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DEVELOPMENT OF A CYCLE DESIGN SOFTWARE FOR TURBOSHAFT ENGINES

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ABSTRACT

The purpose of this study is to develop a computer software to carry out on and off-design performance predictions of a turboshaft engine along with the dynamic analysis. With these abilities of the developed software, the cycle of the engine can be designed in an optimum way to accomplish the previously defined missions for the aircraft. Besides, the transient operation can be simulated in computer environment in order to arrange the limitations of the control system. The software is developed by using Matlab and the reliability of the developed software is validated with comparison to the available literature data and the available commercial software Gasturb 11.

INTRODUCTION

Gas turbine engines are the engines that are widely employed in aircrafts and industrial plants. In modeling of these engines, there are four main matching models namely, thermodynamic matching transient performance model, real time aerothermal transient performance model, real time transfer function transient performance model and real time lumped parameter transient performance model [Walsh and Fletcher, 2004]. The highest accuracy can be reached with the thermodynamic matching transient performance model and the main interest of this study is this type of modeling. It is because that the precision is more important in a cycle design tool rather than the speed. Besides, another advantage is the simplicity of this type. The fundamental thermodynamic equations [Saravanamuttoo, Cohen & Rogers, 2001] and the available software GasTurb [Kurzke, 1995, 2007] are widely used throughout this study.

METHOD

Turboshaft Model and Air Stations

The model used as a turboshaft engine is a twin-spool configuration with a free power turbine which can be seen in Figure 1. The air model [Walsh and Fletcher, 2004] is embedded into software which is a function of fuel to air ratio and temperature.

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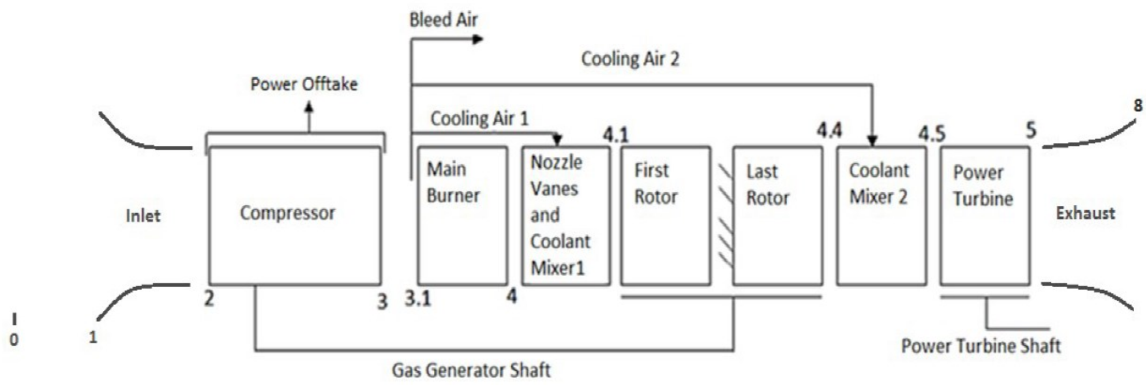

Figure 1: Air Stations of Turboshaft Model

Design Point Calculations

The fundamental thermodynamic relations are used for the design point calculations. The input screen of the software is given in Figure 2.

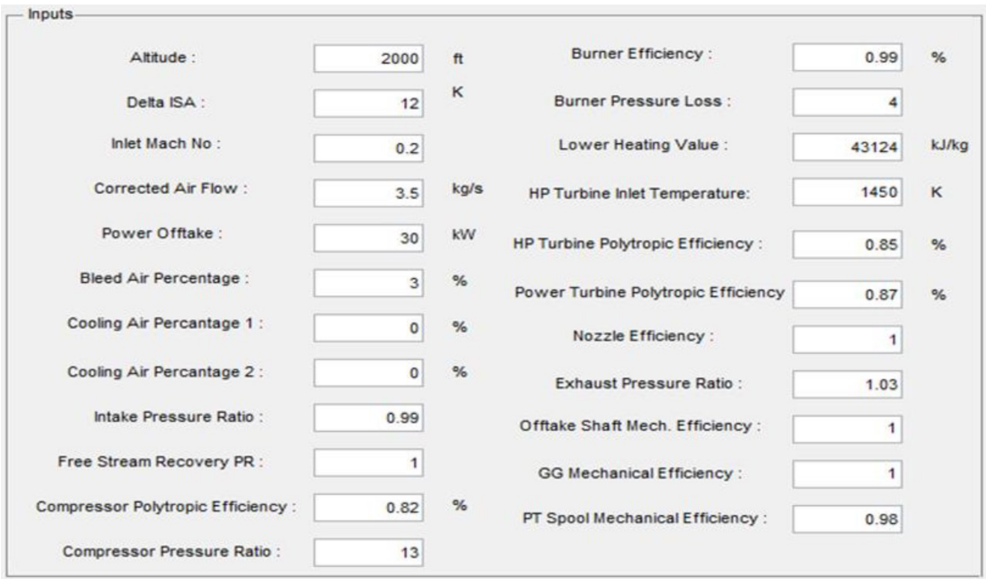

Figure 2: Design Point Inputs

In the developed software, the effect of the change in any of the two design point inputs can be studied. Corresponding cycle result of each intended value is shown in a carpet plot output. The default output graph is the specific fuel consumption versus the shaft power and the parameters represented by the axes can be altered by the user of the software. In addition, it is possible to use the design modes of the rotating components, which gives the user a much more realistic approach than assuming constant component efficiencies.

Component Design Performance Estimations

Component performance estimation is a required feature of a preliminary design tool. The reason is that the component efficiencies should be estimated properly in order to start from a suitable cycle. These estimations are based on empirical correlations and gives user a warning when the inputs or outputs are out of their usage range. The main outputs of the developed component performance estimation modules can be seen in Figure 3.

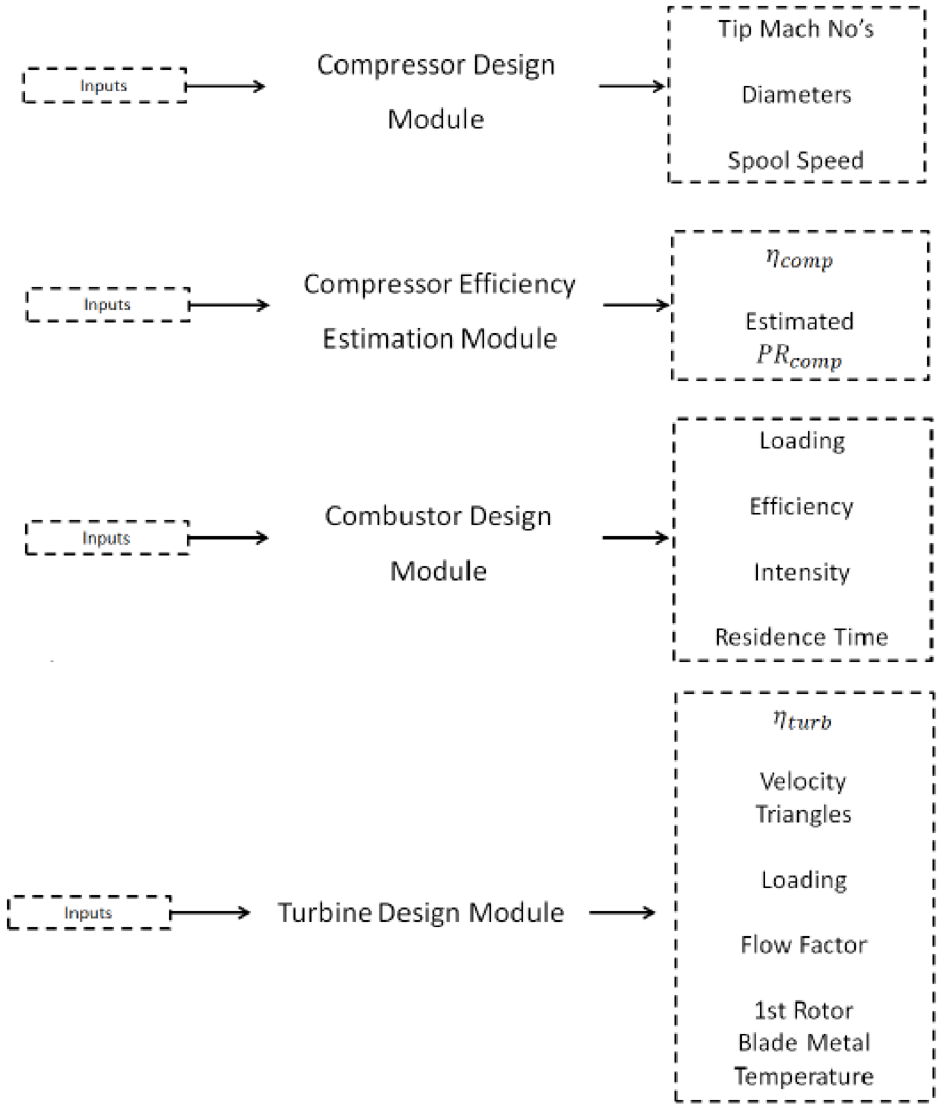

Figure 3: Main outputs of the developed component performance estimation modules

Off-Design Calculations

After determining the design point of the turboshaft engine, it is important to estimate and examine how the engine behaves at different operating points within operating envelope of the aircraft. This is a must since the capability of the engine to cope with the defined missions should be examined by the engine manufacturer while developing the cycle of the engine in the preliminary design phase. In the actual case, compressor and turbine maps are not determined at this point of the engine design phase. In order to estimate the performance, map scaling is used in this study. Available similar maps are scaled to the design values of the engine to be designed by using the scaling factors of Kong, Lim & Kim [2010]. Before matching, new maps formed for the components, are tabulated for the usage in the developed computer software. To provide a precise reading, “beta-line” technique is used in which mass flow, efficiency and pressure ratios for the specified speeds are tabulated with respect to their betas. The map presentation and the respective tabulation of the data can be seen in Figure 4 [Walsh and Fletcher, 2004].

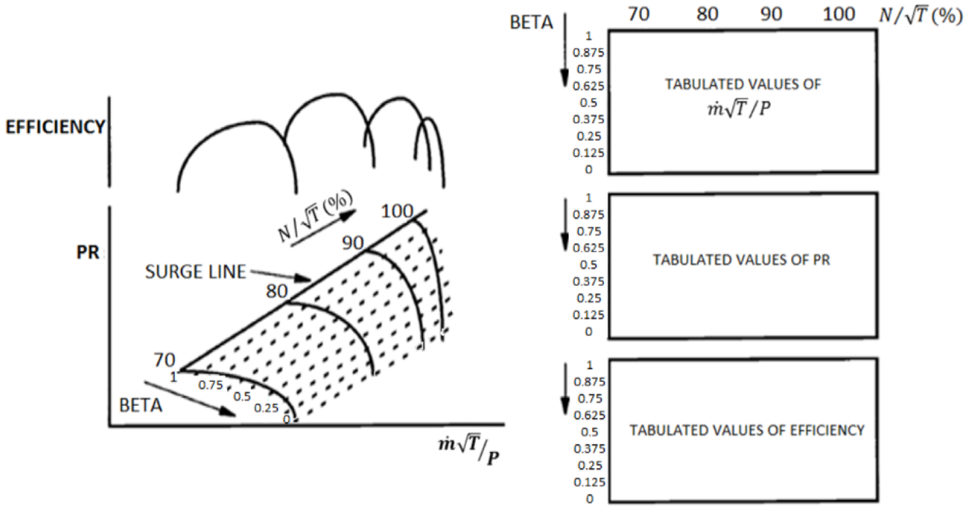

Figure 4: Beta Lines

In the component matching, there are four independent variables and four errors that can arise from mismatching of the rotating components. Iterations begin with initial guesses of these four independent parameters mentioned above and iterations are updated with the Newton-Raphson iteration method. This method calculates the Jacobians and updates these parameters accordingly. This process goes on until the square of the sum of the errors decreases to 10^{-8}.

The algorithm for the off-design calculations are presented in Figure 5.

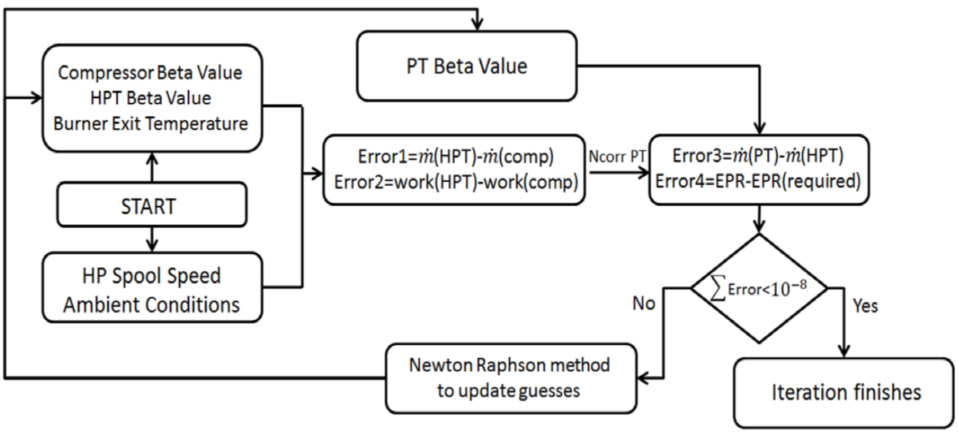

Figure 5: Algorithm of Off-Design Matching

Simulation of Inlet Distortion Effects

Inlet distortion is the spatial variation of inlet pressure or temperature. Methodology of the inlet distortion part of the software follows mainly the parallel compressor theory. It should be noted that, the coupling factor is not considered in this thesis since the main interest is the turboshaft engine. Because these engines are small gas turbines, there are no serially connected low and high pressure compressors in general.

The parallel compressor theory, was first proposed by Pearson and it is the common method in modeling the inlet distortion. The main idea of this theory is that two different streams (different inlet properties such as temperature and pressure due to distortion) in the compressor is assumed to be working at the same time and matched with each other to have the same exit static pressures. The compressor map is divided into parts for the parallel compressor operation and new maps are required for each section of the compressor. In order to create new maps, same maps with the only difference of corrected mass flows are used for each section. The design point corrected mass flow rate of the distorted part is calculated by the user input distorted angle divided by 360 degrees and multiplied with the whole design point mass flow rate of the compressor. The remaining corrected mass flow is the design point of clean section of the compressor used. New betas are defined in each map and the Newton-Raphson iteration is performed with five parameters and five constraints. The new constraint is that the static pressures at each compressor section exit must be the same. In the developed software, Mach number of 0.2 is the default value at the exit of the compressor and the static pressure is calculated by this value and the total pressure for each section is found via the related compressor maps.

Transient Calculations

On and off designs of a system can give outputs on state changes. If one needs to determine how the engine and its outputs react to varying inputs (such as fuel input), dynamic analysis of the turboshaft engine is required. This means that a modification is required on the steady state model in order to get the transient model of the engine. This can be accomplished by taking the polar moment of inertia into account while establishing the power balance between the compressors and turbines. It is obvious that more fuel is required during accelerations than that for steady state design point. For decelerations, less fuel is required in the same sense [Kurzke, 2007].

During accelerations, there is an additional power on the high speed spool due to the increased fuel input. In other words, the power output of the HP turbine exceeds the power that required to drive the compressor, auxiliaries and mechanical losses. Conversely, the power output of the HP turbine decreases and becomes insufficient to drive compressor, auxiliaries and mechanical losses due to the decreased fuel flow rate during decelerations. To take these effects into account, unbalanced power is introduced to the work compatibility equation of the compressor and the gas generator turbine in order to demonstrate the effect of transients. The algorithm that explains the transient process in the developed code is given in Figure 6.

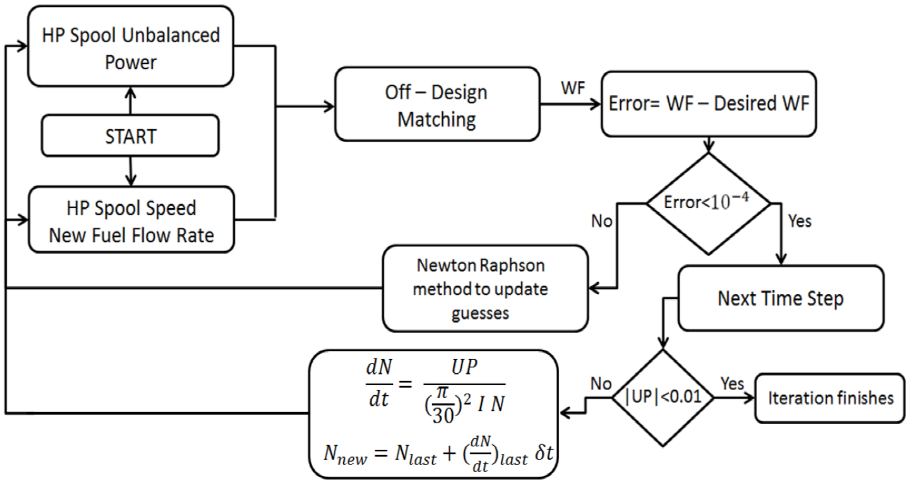

Figure 6: Algorithm of Transient Matching

Code Validation

In Table 1, the sample outputs of the operating lines of the developed software and GasTurb are compared while resulting power outputs are presented in Table 2. It can be seen that there is a good agreement between the results of the two softwares.

Table 1: Airflow, Pressure Ratio and Burner Exit Temperature Comparison

Relative Speed	Developed Code			Gasturb		
	m	PRc	Tt4	m	PRc	Tt4
0.75	1.87	6.05	1190	1.8800	6.07	1187
0.8	2.25	7.46	1217	2.2540	7.46	1214
0.85	2.63	8.99	1270	2.6310	8.99	1272
0.9	2.97	10.45	1333	2.9650	10.44	1331
0.95	3.25	11.74	1387	3.2450	11.72	1384
1	3.50	12.99	1445	3.5000	13.00	1450
1.05	3.66	14.12	1545	3.6630	14.09	1544

Table 2: Shaft Power Comparison

Relative Speed	Developed Code	Gasturb	Absolute Difference
	POWER (kW)		%
0.75	151.2	153.2	1.2
0.8	259.4	259.2	0.1
0.85	395.1	396.0	0.2
0.9	541.6	540.5	0.2
0.95	677.8	673.8	0.5
1	815.6	818.5	0.4
1.05	957.4	955.7	0.2

The transient performance estimation capability of the developed software is compared with the simulation results [Ballin, 1988]. In this reference paper, there is a comparison of a developed real time model of the T700 engine of General Electric with the NASA Lewis simulation. The latter simulation is also validated with the NASA Lewis experimental test engine and referenced in the same paper. The models mentioned in this paper are embedded with the heat sink and volume dynamics approximations with the constants developed specifically for the T700 engine. In Spack's study [2011], the digitized T700 engine map is available and this map is used in the transient performance estimation in the developed software. The transient scenario used in this comparison is that the fuel flow of the engine is increased from 400 lbm to 775 lbm per hour (step increase). Resultant turbine 1st rotor inlet temperatures are given in Figure 7.

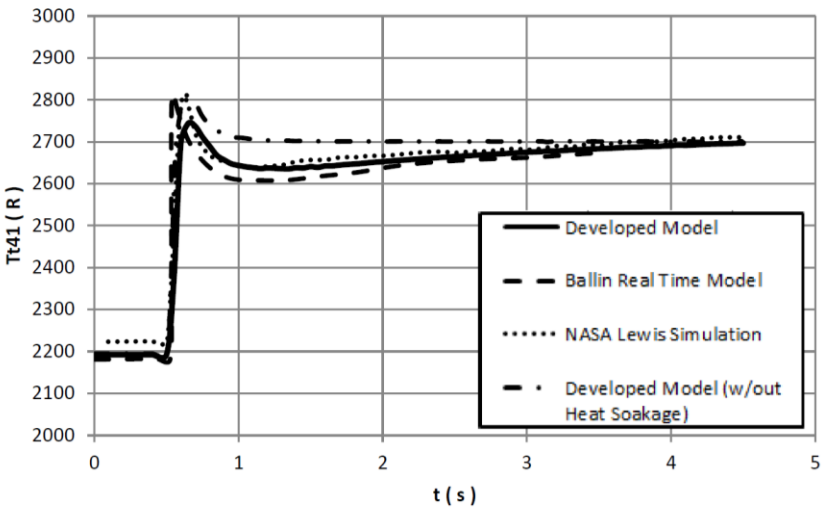

Figure 7: Gas Generator Turbine 1st Nozzle Guide Vane Exit Total Temperature Comparison

There are small deviations mainly due to the different heat soakage and volume dynamics approaches between the simulation models. In these kind of preliminary design calculations, the important examination of the transient applications are the initial and final points of the transient scenario. In other words, if the initial and final parameters (steady-state values with considering the elapsed time after initiation of the transient) of the transient scenario match well with real application results, this software can be categorized as sufficient for preliminary design transient estimations. As expected, similar trends in transient performances can be seen in Figure 6. In addition, properties at steady state performances (i.e. at t = 0 s and t = 5 s) nearly match with each other, which implies that the developed model matches well with the engine holding on the interested scope.

To conclude, a computer software that can model the design, off-design and transient performances of a turboshaft engine is developed for the use of performance engineers. The reliability of the developed software is also validated by the data available in the literature and the available commercial software Gasturb 11.

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