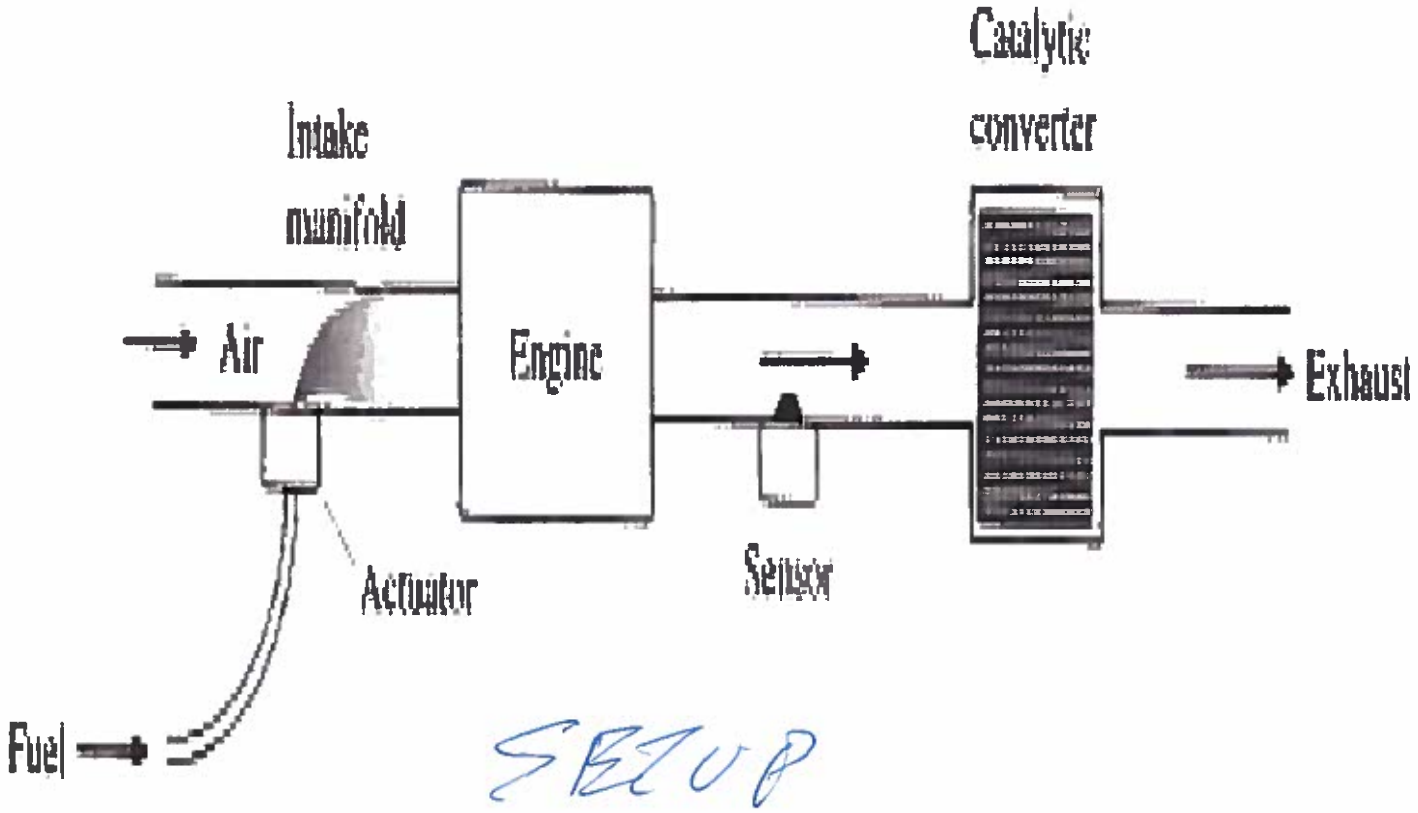
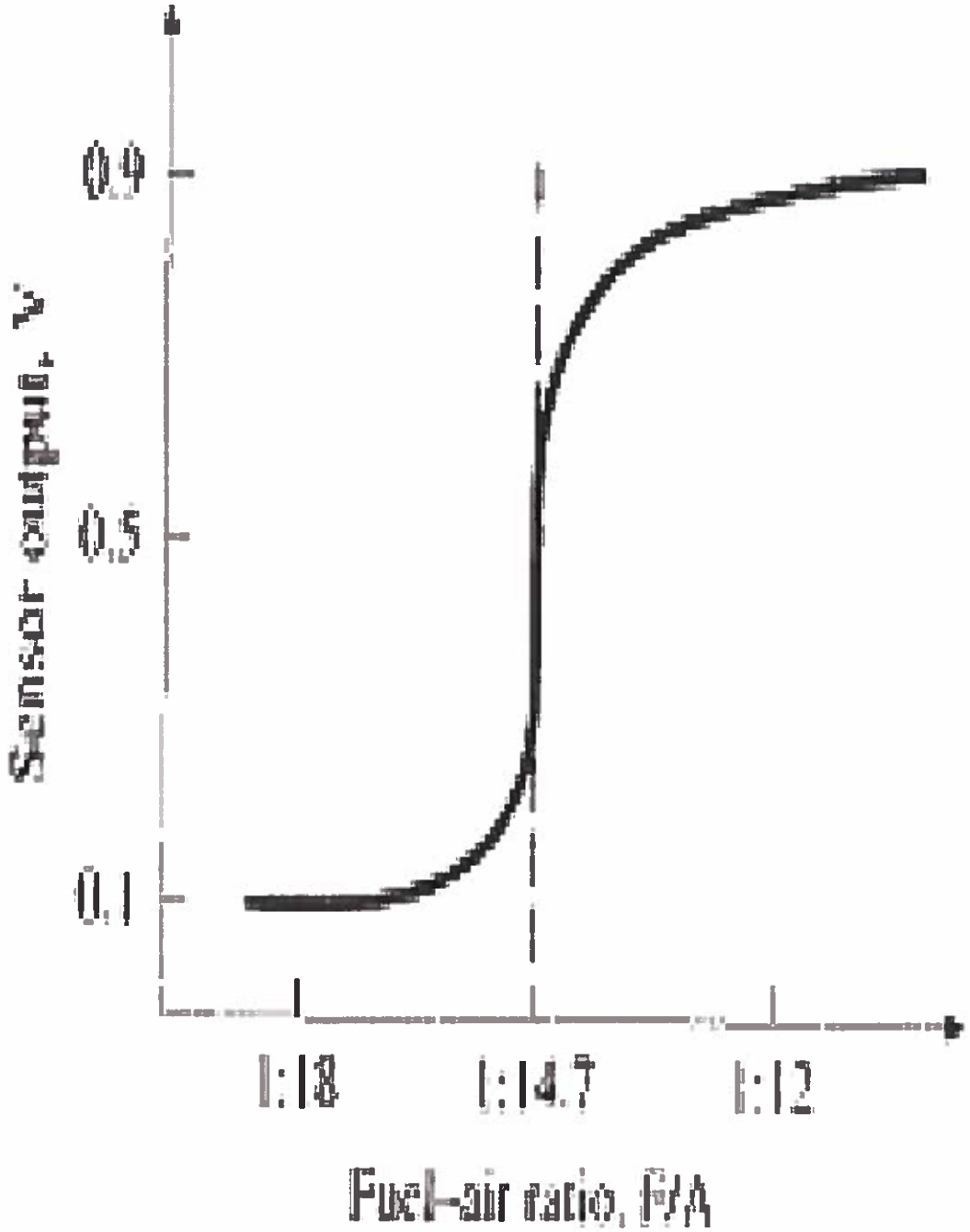
CONTROLS CASE STUDY

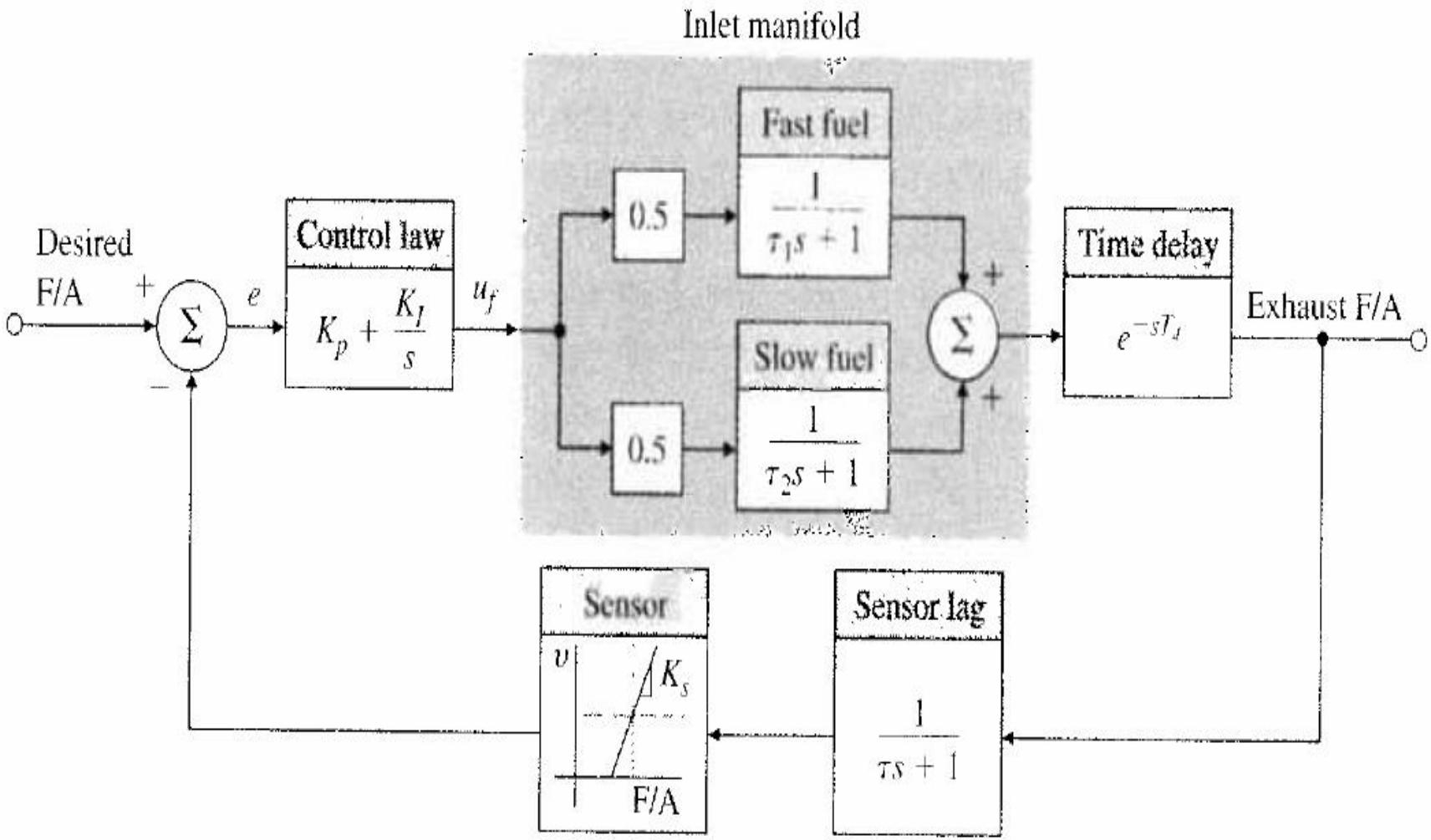
CAR EXHAUST SYSTEM


Catalytic converter
Intake manifold
Air
Engine
Exhaust
Actuator
Sensor
Fuel

SETUP

SENSOR CHARACTERISTIC




Inlet manifold
Desired
F/A
+
−
Σ
e
Control law
$K_p + \frac{K_I}{s}$
u_f
0.5
Fast fuel
$\frac{1}{\tau_1 s + 1}$
0.5
Slow fuel
$\frac{1}{\tau_2 s + 1}$
+
+
Σ
Time delay
e^{-sT_d}
Exhaust F/A
Sensor
v
K_s
F/A
Sensor lag
$\frac{1}{\tau s + 1}$

GOVERNING EQUATIONS

CONTROLLED $\quad Q = G_p \left(E + d \int_0^t E \, dt \right)$

FAST FLOW $\quad J \frac{dx}{dt} + fx = MQ$

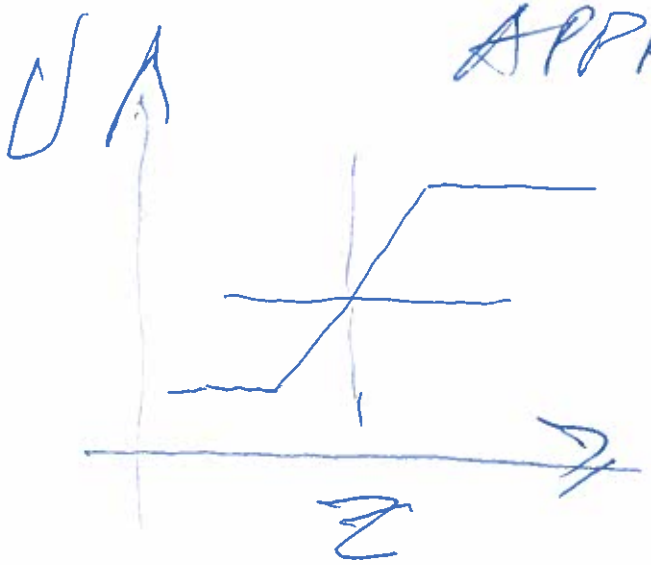
SLOW FLOW $\quad I \frac{dy}{dt} + y = NQ$

TOTAL FLOW $\quad V = x + y$

TRANSPORT LAG $W(t) = V(t-T)$

SENSOR LAG $A\frac{dz}{dt} + z = w$

SENSOR CHARACTERISTIC APPROXIMATION

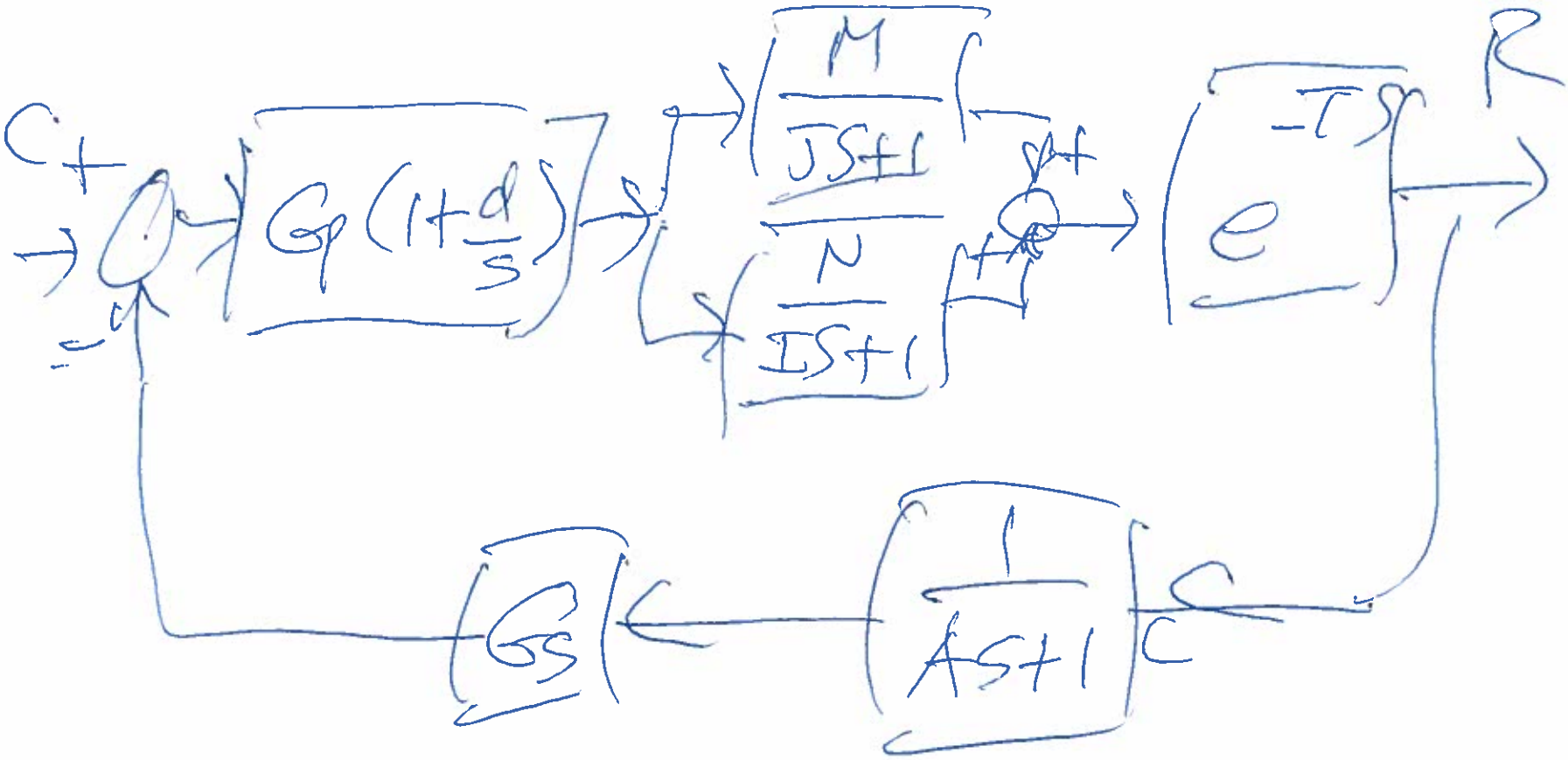


$U = a + (z-b) * GS$

$U > m \Rightarrow U = m$

$U < n \Rightarrow U = n$

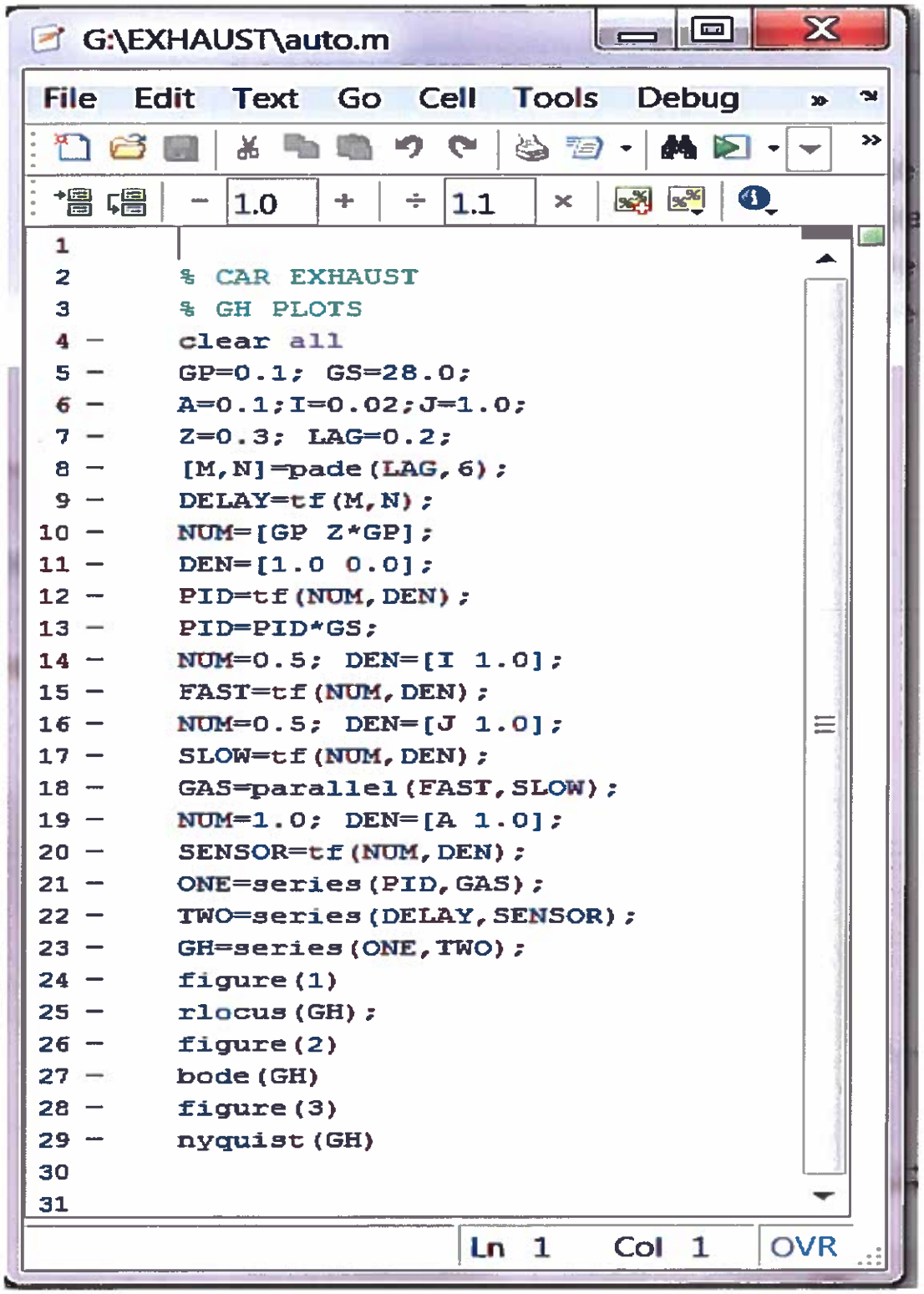
OVERALL BLOCK DIAGRAM

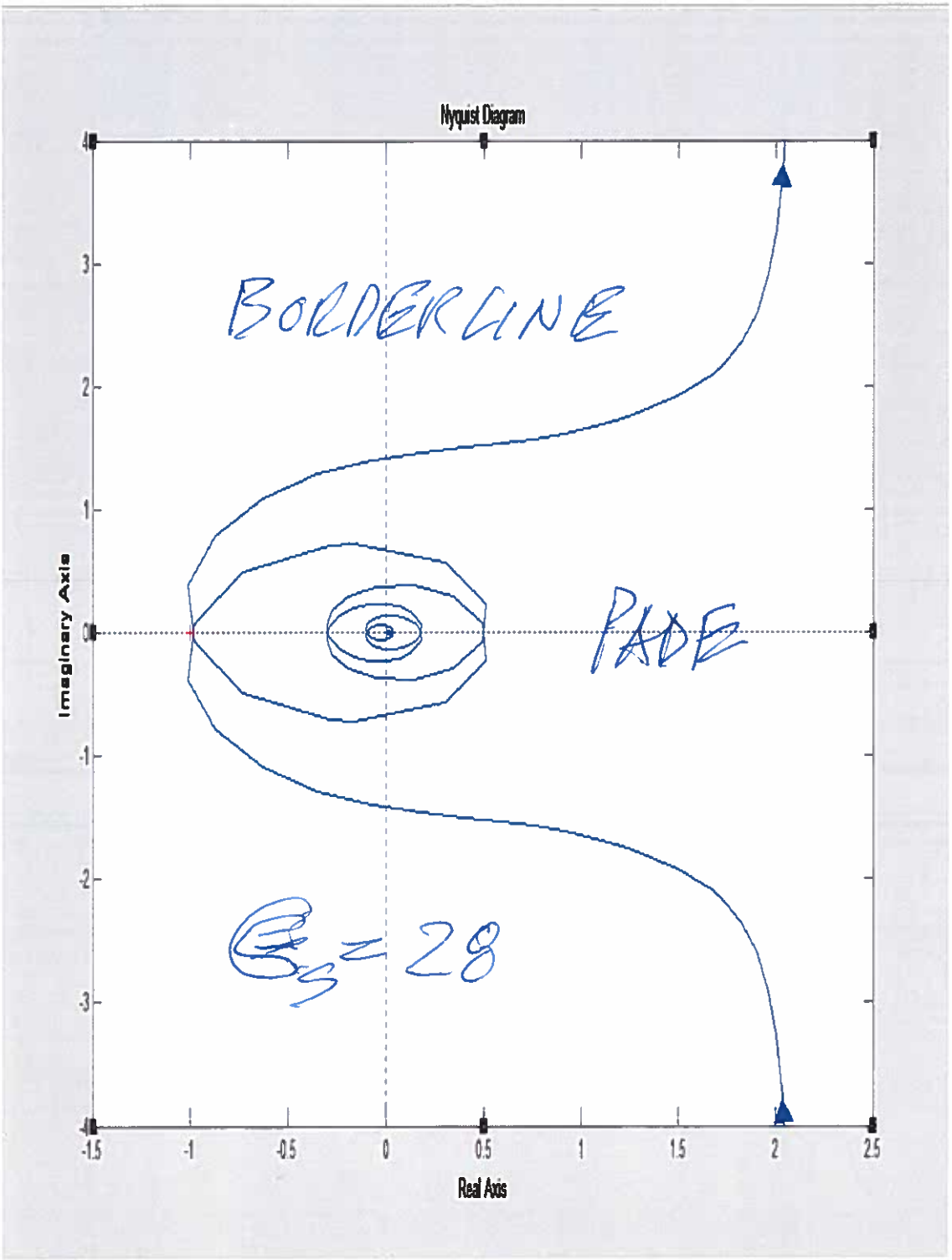


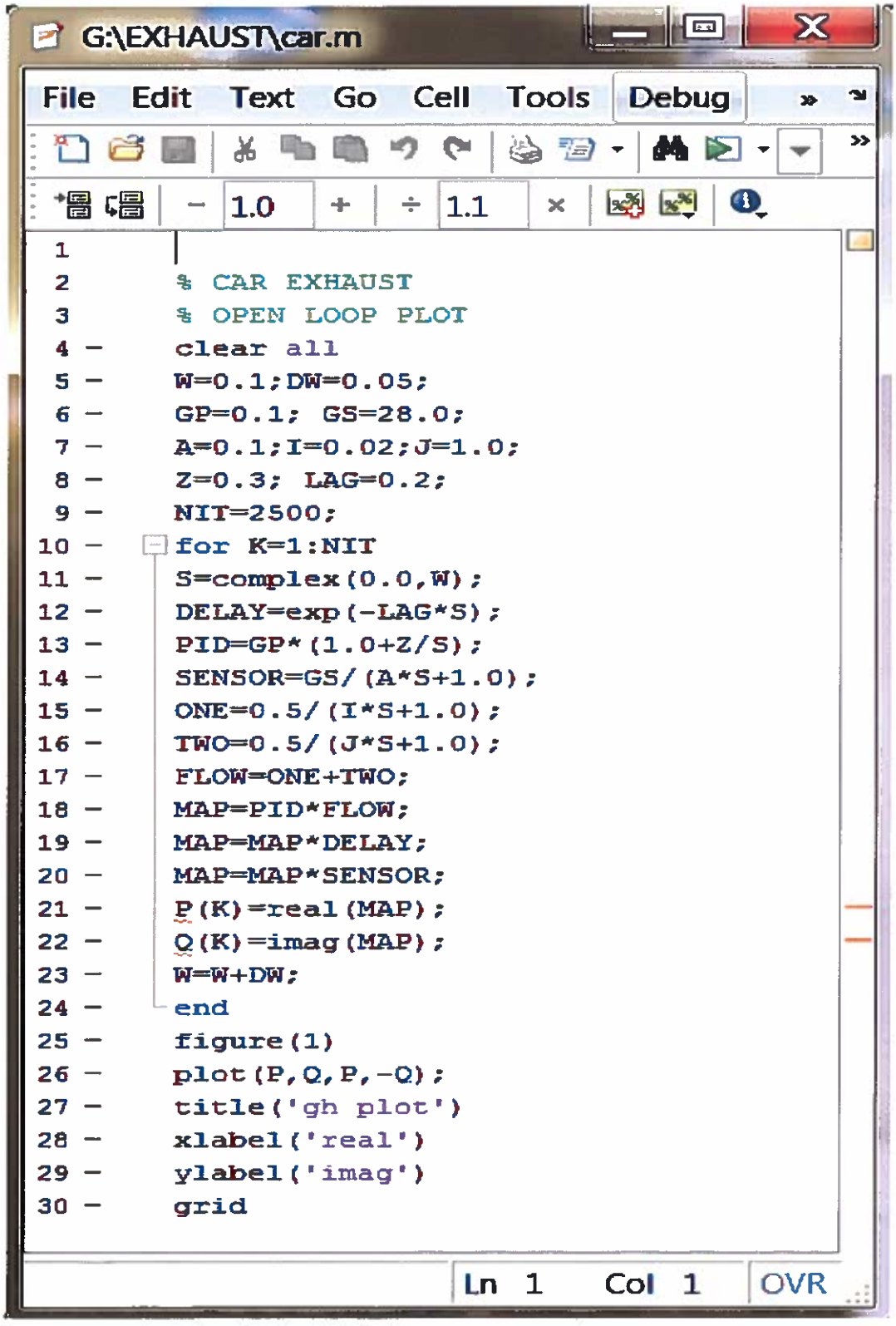
GH FUNCTION

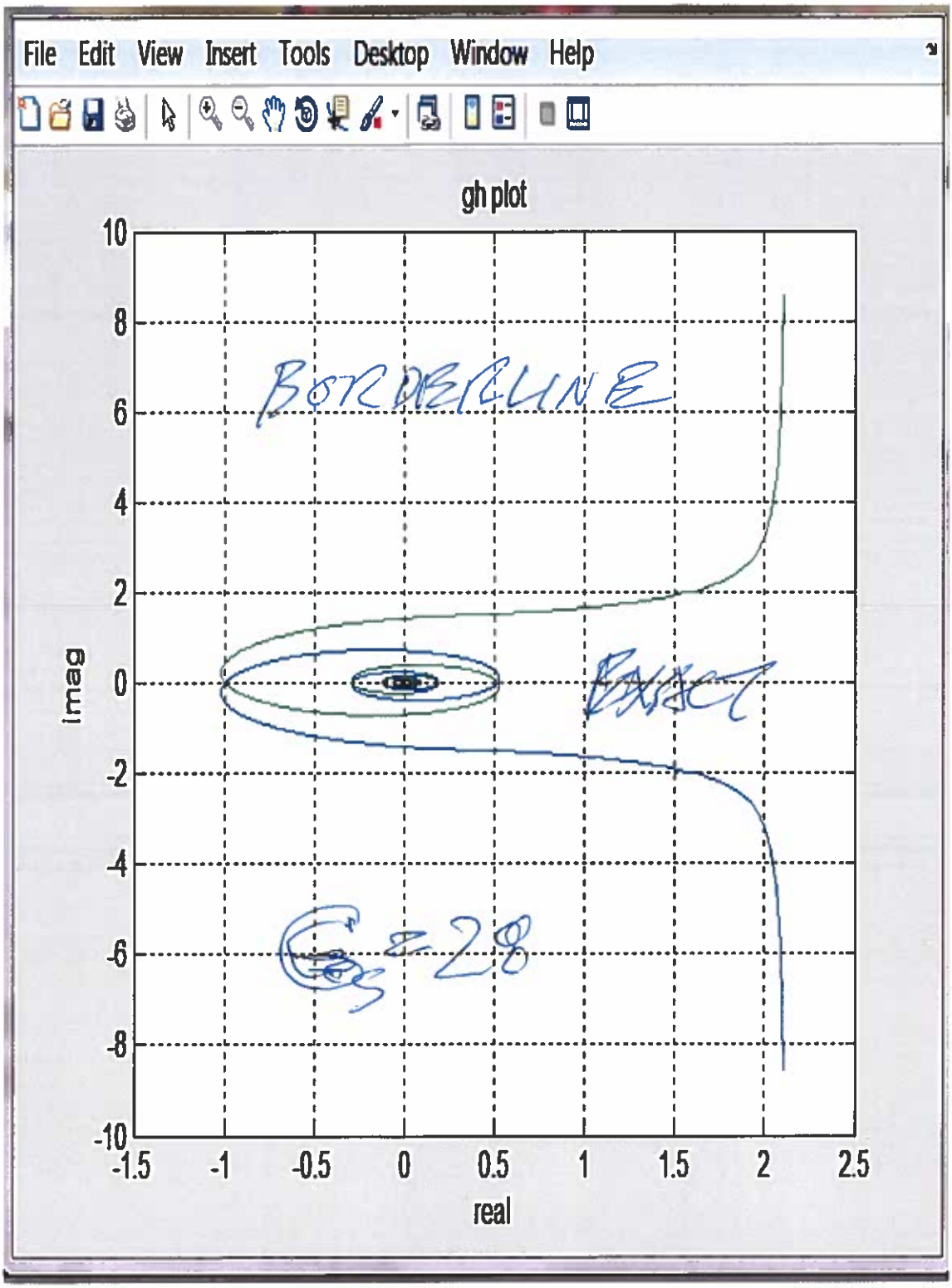
$$\frac{G_S G_p \left(1+\frac{d}{s}\right)\left(M(Is+1)+N(Ss+1)\right)e^{-Ts}}{(As+1)(Ss+1)(Is+1)}$$

PADE $\quad \dfrac{\left(1-\frac{T}{2}s\right)}{\left(1+\frac{T}{2}s\right)} \cong e^{-Ts}$

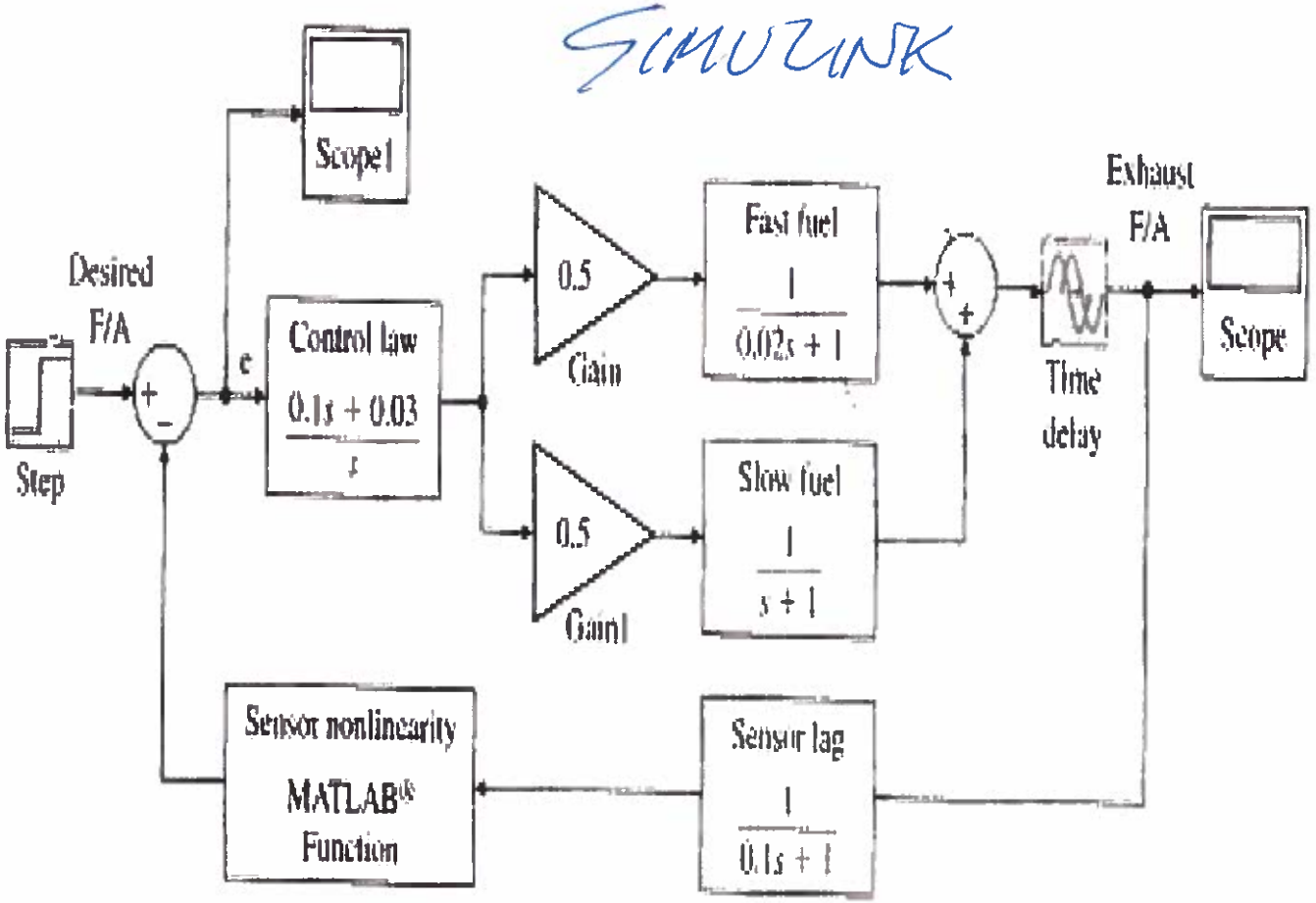

G:\EXHAUST\auto.m
File Edit Text Go Cell Tools Debug
1.0
1.1
1
2 % CAR EXHAUST
3 % GH PLOTS
4 clear all
5 GP=0.1; GS=28.0;
6 A=0.1;I=0.02;J=1.0;
7 Z=0.3; LAG=0.2;
8 [M,N]=pade(LAG,6);
9 DELAY=tf(M,N);
10 NUM=[GP Z*GP];
11 DEN=[1.0 0.0];
12 PID=tf(NUM,DEN);
13 PID=PID*GS;
14 NUM=0.5; DEN=[I 1.0];
15 FAST=tf(NUM,DEN);
16 NUM=0.5; DEN=[J 1.0];
17 SLOW=tf(NUM,DEN);
18 GAS=parallel(FAST,SLOW);
19 NUM=1.0; DEN=[A 1.0];
20 SENSOR=tf(NUM,DEN);
21 ONE=series(PID,GAS);
22 TWO=series(DELAY,SENSOR);
23 GH=series(ONE,TWO);
24 figure(1)
25 rlocus(GH);
26 figure(2)
27 bode(GH)
28 figure(3)
29 nyquist(GH)
30
31
Ln 1 Col 1
OVR


Nyquist Diagram
BORDERLINE
PADE
$K_s = 28$
Imaginary Axis
Real Axis
4
3
2
1
0
-1
-2
-3
-4
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5

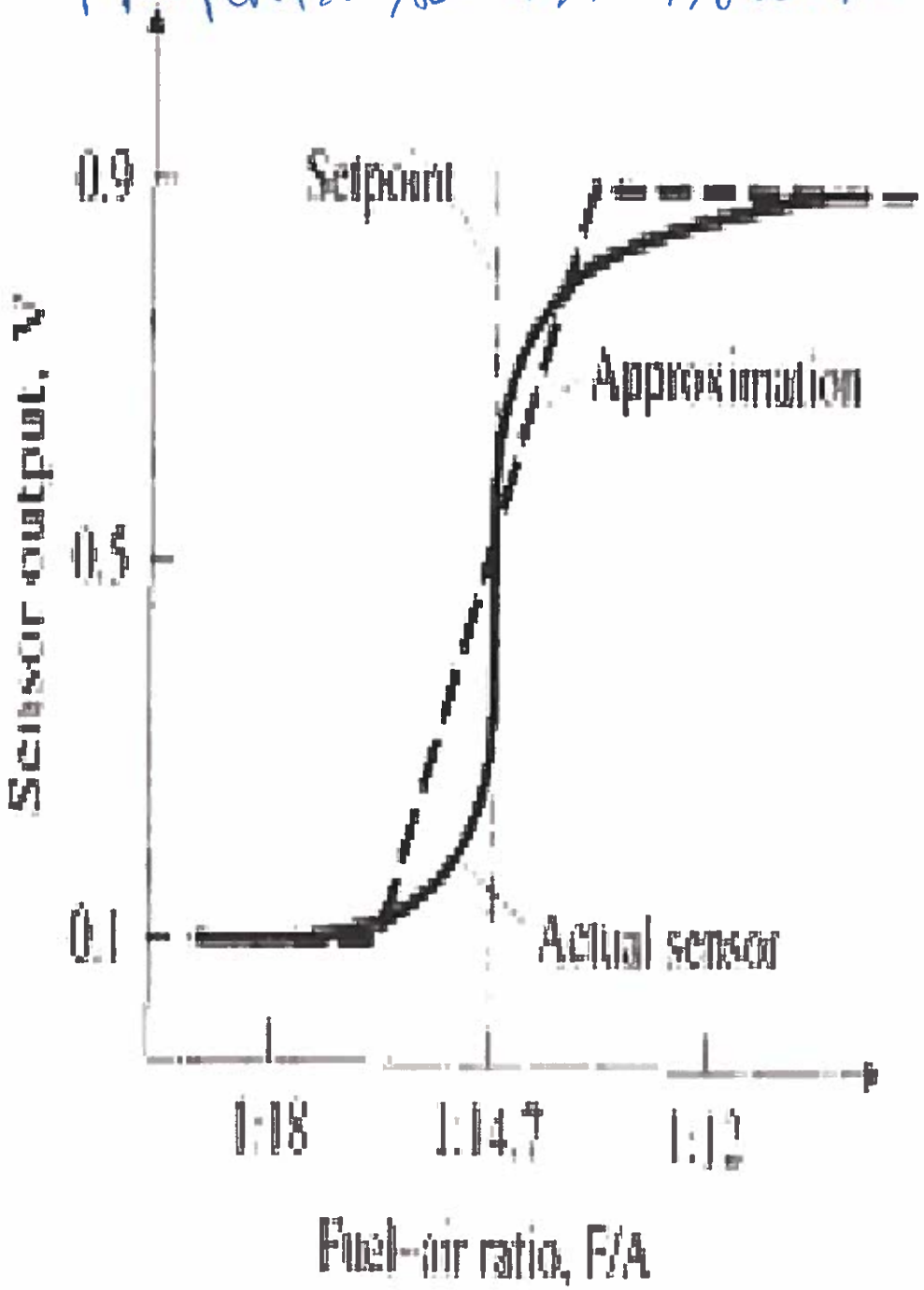

G:\EXHAUST\car.m
File Edit Text Go Cell Tools Debug
1.0
1.1
% CAR EXHAUST
% OPEN LOOP PLOT
clear all
W=0.1;DW=0.05;
GP=0.1; GS=28.0;
A=0.1;I=0.02;J=1.0;
Z=0.3; LAG=0.2;
NIT=2500;
for K=1:NIT
S=complex(0.0,W);
DELAY=exp(-LAG*S);
PID=GP*(1.0+Z/S);
SENSOR=GS/(A*S+1.0);
ONE=0.5/(I*S+1.0);
TWO=0.5/(J*S+1.0);
FLOW=ONE+TWO;
MAP=PID*FLOW;
MAP=MAP*DELAY;
MAP=MAP*SENSOR;
P(K)=real(MAP);
Q(K)=imag(MAP);
W=W+DW;
end
figure(1)
plot(P,Q,P,-Q);
title('gh plot')
xlabel('real')
ylabel('imag')
grid
Ln 1 Col 1 OVR

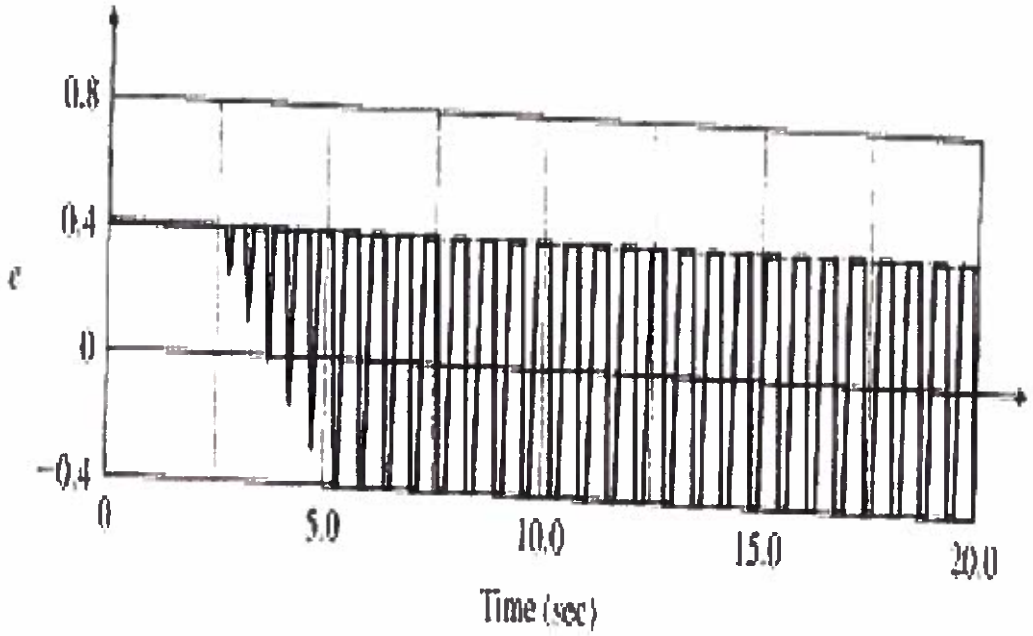

File Edit View Insert Tools Desktop Window Help
gh plot
imag
real
10
8
6
4
2
0
-2
-4
-6
-8
-10
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
BORDERLINE
STABLE
G=28

SIMULINK

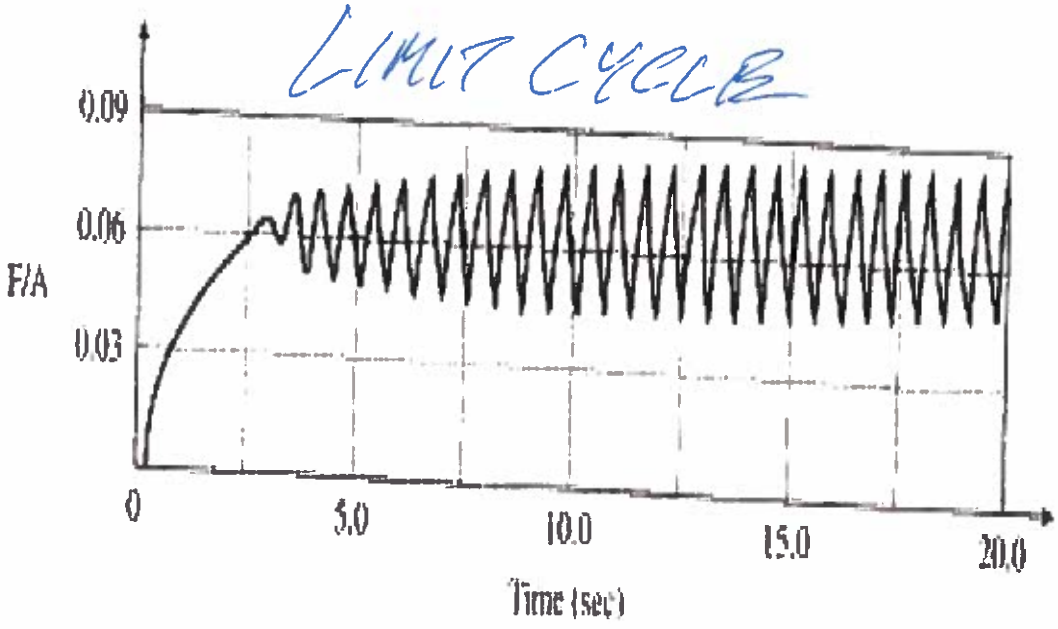

Scope1
Desired
F/A
Step
e
Control law
0.1s + 0.03
s
0.5
Gain
0.5
Gain1
Fast fuel
1
0.02s + 1
Slow fuel
1
s + 1
Time
delay
Exhaust
F/A
Scope
Sensor nonlinearity
MATLAB®
Function
Sensor lag
1
0.1s + 1

SENSOR APPROXIMATION
PROPORTIONAL SATURATION




0.8
0.4
e
0
−0.4
0
5.0
10.0
15.0
20.0
Time (sec)

LIMIT CYCLE

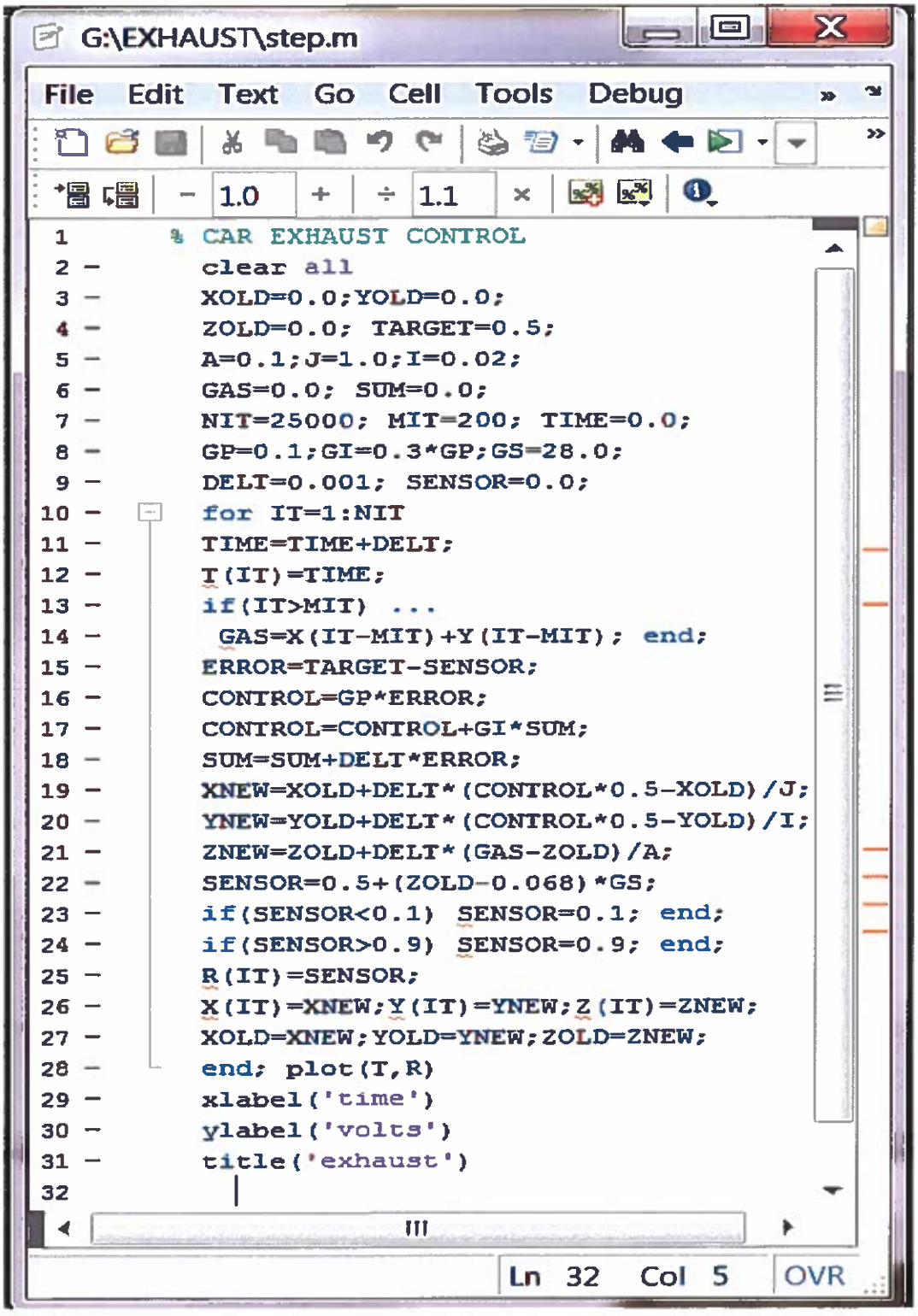

0.09
0.06
F/A
0.03
0
5.0
10.0
15.0
20.0
Time (sec)

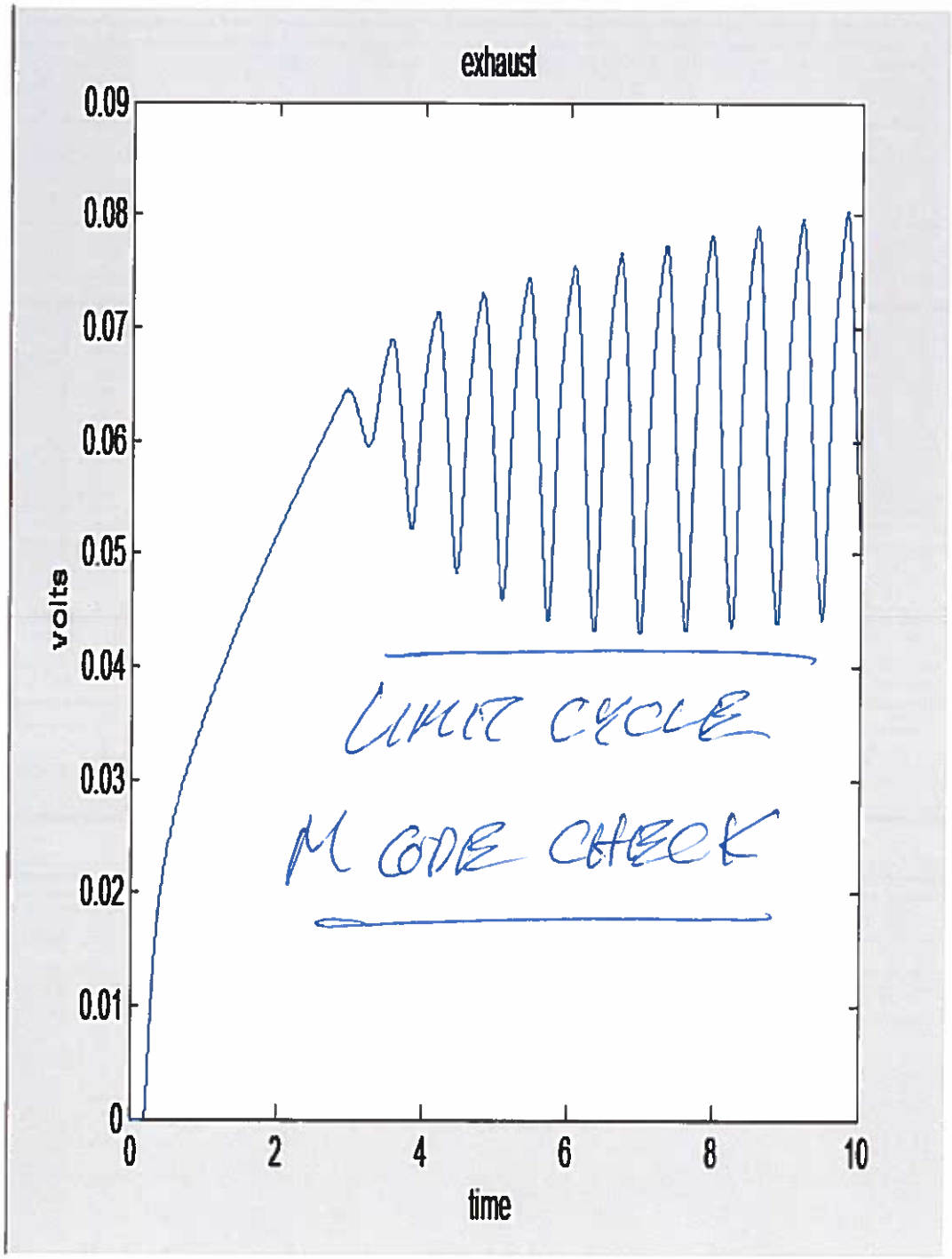
IDEAL RELAY SWITCHING SENSOR APPROXIMATION

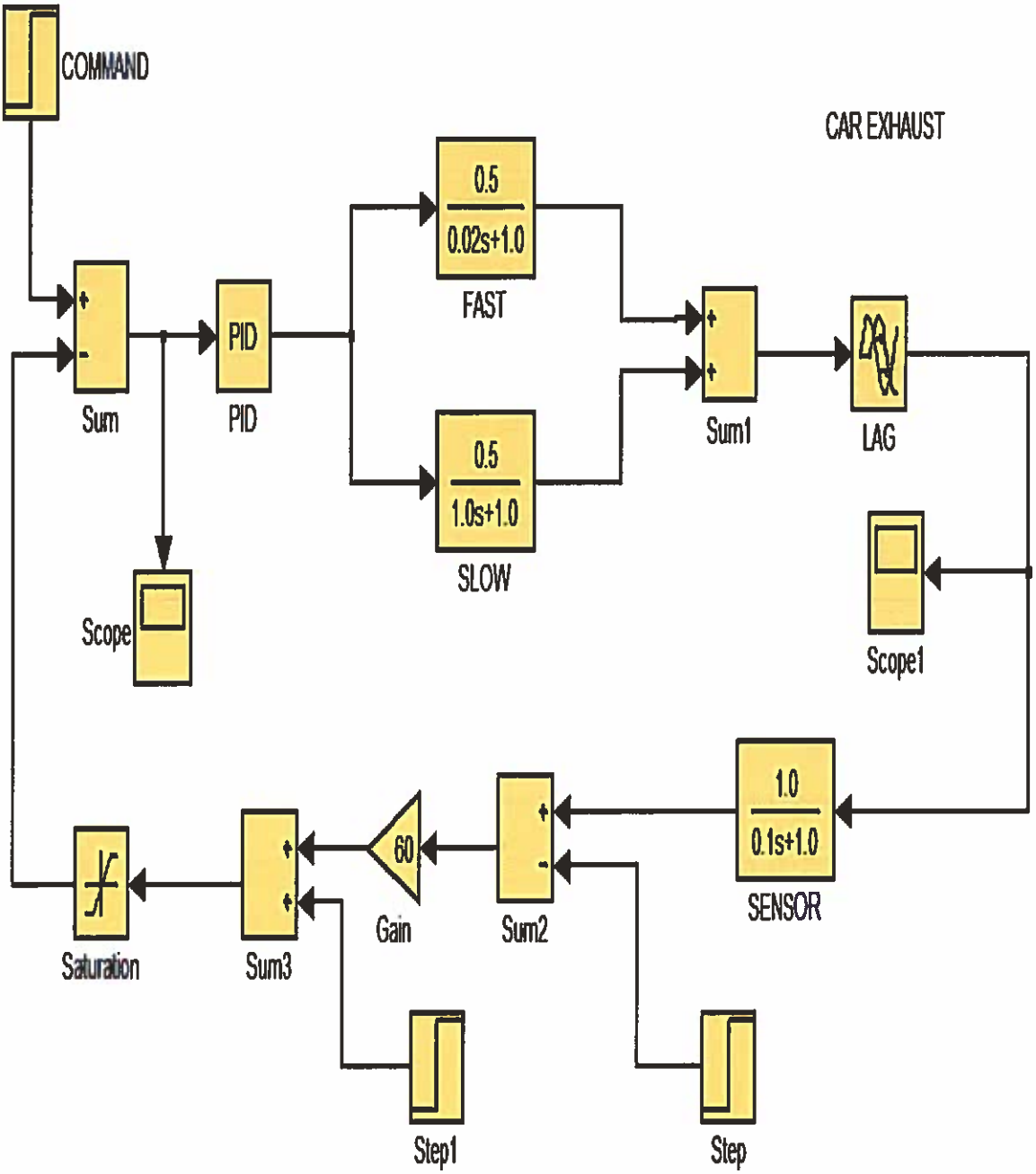
DESCRIBING FUNCTION

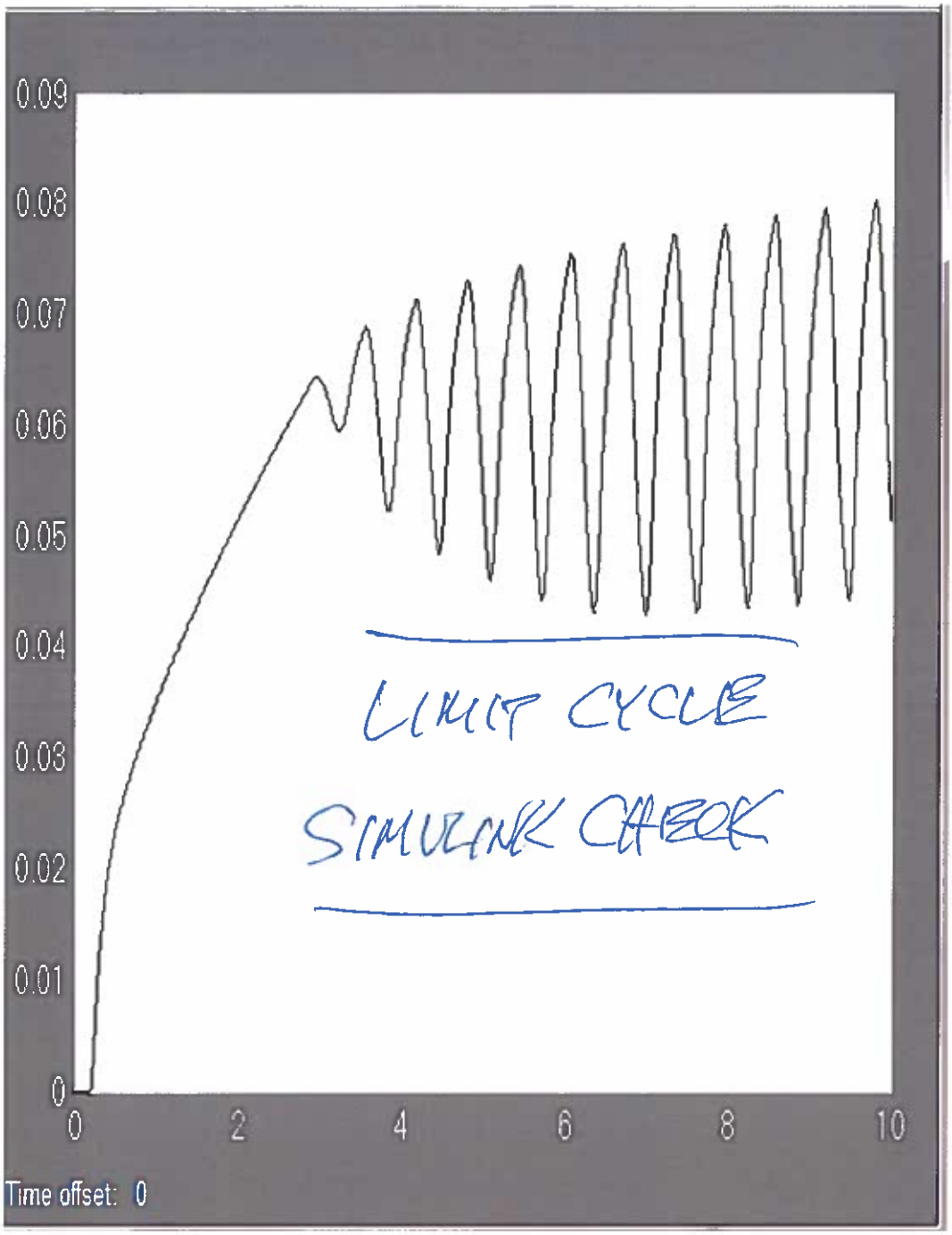
$$DF = \frac{4Q_0}{\pi E_0} \qquad G_s = 28$$

$$E_0 = \frac{4Q_0}{\pi G_s} = \frac{4 \cdot 10.4}{\pi \cdot 28} = 0.118$$


G:\EXHAUST\step.m
File Edit Text Go Cell Tools Debug
1.0
1.1
% CAR EXHAUST CONTROL
clear all
XOLD=0.0;YOLD=0.0;
ZOLD=0.0; TARGET=0.5;
A=0.1;J=1.0;I=0.02;
GAS=0.0; SUM=0.0;
NIT=25000; MIT=200; TIME=0.0;
GP=0.1;GI=0.3*GP;GS=28.0;
DELT=0.001; SENSOR=0.0;
for IT=1:NIT
TIME=TIME+DELT;
T(IT)=TIME;
if(IT>MIT) ...
GAS=X(IT-MIT)+Y(IT-MIT); end;
ERROR=TARGET-SENSOR;
CONTROL=GP*ERROR;
CONTROL=CONTROL+GI*SUM;
SUM=SUM+DELT*ERROR;
XNEW=XOLD+DELT*(CONTROL*0.5-XOLD)/J;
YNEW=YOLD+DELT*(CONTROL*0.5-YOLD)/I;
ZNEW=ZOLD+DELT*(GAS-ZOLD)/A;
SENSOR=0.5+(ZOLD-0.068)*GS;
if(SENSOR<0.1) SENSOR=0.1; end;
if(SENSOR>0.9) SENSOR=0.9; end;
R(IT)=SENSOR;
X(IT)=XNEW;Y(IT)=YNEW;Z(IT)=ZNEW;
XOLD=XNEW;YOLD=YNEW;ZOLD=ZNEW;
end; plot(T,R)
xlabel('time')
ylabel('volts')
title('exhaust')
Ln 32 Col 5
OVR


exhaust
volts
time
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
2
4
6
8
10
LIMIT CYCLE
M CODE CHECK


COMMAND
CAR EXHAUST
0.5
0.02s+1.0
FAST
Sum
PID
PID
Sum1
LAG
0.5
1.0s+1.0
SLOW
Scope
Scope1
1.0
0.1s+1.0
SENSOR
60
Gain
Sum2
Saturation
Sum3
Step1
Step


0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
2
4
6
8
10
Time offset: 0
LIMIT CYCLE
SIMULINK CHECK