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ENGINE DESIGN MODEL FOR SEPARATE FLOW TURBOFAN ENGINE

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ABSTRACT

The first step in Engine Design for an airframe is being the on-design cycle analysis. The results of this analysis are later used in off-design cycle analysis, which gives critical information about the performance of the engine on the whole flight envelope. Both analysis results are later used in turbo machinery component design. In order to accomplish these objectives, an engine design model in MATLAB Simulink® (named as Engine Design Model, EDM) is developed for Separate Flow Turbofan Engines. This engine type is chosen according to its wide usage in Aerospace Industry, but the model can also be extended to the other types of Turbofan and Turbojet Engines. The Engine Design Model uses Variable Specific Heat Model in order to obtain best estimates in thermodynamic parameters throughout the whole cycle. The model use the solution algorithms given in Aircraft Engine Design, 2nd Edition [Mattingly, J.D., Heiser W.H., and Pratt, D.T., 2002] and its verification is made with AEDsys Software, which also uses the same algorithm. The model is intended to be used in an optimization process, which select the best engine according to the constraints determined by the user by using SIMPLEX and gradient descent algorithms.

NOMENCLATURE

α : By-pass ratio
β : Bleed-air fraction
ε : Coolant air fraction
η_x : Efficiency at engine section x
π_x: Pressure ratio of engine section x
τ_X : Temperature ratio of engine section x
a_x : Speed of Sound at engine section x
f_x : Fuel-to air ratio at engine section x
h_{PR} : Fuel heating value
M_x : Mach Number at engine section x
P_x : Static Pressure at engine section x
P_{tx} : Total Pressure at engine section x
T_x : Static Temperature at engine section x
T_{tx} : Total Temperature at engine section x
V_x : Speed at engine section x

Note: x value is consistent with the given station numbering and engine station abbreviations in [1].

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INTRODUCTION

Engine design process is a cyclic method, in which on and off-design methods should be called repeatedly depending on the design criteria. After the finalization of the on-design process, the off-design section which contains excessive amount of nested loops, initiate computations. This situation requires lower execution times, and high conversion speed which can be attained by speed and convergence optimization methods in coding. Different coding languages may require different optimization methods and those may be sometimes too complex to be applied by a standard programmer. In addition to the expertise in programming, dealing with the compiler and builder errors in an engine design algorithm may cause the loss of focus of the designer from the possible errors in the design method itself.

In order to get rid of these possible disadvantages in hard coding, MATLAB Simulink® tool can be used for an engine design algorithm. The ease of setting and modifying the subcomponents gives speed in error handling and expanding a design algorithm for a single type of engine to another.

Engine Design Model (EDM) is developed for separate flow turbofan engines. These engines are the most common engine types used in several aircrafts, and being the base of more complex engine types. The model consists of sub-models which named after the two design processes: Parametric Cycle and Performance Cycle. Each sub-model performs calculations for these two design process and the required engine design parameters are obtained in the end. The cycle algorithms are based on the algorithms introduced in [1], and the validation of the results of the model is made with the AEDsys Software [1].

METHOD

Application of the Variable Specific Heat Model

For the sake of reflecting the changes on thermodynamic parameters such as temperature, reduced pressure, enthalpy, heat capacity, gas constant and the speed of sound to temperature and pressure ratio calculations precisely, Variable Specific Heat Model given in [2] is used throughout the cycle.

Because of the dependency of these thermodynamic properties on the fuel-to-air ratio, which is also changing between different engine sections, this parameter is used as the main input. The other inputs are either one of the following properties: Temperature, enthalpy or reduced pressure.

The Parametric Cycle Sub-Model

The model includes blocks named after the engine sections that they are intended to perform the relevant calculations. The model is outlined in Figure 1 as follows.

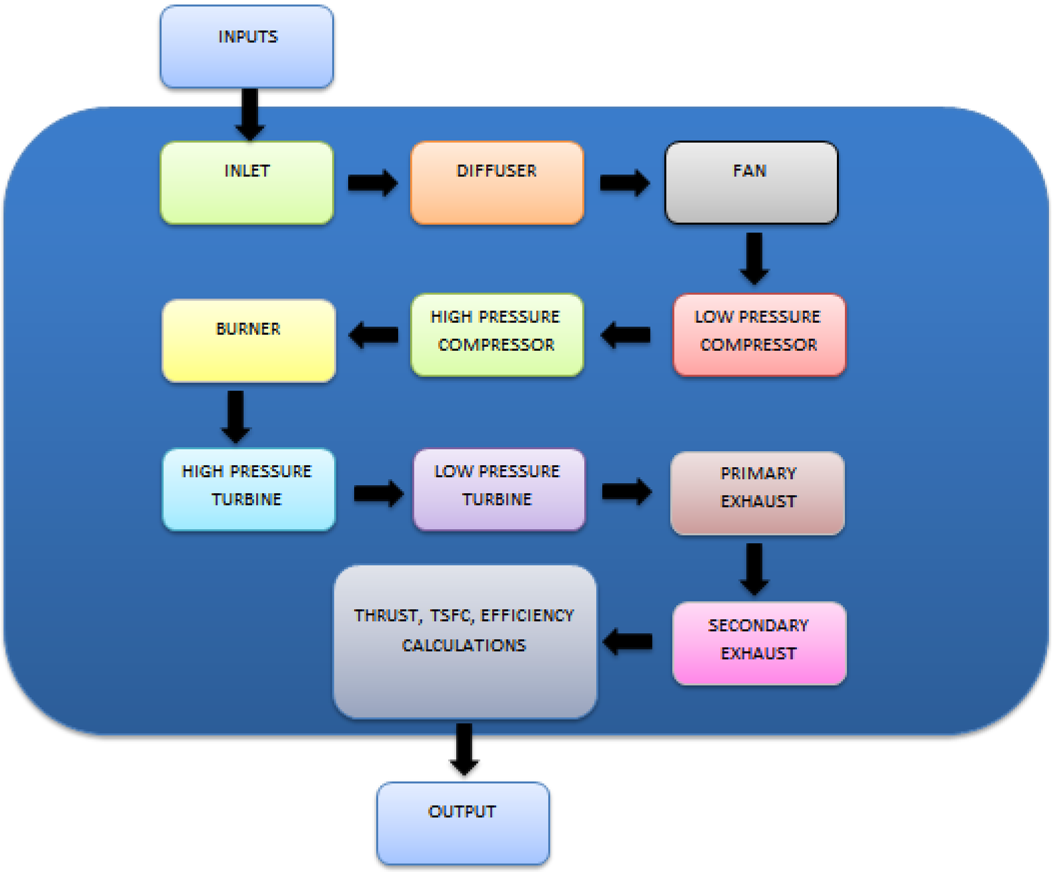

Figure 1: *A summary of the Parametric Cycle Model for Separate Flow Turbofan Engine*

The Parametric Cycle Model consists of the following blocks:

-Inlet (for calculation of the input conditions such as τ_r and π_r)
-Diffuser (for calculation of inlet diffuser properties such as π_d)
-Fan (for calculation of fan properties such as τ_f and π_f)
-Low Pressure Compressor (for calculation of low press. comp. properties such as τ_{cL})
-High Pressure Compressor (for calculation of high press. comp. properties such as τ_{cH})
-Burner (for calculation of burner properties such as $\tau_{\lambda,}$ and fuel-to-air ratio (*f*))
-Coolant Mixer1 (for calculation of 1st coolant mixer properties such as τ_{m1})
-High Pressure Turbine (for calculation of high press. turbine properties such as τ_{tH} and π_{tH})
-Coolant Mixer2 (for calculation of 2nd coolant mixer properties such as τ_{m2})
-Low Pressure Turbine (for calculation of low press. turbine properties such as τ_{tL} and π_{tL})
-Primary (inner) Exhaust (for calculation of primary exhaust parameters such as M_9, and P_0/P_9)
-Secondary (outer) Exhaust (for calculation of secondary exhaust Parameters such as M_{19}, and P_0/P_{19})
-Final Calculations (Thrust, thrust specific fuel consumption and efficiency calculations)

The model is shown in Figure 2 below.

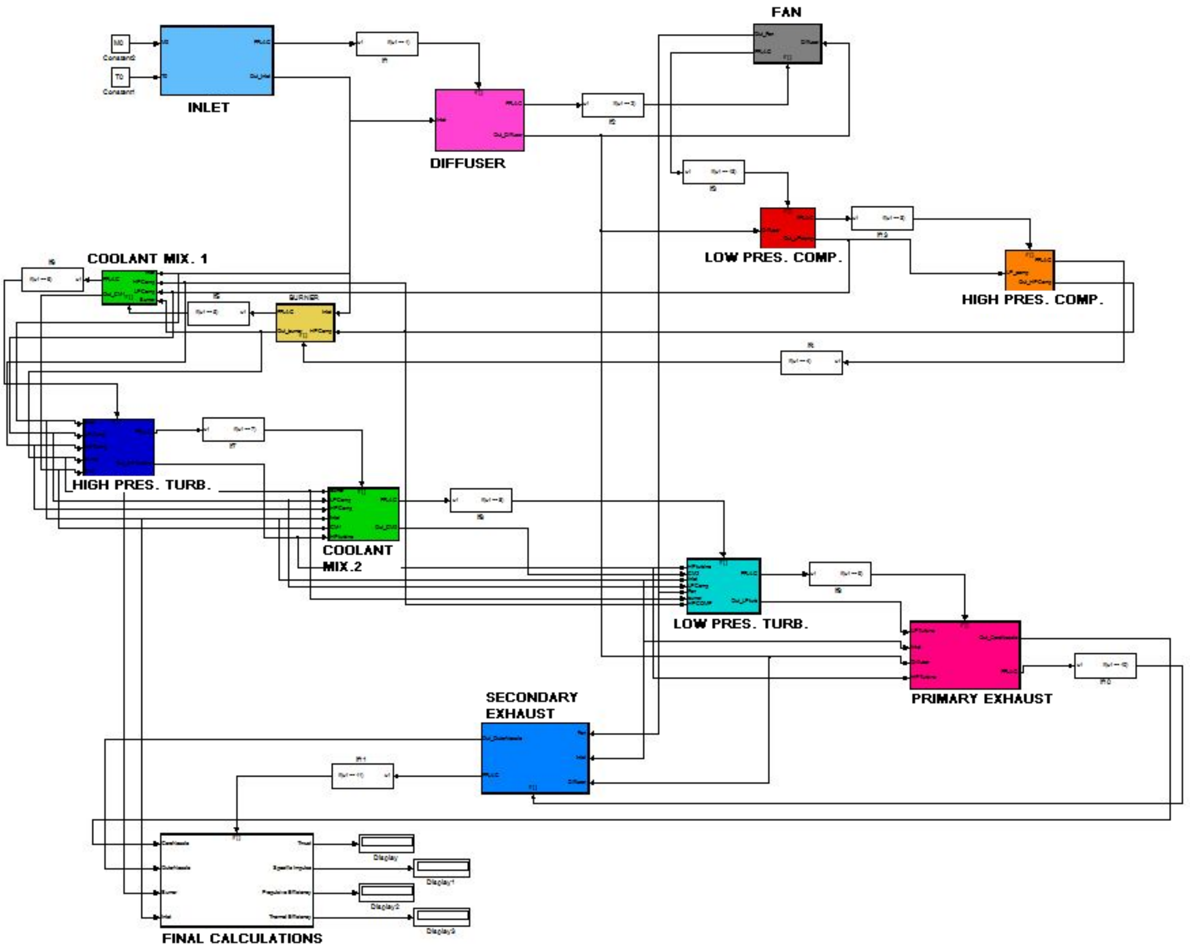

Figure 2: *An overview of the Parametric Cycle Model*

The Performance Cycle Sub-Model

The model includes blocks named after the sequential off-design processes which are described in [1]. The model is outlined in Figure 3 as follows.

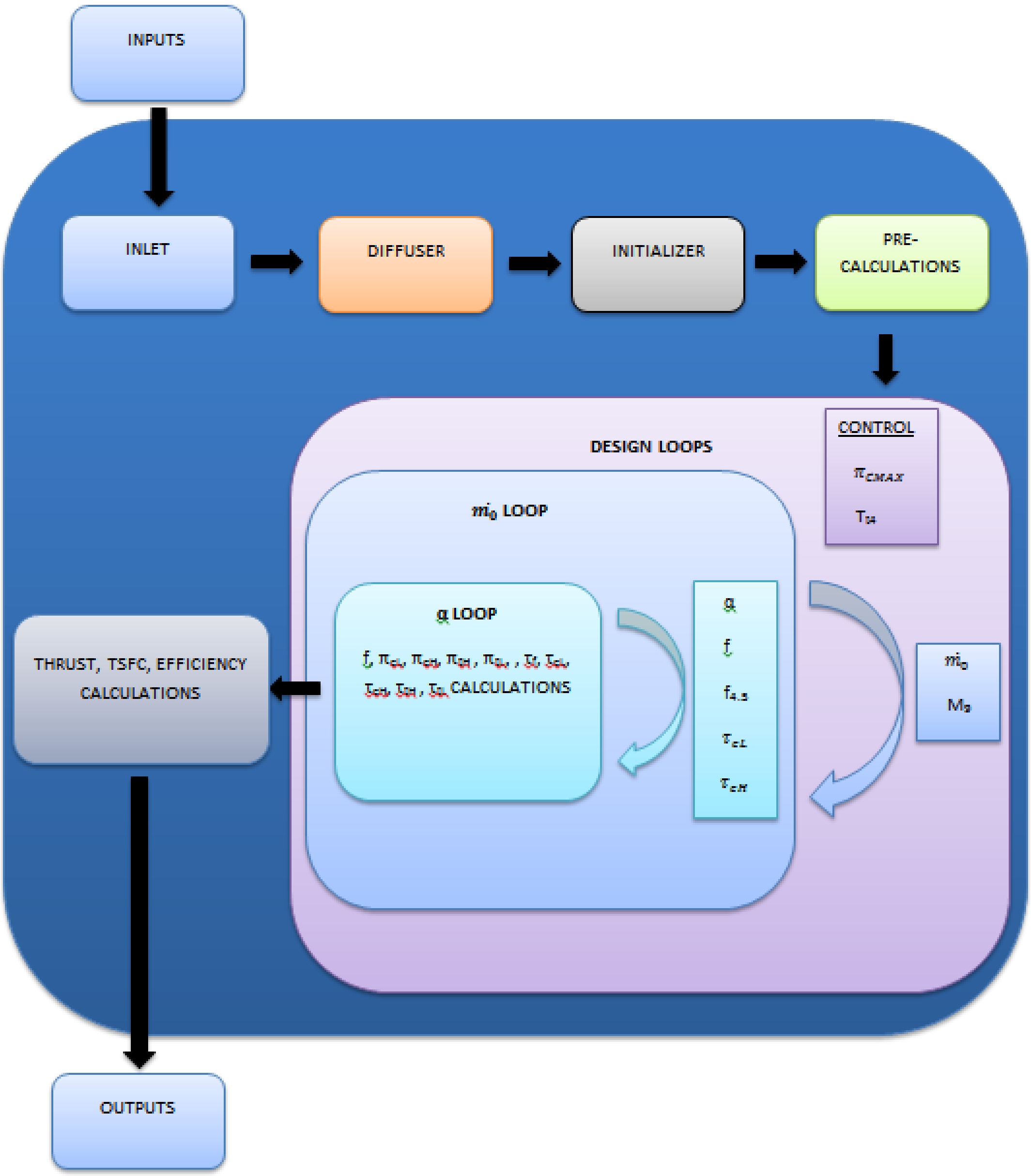

Figure 3: *A summary of the Performance Cycle Model*

The Performance Cycle consists of the following blocks:

-Inlet (for calculation of the input conditions such as τ_r and π_r)

-Diffuser (for calculation of inlet diffuser properties such as π_d)

-Initializer (passes the parameters come from the on-design model to the relevant variables in off-design process)

-Pre-Calculations (perform initial fuel to air ratio and enthalpy calculations for low pressure turbine (engine stations 4.5 and 5) before starting the performance cycle design loops)

-Design Loops (the three nested loops that are named after the main decision parameter used)

> -T_{t4} Control Loop (The outer control loop that controls the convergence to the High Pressure Compressor Inlet Temperature (defined by user) and compressor pressure ratio (defined by user))
>
> -$\dot{m}_0$ Loop (The loop that obtains the mass flow rate and the primary exhaust flow Mach Number (M_9))

-α Loop (The innermost loop that obtains the engine by-pass ratio, overall fuel-to air ratio(f), fuel-to air ratio at the low pressure turbine inlet ($f_{4.5}$), low pressure compressor temperature ratio (τ_{cL}) and high pressure compressor temperature ratio(τ_{cH}))

The final calculations (Thrust, Thrust specific fuel consumption, % RPM and efficiency calculations) are made after the convergence of the T_{t4} Loop.

The model is shown in Figure 4 below.

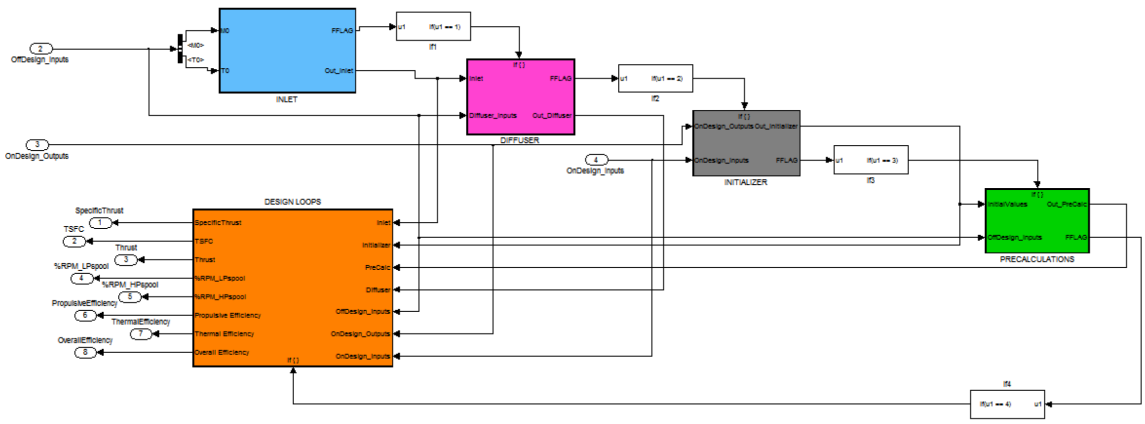

Figure 4: *An overview of the Performance Cycle Model*

The Engine Design Model

The Engine Design Model consists of the two sub-models which are named after their roles in the Engine Design Process. The model is shown in Figure 5 as follows.

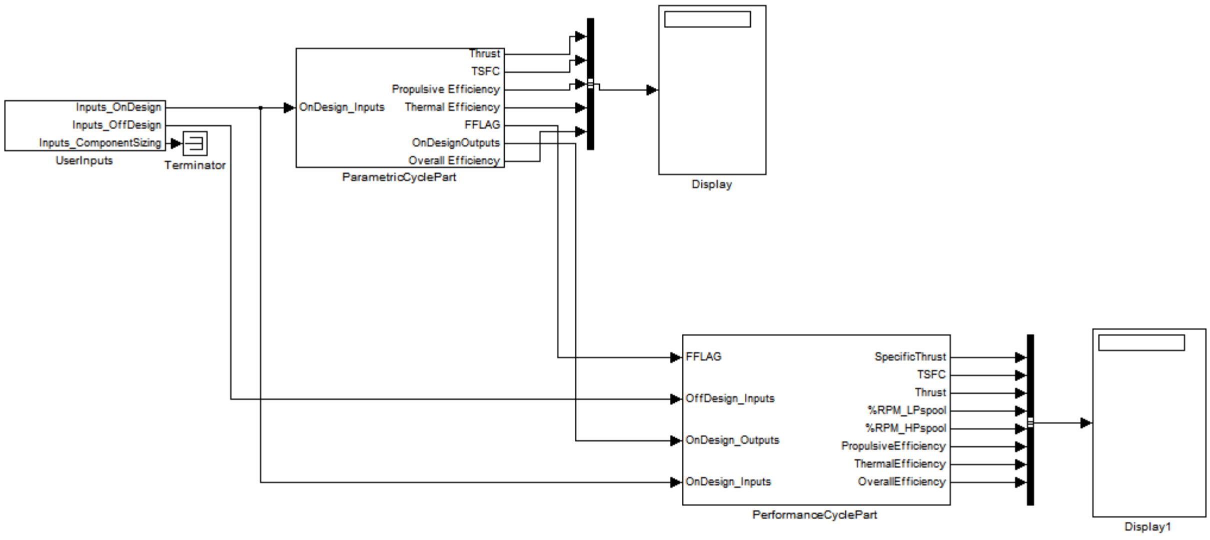

Figure 5: *An overview of the Engine Design Model for Separate Flow Turbofan Engine*

The Engine Design Model is formed by connecting the sub-models described in the previous sections. The blocks shown in Figure 5 are described as follows:

-UserInputs: Takes the user inputs from the input “m” file and send them to the blocks which they are required from

-ParametricCyclePart: Performs the on-design calculations

-Performance Cycle Part: Performs the off-design calculations

The user inputs are given in Table 1 as follows.

Table 1: *The list of user inputs to the Engine Design Program*

Parametric Cycle Inputs (on-design)	
Flight Conditions	M_0,P_0,T_0, CTOL,CTOH
Fuel Properties	h_{PR}
Bleed Air and Coolant Air Ratios	β,ε_1, ε_2
Pressure Ratios	π_b, π_{dMAX} , π_n, π_f , π_{nF}, π_{cL}, π_c
Polytropic Efficiencies	η_f , η_{cL} , η_{cH} , η_{tH} , η_{tL}
Component Efficiencies	η_b , η_{mL} , η_{mH} , η_{mPL} , η_{mPH}
Others	α, T_{t4} , $\dot{m}_0$

Performance Cycle Inputs (off-design)	
Flight Conditions	M_0,P_0,T_0,CTOL,CTOH,PTOL,PTOH
Fuel Properties	h_{PR}
Bleed Air and Coolant Air Ratios	β,ε_1, ε_2
Pressure Ratios	π_b, π_{dMAX} , π_n, π_f , π_{nF}
Polytropic Efficiencies	η_f , η_{cL} , η_{cH} , η_{tH} , η_{tL}
Component Efficiencies	η_b , η_{mL} , η_{mH} , η_{mPL} , η_{mPH}
Limiting Conditions	T_{t4} , $\pi_{c(max)}$

The output list of each sub-model is given in Table 2.

Table 2: *The list of outputs of the Engine Design Program*

Parametric Cycle Outputs (on-design)	
Thrust	$F/\dot{m}_0$
Thrust Specific Fuel Consumption	S
Propulsive Efficiency	η_p
Thermal Efficiency	η_{th}
Overall Efficiency	η_o
Speeds at the Nozzles	V_9, V_{19}
Component Behavior	τ_f, τ_{cL}, τ_{cH}, τ_{tH} , τ_{tL} , τ_λ, f , η_f, η_{cL}, η_{cH}, $\eta_{tH,}$ η_{tL} , M_9, P_{t9}/P_9 , P_9/P_0 , T_9/T_0 , M_{19} , P_{t19}/P_{19} , P_{19}/P_0 , T_{19}/T_0

Performance Cycle Outputs (off-design)	
Thrust	F
Mass Flow Rate	$\dot{m}_0$
Thrust Specific Fuel Consumption	S
Efficiencies	η_p, η_{th}, η_o
Fuel to Air Ratio	f_o
Overall Performance	V_9/a_0 , V_{19}/a_0 , α , P_{t9}/P_9 , P_9/P_0 , T_9/T_0, P_{t19}/P_{19} , P_{19}/P_0 , T_{19}/T_0
Component Behavior	π_f, π_{cL}, π_{cH}, π_{tH} , π_{tL} , τ_f, τ_{cL}, τ_{cH}, τ_{tH} , τ_{tL} , τ_λ, f, M_9, M_{19}

The items in the outputs list in Table 2 can be increased according to the user needs.

VALIDATION OF THE MODELS

The validation is carried out by giving the same input values to both of AEDsys Software, and newly coded Engine Design Model. Some output parameters are compared and the differences are evaluated. The results from one of the test cases for on-design sub-model are shown in Table 3.

Table 3: *Comparison of output parameters of Parametric Cycle Model with AEDsys (ONX)*

Test Parameter	**Result from ONX**	**Result from Parametric Cycle Model**	**%Difference**
V0	775.6	735.1	5.221764
a0	969.5	918.9	5.219185
TAU_r	1.128	1.128	0
PI_r	1.524	1.525	0.065617
PI_d	0.97	0.97	0
TAU_f	1.4957	1.498	0.153774
Pt19/P19	1.8834	1.726	8.357226
TAU_cL	1.4957	1.498	0.153774
TAU_cH	1.6214	1.619	0.14802
PI_tH	0.578	0.5838	1.00346
TAU_tH	0.8876	0.8882	0.067598
PI_tL	0.2061	0.2093	1.552644
TAU_tL	0.6957	0.6956	0.014374
P0/P9	0.6876	0.5904	14.13613
f	0.03858	0.03835	0.596164
f0	0.00815	0.0081	0.613497
TAU_m1	0.9858	0.9858	0
TAU_m2	0.9869	0.9868	0.010133
Tt19/T0	1.6863	1.6878	0.088952
P0/P19	0.3715	0.3402	8.425303
V19/V0	1.4823	1.3794	6.941915

Specific Thrust	33.725	31.93	5.322461
Specific Impulse	0.8695	0.9128	4.979873
T9/T0	4.5286	4.682	3.38736
V9/V0	2.577	2.314	10.20567
M9/M0	1.25	1.1065	11.48

The change in Thrust and Thrust Specific Fuel Consumption is tracked for the On-Design Sub-Model of Engine Design Model and compared with AEDsys program results in order to validate the model for an extended input ranges. The difference from the reference program outputs are 5% both in Thrust and Thrust Specific Fuel Consumption, which is coherent with the comparison in Table 3. The change in Thrust and Specific Fuel Consumption with respect to By-Pass Ratio is given in Figure 6 as follows.

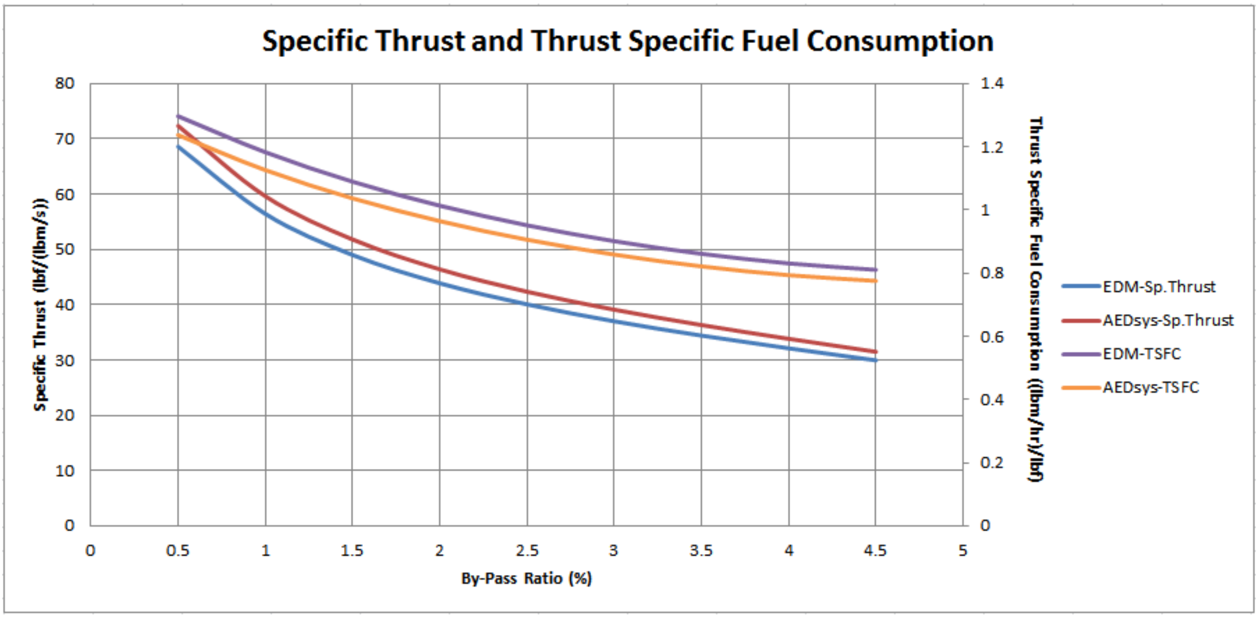

Figure 6: *Variation of On-Design Thrust and Thrust Specific Fuel Consumption with respect to By-Pass Ratio compared for Engine Design Model (EDM) and AEDsys Program (ONX)*

Another comparison is made for different High Pressure Compressor Pressure Ratios (Low Pressure Compressor Pressure Ratio kept constant) in order to observe the change in Thrust and Thrust Specific Fuel Consumption and the 5% difference from the reference program results is remaining the same as in the previous analysis and the comparison in Table 3. The change in Specific Thrust and Thrust Specific Fuel Consumption with respect to Compressor Pressure Ratio is given in Figure 7 as follows.

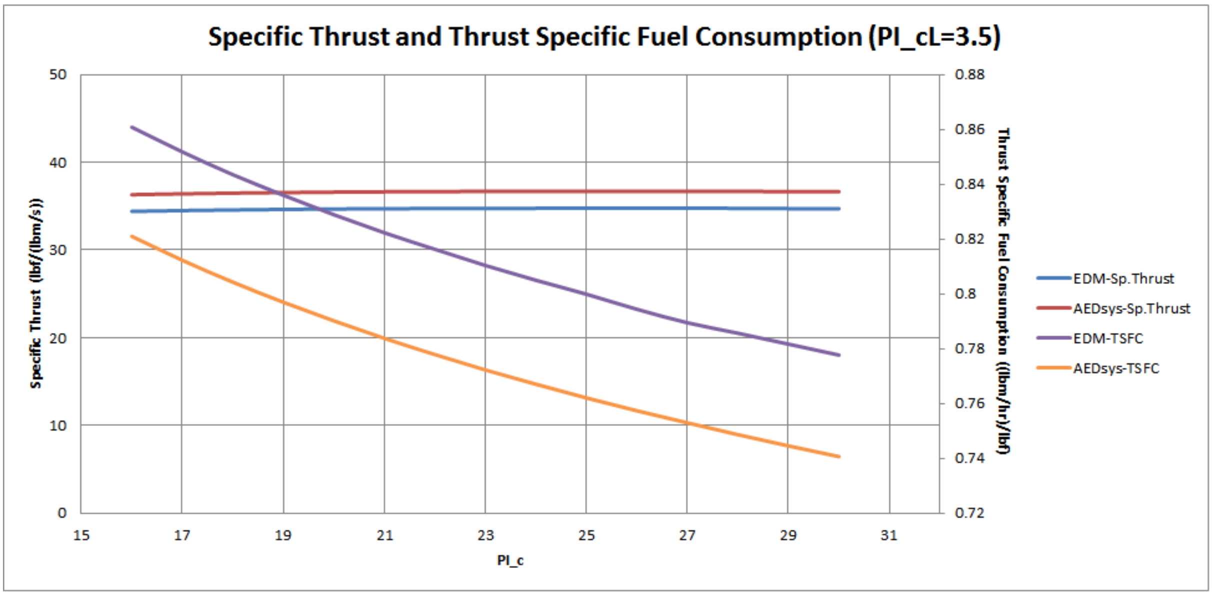

Figure 7: *Variation of On-Design Specific Thrust and Thrust Specific Fuel Consumption with respect to High Pressure Compressor Pressure Ratio compared for Engine Design Model (EDM) and AEDsys Program (ONX)*

Third comparison is made for the preferred design region estimation of Engine Design Model and AEDsys Software. The preferred design region is the one that has minimum Thrust Specific Fuel Consumption change, whereas the Specific Thrust is increasing. In this comparison, high pressure turbine inlet temperature (Tt4) is altered and the changes in Specific Thrust and Thrust Specific Fuel Consumption are observed. The 5% difference from the reference program results is remaining the same as in the previous analysis and the comparison in Table 3. The change in Specific Thrust and Thrust Specific Fuel Consumption with respect to high pressure turbine inlet temperature is given in Figure 8 as follows.

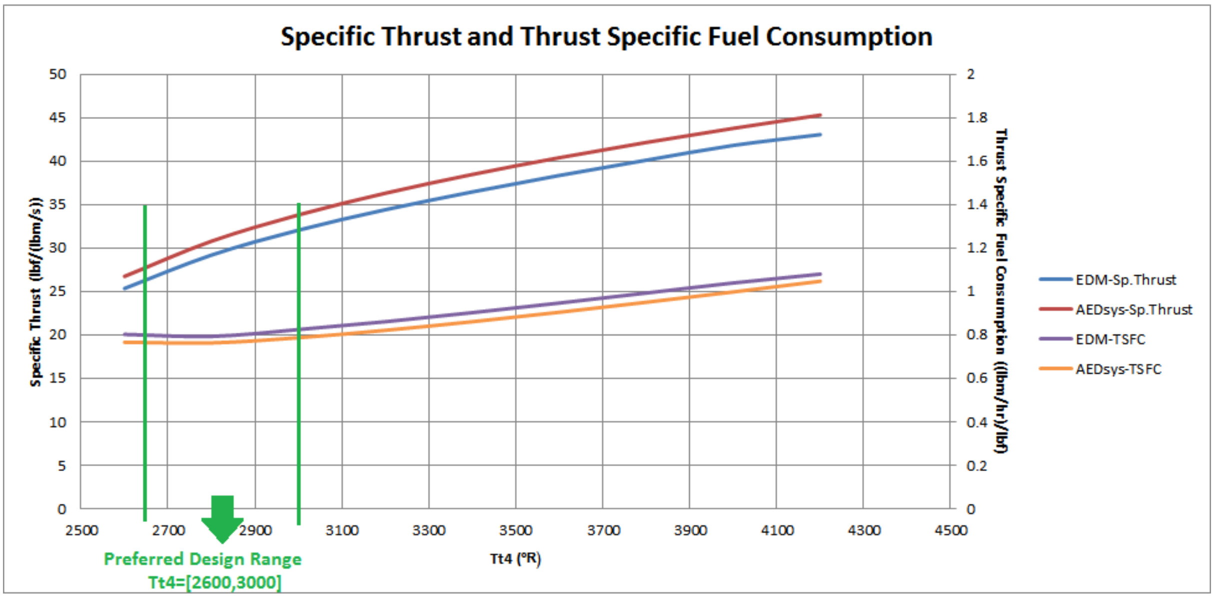

Figure 8: *Variation of on-design Specific Thrust and Thrust Specific Fuel Consumption with respect to high pressure turbine inlet temperature compared for Engine Design Model (EDM) and AEDsys Program (ONX)*

From Figure 8, it can be deduced that Engine Design Model gives a coherent design region with AEDsys Software because of the same curve trends and constant differences throughout the same high pressure turbine inlet temperature range.

In the comparisons made in Figure 6, 7 and 8, the constant differences between the predictions of Specific Thrust and Thrust Specific Fuel Consumption parameters of both programs stems from the fact that a different Variable Specific Heat Model is used in Engine Design Model (given in [2]) than the AEDsys Software. The variable specific heat model calculates the thermodynamic properties throughout the cycle and the constant error between the predictions of different heat models causes a constant difference in pressure ratios, hence giving constant differences in result parameters which are using them.

The results from one of the test cases for Off-Design Sub-Model are shown in Table 4.

Table 4: *Comparison of output parameters of Performance Cycle Model with AEDsys (OFFX)*

Test Parameter	Result from OFFX	Result from Performance Cycle Model	%Difference
PI_r	1.5204	1.525	0.302552
TAU_r	1.1275	1.128	0.044346
PI_d	0.97	0.97	0
PI_f	2.1584	2.189	1.417717
TAU_f	1.2843	1.29	0.443822
PI_cL	2.1584	2.189	1.417717
TAU_cL	1.2843	1.29	0.443822
PI_cH	3.4511	3.046	11.73829
TAU_cH	1.4844	1.426	3.93425
PI_tH	0.5778	0.6239	7.978539
TAU_tH	0.8845	0.9118	3.08649
PI_tL	0.2269	0.243	7.095637
TAU_tL	0.705	0.7207	2.22695
LP Spool RPM %	87.34%	87.97%	0.721319
HP Spool RPM%	94.35%	88.81%	5.871754
Alpha	3.995	4.519	13.1164
Pt9/P9	1.3688	1.421	3.813559
P0/P9	1	1	0
M9	0.7035	0.75	6.609808
mdot	297.48	299.2	0.57819
f	0.03076	0.03755	22.07412
f0	0.00585	0.006462	10.46154
Specific Thrust	20.17	20.73	2.776401
TSFC (S)	1.0444	1.122	7.430103
Thrust	5999	6204	3.417236

In the validation of the off-design section of the Engine Design Model, the variation in Predicted Mass Flow Rate, Specific Thrust, Thrust Specific Fuel Consumption and Propulsive Efficiency with respect to Mach Number (for the same on-design output reference case) is tracked in order to observe the outputs of Off-Design Sub-Model in a wider operational range. The change in mass flow rate and propulsive efficiency with respect to Mach Number is given in Figure 9 as follows. The average difference between the outputs of the Engine Design Model and AEDsys is 3% and 5% in mass flow rate and propulsive efficiency respectively.

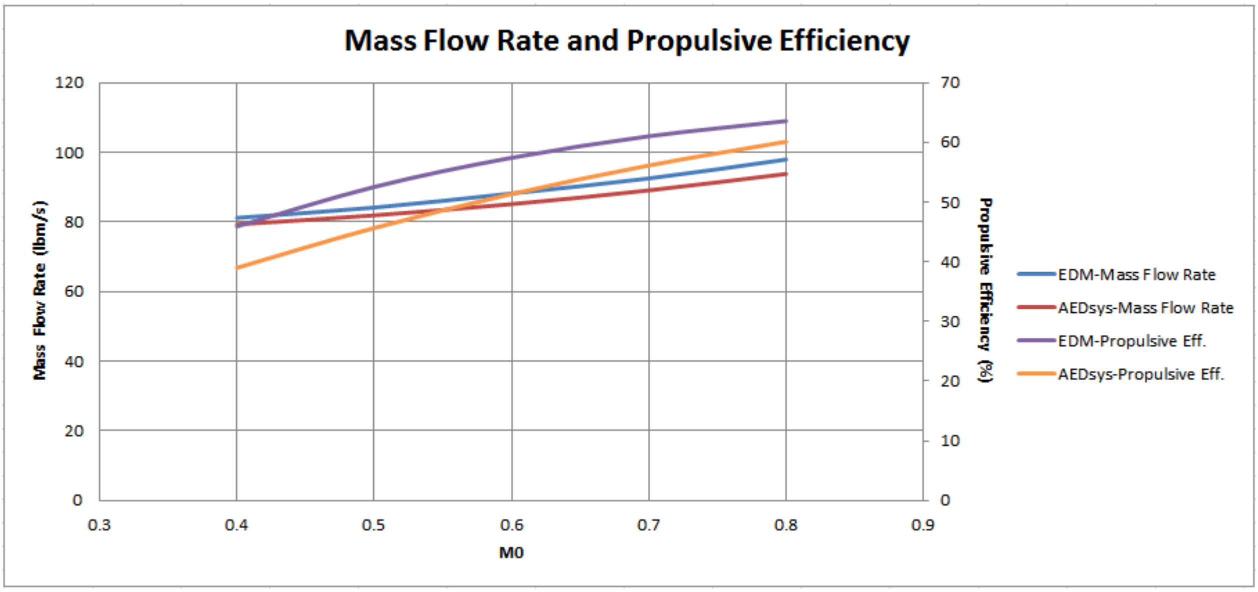

Figure 9: *Variation of Off-Design Mass Flow Rate and Propulsive Efficiency with respect to Mach Number compared for Engine Design Model (EDM) and AEDsys Program (OFFX)*

The change in Specific Thrust and Thrust Specific Fuel Consumption with the change in Mach Number is given in Figure 10. The average difference between the outputs of the Engine Design Model and AEDsys is 8% and 3% in Specific Thrust and Thrust Specific Fuel Consumption respectively.

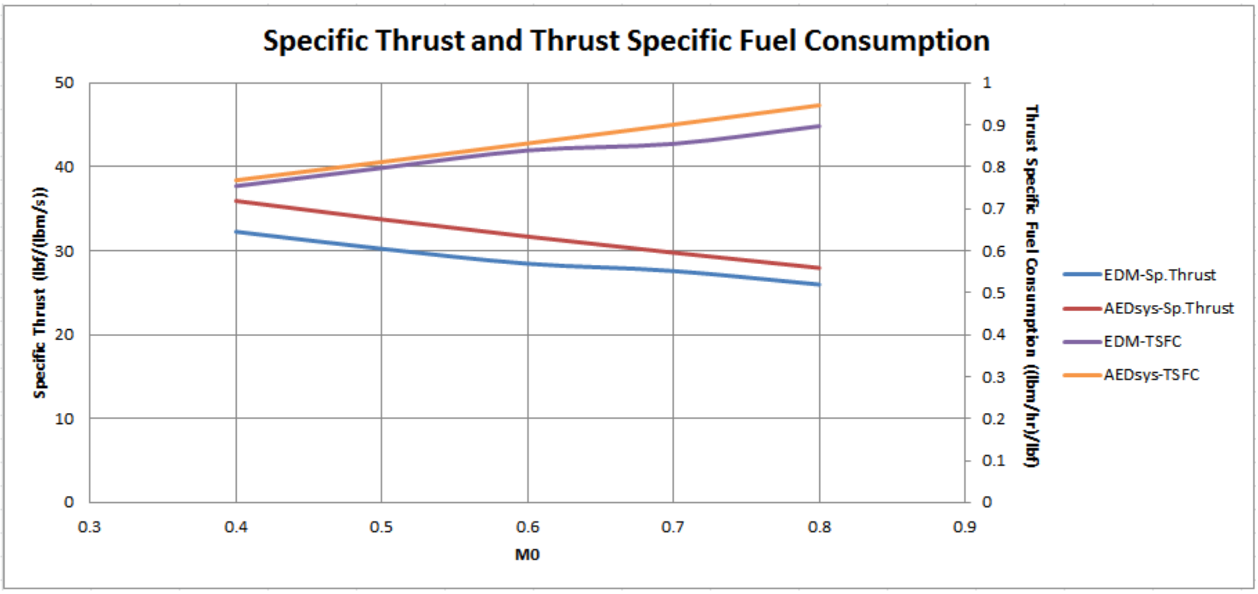

Figure 10: *Variation of Off-Design Specific Thrust with respect to Mach Number compared for Engine Design Model (EDM) and AEDsys Program (OFFX)*

In Figures 9 and 10, the constant differences between the results of two programs can be seen as in the on-design comparison, as a result of using the same variable specific heat model with the on-design section. In addition to this difference, the constant difference between the results of the programs has a slight increase in Specific Thrust and Thrust Specific Fuel Consumption around 0.7 Mach which is caused by the initial prediction value of the secondary exhaust flow Mach Number used in off-design section. This value is taken as unity (i.e. equal to the sound speed) in AEDsys algorithm, whereas in the Engine Design Model it is taken as 0.85 because the choked secondary exhaust case is not preferred due to noise and heating problems.

CONCLUSION AND FUTURE WORK

The Engine Design Model is developed for the purposes of the on-design and off-design analysis of separate flow turbofan engines. The advantages of MATLAB Simulink ® software on modeling are aimed to be used in engine design algorithms introduced in designing a separate flow turbofan engine. The validation showed that the Engine Design Model gives both the on-design and off-design analysis output parameters close to the reference software and its results can be used in aircraft engine design studies including optimization methods. In the future studies, a turbo machinery design section will be added and this model will be used as a mathematical model to an optimization problem, which constraints are determined by the user and as a result the optimization will give the best engine that meets the design requirements.

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