



Commercial Modular Aero-Propulsion System Simulation 40k (C-MAPSS40k)

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4th NASA GRC Propulsion Control and Diagnostics Workshop
December 11-12, 2013



Team members

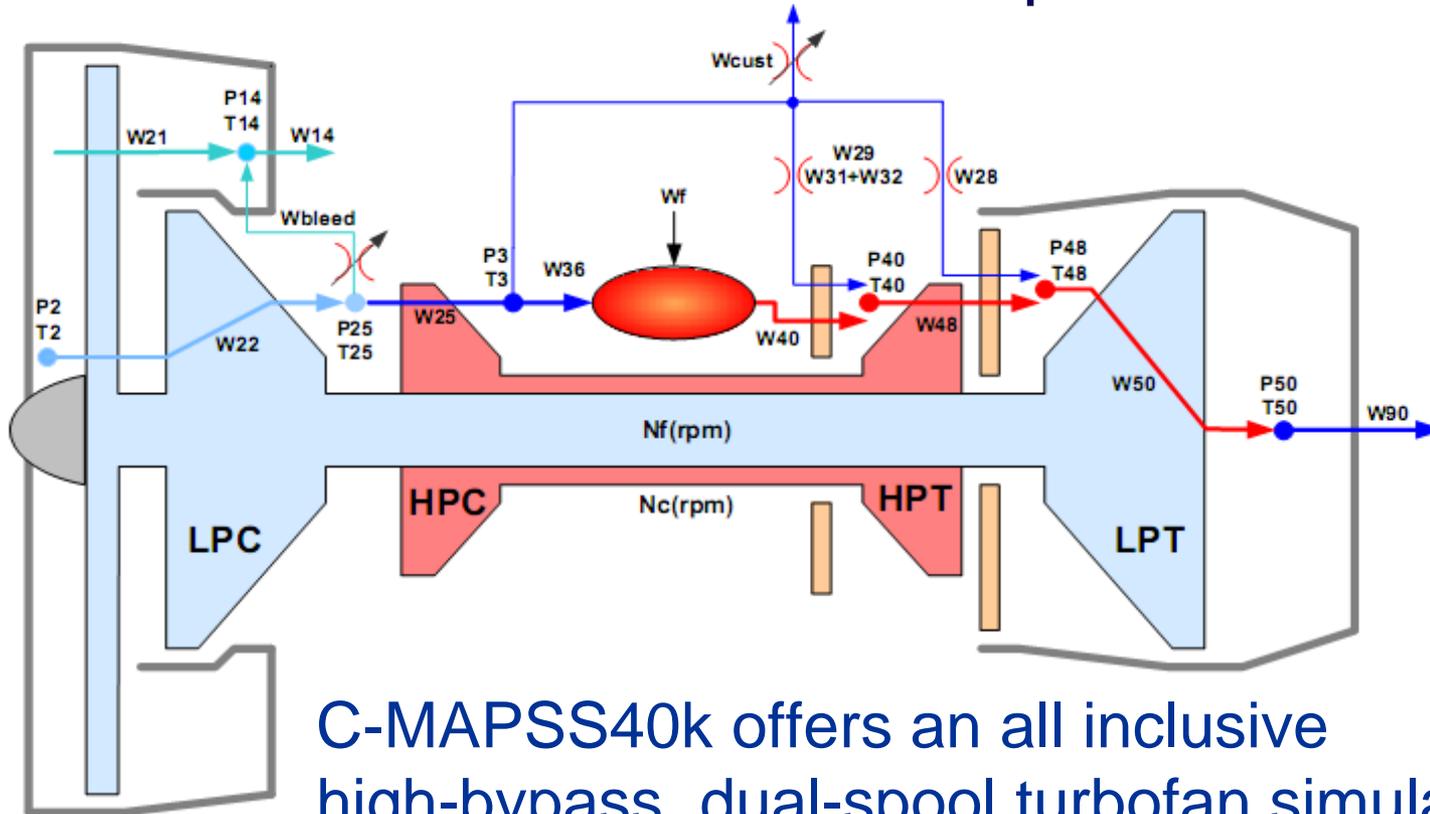
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C-MAPSS40k Overview

- Simulation description
- Engine simulation
- Control system
- User features
- Recent updates
- Conclusion

Simulation Description

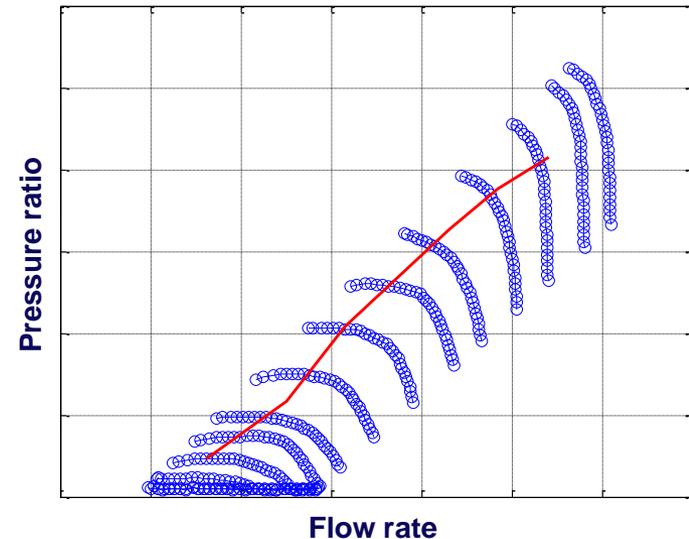
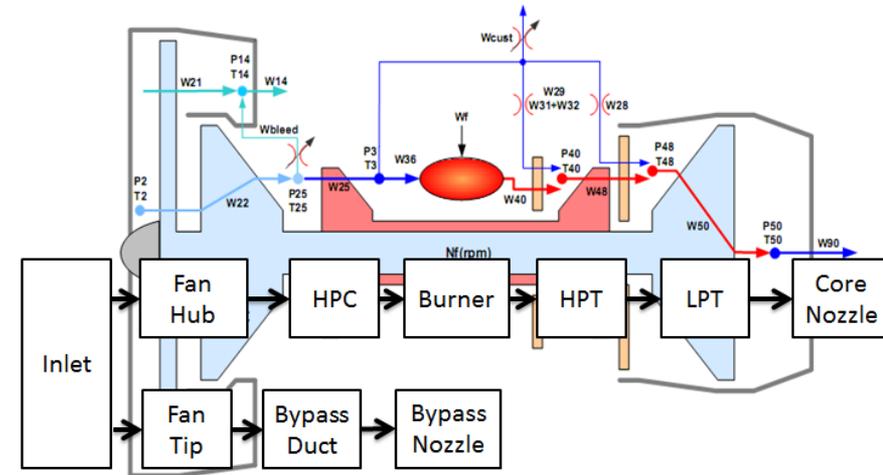


C-MAPSS40k offers an all inclusive high-bypass, dual-spool turbofan simulation

- 40,000-lb_f thrust class
- MATLAB/Simulink
- Steady state and dynamic operation
- Realistic control system

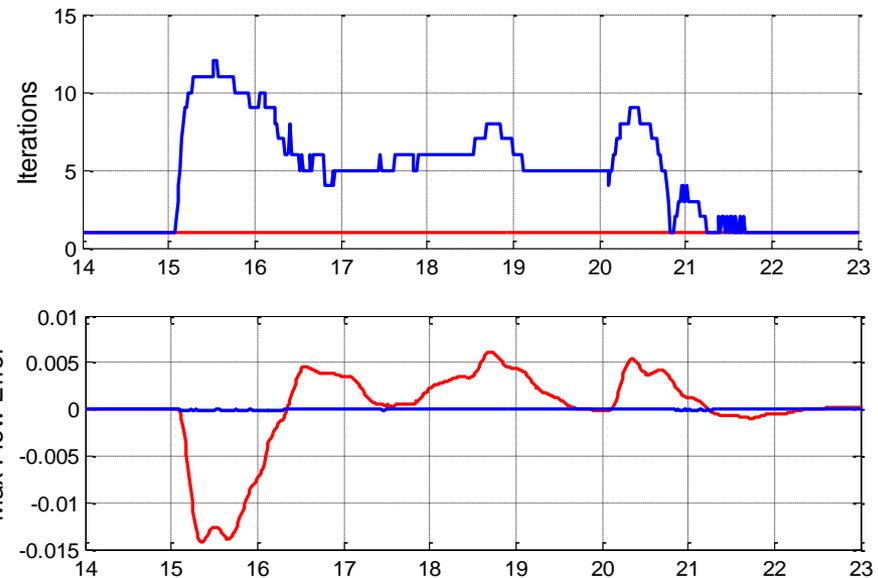
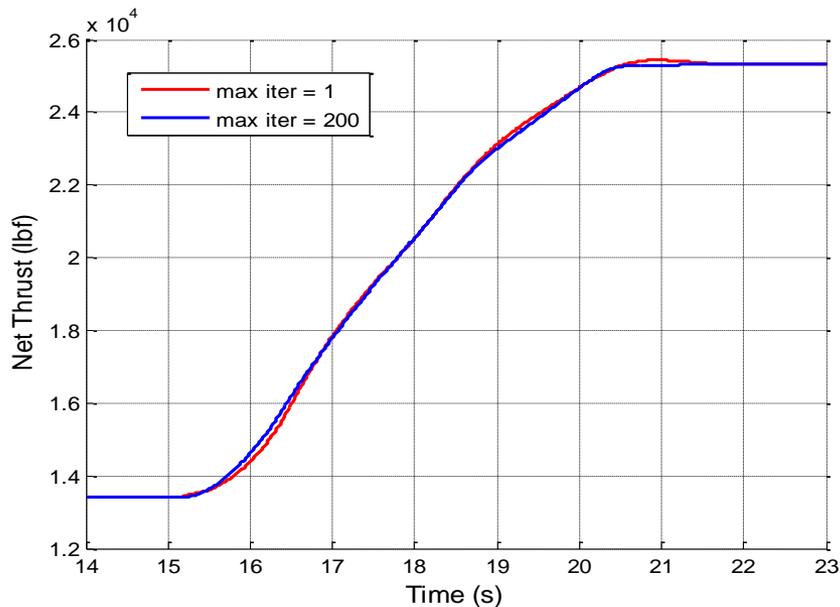
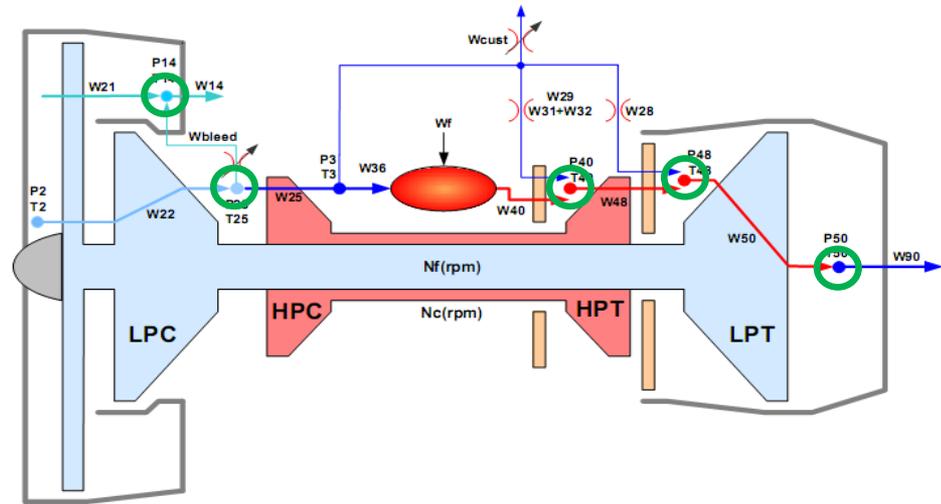
Engine Simulation

- Component-level modeling
- Physics-based
 - Aerothermodynamics
 - Performance maps
- Operates over wide range of environmental conditions
 - Mach, altitude, DT_{amb}
- Faster than real-time
 - Components coded in C
 - Assembled in Simulink
 - Run via MATLAB
- Detailed stall margin model
- Engine health condition



Engine Simulation

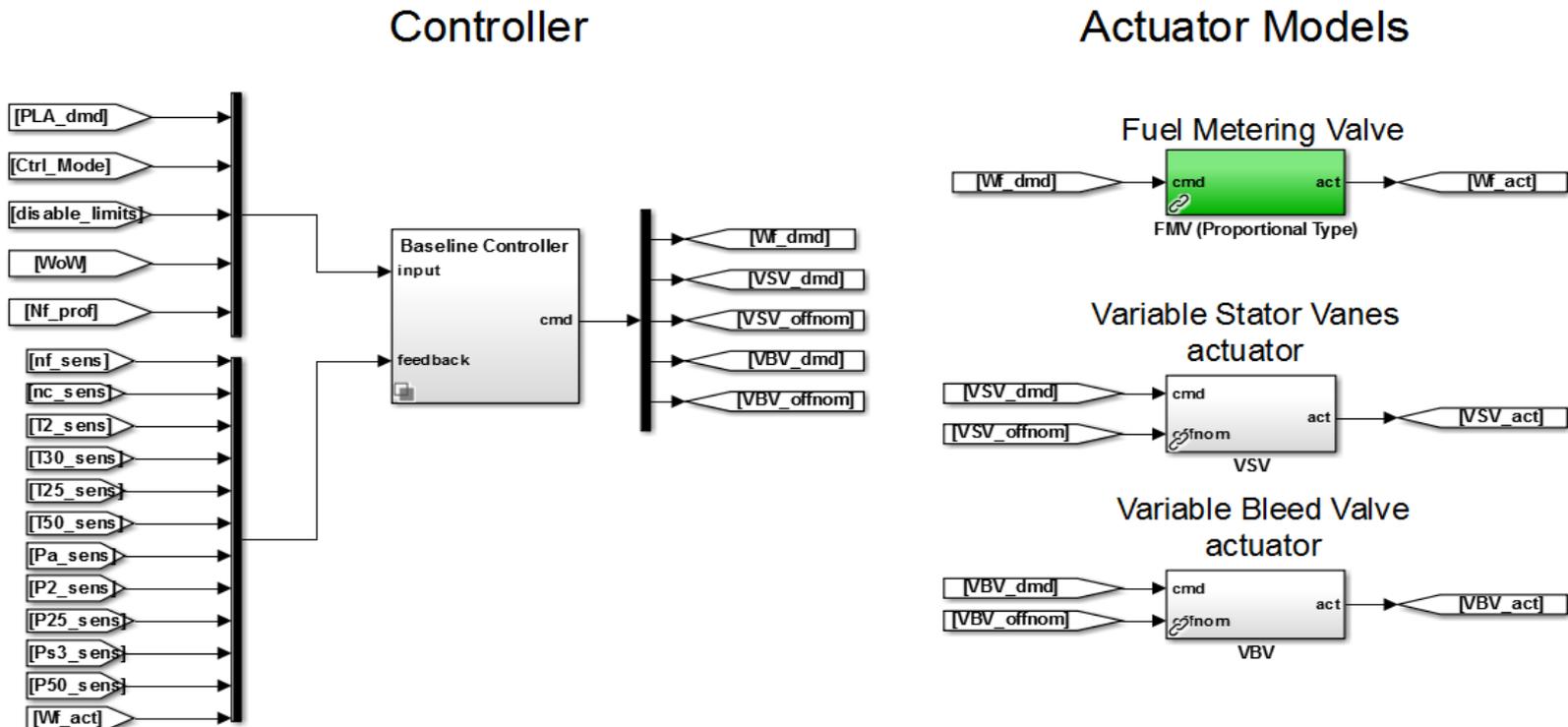
- Dynamics
 - Nonlinear dynamical system with spool speeds as state variables
- Flow continuity
 - Iterate to ensure conservation of mass and energy at each time step
 - Realistic transient performance





Control System

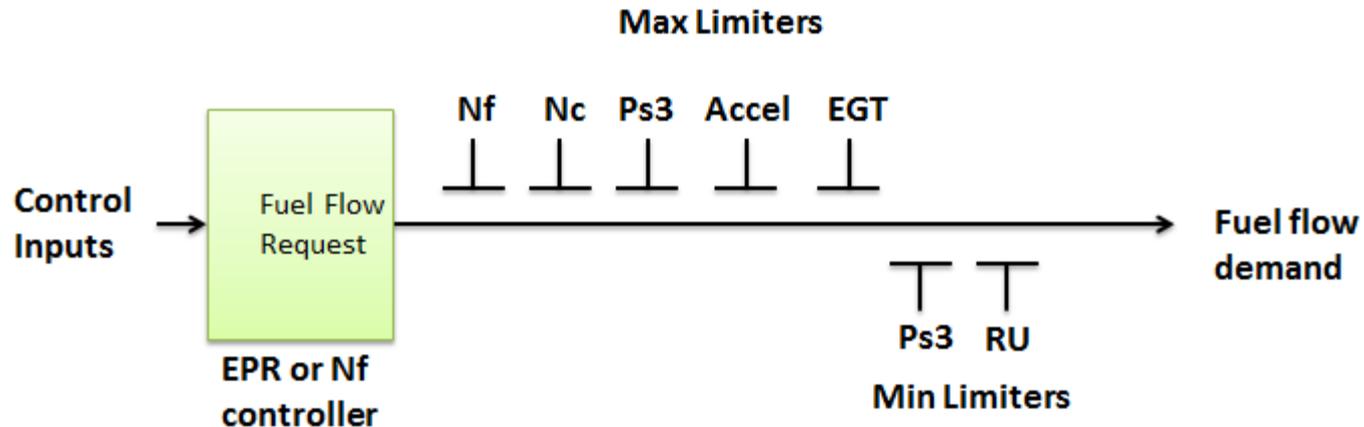
- Representative of industry standard
- Controls engine based on throttle input
- Calculates fuel flow, variable stator vane position (VSV), variable bleed valve position (VBV)
- Uses typically sensed engine outputs
- Simulates actuator/sensor dynamics





Control System

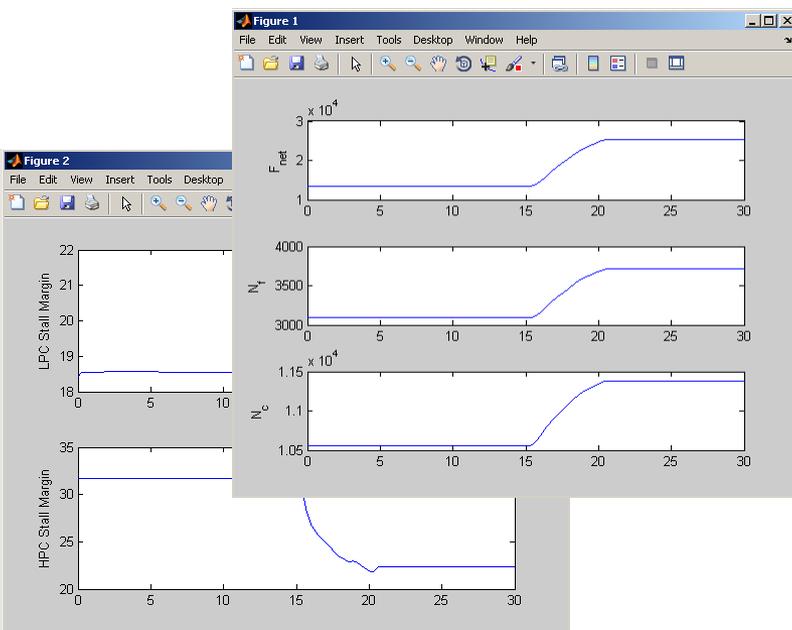
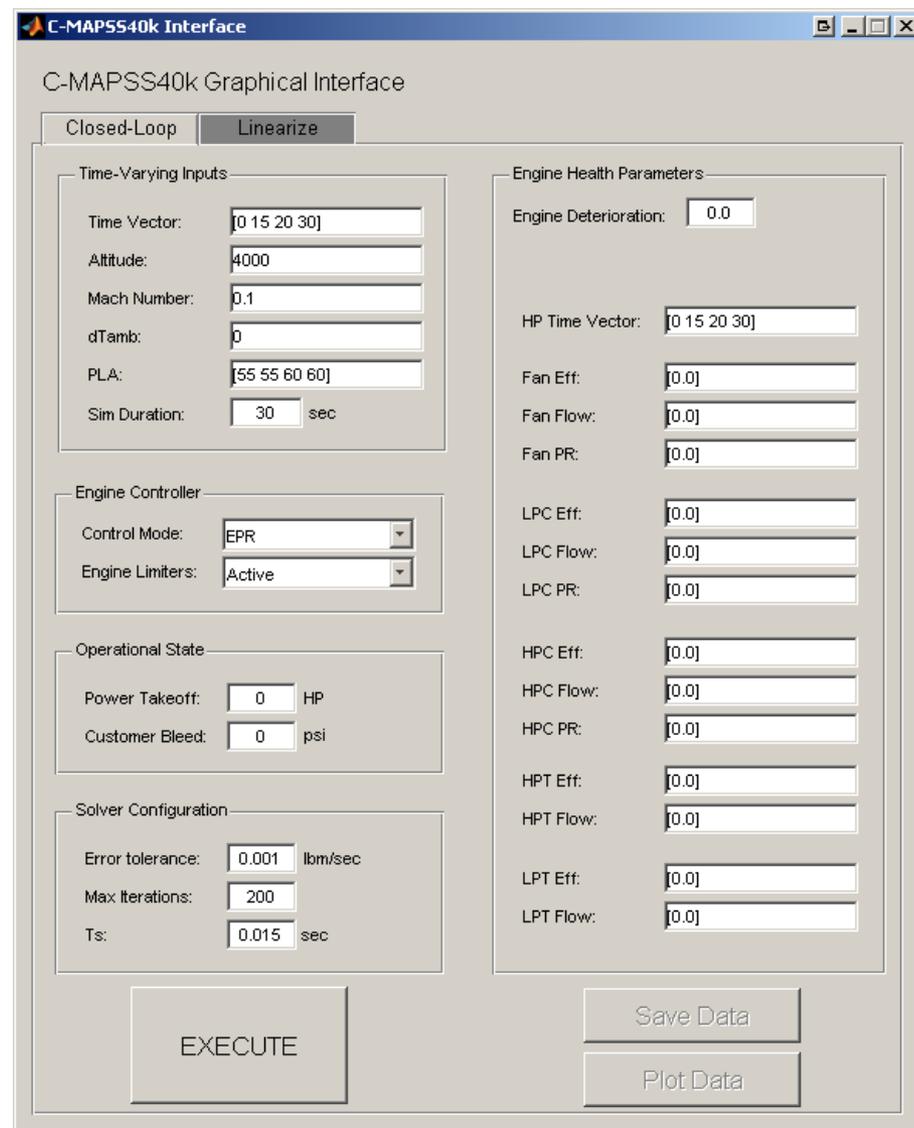
- VSV, VBV are scheduled on sensed engine parameters
- Fuel: gain-scheduled PI feedback control on EPR/Nf with protection logic



Protection Logic Architecture representative of Industry Standard

User Features: Graphical Interface

- Environmental & throttle inputs
- Control settings
- Simulation settings
- Engine health settings
- Plot & save data

C-MAPSS40k Interface

C-MAPSS40k Graphical Interface

Time-Varying Inputs

Time Vector: [0 15 20 30]
 Altitude: 4000
 Mach Number: 0.1
 dTamb: 0
 PLA: [55 55 60 60]
 Sim Duration: 30 sec

Engine Health Parameters

Engine Deterioration: 0.0
 HP Time Vector: [0 15 20 30]
 Fan Eff: [0.0]
 Fan Flow: [0.0]
 Fan PR: [0.0]
 LPC Eff: [0.0]
 LPC Flow: [0.0]
 LPC PR: [0.0]
 HPC Eff: [0.0]
 HPC Flow: [0.0]
 HPC PR: [0.0]
 HPT Eff: [0.0]
 HPT Flow: [0.0]
 LPT Eff: [0.0]
 LPT Flow: [0.0]

Engine Controller

Control Mode: EPR
 Engine Limiters: Active

Operational State

Power Takeoff: 0 HP
 Customer Bleed: 0 psi

Solver Configuration

Error tolerance: 0.001 lbm/sec
 Max Iterations: 200
 Ts: 0.015 sec



User Features: Script/Command Line

- MATLAB command line
- MATLAB scripts
- MS Excel input profile generation

	A	B	C	D	E	F
1	C-MAPSS40k Input Flight Profile					
2						
3	Environmental Inputs					
4	Time Vector (sec)	0	10	15	135	137
5	Altitude (ft)	971	971	971	6000	6000
6	Mach Number	0	0	0.15	0.4	0.4
7	dTamb (deg F)	0	0	0	0	0
8	PLA (deg)	40	40	78	78	73

```

>> run_gui
Starting C-MAPSS40k...
All subdirectories added to MATLAB path
Have loaded data for nozzle tables
Have loaded data for Powerset tables
Have loaded data for Controller tables
Have defined initial conditions
All simulation components setup
Engine properties loaded
** C-MAPSS40k ready to execute **

%=====
% Environmental Inputs
%=====
try
    var_names = {'t_vec','alt','MN','dTamb','PLA'};
    for i=1:length(var_names)
        eval(['var_names(i) = in_' var_names(i) ''])
    end
catch
    t_vec = [0 15 15.1 30];
    alt = 971; %altitude (0 to 40,000 ft)
    MN = 0.2; %Mach Number (0 to 0.8)
    dTamb = 0; %Delta Temperature (-30 to +50)
    PLA = [55 55 75 75]; %PLA or Power Code (40 to 80.5)
end

%=====
% Operational Inputs
%=====
try
    var_names = {'pwrTakeoff','custBleed'};
    for i=1:length(var_names)
        eval(['var_names(i) = in_' var_names(i) ''])
    end
catch
    pwrTakeoff = 0; % power takeoff (Hp)
    custBleed = 0.0; % customer bleed (lb/s)
end

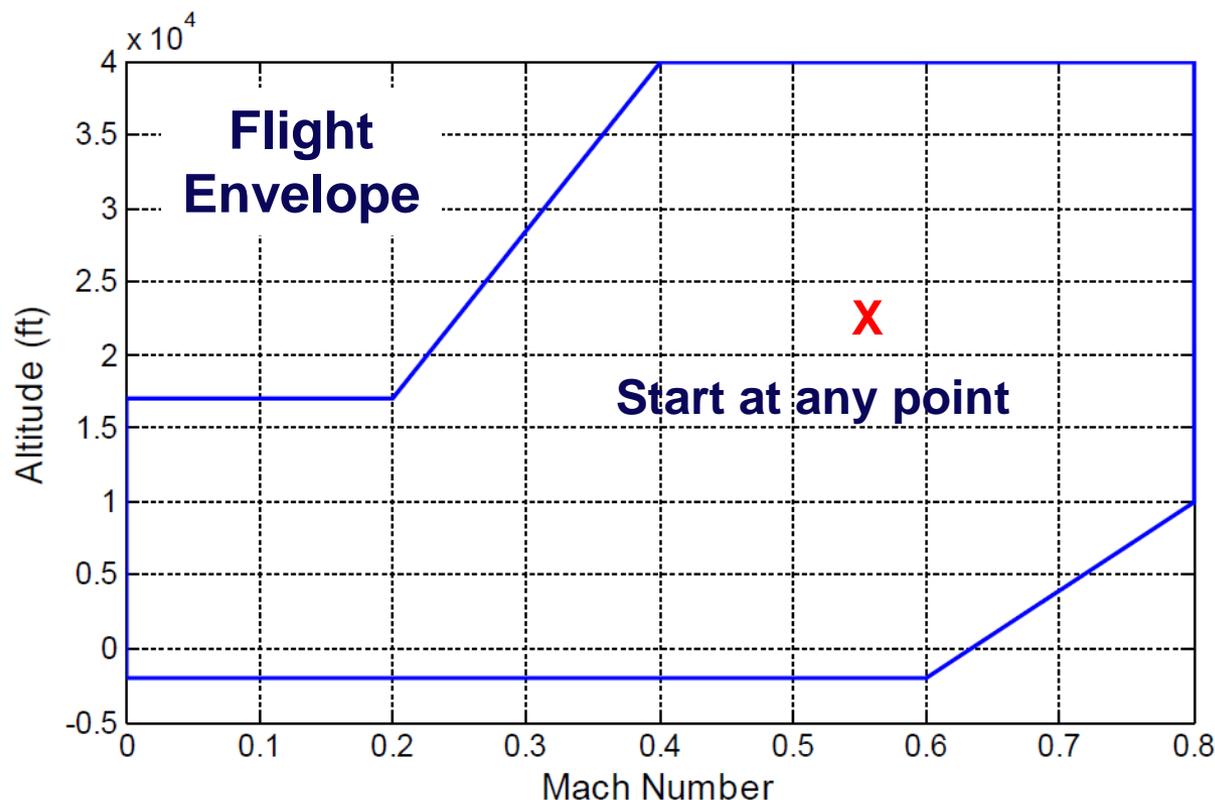
%=====
% Controller Inputs

```



User Features: Steady-State Solver

- Steady-state engine model calculates the initial conditions for any point in flight envelope before simulation run
- Faster and more elegant than “flying” to desired starting point from a known initial flight condition





User Features: Linear Models

$$\dot{x} = Ax + Bu + Lh$$

$$y = Cx + Du + Mh$$

- Generate linear models about any equilibrium point (i.e., flight condition)
- Specify flight/health condition
- Specify state/input variable vectors
- Verify and save linear model

C-MAPSS40k Interface

File About

C-MAPSS40k Graphical Interface

Closed-Loop Linearize

Environmental Conditions

Altitude: 4000

Mach Number: 0.1

dTamb: 0

Power Ref: PLA: 68.5

Operational State

Power Takeoff: 0 HP

Customer Bleed: 0 ps

Engine Health Parameters

Engine Det: 0.0

Fan Eff: 0.0

Fan Flow: 0.0

Fan PR: 0.0

LPC Eff: 0.0

LPC Flow: 0.0

LPC PR: 0.0

HPC Eff: 0.0

HPC Flow: 0.0

HPC PR: 0.0

HPT Eff: 0.0

HPT Flow: 0.0

LPT Eff: 0.0

LPT Flow: 0.0

State Vector (x): [Nf ; Nc]

Control Inputs (u): Wf

Use Simulink model 3 sec

Input Perturbation Size

Nf: 30.0 Fan Eff: 1e-3

Nc: 30.0 Fan Flow: 1e-3

Fan PR: 1e-3

LPC Eff: 1e-3

LPC Flow: 1e-3

LPC PR: 1e-3

HPC Eff: 1e-3

HPC Flow: 1e-3

HPC PR: 1e-3

HPT Eff: 1e-3

HPT Flow: 1e-3

LPT Eff: 1e-3

LPT Flow: 1e-3

Wf: 0.017

Verification Parameters

Initial PLA: 68.5 deg

Change in PLA: 2 deg

PLA transient duration: 3 sec

Linearize

Verify System

Save System



Major Updates

- **Controller input realism**
 - Adjusted control logic to be based exclusively on typical sensed parameters and control inputs
- **Adjusted PLA to Fuel flow request mapping**
 - Ground idle speeds (Nf and Nc) reflect more realistic levels
 - Increased linear relationship between PLA and Thrust
- **Fuel flow limiter updates**
 - Added an EGT limiter to the controller
 - Updated Ps3max, Nfmax, and Accel Limiters to be more realistic
- **Linear model Power Reference**
 - Added feature to allow a user to linearize the engine about a specified set point type: Nc, Nf, or PLA.
- **Off-nominal variable stator vane positions**
 - Updated off nominal VSV effects to be more realistic in its effect on stall margin and engine performance



Summary

- Simulation of 40,000-lb_f class, high-bypass, dual-spool turbofan engine
- Physics-based, component-level model
- Faster than real-time
- Realistic control system
- Graphical/command-line user interfaces
- Linear model generation



Related NASA Publications

- Csank, Jeffrey, May, Ryan D., Litt, Jonathan S., and Guo, Ten-Huei, "Control Design for a Generic Commercial Aircraft Engine," AIAA-2010-6629, 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Nashville, TN, July 25-28, 2010, also NASA/TM—2010-216811, October 2010.
- May, Ryan D., Csank, Jeffrey, Lavelle, T. M., Litt, Jonathan S., and Guo, Ten-Huei, "A High-Fidelity Simulation of a Generic Commercial Aircraft Engine and Controller," AIAA-2010-6630, 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Nashville, TN, July 25-28, 2010, also NASA/TM—2010-216810, October 2010.

Available for download from the NASA Software Repository

- *Software availability limited to U.S. citizens due to export control regulations*

<https://sr.grc.nasa.gov/public/project/77/>