SUB-OPTIMAL CONTROL OF SINGLE-SPOOL JET ENGINE USING REAL-TIME MODEL

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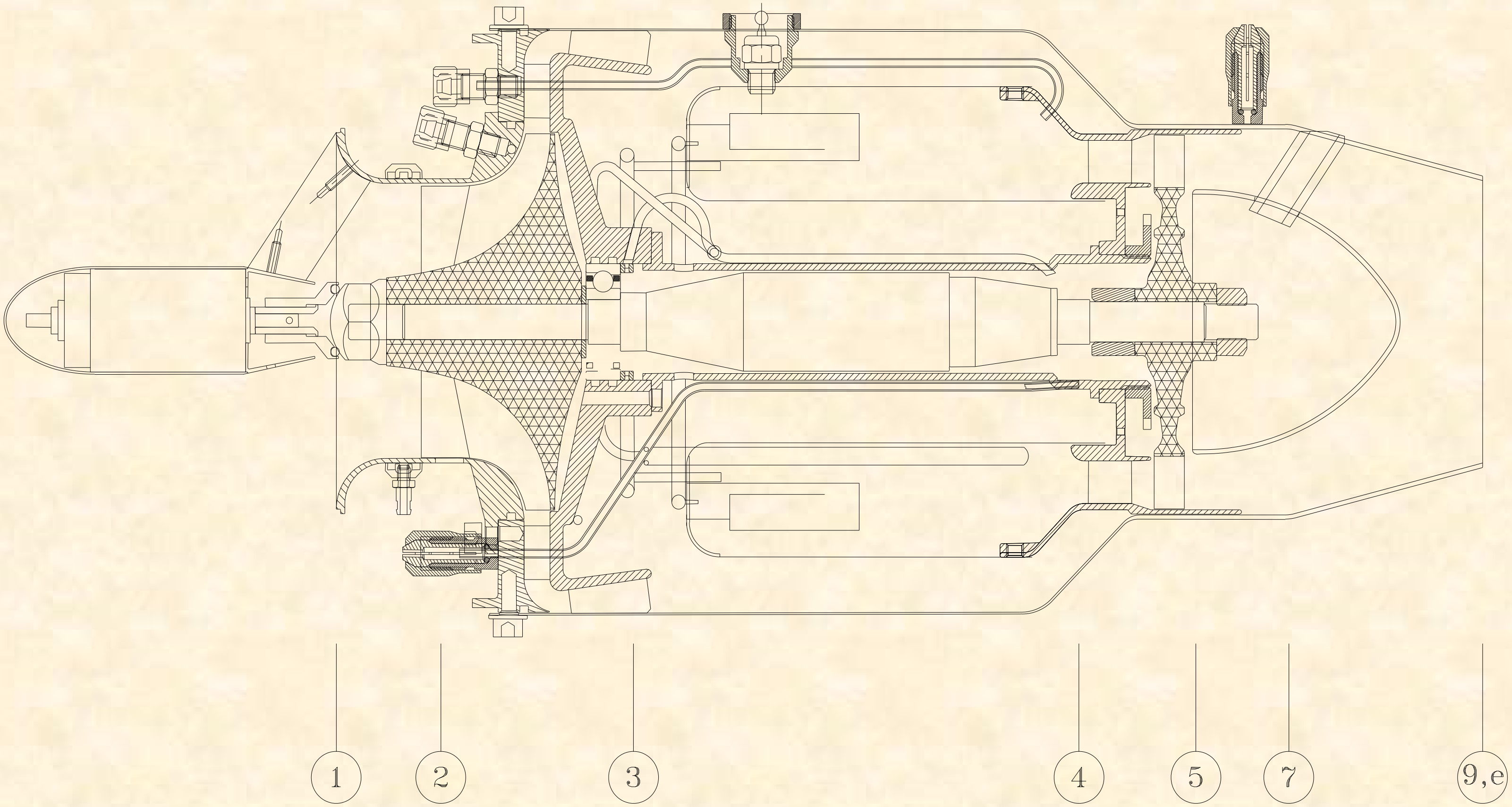
Objectives:

- Development of a sub-optimal minimum-time controller for single - spool jet engine
- Development of algorithm for engine control based on back-up for faulty sensors

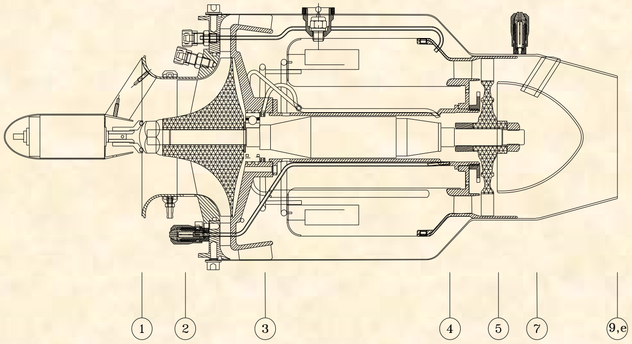
Engine Stations

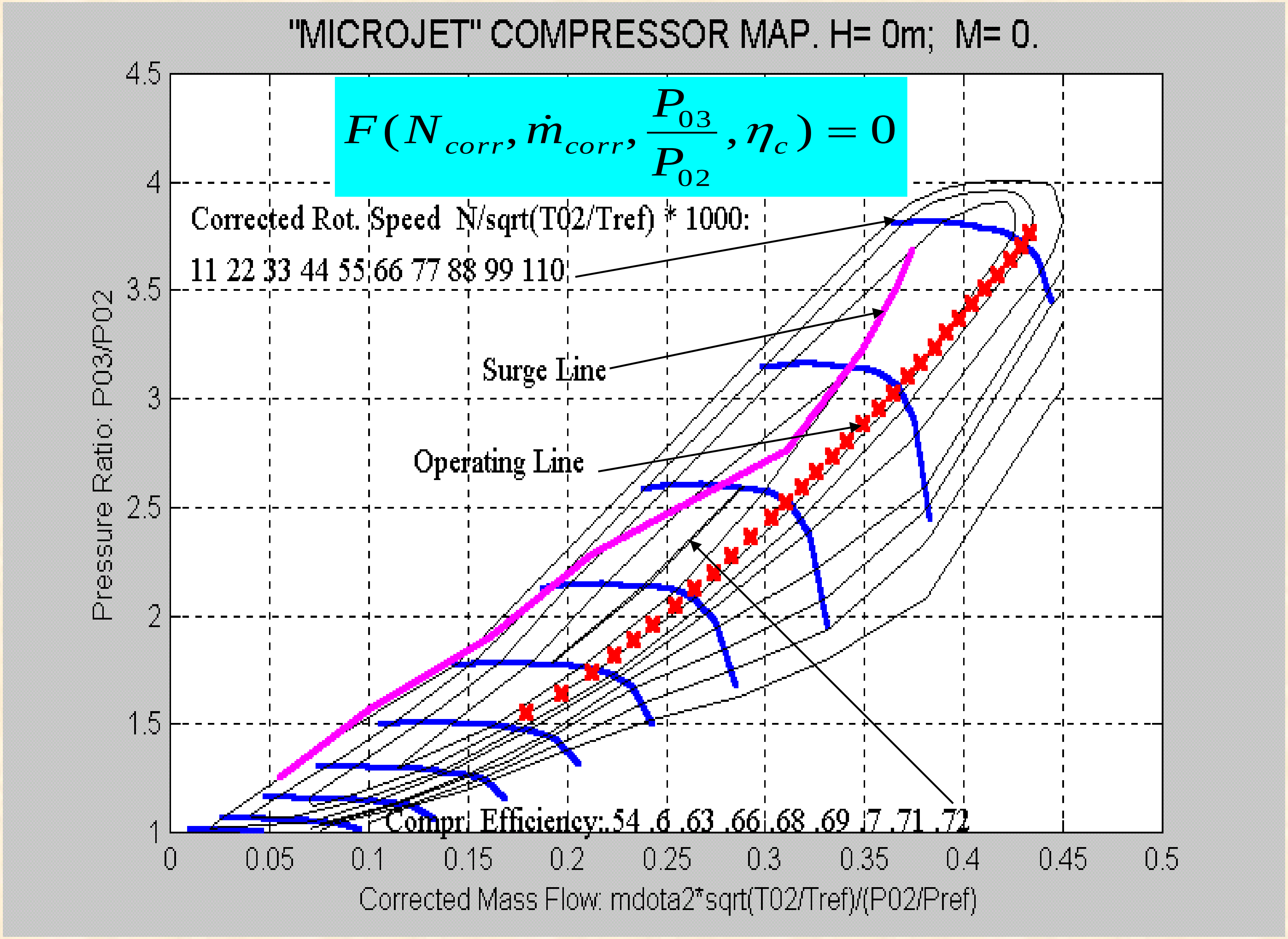


Conventional Nonlinear Engine Model

$$F_D[\frac{dx}{dt}, x, y, u, A(x, y, u)] = 0$$

$$F_A[x, y, u, B(x, y, u)] = 0$$




"MICROJET" COMPRESSOR MAP. H= 0m; M= 0.
$F(N_{corr}, \dot{m}_{corr}, \frac{P_{03}}{P_{02}}, \eta_c) = 0$
Corrected Rot. Speed N/sqrt(T02/Tref) * 1000:
11 22 33 44 55 66 77 88 99 110
Surge Line
Operating Line
Compr. Efficiency: .54 .6 .63 .66 .68 .69 .7 .71 .72
Pressure Ratio: P03/P02
Corrected Mass Flow: mdota2*sqrt(T02/Tref)/(P02/Pref)
4.5
4
3.5
3
2.5
2
1.5
1
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5

Conventional Nonlinear Engine Model (Continued)

Four Types of Differential Equations

1. The power balance
2. Unsteady flow volume dynamics:
   a. Continuity
   b. Energy storage
3. Metal – fluid heat exchange (“heat soakage”)
4. Time delay in the combustion process

1. Power Balance Differential Equation

$$\dot{m}_T \cdot \Delta h_{0,T} \cdot \eta_m - \dot{m}_C \cdot \Delta h_{0,C} - altpower = \frac{dE}{dt}$$

$$E = \frac{J \cdot \left(\frac{N \cdot 2\pi}{60}\right)^2}{2} = \frac{J \cdot N^2 \cdot \pi^2}{1800}$$

$$N = \frac{30}{\pi} \cdot \sqrt{\frac{2E}{J}}$$

2. Unsteady Flow Volume Dynamics

a. Continuity Equation

$$\dot{m}_{out} - \dot{m}_{in} = Vol \cdot (1 + \frac{\gamma - 1}{2} * M^2)^{\frac{1}{1-\gamma}} \cdot \frac{1}{R \cdot \bar{\bar{T}}_0} \cdot (\frac{d\overline{P}_0}{dt} - \frac{d\overline{T}_0}{dt} \cdot \frac{\overline{P}_0}{\bar{\bar{T}}_0})$$

b. Energy Storage (Equation of Power for Combustor Chamber)

$$\dot{m}_{out} \cdot C_{p,out} \cdot T_{0,out} - \dot{m}_{in} \cdot C_{p,in} \cdot T_{0,in} - \frac{dQ_f}{dt} - \frac{dQ_{soak}}{dt} =$$

$$(\dot{m}_{out} - \dot{m}_{in} - \dot{m}_f) \cdot \frac{C_v}{1 + \frac{\gamma - 1}{2} \cdot M^2} \cdot \bar{\bar{T}}_0 + \frac{Vol \cdot C_V}{R} \cdot \frac{1}{(1 + \frac{\gamma - 1}{2} \cdot M^2)^{\frac{\gamma}{\gamma - 1}}} \cdot \frac{\overline{P}_0}{\bar{\bar{T}}_0} \cdot \frac{d\overline{T}_0}{dt}$$

3. Heat Soakage

$$\frac{dQ_{soak}}{dt} = h \cdot A \cdot (\bar{T}_{metal} - \bar{T}_{gas})$$

$$m_{metal} \cdot C_{p,metal} \cdot \frac{d\bar{T}_{metal}}{dt} + h \cdot A \cdot \bar{T}_{metal} = h \cdot A \cdot \bar{T}_{gas}.$$

h - heat transfer coefficient, $\frac{W}{m^2 \cdot K}$

4. Time Delay of the Combustion Process

$$\tau_f \cdot \frac{d\dot{m}_{f,out}(t)}{dt} + \dot{m}_{f,out}(t) = \dot{m}_{f,in}(t - \tau_0)$$

Control System Specifications:

1. Corrected rotational speed control: $\left(\frac{N}{\sqrt{T_{02}}}\right)$

   a) Steady-state error: <1%

   b) Settling time: <u>minimum</u>

   c) Overshoot: <2%

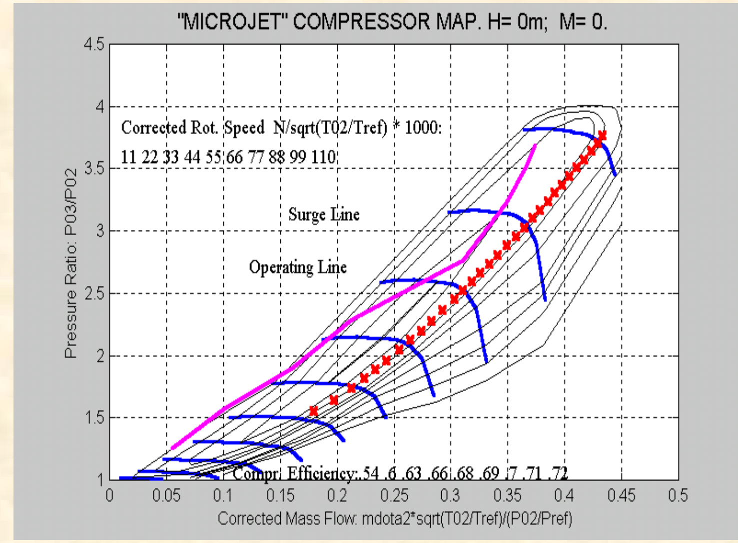
2. T05 <T05max (EGT)

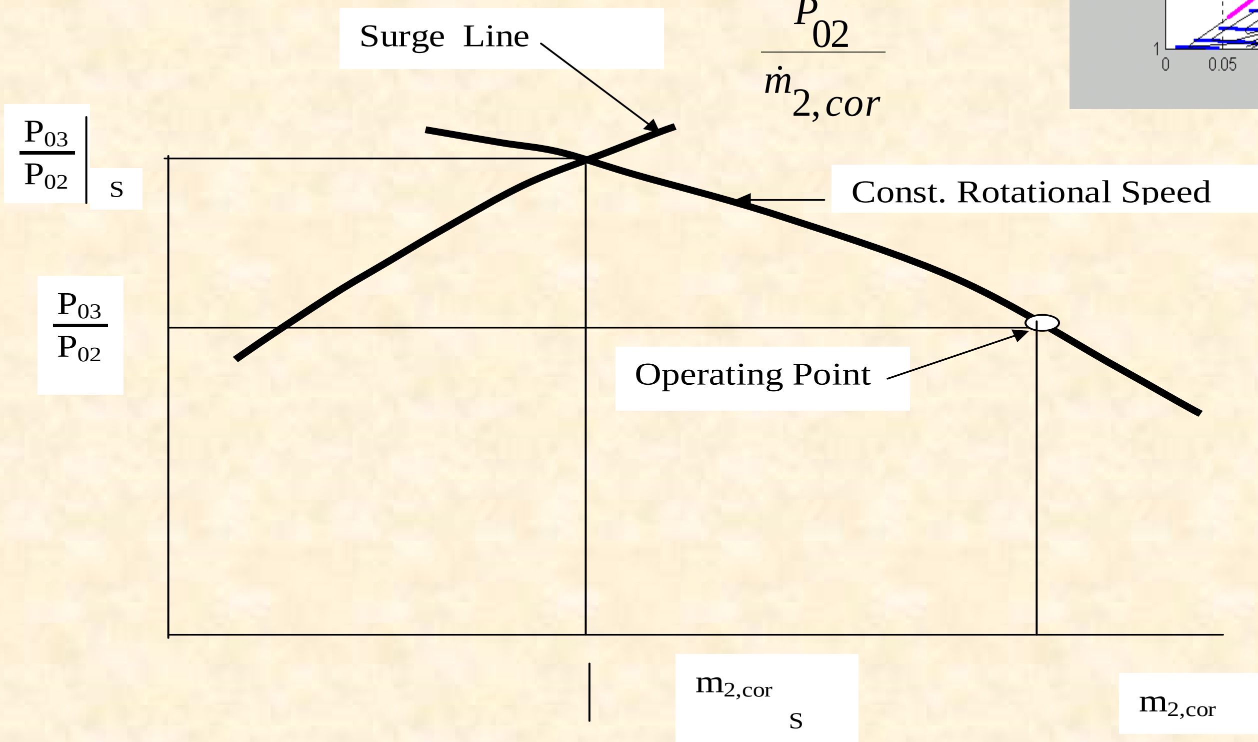
3. Equivalence Ratio: ϕmin < ϕ < ϕmax

$$\phi = \frac{\dfrac{\dot{m}_f}{\dot{m}_a}}{\dfrac{\dot{m}_f}{\dot{m}_a}\Big|_{stoichiom}}$$

4. ***Stall margin: >5%***

$$SM=\frac{\dfrac{\left(\dfrac{P_{03}}{P_{02}}\right)_S}{(\dot m_{2,cor})_S}-\dfrac{\dfrac{P_{03}}{P_{02}}}{\dot m_{2,cor}}}{\dfrac{\dfrac{P_{03}}{P_{02}}}{\dot m_{2,cor}}}$$





Concept of Sub-Optimal Control of a Single-Spool Engine

1. Conventional linearization for the nonlinear engine model is not desirable

2. Sub-optimal control has to provide:

   a) dynamic operating line close to the surge line <u>during engine acceleration</u> (maximum fuel rate)

   b) equivalence ratio close to a minimal limiting value <u>during engine deceleration</u> (minimum fuel rate)

Engine Model for Real-Time Simulations

Variable Vectors:

$$u = [\dot{m}_f, H, M]$$

$$x = [N_{corr}, \dot{m}_a, \frac{P_{03}}{P_{02}}, T_{05}, T]$$

$$y = [N_{corr}, \dot{m}_{a,corr}, \frac{P_{03}}{P_{02}}, T_{05}, T, SM, \varphi, \ldots$$

$$x_0 = [N_{corr\,0}, \dot{m}_{a\,0}, (\frac{P_{03}}{P_{02}})_0, T_{05\,0}, T_0]$$

Engine Model for Real-Time Simulations (continued)

Differential Equations:

$$\tau_{Ncor}(H, M, \Delta N_{cor}) \frac{d(\Delta N_{cor})}{dt} + \Delta N_{cor} = K_{Ncor}(H, M, \Delta N_{cor}) \Delta \dot{m}_f$$

$$\tau_{P32}(H, M, \Delta N_{cor}) \frac{d(\Delta P_{32})}{dt} + \Delta P_{32} = K_{P32}(H, M, \Delta N_{cor}) \Delta \dot{m}_f$$

$$\tau_{T}(H, M, \Delta N_{cor}) \frac{d(\Delta T)}{dt} + \Delta T = K_{T}(H, M, \Delta N_{cor}) \Delta \dot{m}_f$$

$$\tau_{2,\dot{m}_a}(H, M, \Delta N_{cor}) \frac{d(\Delta \dot{m}_a)}{dt} + \Delta \dot{m}_a = K_{\dot{m}_a}(H, M, \Delta N_{cor})(\tau_{1,\dot{m}_a}(H, M, \Delta N_{cor}) \frac{d(\Delta \dot{m}_f)}{dt} + \Delta \dot{m}_f)$$

$$\tau_{2,T_{05}}(H, M, \Delta N_{cor}) \frac{d(\Delta T_{05})}{dt} + \Delta T_{05} = K_{T_{05}}(H, M, \Delta N_{cor})(\tau_{1,T_{05}}(H, M, \Delta N_{cor}) \frac{d(\Delta \dot{m}_f)}{dt} + \Delta \dot{m}_f)$$

Engine Model for Real-Time Simulations (continued)

Algebraic Equations:

$$\dot{m}_f = \dot{m}_{f0} + \Delta \dot{m}_f$$

$$N_{cor} = N_{cor0} + \Delta N_{cor}$$

$$P_{32} = P_{320} + \Delta P_{32}$$

$$T = T_0 + \Delta T$$

$$\dot{m}_a = \dot{m}_{a0} + \Delta \dot{m}_a$$

$$T_{05} = T_{050} + \Delta T_{05}$$

$$\left(\frac{P_{02}}{P_a} \right) = \left[1 + \eta_d \frac{\gamma_a - 1}{2} M^2 \right]^{\frac{\gamma_a}{\gamma_a - 1}}$$

$$\left(\frac{T_{02}}{T_a} \right) = 1 + \frac{\gamma_a - 1}{2} M^2$$

Engine Model for Real-Time Simulations (continued)

Algebraic Equations:

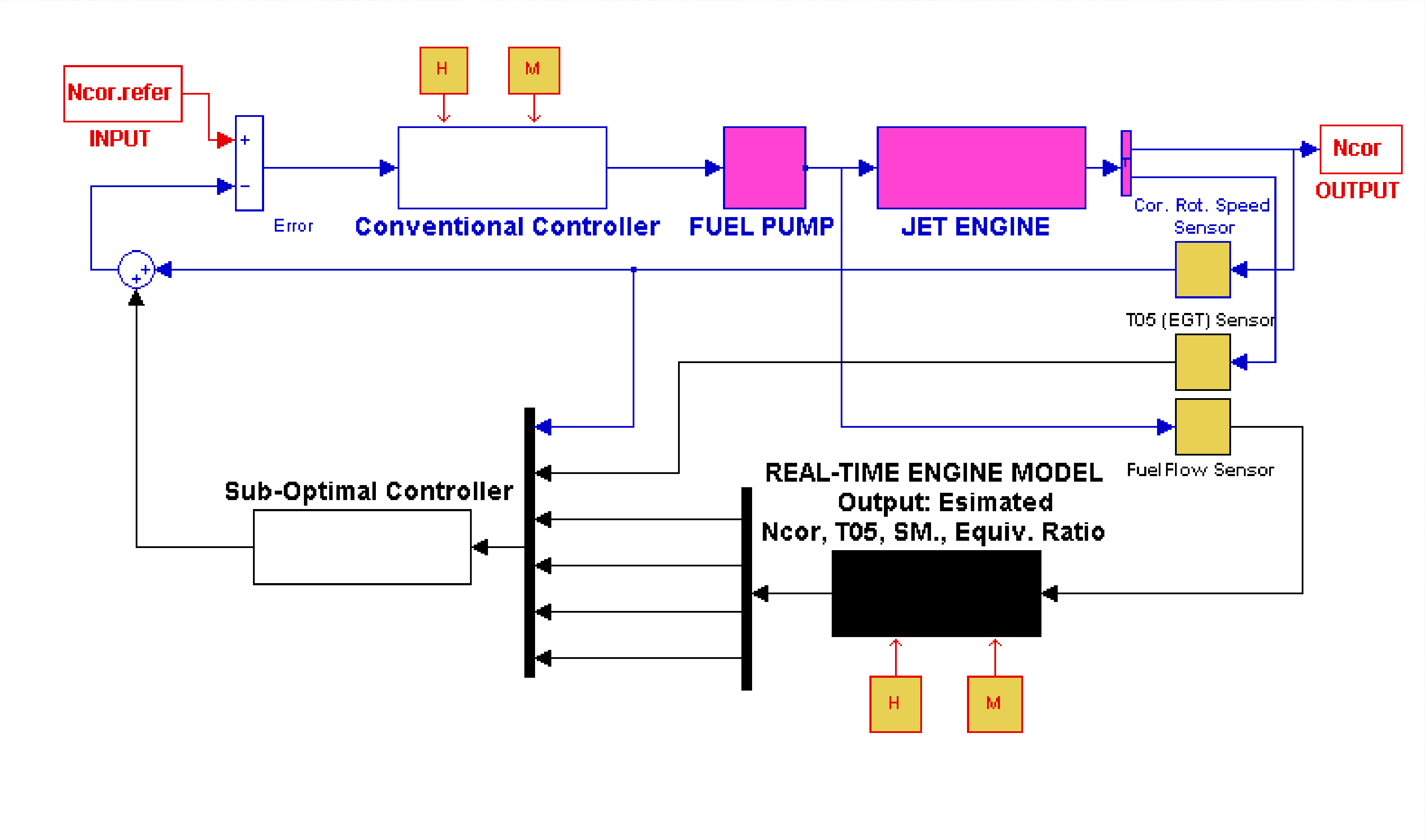
$$\dot{m}_{2a_{cor}} = \frac{\dot{m}_a.(1+\varepsilon).\sqrt{\dfrac{T_{02}}{T_{ref}}}}{\dfrac{P_{02}}{P_{ref}}}$$

$$SM = \frac{\dfrac{(P_{32})_{stall}}{(\dot{m}_{2a_{cor}})_{stall}} - \dfrac{P_{32}}{\dot{m}_{2a_{cor}}}}{\dfrac{P_{32}}{\dot{m}_{2a_{cor}}}}$$

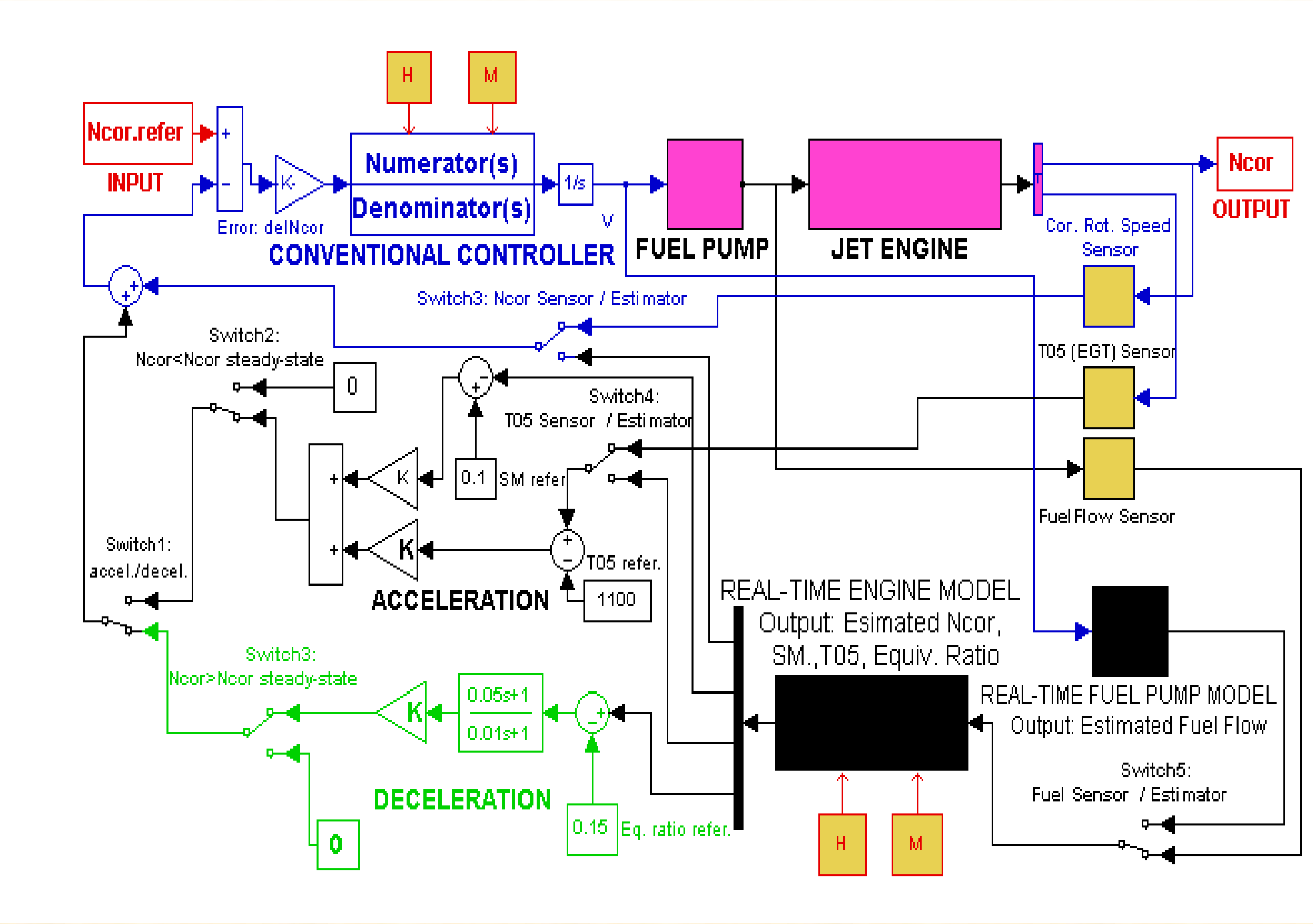
$$\phi = \frac{\dfrac{\dot{m}_f}{\dot{m}_a}}{\dfrac{\dot{m}_f}{\dot{m}_a}|_{stoichiom}}$$

$$Note: P_{32} = \frac{P_{03}}{P_{02}}$$

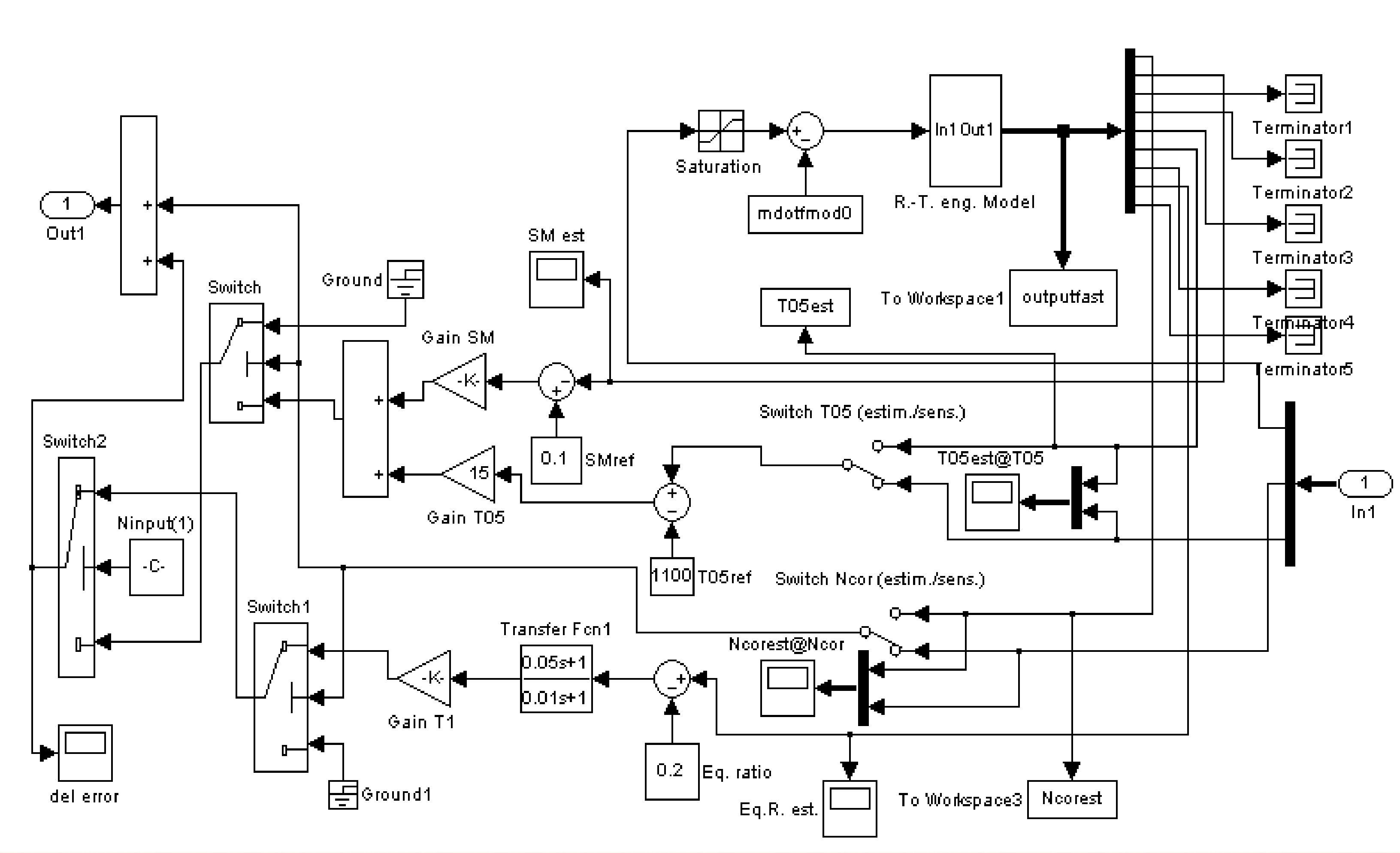
Block-Diagram of Sub-Optimal Engine Control System



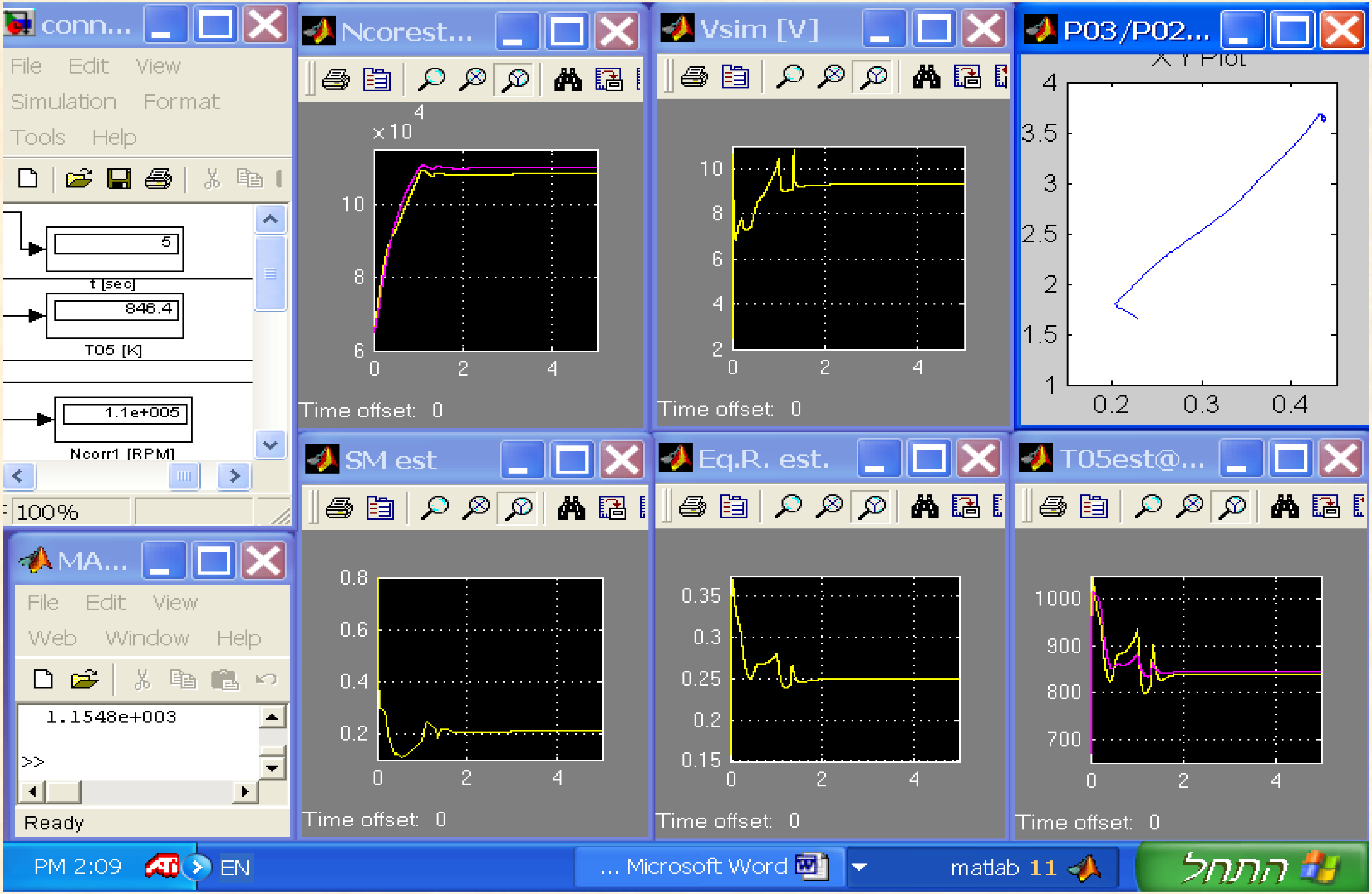
Sub-Optimal Controller



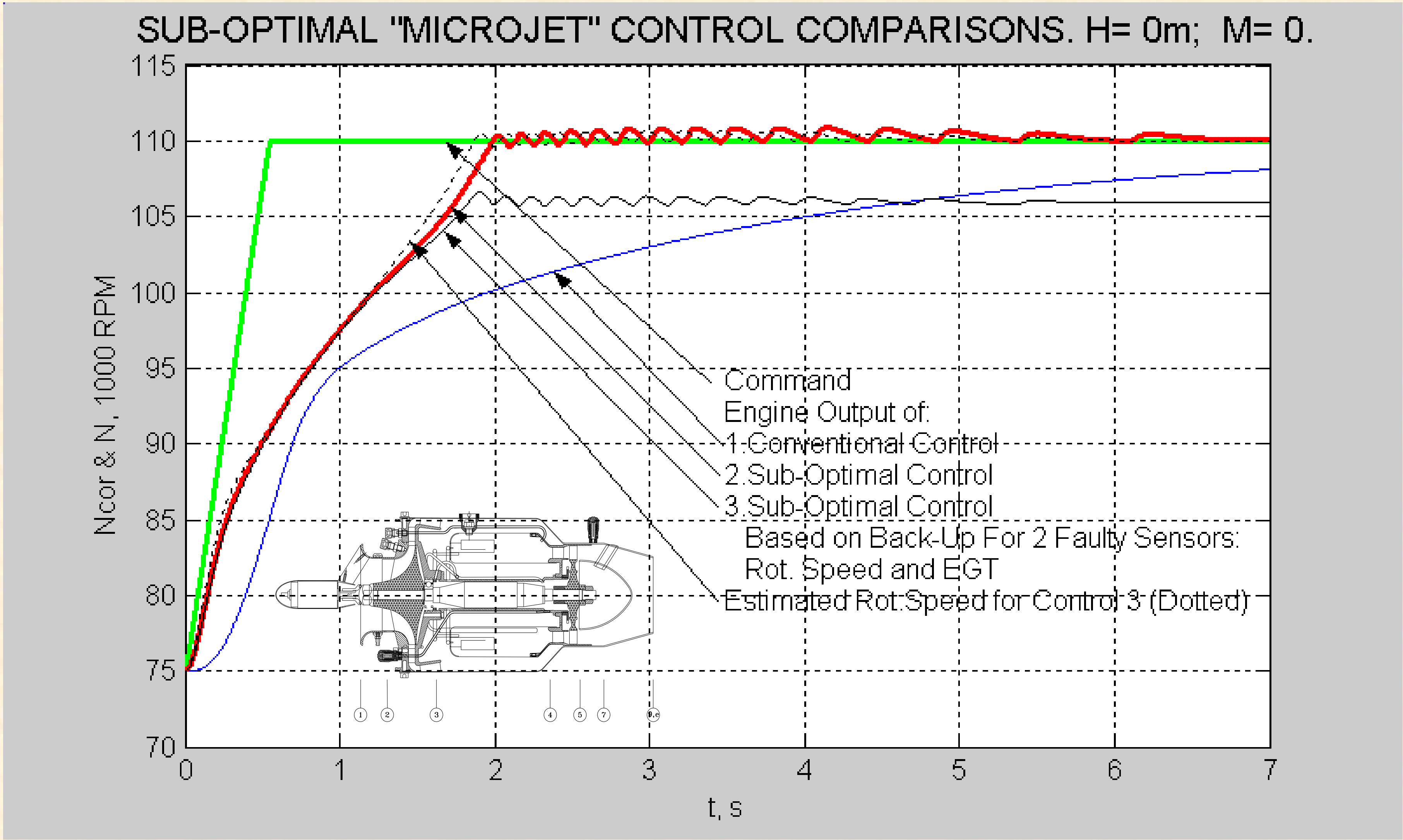
Simulink Code of Sub-Optimal Engine Controller



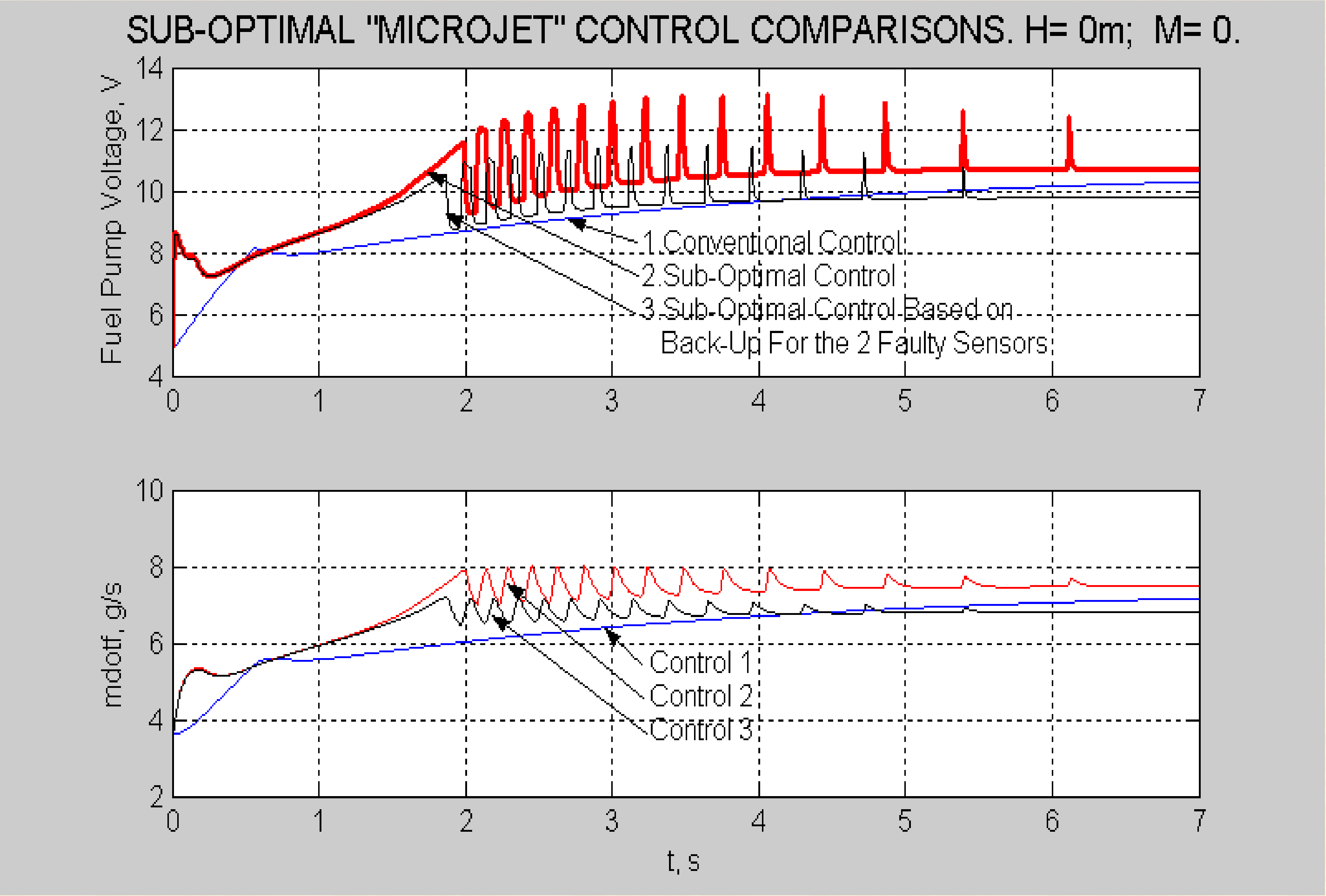
Screen View During Simulations of Sub-Optimal Control



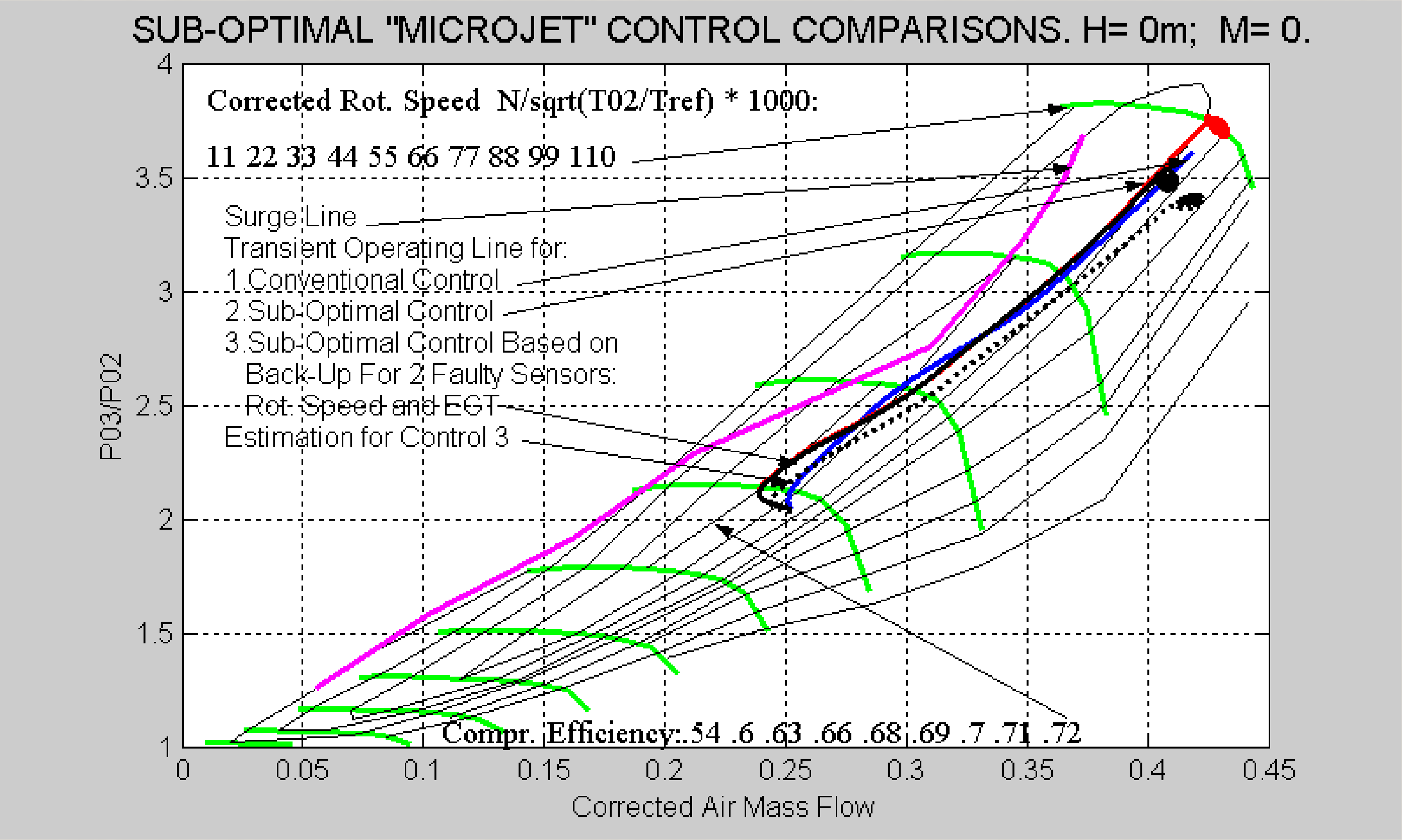
Corrected Rotational Speed During Engine Acceleration



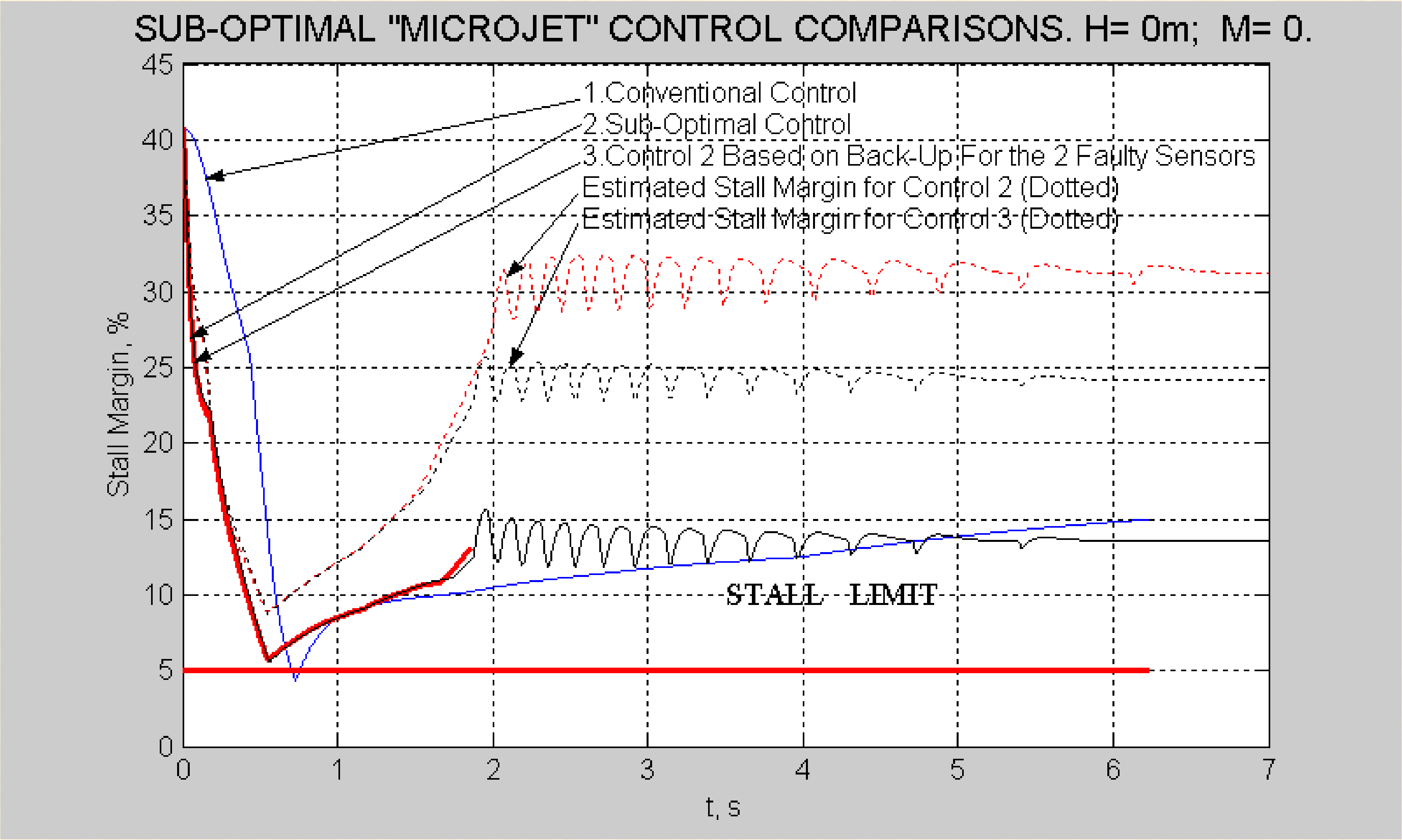
Fuel Pump Voltage and Fuel Mass Flow During Engine Acceleration



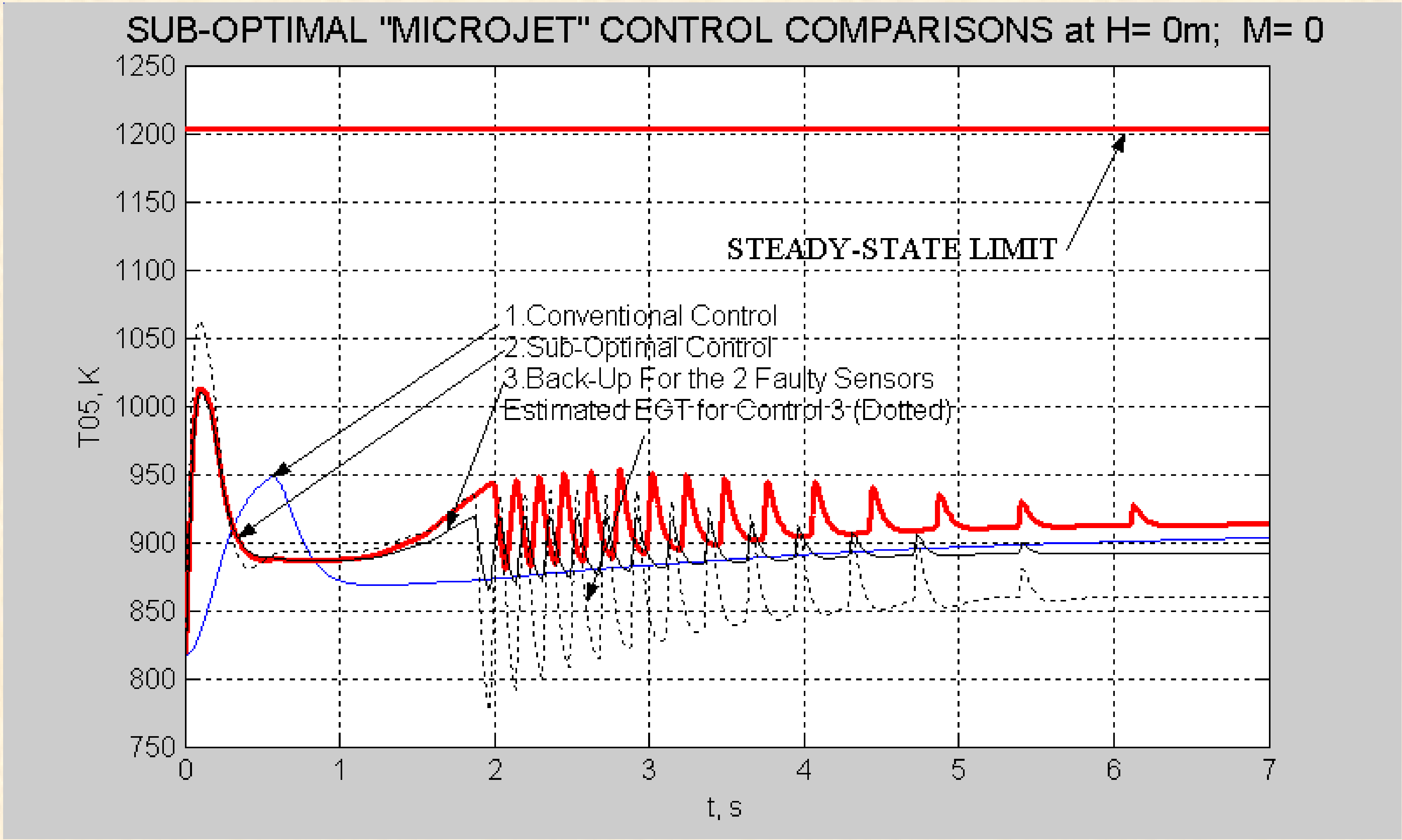
Transient Operating Line During Engine Acceleration



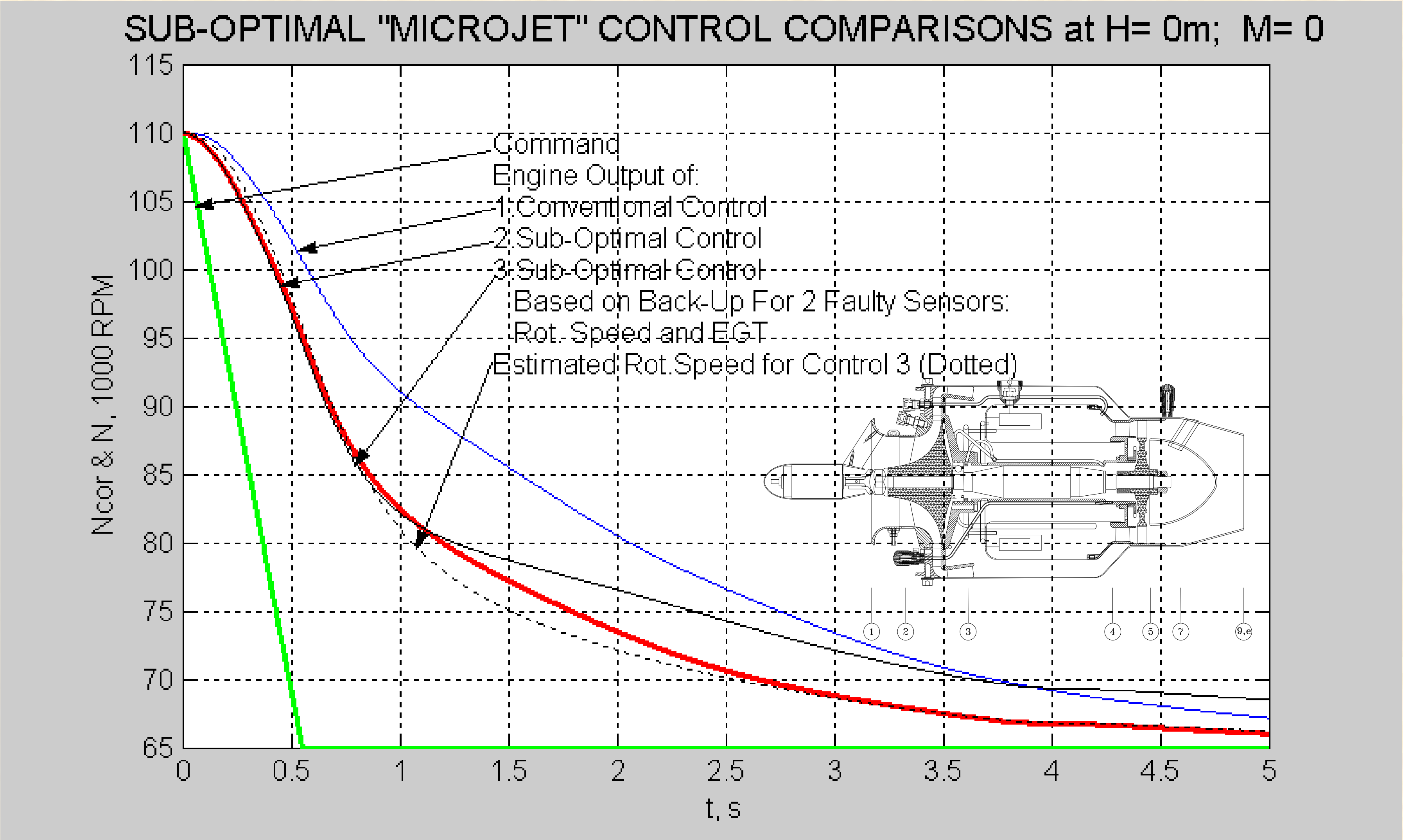
Stall Margin During Engine Acceleration



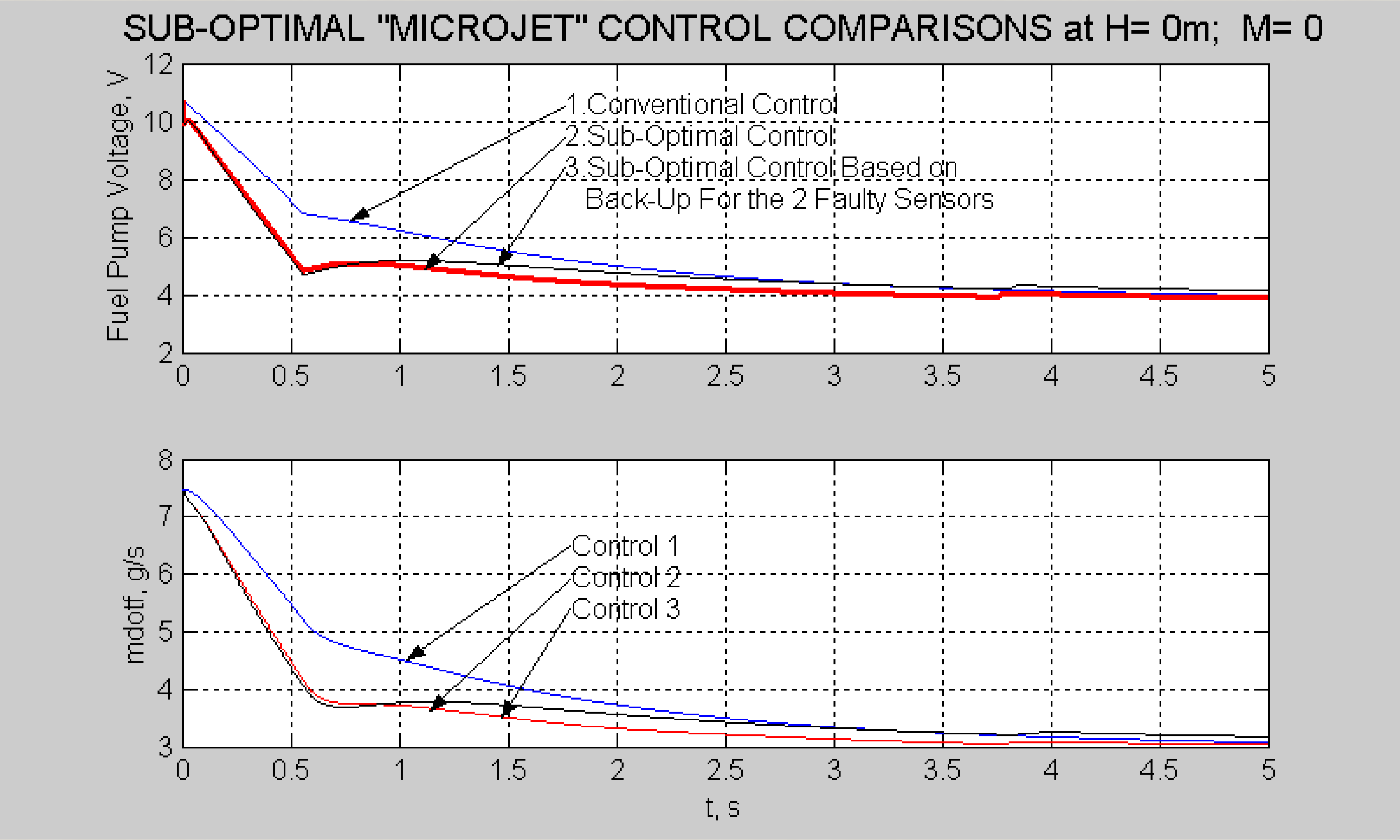
Output Turbine Temperature (EGT)



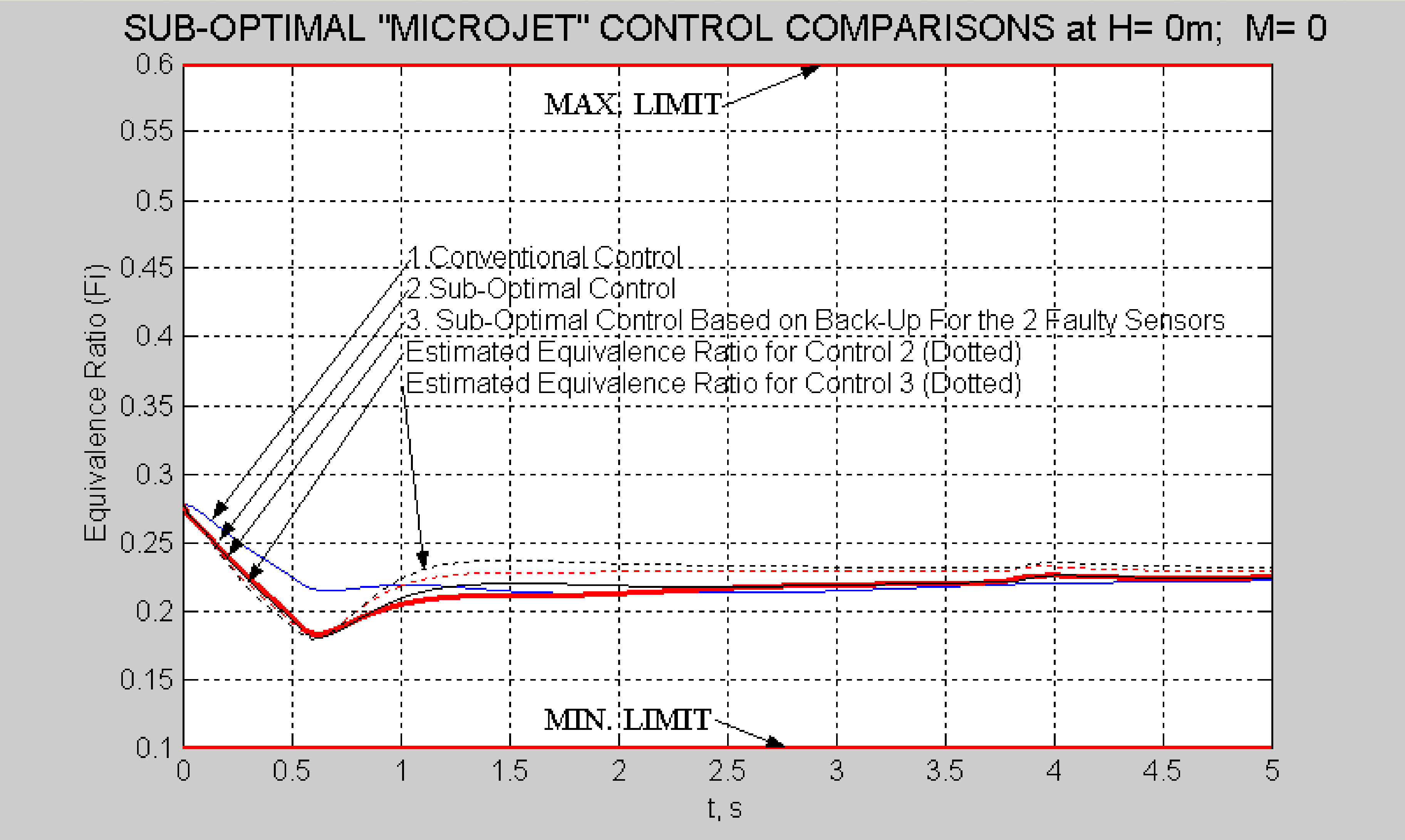
Corrected Rotational Speed **<u>During Engine Deceleration</u>**



Fuel Pump Voltage and Fuel Mass Flow



Equivalence Ratio During Engine Deceleration



CONCLUSIONS

- .Conventional linearization for the nonlinear engine model is not desirable
- Sub-optimal control provides:

  a) dynamic operating line close to the surge line during engine acceleration (maximum fuel rate)

  b) equivalence ratio close to a minimal limiting value during engine deceleration (minimum fuel rate)
- The fast engine model may be used on-line, both, for unmeasured parameter estimations and as a back-up for faulty sensors

THE END