SimTurbo©: Innovative, Graphical Gas Turbine Engine Simulation

Abstract

Gas turbine engines have been used for air transportation and power generation since the early 1900s. The design of the engine systems requires complex, integrated knowledge in the disciplines of thermodynamics, heat transfer, fluid dynamics, control systems, and various other mechanical and electrical engineering knowledge bases. Several tools currently exist in the marketplace for engineers to organize these disciplines for gas turbine engine design. This paper introduces a new tool that addresses some of the open needs in gas turbine engine thermodynamic and control system design, analysis and simulation. SIMTURBO© provides intuitive understanding, ease of use in addition to analysis accuracy and high level to detailed presentation formats. SIMTURBO© is an innovative, new software system which provides aerospace and power system design engineers with a Windows-based, graphical user interface for design, analysis, development and simulation of gas turbine engine systems. This software has the benefits and advantages over existing simulation and performance design software tools by enabling the design engineers to rapidly synthesize, architect, parameterize, simulate and analyze new aero-thermodynamic systems with visual components. The complex gas turbine engine component equations are built in, implemented, and ready for system design. The user also has the capability to modify the components to match custom and new designs. SIMTURBO© contains a large set of tools and components ranging from modifiable engine components (i.e. inlets, compressors, combustors, turbines, nozzles, shafts, etc.), control components (i.e. PID, limiters, etc.), actuators, sensors, signals, sources, and many others. The simulation runs in real-time on a standard PC with updating time graphs and displays of transient parameters, component maps, flight and environmental conditions and thermodynamic cycle diagrams.

SIMTURBO© was validated versus NASA Lewis Research Center Test Data for the J-85-21 turbojet engine at design speed of 16500 RPM and sea level static standard condition. SimTurbo© simulation results matched the test data for parameters such as thrust, temperatures, and flowrates within +/- 2 percent.

A key benefit of SIMTURBO© are the educational benefits for Aerospace University students. Users can view real-time data on internal engine dynamics, including pressure ratios, temperature dynamics, and fuel efficiency. SIMTURBO© bridges the gap between courses in thermodynamics, heat transfer, control theory and gas turbine engine design in a visual, hands-on, integrated platform. This allows students to grasp fundamental concepts in closer to real life and real-time, visual simulations.

Keywords—gas turbine engines, simulation, turbojet, real-time simulation.

I. Introduction

Gas turbine engines have been widely used in numerous industries world-wide since the early 1900s. These industries and applications include aircraft engine propulsion, other vehicle production (such as helicopters and naval vessel propulsion), and small to large scale energy production. Despite the existence of various thermodynamic and control simulation tools for gas turbine applications, there are still opportunities to improve on the gas turbine engine design processes and tools. These opportunities include the need for a user-friendly, efficient, computer tool to simulate and provide flexible design capabilities for the steady state and transient operations of gas turbine engines and controls. This paper introduces SIMTURBO© a new graphical user simulation tool that provides many of these capabilities. Utilizing SIMTURBO©, a user can configure and model a gas turbine engine simulation with the ease of computer mouse/keyboard operations to select and layout pre-constructed thermodynamic model blocks with flexible design parameters. SIMTURBO© currently provides the modeling and design capability for single spool gas turbine engines, but will in the near future provide the capabilities to model and design more complex systems such as dual spool turbofans, regeneration, turboprops and many other gas turbine engine configurations. This paper shows the use of SIMTURBO© applied for the steady state, transient and control simulation for the single spool gas turbine engine, J-85-21 [2]; the military gas turbine engine developed by General Electric in the late 1950s. This paper is partitioned into nine main sections: I) Introduction, II) Overview of Model Thermodynamic Components, III) SIMTURBO© System Overview, IV) Overview of Control Components, V) Steady State Results, VI) Transient Results, VII) Real-Time Operation, VIII) Educational Benefits, IX) Conclusion.

II. Overview of Model Thermodynamic Components

The single spool gas turbine consists of six components: inlet, compressor, combustor, turbine, duct, and nozzle. The goals of the gas turbine engine vary depending upon the application. For aircraft and naval vessel engines, the goal is to convert the atmospheric air and input fuel into thrust to propel the vehicle. For energy generation systems, the goal is to convert the atmospheric air and input fuel into rotational energy to provide electrical energy via generators. Figure 1. shows a schematic of a basic single spool gas turbine engine, as represented in SIMTURBO©. The blue lines show the gas flows between components in-ports and out-ports with flow directions shown by the arrowheads. The blue dots on the edges of the inlet, compressor and nozzle ports represent the component flows from and to the atmospheric air. The red/black dashed line represents the shaft connecting the compressor and turbine. The white arrowheads are control signal ports. The yellow arrowhead is a fuel entrance port for

Author: Paul J. Hoffman,
President and CEO Controls Research LLC

the combustor. The red arrowheads are shaft power ports. These ports are explained later in the paper. The black numbers represent station designations for the ports to facilitate modeling based on the SAE gas turbine engine standard. Station Number 0 is at Ambient conditions. The other Station Numbers correspond to component entrances, exit for Station Number 8 which represents the Nozzle Throat section.

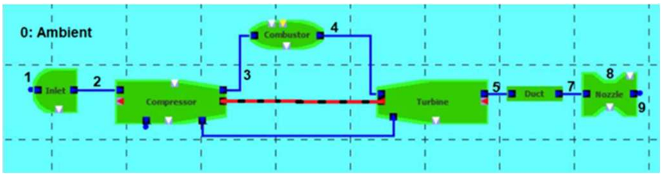

Figure 1. Schematic of Basic Single Spool Gas Turbine Engine

A. Atmosphere Modeling

The atmosphere (ambient) air is modeled as a function of engine system altitude and inlet Mach Number using the International Standard Atmosphere (ISA) standard. [1]

For Sea Level to 11000 meters in Altitude:

$Tt0 = 288.15 – (0.0065 * Alt)$ Equation 1

$Pt0 = 101325 * (Tt0/288.115) ^{\wedge}.2561)$ Equation 2

B. Inlet Thermodynamic Modeling

The inlet is typically the first component of the engine. The inlet takes in atmospheric air and is designed to provide a relatively distortion-free flow of air to the remainder of the engine. The basic inlet is modeled using Ram recovery and assuming isentropic flow for the inlet.

C. Compressor Thermodynamic Modeling

The airflow exits the inlet and enters the next component, the compressor. The compressor adds energy by compressing the air to the highest pressure in the engine. The compressor steady state operation is modeled using its particular compressor map. As represented in SIMTURBO©, the compressor map for the General Electric, military J-85-21 turbojet engine is shown in Figure 2:

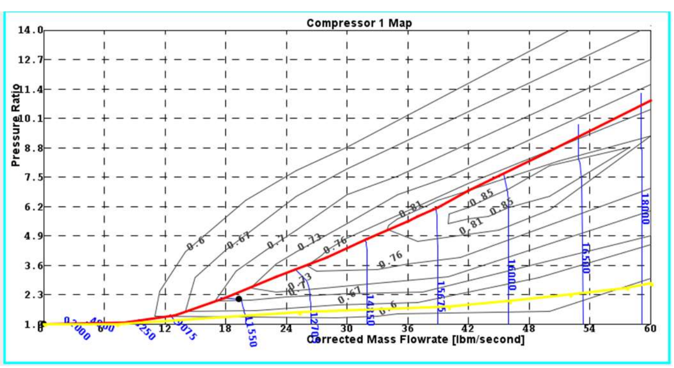

Figure 2 J-85 Compressor Map

D. Combustor Thermodynamic Modeling

he pressurized airflow exits the compressor and enters the next component, the combustor and is mixed with the controlled fuel. The compressor is modeled using conservation of mass and energy for a combustible gas mixture as follows:

$W_{combustor} = W_{combustor}$ Equation 3

$Tt4 = [(W_{combustor}*cp3*Tt3) + \eta_B*W_f*Q_{LHV} - Q_{Loss}]/(W_{combustor}*cp4)$ Equation 4

Where: cp4 is combustor exit specific heat

η_B is combustor effective burner efficiency

W_f is fuel mass flowrate entering combustor

Q_{LHV} is the lower heating value of the fuel

Q_{Loss} is the rate of heat loss from the combustor to ambient

E. Turbine Thermodynamic Modeling

Hot gas from the exit of the combustor enters the turbine inlet. The turbine expands the hot gas delivered by the combustor across its turbine blades to provide power to drive the compressor. The turbine steady state operation is modeled using its particular turbine map. As represented in SIMTURBO©, the turbine map for the J-85-21 engine is shown in Figure 3:

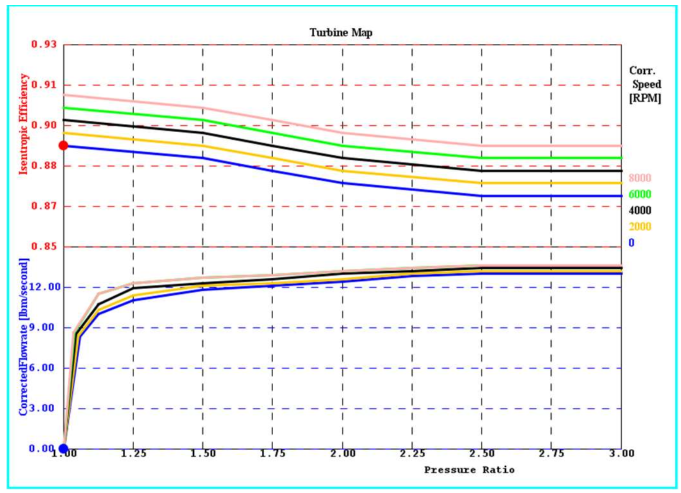

Figure 3. J-85-21 Turbine Map

The expansion of the air/fuel mixture across the turbine is calculated using conservation of mass and energy as follows:

$W_{turbine} = W_{combustor}$ Equation 5

$Tt5 = \{(Tt4+\Delta T)*[\Gamma 4/5^{\wedge}(1.0-\gamma 4)/\gamma 4]\} - \Delta T$ Equation 6

Where: $\Gamma 4/5$ is the turbine inlet to exit pressure ratio

$\gamma 4$ is the turbine inlet ratio of specific heats

The turbine power is calculated as follows:

$P_{turbine} = W_{turbine}*(cp5*Tt5 – cp4*Tt4)*\eta_T$ Equation 7

Where: η_T is the turbine isentropic efficiency provided by the turbine map for given flow condition.

F. Compressor / Turbine Power Balance

For the single spool gas turbine engine, the power balance between the turbine and compressor is calculated to provide the shaft spool acceleration as follows:

$dN/dt = (P_{turbine} - P_{compressor})/(J*N)$

Where: Shaft Spool Speed = N

d denotes differential

t = time

J = Spool Rotational Inertia accounting for shaft, coupling, compressor and turbine inertias

G. Duct Thermodynamic Modeling

Downstream of the turbine, the gas flow is straightened by the duct prior to entering the nozzle. The duct pressure loss is calculated as proportional to the inlet pressure. The duct exit temperature is calculated assuming appropriate heat loss to ambient.

H. Nozzle Thermodynamic Modeling

The nozzle is located at the exit of the engine and is used to convert internal energy of the engine exhaust into high velocity thrust for propulsion.

Conservation of Mass:

Exit flowrate equals inlet flowrate:

$W_9 = W_7$; Equation 8

Nozzle Thrust = T_N

$T_N = W_9 * V_J / Gc$ Equation 9

Where: W_9 *is nozzle exit flowrate*

V_J *is nozzle jet velocity*

Gc is gravitational constant

The nozzle is modeled for convergent or convergent/divergent configuration under two flow conditions:

1) unchoked and

2) choked.

For unchoked flow, the nozzle inlet pressure is greater than the Critical Pressure.

Critical Pressure, Pc = P7*[2/(γ7 + 1)]^(γ7/γ7-1) Equation 10

For unchoked flow, the nozzle follows isentropic flow conditions: Ps9 = P0 Exit Static Pressure equals Ambient Pressure

Jet Velocity = VJ = W9/(ρ9*A9) Equation 11

For choked flow, sonic flow conditions exist:

Ps9 = Maximum (P0, Pc)

Exit flowrate is choked:

W9 = [(A8*Pc)/(T8+ΔT)]/[γ9/[(Gc*R) *(γ9+1)/2] ^{-(γ9+1)/[2*(γ9-1)]} Equation 12

Jet Velocity = speed of sound

VJ = [Gc*γ9*R*(Ts9 + ΔT)] ^0.5 Equation 13

Where: A8 is nozzle throat area

γ9 is nozzle exit ratio of specific heats

R is gas constant

III) SIMTURBO© System Overview

A schematic showing the SIMTURBO© Design Palette with a single spool, turbojet engine system is shown in Figure 4.

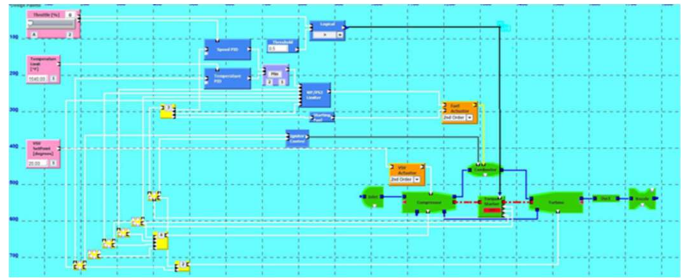

Figure 4. SIMTURBO© Design for Single Spool, Turbojet

In the upper left hand corner, first we have the control set points (pink components) provided as a Throttle input, the system Temperature limit, and the Variable Stator Vane (VSV) set point. These provide the set point inputs to the blue control system components (more about them in section IV of this paper). The control provides regulation inputs to the actuator components (fuel and VSV actuators) shown in orange. The actuators provide the modeled component inputs to the engine components, in this case, regulated fuelrate and VSV angle. The white lines denote communication signals between components such as control signals or sensor feedback signals. The black lines denote boolean signals: 1) from the ignitor control to the combustor ignition input, and 2) from the Logical block to start the Torque Starter. Physical engine output signals are transmitted from the green engine components to the various sensor components shown in yellow, such as the speed, temperature, pressure and flowrate sensors. These sensors provide feedback signals to the Control (blue) components. Both the sensors and actuators can be modeled as first or second order components using SIMTURBO©.

A Torque Starter component is located between the Compressor and Turbine, with a connecting shaft shown as a dashed red line. Since a gas turbine engine is not self-starting, the torque starter on engine startup command provides a simulated hydraulic air or electrical starting torque to spin up the compressor/turbine system.

IV) Overview of Control Components

The control (blue) components shown in Figure 4, model a basic single input/single output, dual speed and temperature control typical of many gas turbine engine controls. The Speed PID (Proportional Integral-Derivative) Control and Temperature PID monitor and regulate Turbine Speed and Turbine Exit Temperature respectively. The J-85-21 engine turbine exit temperature was limited to 2000 Rankine by the control as a turbine material blade design protection. The minimum of these two outputs are inputted into the WF/PS3 Limiter control, which limits system fuel flow rate which when properly designed prevents compressor surging during large rotor accelerations. The Ignitor Control is activated during the engine starting process and is regulated by the sensed turbine speed and sensed turbine exit temperature. The Starting Fuel Control is used to provide a small starting fuel rate to prime the combustor during starting. SIMTURBO© provides a huge library of control, actuator, and signal components for modeling gas simple to very complex control systems.

V) Steady State Results

SIMTURBO© has the capabilities to show engine cycle plots both in steady state and transiently. Figure 5 shows the cycle plot captured during a steady state point.

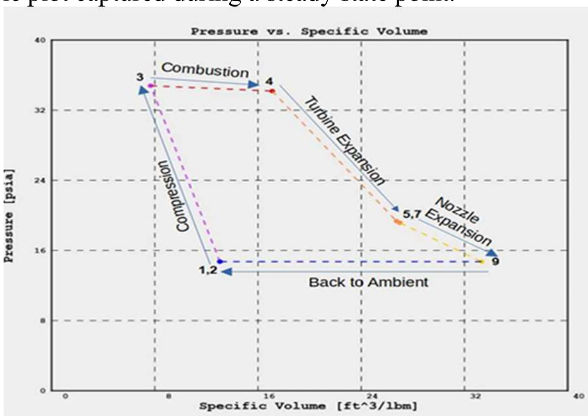

Figure 5. Cycle Plot prepared using SIMTURBO©

SIMTURBO© has capabilities to simulate engine performance for constant as well as variable flight envelope (altitude and flight Mach number) conditions. For this paper, the J-85-21 engine was simulated at two steady state flight envelope conditions: 1) Sea Level Static (altitude = 0 feet, flight Mach = 0), and 2) Cruise (altitude = 35000 feet, flight Mach = 0.8). These results are shown in Figures 6 and 7.

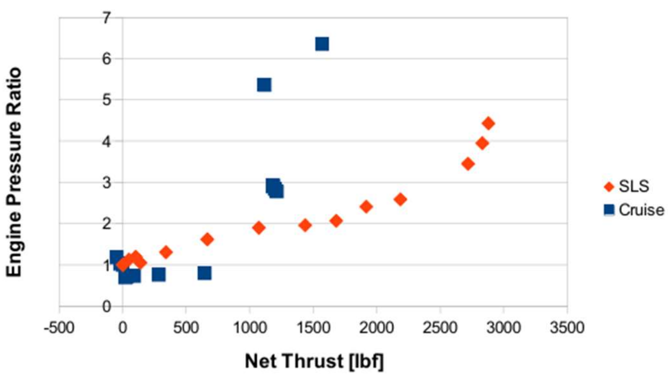

Figure 6. Engine Pressure Ratio as a function of Net Thrust

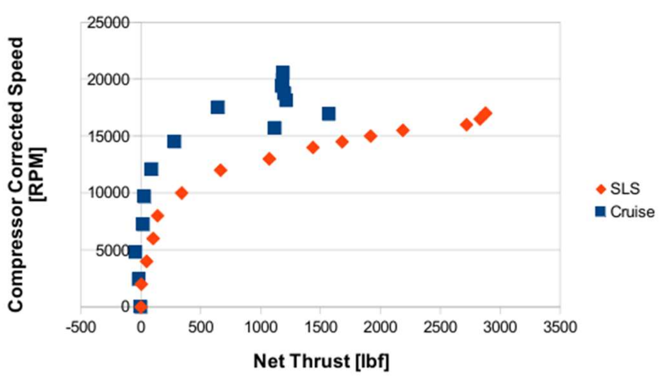

Figure 7. Compressor Corrected Speed as function of Net Thrust

VI) Validation of SimTurbo© versus NASA Test Results

SIMTURBO© was validated versus NASA Test Results [9] for the J-85-21 single spool turbojet engine at the design speed of 16500 RPM at sea level static, non-afterburning condition. The results are provided in Table 1. In particular, the following parameters (inlet air flowrate, net thrust, TSFC, fuel mass flowrate, turbine exit temperature, exhaust gas temperature) all matched within +/- 2 percent.

Table 1. Validation of SimTurbo© Simulation versus NASA Research Center Test for GE-J85-21 Engine for Dry (Non-Afterburning) Condition

Inputs			
Altitude [feet]	0		
Day Temperature [deg. F]	Standard Day		
Mach	0		
Inlet Diffuser Efficiency	0.87		
Compressor Pressure Ratio	8.3		
Compressor Isentropic Efficiency	0.85		
Compressor Bleed Flow Ratio	0.035		
Combustor Burner Efficiency	0.99		
Combustor Pressure Loss Ratio	0.05		
Turbine Inlet Maximum Temperature [deg. F]	1790		
Turbine Isentropic Efficiency	0.89		
Mechanical Efficiency	0.99		
Nozzle Throat Area [square feet]	0.7986		
Nozzle Expansion Ratio	1.0		
Nozzle Efficiency	0.97		
Outputs	GE J85-21 Turbojet		Percent Error
	NASA Research Engine Test	SimTurbo©	

Inlet Air Mass Flowrate [lbm/sec]	53.0	53.0	0
Net Thrust at 16500 RPM	3500	3430	-2.0
Thrust Specific Fuel Consumption [lbm/(lbf*hr)]	1.21 to 1.28	1.24	-0.4
Fuel Mass Flowrate [lbm/sec]	1.18 to 1.24	1.22	0
Turbine Exit Temperature [deg. F]	1290	1306	1.2
Exhaust Gas Temperature [deg. F]	1285	1272	-0.5

VII) Transient Results

SIMTURBO© has capabilities to simulate engine transients from Take-Off to accelerations and decelerations under various flight envelope (altitude and flight Mach number) conditions. The transient simulations run in real time. For this paper, the J-85-21 engine was simulated from Take-Off to Idle to high speed demonstrating rapid accelerations and decelerations, as shown in Figures 8 through 10.

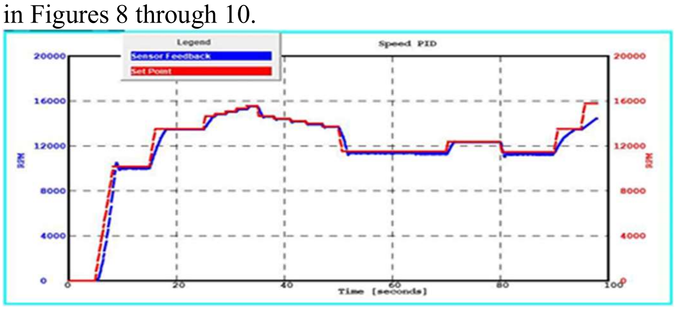

Figure 8. Simulation of J-85-21 Engine Speed Transient

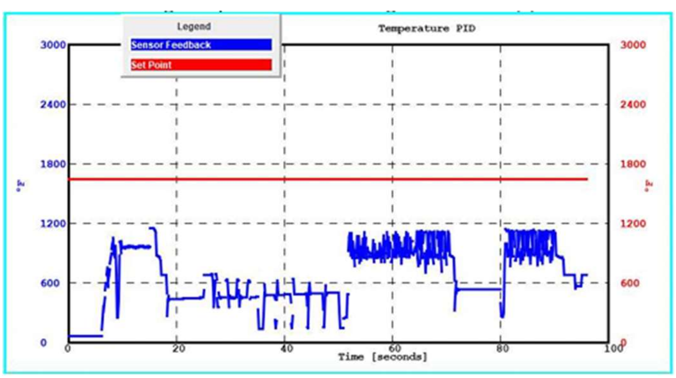

Figure 9. Simulation of J-85 Turbine Exit Temperature Transient

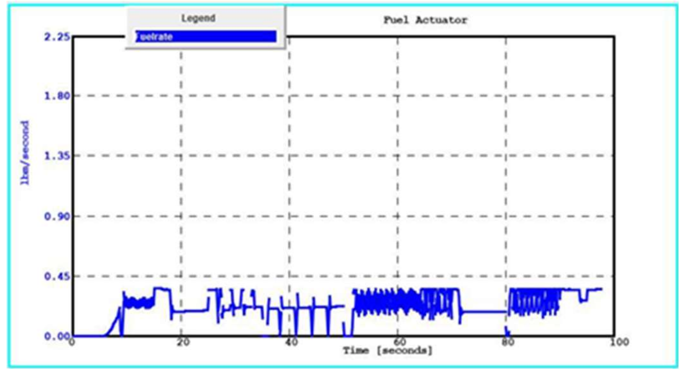

Figure 10. Simulation of J-85 Engine Fuel Actuator

In Figure 8, the engine Take-Off starts at Time = 5 seconds, by ramping up the Starter Torque. The engine ramps from 0 to 10000 RPM in 5 seconds. The speed Set Point is provided in red, and the speed Sensor Feedback is provided in blue. The Speed PID shows excellent control as the engine settles at various conditions and exhibits fast, controlled responses to accel and decel requests. For the same transient, the Turbine Exit Temperature Transient is plotted in Figure 9. The temperature Limit is in red; the temperature Sensor Feedback is in blue. The temperature responds appropriately to speed accels and decels. For the same transient, the Fuel Actuator Transient is plotted in Figure 10. This plot shows the rapid response to speed accels and decels by the fuel actuator. Examining Figures 8 through 10 together, it is observed that improvements can be made to the control system, to reduce unwanted fluctuations in the speed and temperature transients.

VIII) Real Time Operation

A key benefit of SIMTURBO© is the ability to provide real time simulation of the gas turbine engine using standard personal computer hardware. Use cases for SIMTURBO© real time simulation include digital twin operation where the simulation runs side-by-side with the actual gas turbine engine. The real time simulation would enable predictive maintenance, real time health monitoring, performance optimization, and virtual testing to reduce costs and downtime.

This real time operation is achieved with the utilization of the zero-dimensional (0D) and one-dimensional (1D) models as described in earlier sections of this paper. 0D simulation models the components of the engine as lumped-element models. The important parameters of flowrate, pressure, temperature are calculated with strict accounting of the first law thermodynamics at the inlet and exit of the components. Also, the constitutional equations of the air and fuel properties during the flow, compression, expansion and combustion processes are properly evaluated. 1D simulation techniques used by SIMTURBO© include conductive, convective and radiative heat transfer between the engine flows, engine structure and ambient. SIMTURBO© properly accounts for the transient thermal effects of metal heat soak and heat loss to ambient.

IX) Educational Benefits

Another key benefit of SIMTURBO© are the educational benefits for Aerospace University students. Users can view real-time data on internal engine dynamics, including pressure ratios, temperature dynamics, and fuel efficiency. SIMTURBO© bridges the gap between courses in thermodynamics, heat transfer, control theory and gas turbine engine design in a visual, hands-on, integrated platform. This allows students to grasp fundamental concepts in closer to real life and real-time, visual simulations.

X) Conclusion

This paper has provided an overview of the capabilities of SIMTURBO©, a new computer simulation program for analyzing and designing thermodynamic systems and controls for gas turbine engines. Results have been shown from simulation studies of the J-85-21 single spool gas turbine engine using SIMTURBO©. These steady state and transient simulation results show that SIMTURBO© provides the user with the capabilities of quickly creating realistic models of gas turbine engines. The capabilities include: steady state performance analysis over the entire flight envelope, detailed control system design and real time transient analysis including dynamic components for sensors, actuators and controls.

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