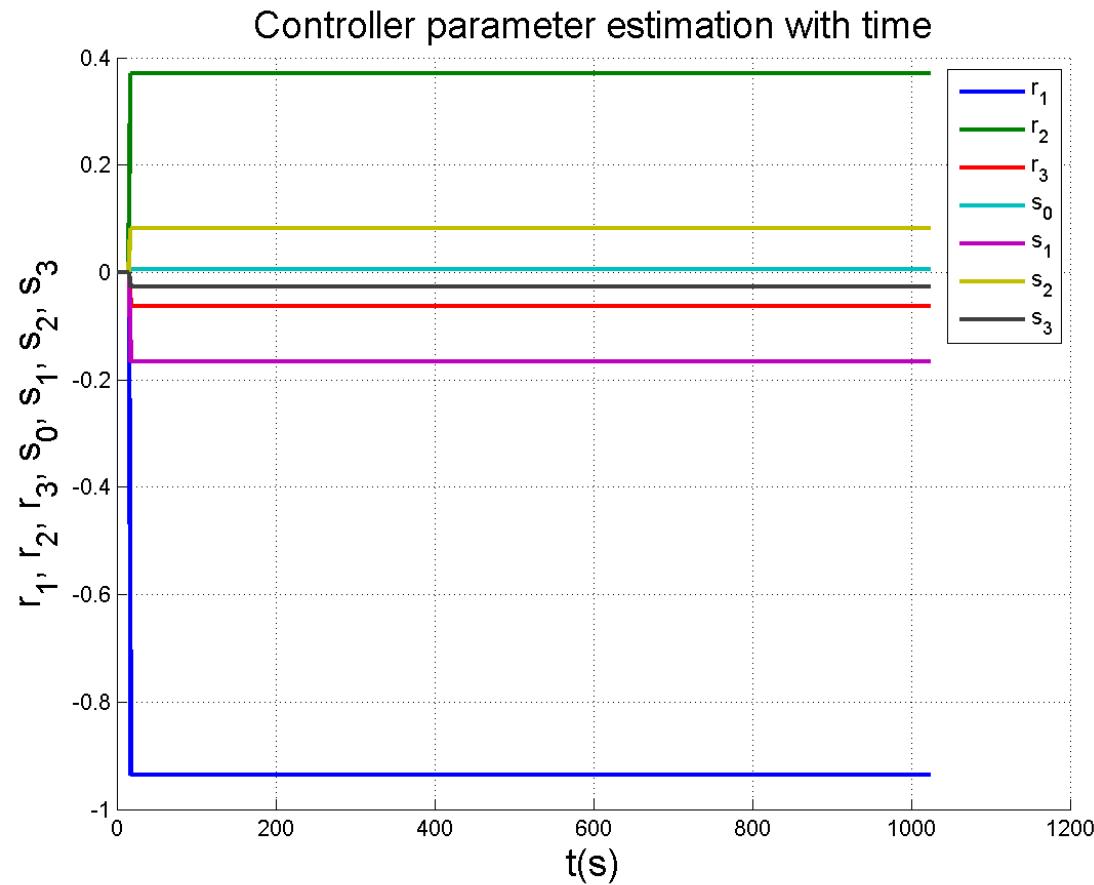
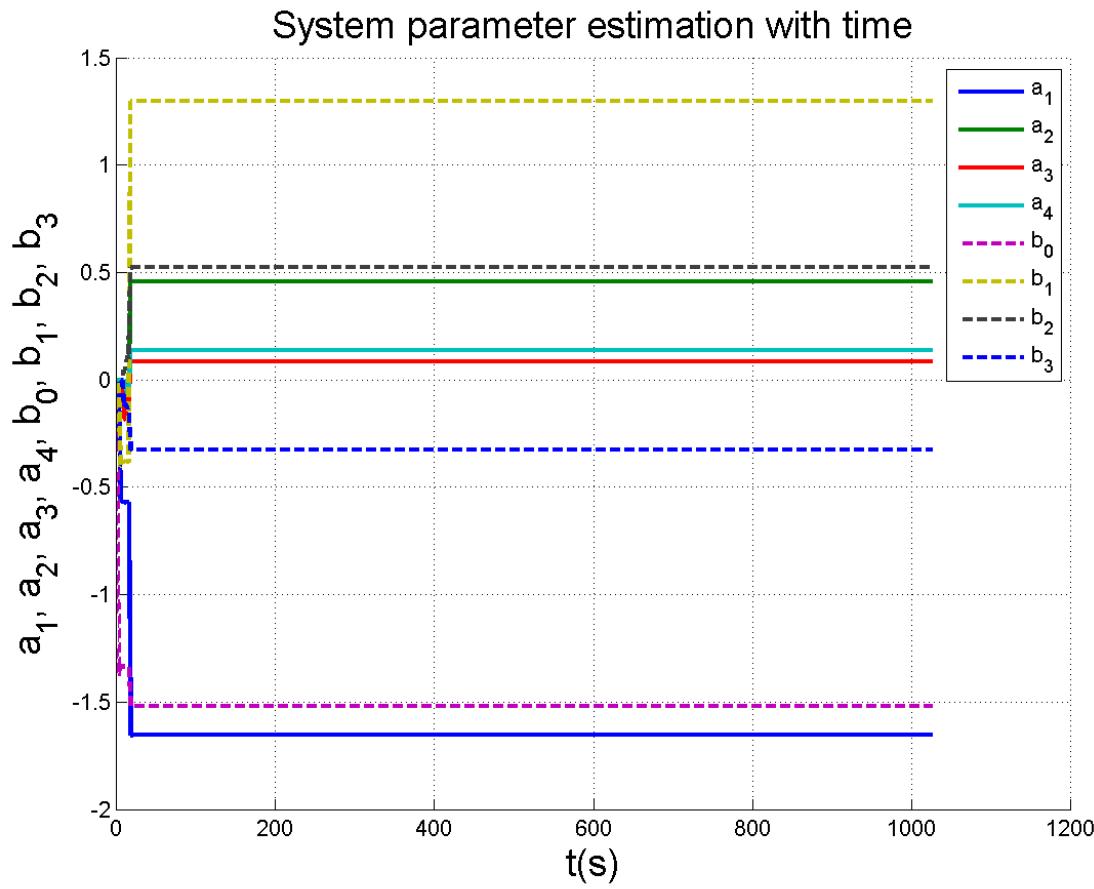
Flight Condition 1

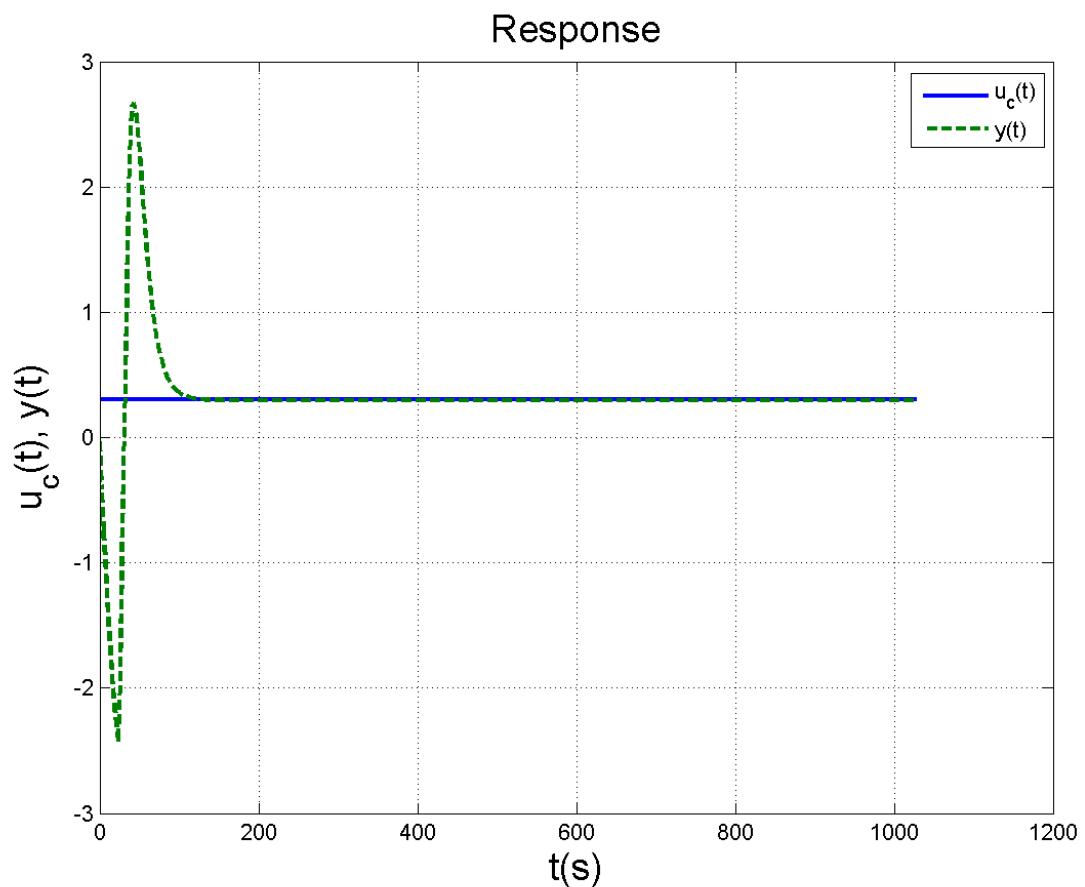
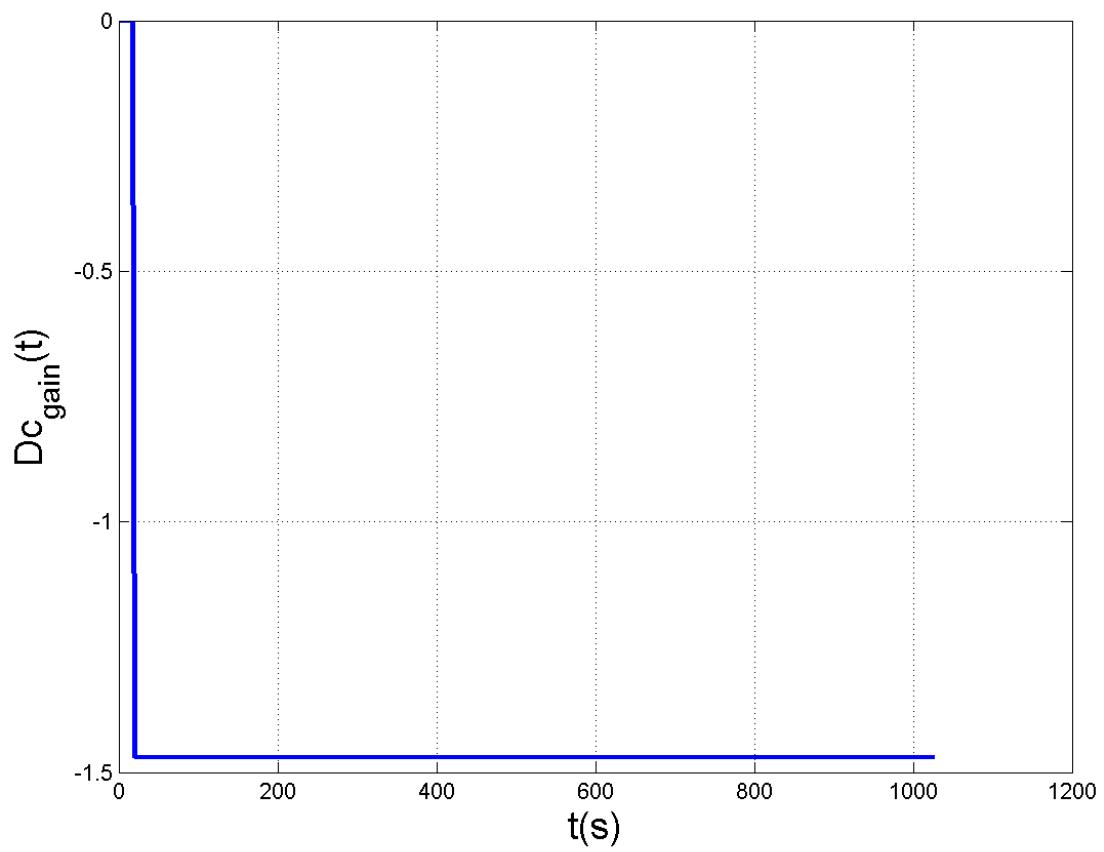


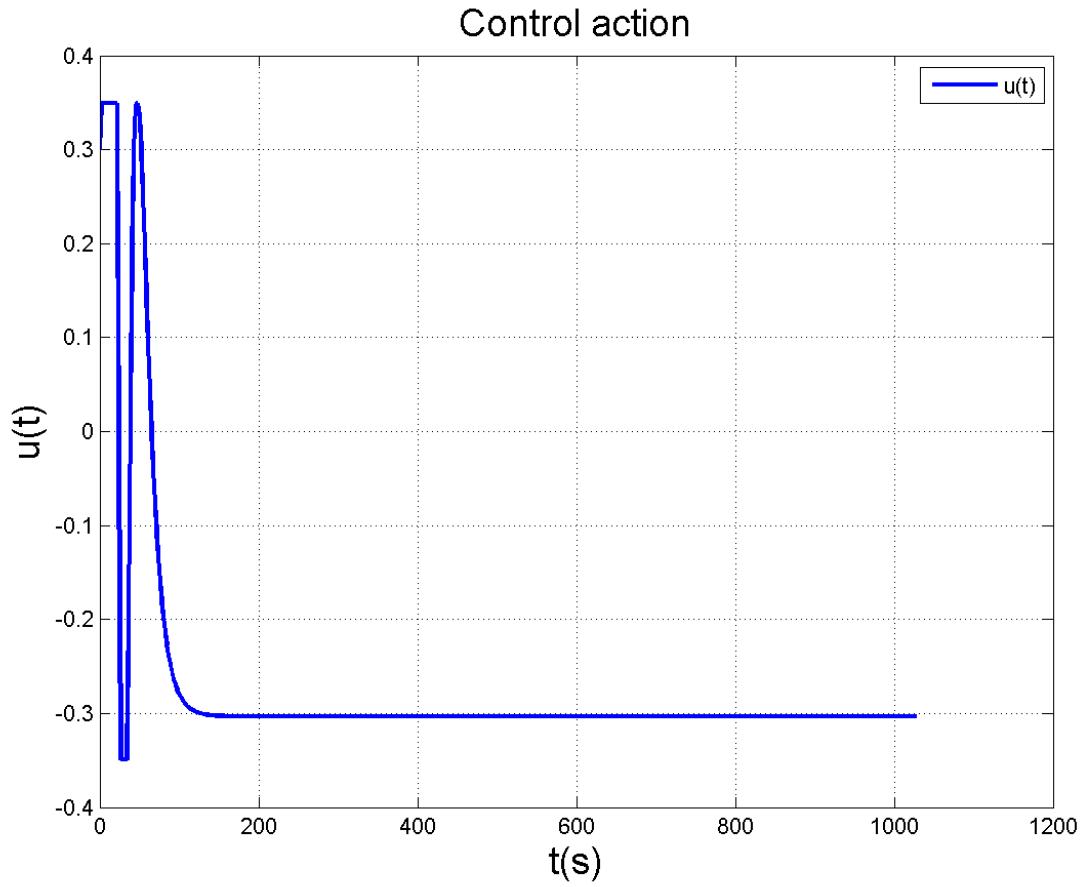




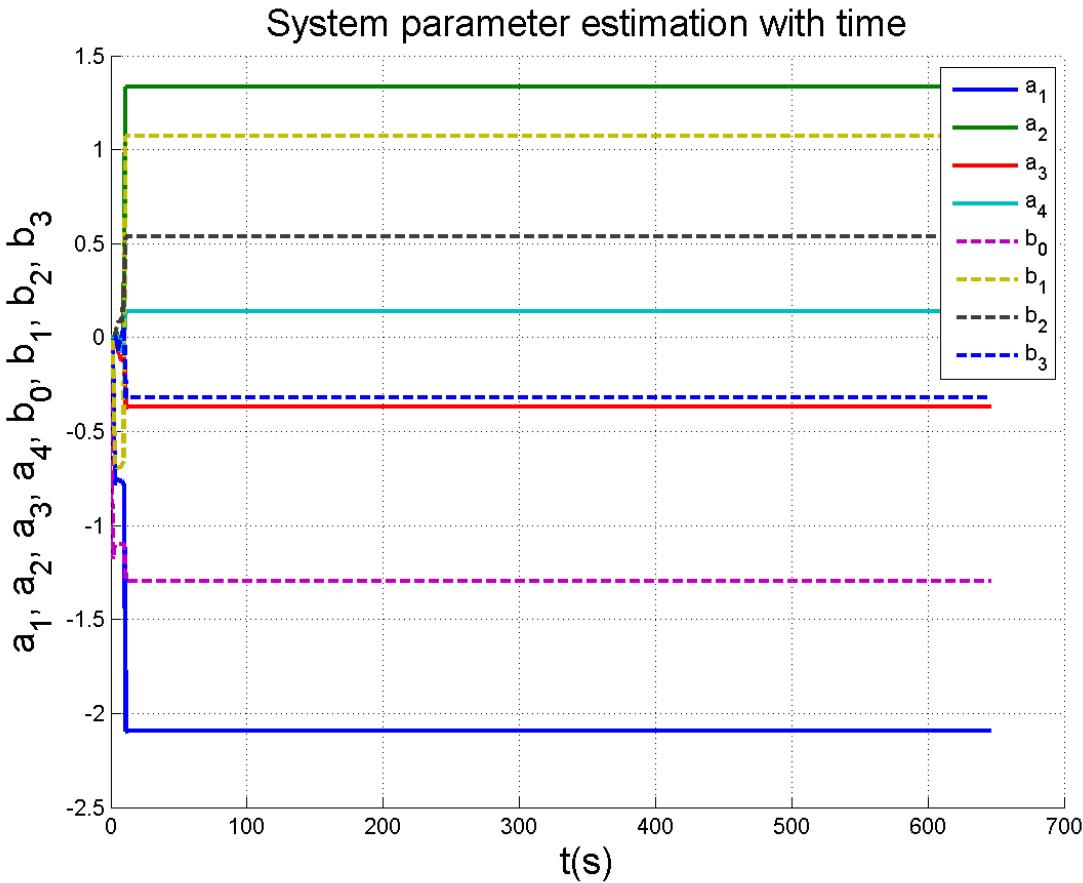
Flight Condition 2

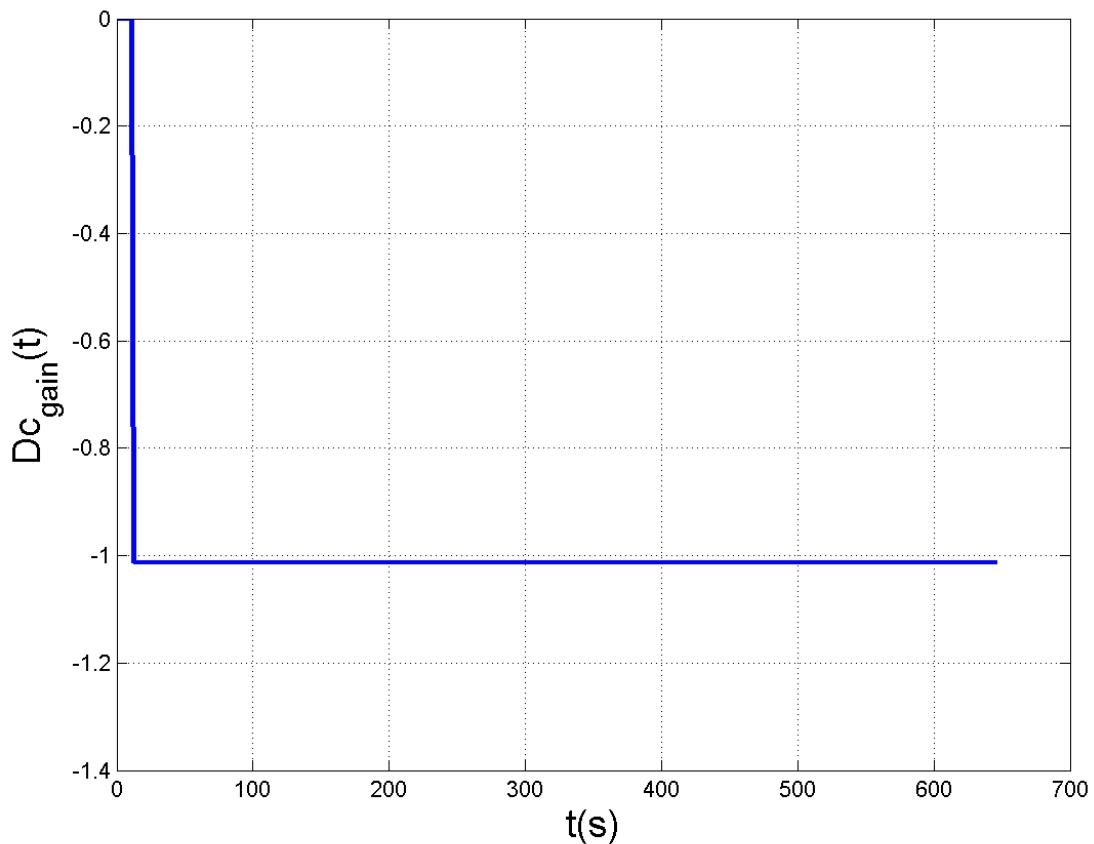
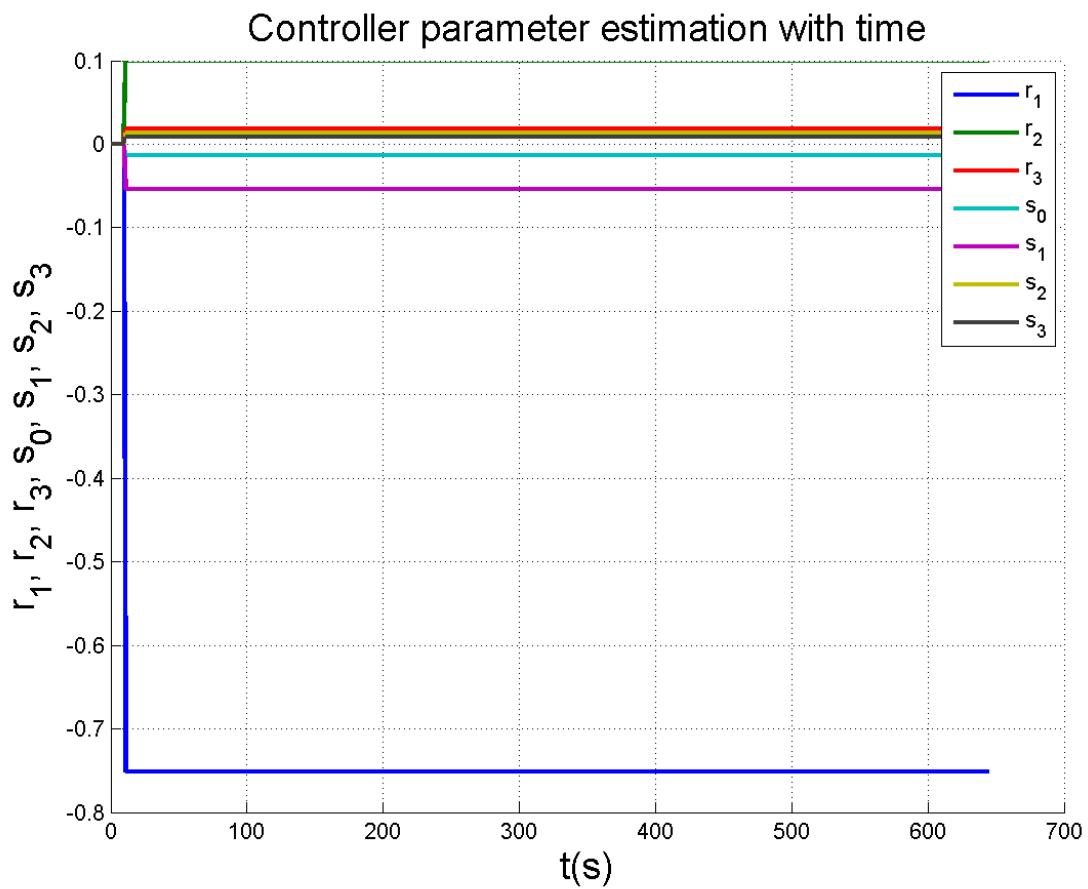


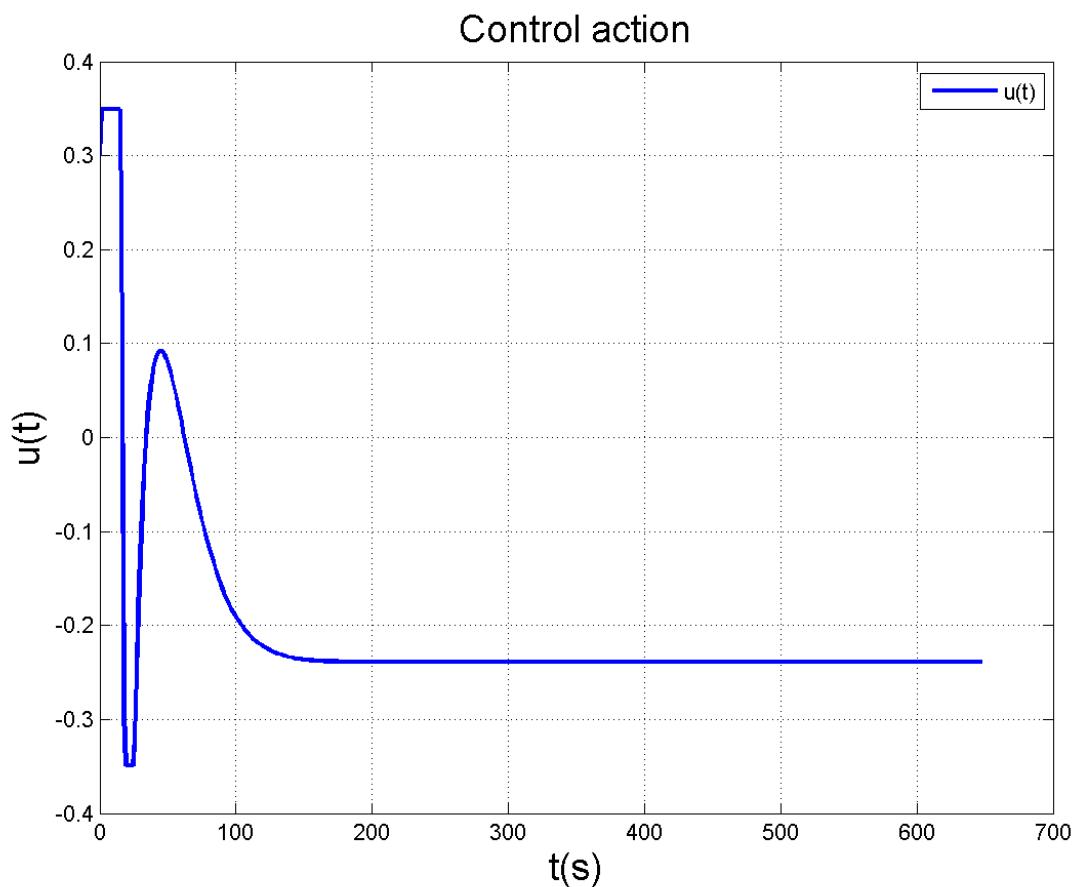
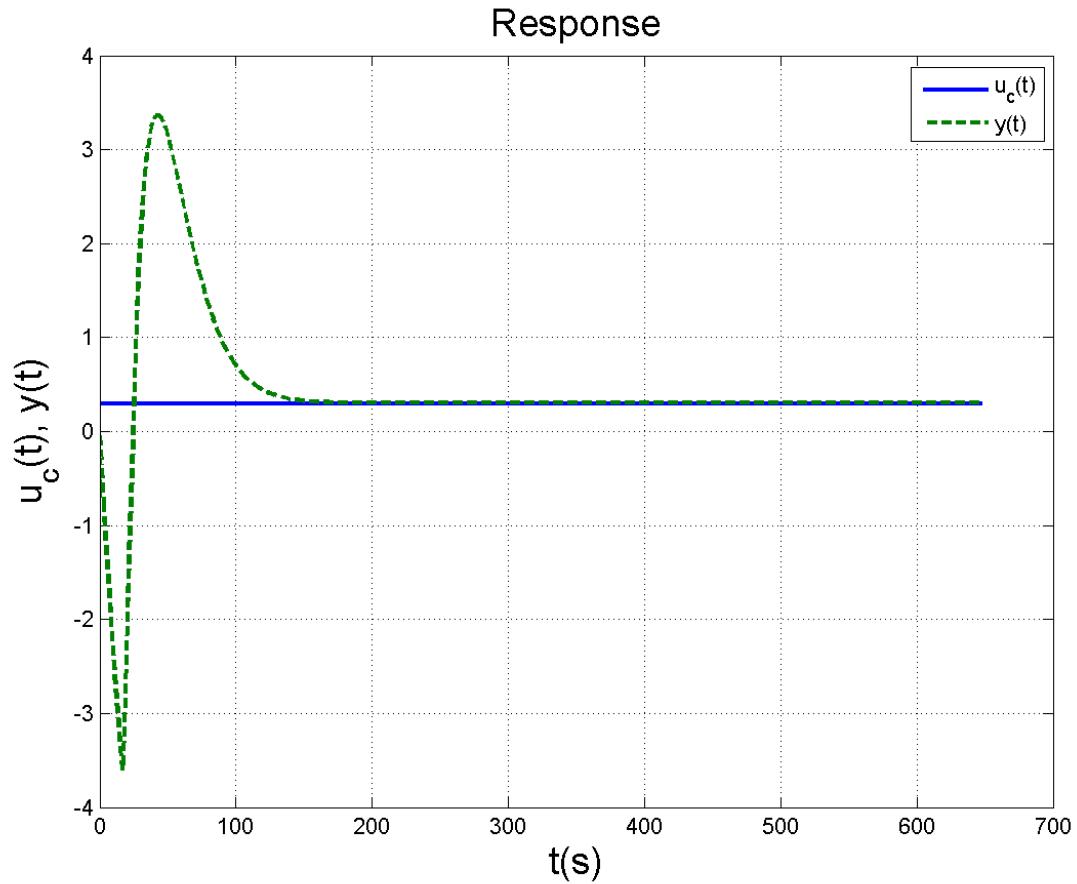




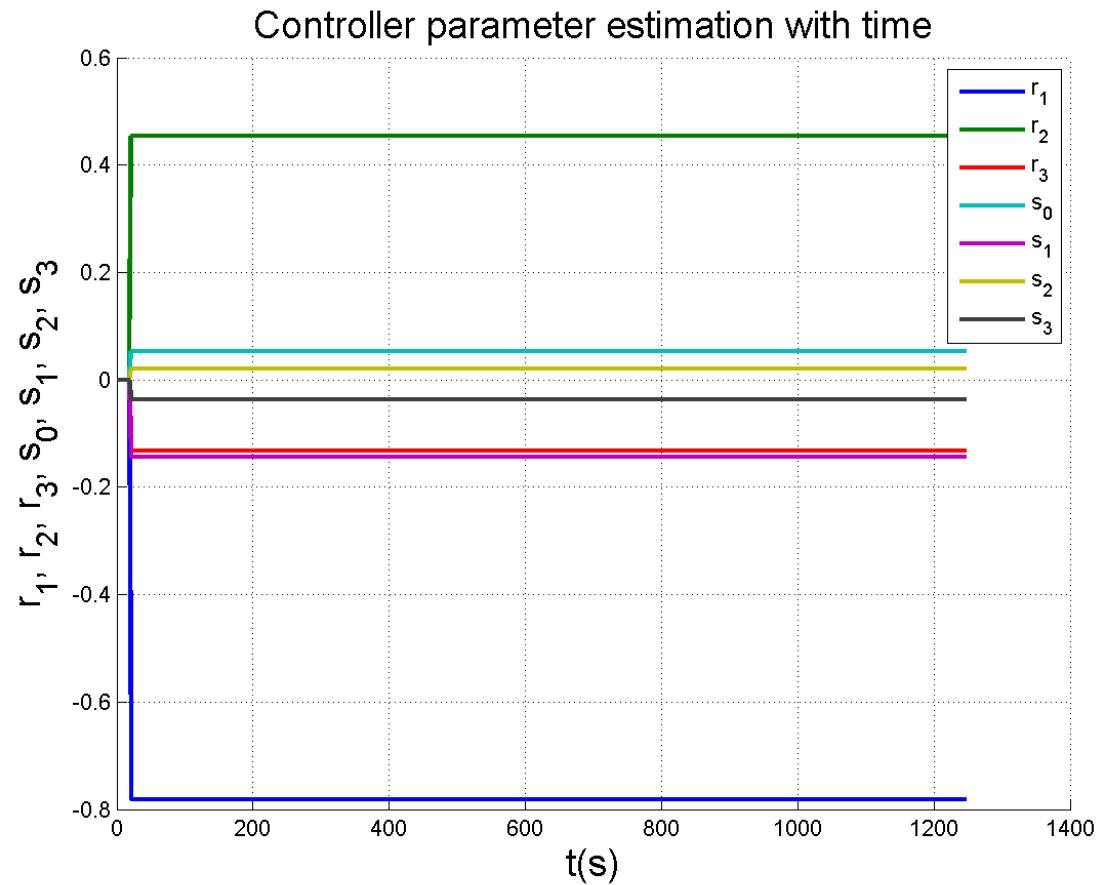
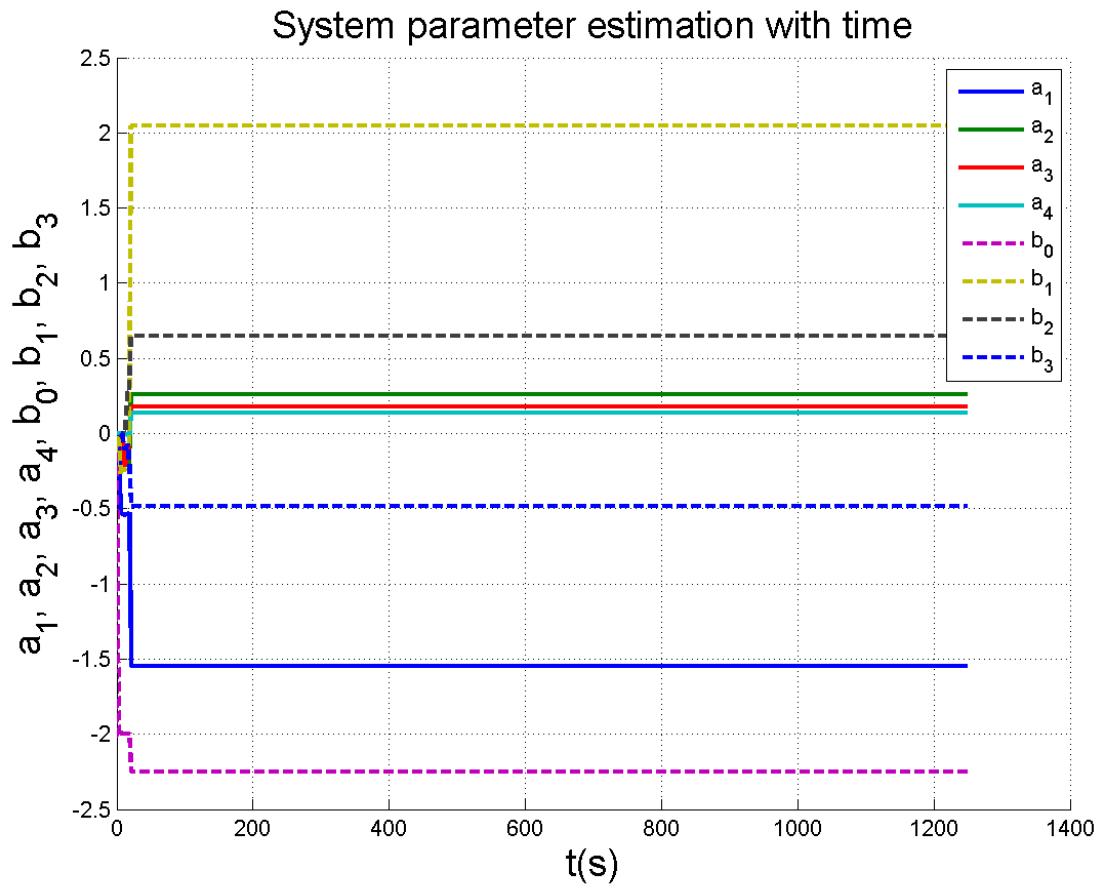
Flight Condition 3

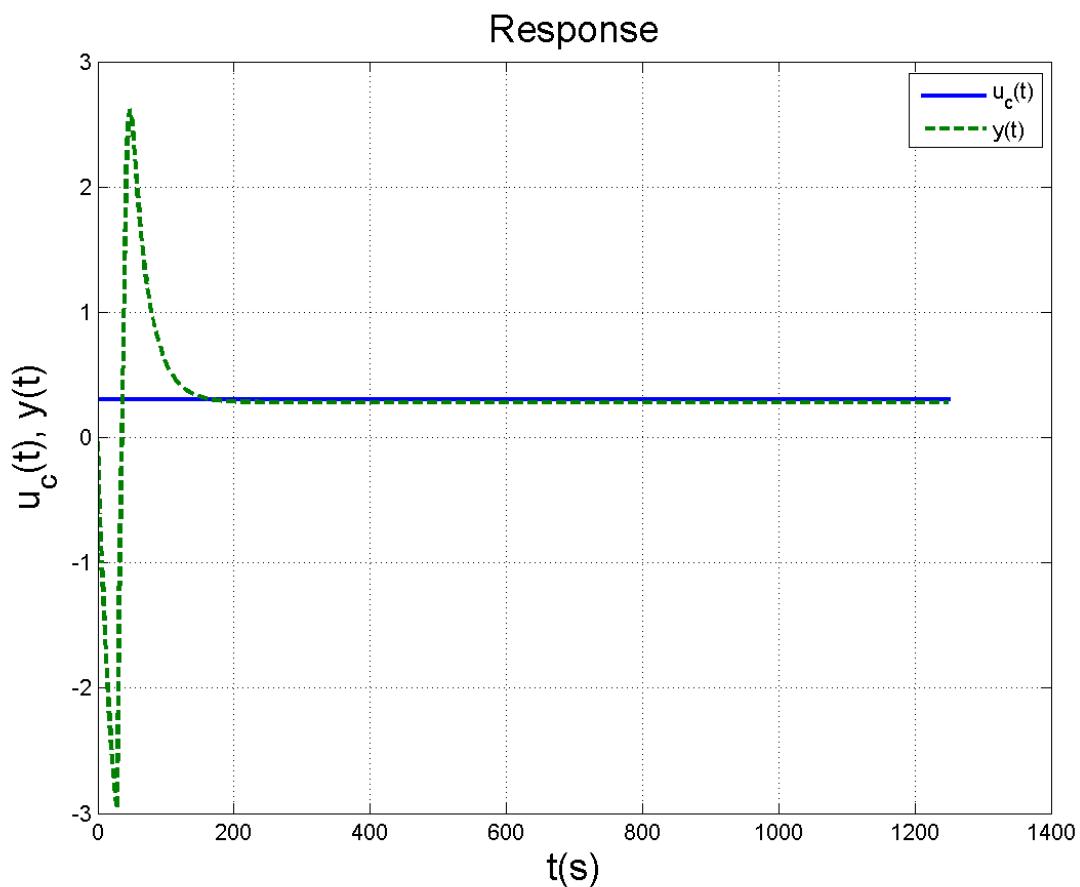
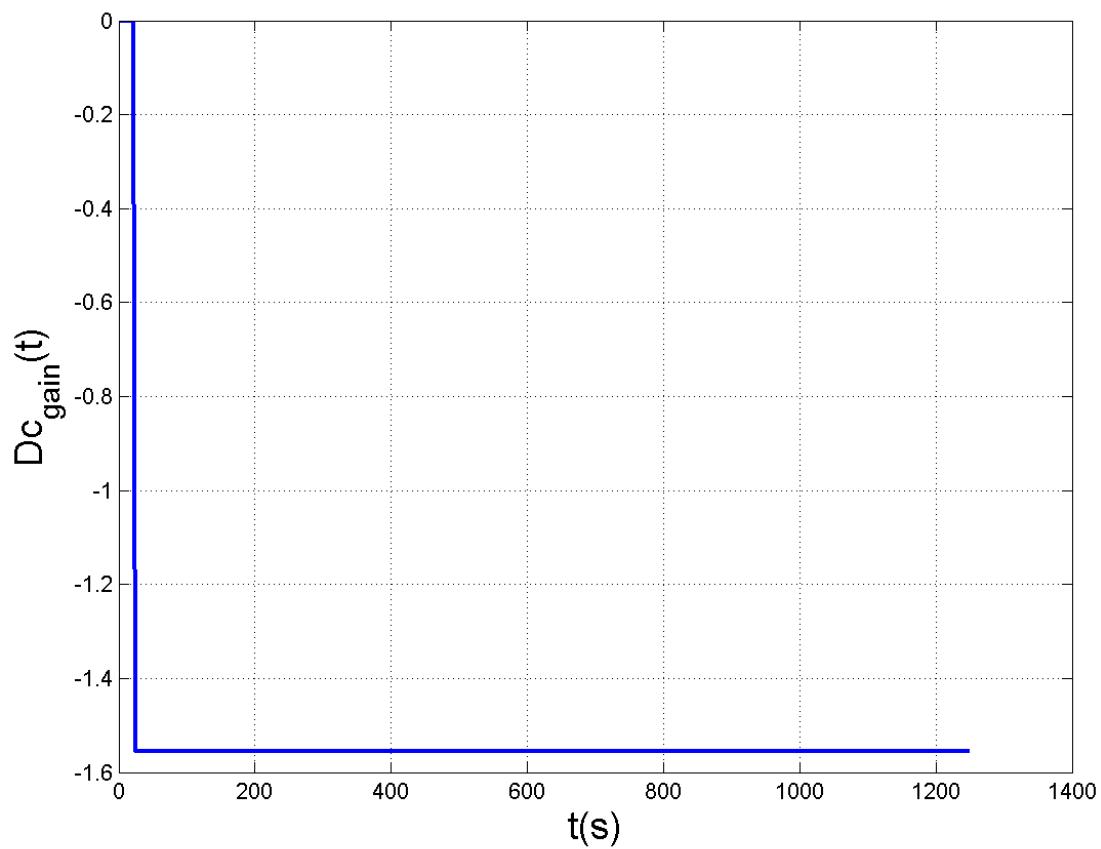


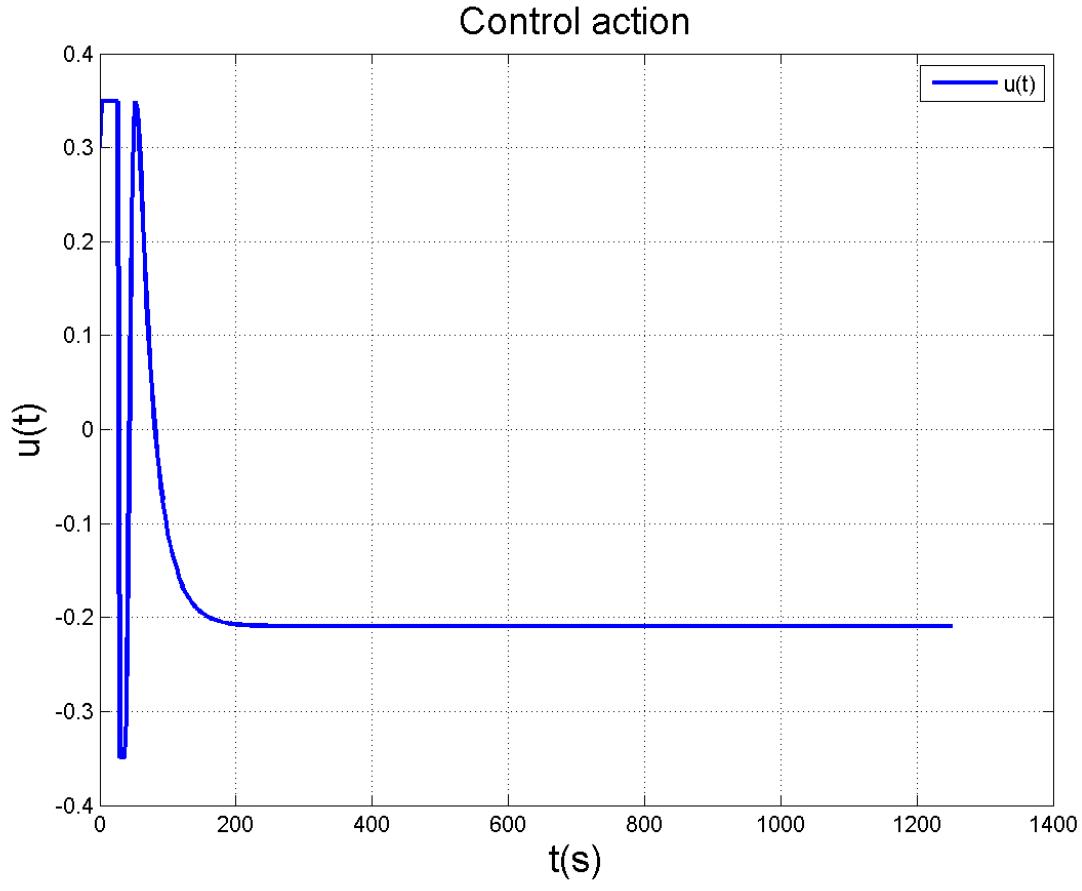




Flight Condition 4



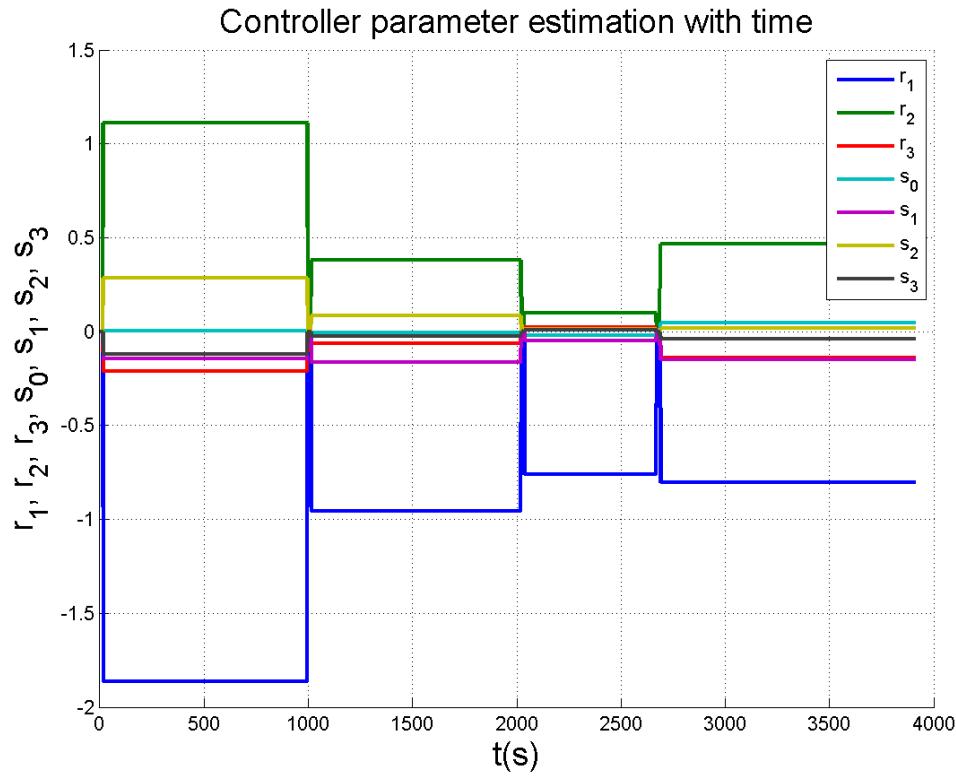
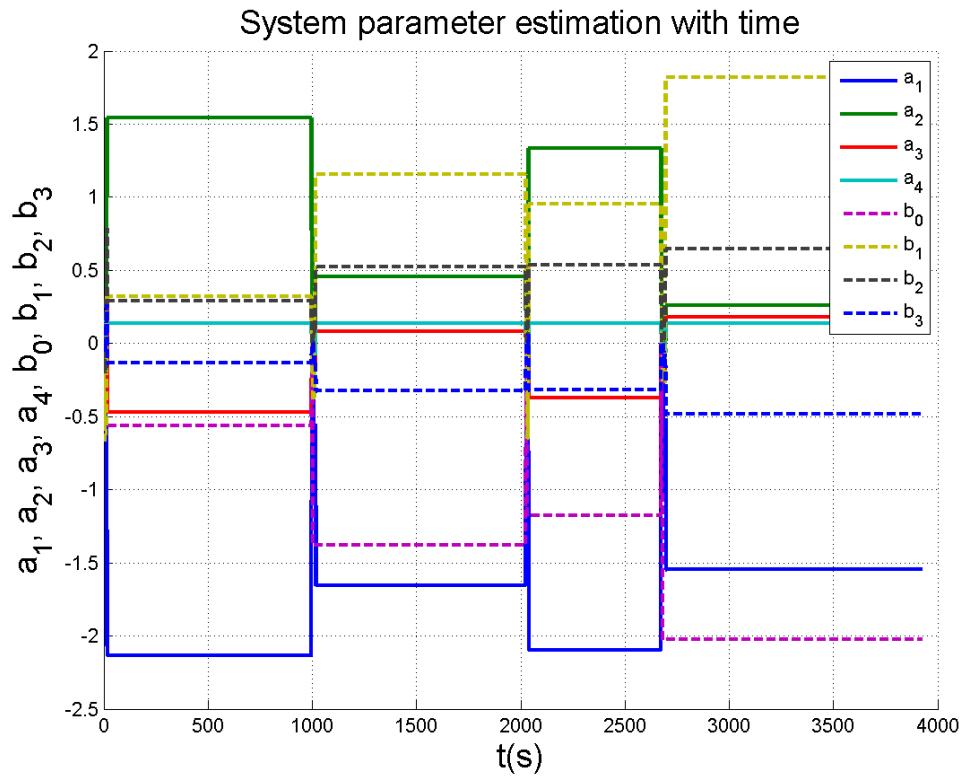


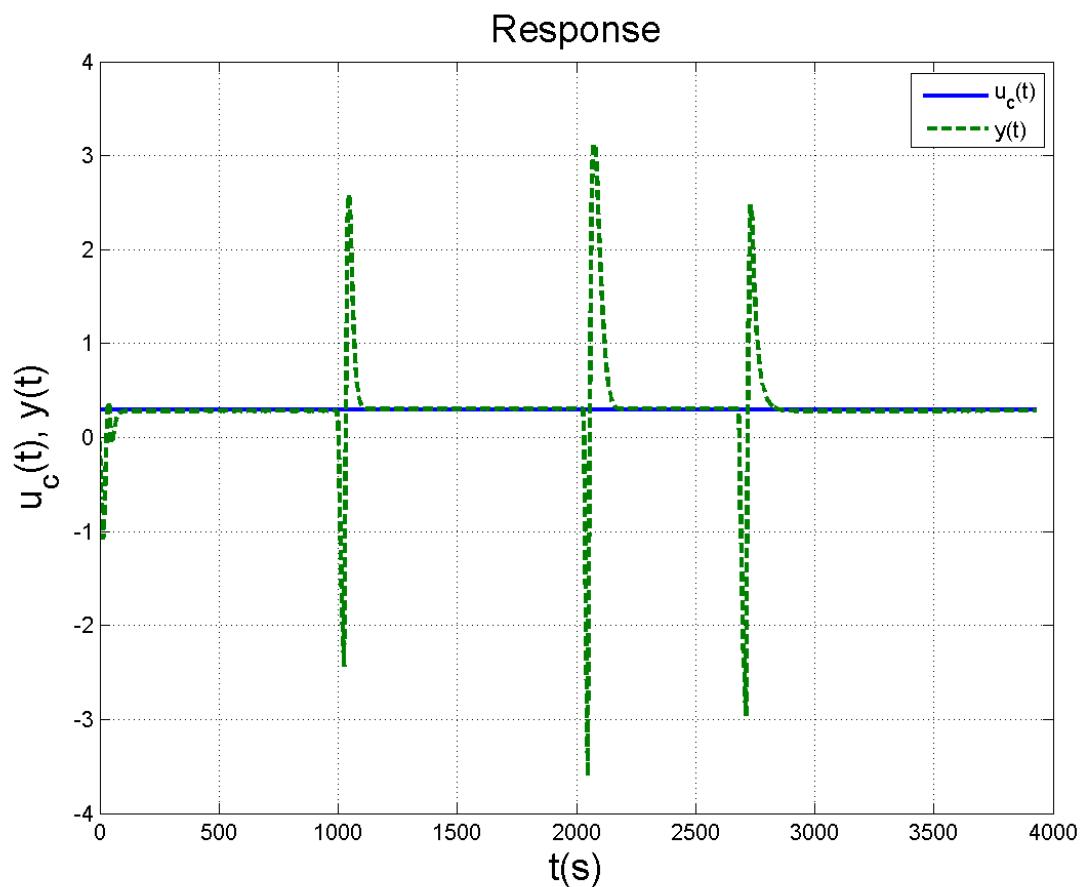
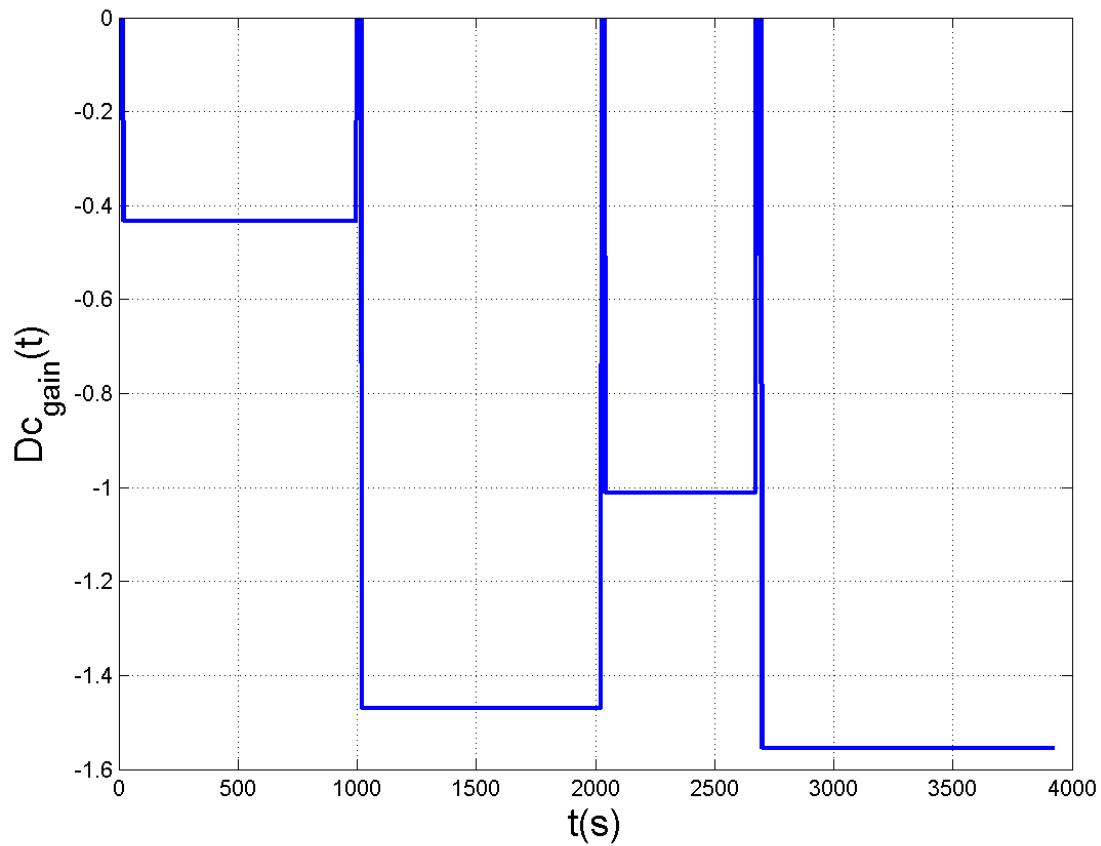


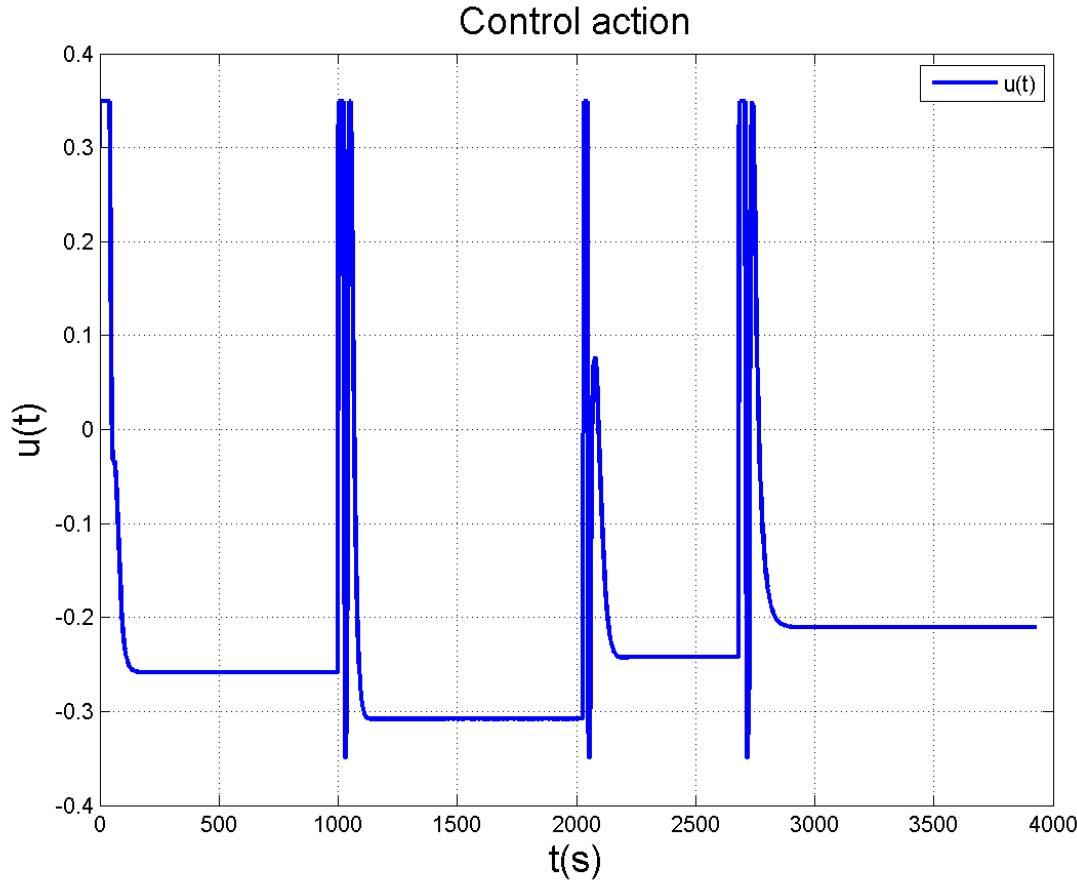
Results

Flight Condition	$G(z)$ Estimated	Feed Back Controller
1	$G(z) = \frac{-0.6048z^3 + 0.3617z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$\frac{S}{R}(z) = \frac{-5.404e-05z^3 - 0.1389z^2 + 0.2756z - 0.1172}{z^3 - 1.866z^2 + 1.107z - 0.2077}$
2	$G(z) = \frac{-1.522z^3 + 1.297z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$\frac{S}{R}(z) = \frac{0.005557z^3 - 0.1664z^2 + 0.08272z - 0.02619}{z^3 - 0.9369z^2 + 0.3706z - 0.06272}$
3	$G(z) = \frac{-1.295z^3 + 1.073z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$\frac{S}{R}(z) = \frac{-0.01341z^3 - 0.05432z^2 + 0.01315z + 0.008526}{z^3 - 0.752z^2 + 0.09983z + 0.01807}$
4	$G(z) = \frac{-2.25z^3 + 2.049z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$\frac{S}{R}(z) = \frac{0.05357z^3 - 0.1444z^2 + 0.02124z - 0.03704}{z^3 - 0.7819z^2 + 0.4547z - 0.1321}$
		Feed Forward Controller
		$\frac{T}{R}(z) = \frac{-0.4332z^5 + 1.04z^4 - 0.9705z^3 + 0.4436z^2 - 0.09982z + 0.008873}{z^3 - 1.866z^2 + 1.107z - 0.2077}$
		$\frac{T}{R}(z) = \frac{-1.47z^5 + 1.47z^4 - 0.5881z^3 + 0.1176z^2 - 0.01176z + 0.0004705}{z^3 - 0.9369z^2 + 0.3706z - 0.06272}$
		$\frac{T}{R}(z) = \frac{-1.012z^5 + 1.012z^4 - 0.405z^3 + 0.081z^2 - 0.0081z + 0.000324}{z^3 - 0.752z^2 + 0.09983z + 0.01807}$
		$\frac{T}{R}(z) = \frac{-1.555z^5 + 1.555z^4 - 0.622z^3 + 0.1244z^2 - 0.01244z + 0.0004976}{z^3 - 0.7819z^2 + 0.4547z - 0.1321}$

For All Flight Conditions Together







Results

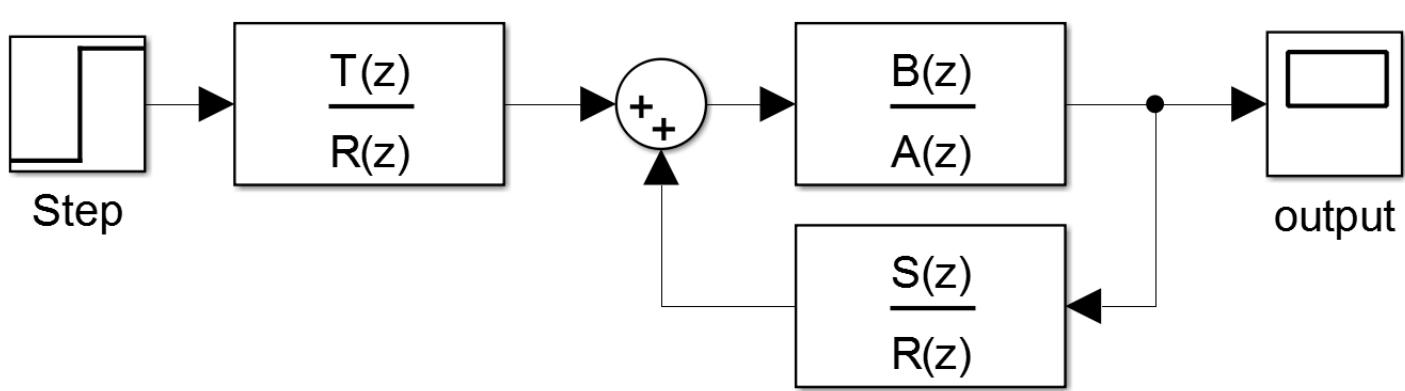
Flight Condition	$G(z)$ Estimated	Feed Back Controller
1	$G(z) = \frac{-0.5646z^3 + 0.3215z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$\frac{S}{R}(z) = \frac{0.001566z^3 - 0.1438z^2 + 0.284z - 0.1204}{z^3 - 1.865z^2 + 1.111z - 0.2109}$
2	$G(z) = \frac{-1.378z^3 + 1.153z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$\frac{S}{R}(z) = \frac{-0.007428z^3 - 0.1656z^2 + 0.08437z - 0.02736}{z^3 - 0.9555z^2 + 0.3805z - 0.06547}$
3	$G(z) = \frac{-1.176z^3 + 0.9539z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$\frac{S}{R}(z) = \frac{-0.02184z^3 - 0.05079z^2 + 0.01204z + 0.009442}{z^3 - 0.7603z^2 + 0.09947z + 0.02022}$
4	$G(z) = \frac{-2.023z^3 + 1.822z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$\frac{S}{R}(z) = \frac{0.005475z^3 - 0.1109z^2 + 0.04074z - 0.03511}{z^3 - 0.9714z^2 + 0.5099z - 0.1254}$
		Feed Forward Controller
		$\frac{T}{R}(z) = \frac{-0.4332z^5 + 1.04z^4 - 0.9705z^3 + 0.4436z^2 - 0.09982z + 0.008873}{z^3 - 1.865z^2 + 1.111z - 0.2109}$
		$\frac{T}{R}(z) = \frac{-1.47z^5 + 1.47z^4 - 0.5881z^3 + 0.1176z^2 - 0.01176z + 0.0004705}{z^3 - 0.9555z^2 + 0.3805z - 0.06547}$
		$\frac{T}{R}(z) = \frac{-1.012z^5 + 1.012z^4 - 0.405z^3 + 0.081z^2 - 0.0081z + 0.000324}{z^3 - 0.7603z^2 + 0.09947z + 0.02022}$
		$\frac{T}{R}(z) = \frac{-1.244z^5 + 1.244z^4 - 0.4976z^3 + 0.09951z^2 - 0.009951z + 0.0003981}{z^3 - 0.9714z^2 + 0.5099z - 0.1254}$

Comments

- The system parameter goes to its true values if i control all flight conditions together.
- There is a change in controller parameter between the controller of all flight conditions and the controller of each flight condition.

1.6.4 Indirect Self-Tuning Regulator Using Model Following With Zero Cancellation For Step Input

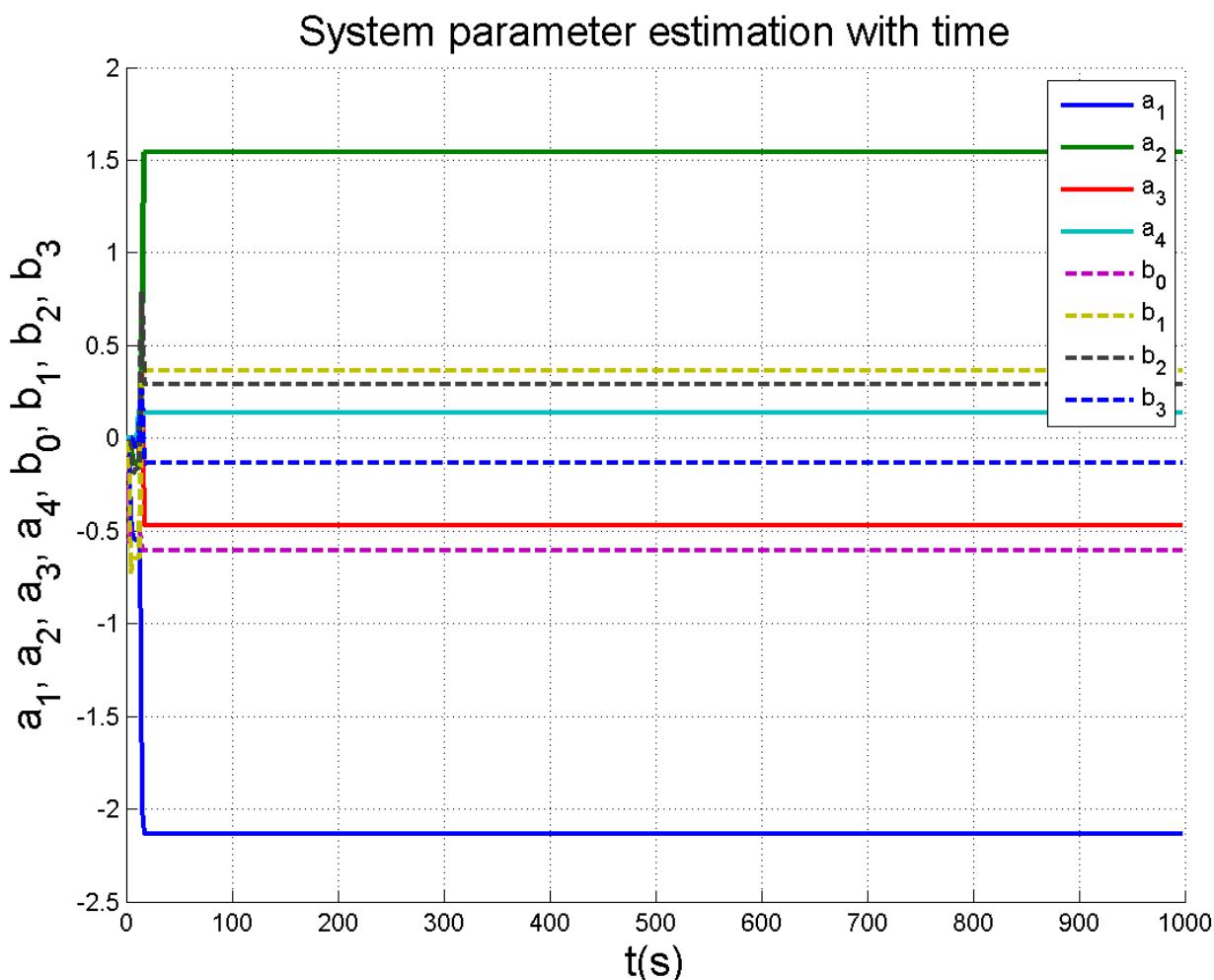
Controller Scheme

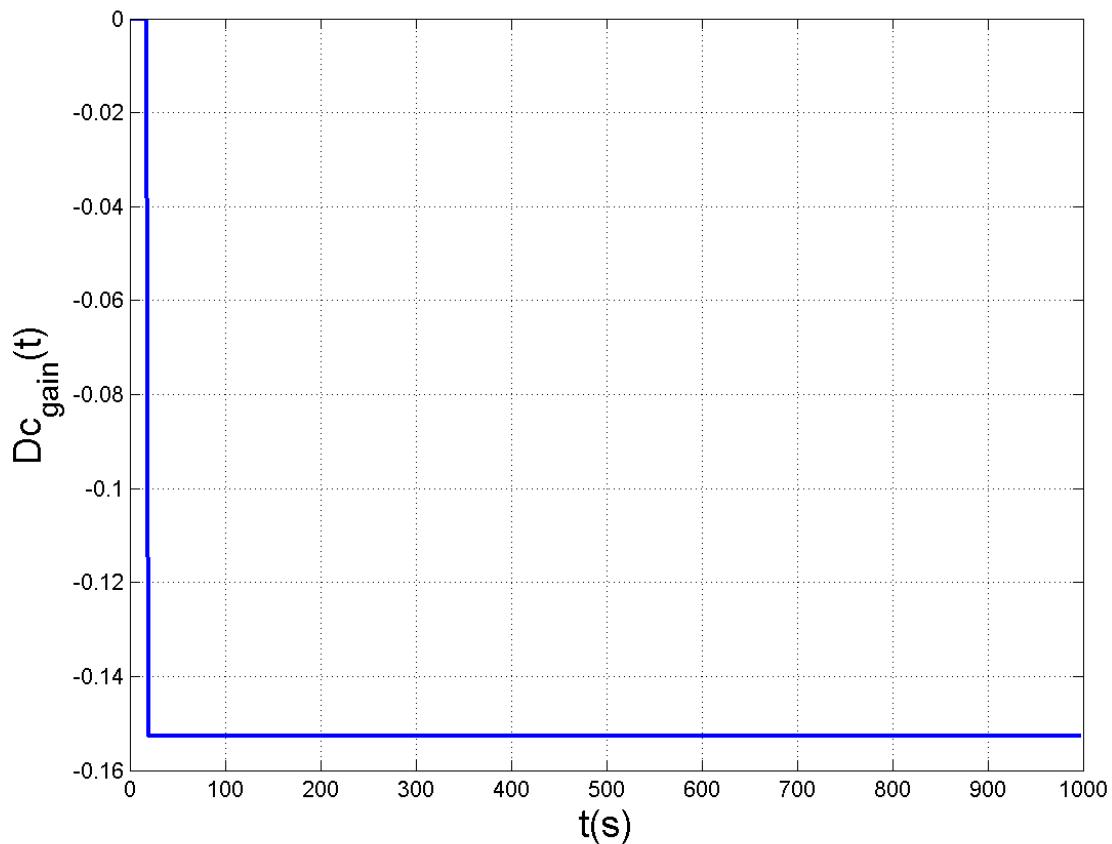
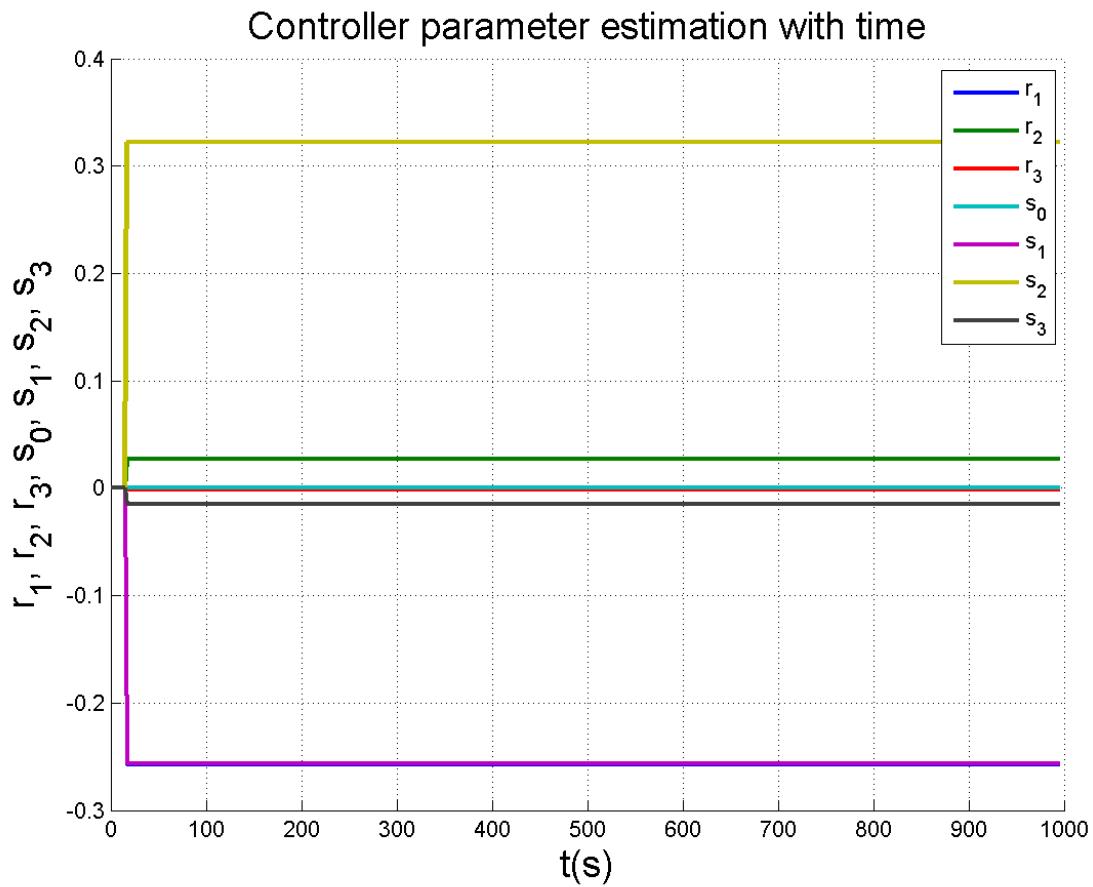


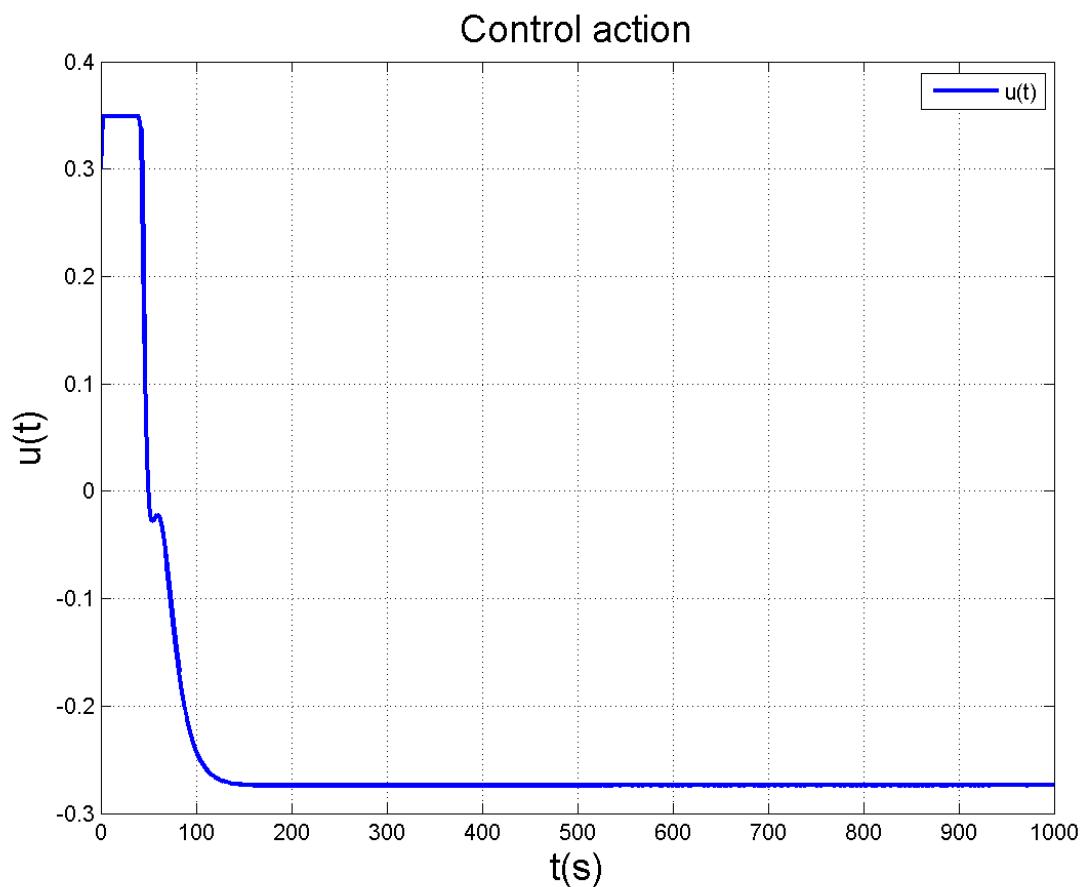
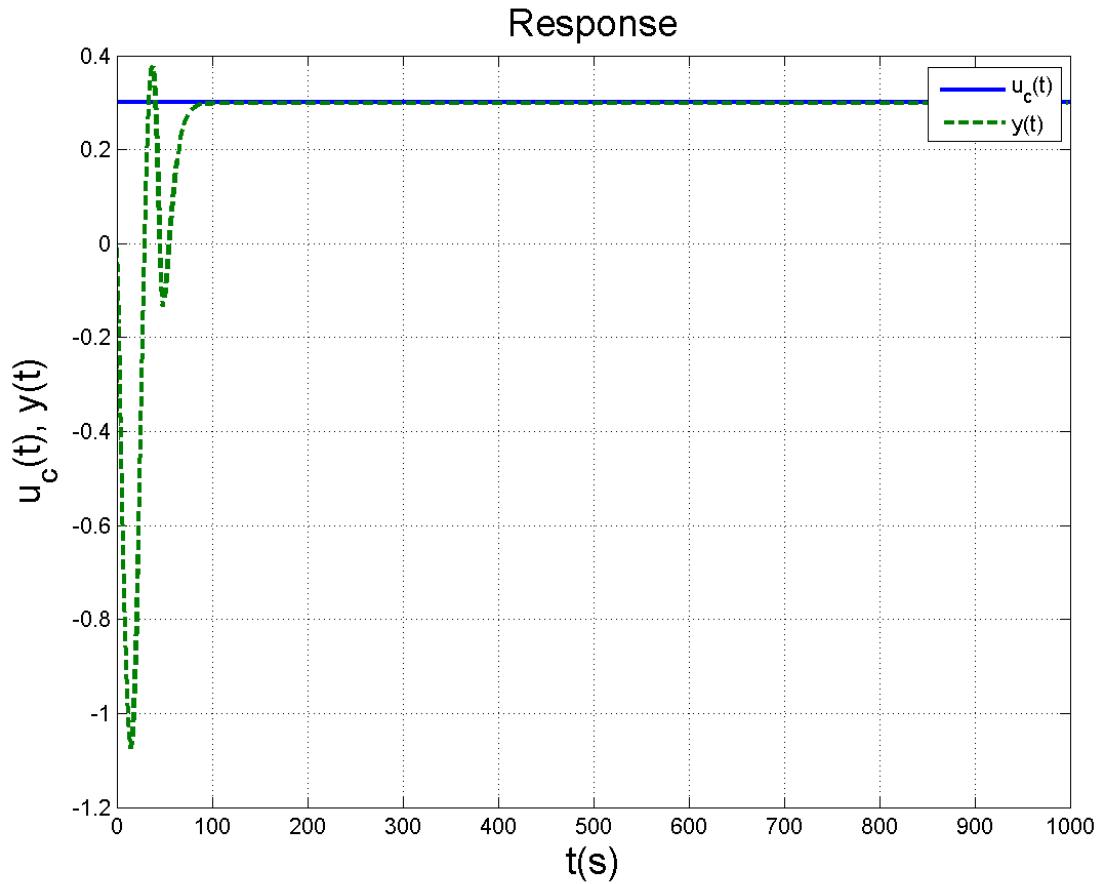
Required Poles in Z-Domain

Flight Condition	A_m	A_0
1	[0.692, 0.7]	[0.2, 0.2, 0.2, 0.2, 0.2]
2	[0.3, 0.5]	[0.2, 0.2, 0.2, 0.2, 0.2]
3	[0.665, 0.7]	[0.2, 0.2, 0.2, 0.2, 0.2]
4	[0.3, 0.37]	[0.2, 0.2, 0.2, 0.2, 0.2]

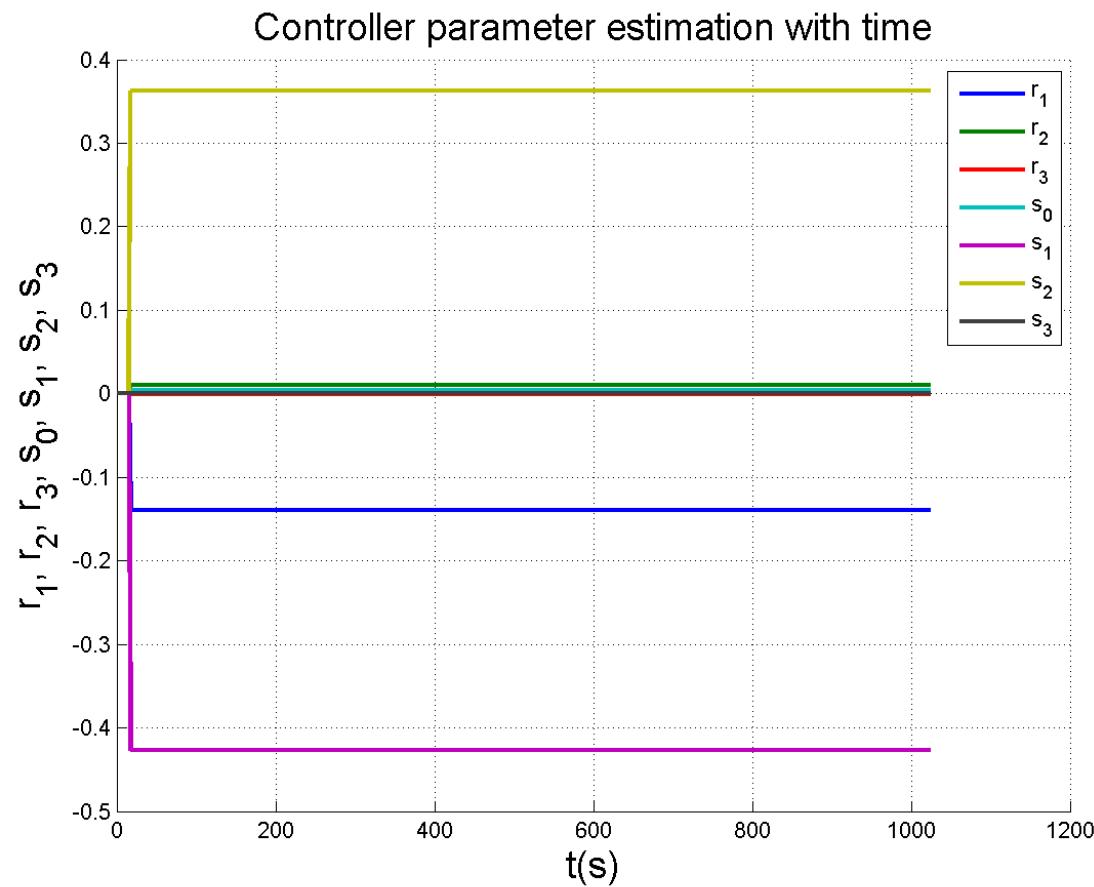
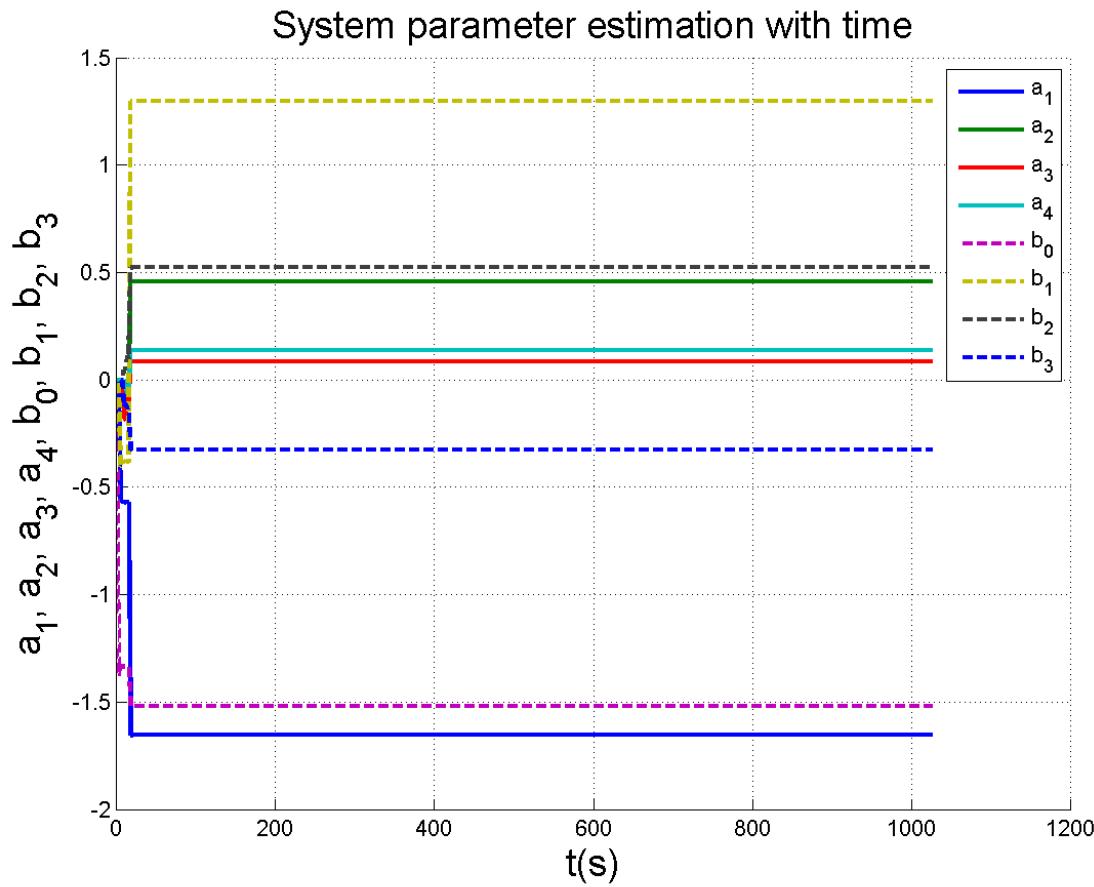
Flight Condition 1

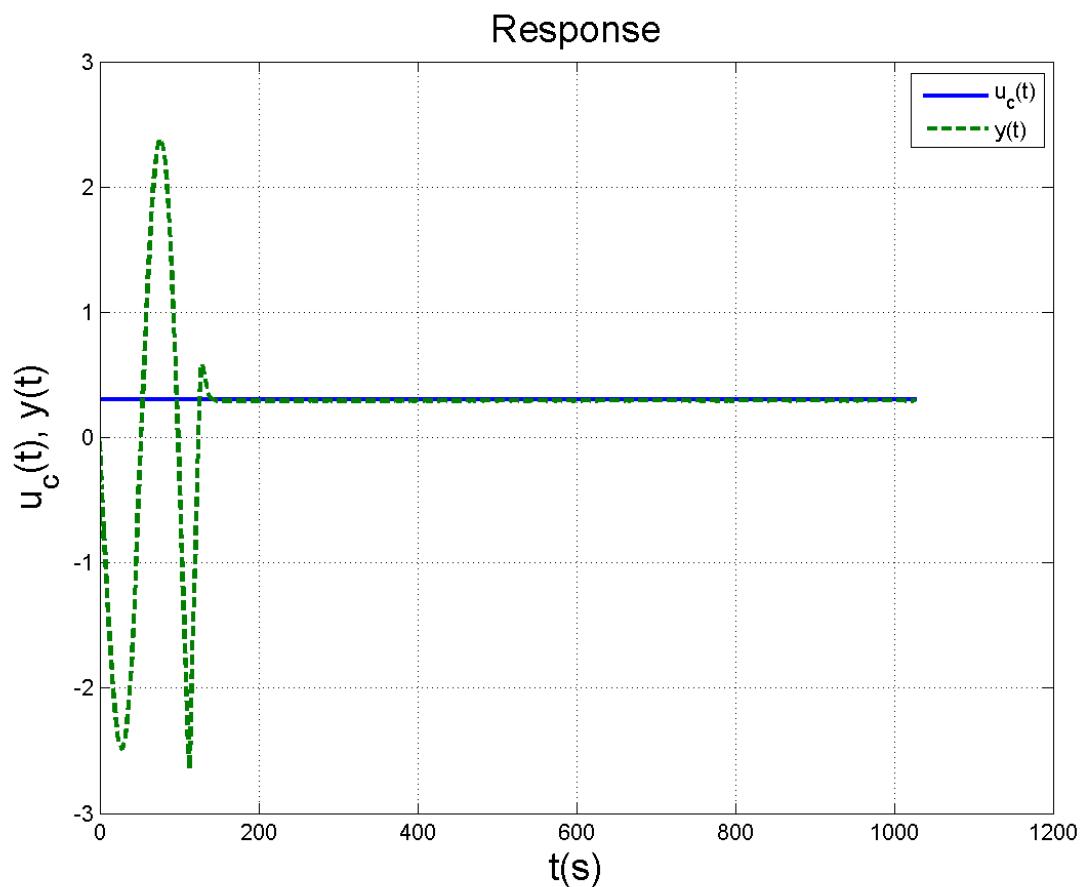
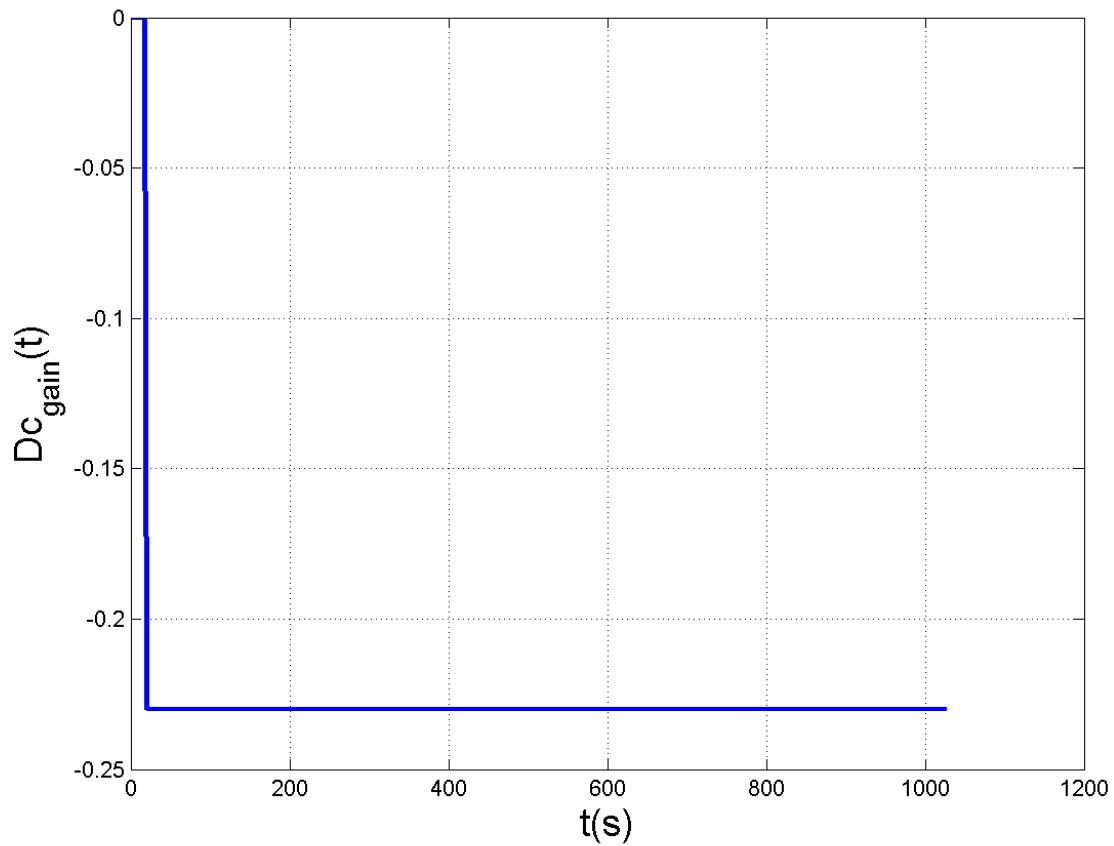


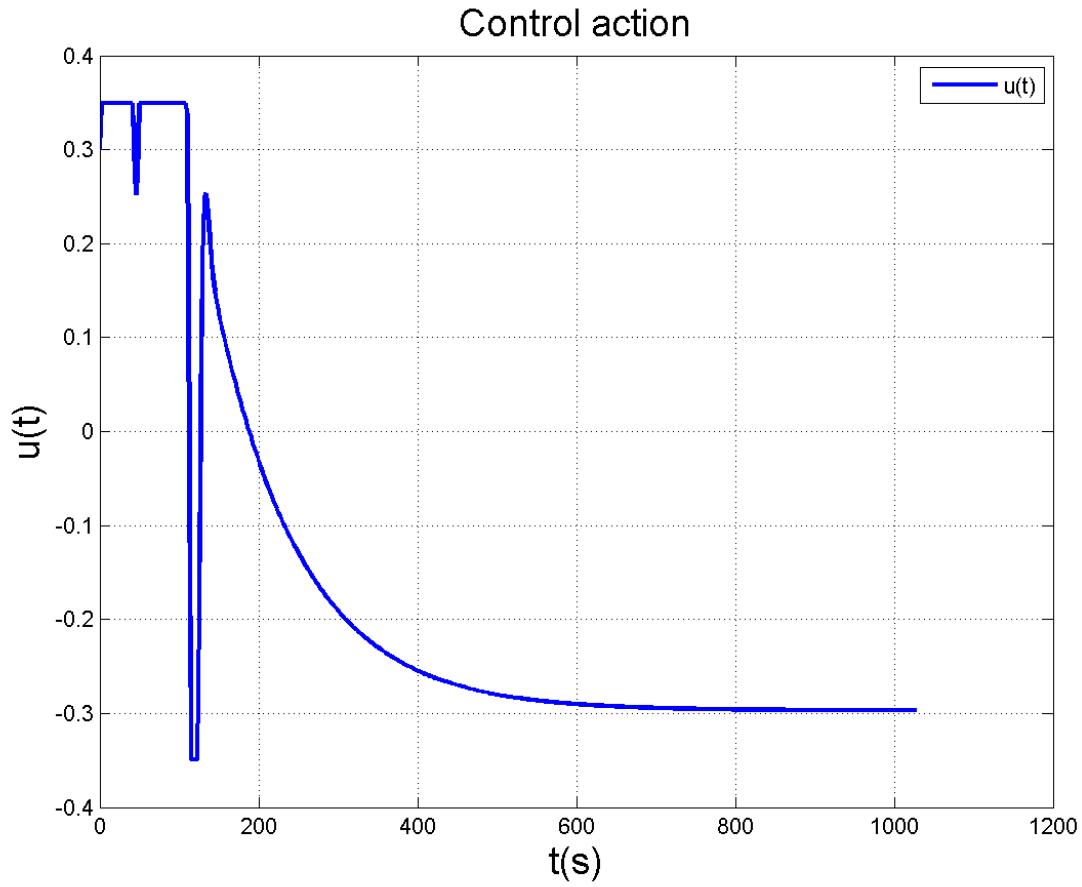




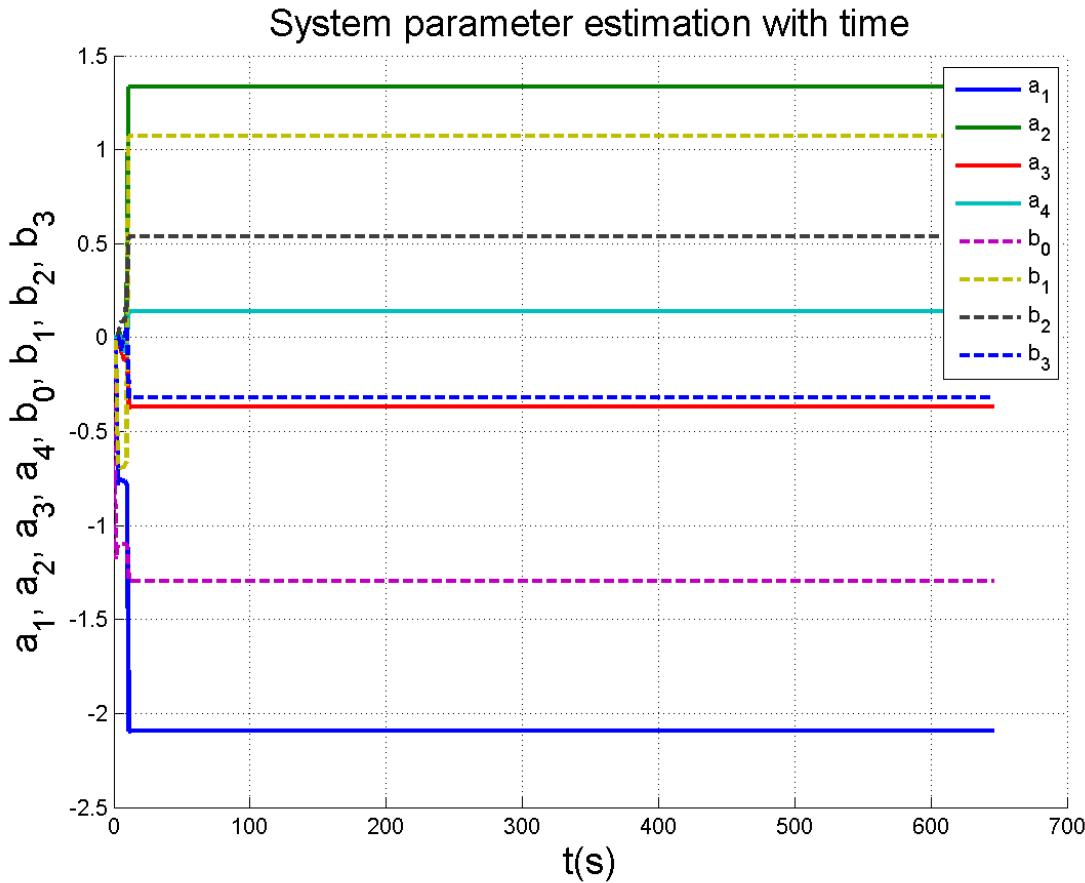
Flight Condition 2

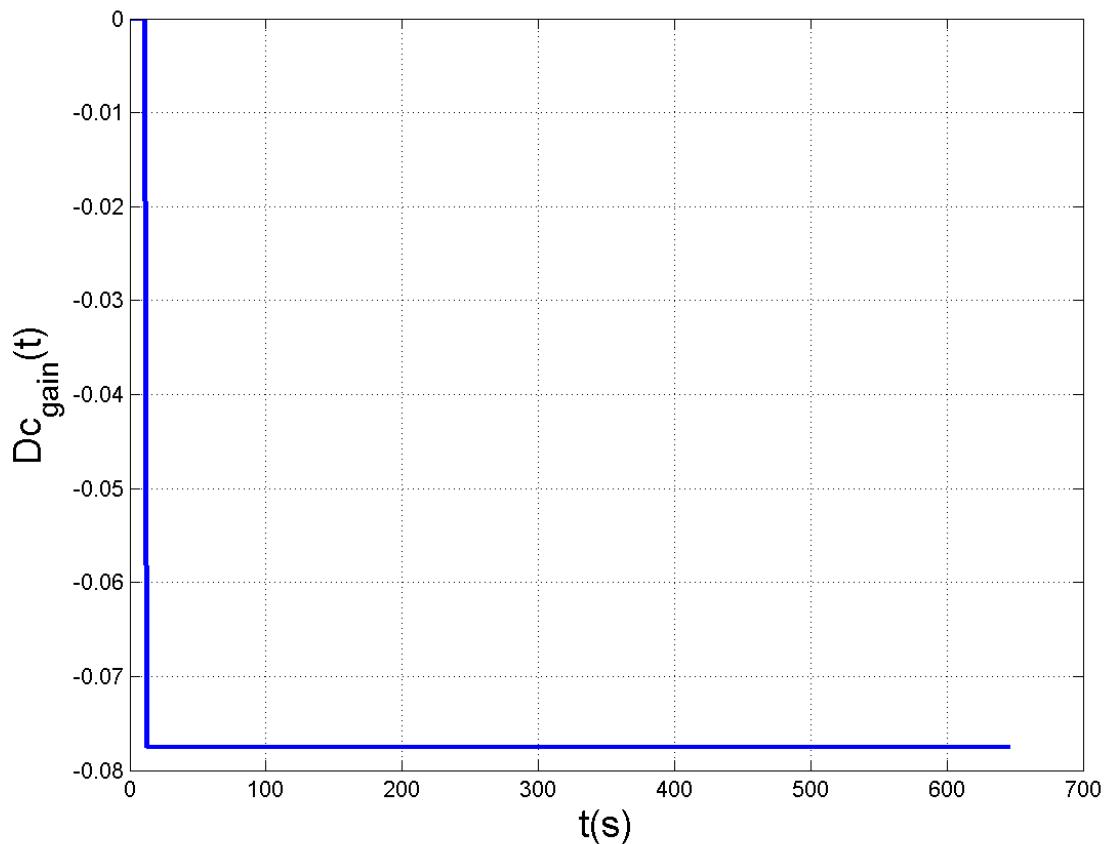
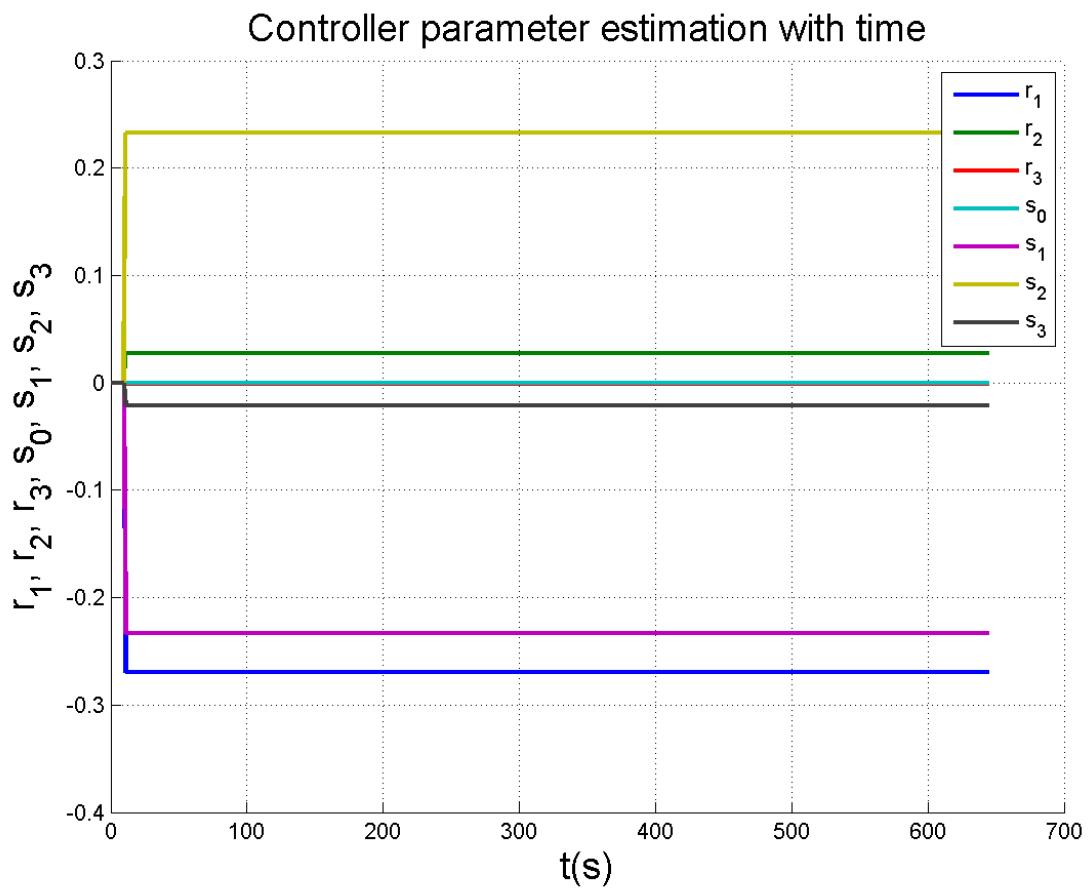


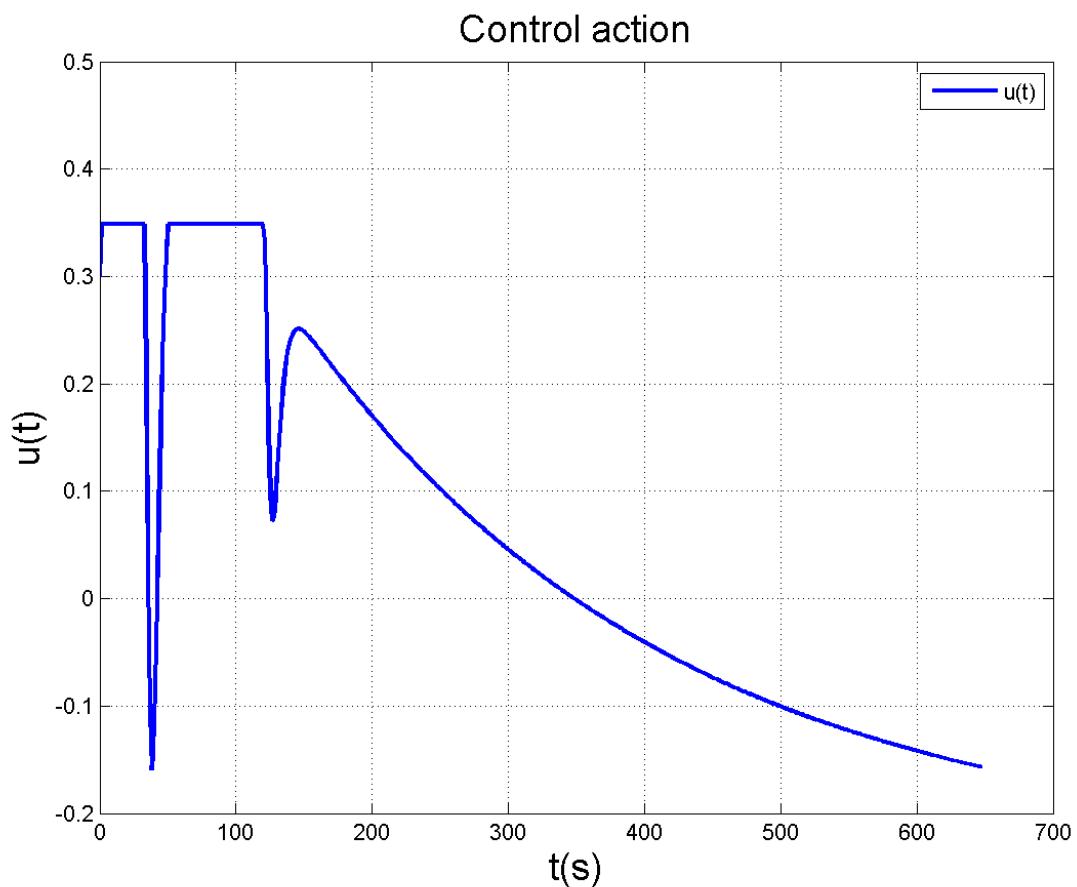
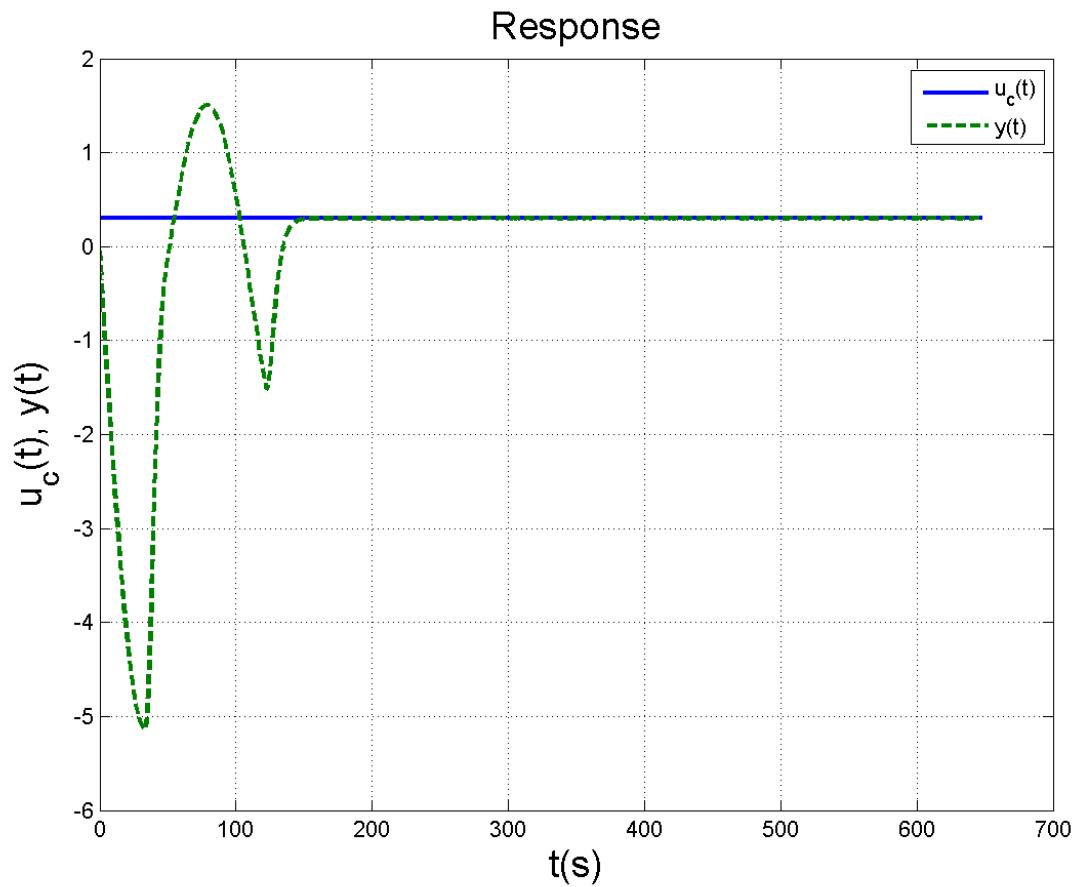




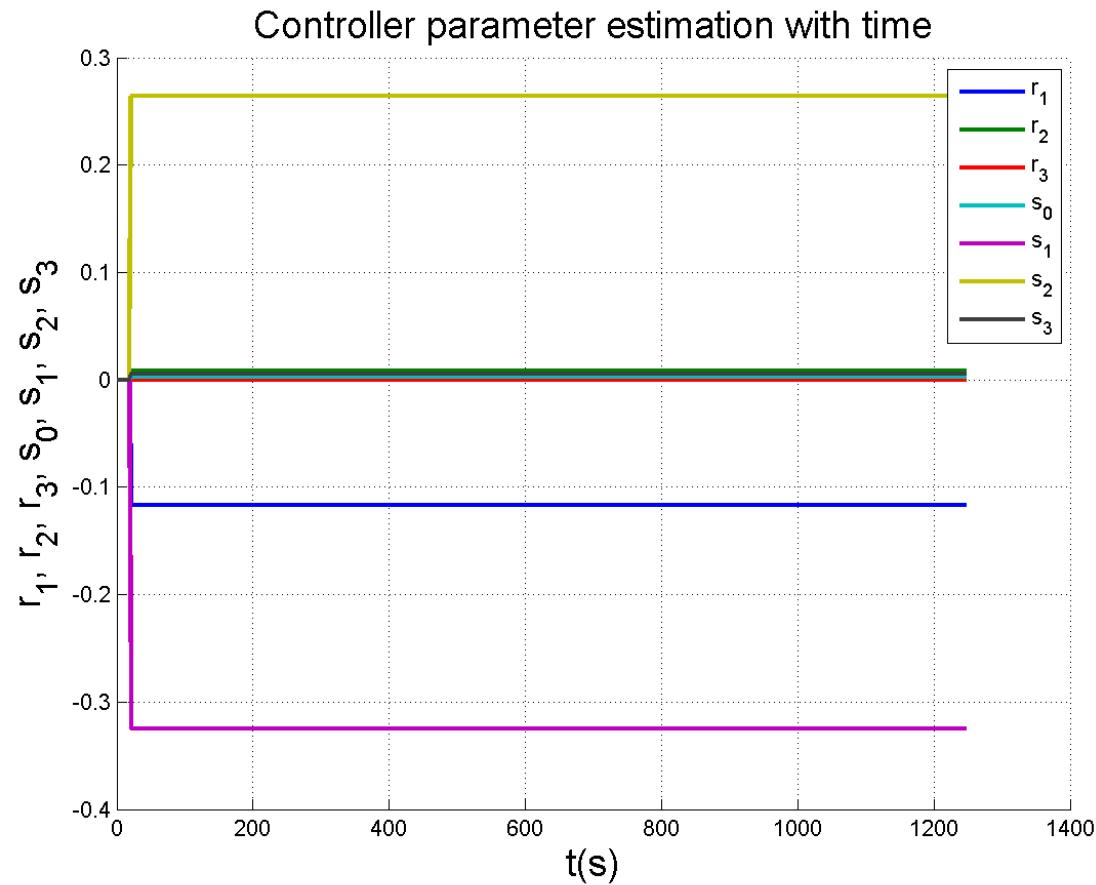
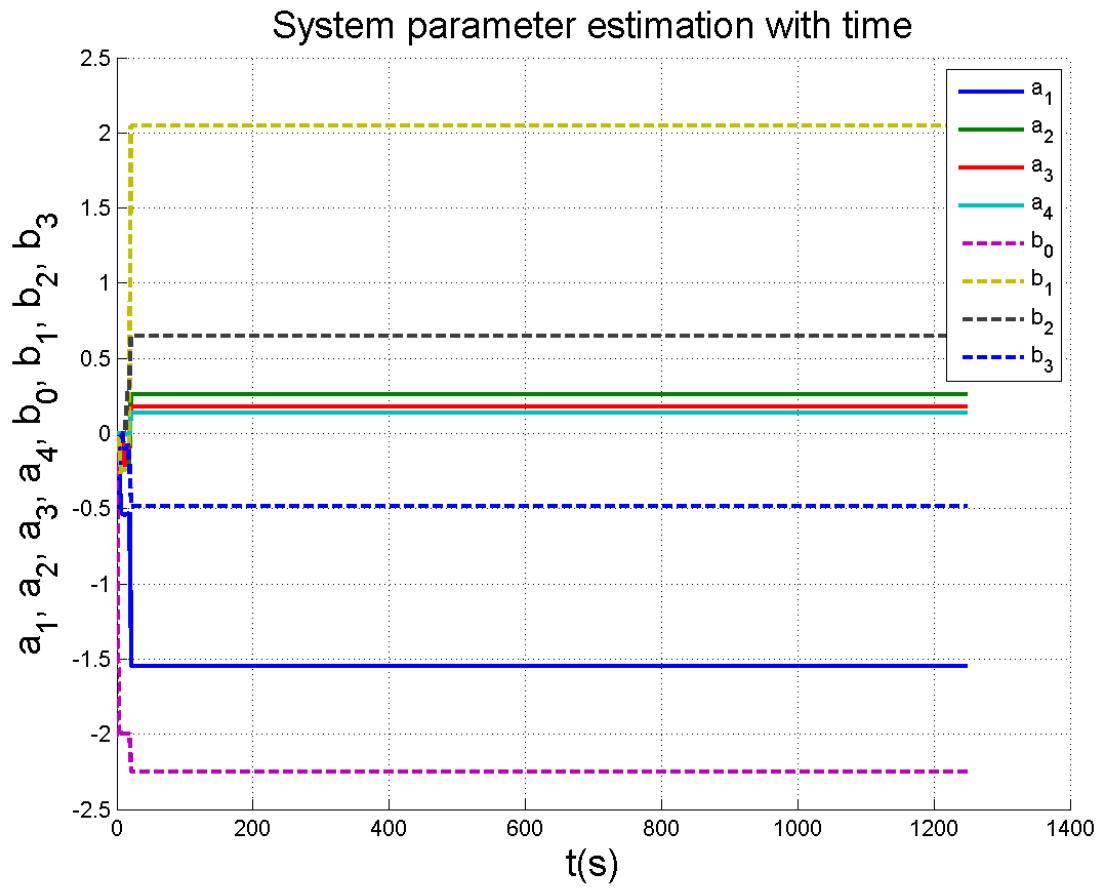
Flight Condition 3

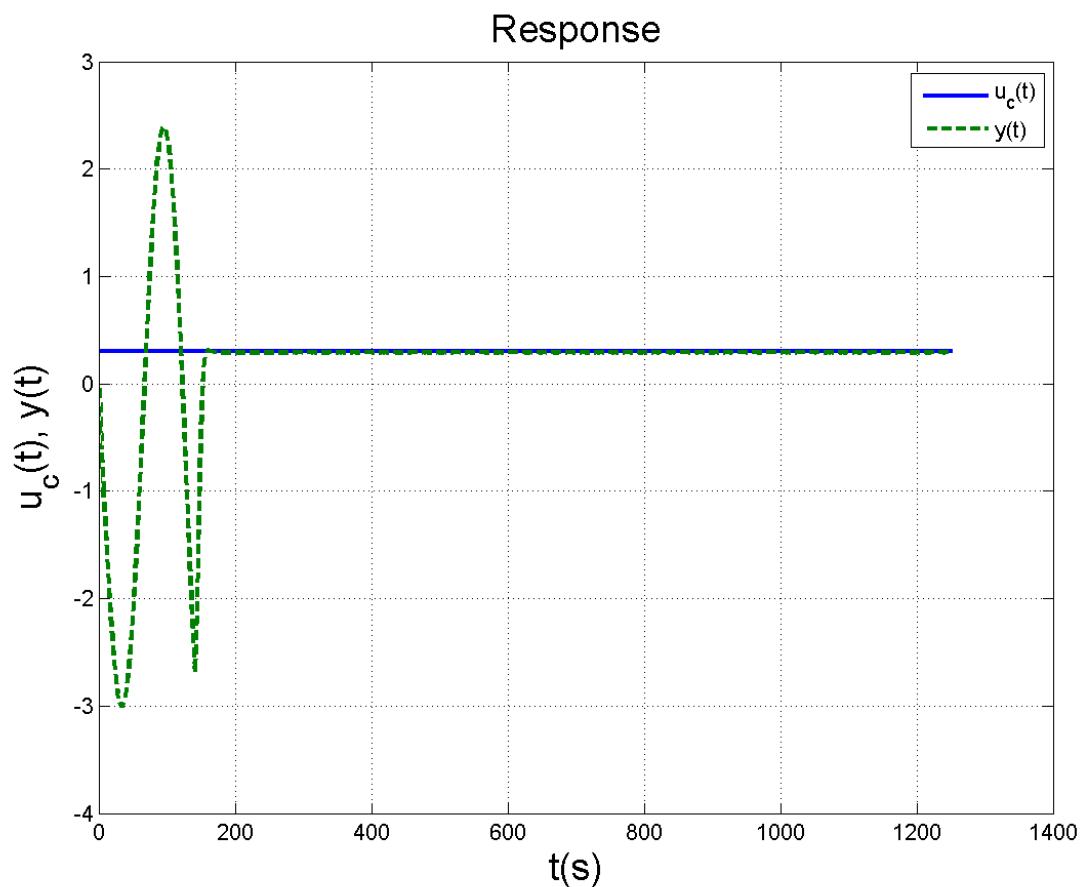
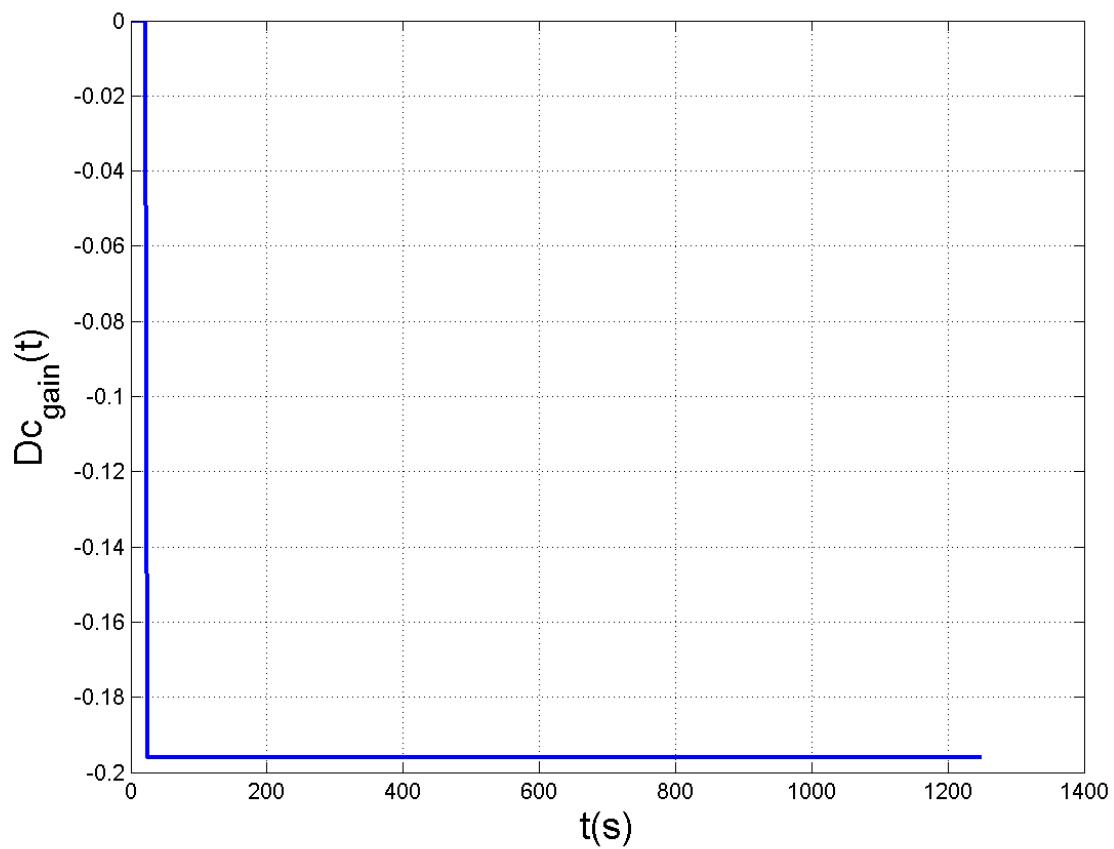


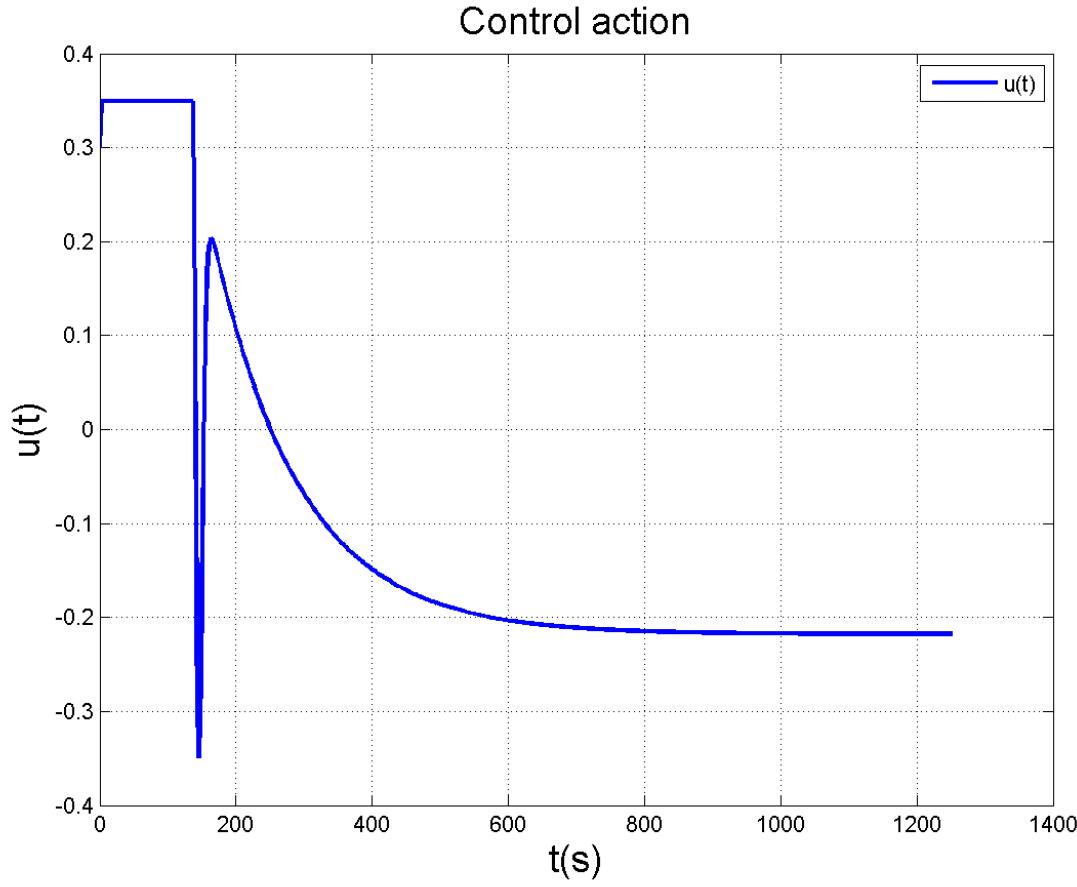




Flight Condition 4



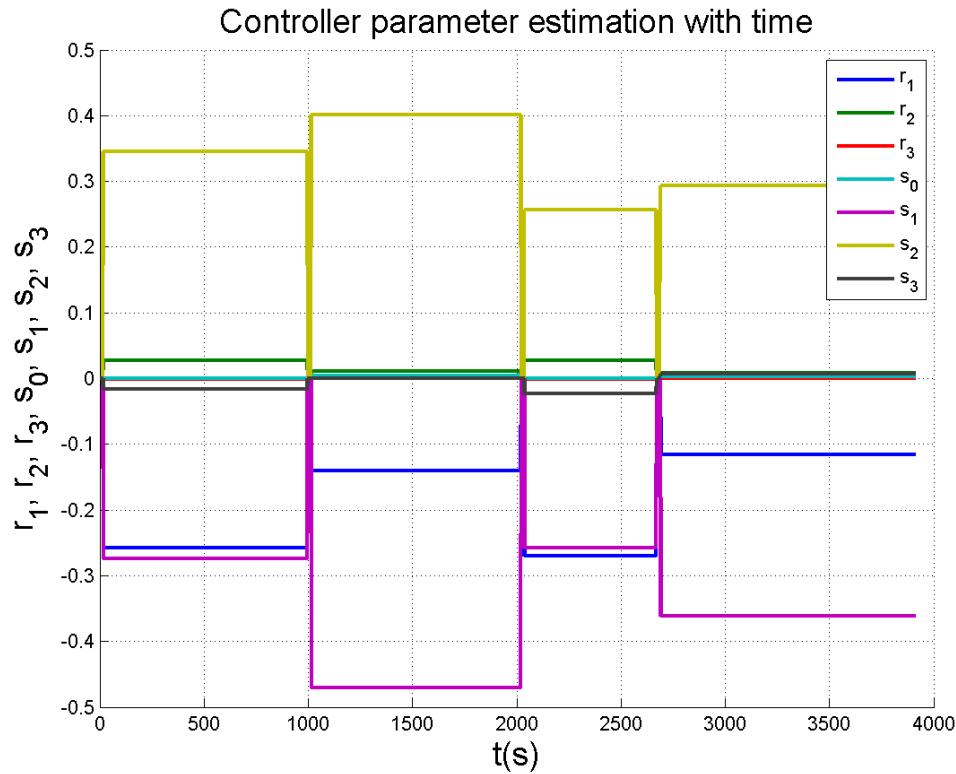
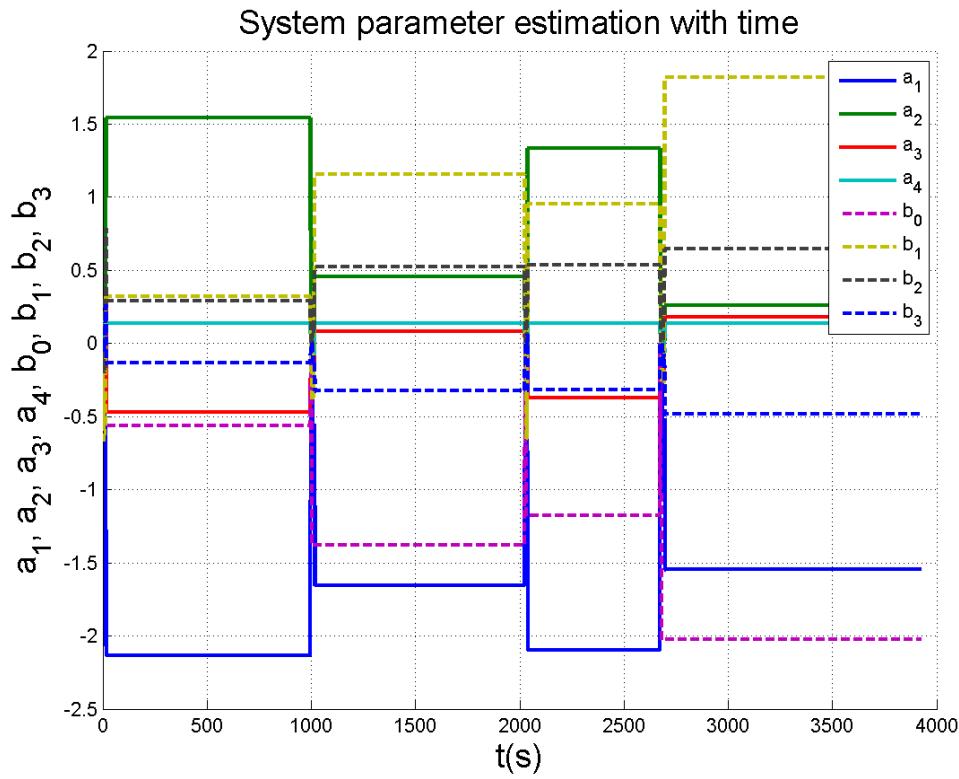


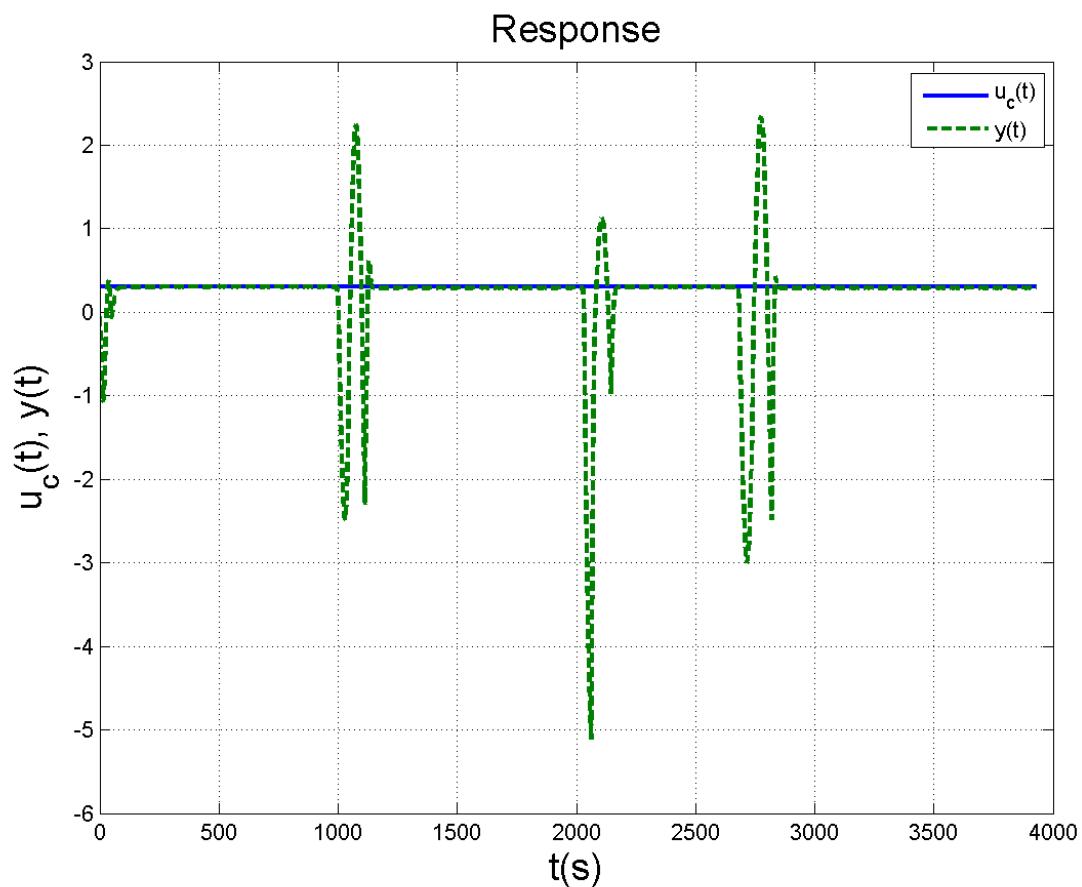
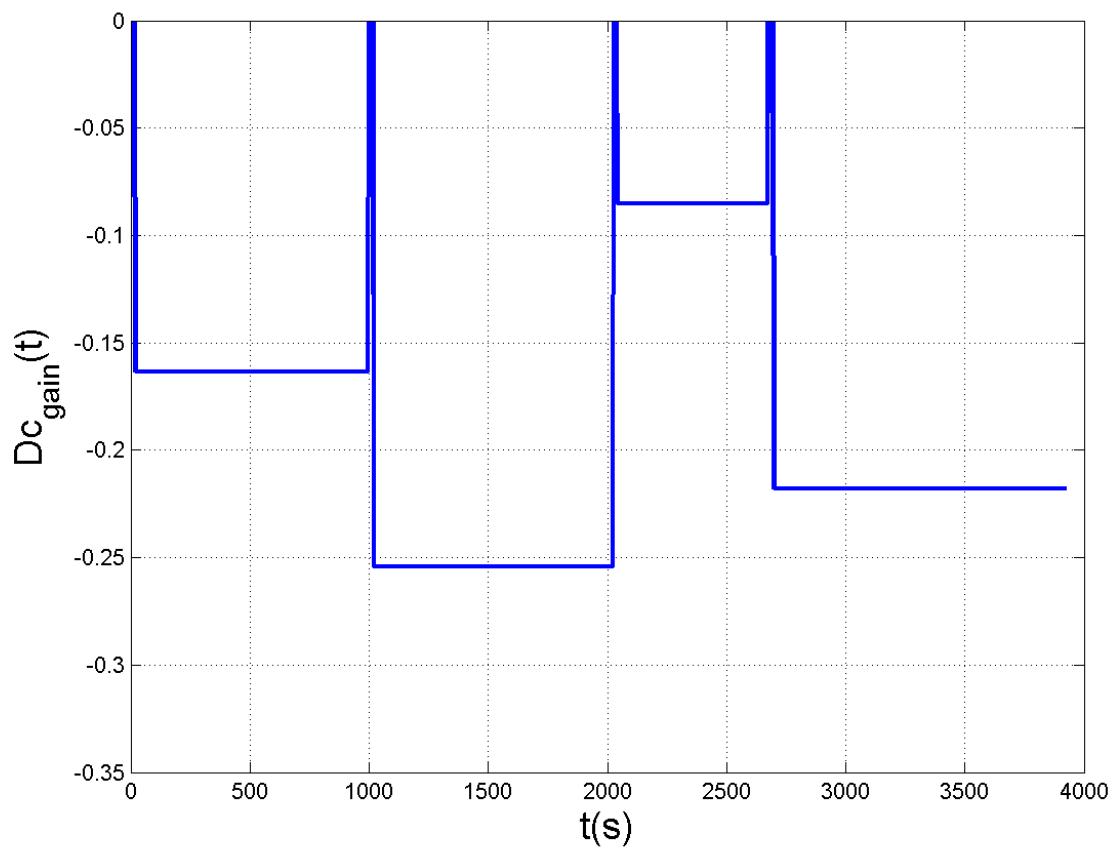


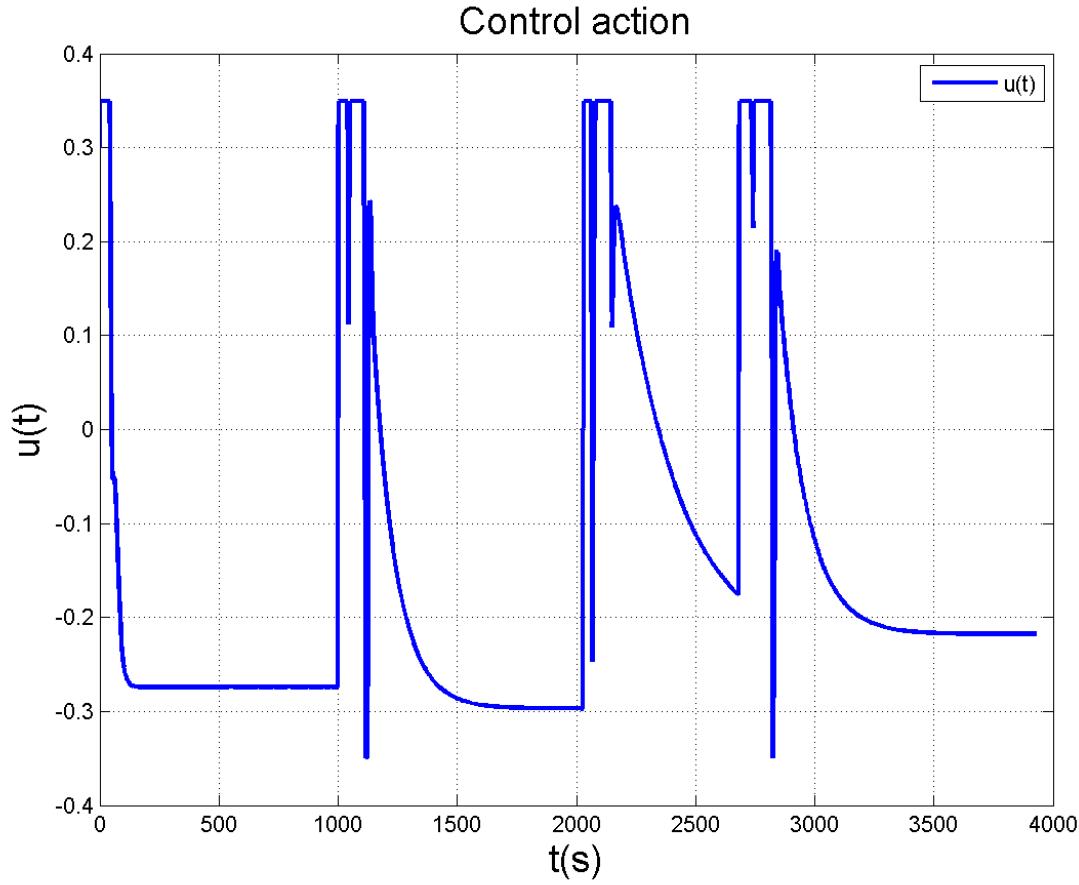
Results

Flight Condition	$G(z)$ Estimated	Feed Back Controller
1	$G(z) = \frac{-0.6048z^3 + 0.3617z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$\frac{S}{R}(z) = \frac{0.0004084z^3 - 0.2561z^2 + 0.3219z - 0.01532}{z^6 - 0.8554z^5 - 0.2986z^4 + 0.3272z^3 - 0.06942z^2 + 0.006605z - 0.0002478}$
2	$G(z) = \frac{-1.522z^3 + 1.297z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$\frac{S}{R}(z) = \frac{0.003497z^3 - 0.4264z^2 + 0.3629z + 0.0004453}{z^6 - 0.9922z^5 - 0.2136z^4 + 0.2523z^3 - 0.03329z^2 + 0.002401z - 7.377e-05}$
3	$G(z) = \frac{-1.295z^3 + 1.073z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$\frac{S}{R}(z) = \frac{-0.0002227z^3 - 0.2338z^2 + 0.2329z - 0.02154}{z^6 - 1.098z^5 - 0.1631z^4 + 0.3352z^3 - 0.07726z^2 + 0.007264z - 0.0002702}$
4	$G(z) = \frac{-2.25z^3 + 2.049z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$\frac{S}{R}(z) = \frac{0.002652z^3 - 0.3252z^2 + 0.2639z + 0.005786}{z^6 - 1.027z^5 - 0.1732z^4 + 0.2411z^3 - 0.02727z^2 + 0.001878z - 5.577e-05}$
		Feed Forward Controller
		$\frac{T}{R}(z) = \frac{-0.1528z^5 + 0.1528z^4 - 0.06111z^3 + 0.01222z^2 - 0.001222z + 4.889e-05}{z^6 - 0.8554z^5 - 0.2986z^4 + 0.3272z^3 - 0.06942z^2 + 0.006605z - 0.0002478}$
		$\frac{T}{R}(z) = \frac{-0.23z^5 + 0.23z^4 - 0.09199z^3 + 0.0184z^2 - 0.00184z + 7.359e-05}{z^6 - 0.9922z^5 - 0.2136z^4 + 0.2523z^3 - 0.03329z^2 + 0.002401z - 7.377e-05}$
		$\frac{T}{R}(z) = \frac{-0.07758z^5 + 0.07758z^4 - 0.03103z^3 + 0.006207z^2 - 0.0006207z + 2.483e-05}{z^6 - 1.098z^5 - 0.1631z^4 + 0.3352z^3 - 0.07726z^2 + 0.007264z - 0.0002702}$
		$\frac{T}{R}(z) = \frac{-0.196z^5 + 0.196z^4 - 0.07839z^3 + 0.01568z^2 - 0.001568z + 6.271e-05}{z^6 - 1.027z^5 - 0.1732z^4 + 0.2411z^3 - 0.02727z^2 + 0.001878z - 5.577e-05}$

For All Flight Conditions Together







Results

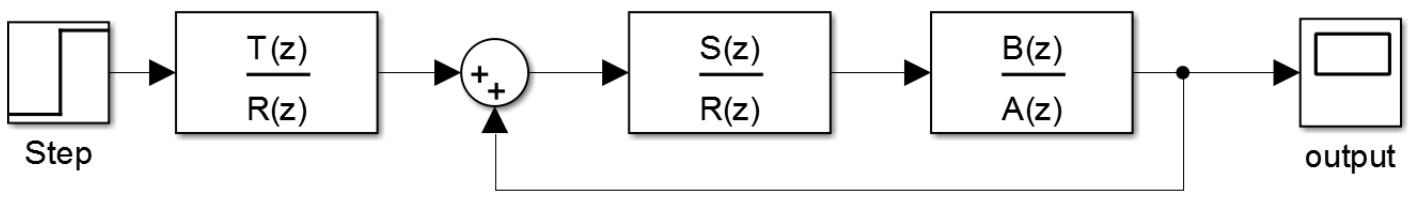
Flight Condition	G(z) Estimated	Feed Back Controller
1	$G(z) = \frac{-0.5646z^3 + 0.3215z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$\frac{S}{R}(z) = \frac{0.0004375z^3 - 0.2744z^2 + 0.3449z - 0.01641}{z^6 - 0.8268z^5 - 0.3402z^4 + 0.3525z^3 - 0.07444z^2 + 0.007075z - 0.0002655}$
2	$G(z) = \frac{-1.378z^3 + 1.153z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$\frac{S}{R}(z) = \frac{0.003863z^3 - 0.471z^2 + 0.4008z + 0.0004919}{z^6 - 0.9768z^5 - 0.2517z^4 + 0.2799z^3 - 0.03681z^2 + 0.002652z - 8.148e-05}$
3	$G(z) = \frac{-1.176z^3 + 0.9539z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$\frac{S}{R}(z) = \frac{-0.0002452z^3 - 0.2575z^2 + 0.2565z - 0.02372}{z^6 - 1.081z^5 - 0.2098z^4 + 0.3721z^3 - 0.08521z^2 + 0.008z - 0.0002975}$
4	$G(z) = \frac{-2.023z^3 + 1.822z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$\frac{S}{R}(z) = \frac{0.002951z^3 - 0.3618z^2 + 0.2936z + 0.006437}{z^6 - 1.017z^5 - 0.2068z^4 + 0.2692z^3 - 0.03037z^2 + 0.002089z - 6.205e-05}$
		Feed Forward Controller
		$\frac{T}{R}(z) = \frac{-0.1637z^5 + 0.1637z^4 - 0.06546z^3 + 0.01309z^2 - 0.001309z + 5.237e-05}{z^6 - 0.8268z^5 - 0.3402z^4 + 0.3525z^3 - 0.07444z^2 + 0.007075z - 0.0002655}$
		$\frac{T}{R}(z) = \frac{-0.254z^5 + 0.254z^4 - 0.1016z^3 + 0.02032z^2 - 0.002032z + 8.129e-05}{z^6 - 0.9768z^5 - 0.2517z^4 + 0.2799z^3 - 0.03681z^2 + 0.002652z - 8.148e-05}$
		$\frac{T}{R}(z) = \frac{-0.08545z^5 + 0.08545z^4 - 0.03418z^3 + 0.006836z^2 - 0.0006836z + 2.734e-05}{z^6 - 1.081z^5 - 0.2098z^4 + 0.3721z^3 - 0.08521z^2 + 0.008z - 0.0002975}$
		$\frac{T}{R}(z) = \frac{-0.218z^5 + 0.218z^4 - 0.08721z^3 + 0.01744z^2 - 0.001744z + 6.977e-05}{z^6 - 1.017z^5 - 0.2068z^4 + 0.2692z^3 - 0.03037z^2 + 0.002089z - 6.205e-05}$

Comments

- The system parameter goes to its true values if i control all flight conditions together.
- There is a change in controller parameter between the controller of all flight conditions and the controller of each flight condition.

1.6.5 Indirect Self-Tuning Regulator Using Model Following Without Zero Cancellation For Square Input

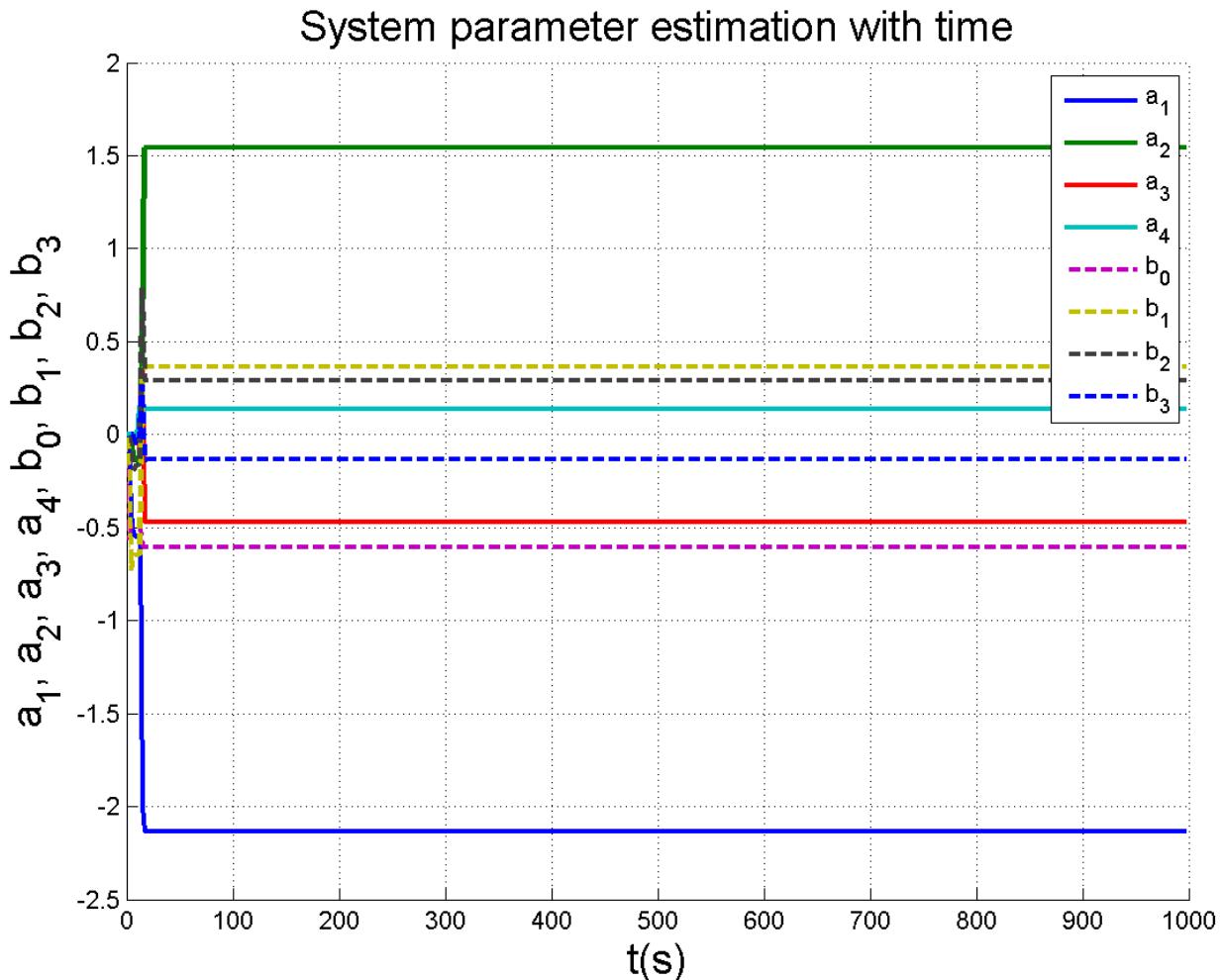
Controller Scheme

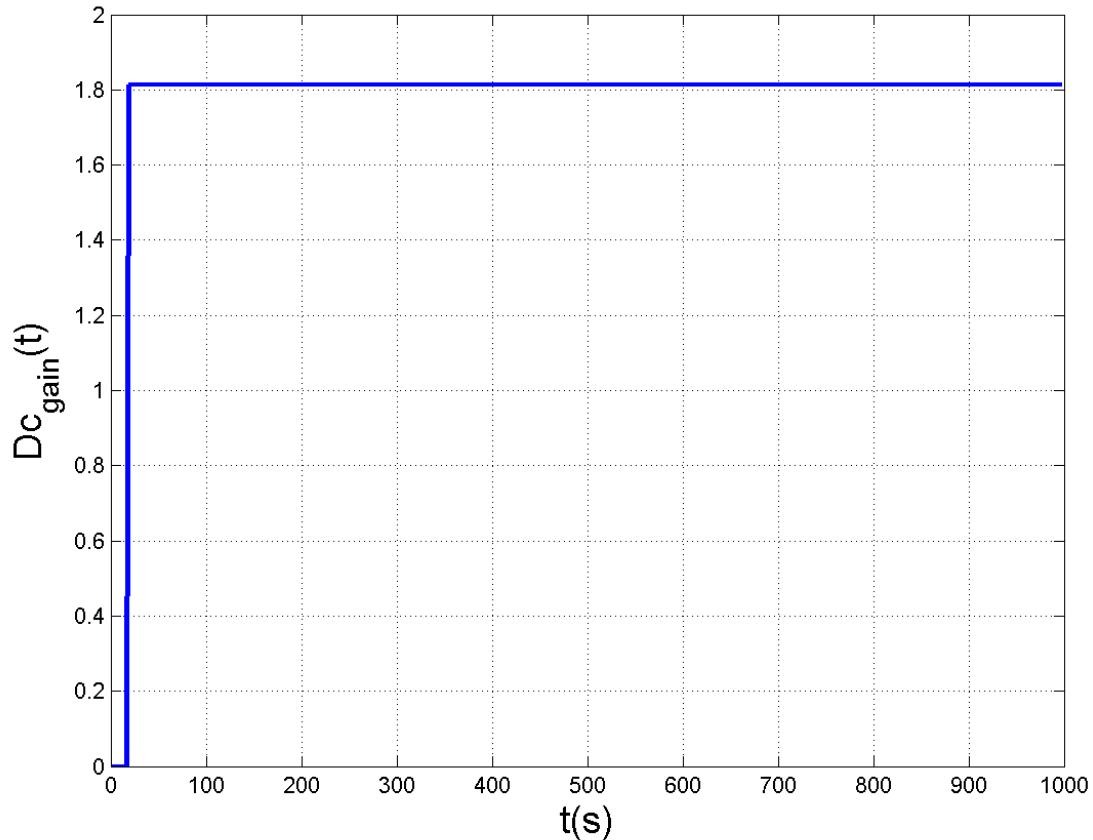
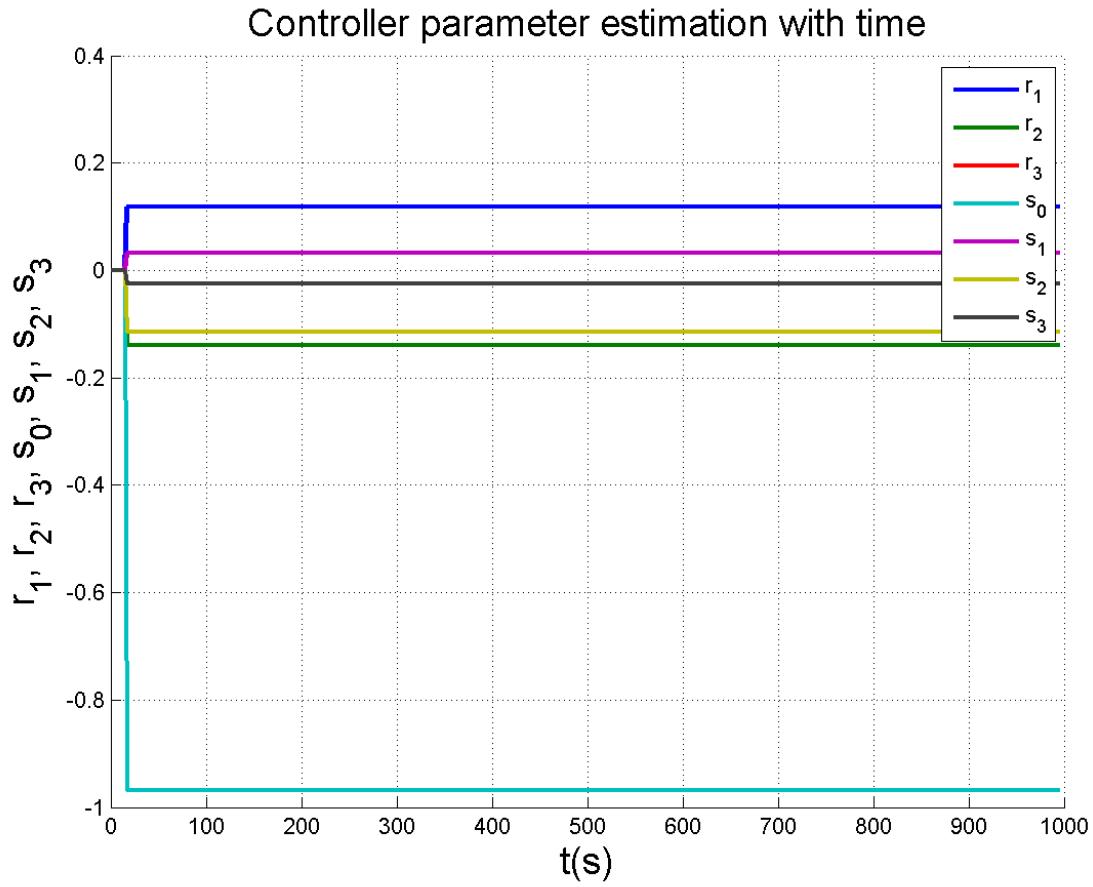


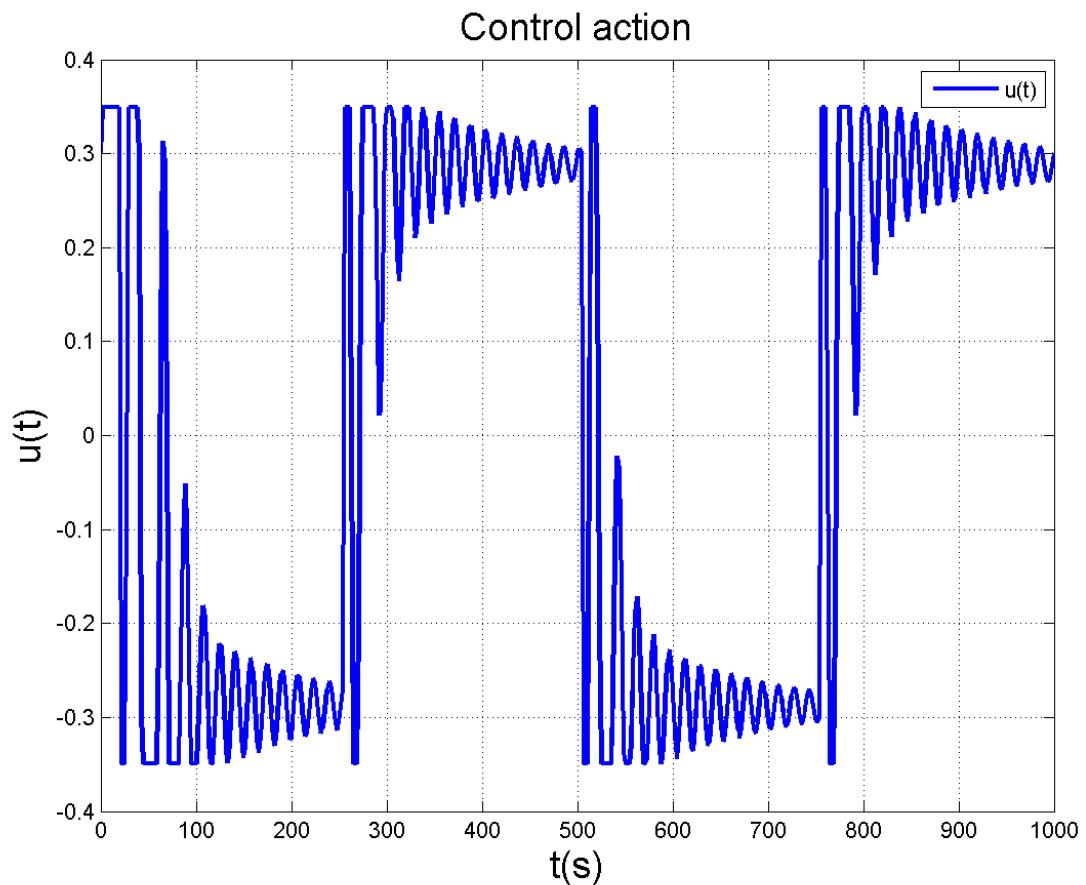
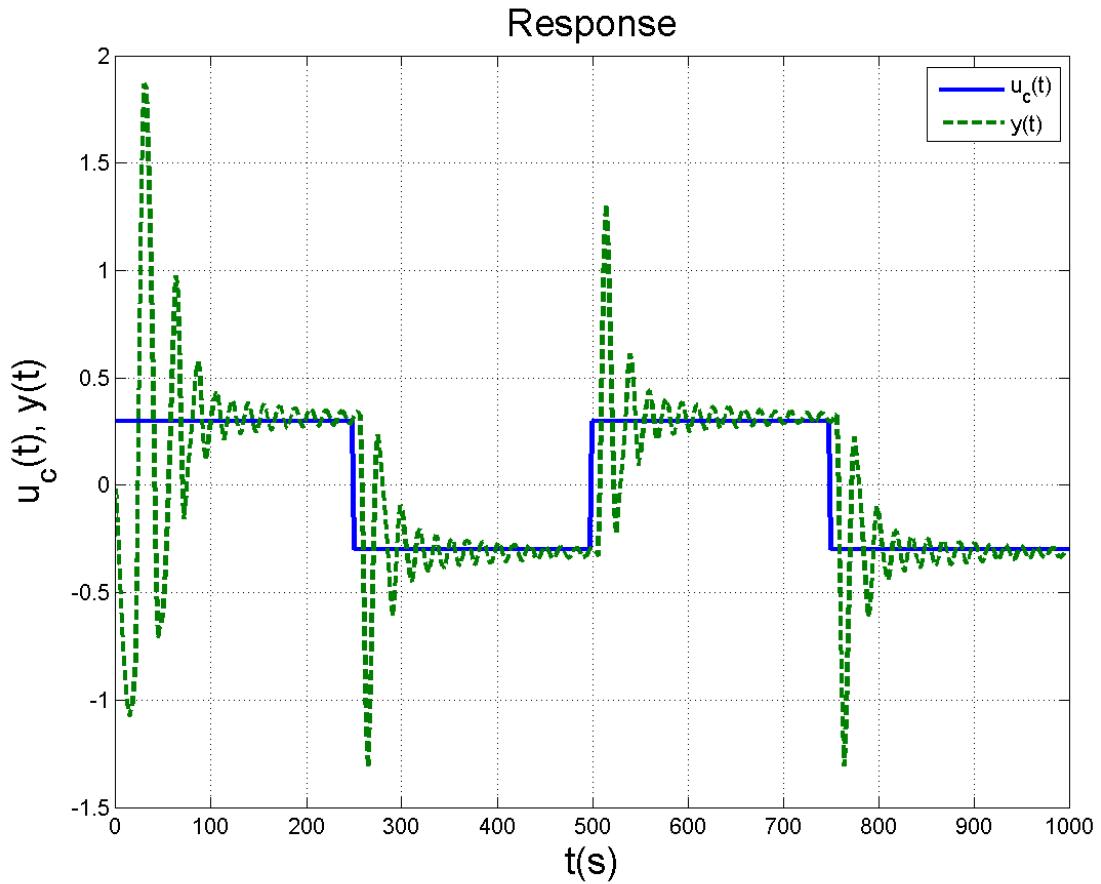
Required Poles in Z-Domain

Flight Condition	A_m	A_0
1	[0.48, 0.45]	[0.1, 0.1, 0.1, 0.1, 0.1]
2	[0.8, 0.8]	[0.02, 0.02, 0.02, 0.02, 0.02]
3	[0.7, 0.9]	[0.3, 0.3, 0.3, 0.3, 0.3]
4	[0.7, 0.55]	[0.24, 0.24, 0.24, 0.24, 0.24]

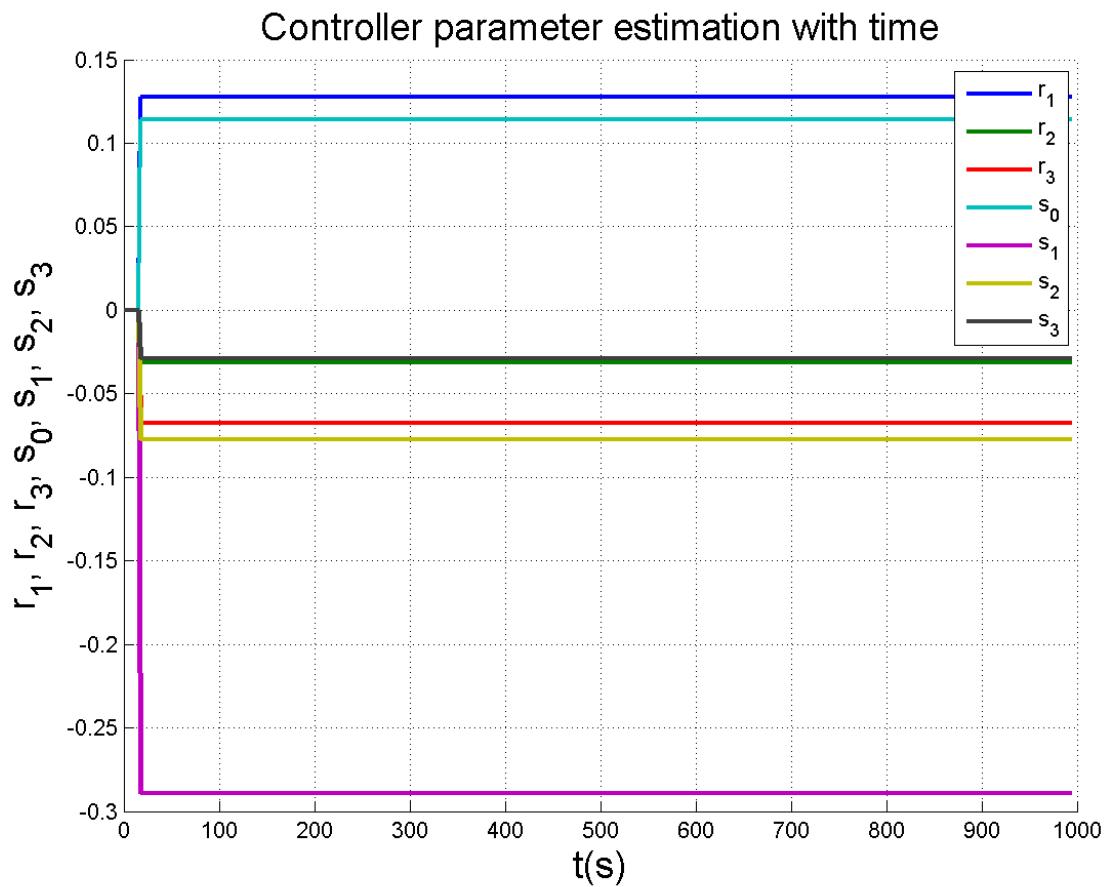
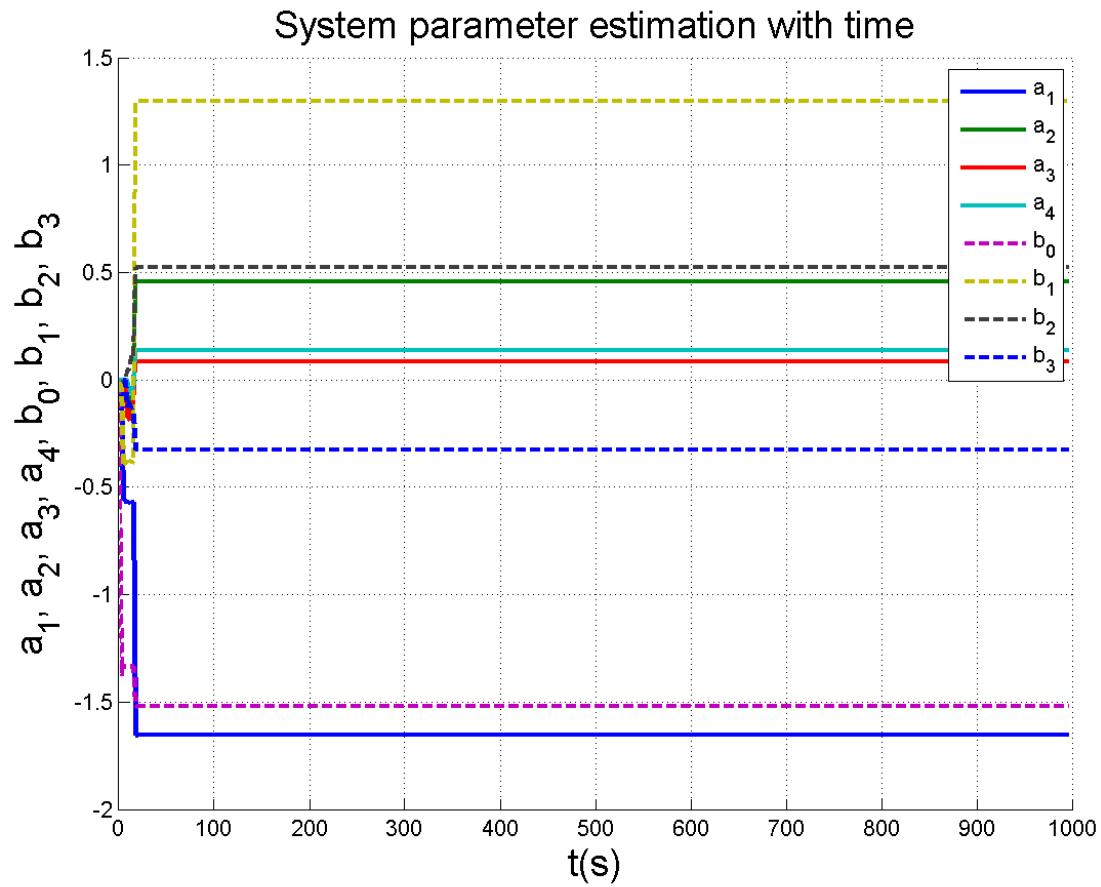
Flight Condition 1

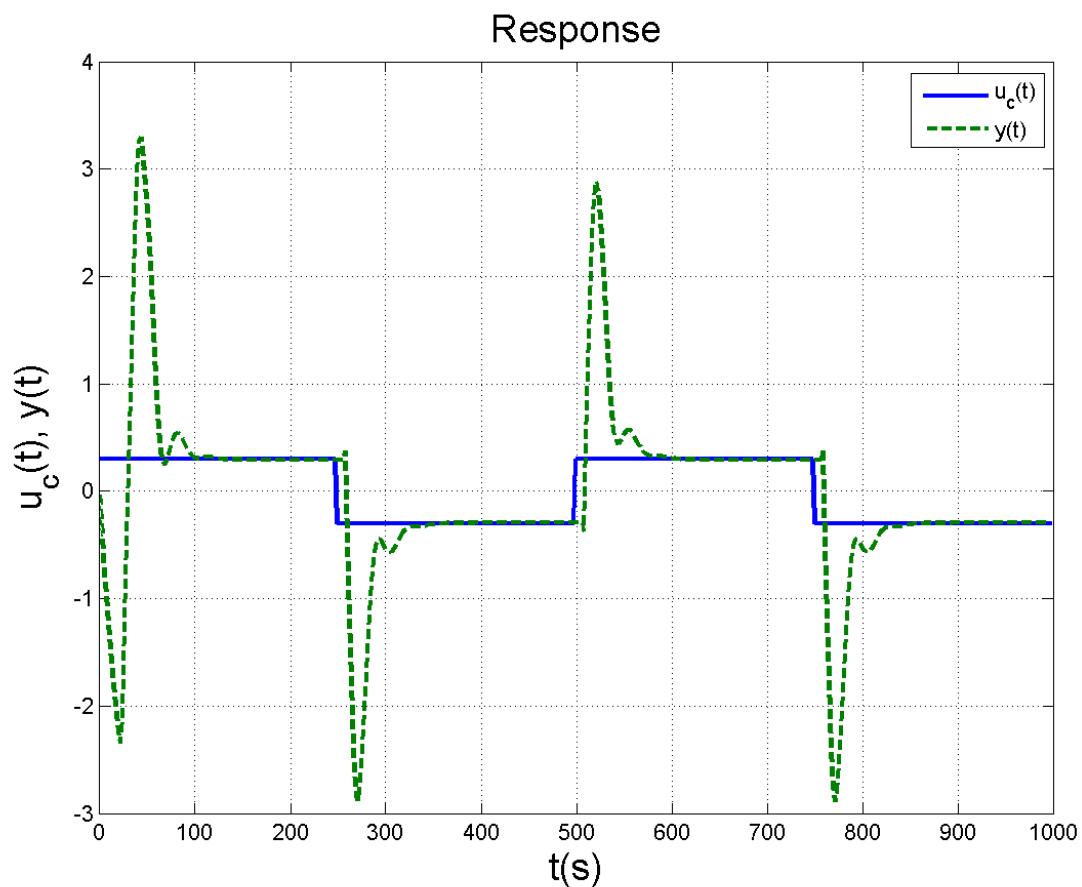
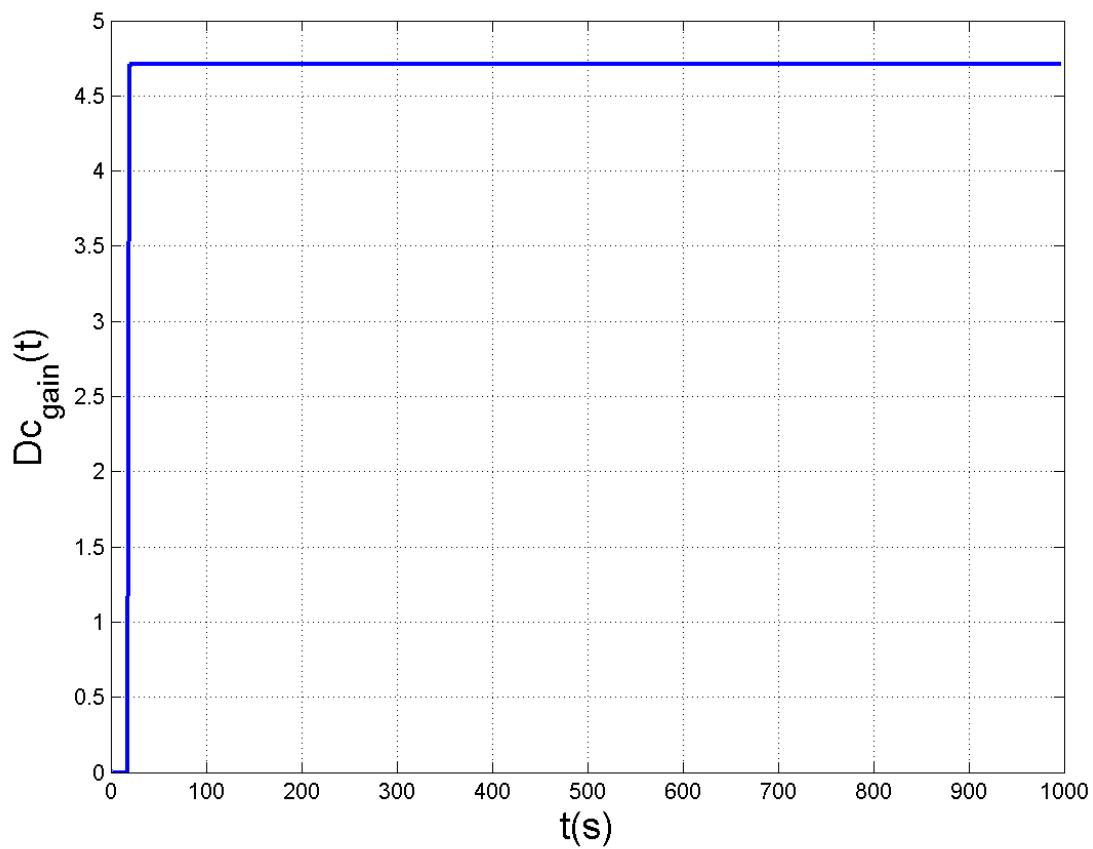


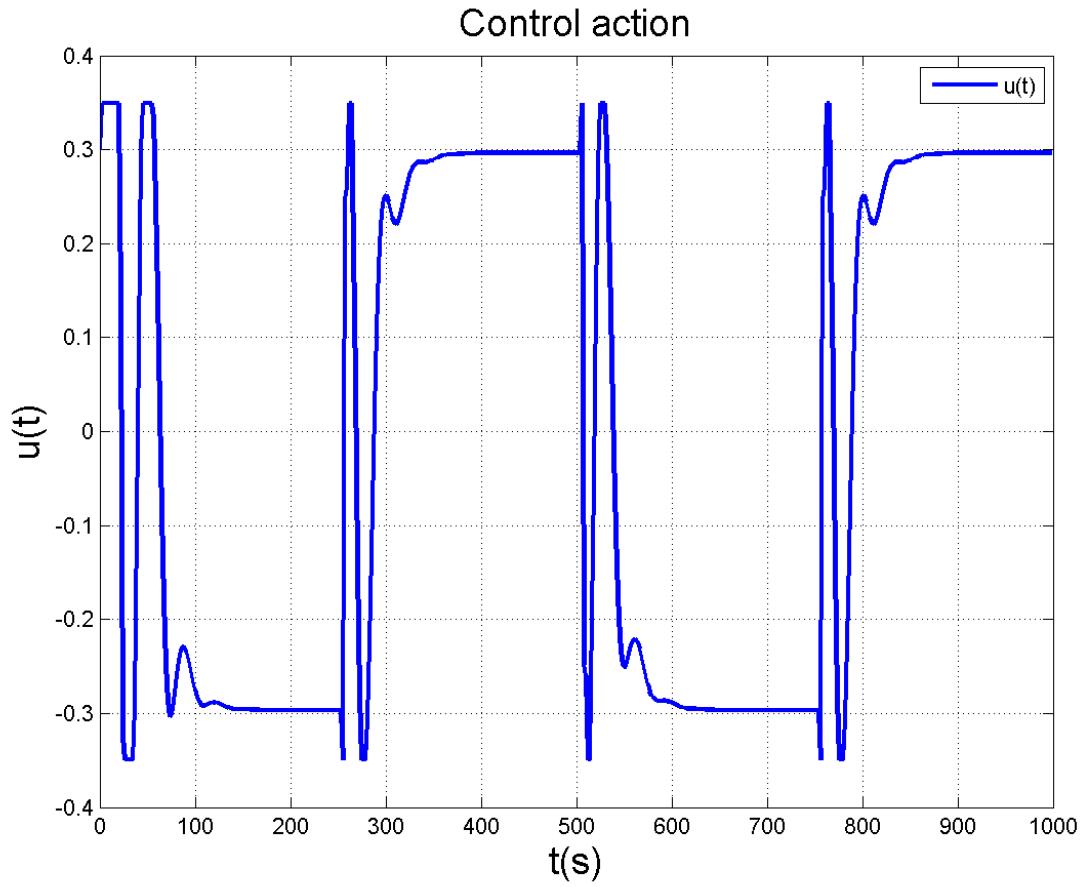




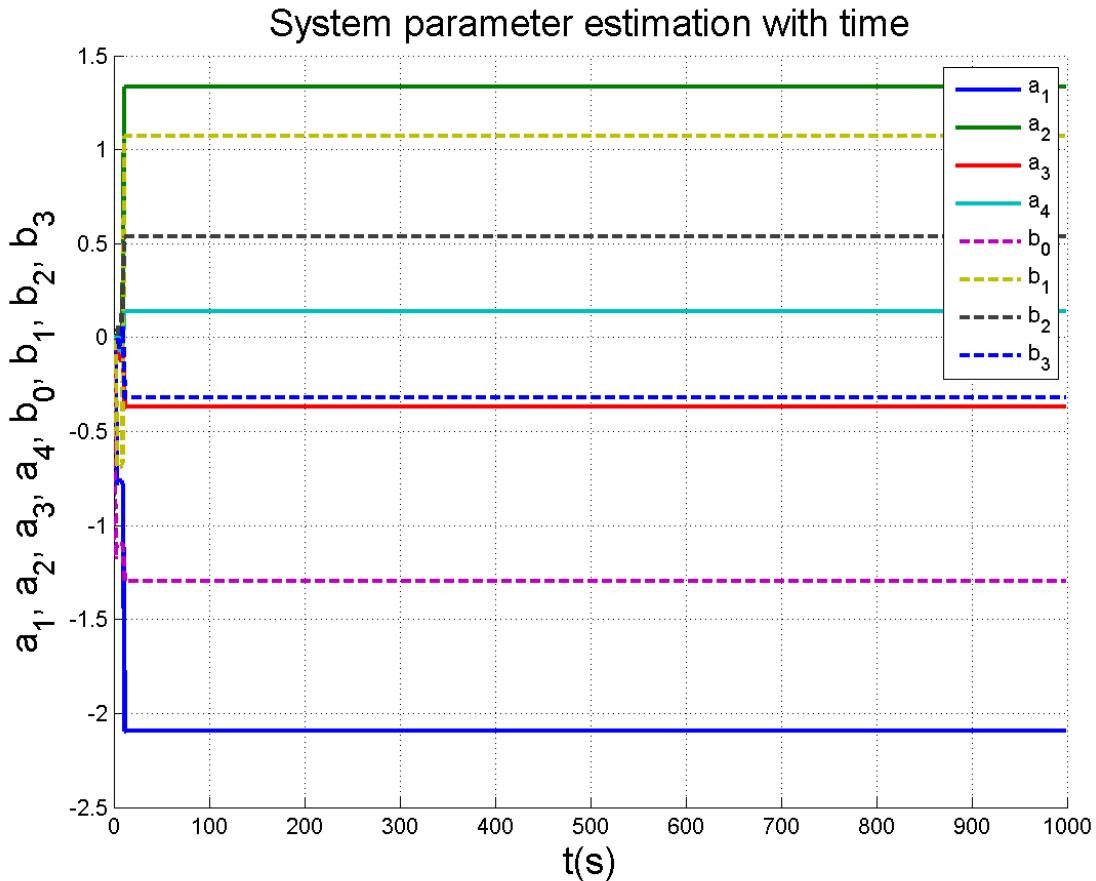
Flight Condition 2

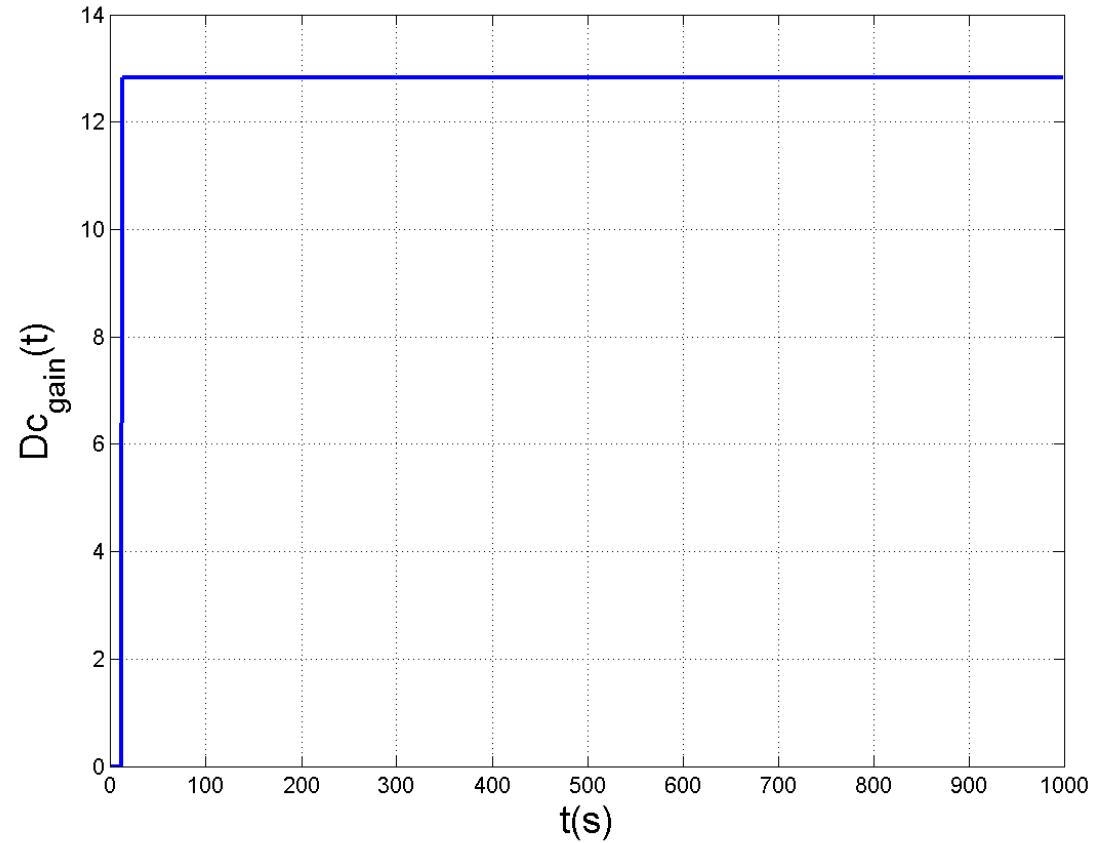
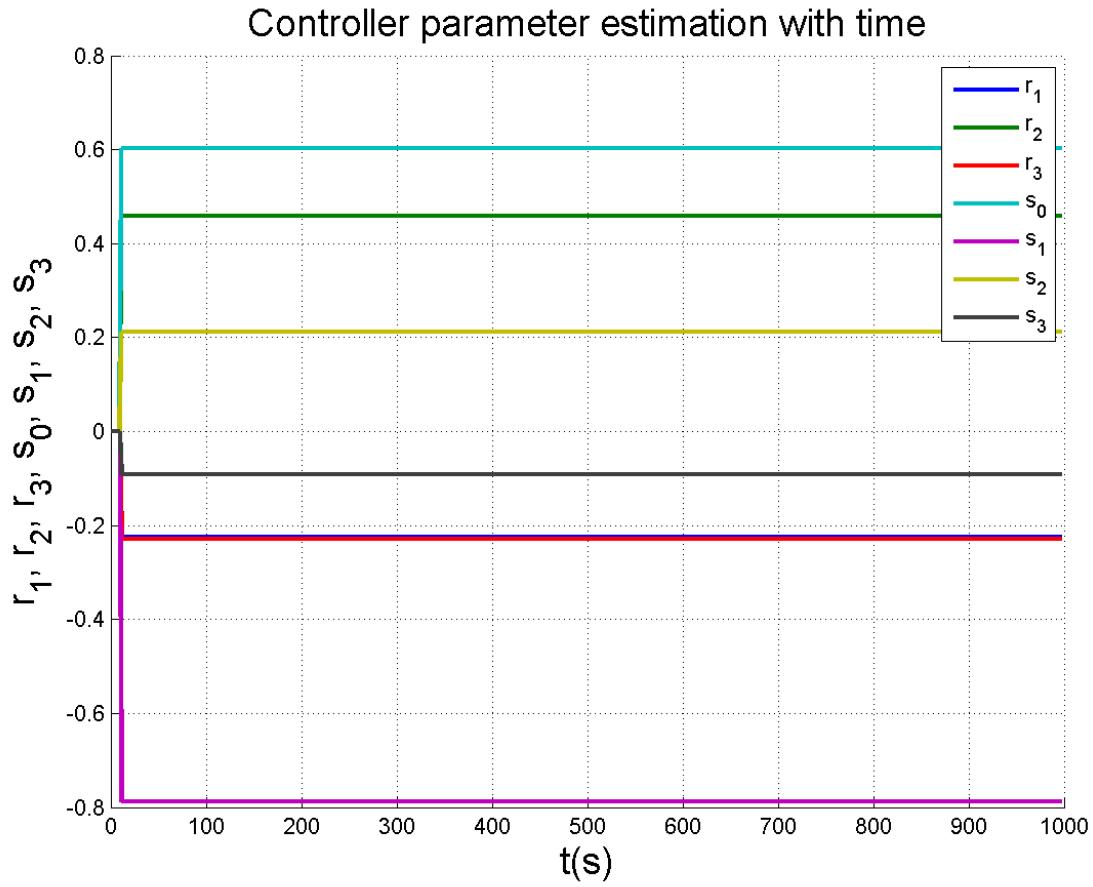


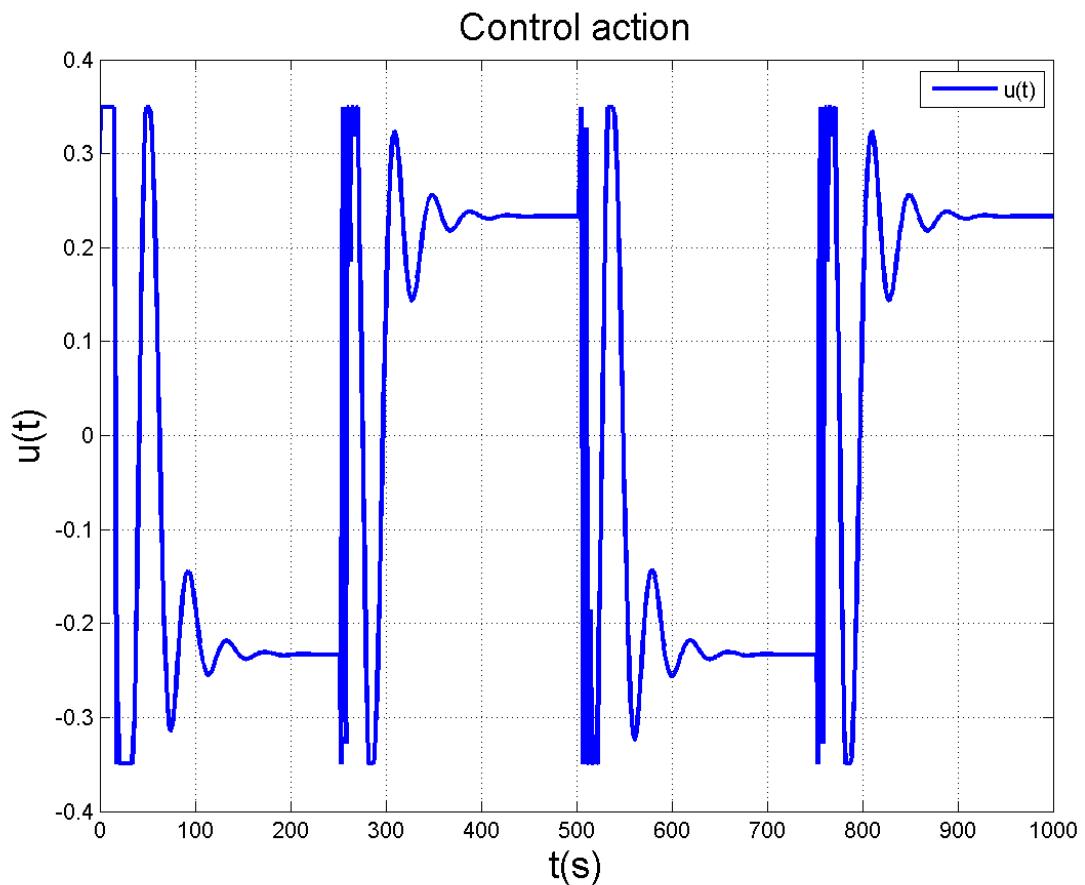
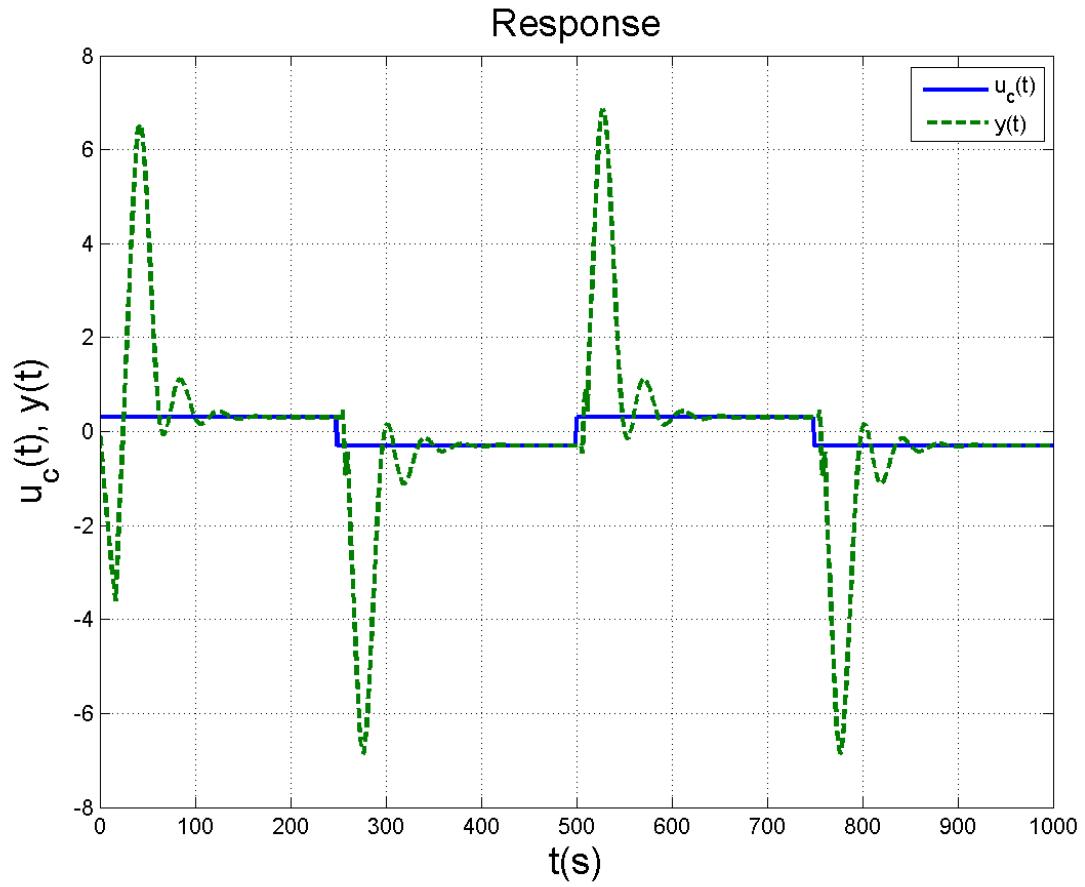




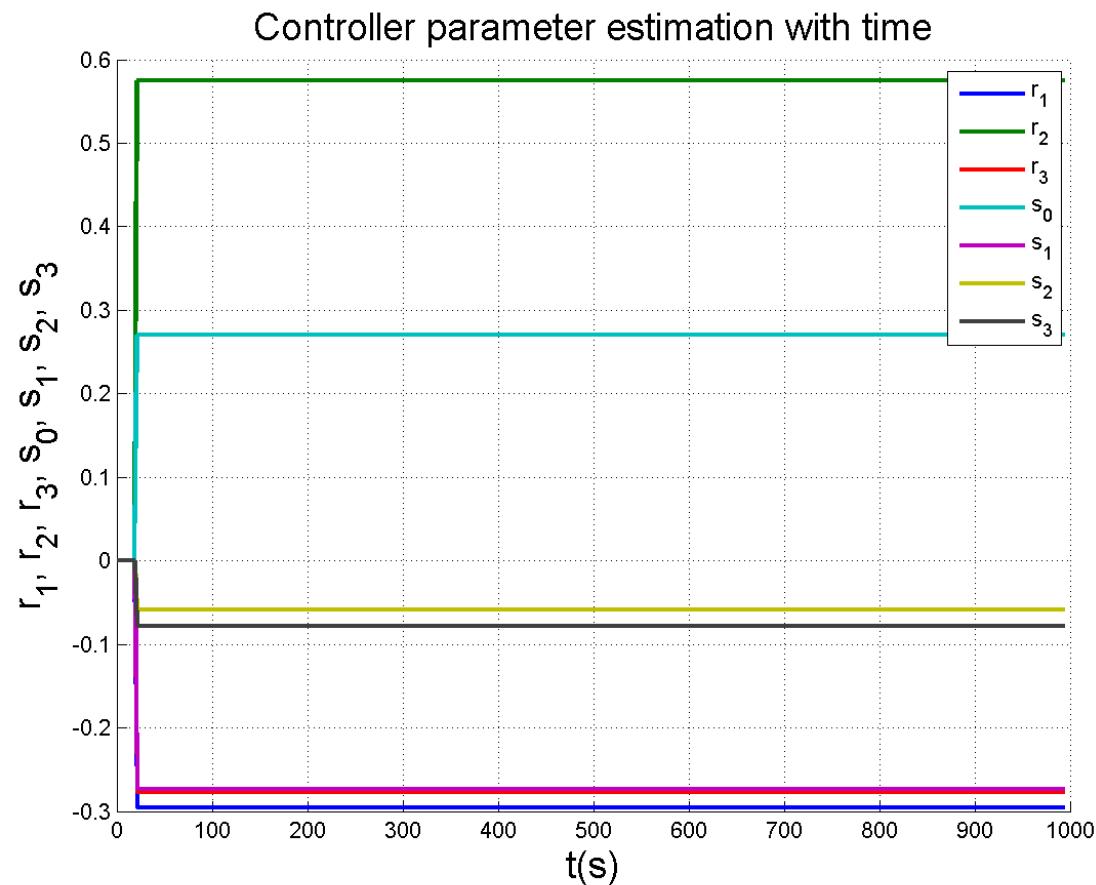
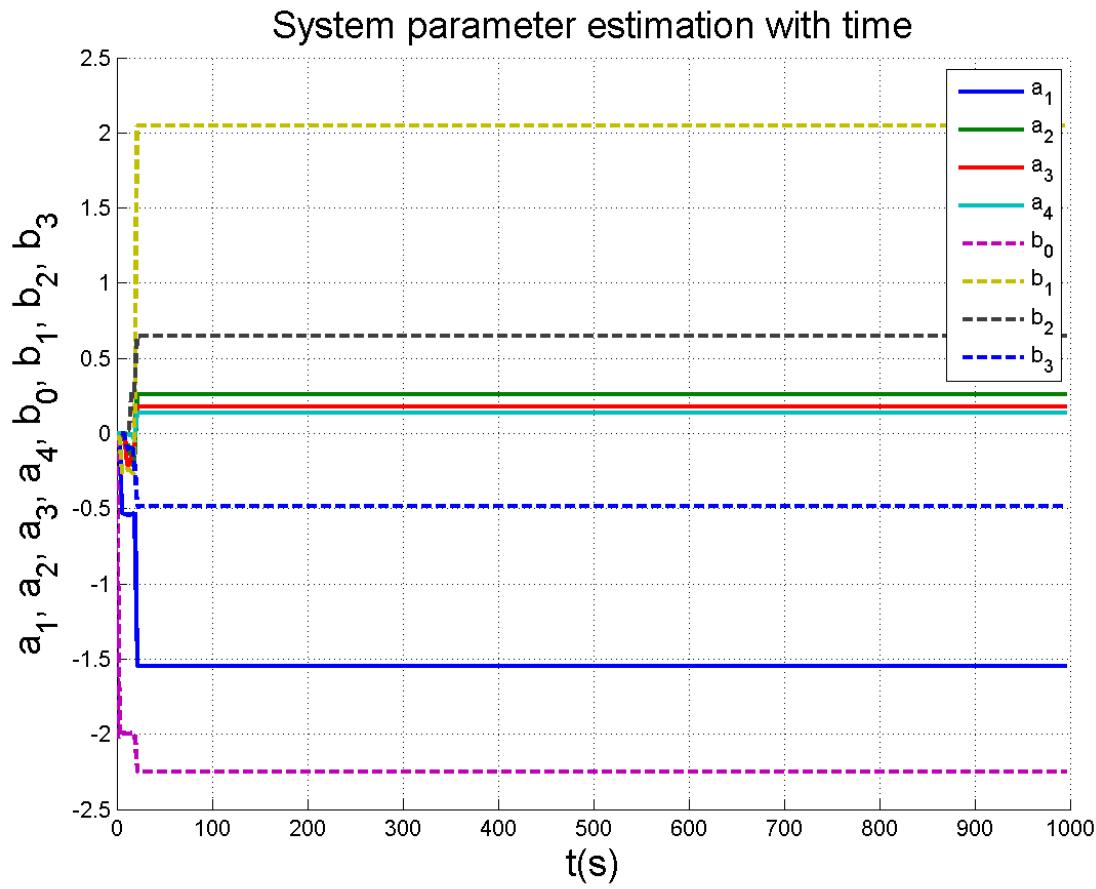
Flight Condition 3

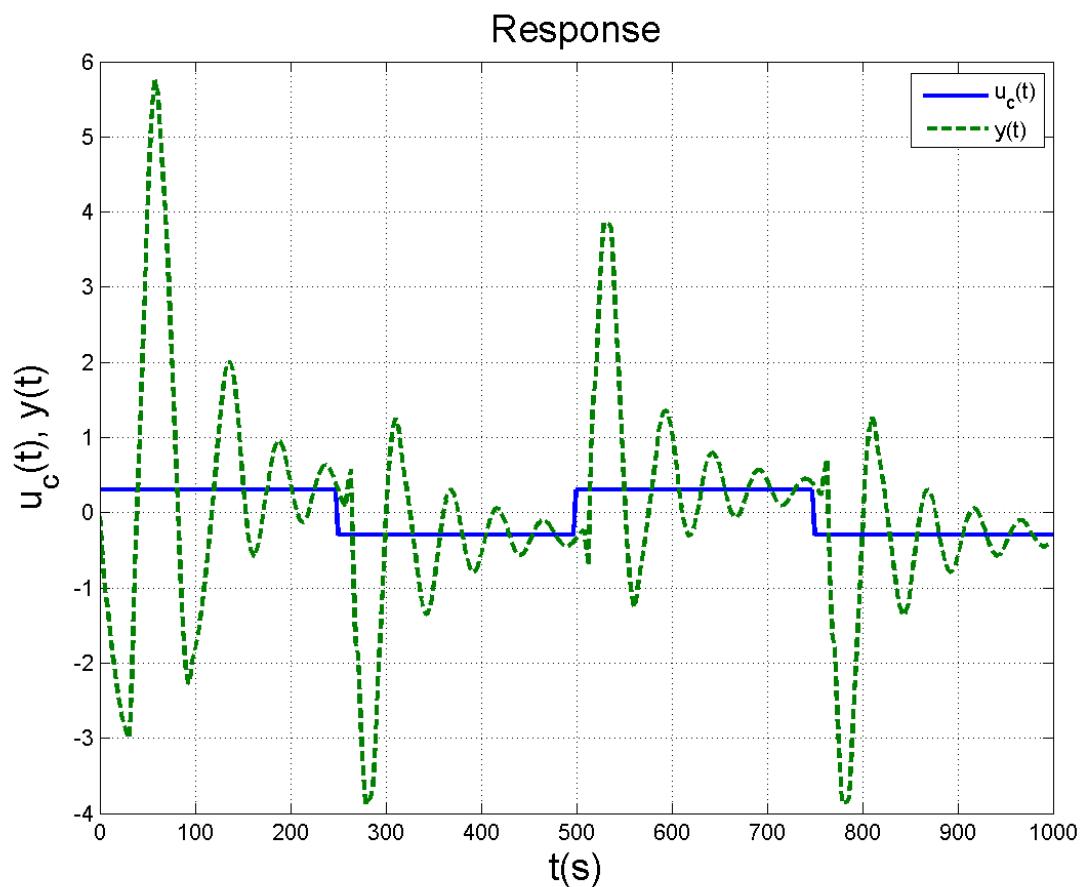
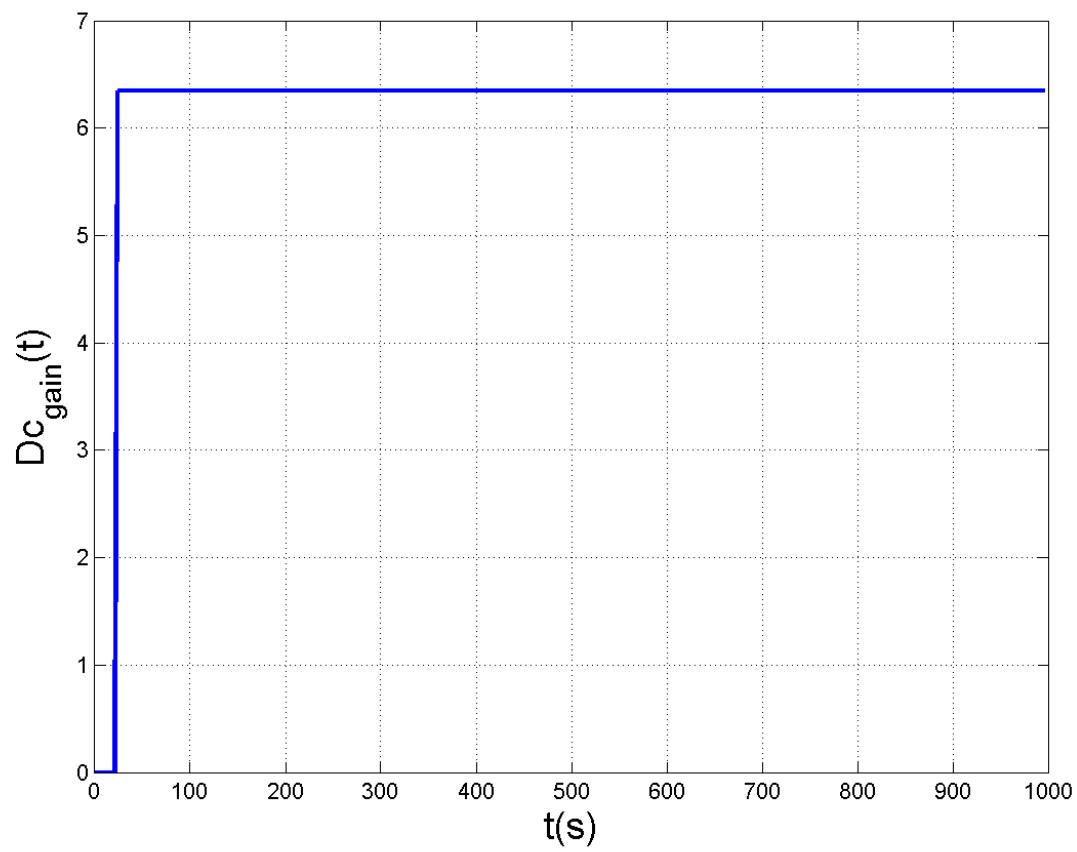


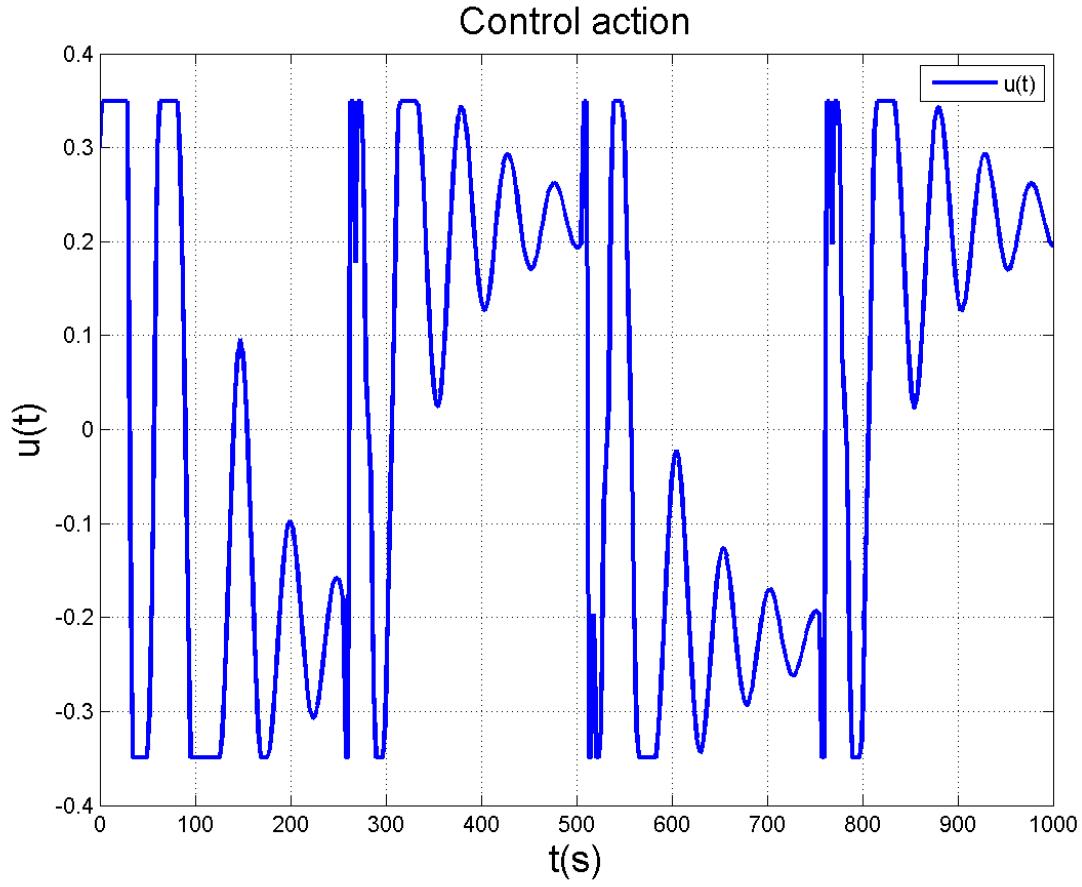




Flight Condition 4



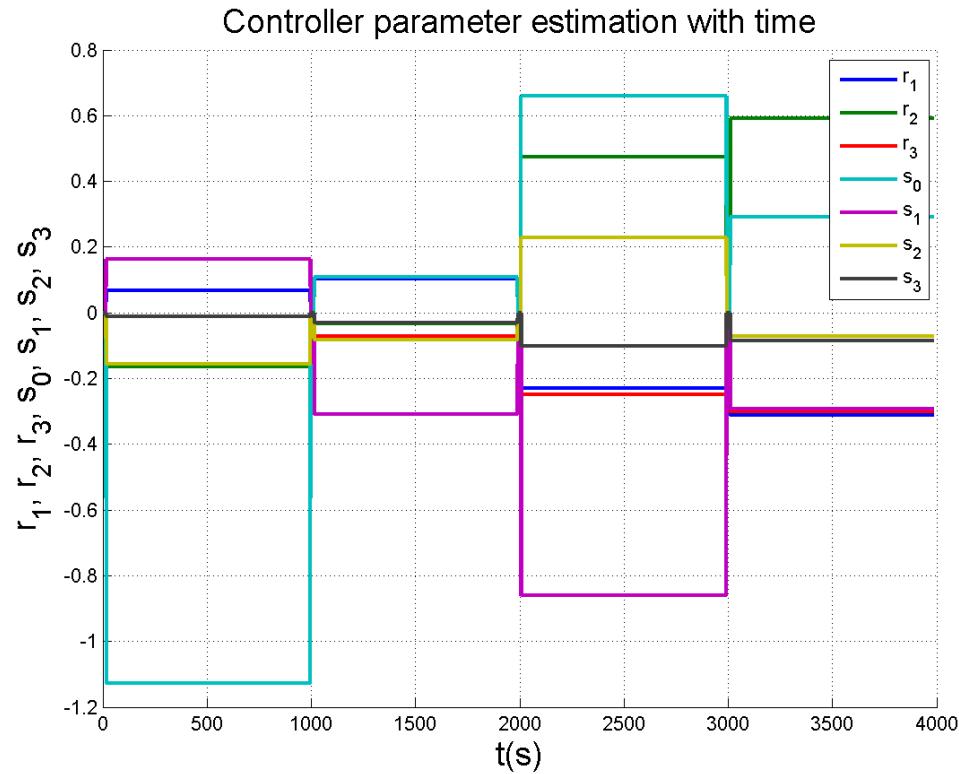
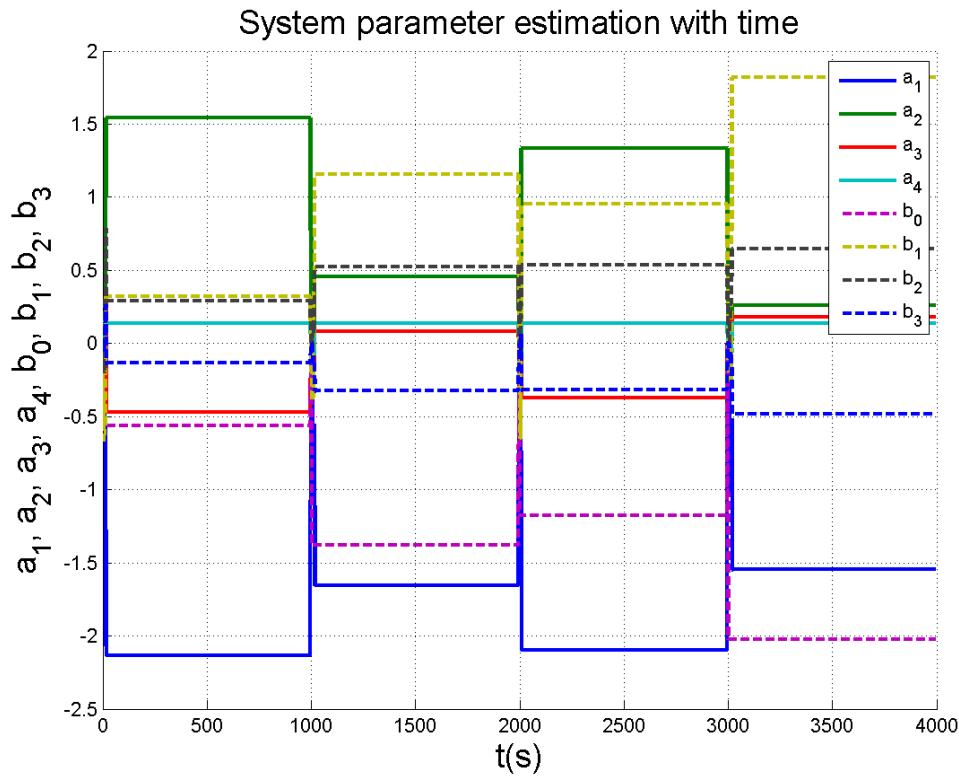


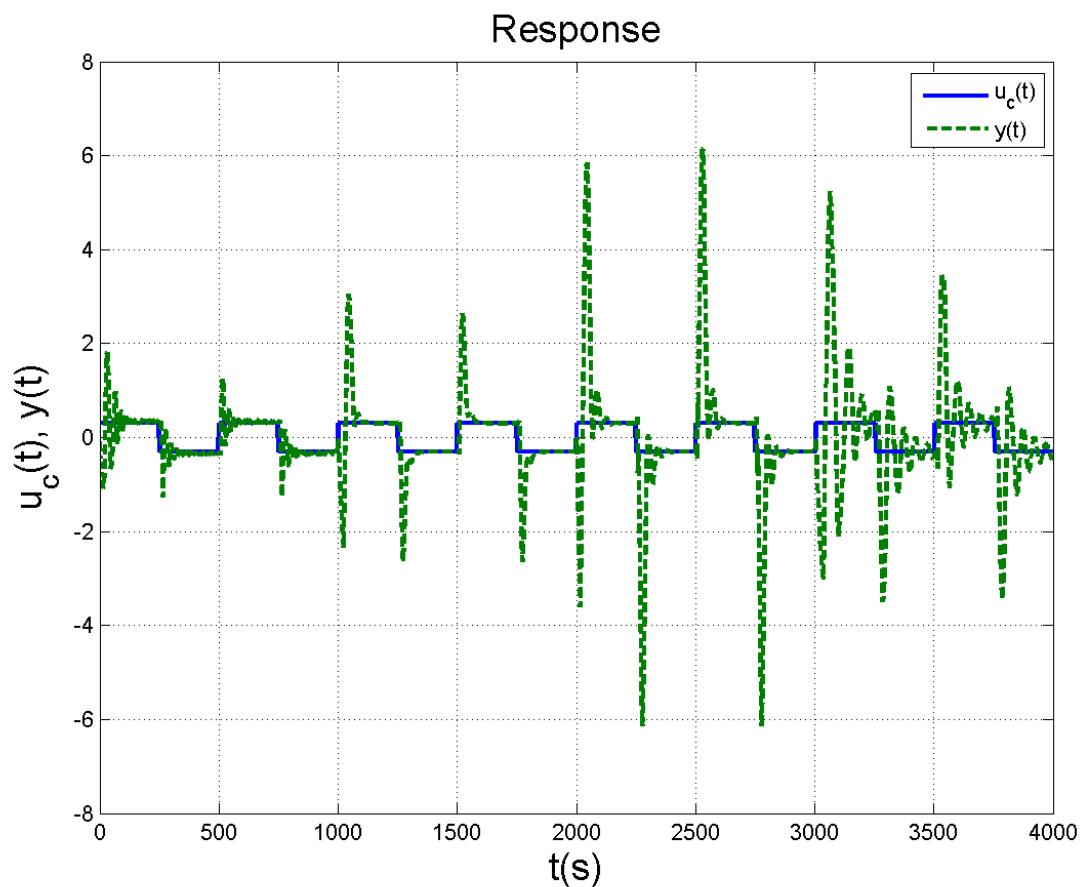
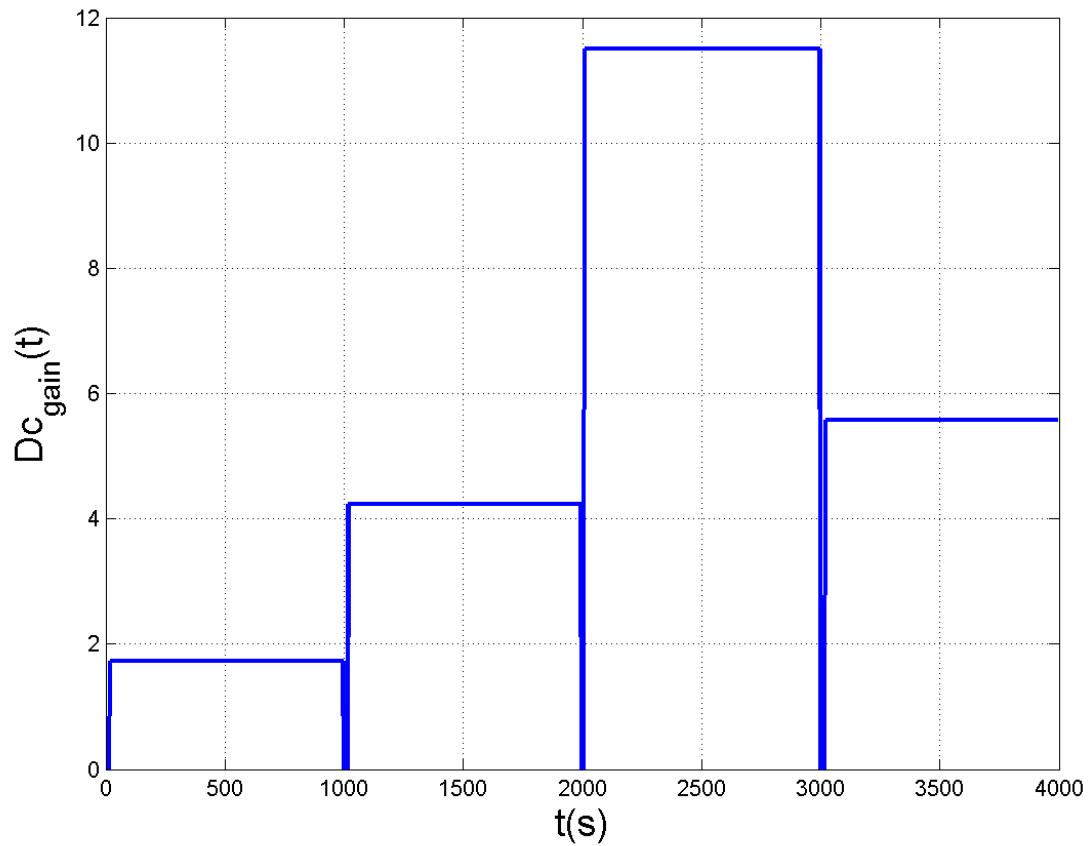


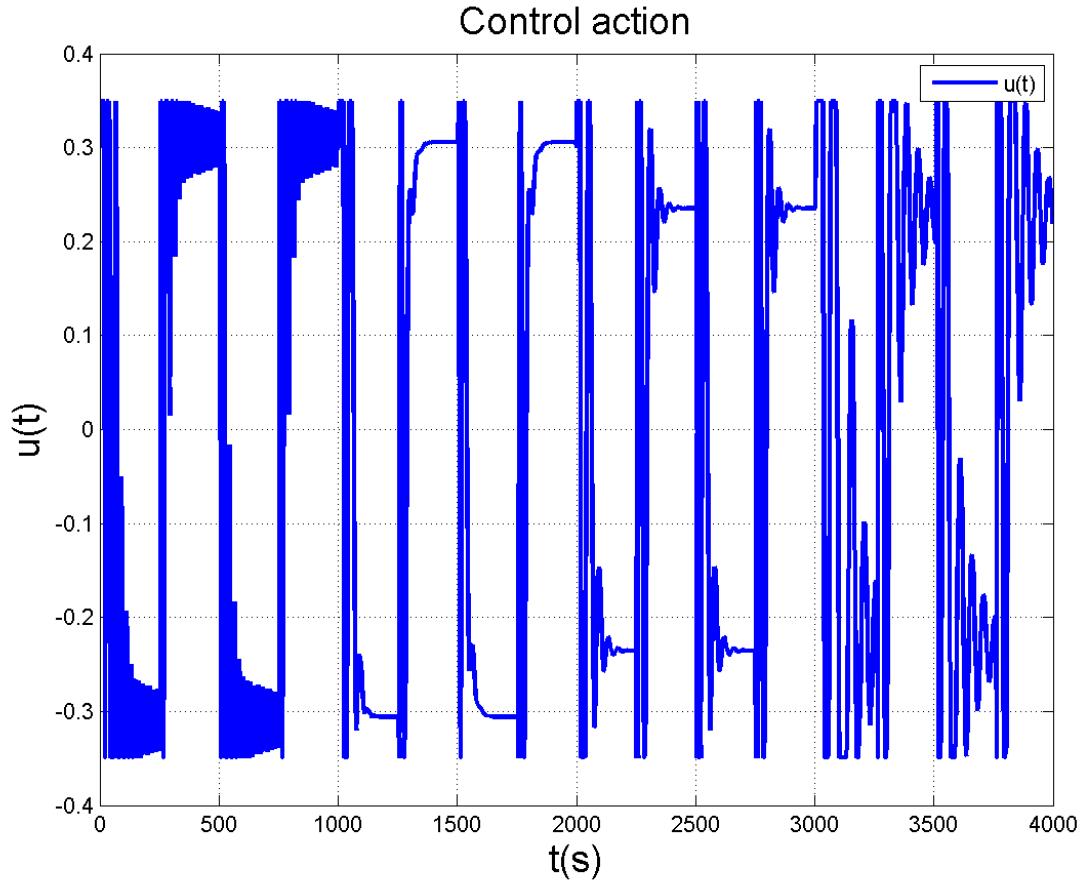
Results

Flight Condition	$G(z)$ Estimated	Feed Forward Controller	DC_{gain}
1	$G(z) = \frac{-0.6048z^3 + 0.3617z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$\frac{S}{R}(z) = \frac{-0.9676z^3 + 0.03209z^2 - 0.1145z - 0.02546}{z^3 + 0.1191z^2 - 0.14z - 0.02463}$	$\frac{T}{R}(z) = 1.814$
2	$G(z) = \frac{-1.522z^3 + 1.297z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$\frac{S}{R}(z) = \frac{0.1138z^3 - 0.2895z^2 - 0.07766z - 0.02899}{z^3 + 0.1279z^2 - 0.03137z - 0.06781}$	$\frac{T}{R}(z) = 4.707$
3	$G(z) = \frac{-1.295z^3 + 1.073z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$\frac{S}{R}(z) = \frac{0.6022z^3 - 0.7886z^2 + 0.2123z - 0.09237}{z^3 - 0.2245z^2 + 0.4573z - 0.2282}$	$\frac{T}{R}(z) = 12.82$
4	$G(z) = \frac{-2.25z^3 + 2.049z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$\frac{S}{R}(z) = \frac{0.2699z^3 - 0.2734z^2 - 0.05836z - 0.07783}{z^3 - 0.2951z^2 + 0.5753z - 0.2772}$	$\frac{T}{R}(z) = 6.348$

For All Flight Conditions Together







Results

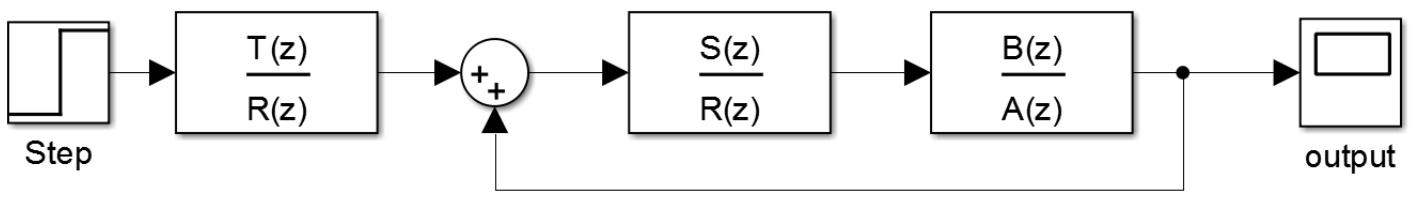
Flight Condition	$G(z)$ Estimated	Feed Forward Controller	DC_{gain}
1	$G(z) = \frac{-0.5646z^3 + 0.3215z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$\frac{S}{R}(z) = \frac{-1.128z^3 + 0.1626z^2 - 0.1567z - 0.01222}{z^3 + 0.06749z^2 - 0.1651z - 0.01184}$	$\frac{T}{R}(z) = 1.72$
2	$G(z) = \frac{-1.378z^3 + 1.153z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$\frac{S}{R}(z) = \frac{0.1076z^3 - 0.3084z^2 - 0.08262z - 0.03083}{z^3 + 0.1029z^2 - 0.03346z - 0.0721}$	$\frac{T}{R}(z) = 4.229$
3	$G(z) = \frac{-1.176z^3 + 0.9539z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$\frac{S}{R}(z) = \frac{0.6583z^3 - 0.8597z^2 + 0.2284z - 0.1011}{z^3 - 0.2304z^2 + 0.4738z - 0.2486}$	$\frac{T}{R}(z) = 11.5$
4	$G(z) = \frac{-2.023z^3 + 1.822z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$\frac{S}{R}(z) = \frac{0.2917z^3 - 0.2937z^2 - 0.07217z - 0.0848}{z^3 - 0.3125z^2 + 0.5914z - 0.3018}$	$\frac{T}{R}(z) = 5.579$

Comments

- The system parameter goes to its true values if i control all flight conditions together.
- There is a change in controller parameter between the controller of all flight conditions and the controller of each flight condition.

1.6.6 Indirect Self-Tuning Regulator Using Model Following With Zero Cancellation For Square Input

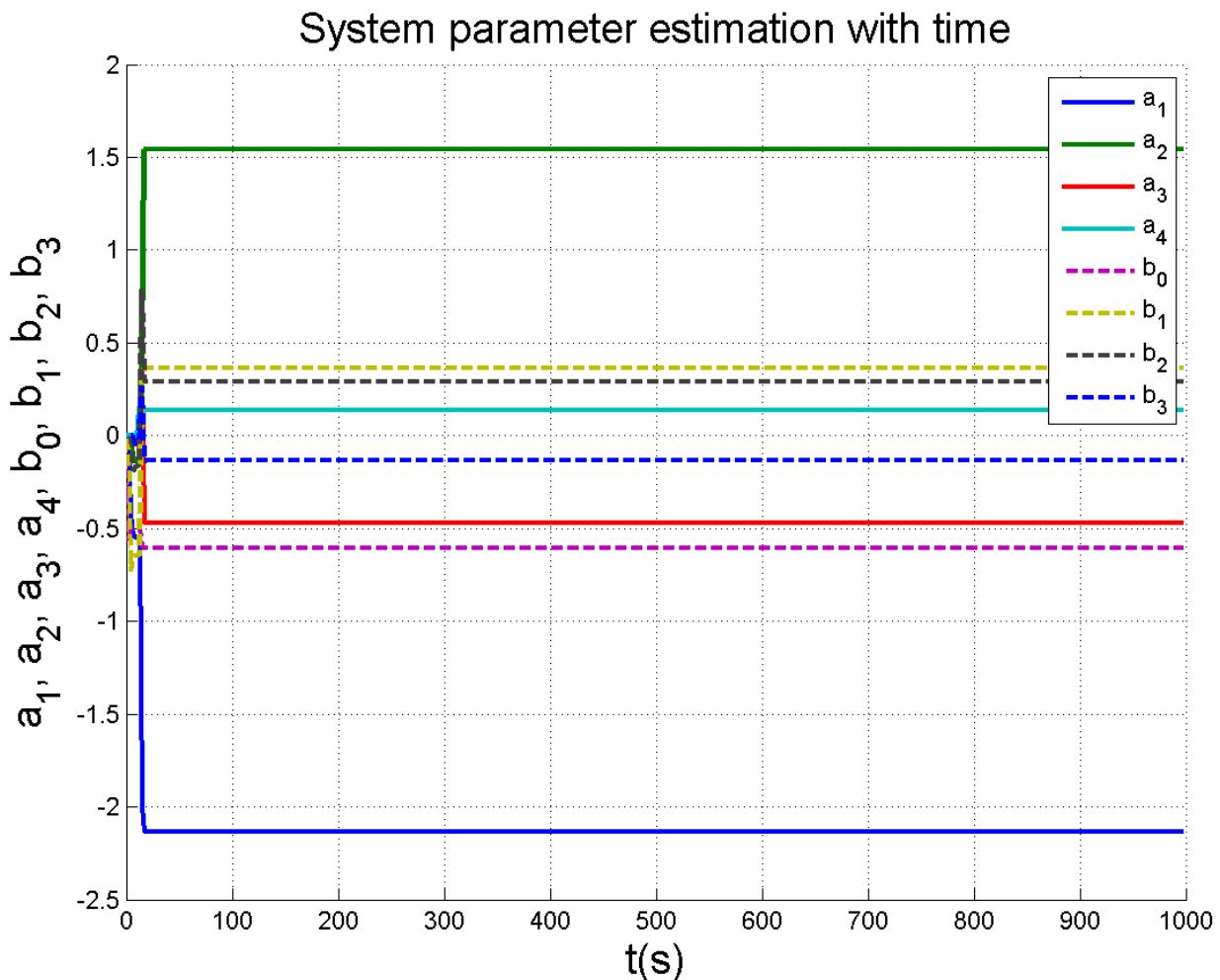
Controller Scheme

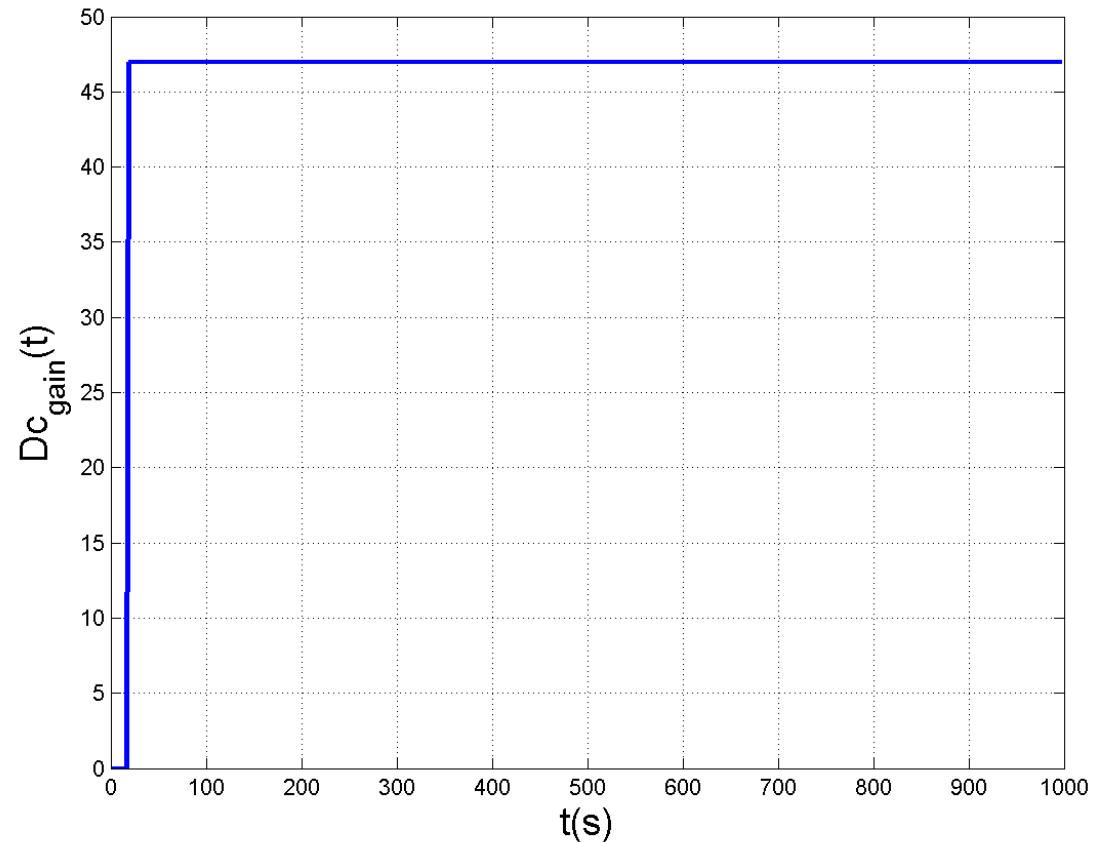
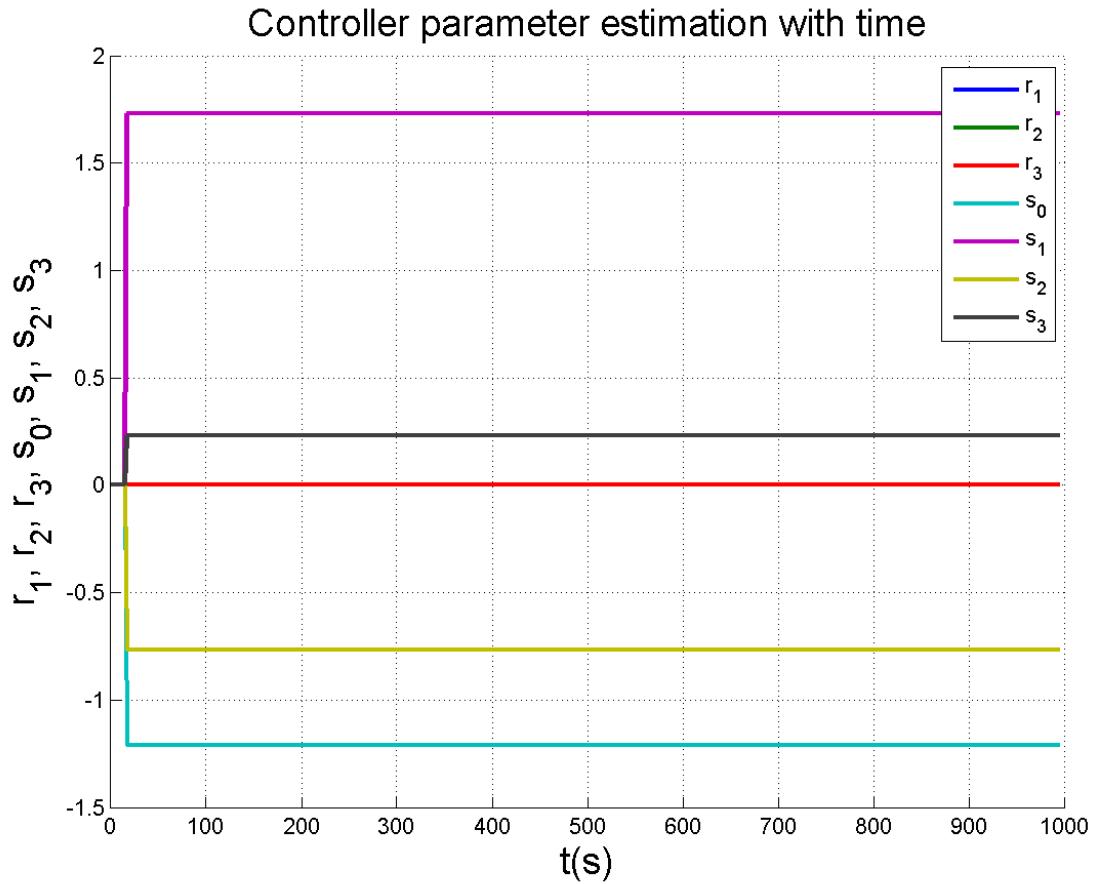


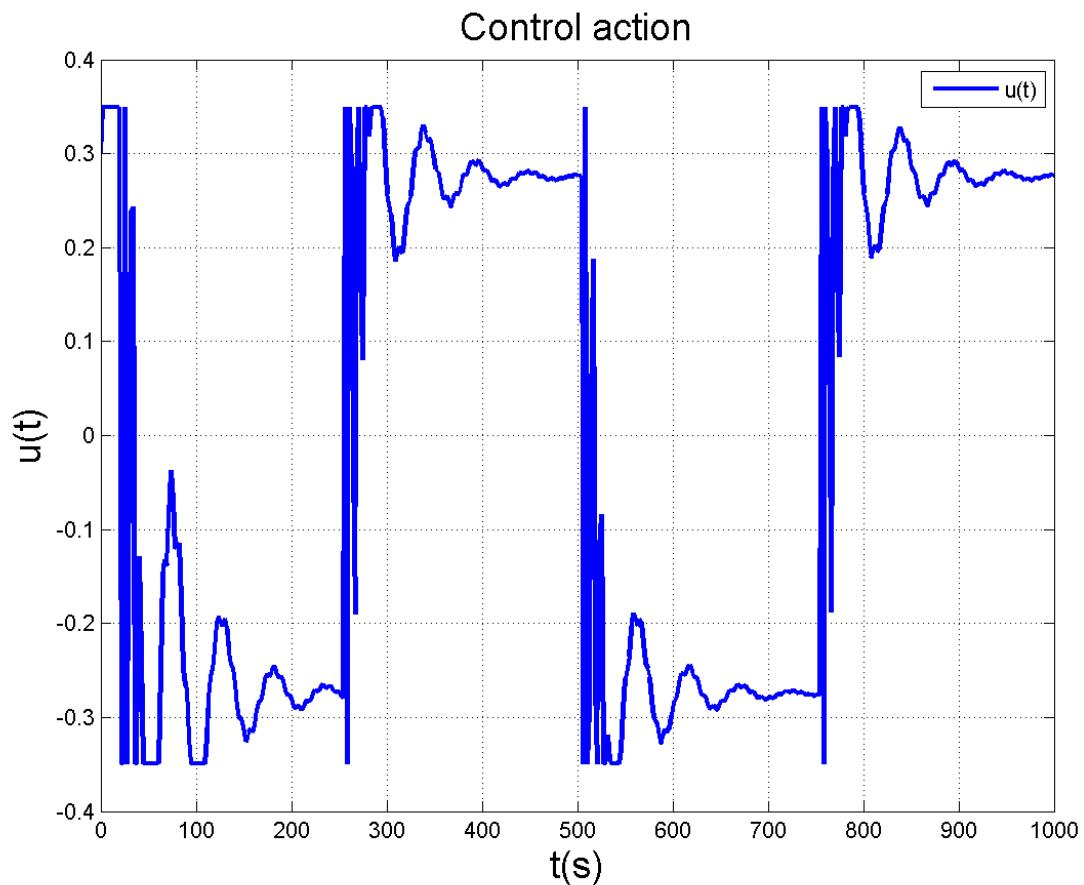
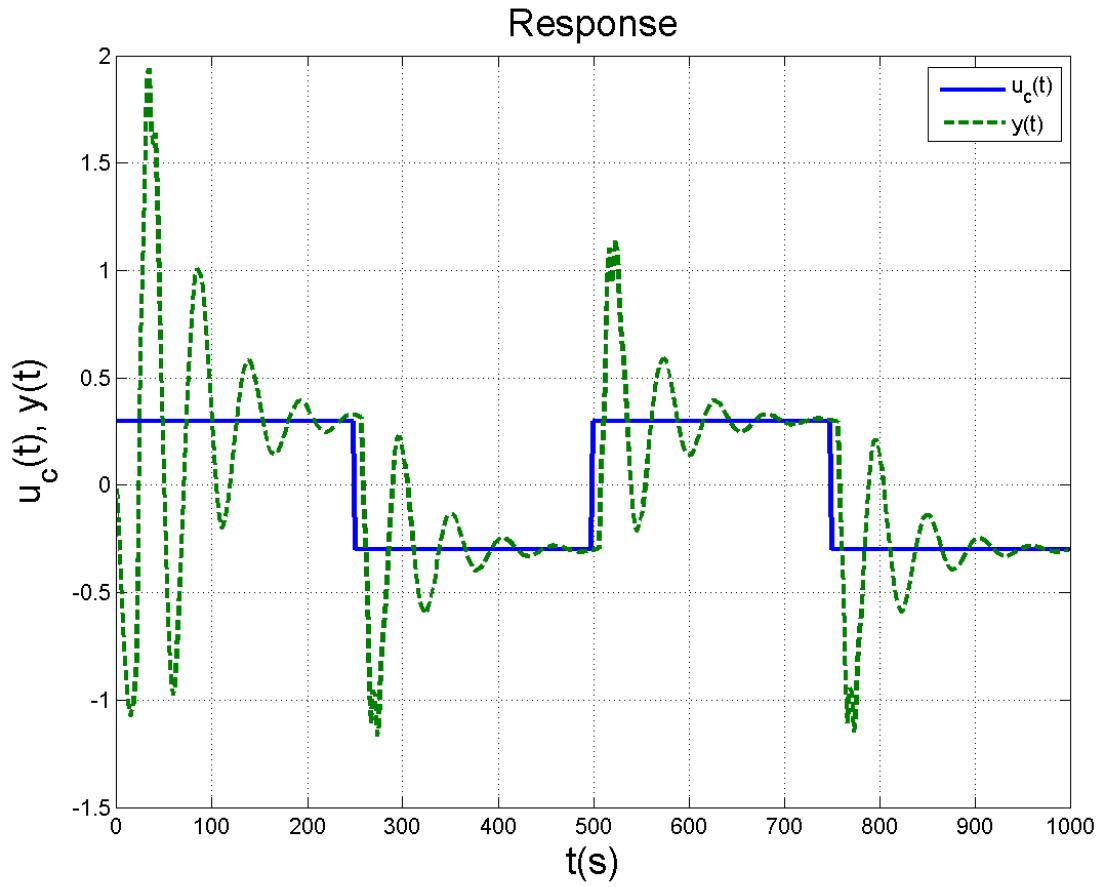
Required Poles in Z-Domain

Flight Condition	A_m	A_0
1	[0.692, 0.7]	[0.002, 0.002, 0.002, 0.002, 0.002]
2	[0.3, 0.5]	[0.02, 0.02, 0.02, 0.02, 0.02]
3	[0.665, 0.7]	[0.002, 0.002, 0.002, 0.002, 0.002]
4	[0.3, 0.2]	[0.1, 0.1, 0.1, 0.1, 0.1]

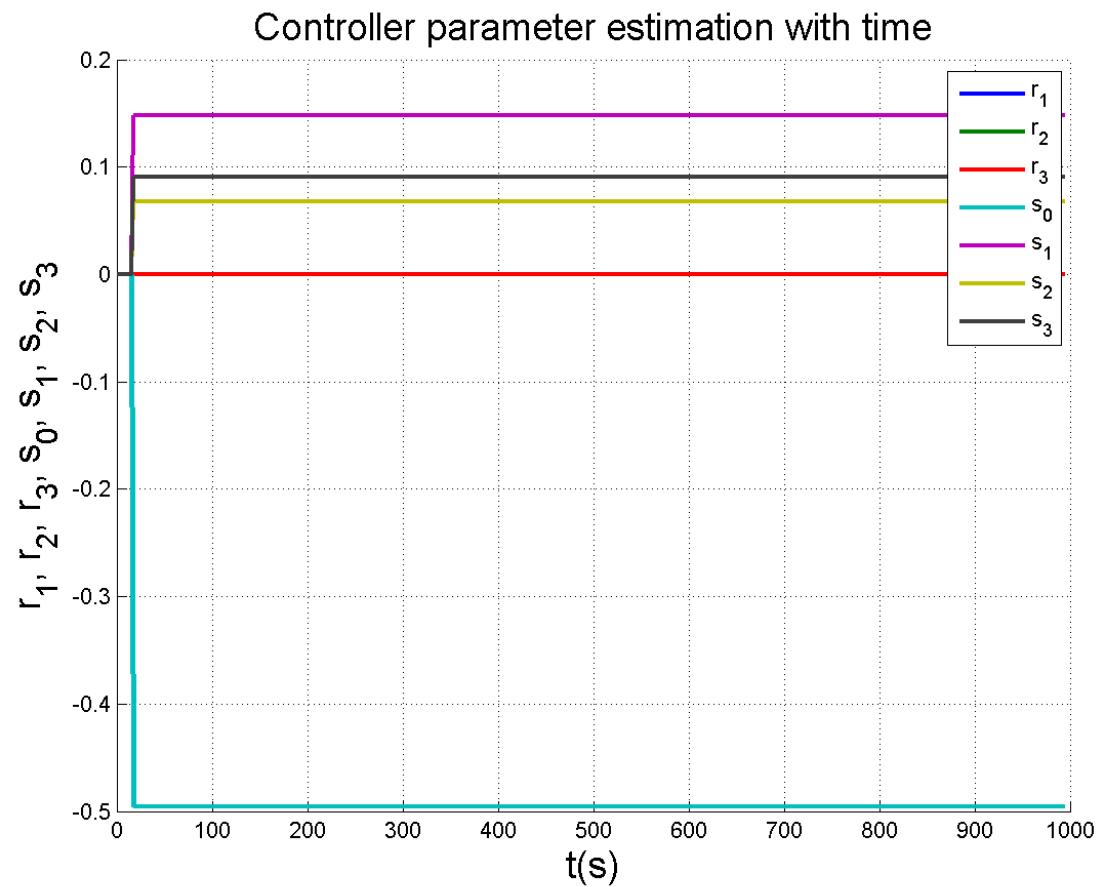
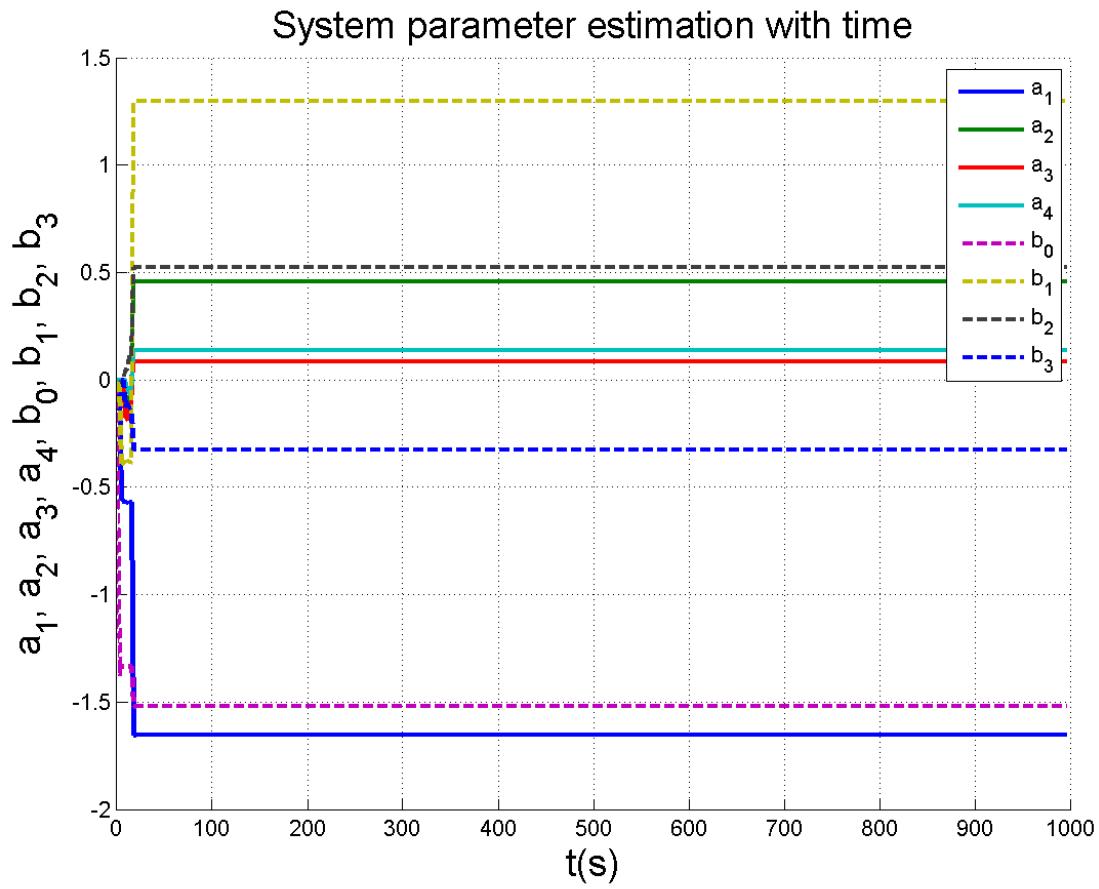
Flight Condition 1

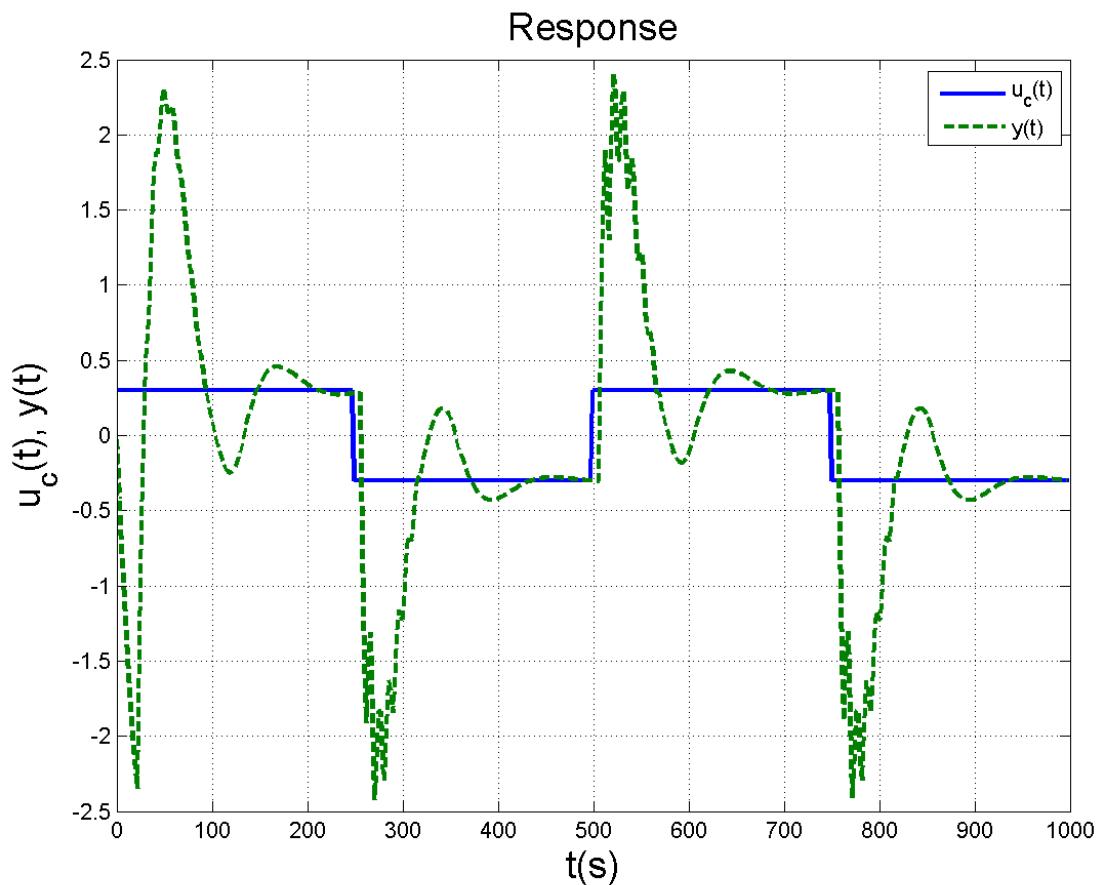
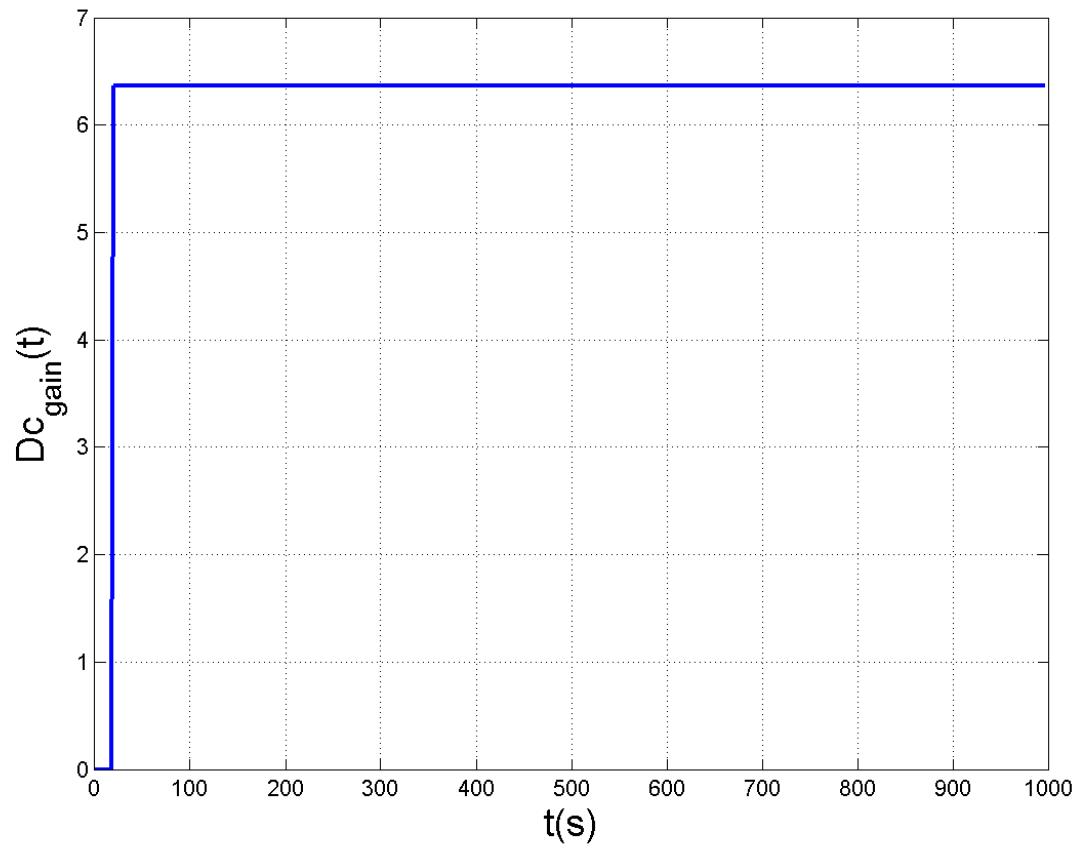


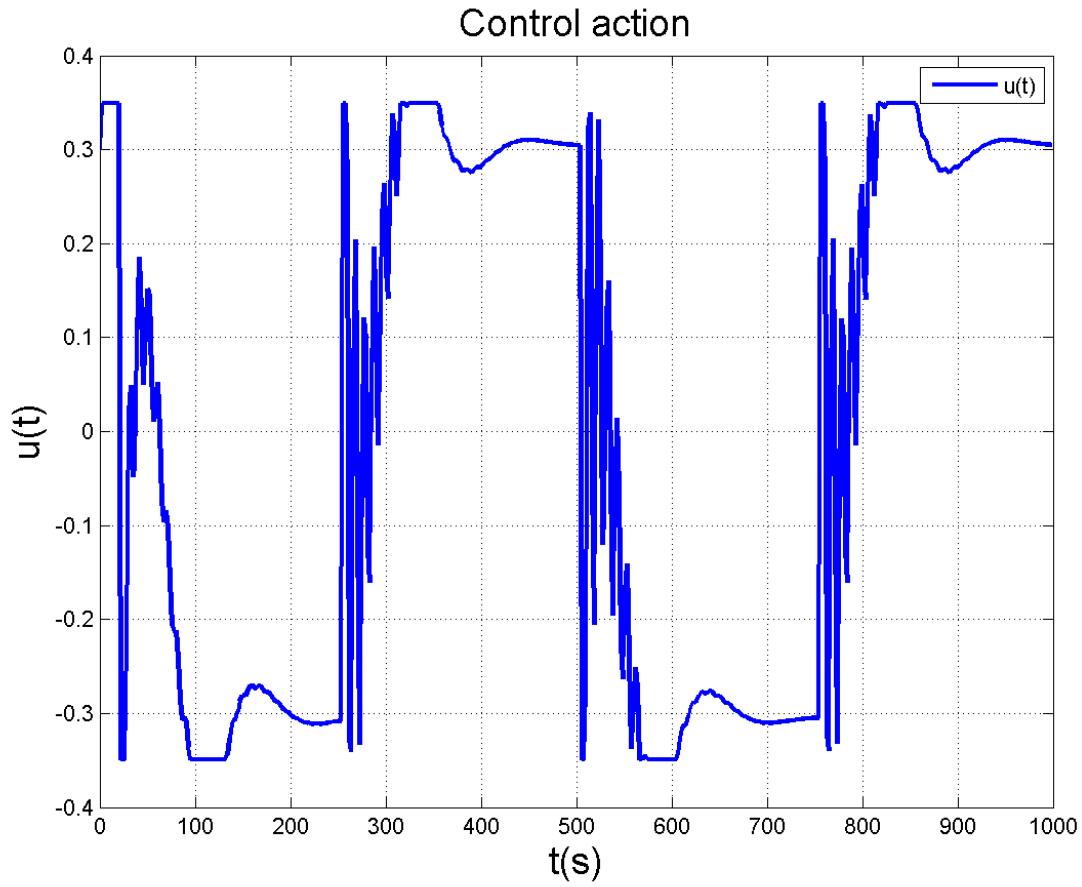




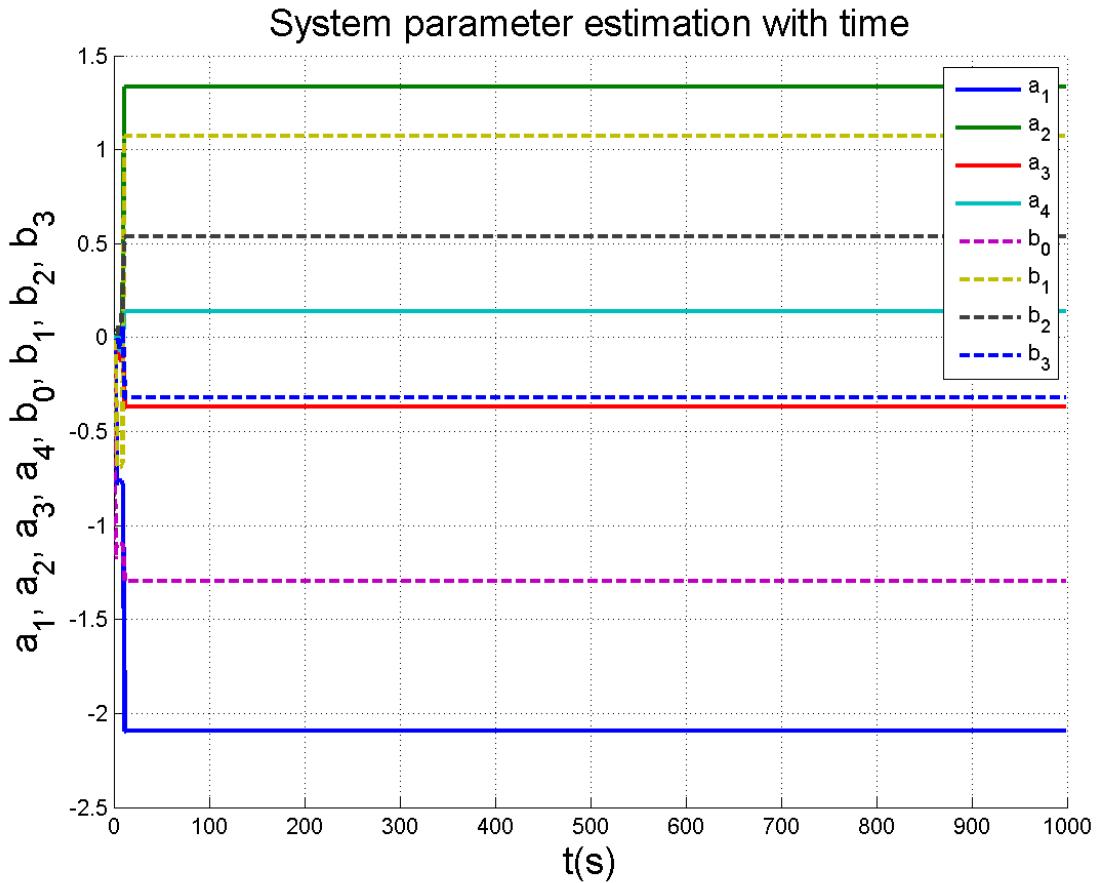
Flight Condition 2

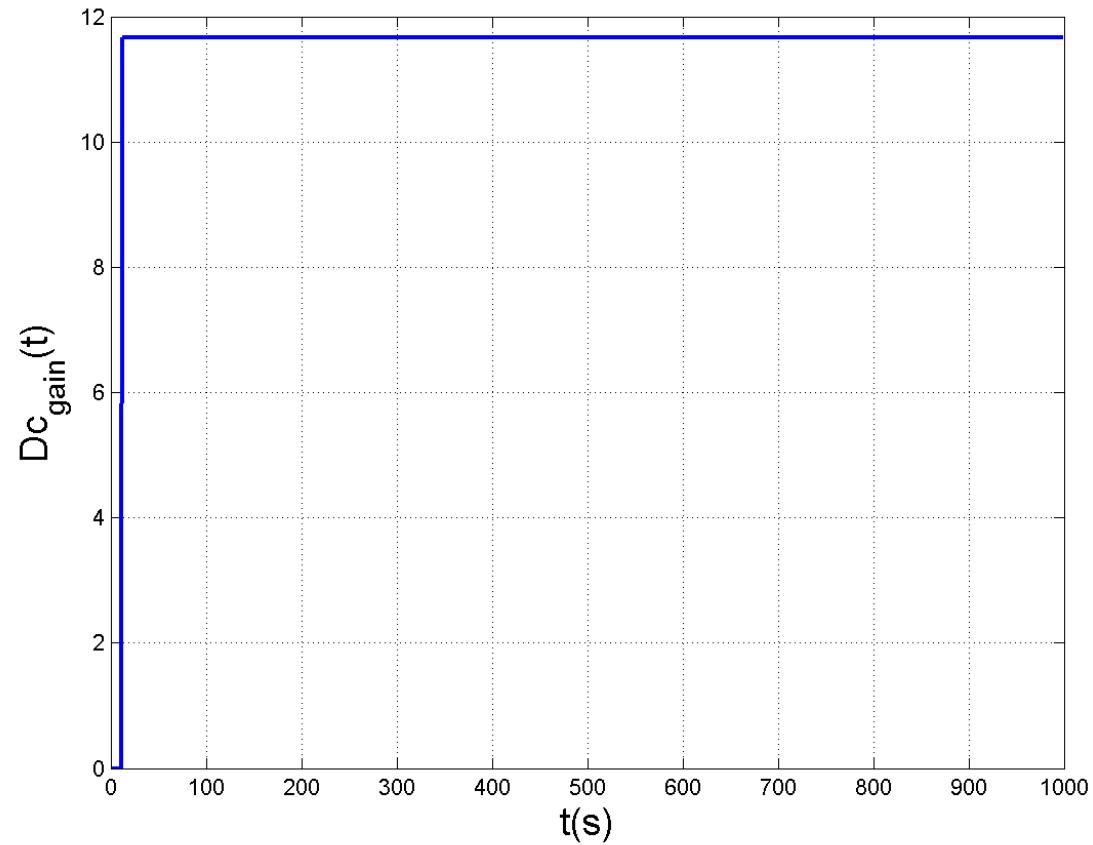
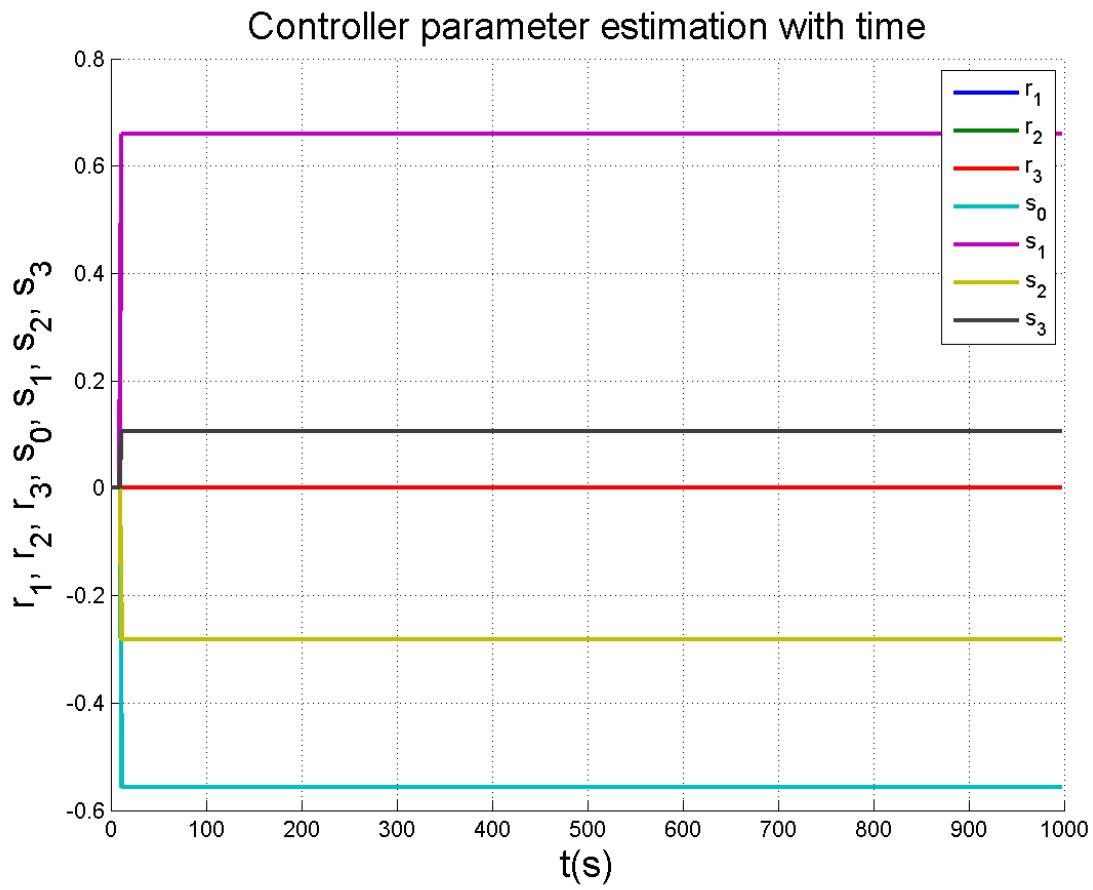


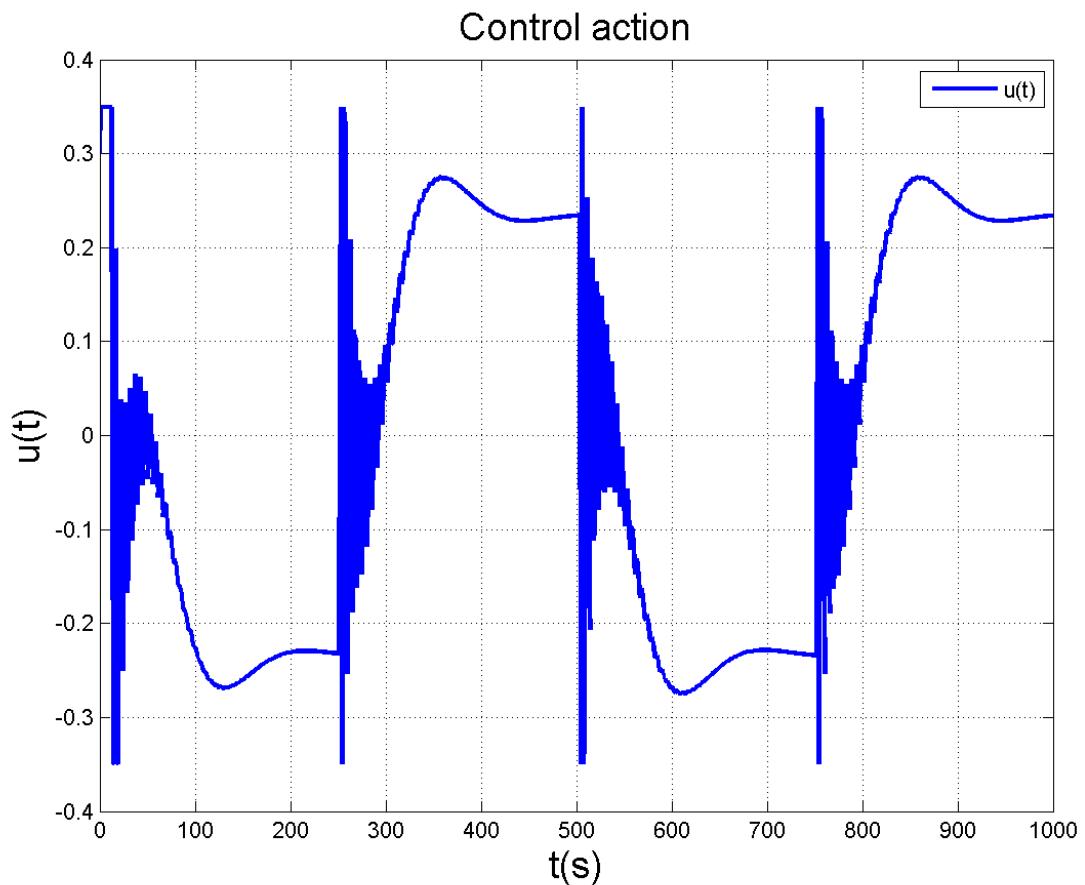
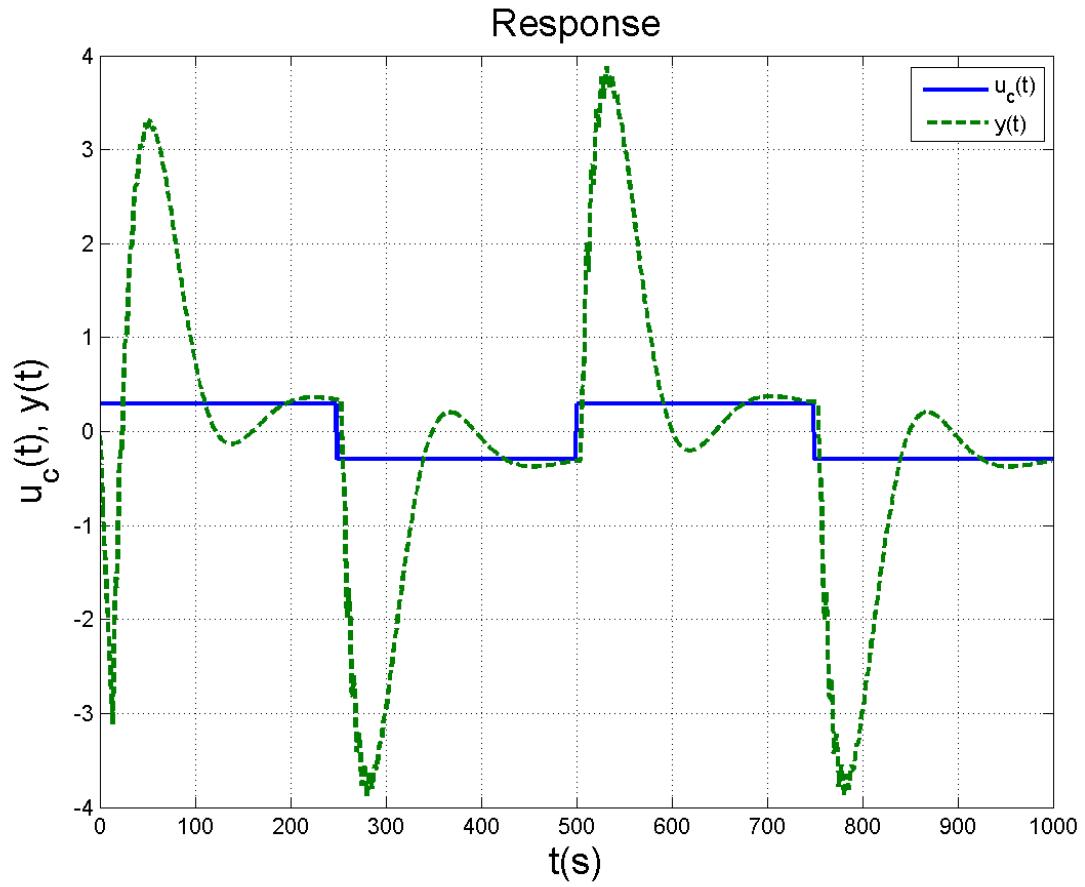




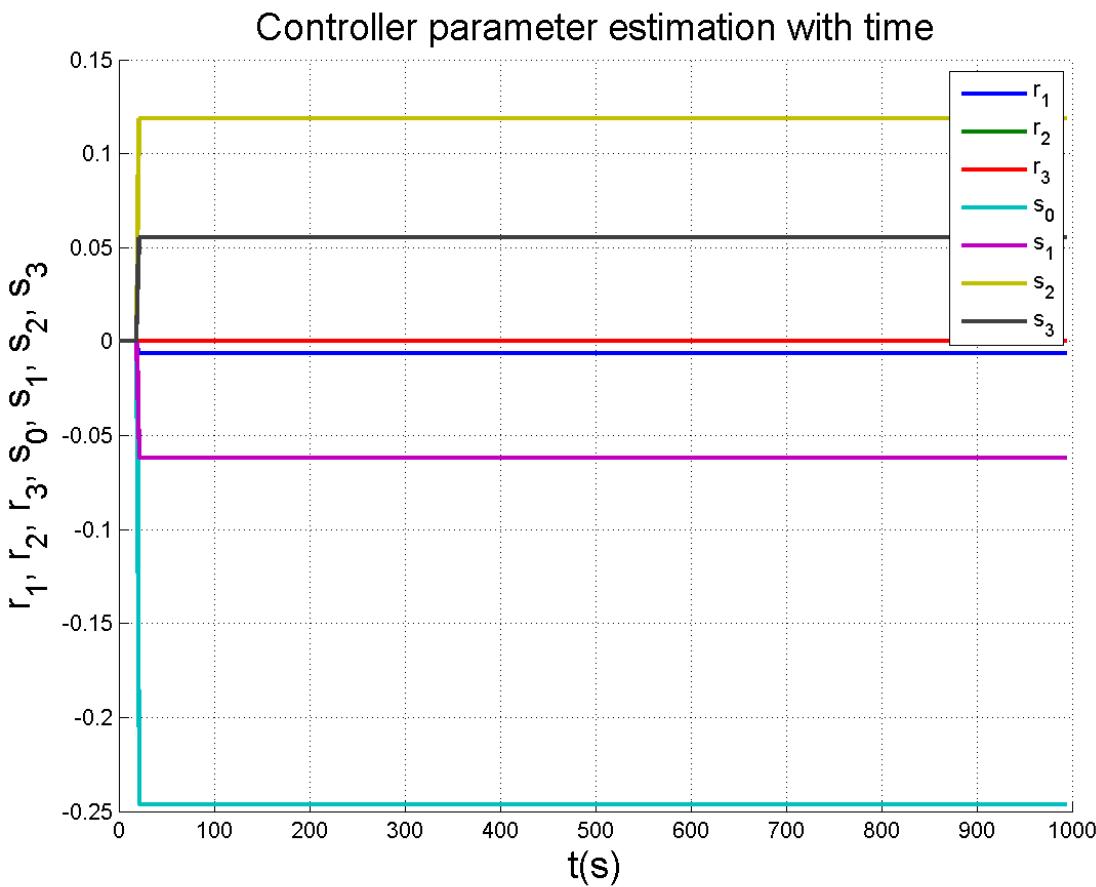
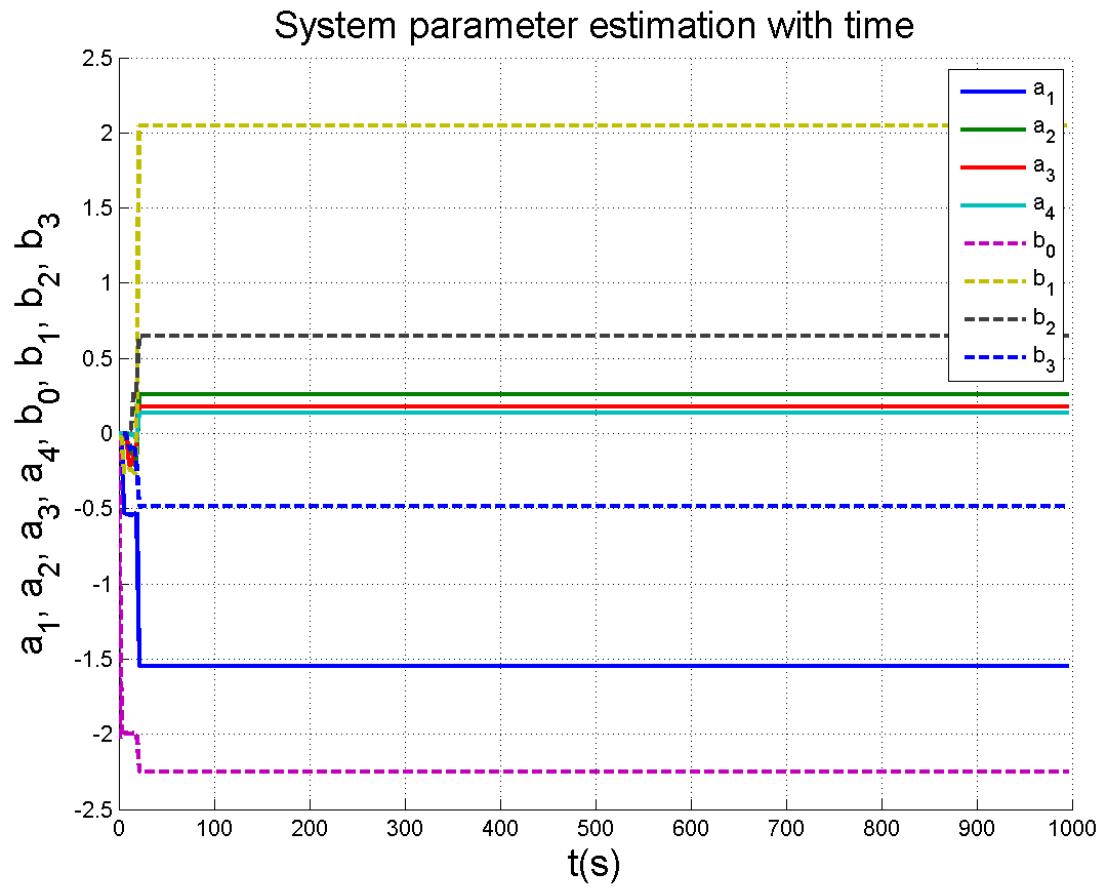
Flight Condition 3

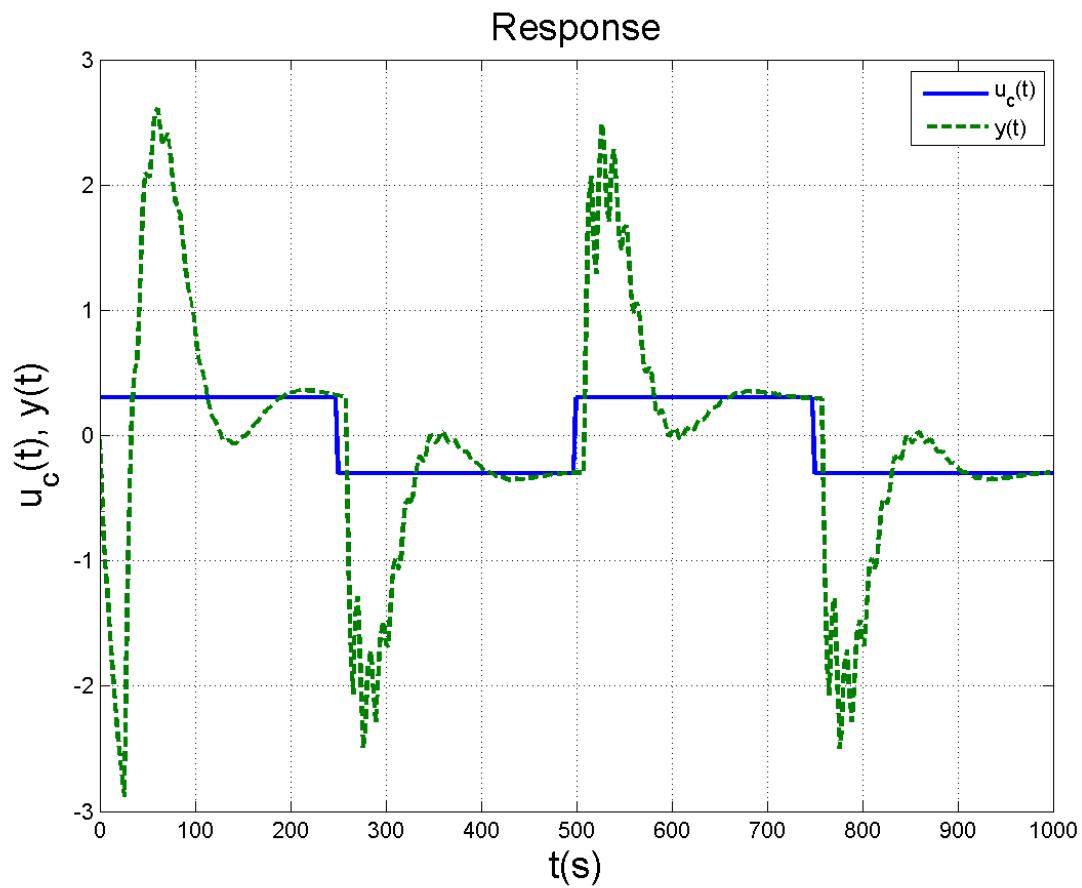
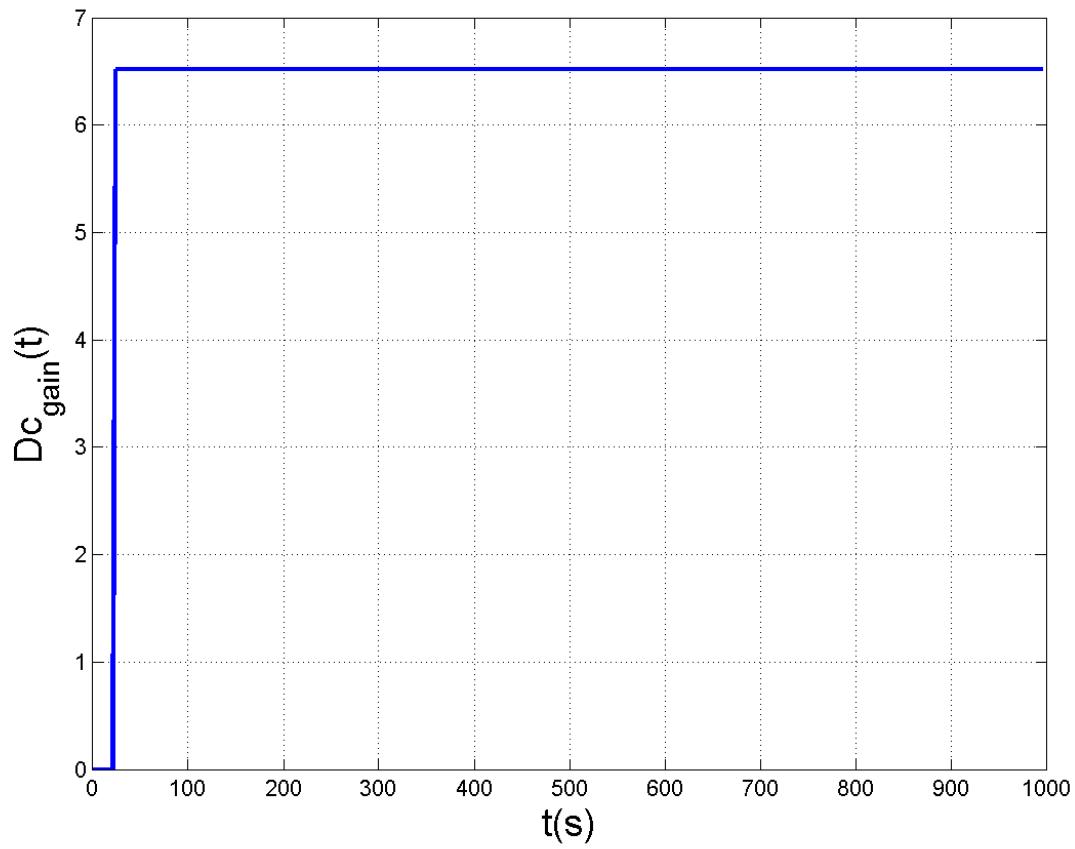


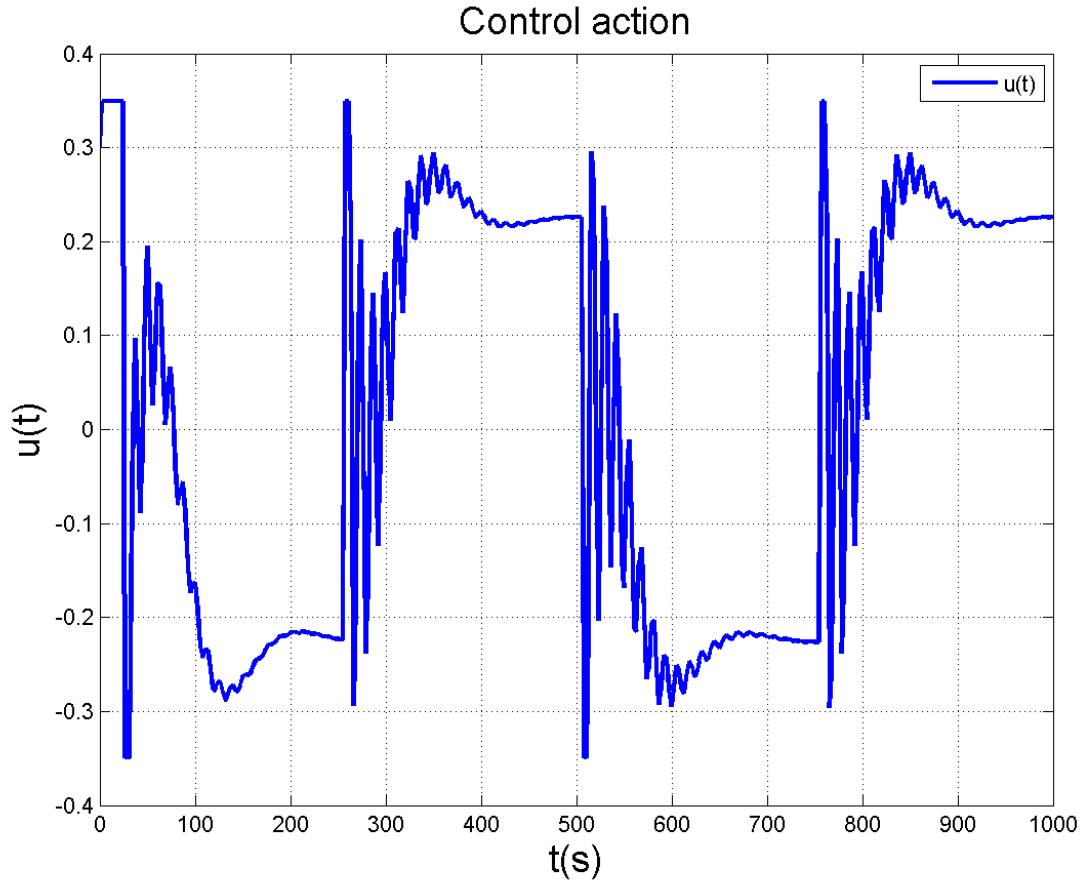




Flight Condition 4



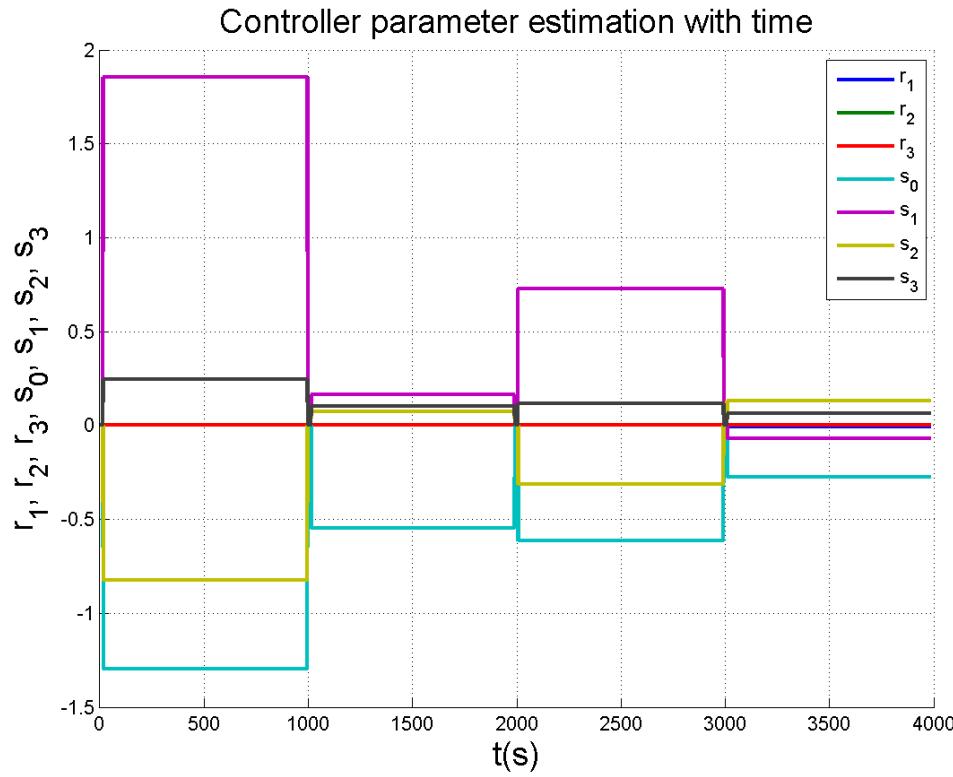
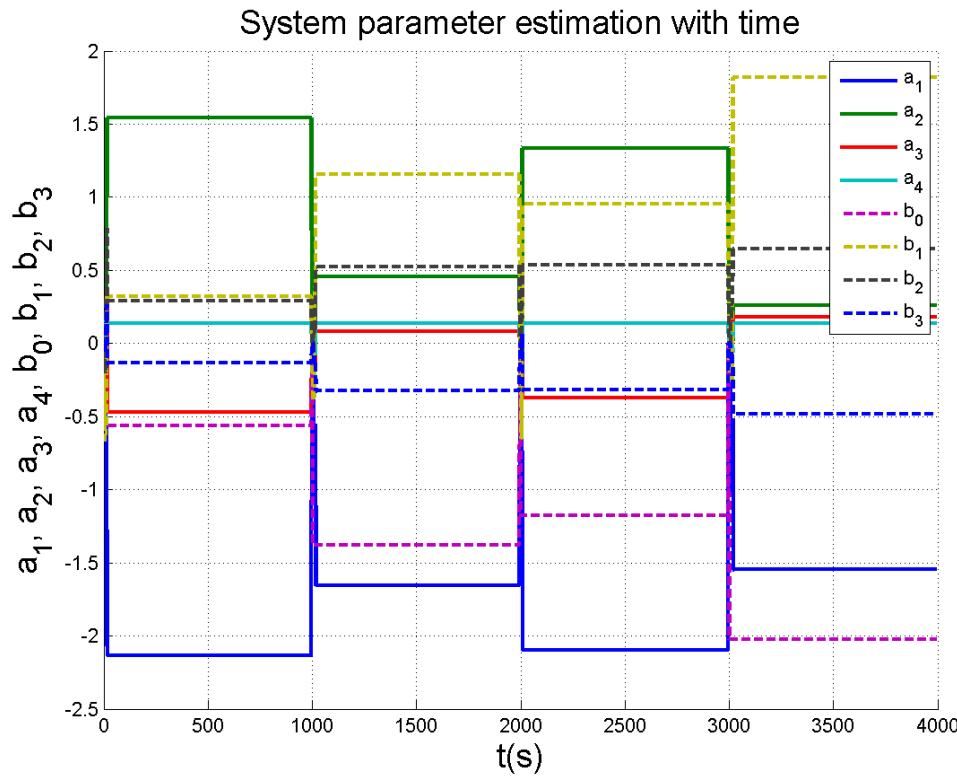


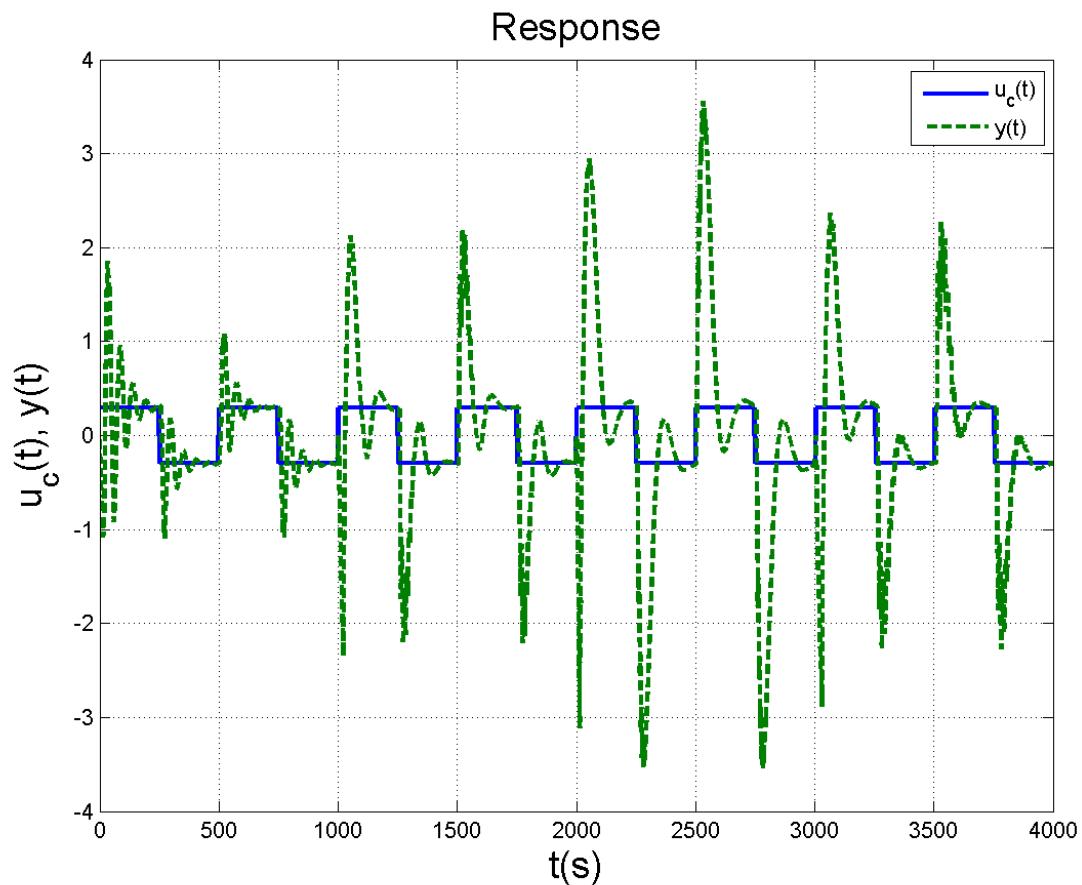
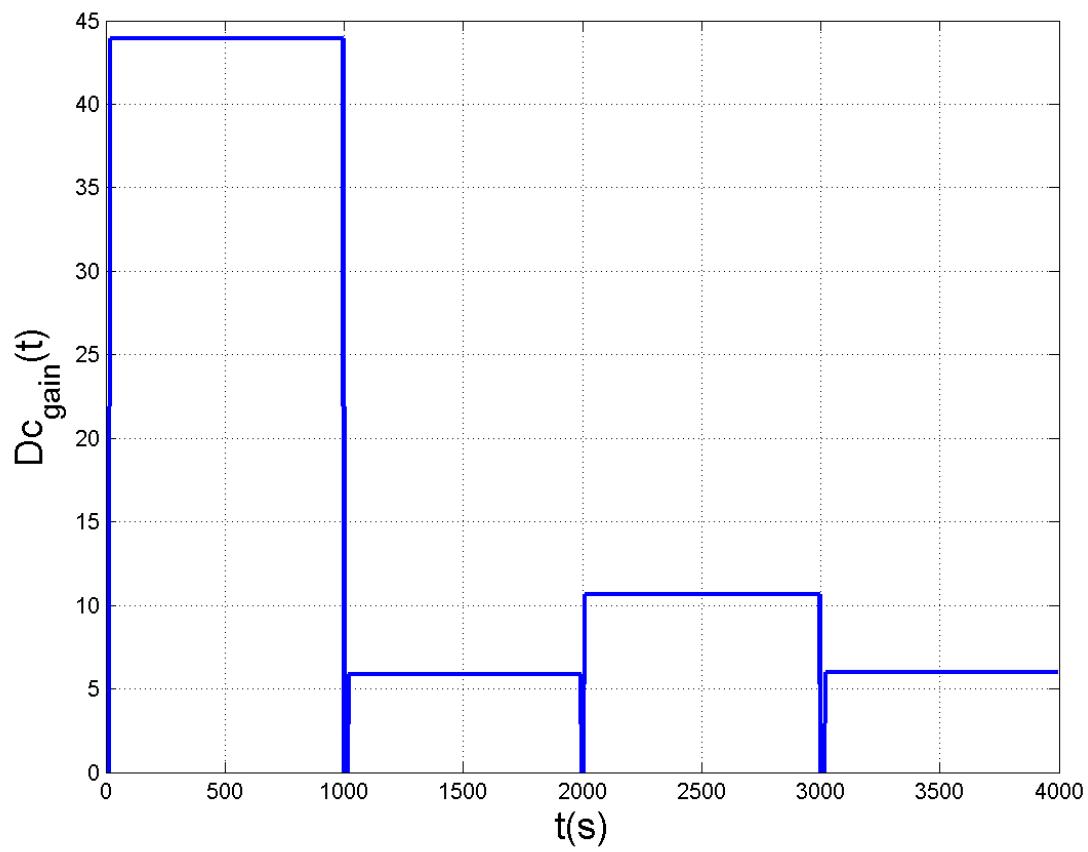


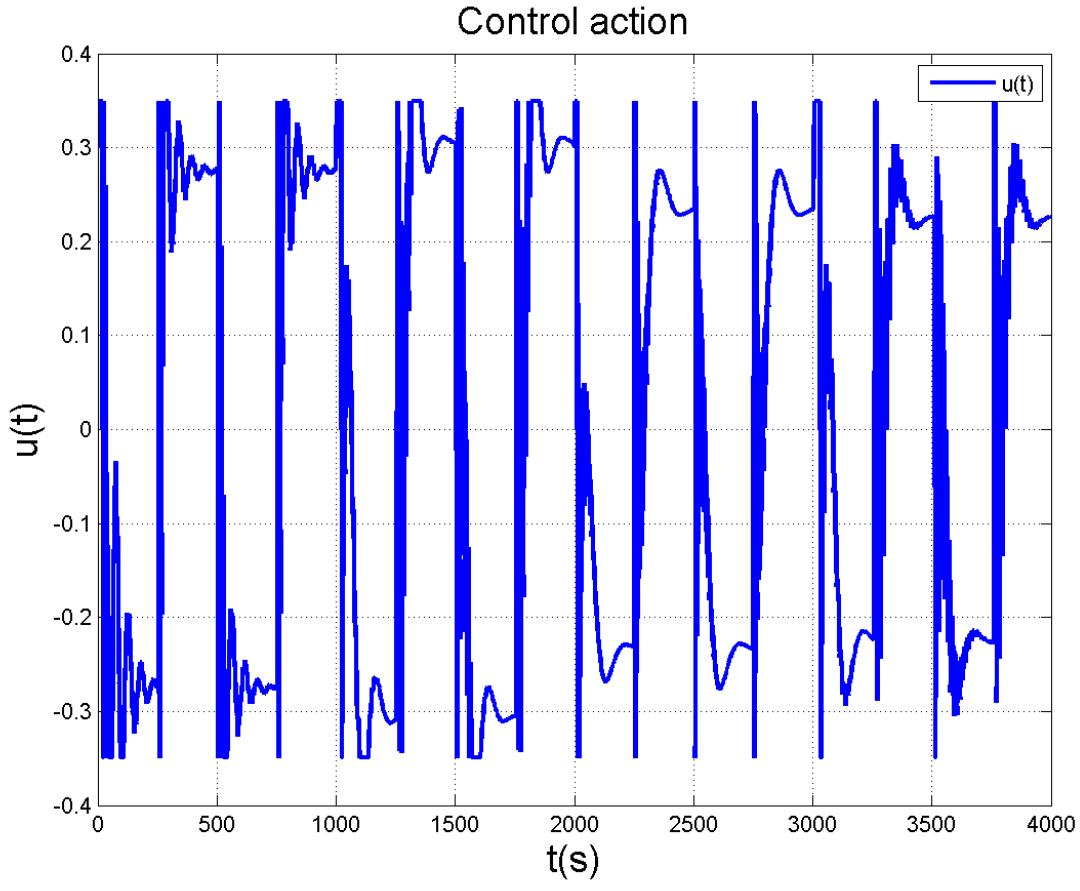
Results

Flight Condition	$G(z)$ Estimated	Feed Forward Controller	DC_{gain}
1	$G(z) = \frac{-0.6048z^3 + 0.3617z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$\frac{S(z)}{R(z)} = \frac{-1.211z^3 + 1.73z^2 - 0.7676z + 0.2286}{z^3 - 2.801e-07z^2 + 2.802e-10z - 1.121e-13}$	$\frac{T}{R}(z) = 46.96$
2	$G(z) = \frac{-1.522z^3 + 1.297z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$\frac{S(z)}{R(z)} = \frac{-0.4959z^3 + 0.1478z^2 + 0.06753z + 0.09092}{z^3 - 9.146e-05z^2 + 8.836e-07z - 3.452e-09}$	$\frac{T}{R}(z) = 6.363$
3	$G(z) = \frac{-1.295z^3 + 1.073z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$\frac{S(z)}{R(z)} = \frac{-0.5561z^3 + 0.6602z^2 - 0.2826z + 0.1052}{z^3 - 2.732e-07z^2 + 2.731e-10z - 1.093e-13}$	$\frac{T}{R}(z) = 11.66$
4	$G(z) = \frac{-2.25z^3 + 2.049z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$\frac{S(z)}{R(z)} = \frac{-0.2462z^3 - 0.06174z^2 + 0.1184z + 0.05538}{z^3 - 0.006598z^2 + 0.0002607z - 4.372e-06}$	$\frac{T}{R}(z) = 6.515$

For All Flight Conditions Together







Results

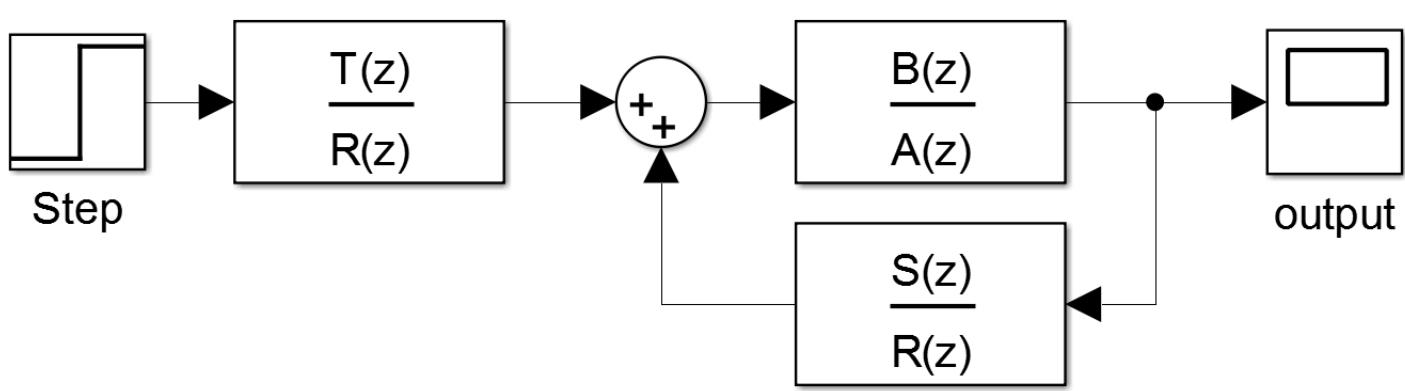
Flight Condition	$G(z)$ Estimated	Feed Forward Controller	DC_{gain}
1	$G(z) = \frac{-0.5646z^3 + 0.3215z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$\frac{S(z)}{R(z)} = \frac{-1.297z^3 + 1.853z^2 - 0.8223z + 0.2449}{z^3 - 2.801e-07z^2 + 2.802e-10z - 1.121e-13}$	$\frac{T}{R}(z) = 43.91$
2	$G(z) = \frac{-1.378z^3 + 1.153z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$\frac{S(z)}{R(z)} = \frac{-0.5478z^3 + 0.1633z^2 + 0.07459z + 0.1004}{z^3 - 9.146e-05z^2 + 8.836e-07z - 3.452e-09}$	$\frac{T}{R}(z) = 5.856$
3	$G(z) = \frac{-1.176z^3 + 0.9539z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$\frac{S(z)}{R(z)} = \frac{-0.6125z^3 + 0.7272z^2 - 0.3113z + 0.1159}{z^3 - 2.732e-07z^2 + 2.731e-10z - 1.092e-13}$	$\frac{T}{R}(z) = 10.68$
4	$G(z) = \frac{-2.023z^3 + 1.822z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$\frac{S(z)}{R(z)} = \frac{-0.274z^3 - 0.06869z^2 + 0.1317z + 0.06162}{z^3 - 0.006598z^2 + 0.0002607z - 4.372e-06}$	$\frac{T}{R}(z) = 5.957$

Comments

- The system parameter goes to its true values if i control all flight conditions together.
- There is a change in controller parameter between the controller of all flight conditions and the controller of each flight condition.

1.6.7 Indirect Self-Tuning Regulator Using Model Following Without Zero Cancellation For Square Input

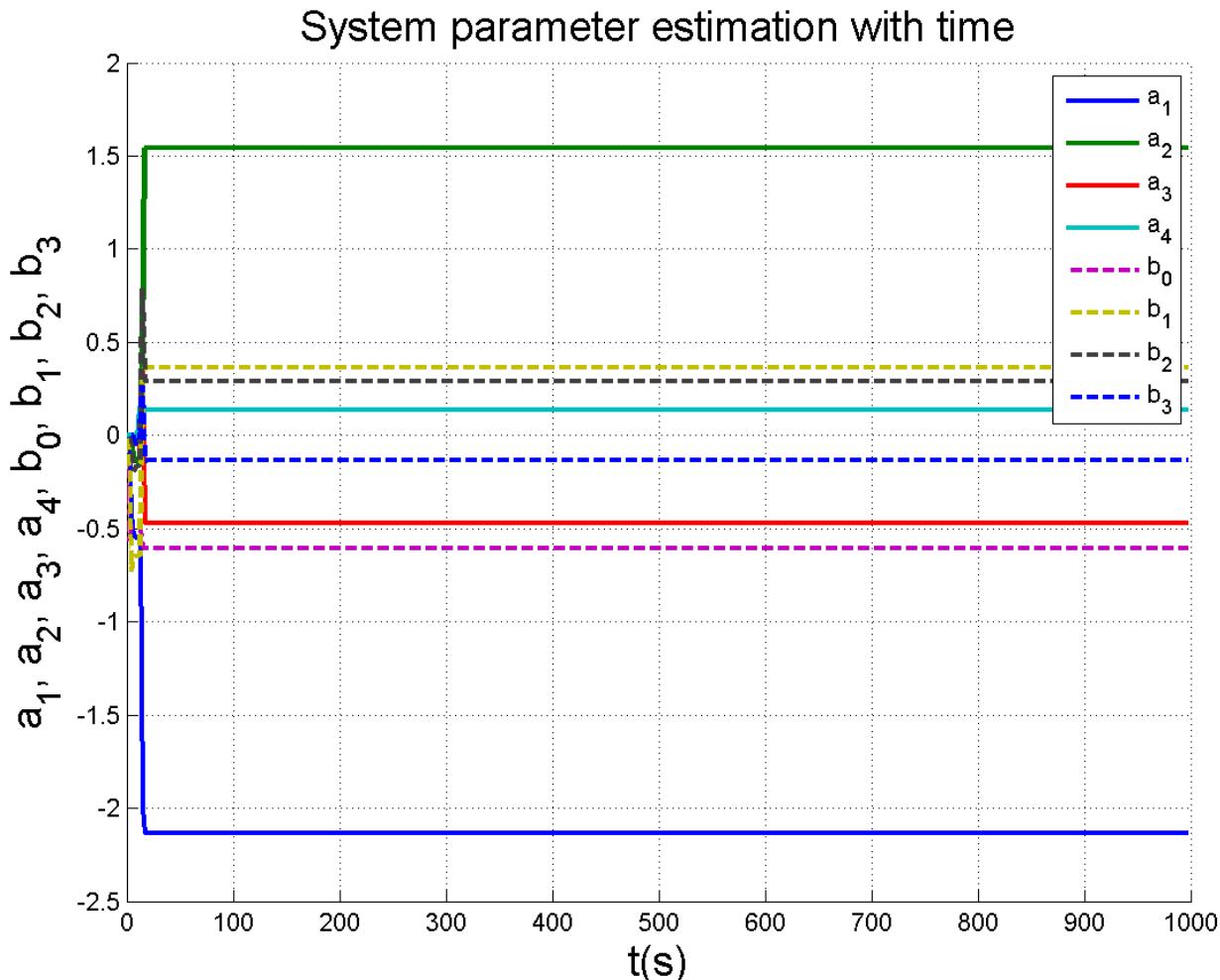
Controller Scheme

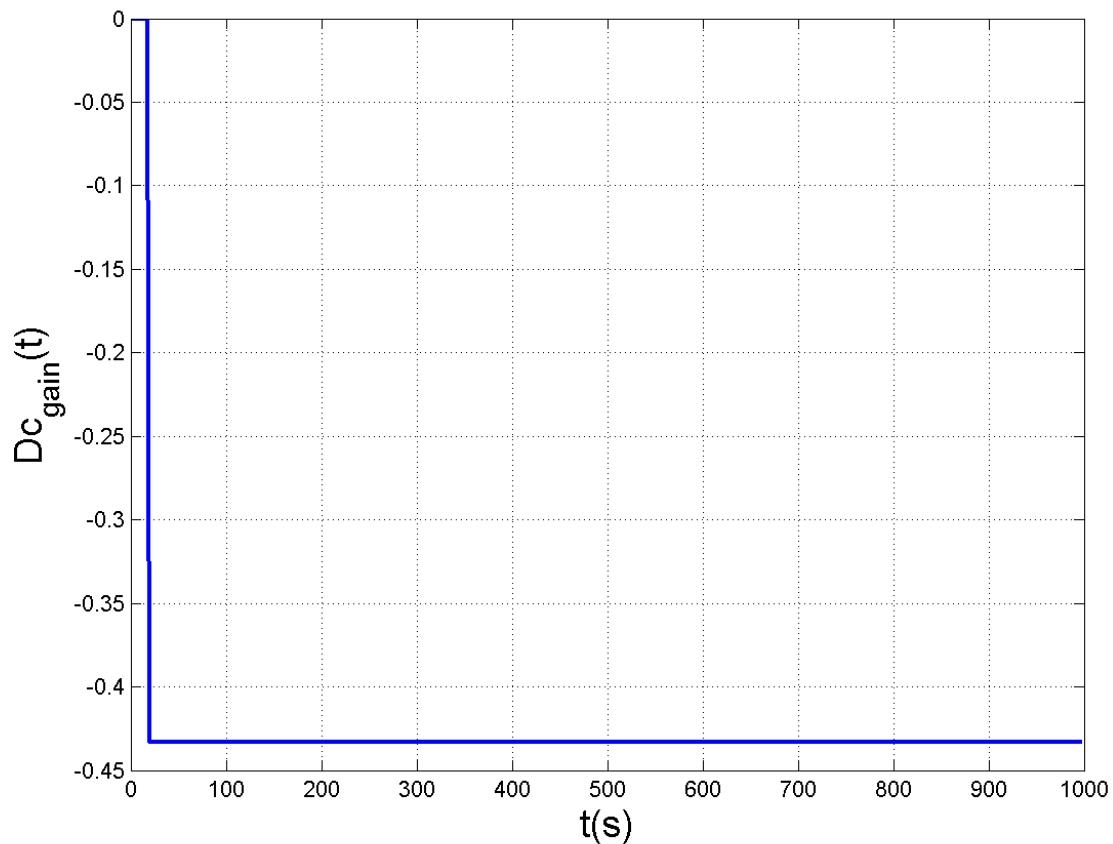
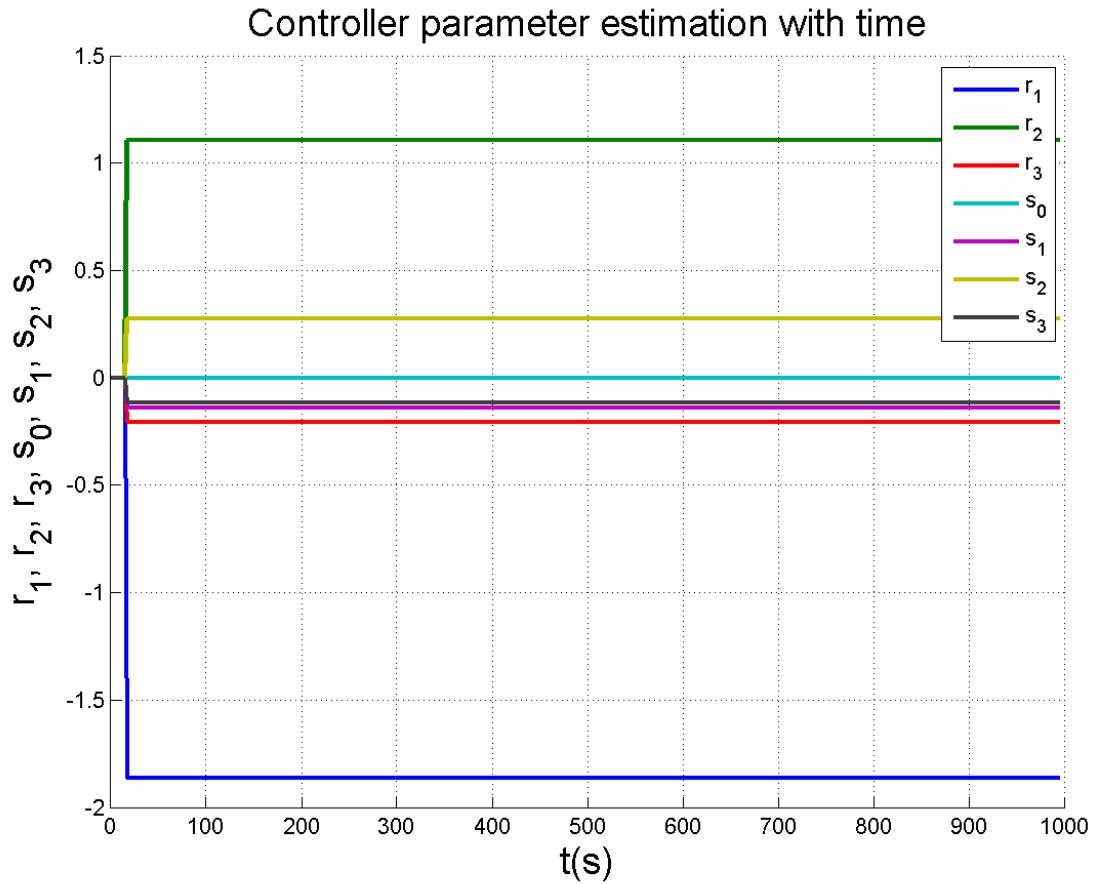


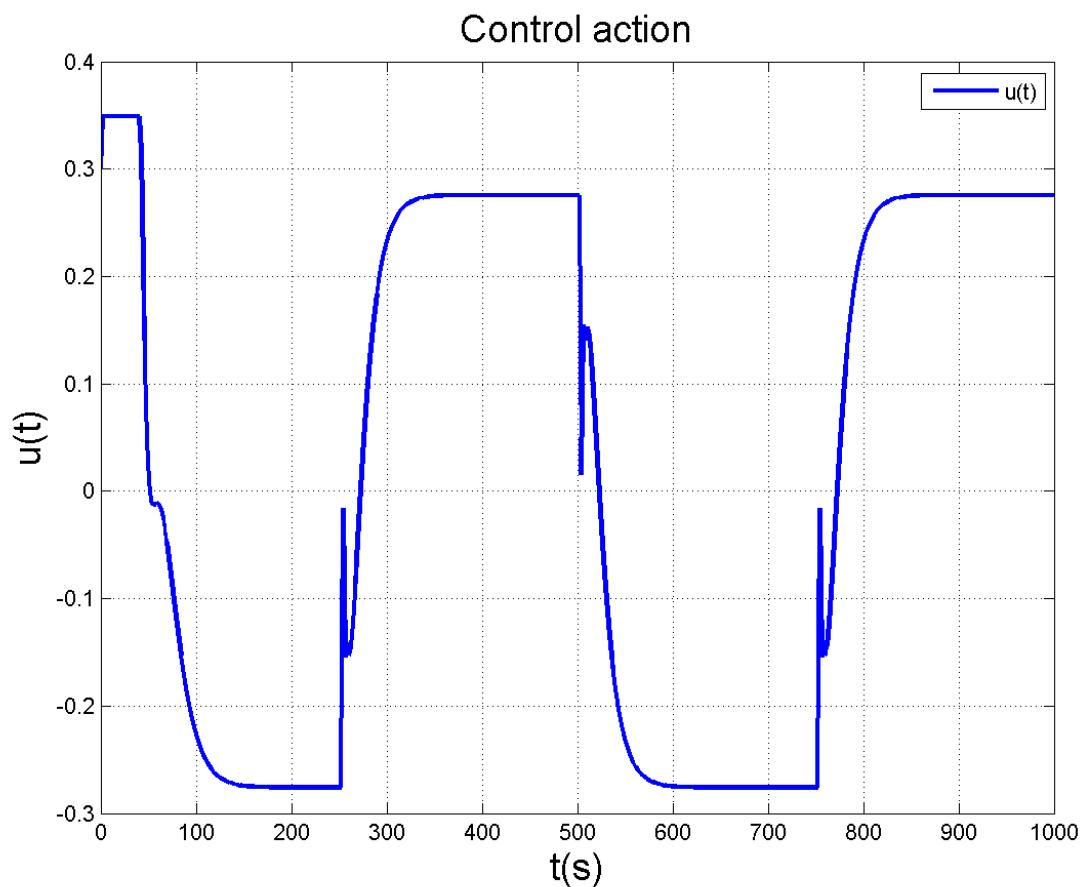
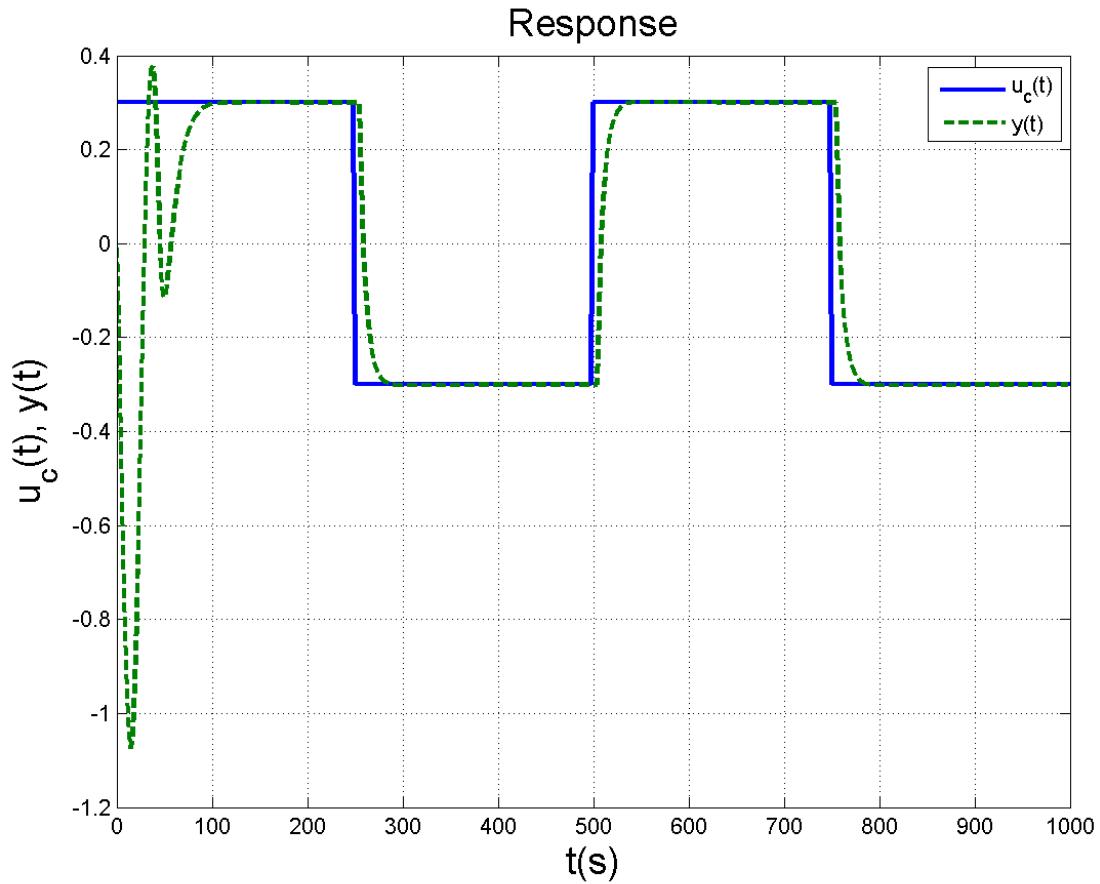
Required Poles in Z-Domain

Flight Condition	A_m	A_0
1	[0.85, 0.75]	[0.4, 0.4, 0.4, 0.4, 0.8]
2	[0.8, 0.8]	[0.2, 0.2, 0.2, 0.2, 0.2]
3	[0.95, 0.88]	[0.2, 0.2, 0.2, 0.2, 0.2]
4	[0.6, 0.85]	[0.2, 0.2, 0.2, 0.2, 0.2]

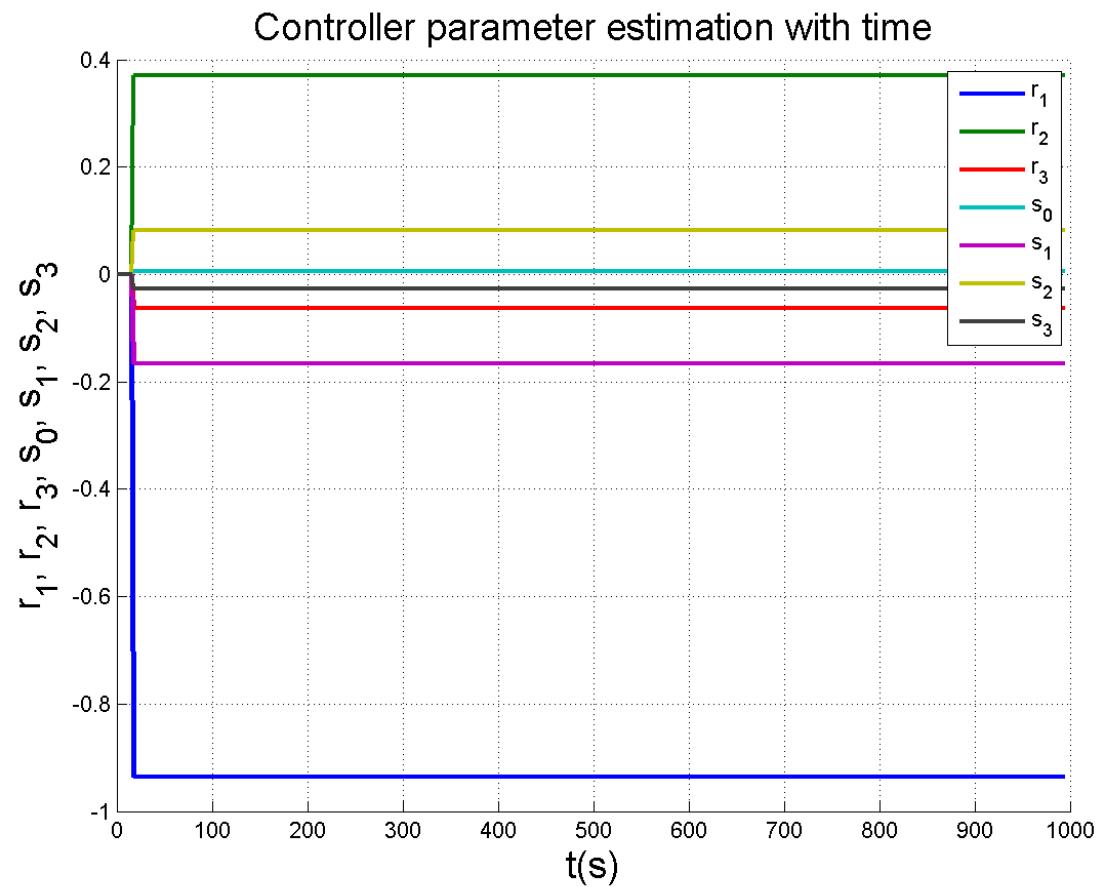
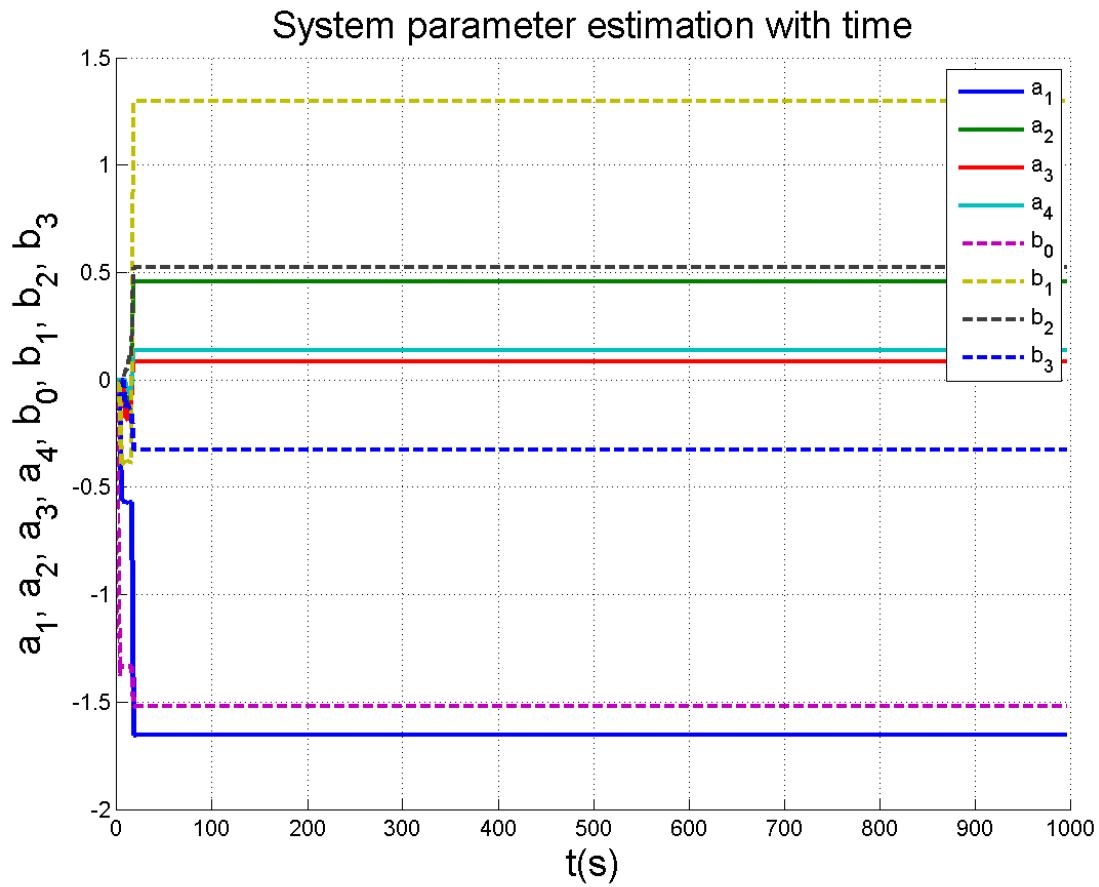
Flight Condition 1

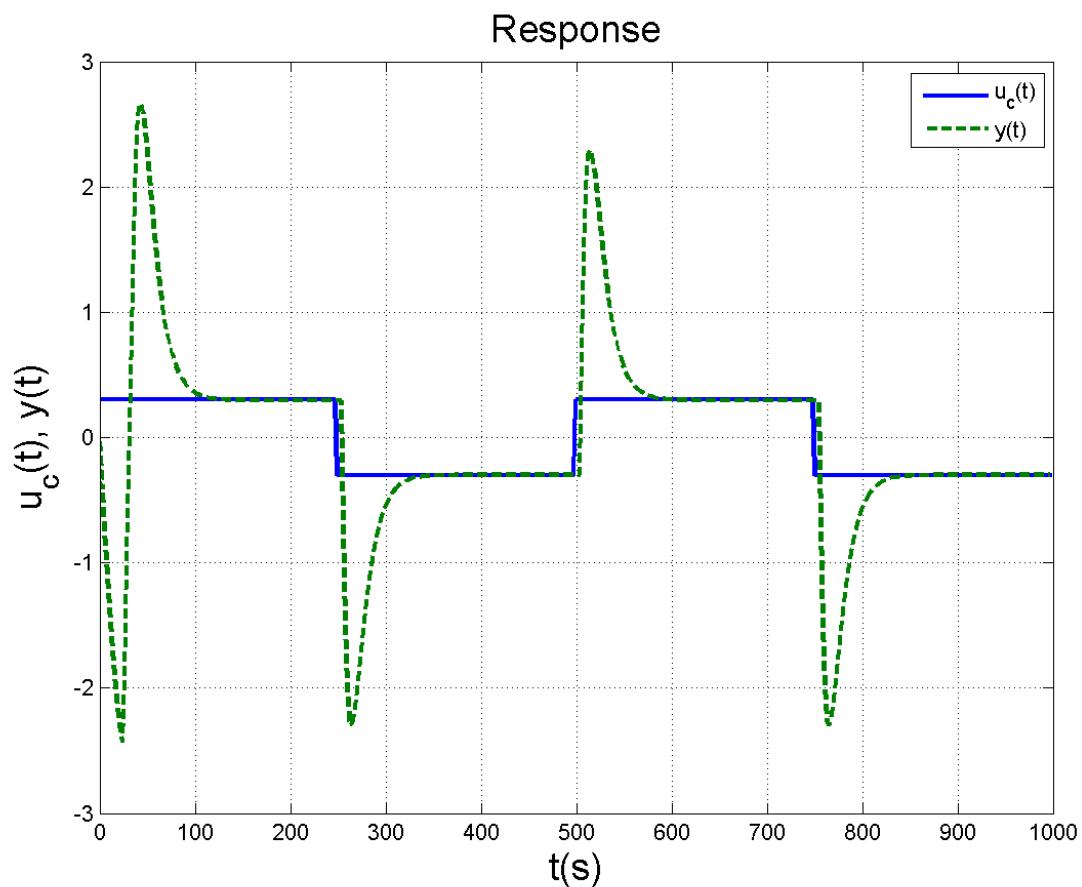
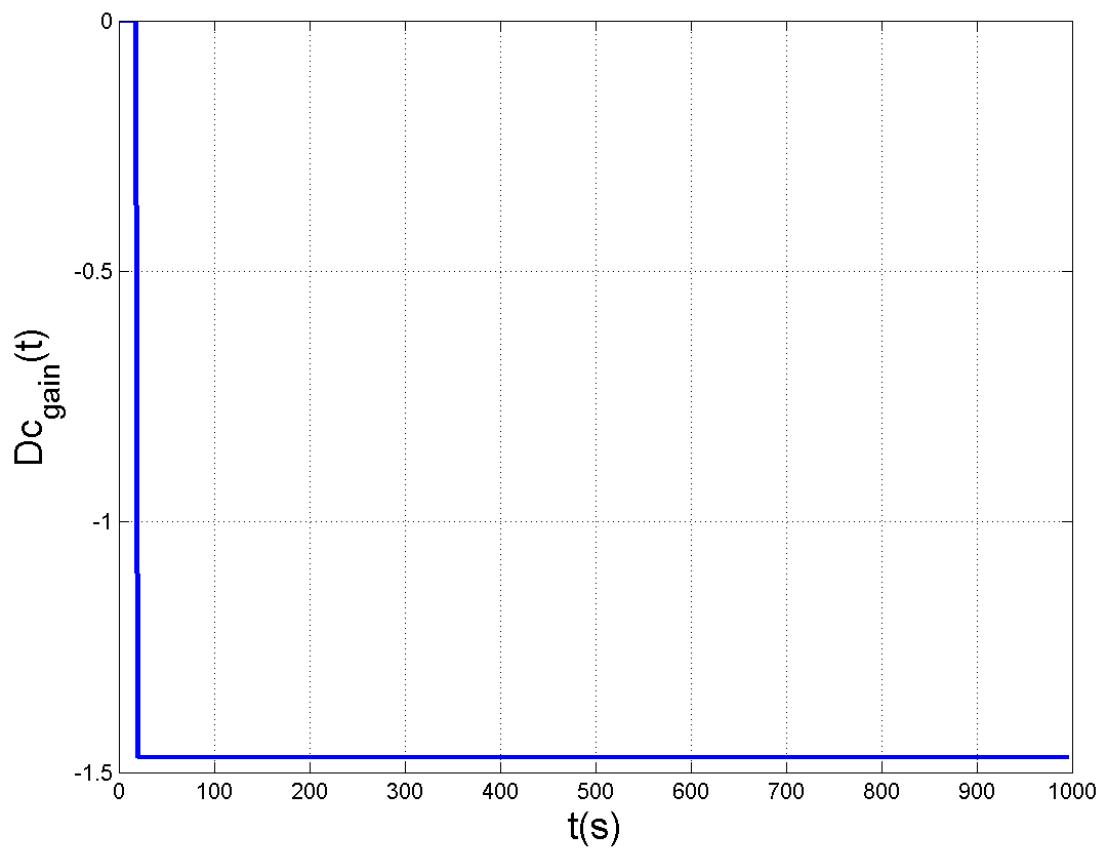


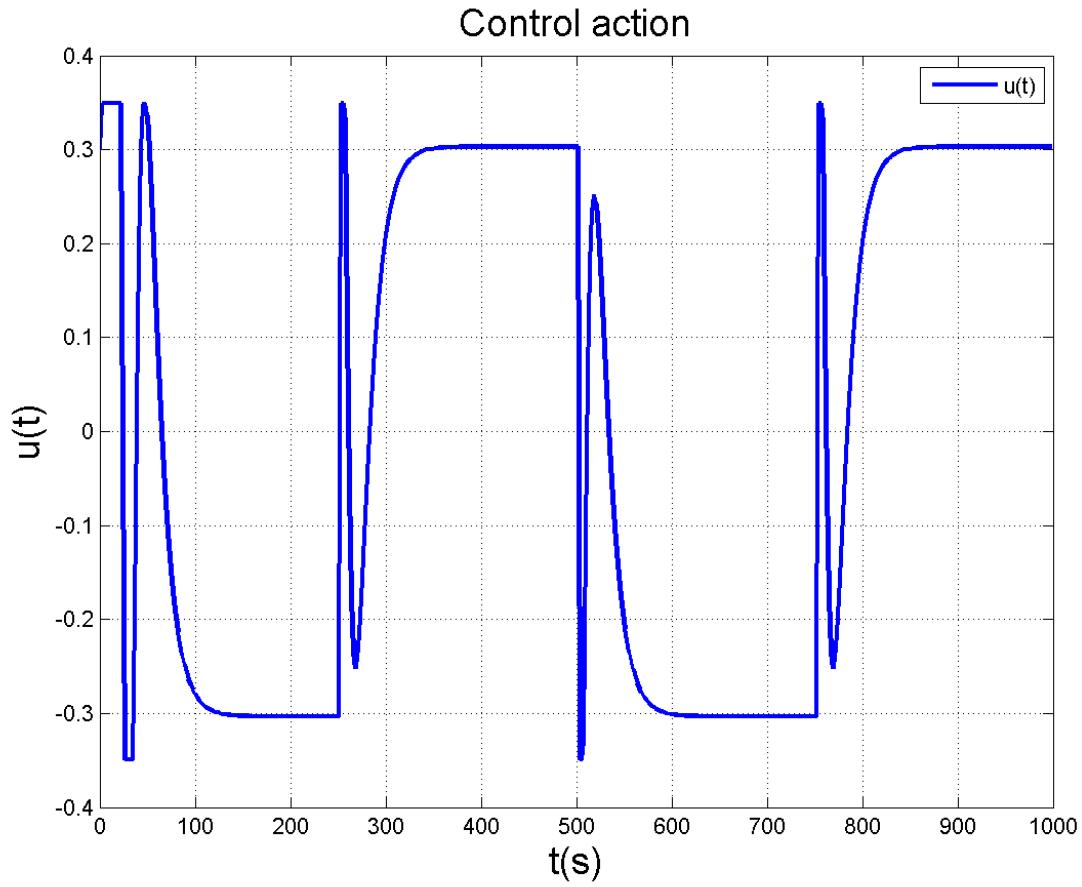




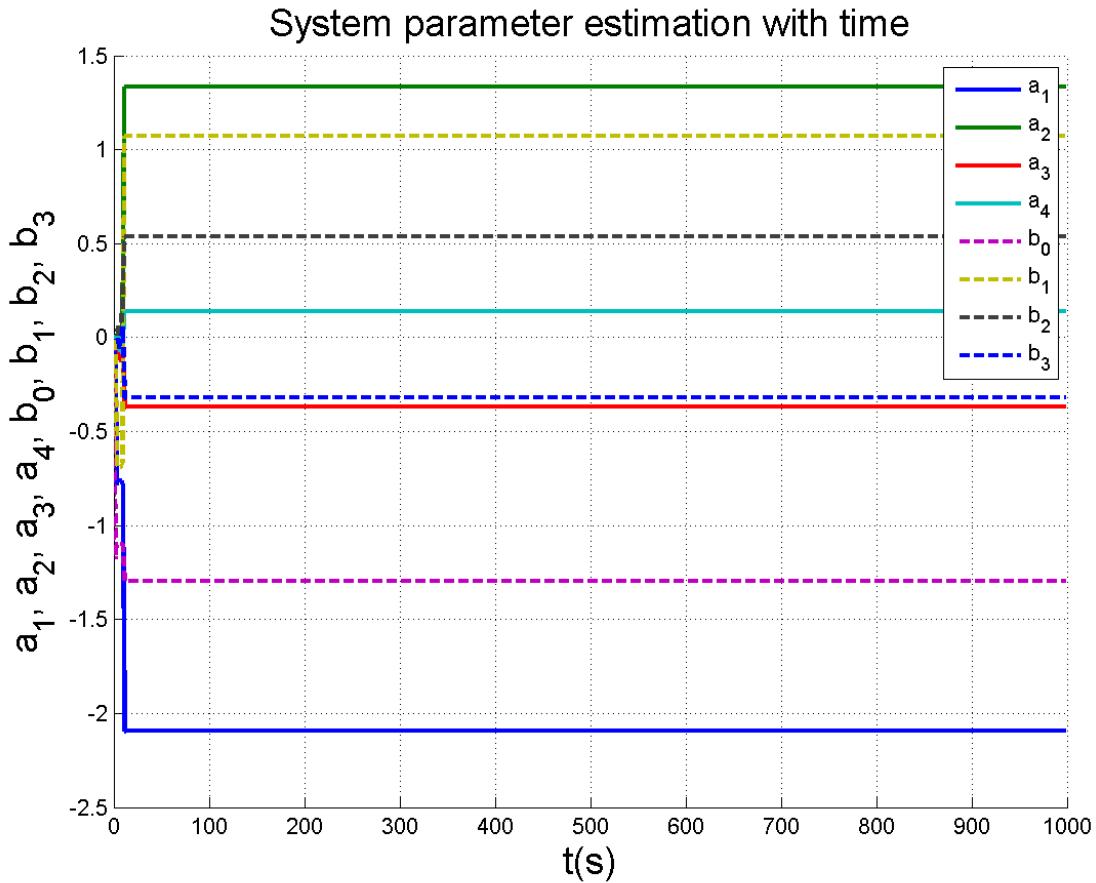
Flight Condition 2

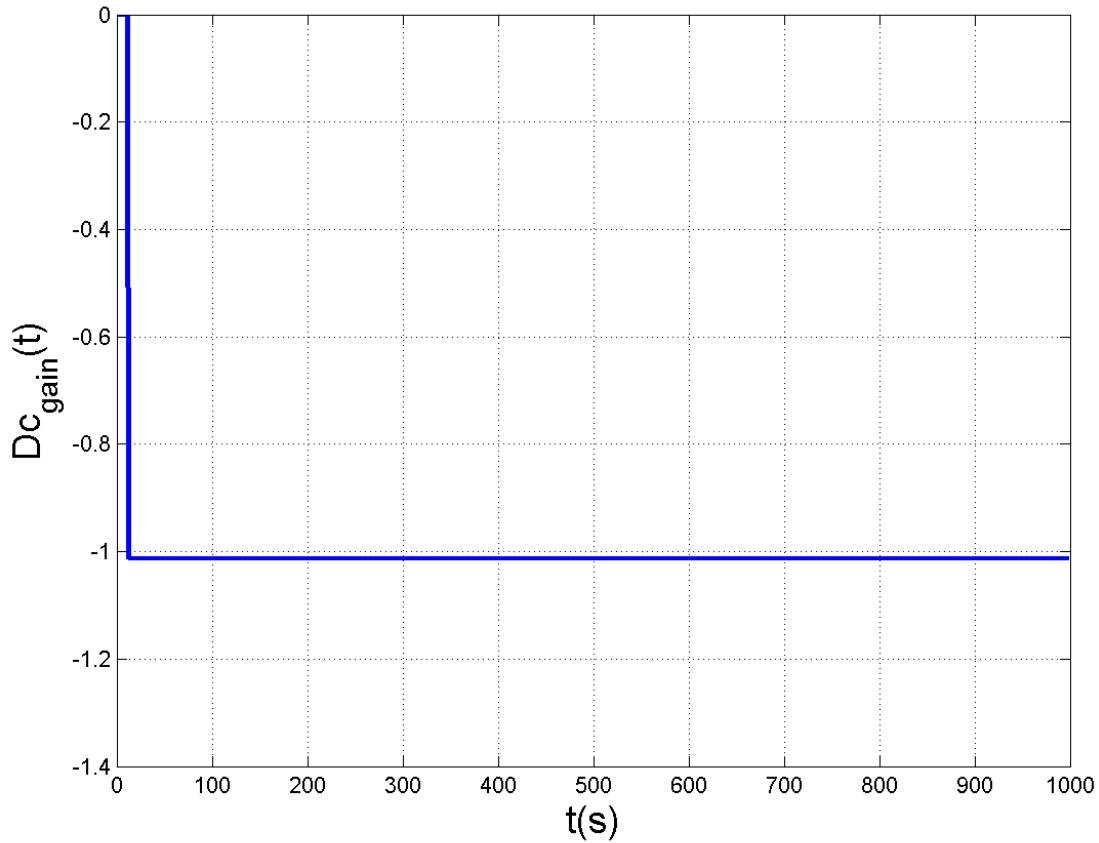
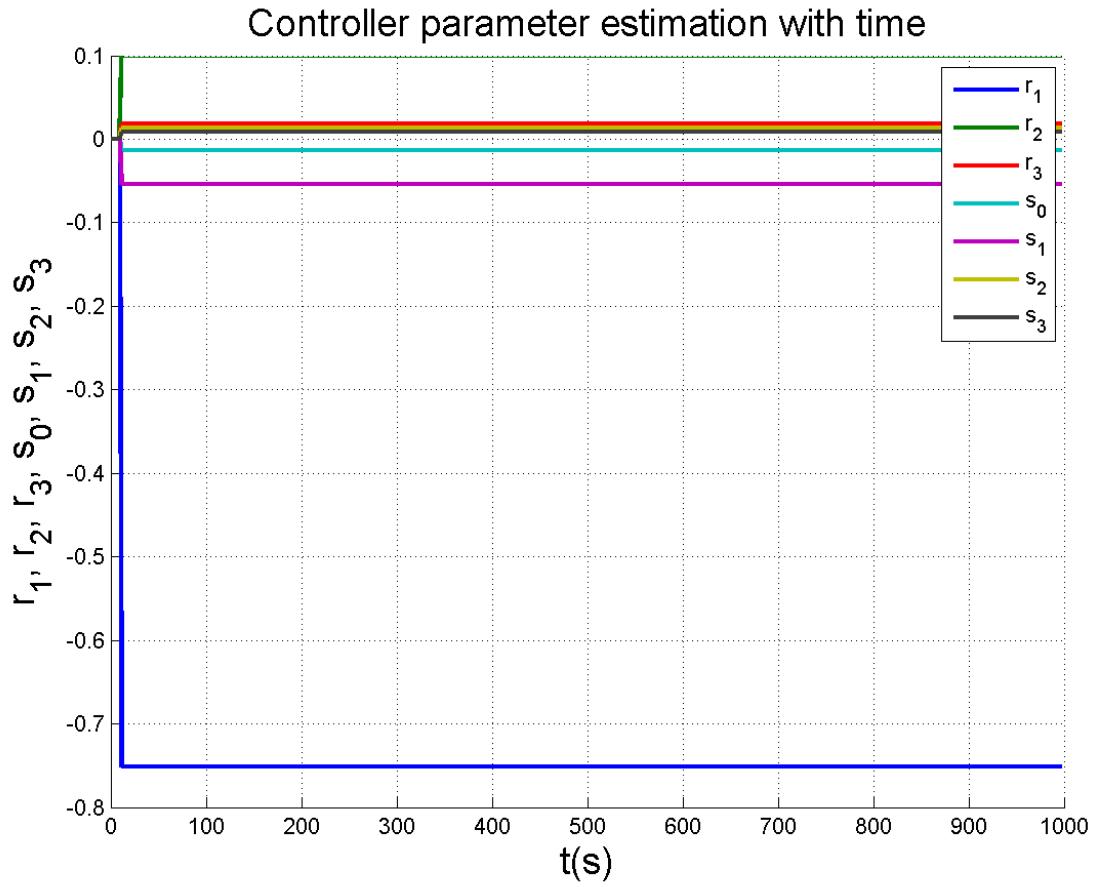


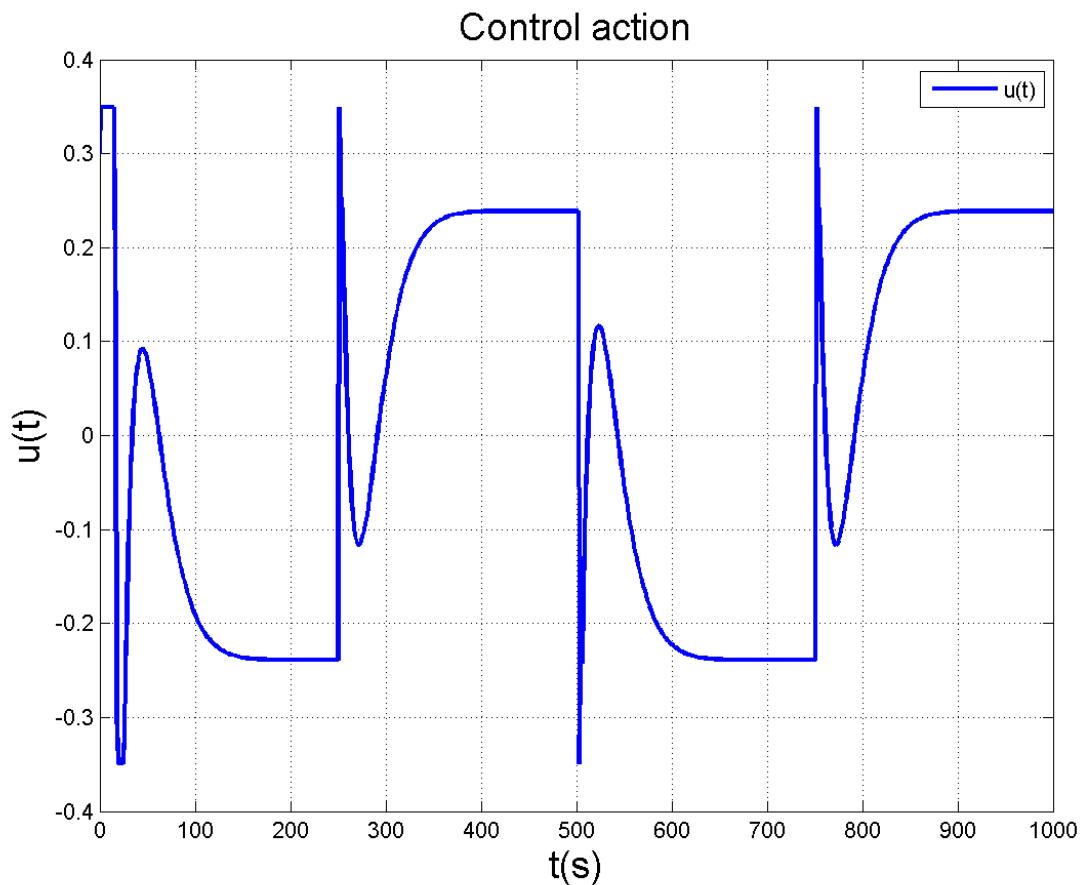
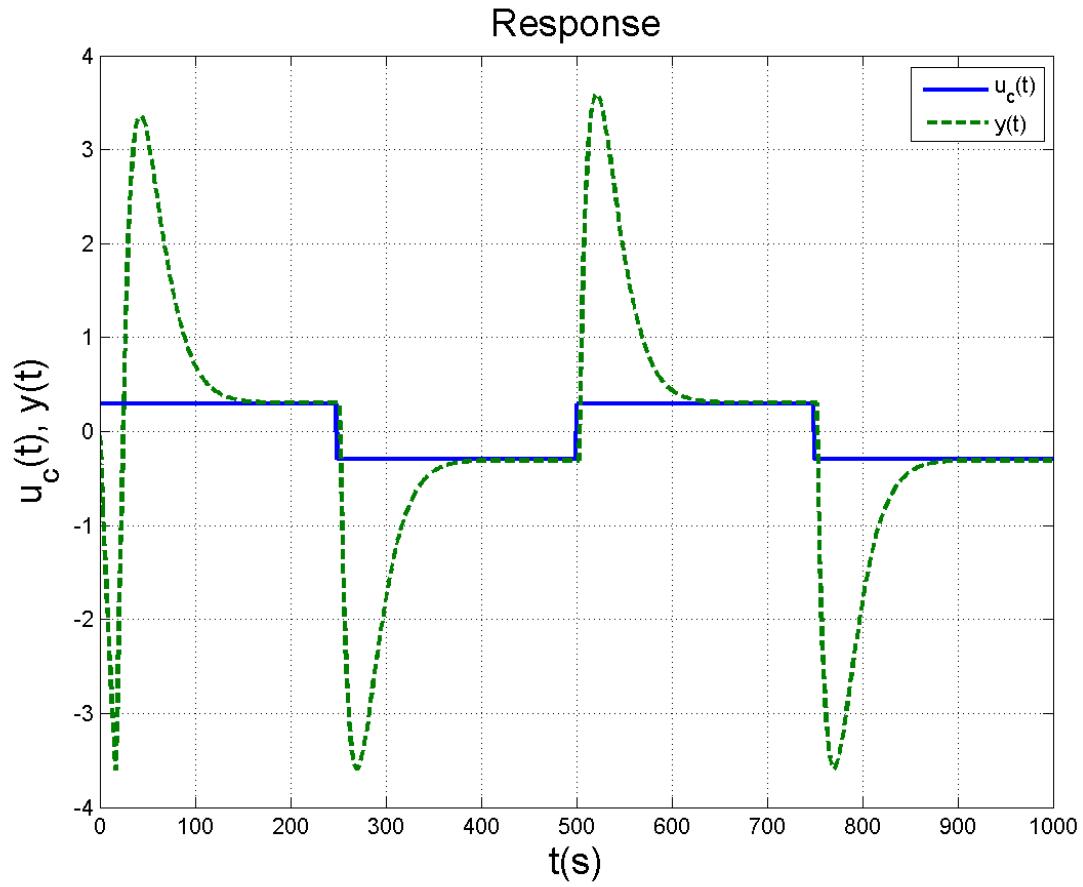




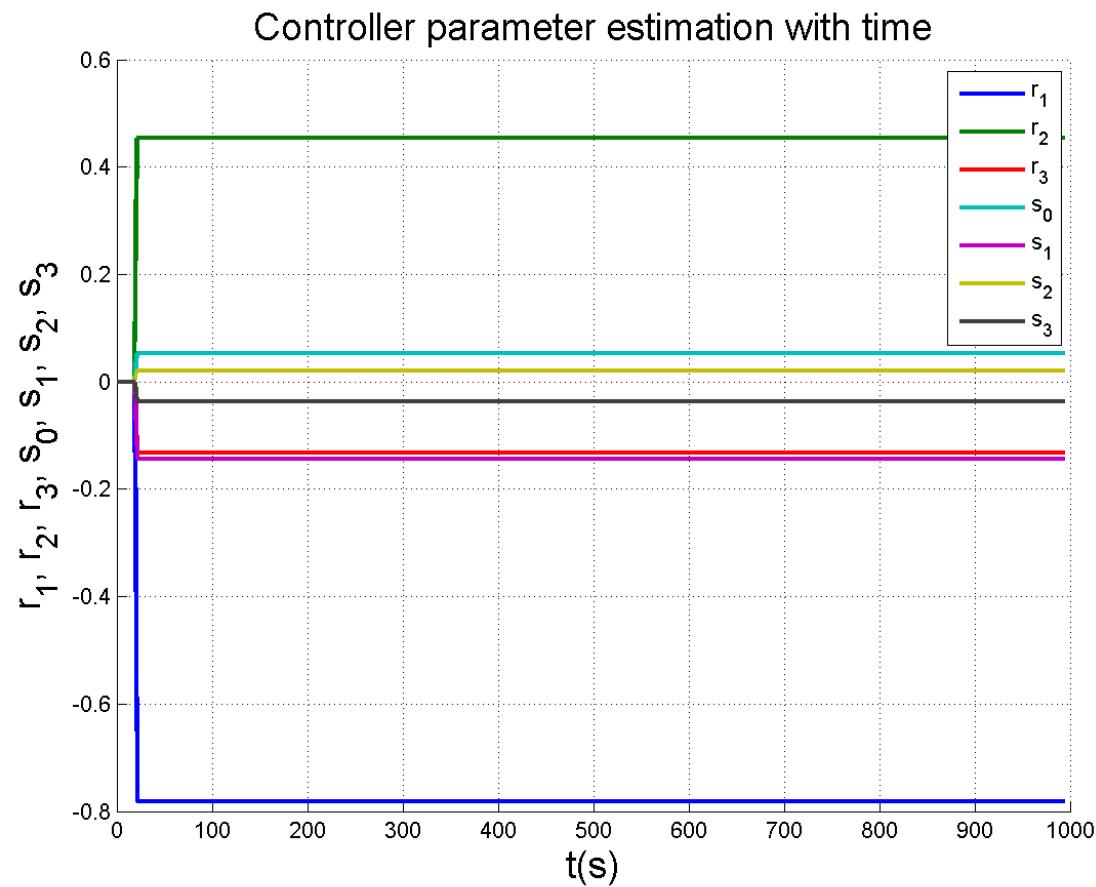
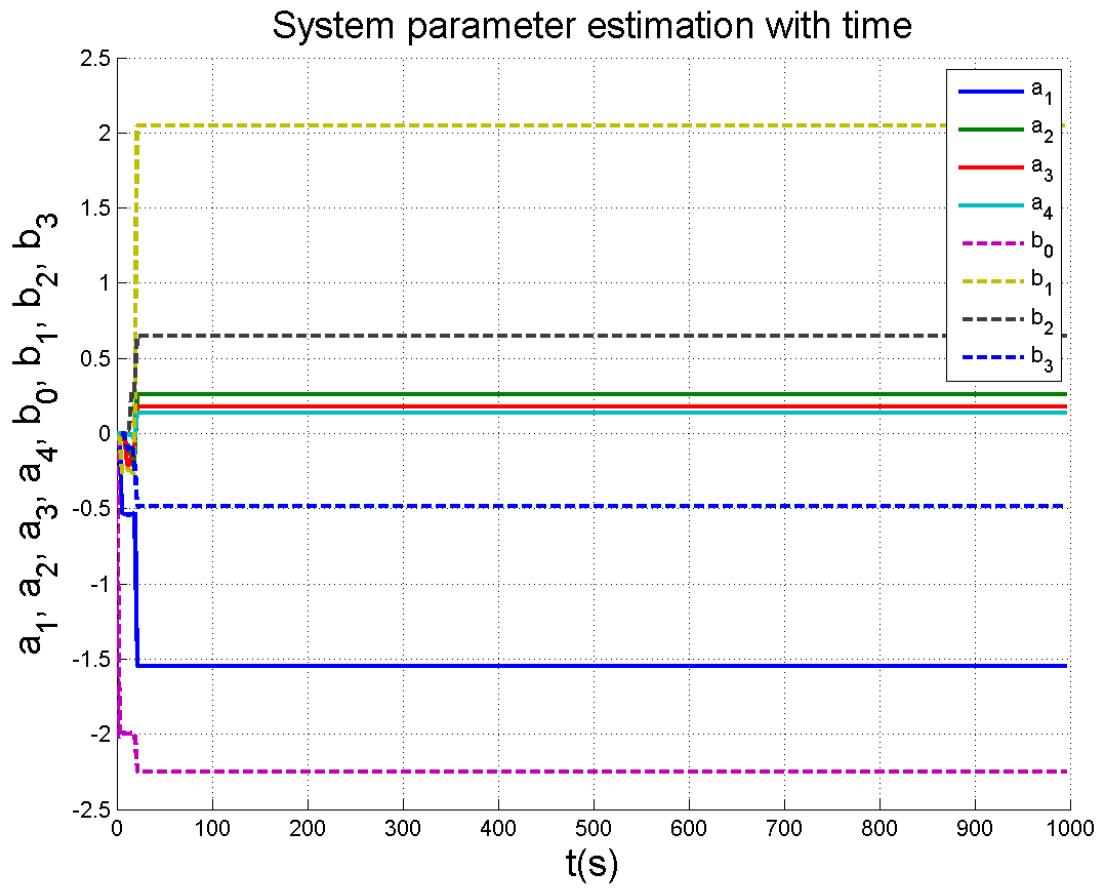
Flight Condition 3

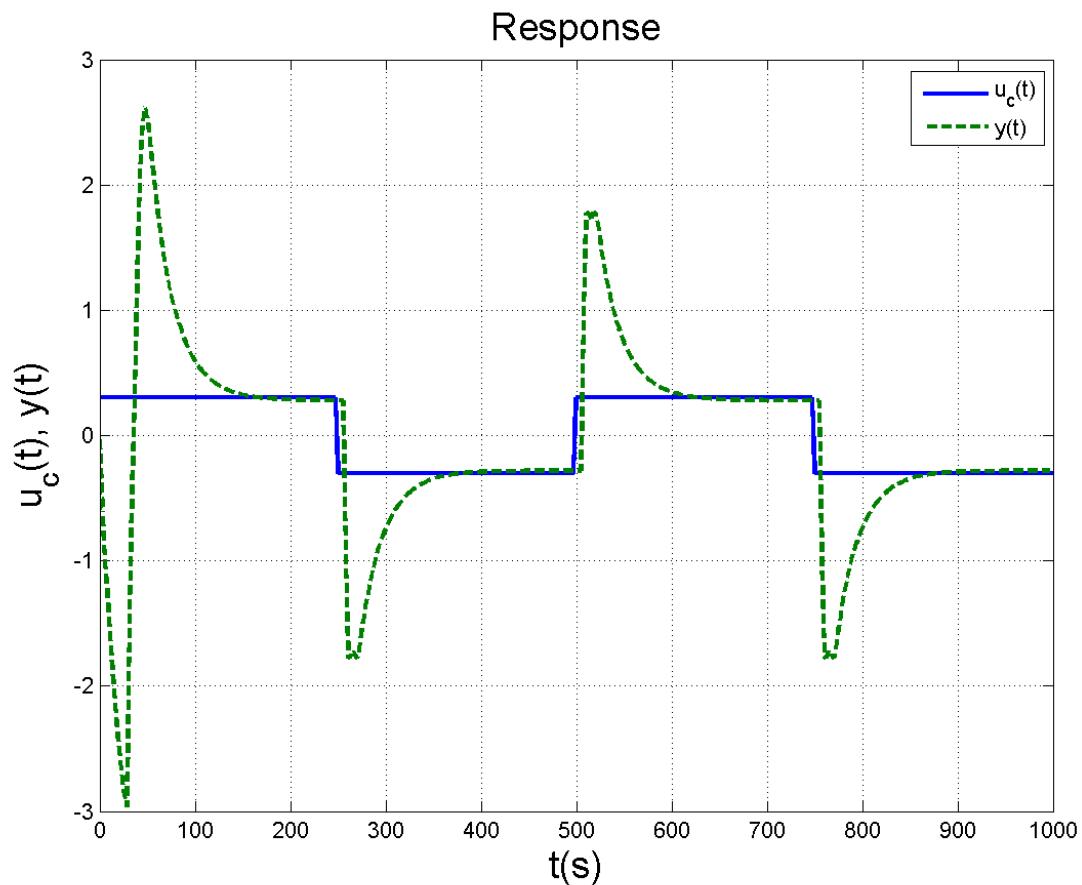
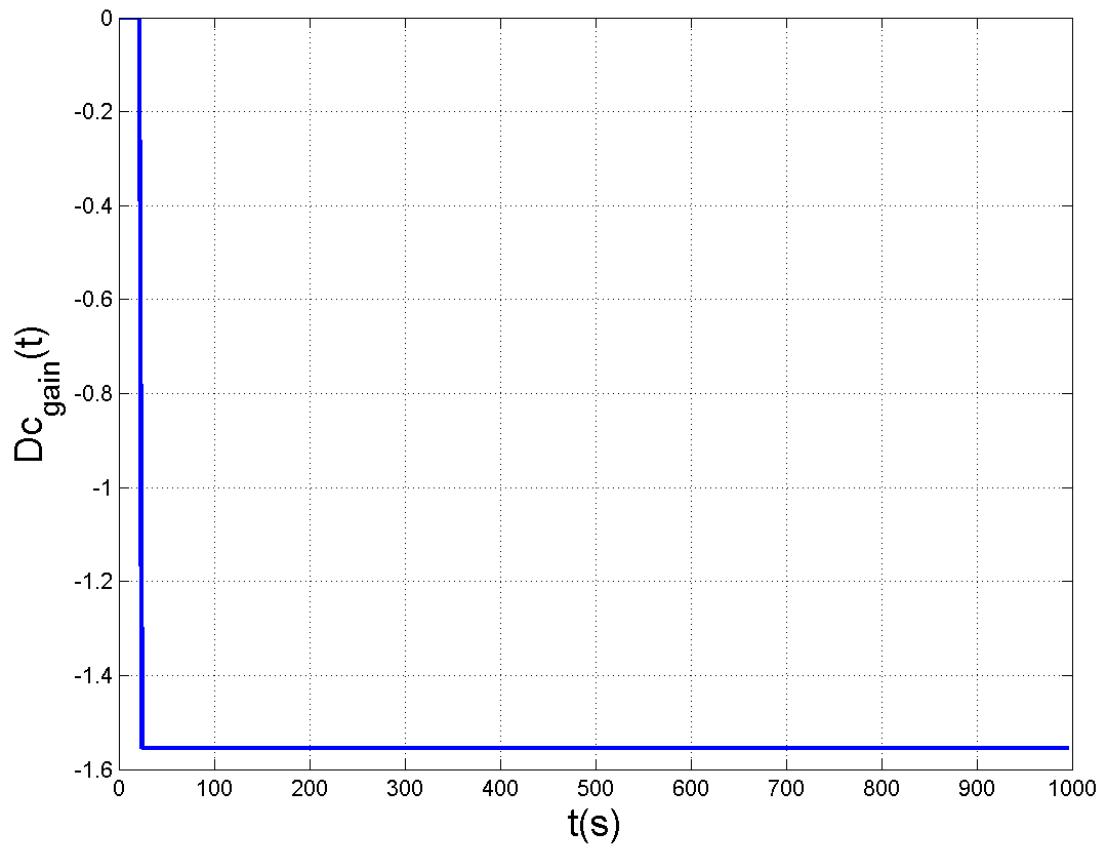


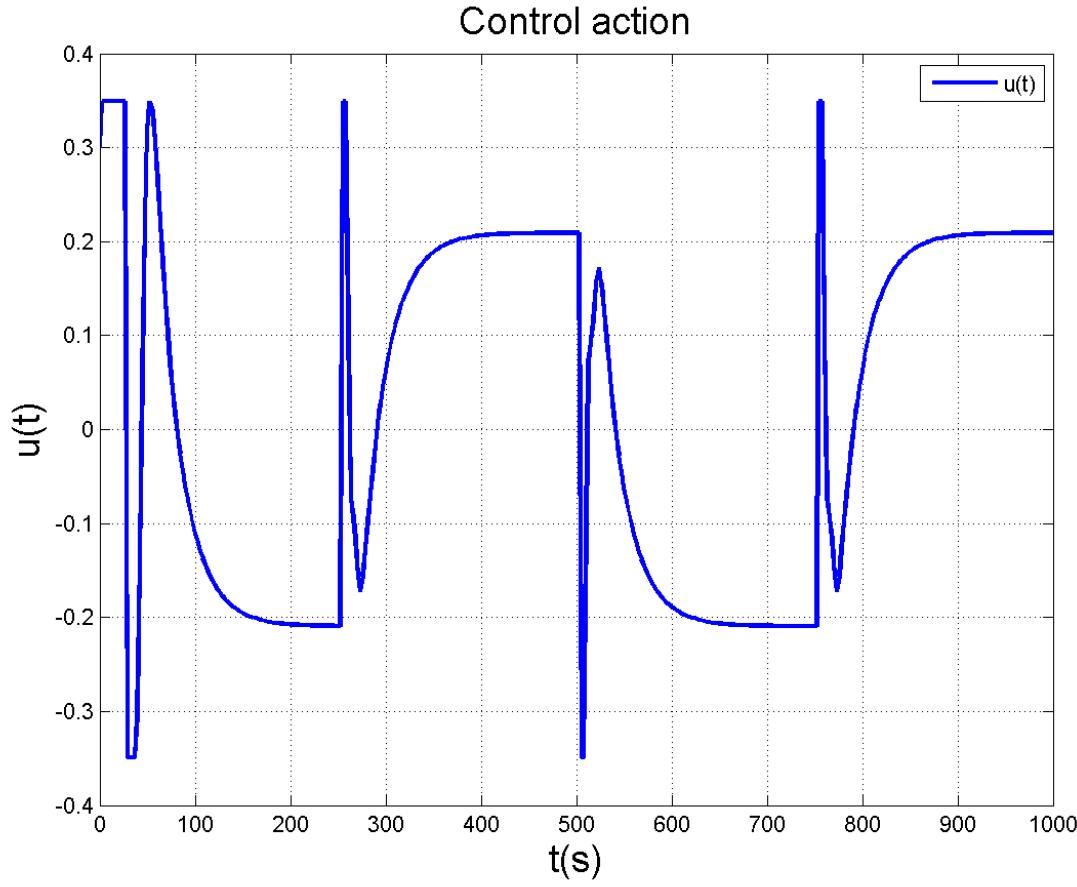




Flight Condition 4



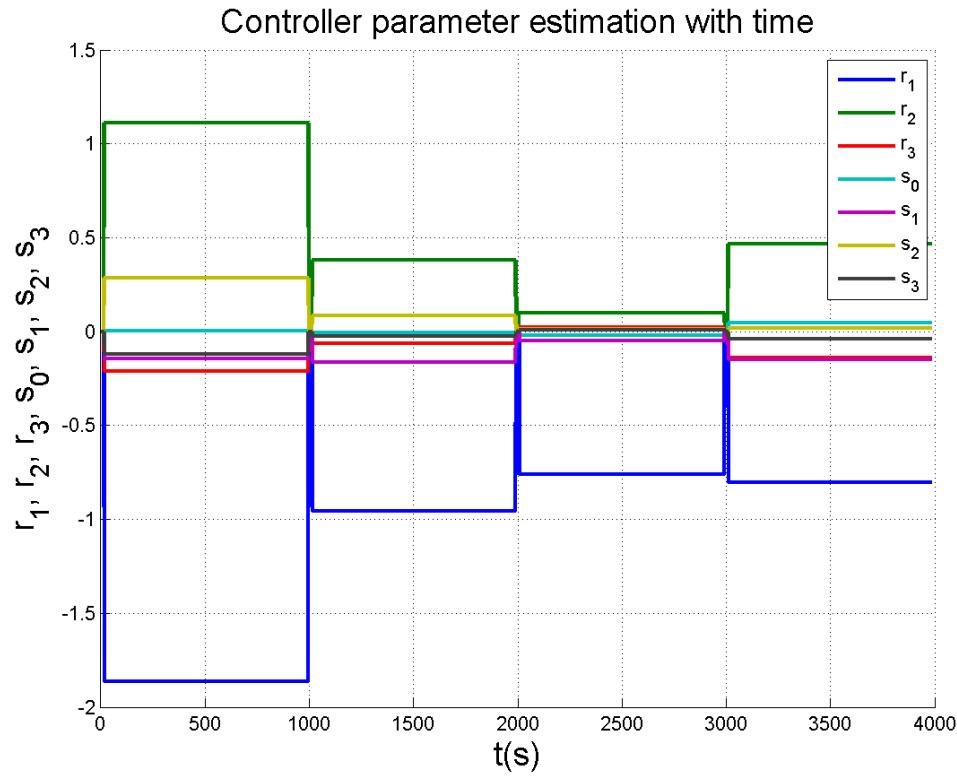
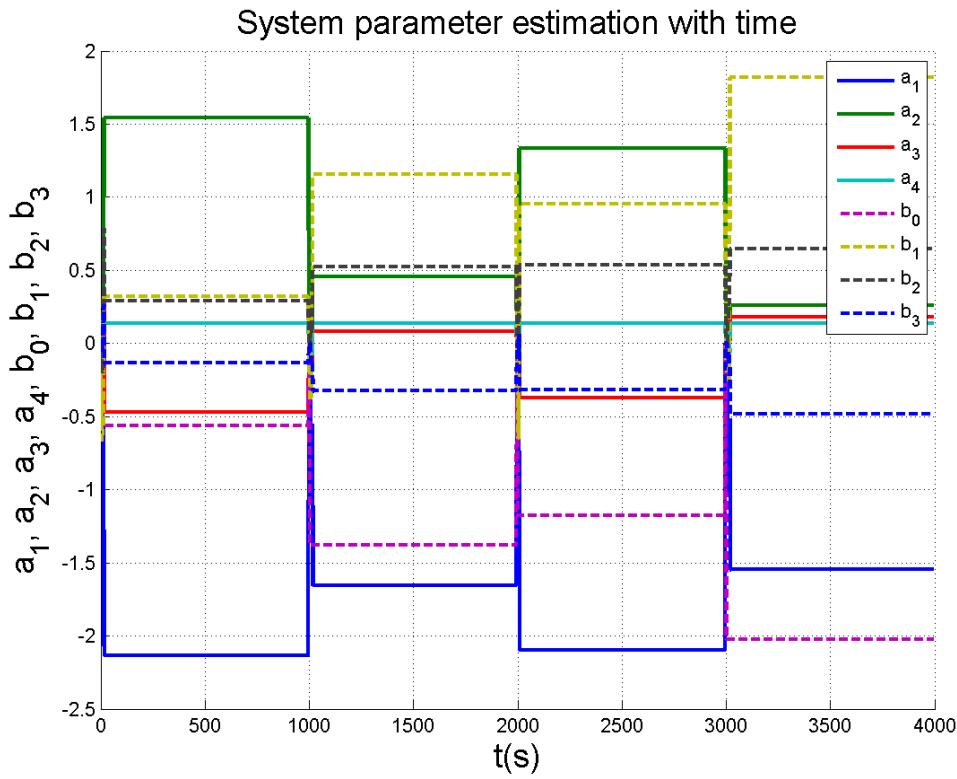


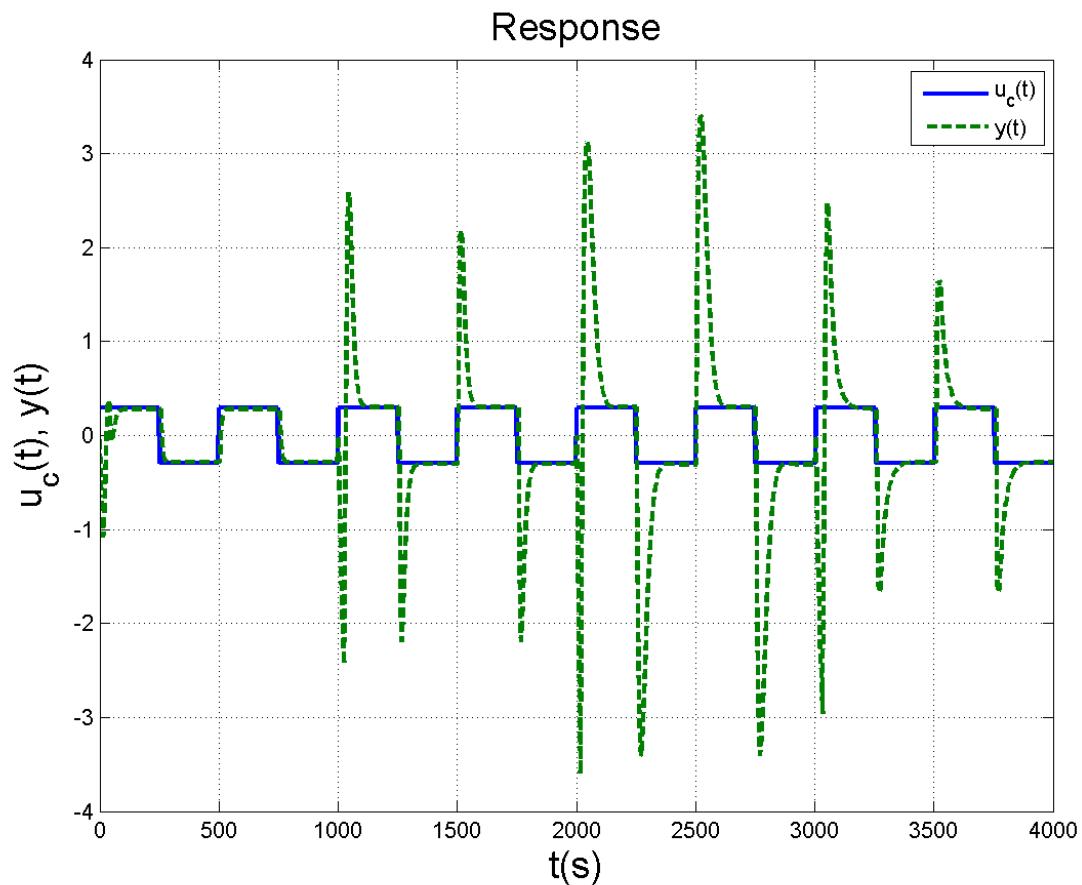
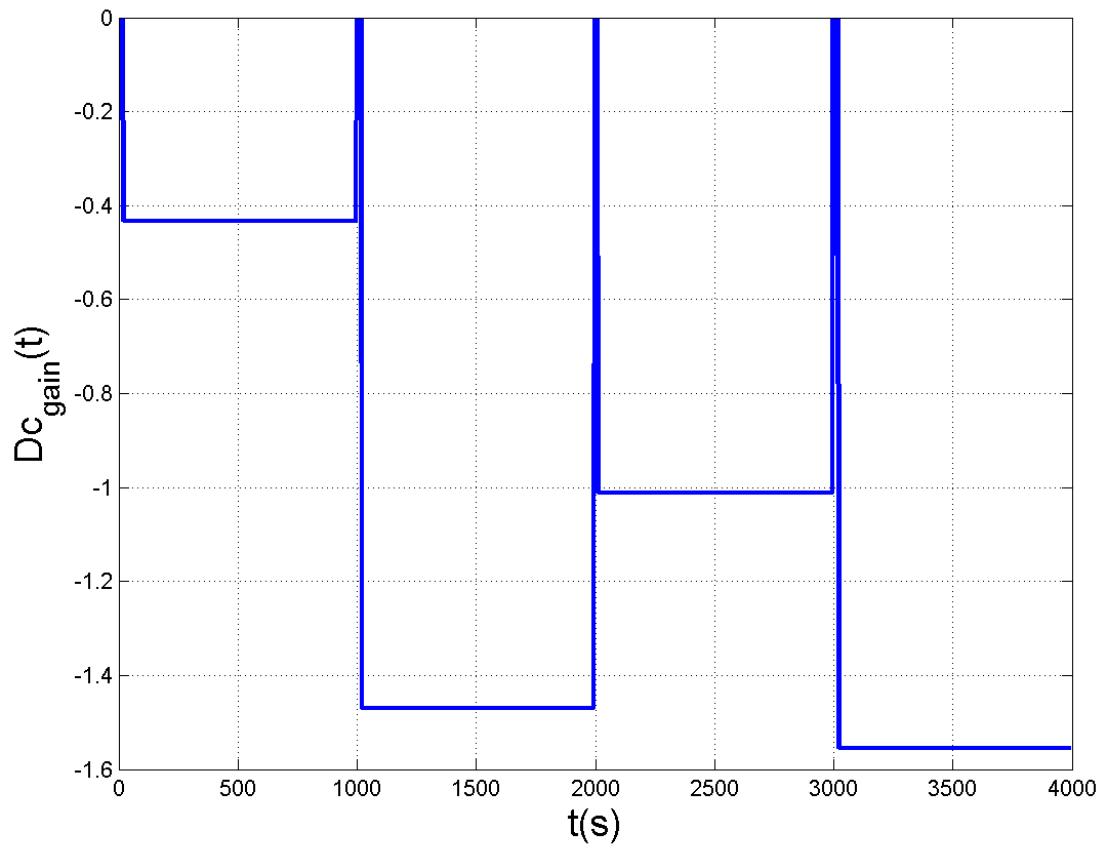


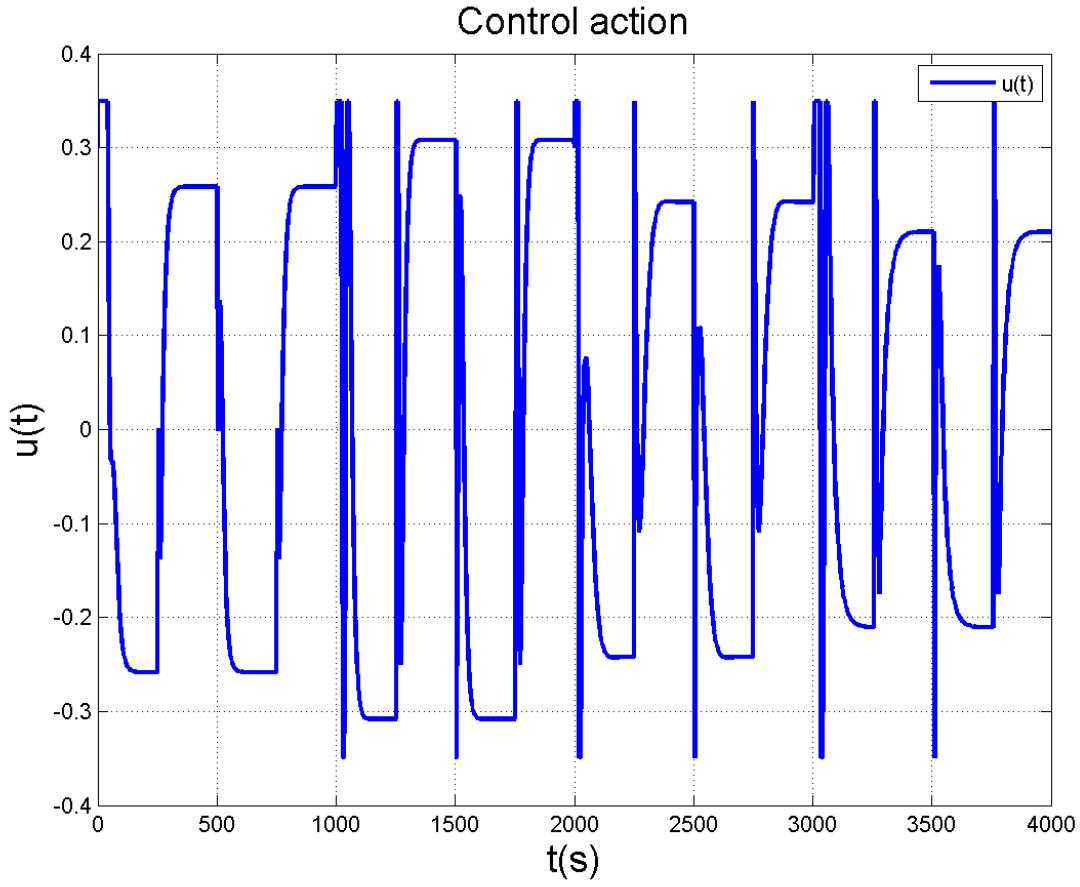
Results

Flight Condition	$G(z)$ Estimated	Feed Back Controller
1	$G(z) = \frac{-0.6048z^3 + 0.3617z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$\frac{S}{R}(z) = \frac{-5.404e-05z^3 - 0.1389z^2 + 0.2756z - 0.1172}{z^3 - 1.866z^2 + 1.107z - 0.2077}$
2	$G(z) = \frac{-1.522z^3 + 1.297z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$\frac{S}{R}(z) = \frac{0.005557z^3 - 0.1664z^2 + 0.08272z - 0.02619}{z^3 - 0.9369z^2 + 0.3706z - 0.06272}$
3	$G(z) = \frac{-1.295z^3 + 1.073z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$\frac{S}{R}(z) = \frac{-0.01341z^3 - 0.05432z^2 + 0.01315z + 0.008526}{z^3 - 0.752z^2 + 0.09983z + 0.01807}$
4	$G(z) = \frac{-2.25z^3 + 2.049z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$\frac{S}{R}(z) = \frac{0.05357z^3 - 0.1444z^2 + 0.02124z - 0.03704}{z^3 - 0.7819z^2 + 0.4547z - 0.1321}$
		Feed Forward Controller
		$\frac{T}{R}(z) = \frac{-0.4332z^5 + 1.04z^4 - 0.9705z^3 + 0.4436z^2 - 0.09982z + 0.008873}{z^3 - 1.866z^2 + 1.107z - 0.2077}$
		$\frac{T}{R}(z) = \frac{-1.47z^5 + 1.47z^4 - 0.5881z^3 + 0.1176z^2 - 0.01176z + 0.0004705}{z^3 - 0.9369z^2 + 0.3706z - 0.06272}$
		$\frac{T}{R}(z) = \frac{-1.012z^5 + 1.012z^4 - 0.405z^3 + 0.081z^2 - 0.0081z + 0.000324}{z^3 - 0.752z^2 + 0.09983z + 0.01807}$
		$\frac{T}{R}(z) = \frac{-1.555z^5 + 1.555z^4 - 0.622z^3 + 0.1244z^2 - 0.01244z + 0.0004976}{z^3 - 0.7819z^2 + 0.4547z - 0.1321}$

For All Flight Conditions Together







Results

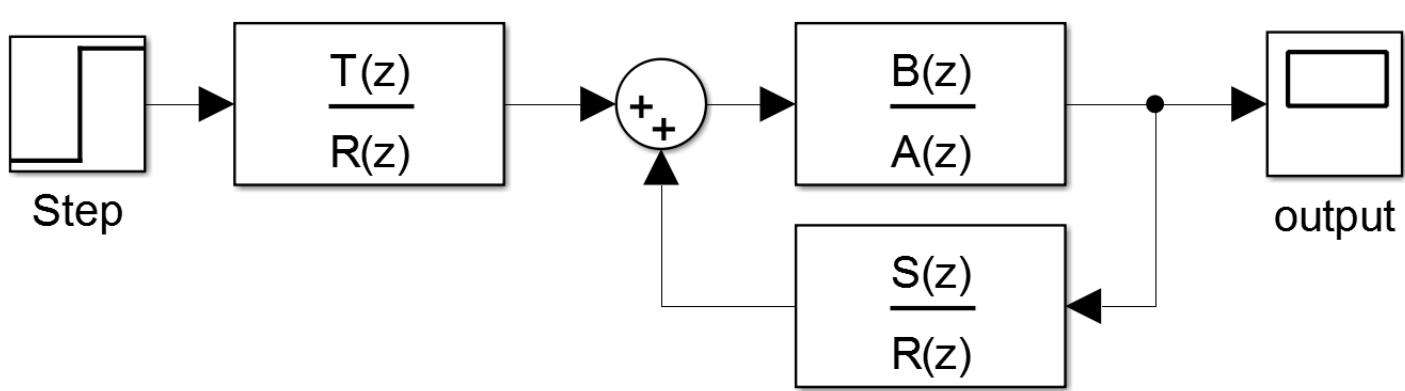
Flight Condition	$G(z)$ Estimated	Feed Back Controller
1	$G(z) = \frac{-0.5646z^3 + 0.3215z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$\frac{S}{R}(z) = \frac{0.001566z^3 - 0.1438z^2 + 0.284z - 0.1204}{z^3 - 1.865z^2 + 1.111z - 0.2109}$
2	$G(z) = \frac{-1.378z^3 + 1.153z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$\frac{S}{R}(z) = \frac{-0.007428z^3 - 0.1656z^2 + 0.08437z - 0.02736}{z^3 - 0.9555z^2 + 0.3805z - 0.06547}$
3	$G(z) = \frac{-1.176z^3 + 0.9539z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$\frac{S}{R}(z) = \frac{-0.02184z^3 - 0.05079z^2 + 0.01204z + 0.009442}{z^3 - 0.7603z^2 + 0.09947z + 0.02022}$
4	$G(z) = \frac{-2.023z^3 + 1.822z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$\frac{S}{R}(z) = \frac{0.005475z^3 - 0.1109z^2 + 0.04074z - 0.03511}{z^3 - 0.9714z^2 + 0.5099z - 0.1254}$
		Feed Forward Controller
		$\frac{T}{R}(z) = \frac{-0.4332z^5 + 1.04z^4 - 0.9705z^3 + 0.4436z^2 - 0.09982z + 0.008873}{z^3 - 1.865z^2 + 1.111z - 0.2109}$
		$\frac{T}{R}(z) = \frac{-1.47z^5 + 1.47z^4 - 0.5881z^3 + 0.1176z^2 - 0.01176z + 0.0004705}{z^3 - 0.9555z^2 + 0.3805z - 0.06547}$
		$\frac{T}{R}(z) = \frac{-1.012z^5 + 1.012z^4 - 0.405z^3 + 0.081z^2 - 0.0081z + 0.000324}{z^3 - 0.7603z^2 + 0.09947z + 0.02022}$
		$\frac{T}{R}(z) = \frac{-1.244z^5 + 1.244z^4 - 0.4976z^3 + 0.09951z^2 - 0.009951z + 0.0003981}{z^3 - 0.9714z^2 + 0.5099z - 0.1254}$

Comments

- The system parameter goes to its true values if i control all flight conditions together.
- There is a change in controller parameter between the controller of all flight conditions and the controller of each flight condition.

1.6.8 Indirect Self-Tuning Regulator Using Model Following With Zero Cancellation For Square Input

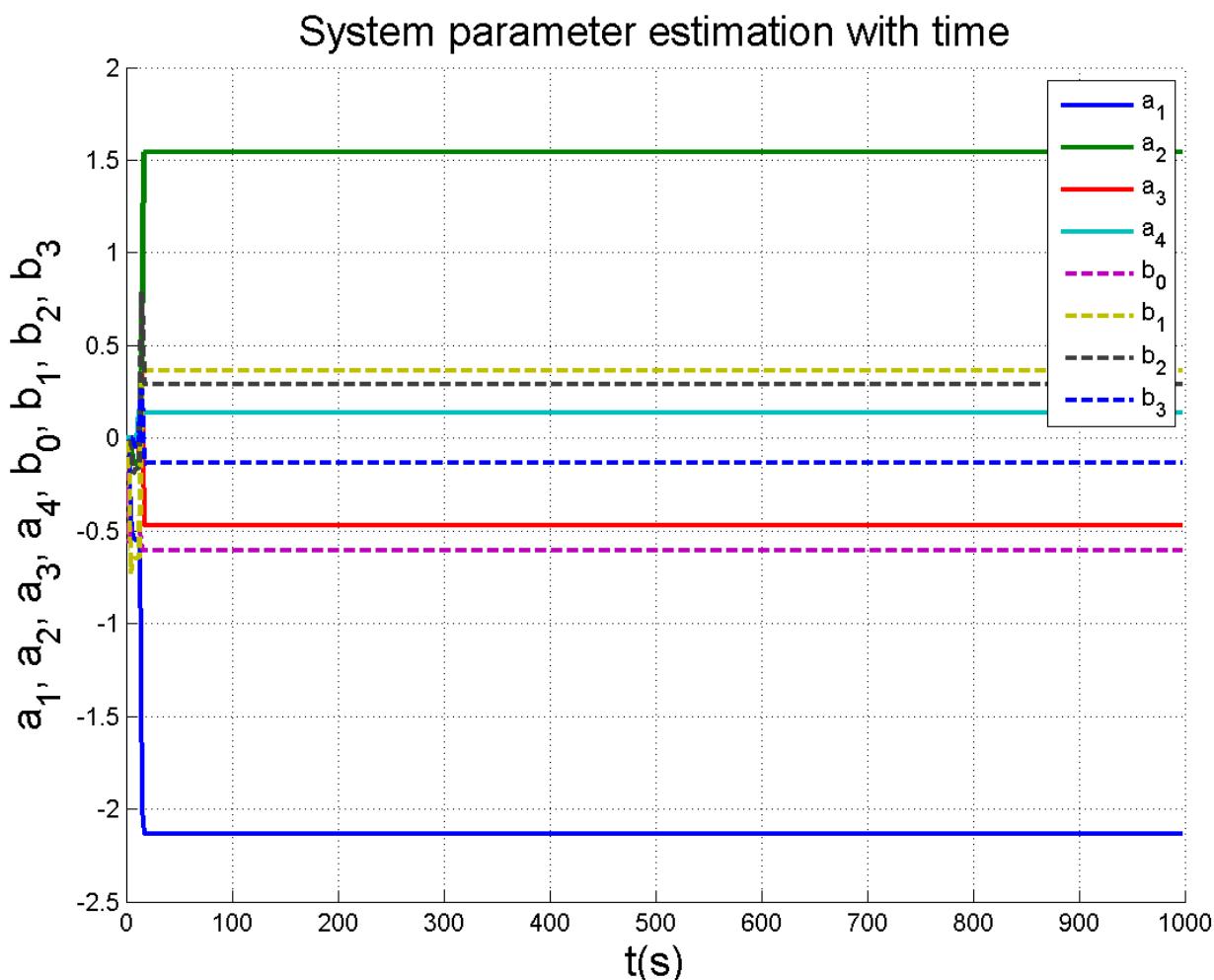
Controller Scheme

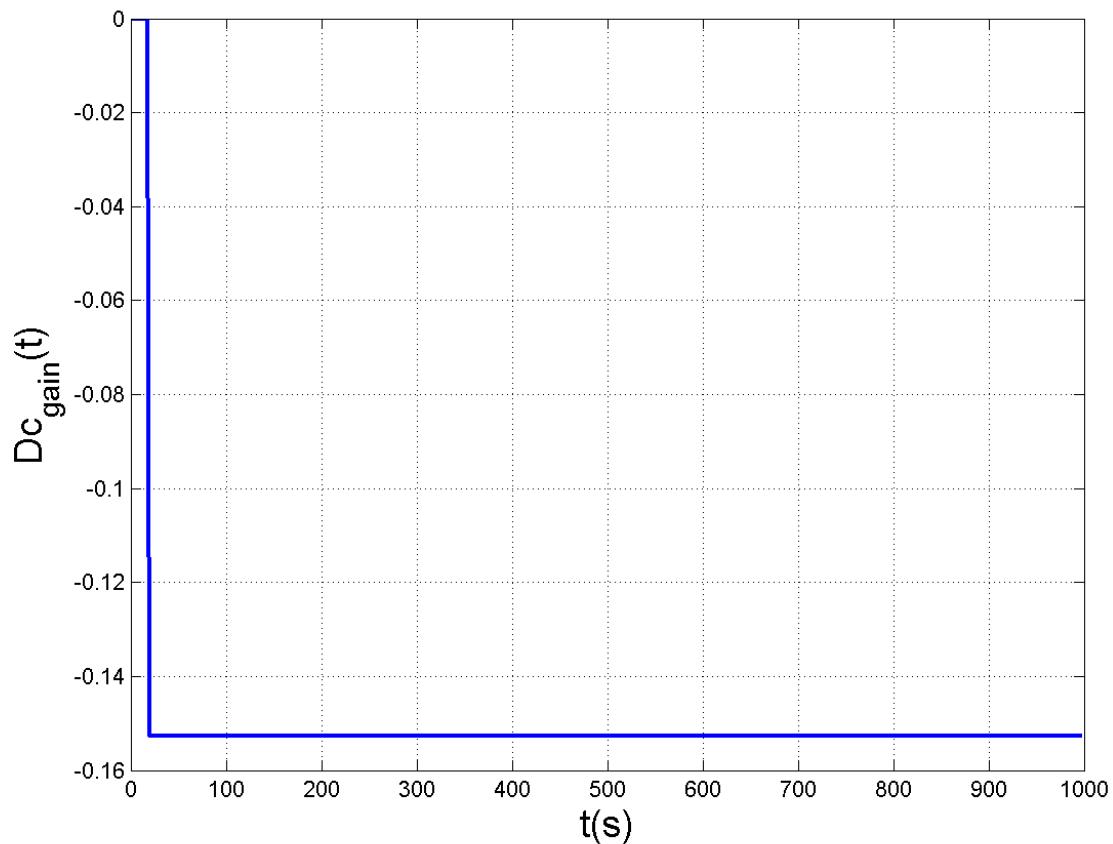
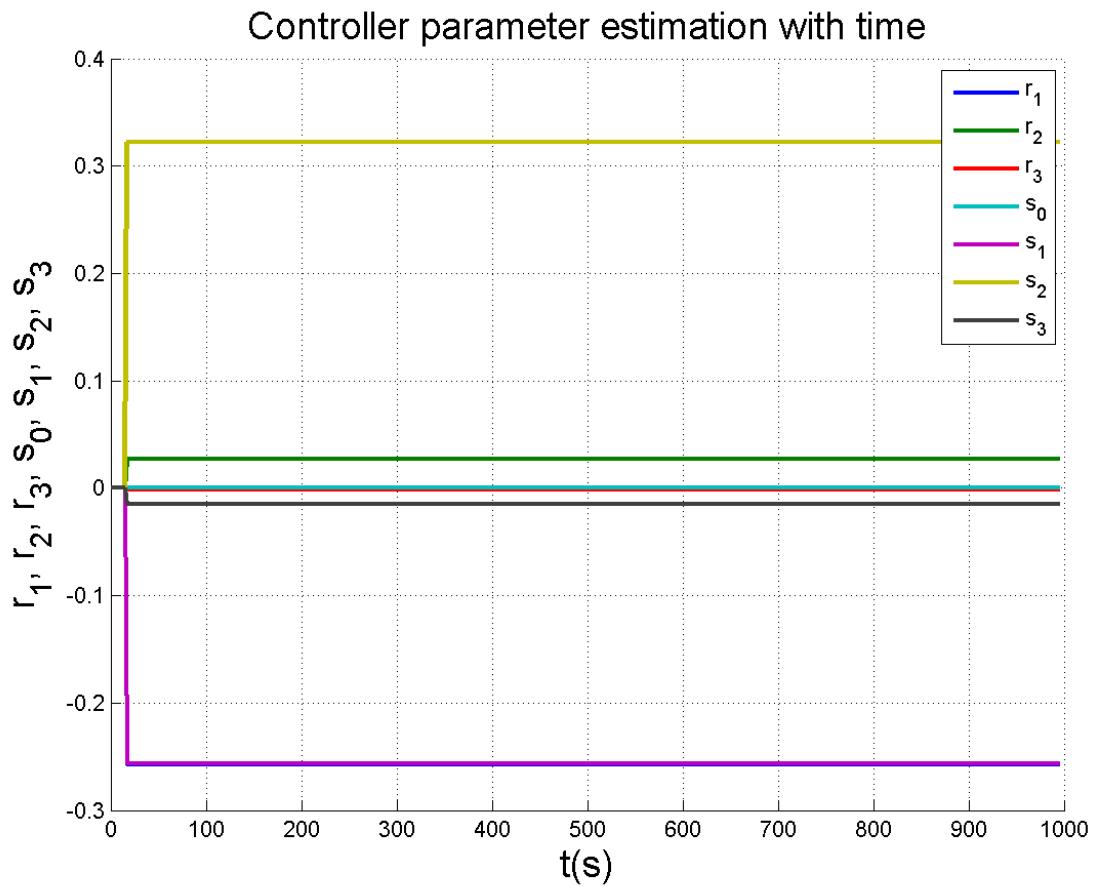


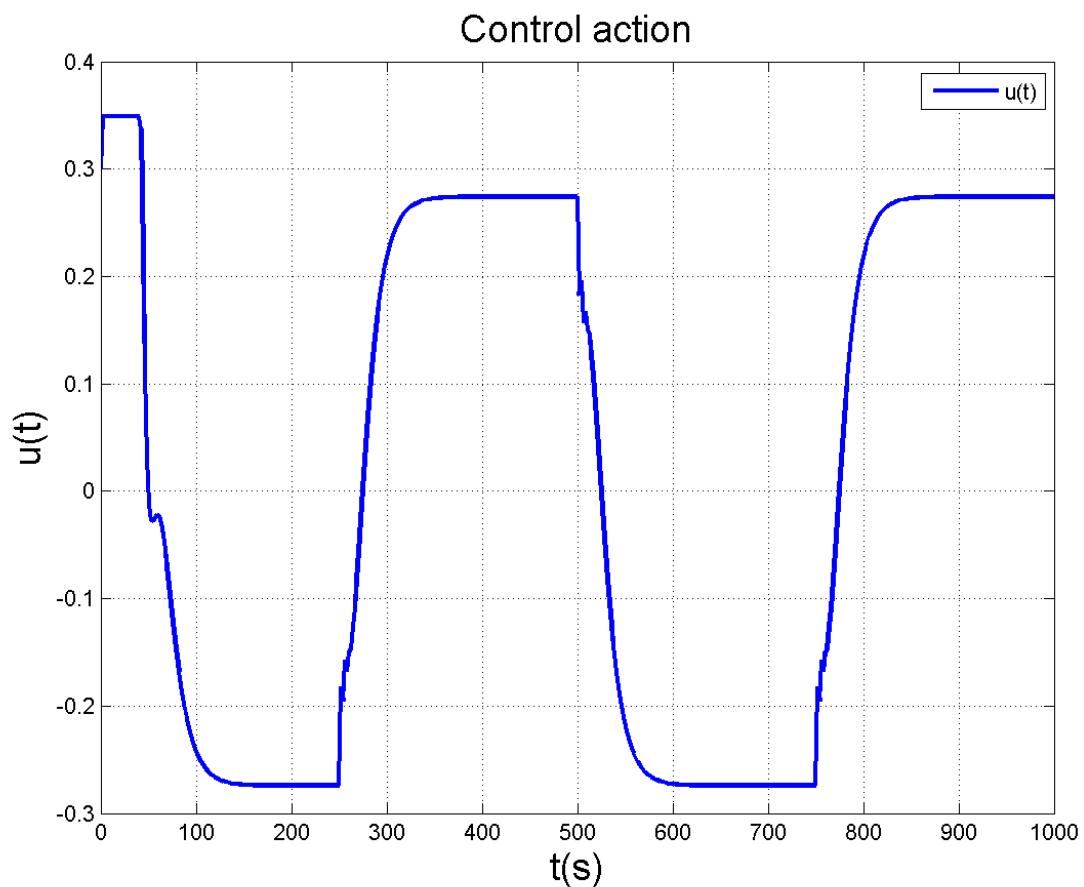
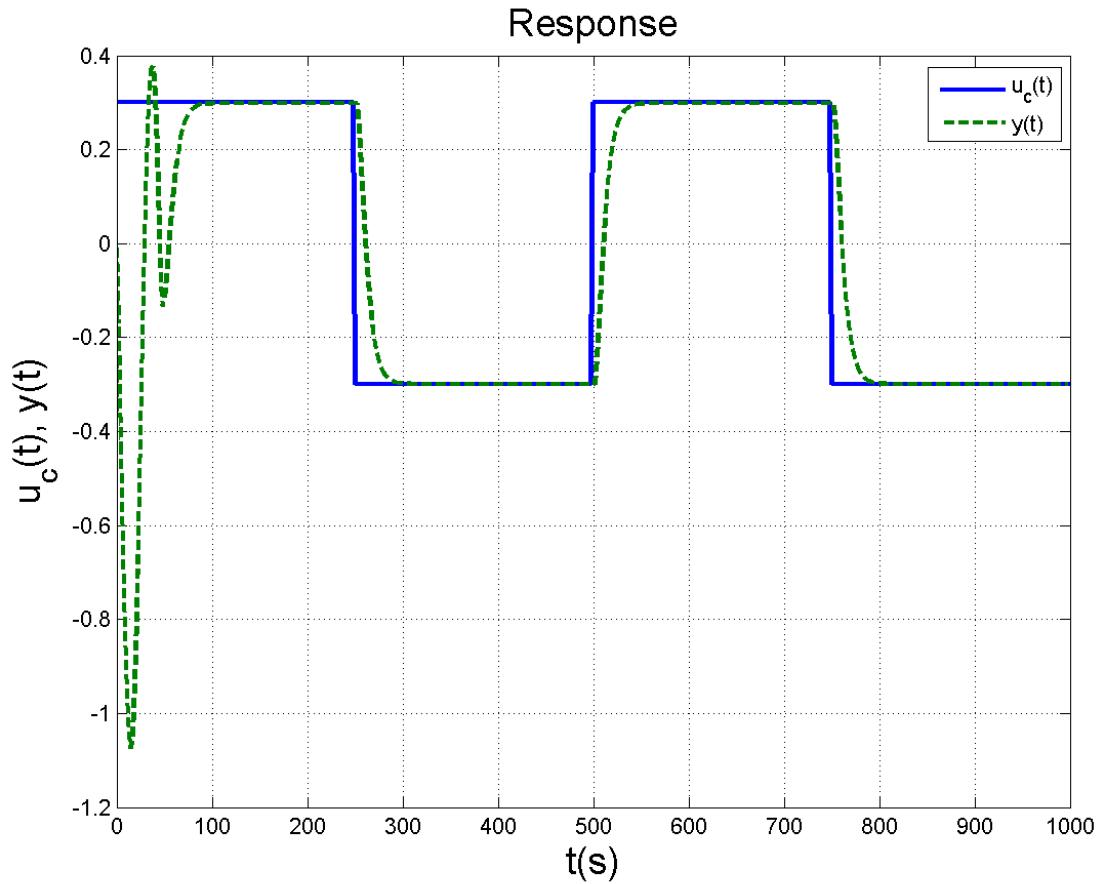
Required Poles in Z-Domain

Flight Condition	A_m	A_0
1	[0.692, 0.7]	[0.2, 0.2, 0.2, 0.2, 0.2]
2	[0.3, 0.5]	[0.2, 0.2, 0.2, 0.2, 0.2]
3	[0.665, 0.7]	[0.2, 0.2, 0.2, 0.2, 0.2]
4	[0.3, 0.37]	[0.2, 0.2, 0.2, 0.2, 0.2]

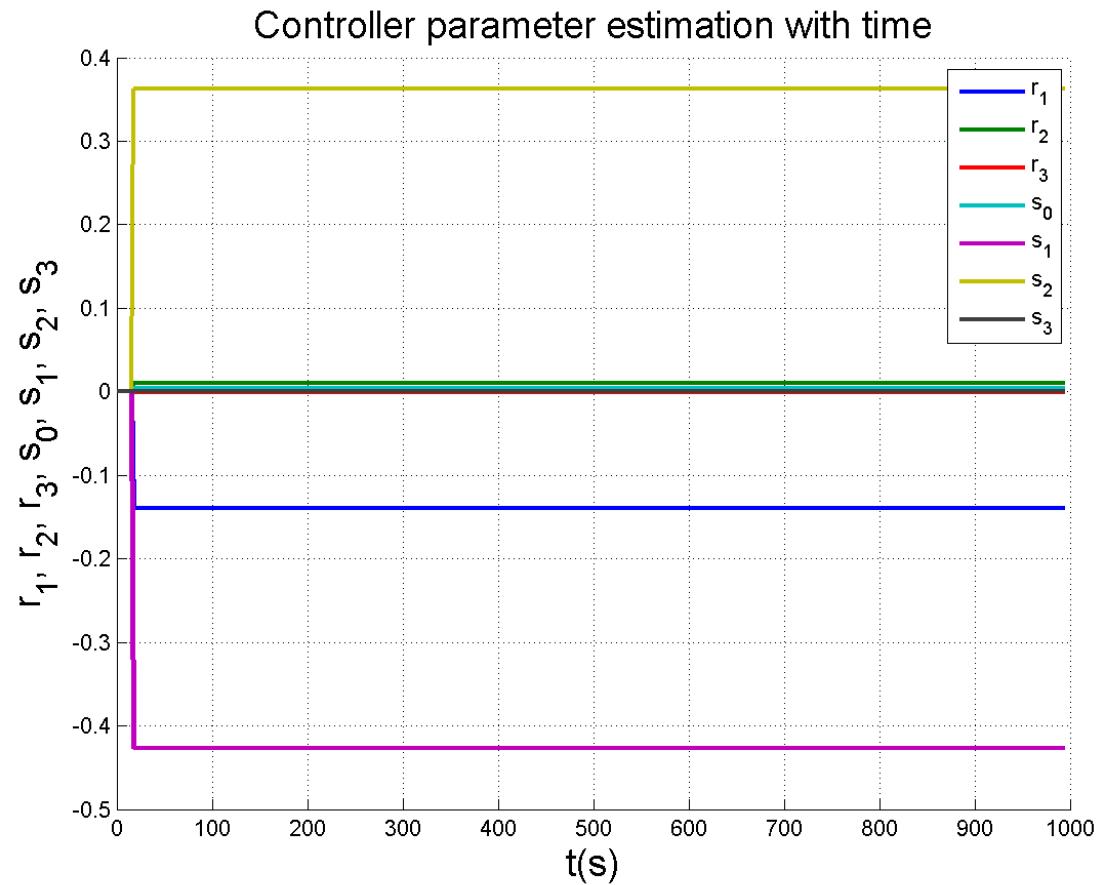
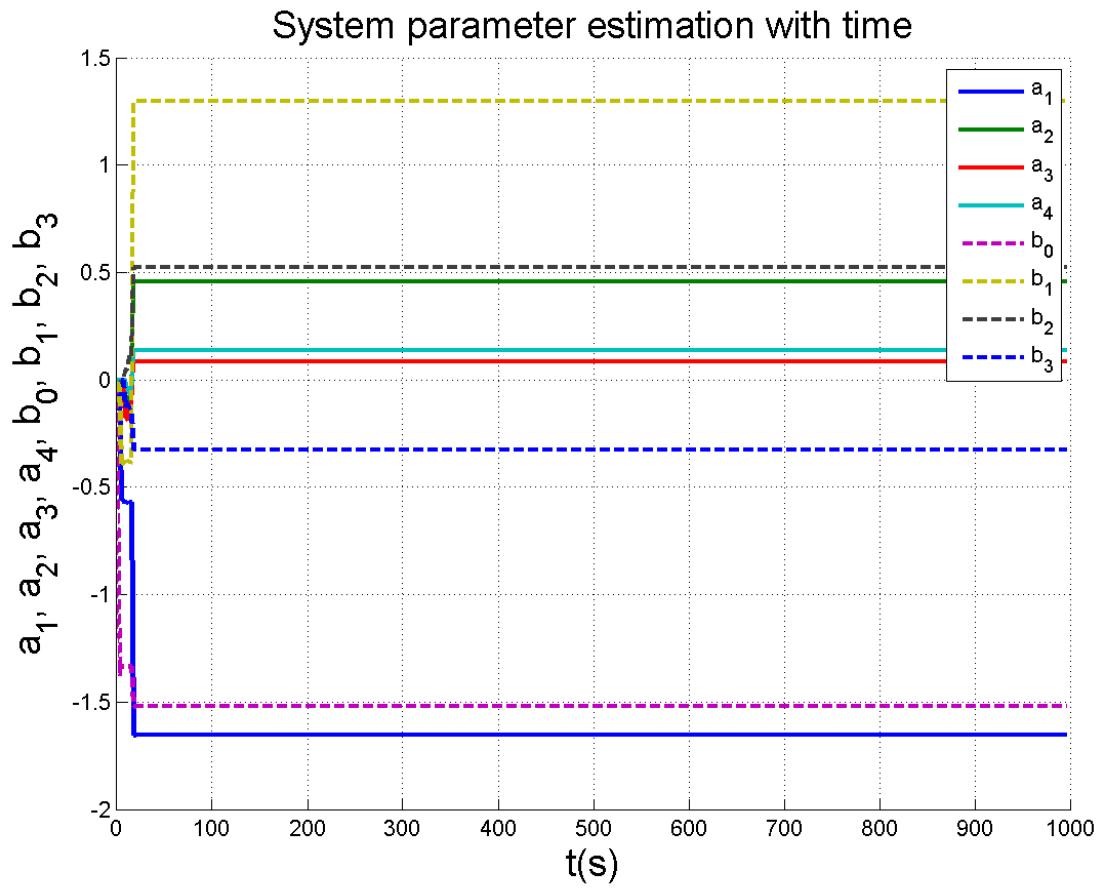
Flight Condition 1

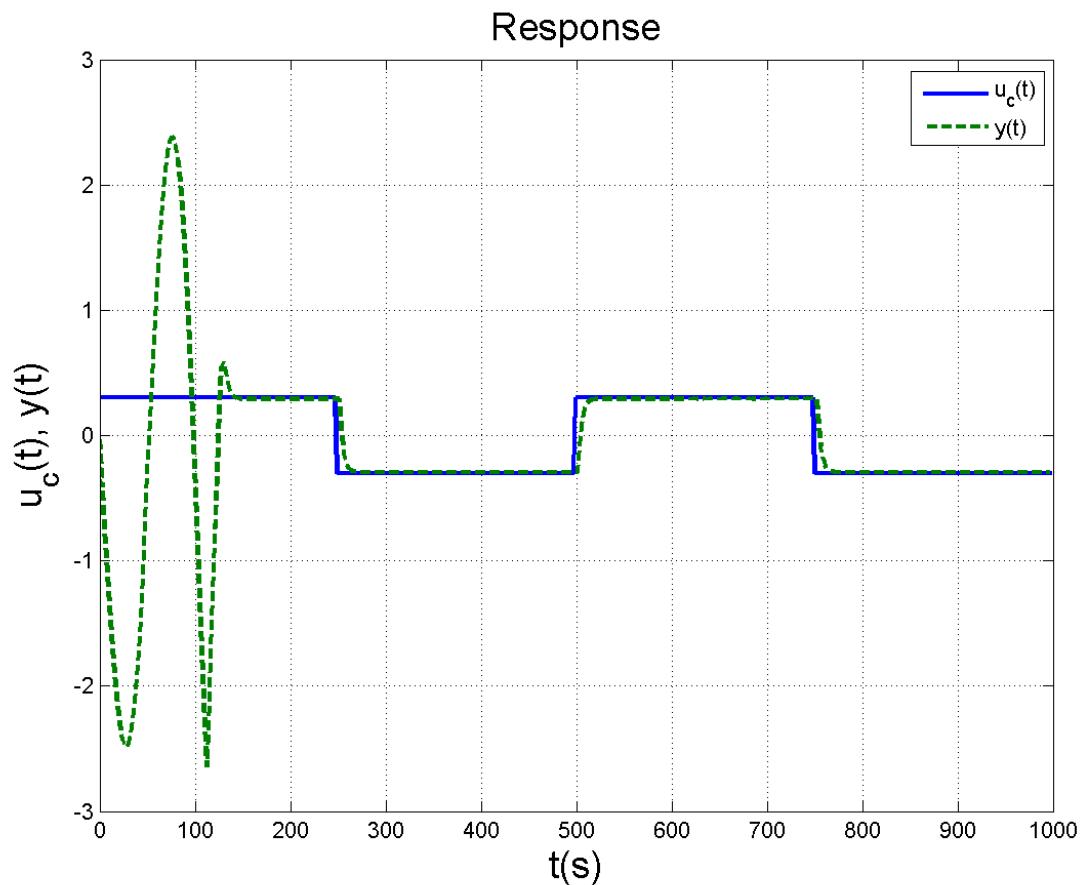
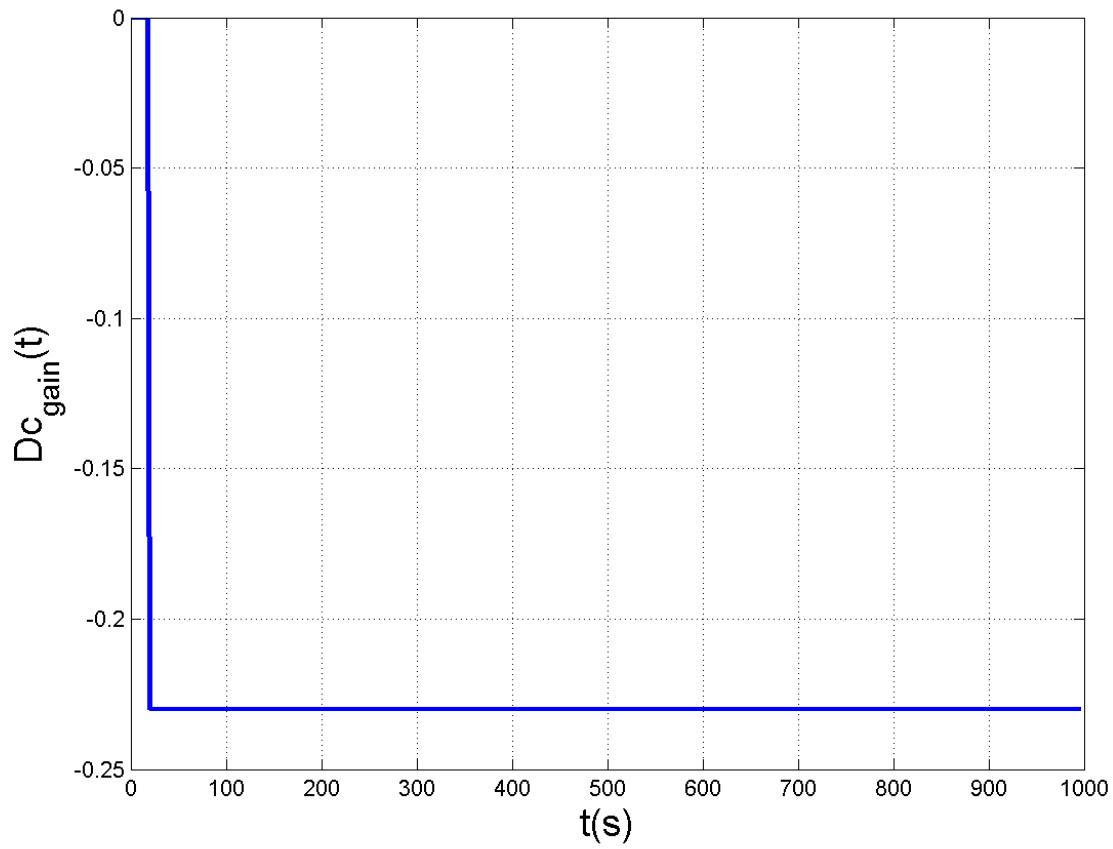


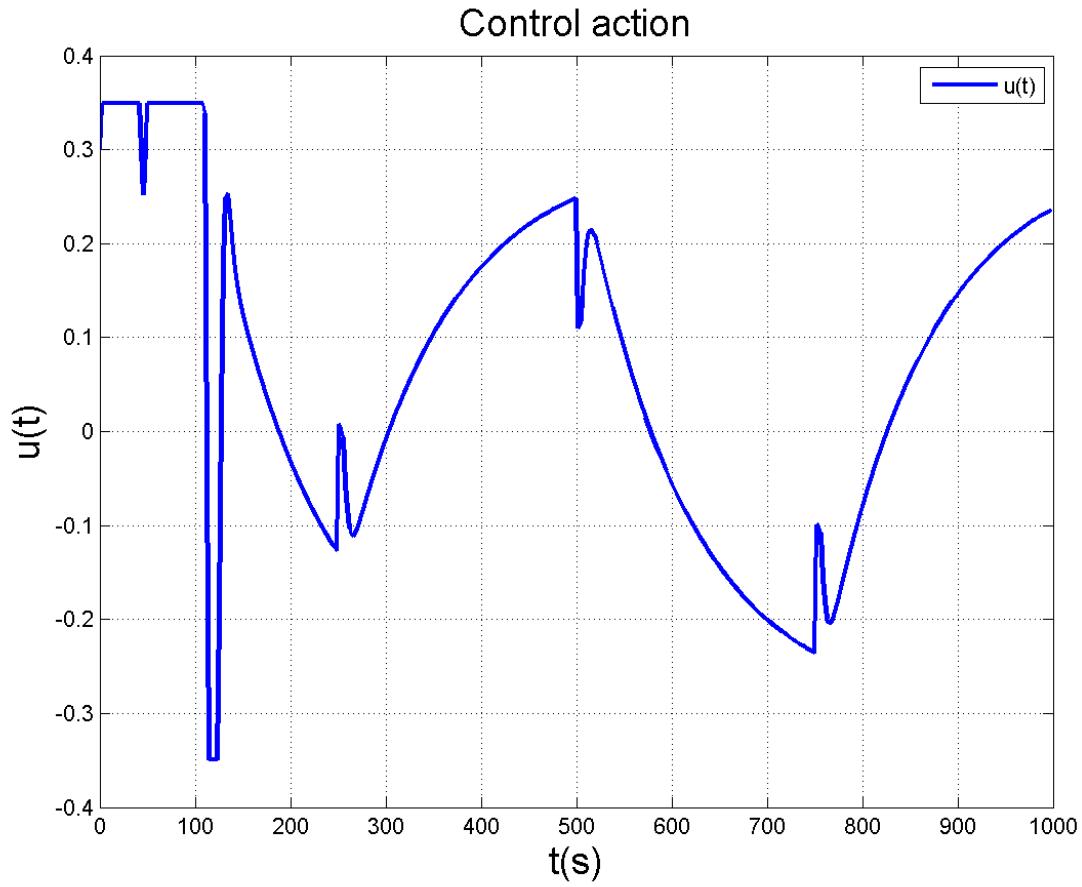




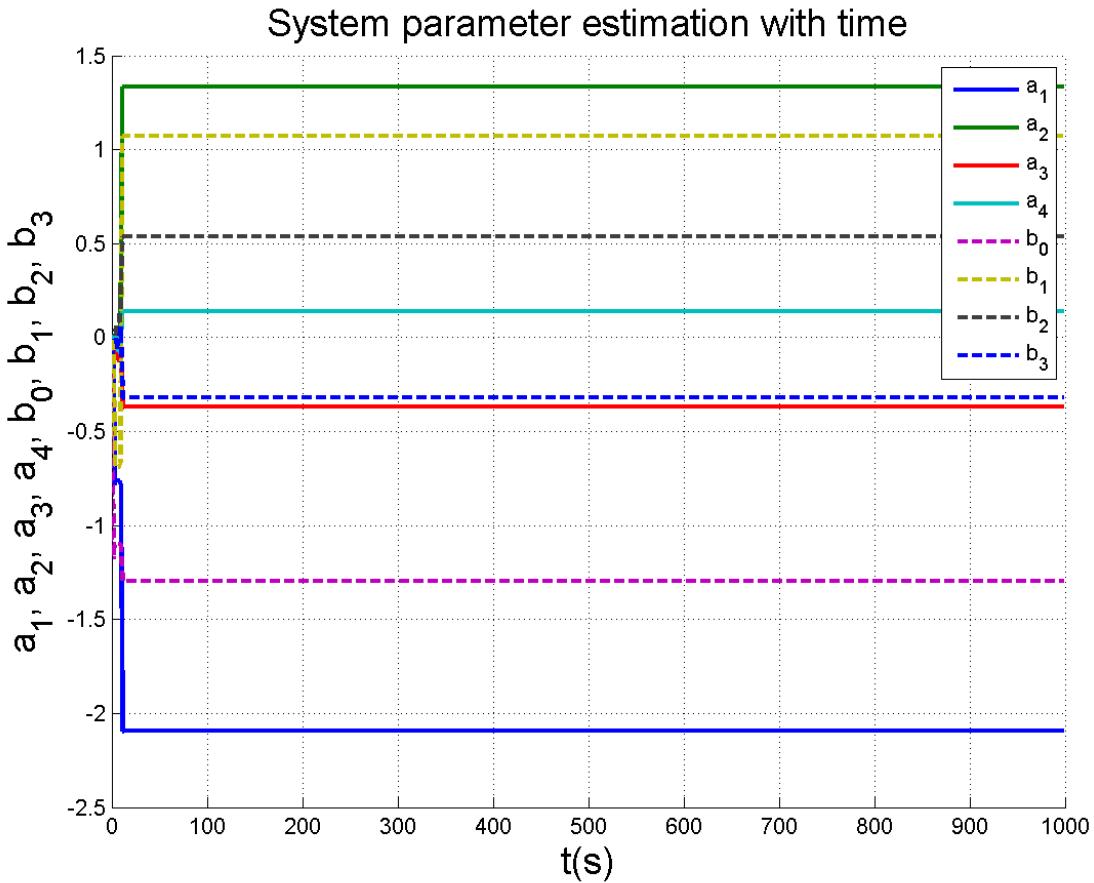
Flight Condition 2

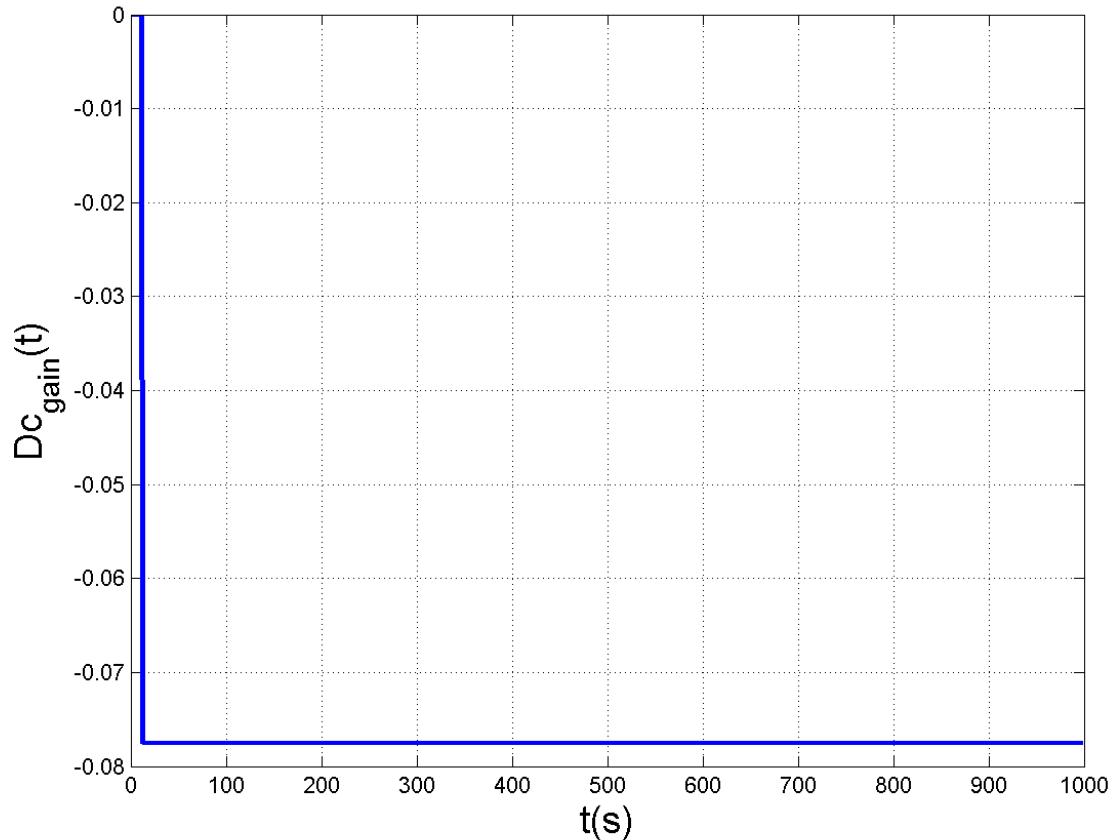
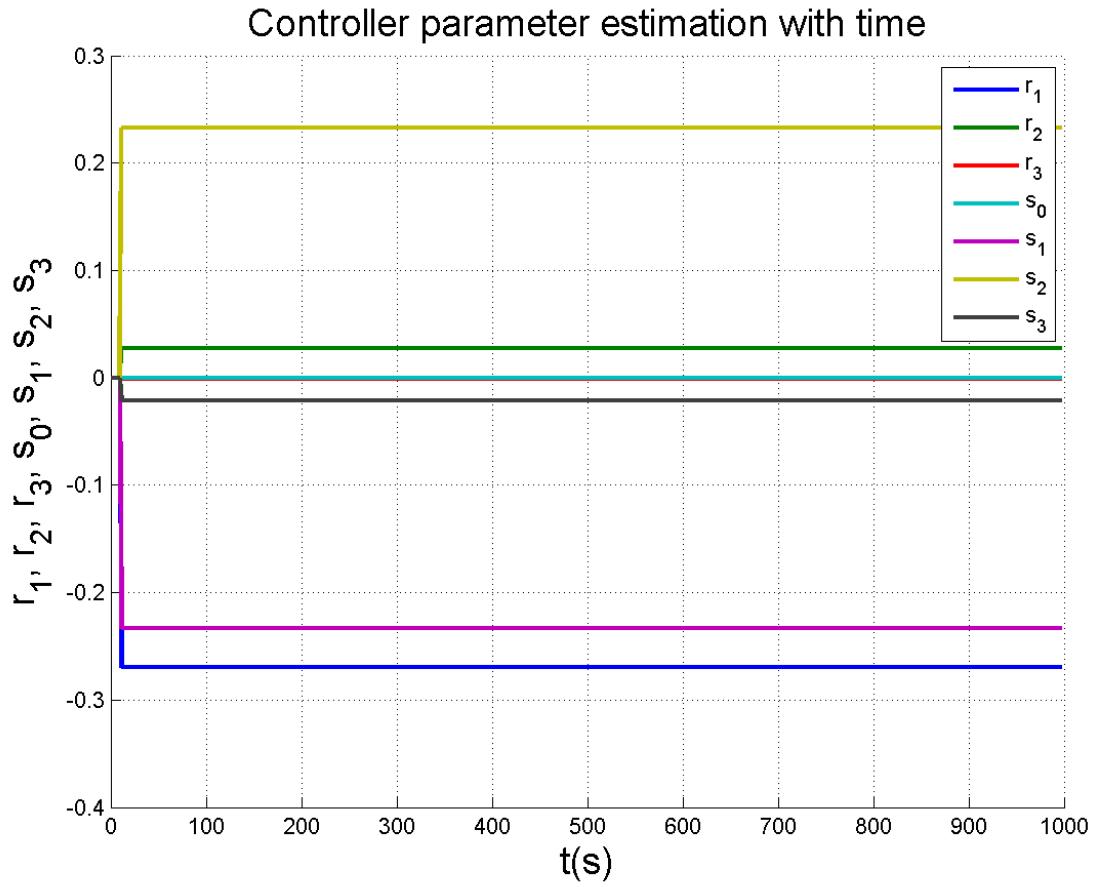


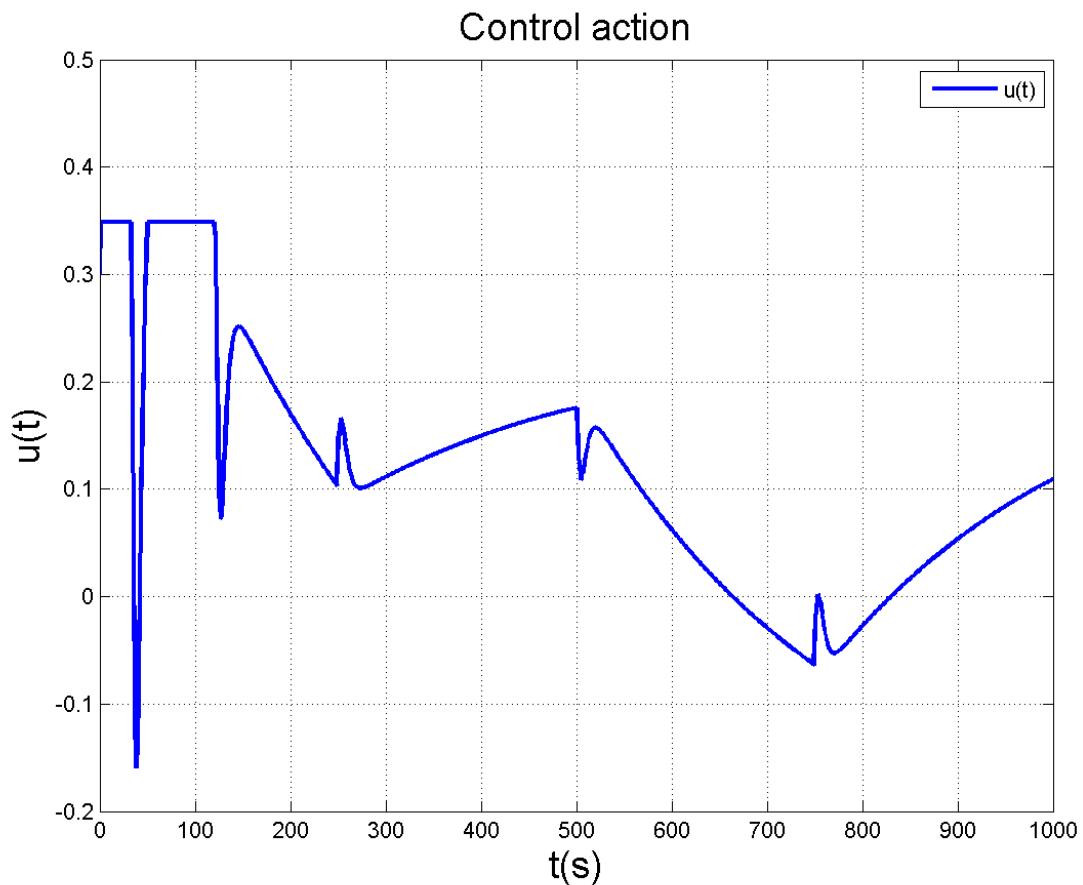
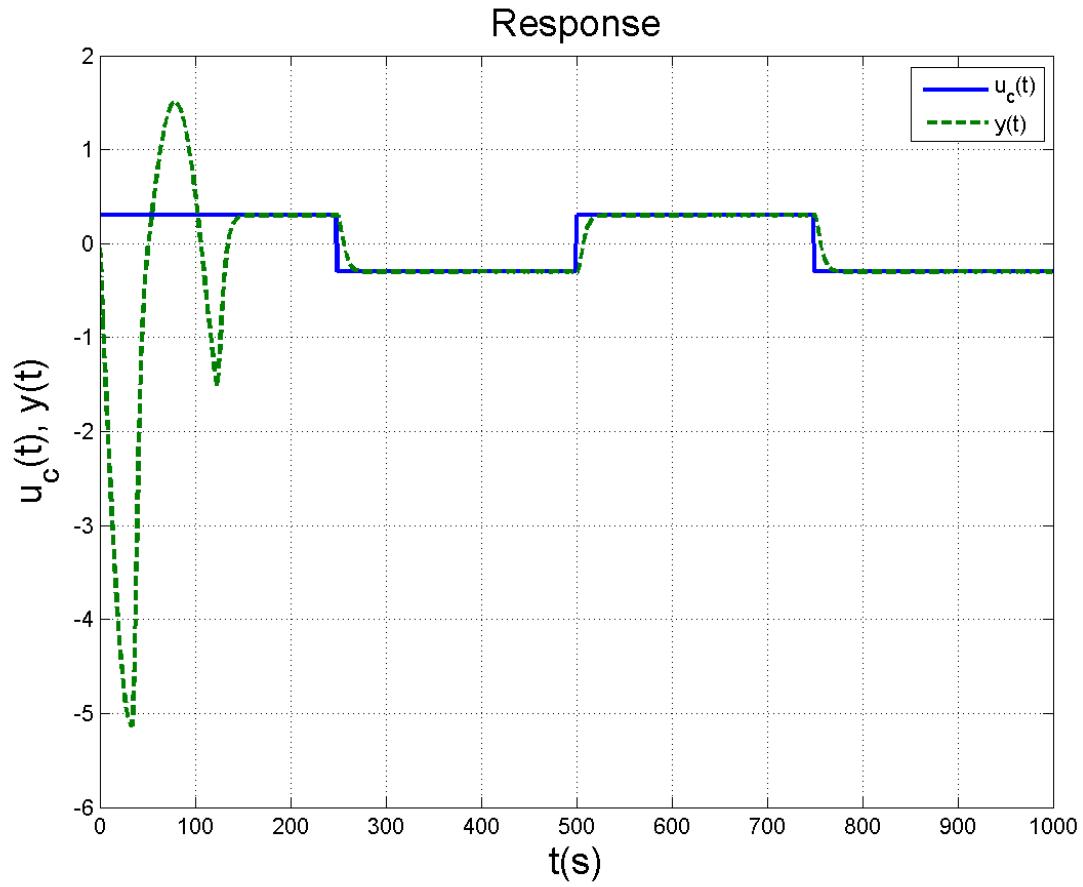




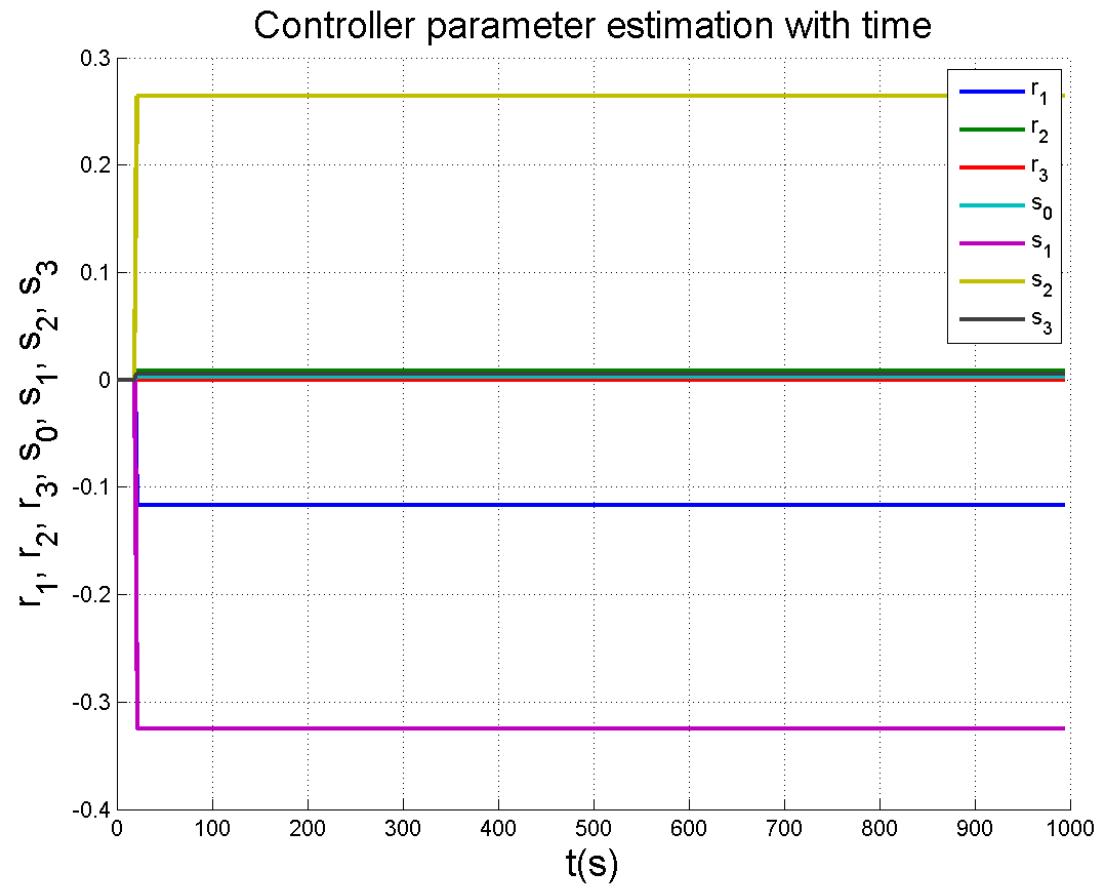
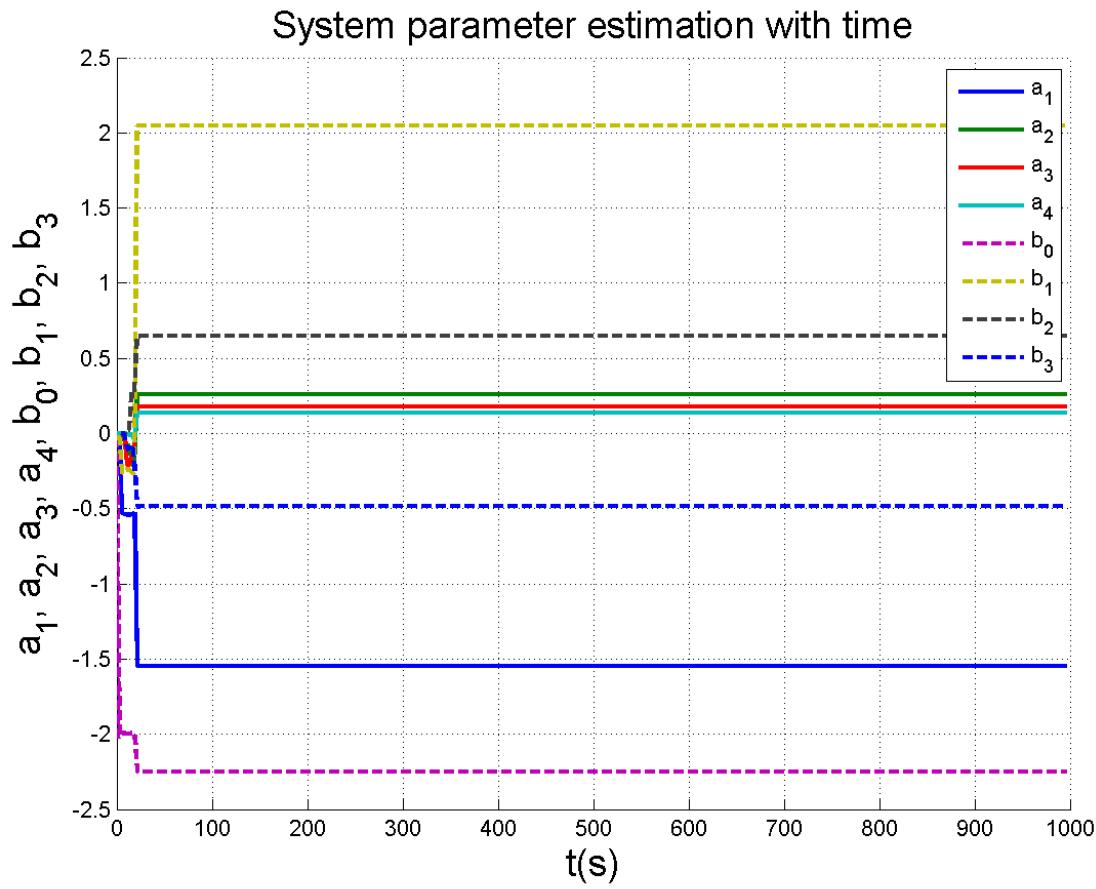
Flight Condition 3

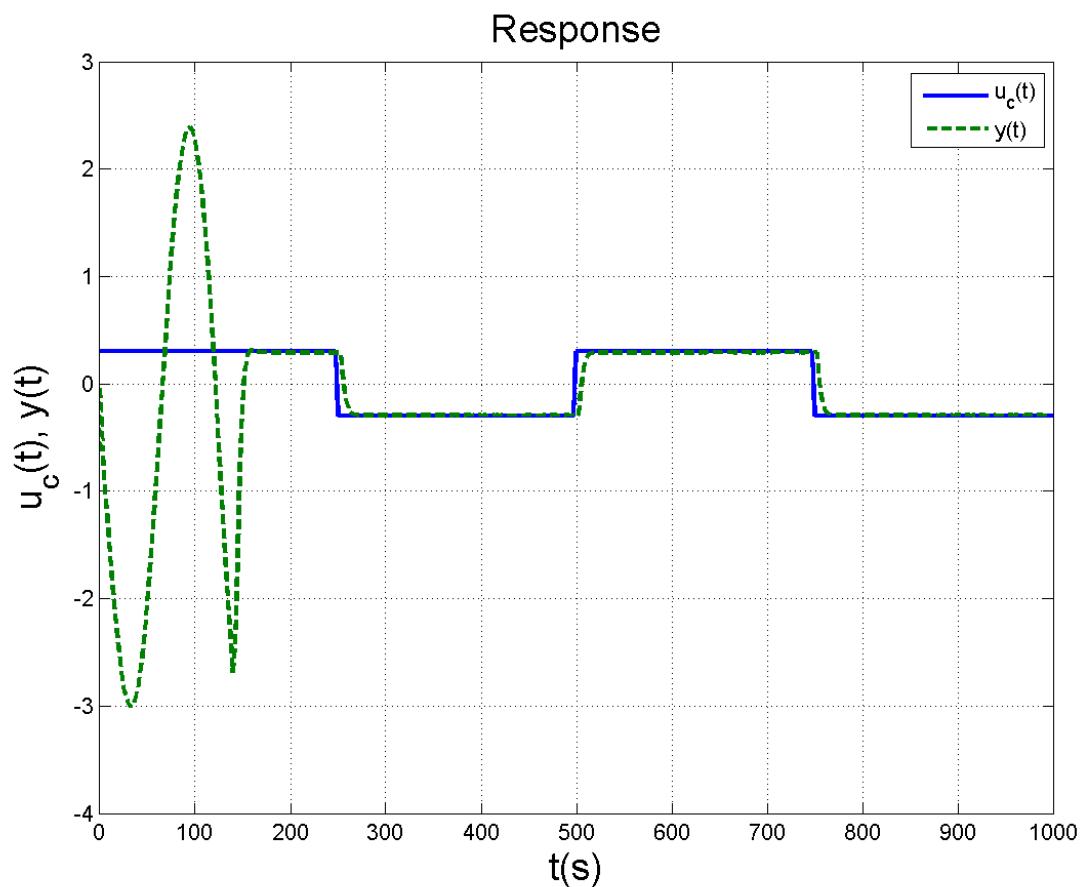
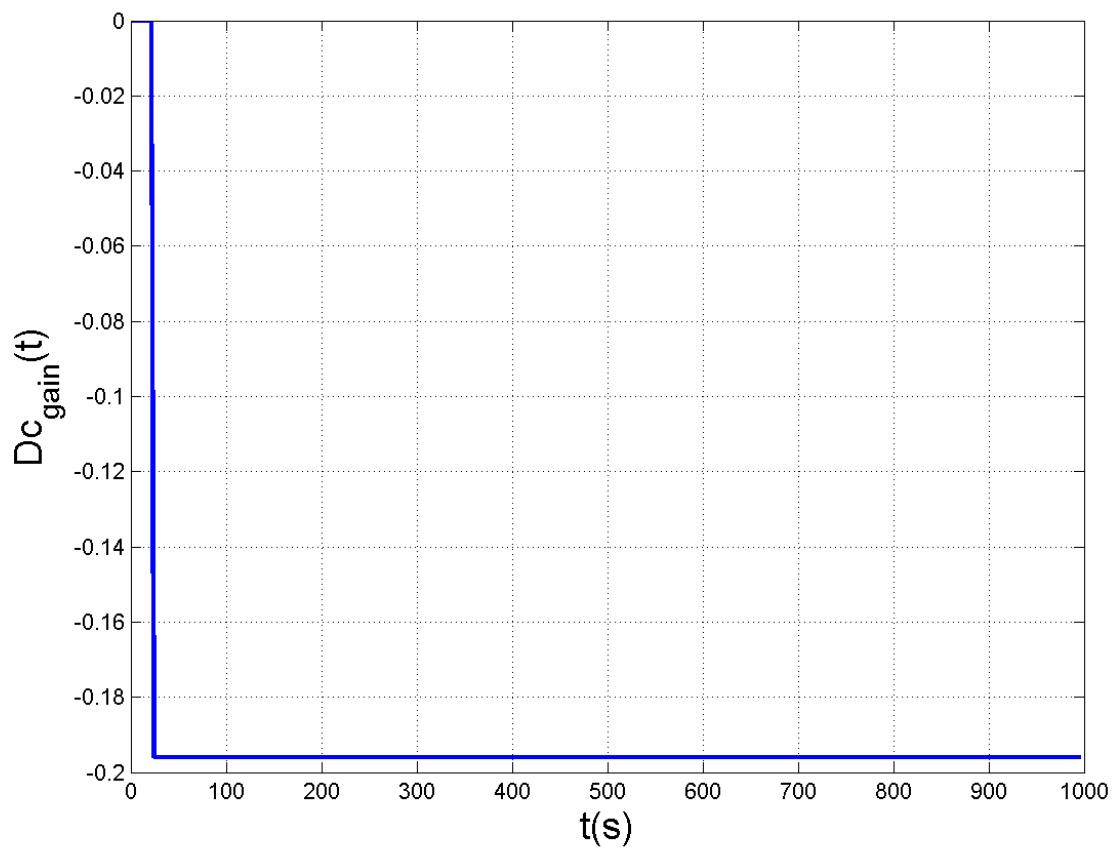


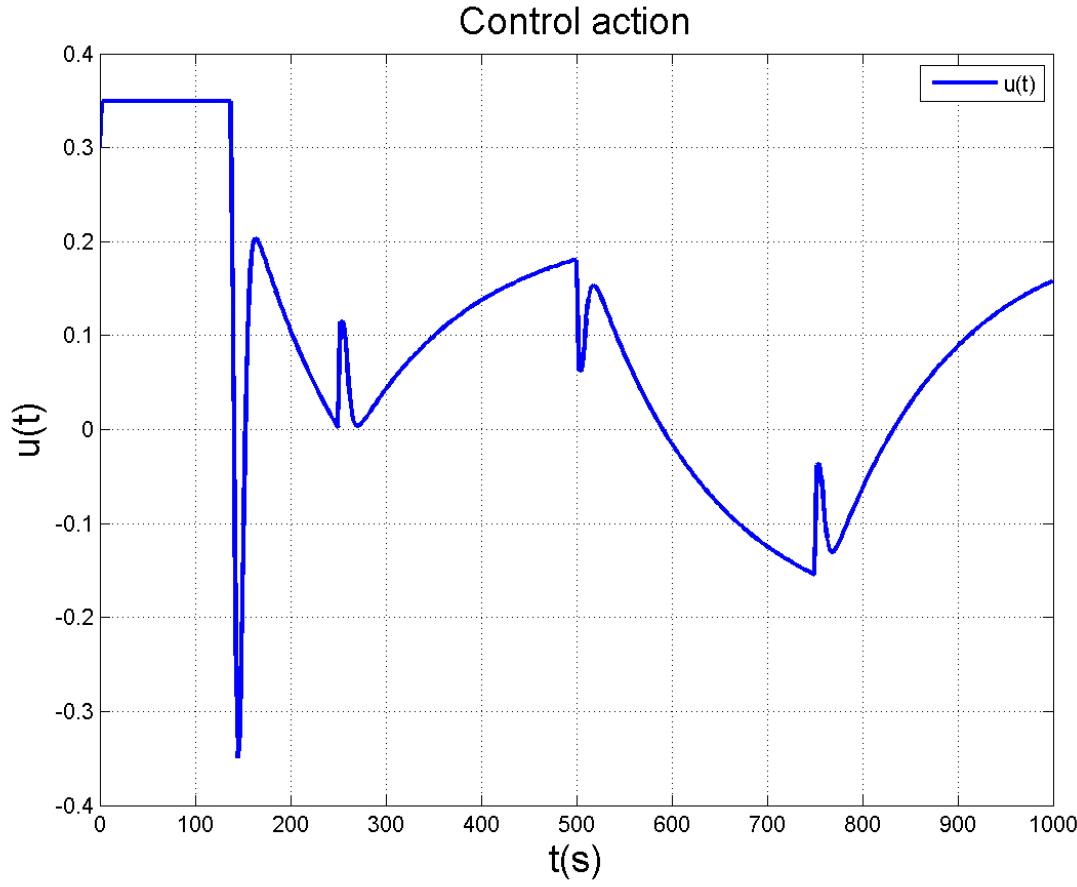




Flight Condition 4



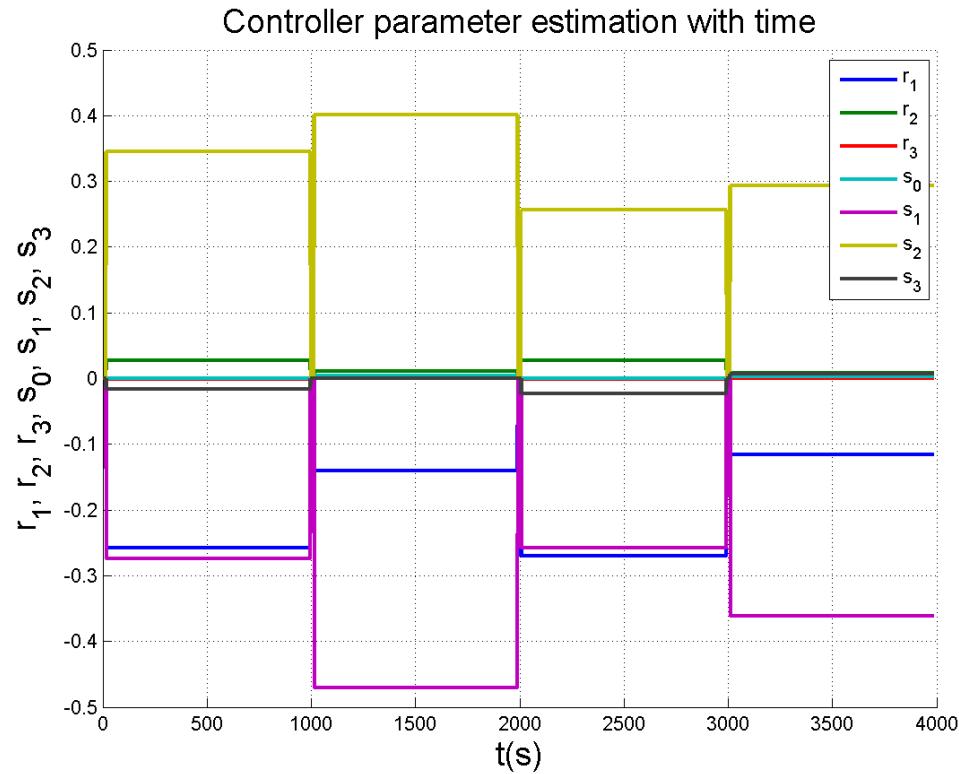
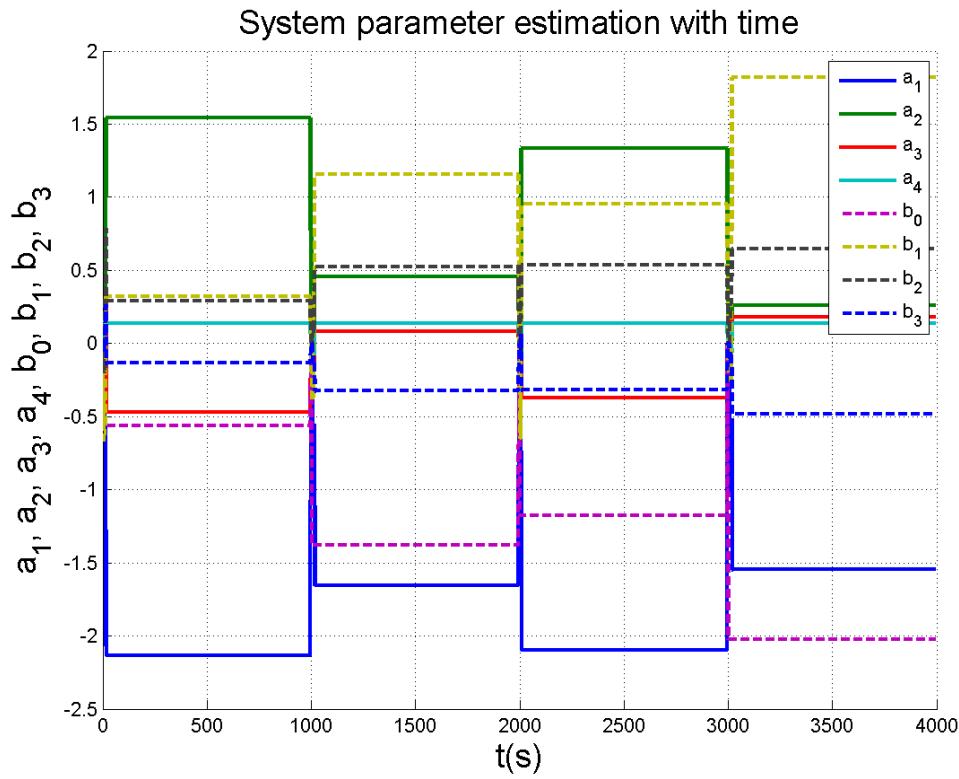


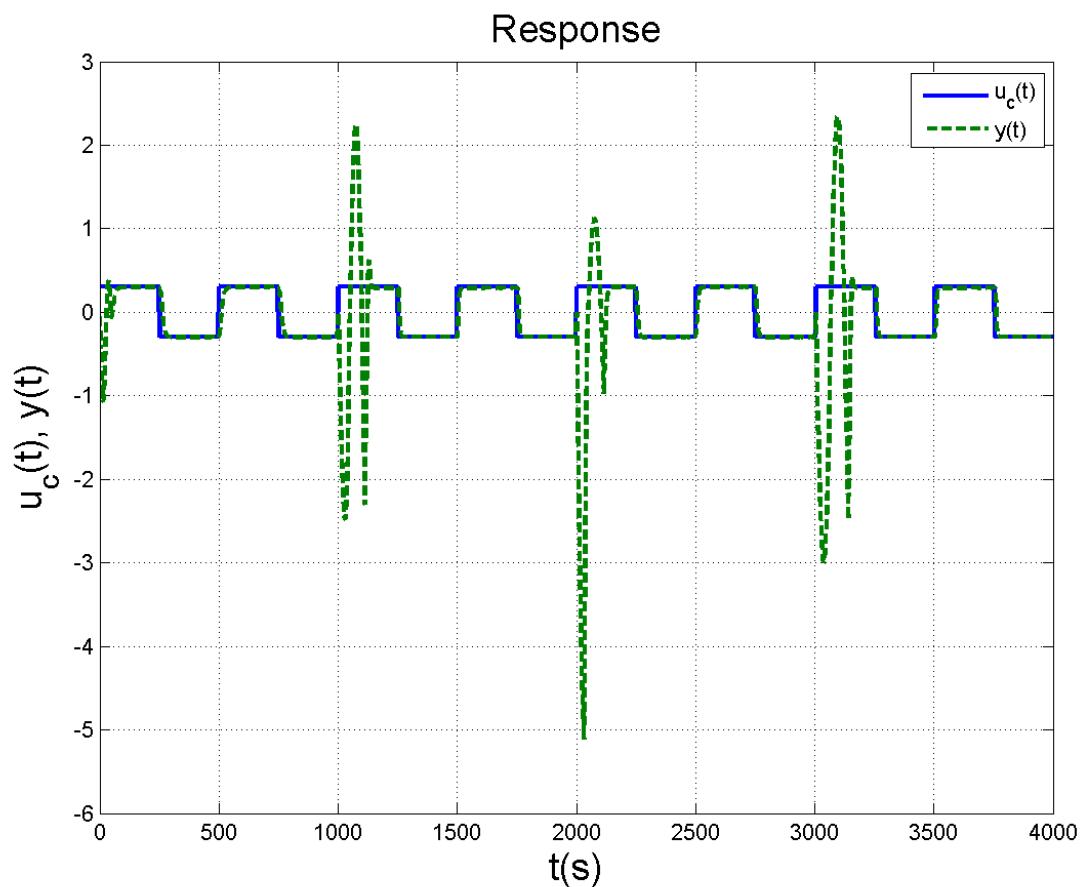
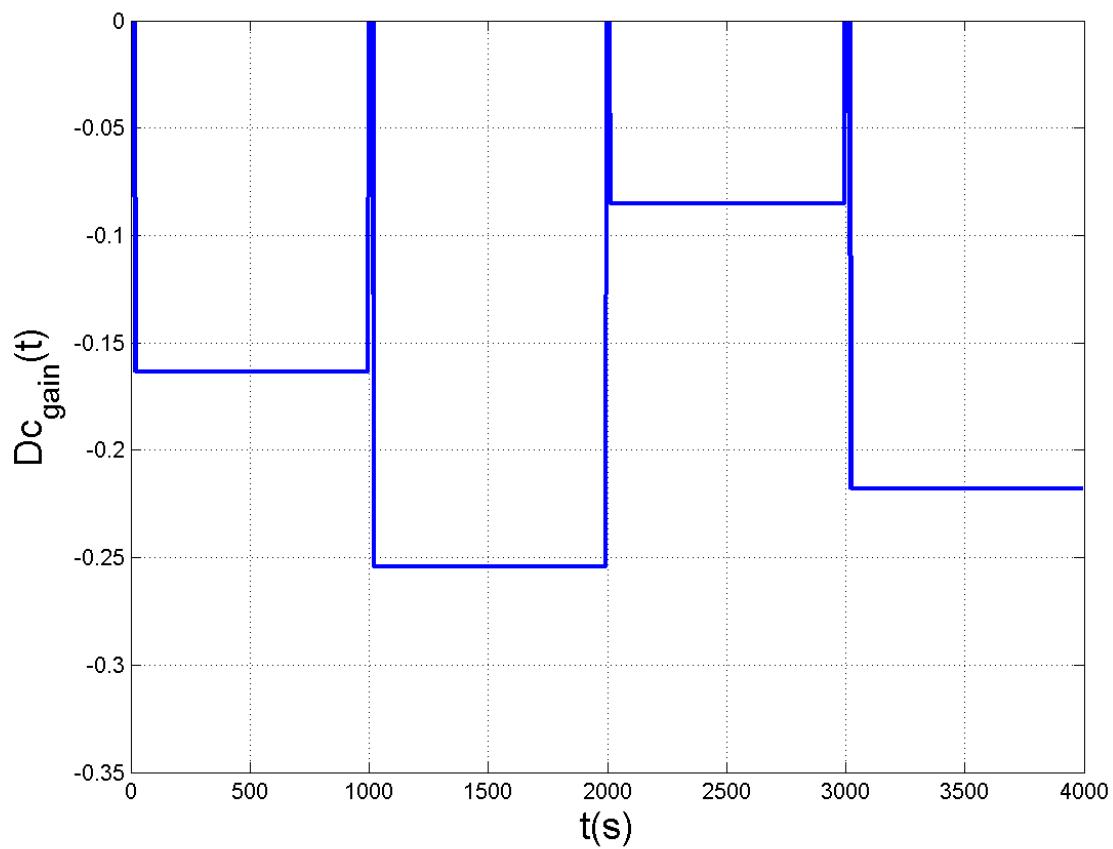


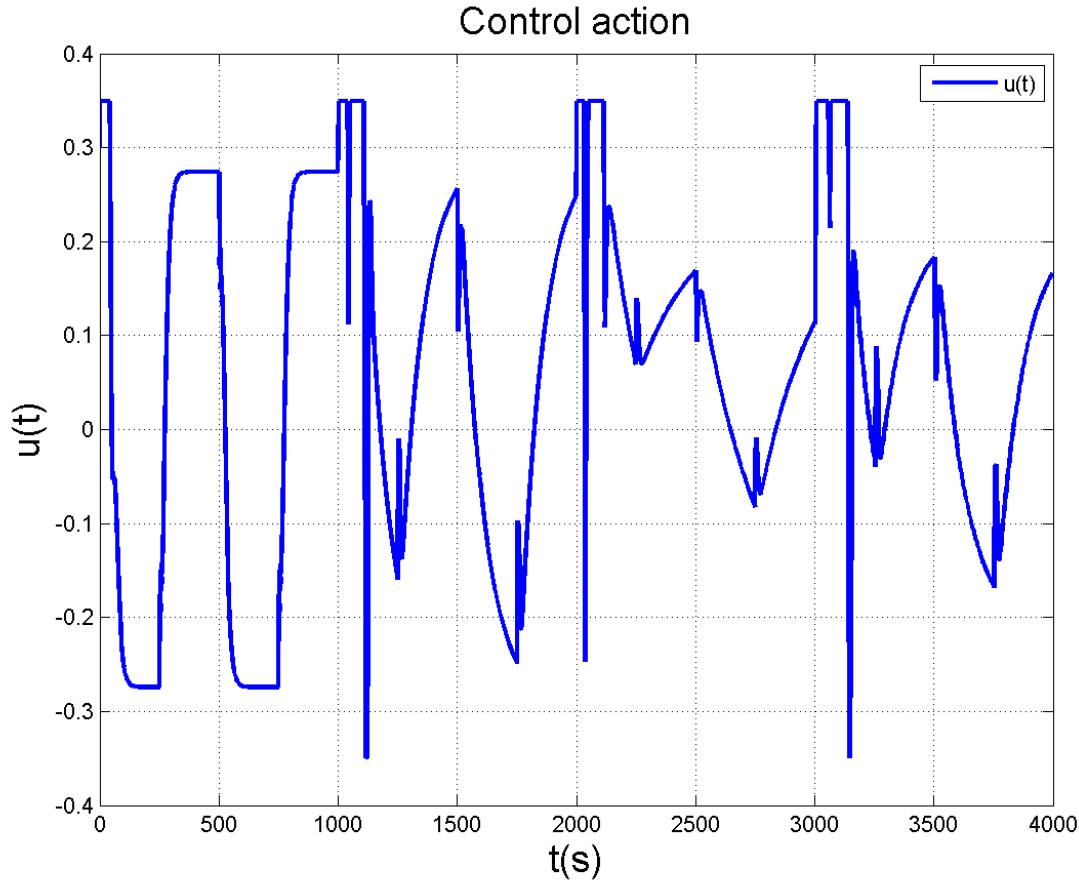
Results

Flight Condition	$G(z)$ Estimated	Feed Back Controller
1	$G(z) = \frac{-0.6048z^3 + 0.3617z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$\frac{S}{R}(z) = \frac{0.0004084z^3 - 0.2561z^2 + 0.3219z - 0.01532}{z^6 - 0.8554z^5 - 0.2986z^4 + 0.3272z^3 - 0.06942z^2 + 0.006605z - 0.0002478}$
2	$G(z) = \frac{-1.522z^3 + 1.297z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$\frac{S}{R}(z) = \frac{0.003497z^3 - 0.4264z^2 + 0.3629z + 0.0004453}{z^6 - 0.9922z^5 - 0.2136z^4 + 0.2523z^3 - 0.03329z^2 + 0.002401z - 7.377e-05}$
3	$G(z) = \frac{-1.295z^3 + 1.073z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$\frac{S}{R}(z) = \frac{-0.0002227z^3 - 0.2338z^2 + 0.2329z - 0.02154}{z^6 - 1.098z^5 - 0.1631z^4 + 0.3352z^3 - 0.07726z^2 + 0.007264z - 0.0002702}$
4	$G(z) = \frac{-2.25z^3 + 2.049z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$\frac{S}{R}(z) = \frac{0.002652z^3 - 0.3252z^2 + 0.2639z + 0.005786}{z^6 - 1.027z^5 - 0.1732z^4 + 0.2411z^3 - 0.02727z^2 + 0.001878z - 5.577e-05}$
		Feed Forward Controller
		$\frac{T}{R}(z) = \frac{-0.1528z^5 + 0.1528z^4 - 0.06111z^3 + 0.01222z^2 - 0.001222z + 4.889e-05}{z^6 - 0.8554z^5 - 0.2986z^4 + 0.3272z^3 - 0.06942z^2 + 0.006605z - 0.0002478}$
		$\frac{T}{R}(z) = \frac{-0.23z^5 + 0.23z^4 - 0.09199z^3 + 0.0184z^2 - 0.00184z + 7.359e-05}{z^6 - 0.9922z^5 - 0.2136z^4 + 0.2523z^3 - 0.03329z^2 + 0.002401z - 7.377e-05}$
		$\frac{T}{R}(z) = \frac{-0.07758z^5 + 0.07758z^4 - 0.03103z^3 + 0.006207z^2 - 0.0006207z + 2.483e-05}{z^6 - 1.098z^5 - 0.1631z^4 + 0.3352z^3 - 0.07726z^2 + 0.007264z - 0.0002702}$
		$\frac{T}{R}(z) = \frac{-0.196z^5 + 0.196z^4 - 0.07839z^3 + 0.01568z^2 - 0.001568z + 6.271e-05}{z^6 - 1.027z^5 - 0.1732z^4 + 0.2411z^3 - 0.02727z^2 + 0.001878z - 5.577e-05}$

For All Flight Conditions Together







Results

Flight Condition	$G(z)$ Estimated	Feed Back Controller
1	$G(z) = \frac{-0.5646z^3 + 0.3215z^2 + 0.2903z - 0.1337}{z^4 - 2.134z^3 + 1.545z^2 - 0.4692z + 0.1383}$	$\frac{S}{R}(z) = \frac{0.0004375z^3 - 0.2744z^2 + 0.3449z - 0.01641}{z^6 - 0.8268z^5 - 0.3402z^4 + 0.3525z^3 - 0.07444z^2 + 0.007075z - 0.0002655}$
2	$G(z) = \frac{-1.378z^3 + 1.153z^2 + 0.5229z - 0.3252}{z^4 - 1.655z^3 + 0.4588z^2 + 0.08454z + 0.139}$	$\frac{S}{R}(z) = \frac{0.003863z^3 - 0.471z^2 + 0.4008z + 0.0004919}{z^6 - 0.9768z^5 - 0.2517z^4 + 0.2799z^3 - 0.03681z^2 + 0.002652z - 8.148e-05}$
3	$G(z) = \frac{-1.176z^3 + 0.9539z^2 + 0.5366z - 0.3203}{z^4 - 2.095z^3 + 1.334z^2 - 0.3708z + 0.1364}$	$\frac{S}{R}(z) = \frac{-0.0002452z^3 - 0.2575z^2 + 0.2565z - 0.02372}{z^6 - 1.081z^5 - 0.2098z^4 + 0.3721z^3 - 0.08521z^2 + 0.008z - 0.0002975}$
4	$G(z) = \frac{-2.023z^3 + 1.822z^2 + 0.6474z - 0.4849}{z^4 - 1.548z^3 + 0.2606z^2 + 0.1785z + 0.1372}$	$\frac{S}{R}(z) = \frac{0.002951z^3 - 0.3618z^2 + 0.2936z + 0.006437}{z^6 - 1.017z^5 - 0.2068z^4 + 0.2692z^3 - 0.03037z^2 + 0.002089z - 6.205e-05}$
		Feed Forward Controller
		$\frac{T}{R}(z) = \frac{-0.1637z^5 + 0.1637z^4 - 0.06546z^3 + 0.01309z^2 - 0.001309z + 5.237e-05}{z^6 - 0.8268z^5 - 0.3402z^4 + 0.3525z^3 - 0.07444z^2 + 0.007075z - 0.0002655}$
		$\frac{T}{R}(z) = \frac{-0.254z^5 + 0.254z^4 - 0.1016z^3 + 0.02032z^2 - 0.002032z + 8.129e-05}{z^6 - 0.9768z^5 - 0.2517z^4 + 0.2799z^3 - 0.03681z^2 + 0.002652z - 8.148e-05}$
		$\frac{T}{R}(z) = \frac{-0.08545z^5 + 0.08545z^4 - 0.03418z^3 + 0.006836z^2 - 0.0006836z + 2.734e-05}{z^6 - 1.081z^5 - 0.2098z^4 + 0.3721z^3 - 0.08521z^2 + 0.008z - 0.0002975}$
		$\frac{T}{R}(z) = \frac{-0.218z^5 + 0.218z^4 - 0.08721z^3 + 0.01744z^2 - 0.001744z + 6.977e-05}{z^6 - 1.017z^5 - 0.2068z^4 + 0.2692z^3 - 0.03037z^2 + 0.002089z - 6.205e-05}$

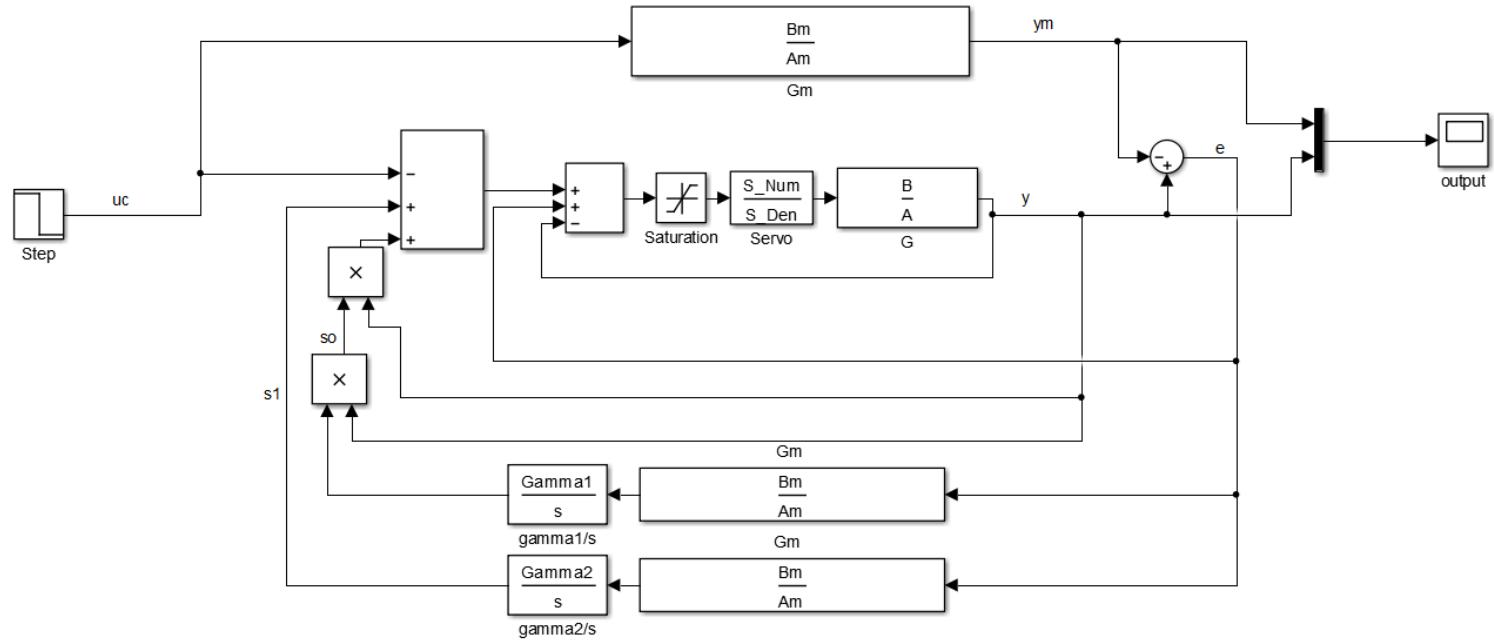
Comments

- The system parameter goes to its true values if i control all flight conditions together.
- There is a change in controller parameter between the controller of all flight conditions and the controller of each flight condition.

1.7 Model Reference Adaptive Systems By MIT Rule

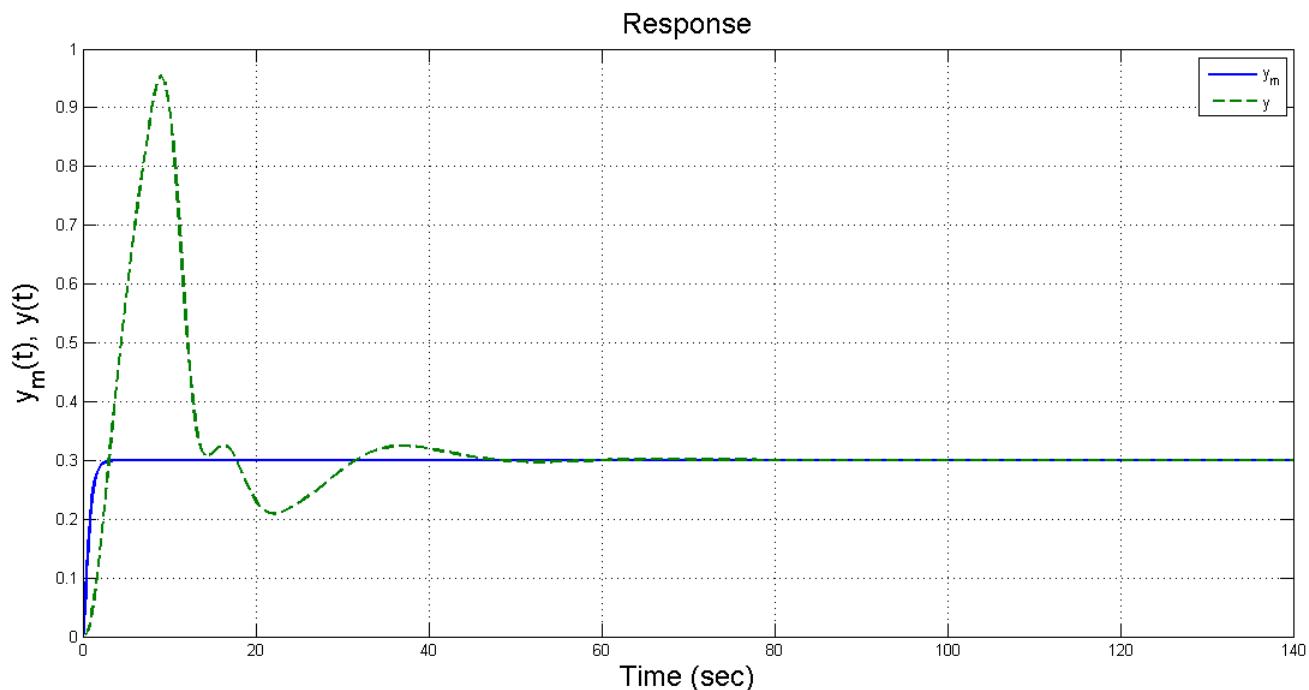
Because of the instability of the A/C I can't design the controller by using MIT rule, but I modify it and use the following scheme, which discussed in the previous report.

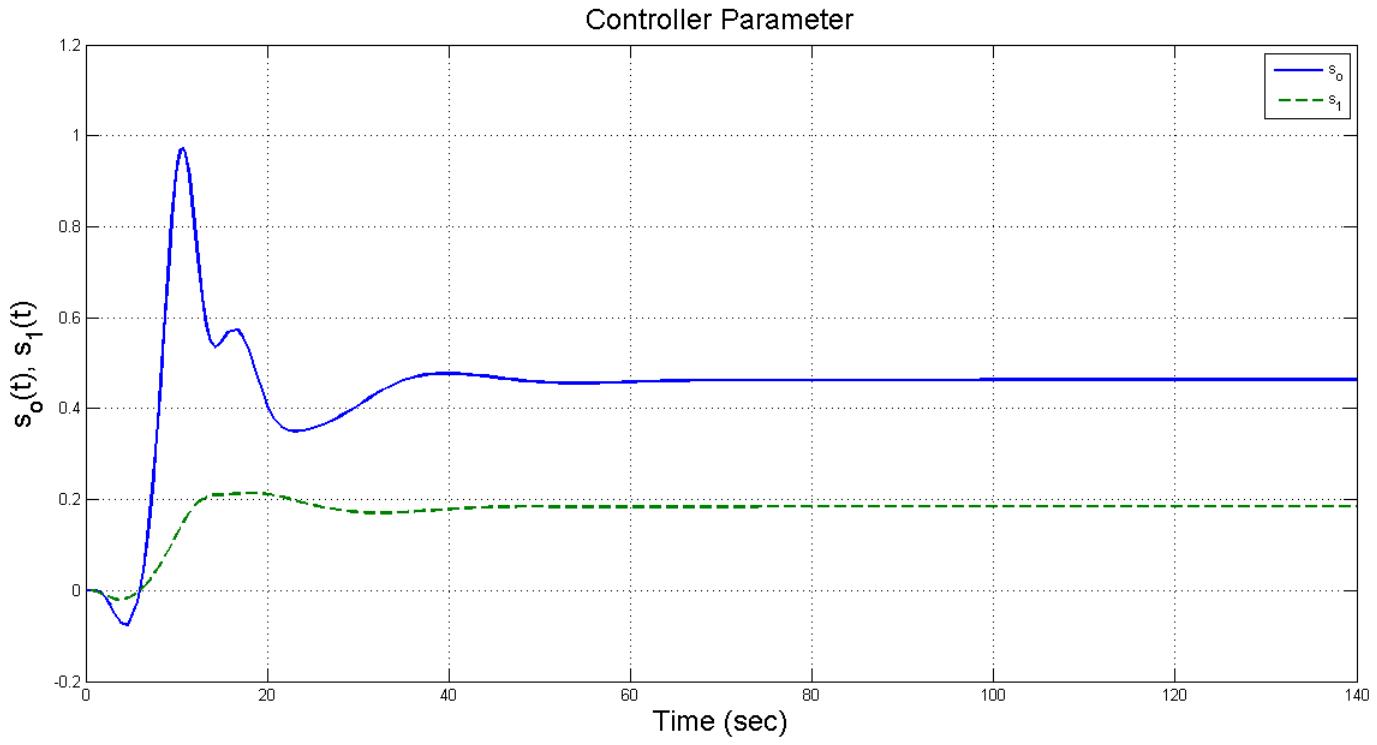
1.7.1 Controller Scheme



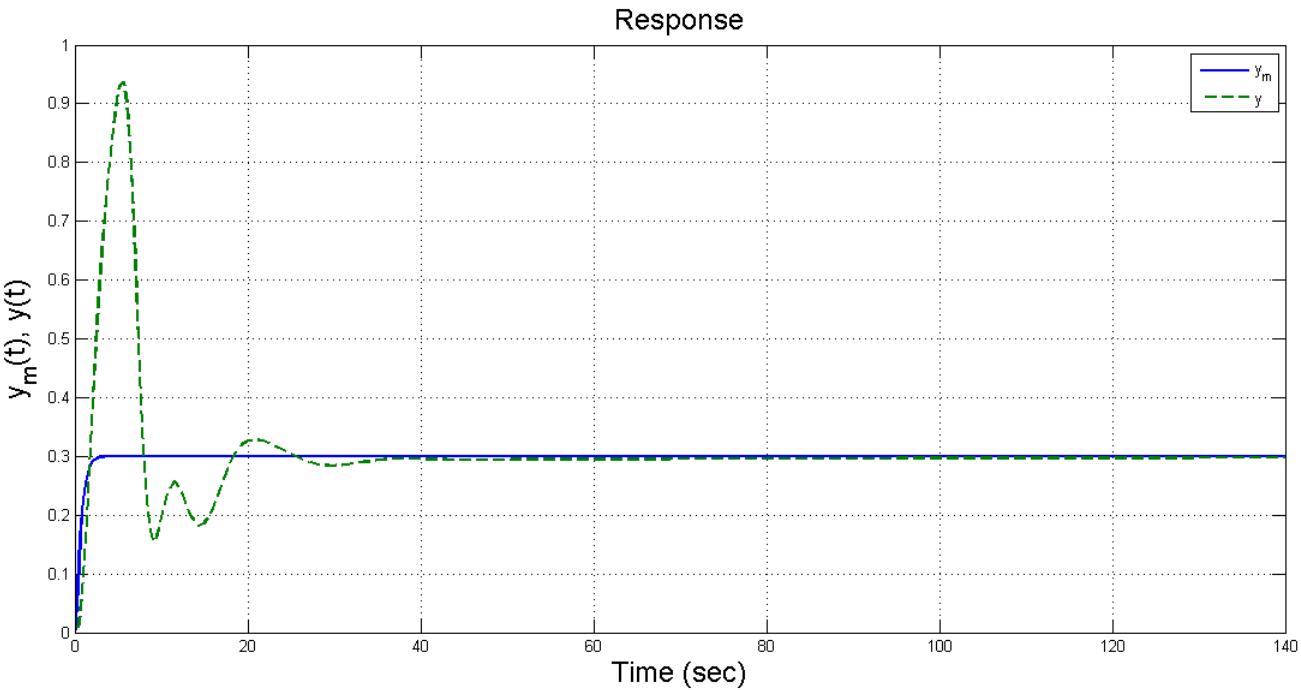
$$G_m(s) = \frac{8}{s^2 + 6s + 8}, \quad G_{servo} = \frac{4}{s + 4}$$

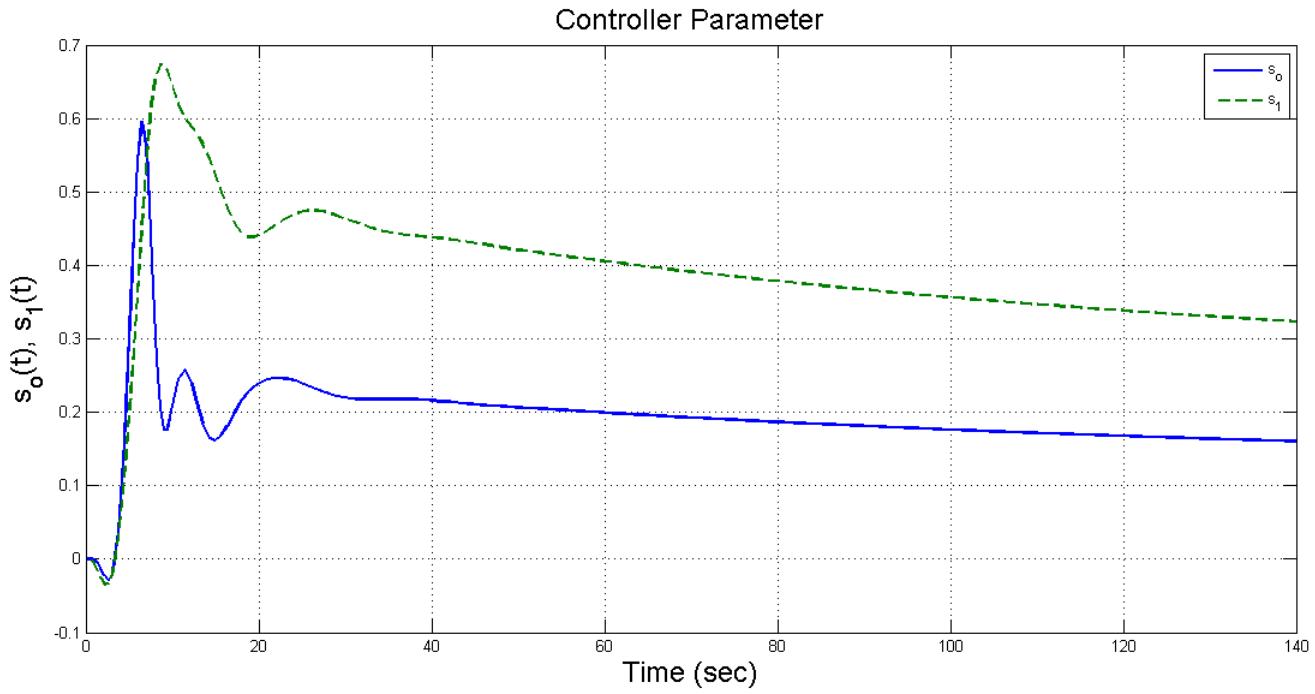
1.7.2 Flight Condition 1



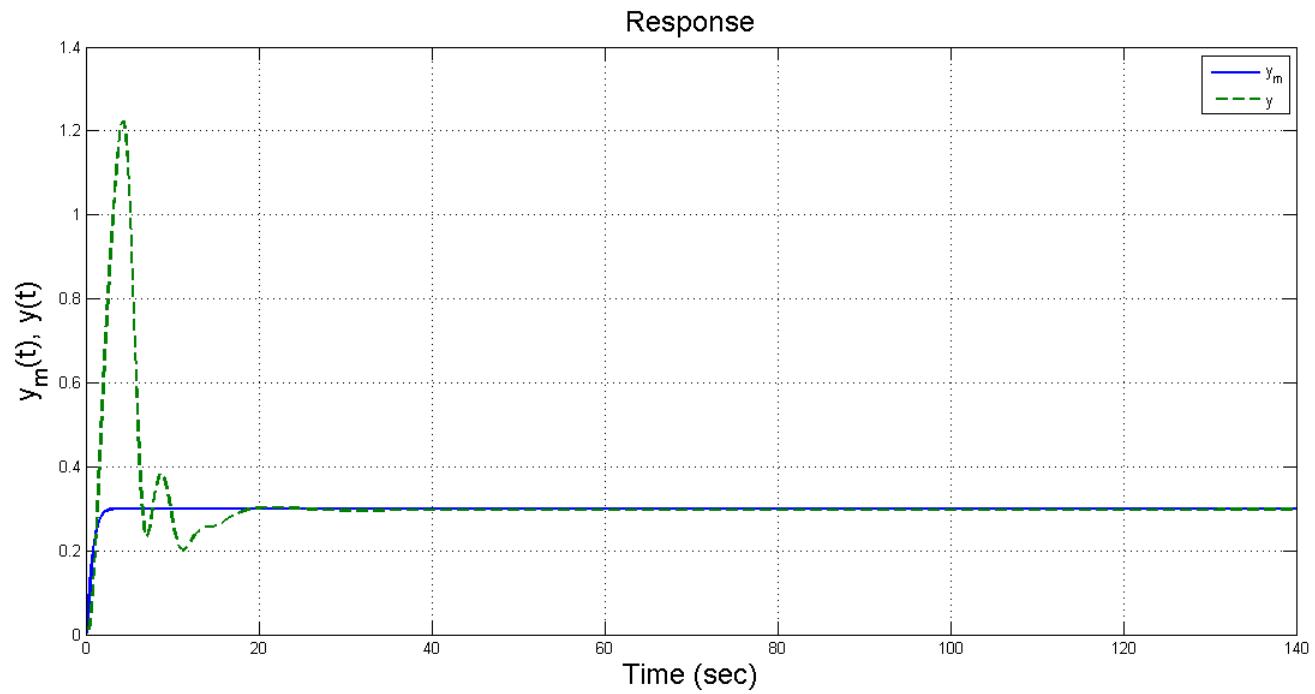


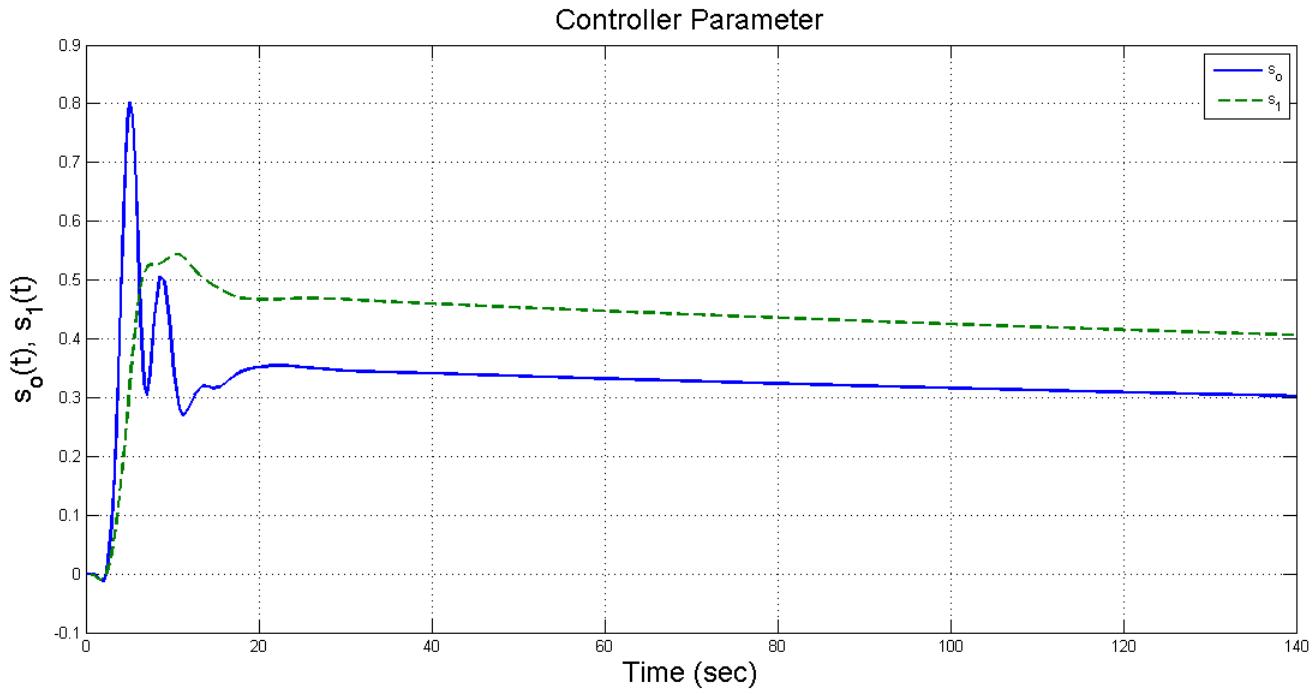
1.7.3 Flight Condition 2



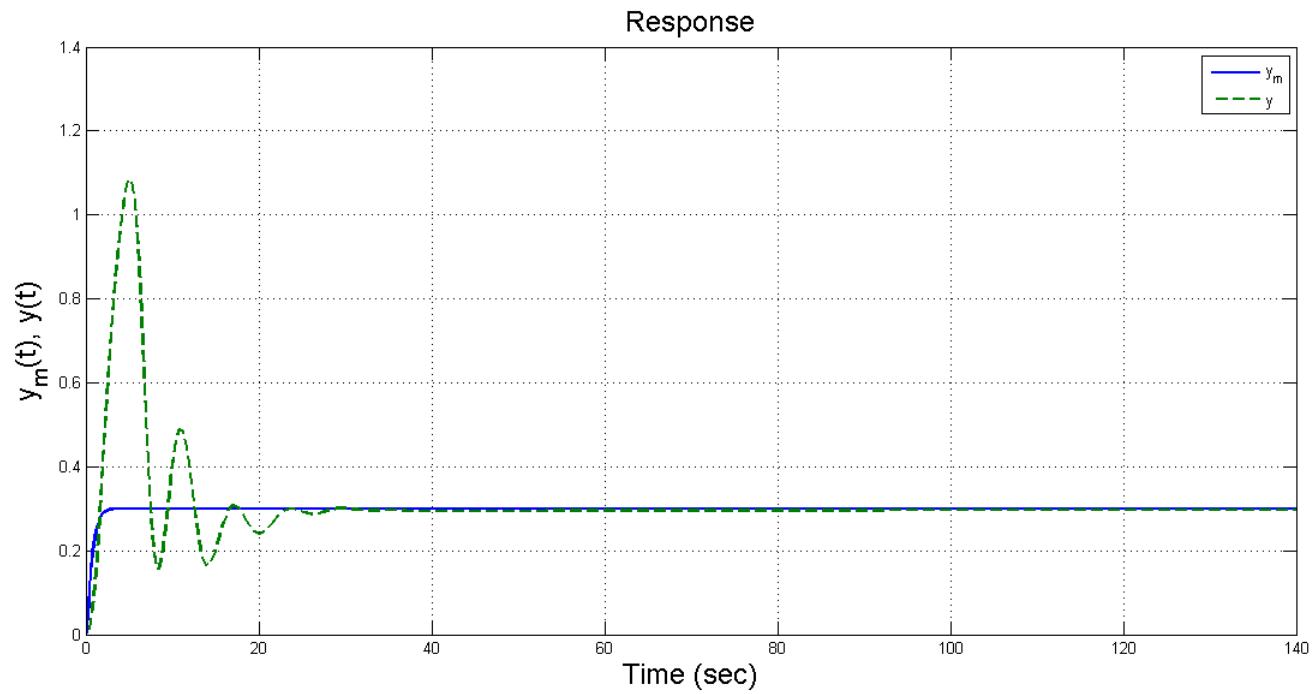


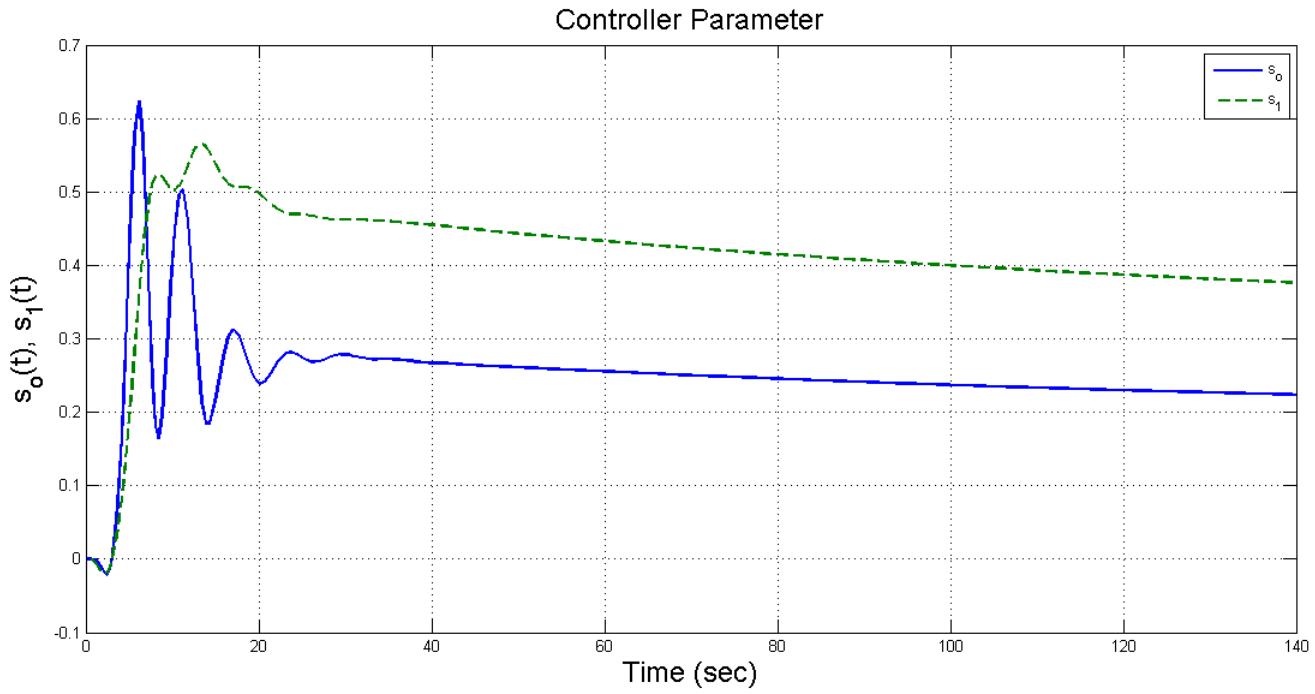
1.7.4 Flight Condition 3





1.7.5 Flight Condition 4





1.7.6 Results

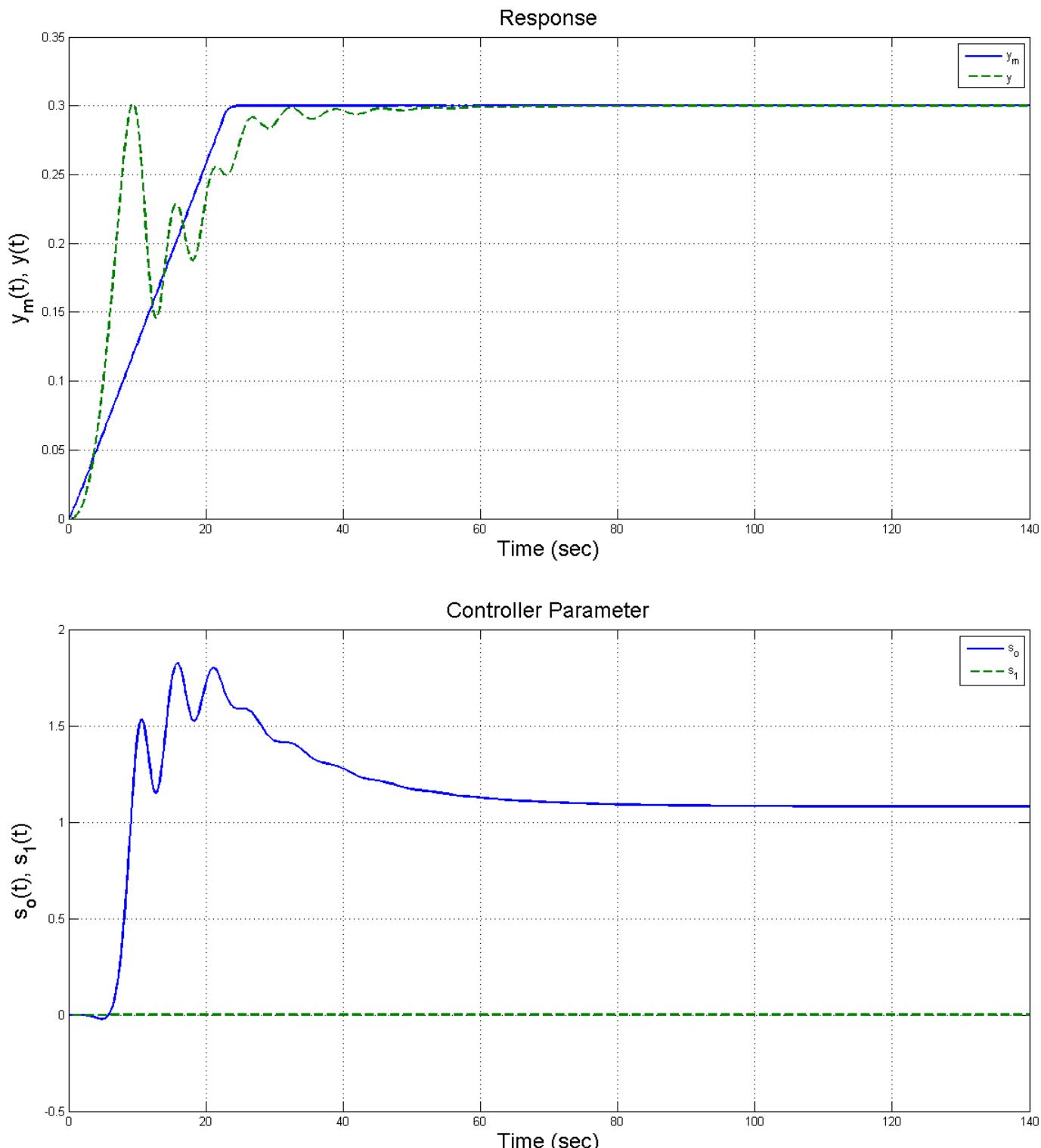
Flight Condition	γ_1	γ_2
1	0.5	0.06
2	0.5	0.3
3	0.5	0.2
4	0.4	0.2

1.7.7 Comments

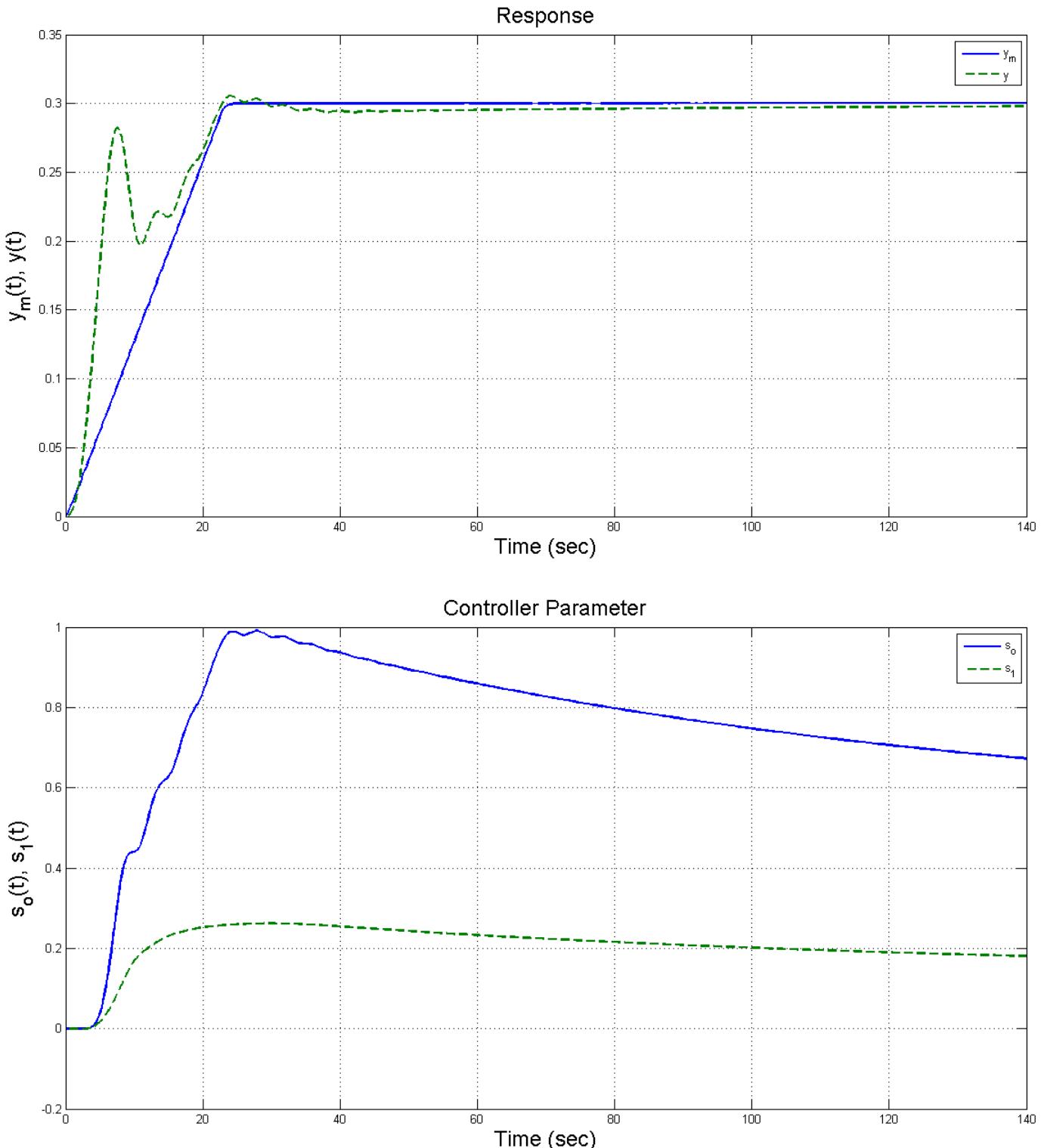
- It seems that A/C flight conditions are stable for step input with very high over shoot
- A/C flight conditions are unstable for small value of step input
- A/C flight conditions are unstable for square input

To overcome this very high over shoot I make the step input as a combination of ramp input to 23 sec and the step input will affect after then, so I get,

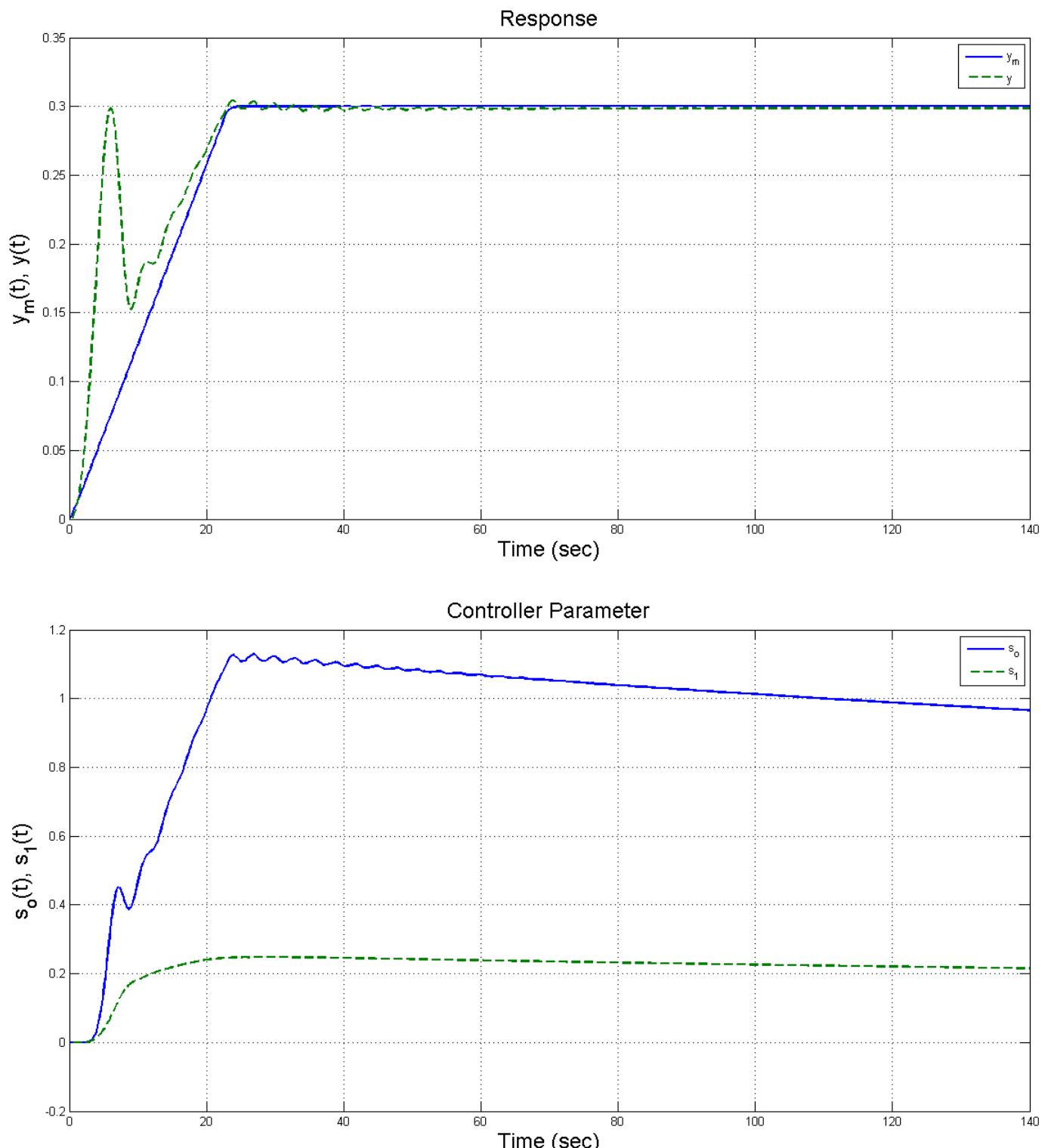
1.7.8 Flight Condition 1



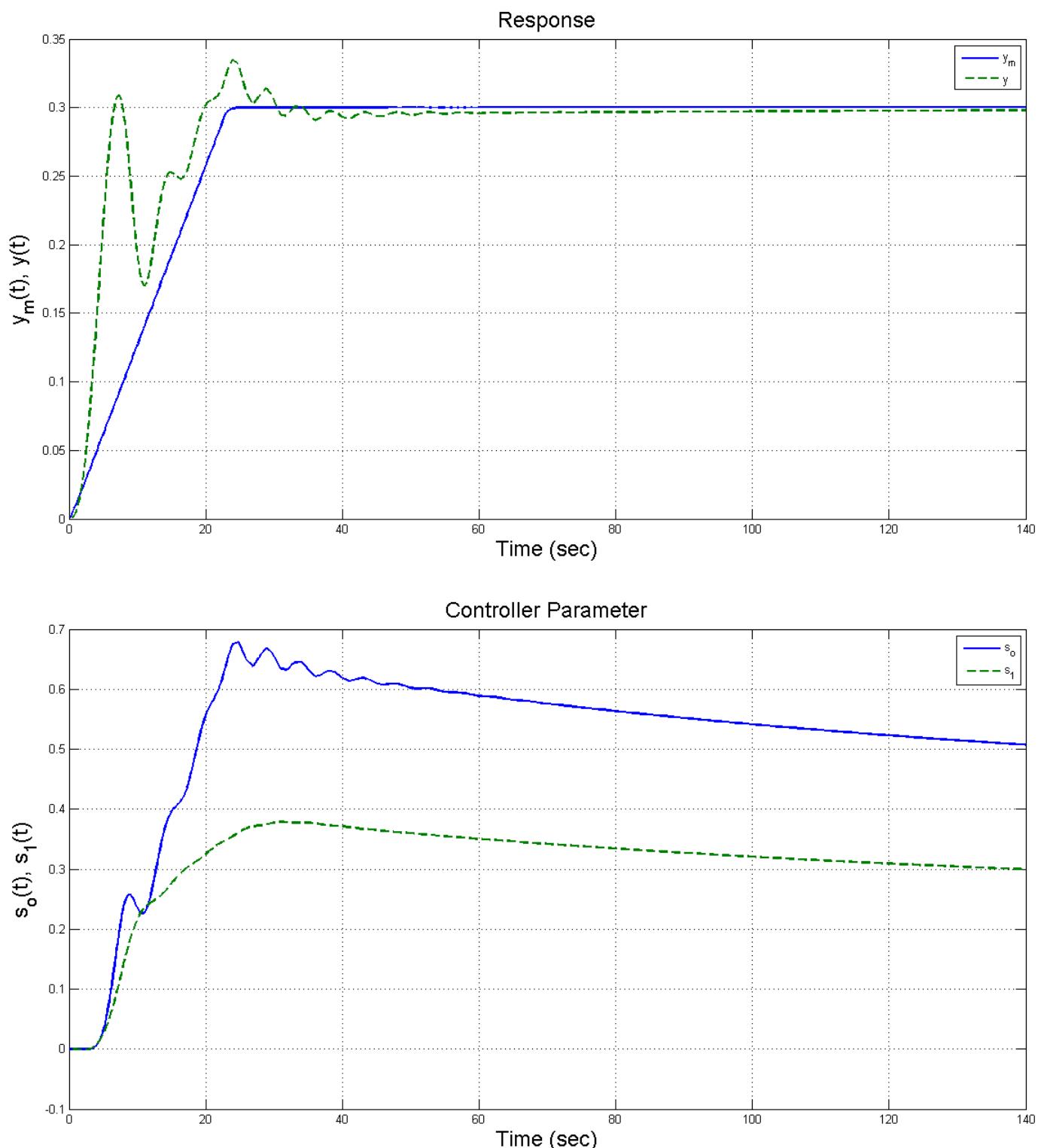
1.7.9 Flight Condition 2



1.7.10 Flight Condition 3



1.7.11 Flight Condition 4



1.7.12 Results

Flight Condition	γ_1	γ_2
1	10	0.001
2	2.5	0.2
3	3	0.2
4	1.25	0.22

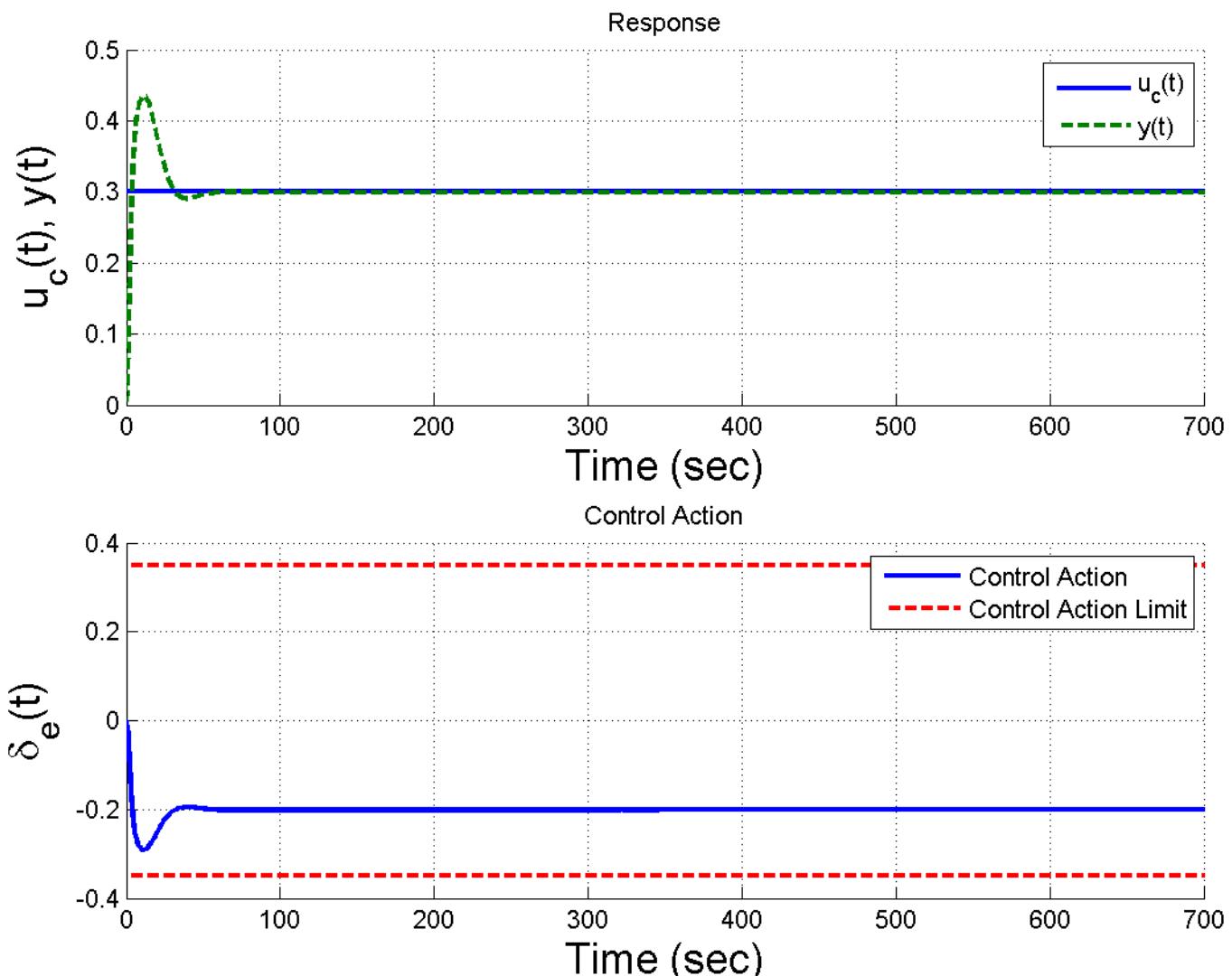
1.7.13 Comments

- The system doesn't flow the ramp input, but over shoot decreases
- The system flow the model in the step input region with small e_{ss}

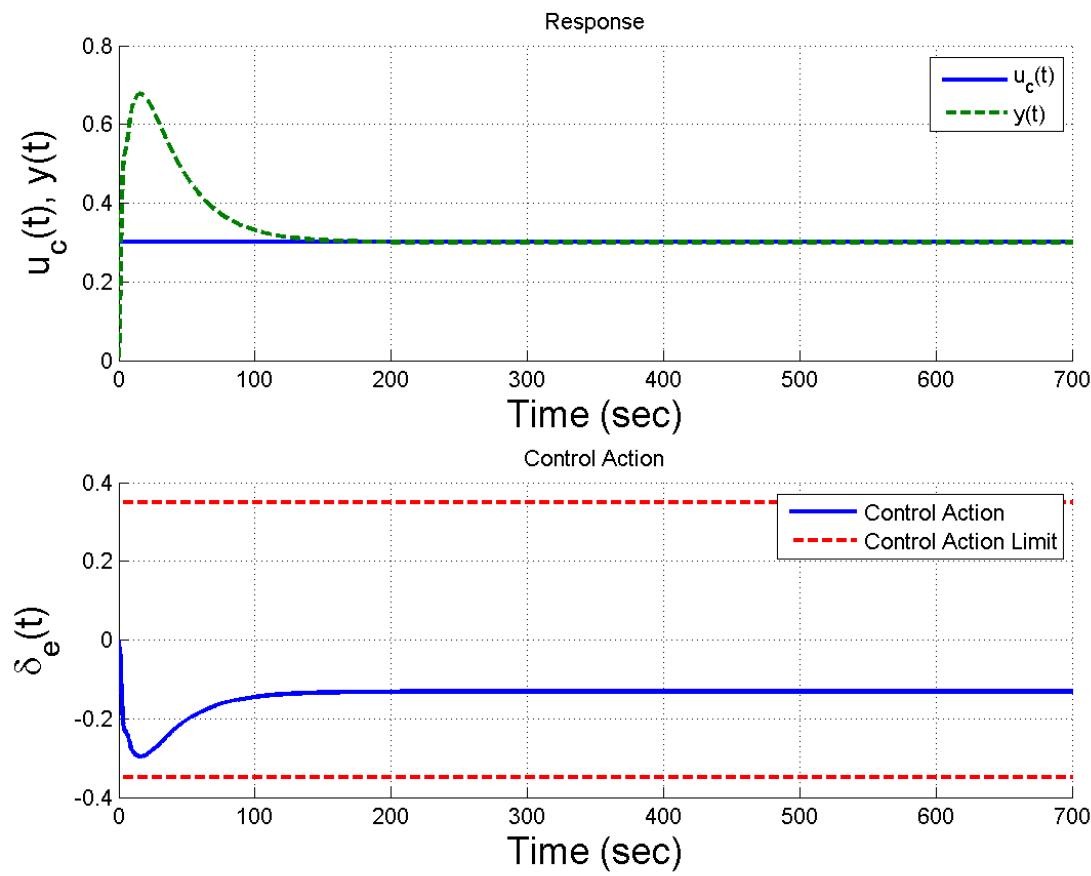
1.8 LQR For Step Input

I designed optimal controller for all flight conditions of A/C using LQR method and get these results

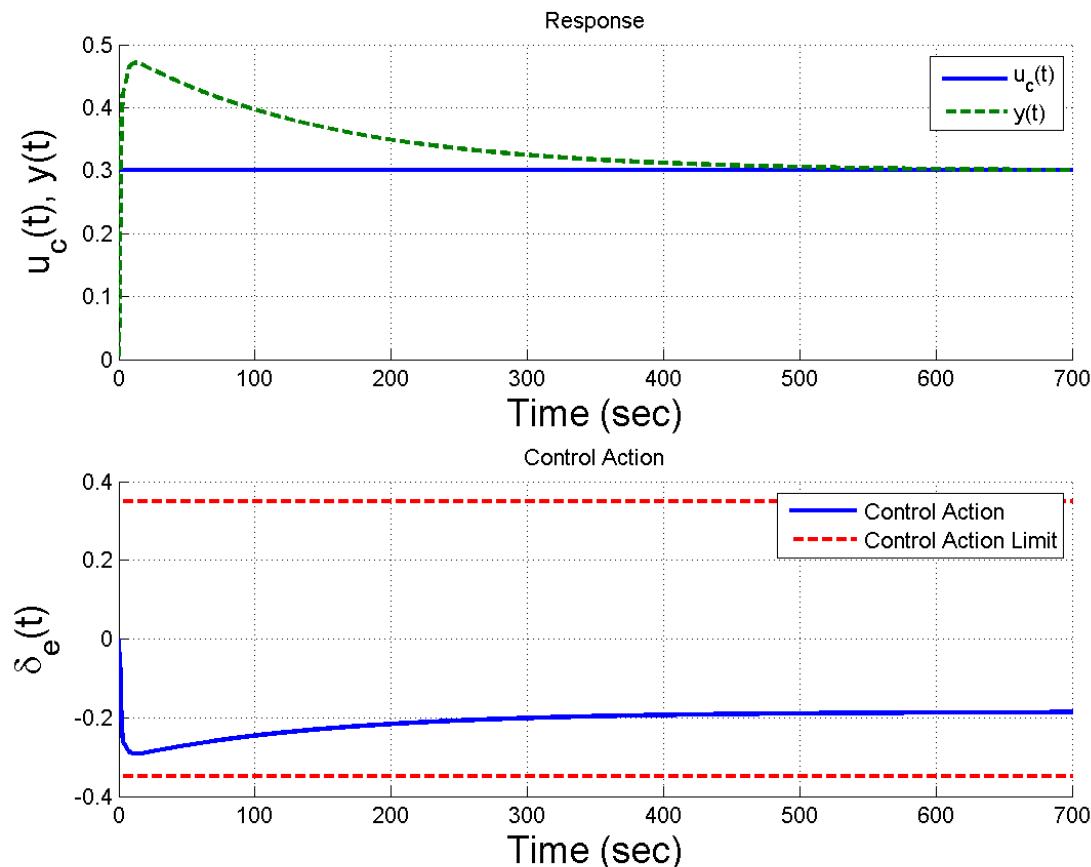
1.8.1 Flight Condition 1



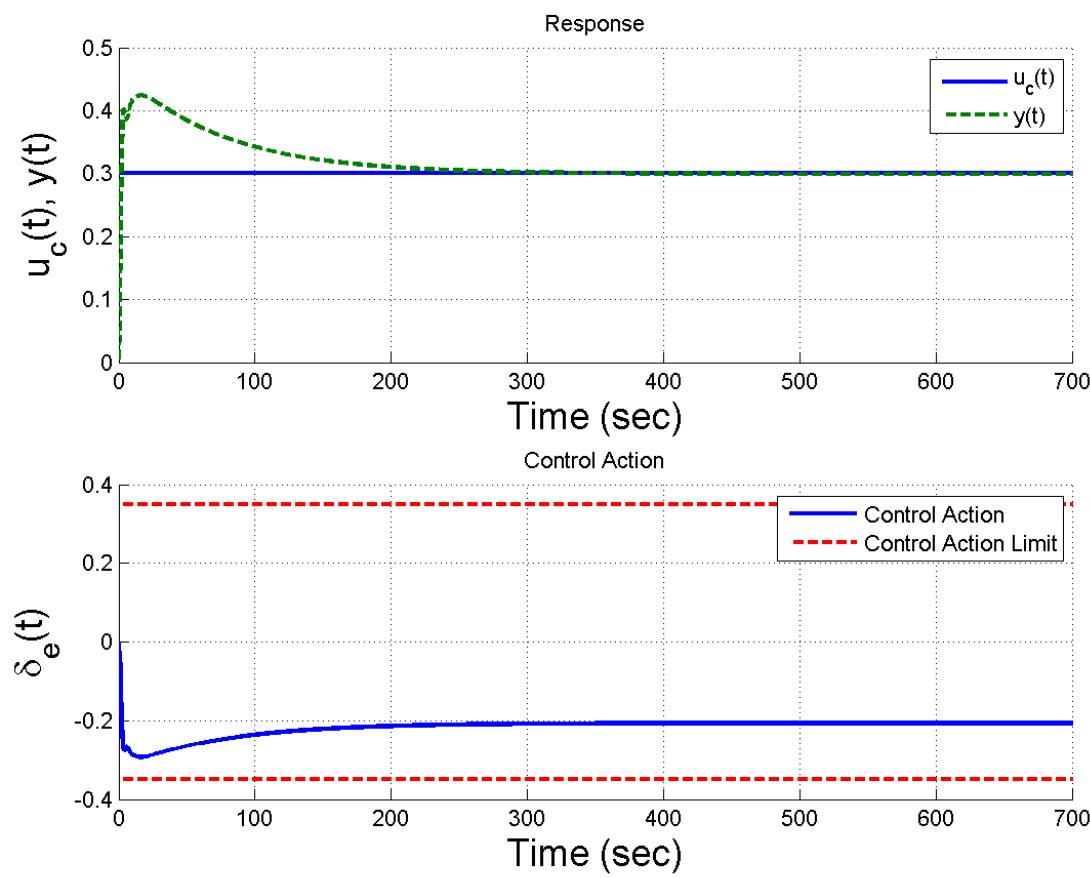
1.8.2 Flight Condition 2



1.8.3 Flight Condition 3



1.8.4 Flight Condition 4



1.8.5 Results

Flight Condition	Q	R	DC_{gain}	K
1	$Q = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3.4907 \end{bmatrix}$	$R = 8.2070$	1.1241	$\begin{bmatrix} -0.0013 \\ 0.0048 \\ -0.6648 \\ -0.6703 \end{bmatrix}$
2	$Q = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 6.9813 \end{bmatrix}$	$R = 39.7946$	1.0998	$\begin{bmatrix} -3.785e-05 \\ 0.001847 \\ -0.2416 \\ -0.4376 \end{bmatrix}$
3	$Q = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3.1416 \end{bmatrix}$	$R = 8.2070$	0.9925	$\begin{bmatrix} -7.5931e-06 \\ 0.0012 \\ -0.3054 \\ -0.6192 \end{bmatrix}$
4	$Q = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3.8397 \end{bmatrix}$	$R = 8.2070$	1.0093	$\begin{bmatrix} -4.2584e-05 \\ 0.0014 \\ -0.4742 \\ -0.6886 \end{bmatrix}$

Where the control action : $u = -Kx$

NOTE:

The code will be sent to your mail.