# ELABORATION OF A ROBUST THERMODYNAMIC MODEL OF AIRCRAFT ENGINE

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**Abstract**

Transient performance usually concerns the behavior of aircraft gas turbine engines during acceleration or deceleration from one steady state point to another steady state point [6]. The acceleration curve follows a dynamic path that puts the compressor closer to the stall/surge line because of a raised pressure ratio. In an aircraft engine, power transients are associated with the transient effects produced by the demand for more power. When the engines accelerate, the compressor operating point follows a dynamic acceleration path which is above the static path, thus putting the compressor closer to stall/surge [26]. These transient effects can put the compressor into stall/surge. If the margin associated with the transient uncertainties is not designed appropriately, the aircraft engine may surge, and the results can be catastrophic. The goal of this presentation is to analysis of the effects of power transients after creation of a steady model of engines (real cycle and operating line) applied to given engines. Analysis programs are created using MATLAB. They calculate the main parameters of aircraft engine cycle from the steady state, either on design working, or operating line, or off design working to the transient phase. In the part of the transient phase, the term “power transient” is used to describe the behavior of the compressors when the engines accelerate or decelerate. The fuel scheduling and the bleed flows are currently employed in the field to ensure the avoidance of stall/surge. The bleed flows reduce the pressure ratio. The margin of power transients is reduced and the efficiency of the system is thus enhanced [31].Analysis shows that control of power transients via bleed flows results in a compromise between performance (engine acceleration) and stability (margin of power transients). Despite the compromise, analysis shows that stability can be guaranteed without completely sacrificing performance.

## 1. INTRODUCTION

Mathematic and aero-thermodynamic modelings of aircraft gas turbine engine performance are required by developments and the phases of the life of a gas turbine. In the stage of development these modelings can provide effectiveness in the behavior and the physics of engine, to make it possible to define specifications of the total control devices. While the effort of modeling can be wide, it should produce a significant output in terms of total development of engine. The performance of model of engine must be checked by using true data collected of the gas turbine, by which the parameters of the models could need the update. Another important field of the application of such models is the handling of engine. Fast control responses are required for reasons of maneuverability and of safety but of the problems such as the pumping of compressor must be avoided. The design of a control device of engine which can face these different conditions is facilitated considerably by the use of the simulation of modeling on the level of the development.

During most of an aircraft engine operational life, it operates at steady sate, however it is transient performance during which engine is exposed to the extreme operating conditions. The most of dynamic performance of the engine can be unfortunately tested by the completely mechanical hardware on a test bed facility. According to the complexity of the overall aircraft engine operation, complete mathematic models are difficulty realized and mainly rely on experimental data and empirical correlations with most of components represented by component map.

During a new aircraft gas turbine engine design, an aero-thermodynamic model is created to predict its performance of all conditions and operations. This paper presents the robust aero-thermodynamic models capable to simulate the aircraft engine performance from on-design, off-design to transient operations by utilising MATLAB and its graphical user interface (GUI) module. The program can calculate thermodynamic cycle of various engine configurations and types and various results are presented in graphical and numerical forms.

## 2. MODELING DESCRIPTION

Aero-thermodynamic model proposed in this paper is particularly for the transient performance simulation for any aircraft gas turbine engine with in-line compressor. The on-design, off-design and transient models used in this research are based on the thermodynamic real cycle with losses and by using polytropic efficiencies for compressors and turbines and real gas enthalpy and specific heat functions for obtaining the results of calculation more accurate.

The enthalpy and specific heat functions [5] used in the model are for real gas mixed between air and kerosene. Theses functions are expressed by

Given

$$a = e^{\frac{3090}{T_T}}$$

Enthalpy function:

$$H_{air} = R \cdot \begin{pmatrix} 3.5 \cdot T_T - 1.4 \cdot 10^{-5} \cdot T_T{}^2 + \\ 7.467 \cdot 10^{-9} \cdot T_T{}^3 + \dfrac{3090}{a-1} \end{pmatrix}$$

$$H_k = R \cdot \begin{pmatrix} -6.12432 \cdot 10^{-7} \cdot T_T{}^3 + 4.00997 \cdot 10^2 \cdot T_T{}^2 \\ +4.47659 \cdot T_T - 149.054 \end{pmatrix}$$

$$H = \frac{H_{air} + \alpha \cdot H_k}{(1+\alpha)}$$

where

$T_T$ : Gas total temperature ($K$)

$H_{air}, H_k, H$ : Total specific enthalpy of air, kerosene and mixed gas ($J/kg$)

$R$ : Gas constant ($J/kg/K$)

$\alpha$ : Fuel air ratio

$$Cp_{air} = R \cdot \begin{pmatrix} 3.5 - 2.8 \cdot 10^{-5} \cdot T_T + 2.24 \cdot 10^{-8} \cdot T_T^2 \\ + \left(\dfrac{3090}{T_T}\right)^2 \cdot \dfrac{a}{(a-1)^2} \end{pmatrix}$$

$$Cp_k = R \cdot \begin{pmatrix} -1.8373 \cdot 10^{-6} \cdot T_T^2 + 8.01994 \cdot 10^{-3} \cdot T_T \\ +4.47659 \end{pmatrix}$$

$$Cp = \frac{Cp_{air} + \alpha \cdot Cp_k}{1+\alpha}$$

where $Cp_{air}$, $Cp_k$, $Cp$ are respectively the specific heat of air, kerosene and mixed gas.

Station numbering of separated-flow turbofan without afterburner, by example, is presented in the figure 1.

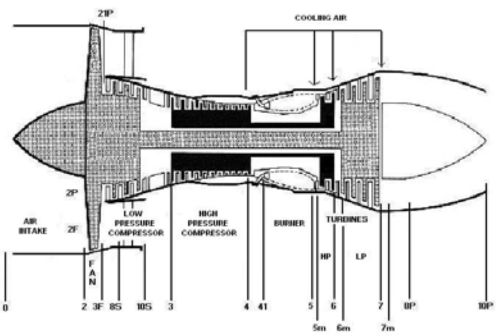


Figure 1: Station numbering of turbofan

(Source : www.aerospaceweb.org)

## 2.1 TRANSIENT PERFORMANCE ANALYSIS

Transient operation corresponds to the parameters variation of the engine, such as fuel flow or rotational speed, with time during the acceleration and the deceleration from an operating steady state point. Acceleration or deceleration of the gas turbine engine depends on the parameters, such as the moment of inertia of the rotor system and the maximum temperature that the turbines can support for a short length of time. The characteristic of the engine has an important effect on its transient operation; by example, a turbofan responds differently and slowly compared to a turbojet.

A complete program of gas turbine modeling must allow calculating transient operation. In order to carry out the transient performance, the program must not only model the equations of thermodynamics but also integrate the data provided by the control system, such as the variation the fuel flow with time.

In the on-design and off-design models, the modelings of these operations are based on the compatibility of the flow and the compatibility of work. On the other hand, in the transient operation, in order to accelerate the engine, additional fuel flow is added, so that the total gas temperature ($T_{T5}$) at exit of the combustion chamber increases. This involves an increase in the power, provided by the turbines, more than the power necessary to the compressors. The revolution speed thus increases until the balance of the rotor torques. By the effect of power excess or positive power imbalance, the flow conservation can be considered validates contrary to the work conservation. The deceleration because of the reduction in the fuel flow produces the opposed effects, such as the reduction of revolution speed and the negative power imbalance.

When the engine functions under the imbalance condition, an important parameter is the moment of inertia, created by this imbalance between turbines and compressors and intervenes in the mathematical and thermodynamic model of transient operation. We consider, for example, the case of the acceleration of the engine. The acceleration of the rotor and the excess torque (or torque of acceleration) $\Delta\Gamma$ can be described by the second law of Newton.

$$\Delta\Gamma = I\dot{\omega} = \Gamma_{turbine} - \Gamma_{compressor} \tag{1}$$

where

$I$ : Rotor moment of inertia ( $kg \cdot m^2$ )

$\dot{\omega}$ : Angular acceleration ($rad/s^2$)

$\Gamma$ : Torque ( $N \cdot m$ )

Angular velocity is given as

$$\omega = \frac{\pi}{30} \cdot N \tag{2}$$

$N$ : Rotation speed ($RPM$)

According to equation (1), the accelerating torque can be calculated by integration on a time interval in order to deduce the change of rotational speed. The problem is now to found the values of the torques for the transient operation. The power delivered by the turbine can be higher or lower than the power required by the compressor, according to the acceleration or the deceleration of the rotor. Generally, the variation of the rotor moment has a small influence on the thrust but it can modify the rotational speed and the operating line of the low pressure compressor.

### 2.2 TRANSIENT PERFOMANCE MODEL

The modeling method for transient operation explained in this paper is called aerothermal model or volume method, [4]. According to the calculation of the operating line, transient operation will be calculated with the time interval defined by the control system or the users.

In the same way that for calculation of on design and off design operation, the gas turbine engine is broken up into components: Air intake, Fan, Compressors, Burner, Turbines, Nozzle and Rotors. The model of each component is described by the aerothermodynamics equations. From equations (1) and (2), the mechanical energy equation of the rotors is given as:

$$\frac{d\omega}{dt} = \frac{1}{I}\cdot\sum\Gamma \tag{3}$$

The characteristic maps of the compressors and the turbines are necessary in order to calculate their operations precisely.

### 2.3 PRESSURE AND TEMPERATURE VARIATION IN VOLUMES

Another important parameter used in this modeling method is intercomponent volume. Intercomponent volumes, connecting two successive components, are assumed to be equal the actual volume of the components considered and are used in order to define total temperatures and total pressures in the volumes.

During steady state operation, the gas flow entering a volume, such as a tube, is equal to the outgoing flow. This is not valid any more for transient operation because the temperature, the pressure and the density of gas vary with time. This phenomenon can have a remarkable impact on the transient performance of the engine, in particular for large volumes such as mixer and combustion chamber.

In the case of the transient flow, the mass flow and the energy flux leaving a volume are not equal to those which enter. The difference is due to the accumulation of mass and internal energy in volume. In this model, mass and energy conservation equations are applied along with the state equation to arrive at governing equations in order to found variations of total temperatures and pressures to time.

Mass flow conservation is defined by

$$\dot{m}_i - \dot{m}_o = \frac{dm_V}{dt} = \frac{V}{\gamma\cdot R\cdot T_T}\cdot\frac{dP_T}{dt} \tag{4}$$

where $\gamma$ is the ratio specific heat.

State equation is given as

$$P_T\cdot V = m_V\cdot R\cdot T_T$$

Then, the variation of total pressure with time can be expressed by

$$\frac{dP_T}{dt} = \frac{\gamma\cdot R\cdot T_T}{V}\left(\dot{m}_i - \dot{m}_o\right) \tag{5}$$

In addition, the conservation of energy is written as

$$\begin{aligned}\dot{m}_i\cdot H_i - \dot{m}_o\cdot H_o + \dot{q} + \dot{W} &= \frac{d\left(m_V\cdot C_V\cdot T_T\right)}{dt}\\ &= C_V\cdot\left(T_T\cdot\frac{dm_V}{dt} + m_V\cdot\frac{dT_T}{dt}\right)\end{aligned} \tag{6}$$

Combining equations 4and 6, we have

$$\dot{m}_i\cdot H_i - \dot{m}_o\cdot H_o + \dot{q} + \dot{W} = C_V\cdot\begin{pmatrix} T_t\cdot\left(\dot{m}_i - \dot{m}_o\right) + \\ \dfrac{P_T\cdot V}{R\cdot T_T}\cdot\dfrac{dT_T}{dt}\end{pmatrix} \tag{7}$$

So, the variation of total temperature with time can be expressed by

$$\begin{aligned}\frac{dT_T}{dt} = &\left(\dot{m}_i\cdot H_i - \dot{m}_o\cdot H_o + \dot{q} + \dot{W}\right)\cdot\\ &\frac{R\cdot T_T}{C_V\cdot P_T\cdot V} - \frac{T_T^2\cdot R}{P_T\cdot V}\cdot\left(\dot{m}_i - \dot{m}_o\right)\end{aligned} \tag{8}$$

where

$\dot{m}_i$ : Upstream mass flow entering the volume which is calculates from component previous to the volume (*kg/s*)

$\dot{m}_o$ : Mass flow exiting from the volume which is calculates from component after the volume (*kg/s*)

$m_V$ : Mass of fluid contained by the volume (*kg*)

$C_V$ : Gas specific heat at volume constant (*J/kg/K*)

$H_i, H_o$ : Inlet and outlet total enthalpy by unit of mass respectively (*J/kg*)

$\dot{q}$ : Heat flux entering to the volume (*W*)

$\dot{W}$ : Lost power (*W*)

$T_T, P_T$ : Total temperature (*K*) and pressure (*Pa*)

V : Intercomponent volume ($m^3$)

The Intercomponent volumes considered in this model are the volumes that situate between compressor to compressor, turbine to turbine and turbine to nozzle. For the calculation more precise, the variation of total pressure, by WALSH [4], can be expressed by

$$\frac{dP_T}{dt} = \left(1 + \frac{(\gamma-1)}{2}\cdot M^2\right)^{\frac{1}{\gamma-1}}\frac{R\cdot T_T}{V}\left(\dot{m}_i - \dot{m}_o\right) \tag{9}$$

where *M* is Mach number entering the volume calculated by

$$\frac{\dot{m}_i\cdot\sqrt{T_T}}{P_T\cdot A} = M\cdot\sqrt{\frac{\gamma}{R}}\cdot\left(1 + \frac{\gamma-1}{2}\cdot M^2\right)^{\frac{\gamma-1}{-2\cdot(\gamma-1)}} \tag{10}$$

where *A* is the enter area of the volume.

### 2.4 HEAT TRANSFER EFFECT

A gas turbine engine running at high rotational speed has temperature higher than when it functions at low speed. Consequently, the metallic parts of the engine are so hotter at high speed than at low speed. During acceleration, the metallic parts absorb the heat of the gas which crosses the engine. The inverse phenomenon occurs for deceleration. The quantity of heat that is absorbed can vary considerably according to the operation of the engine. It also depends on engine size, mechanical components, materials and operation. The effect of heat absorption is complex and depends on the place where it occurs how the engine is controlled.

For a fixed operating line of a high pressure compressor, the augment in the heat absorption has effects over the acceleration time of the components, for example time is increased for compressor and turbine but it is reduced for nozzle. Generally, the effect over the acceleration time is not important but the push reached at the end of a fast acceleration can be reduced up to 5 percent.

For transient performance simulation, the heat transfer effect could be taken into account in the calculation. The calculation of the heat transfer is carried out in each component having an influence on the gas temperature, by considering that the crossing gas flow is non adiabatic.

Heat flux is given by

$$\dot{q} = m^m \cdot C^m \cdot \frac{dT_T}{dt} = h \cdot A^m \cdot \left(T^g_{T,av} - T^m\right) \qquad (11)$$

where

$m^m$ : Metallic part weight (*kg*)

$C^m$ : Gas specific heat of metal (*J/(kg·K)*)

$h$ : Convection heat transfer Coefficient (*W/(m$^2$·K)*)

$A^m$ : Metal surface area (*m$^2$*)

$T^m$ : Metal Temperature (*K*)

$T^g_{T,av}$ : Mean gas total temperature (*K*) given by

$$T^g_{T,av} = \frac{T^g_{T,i} + T^g_{T,o,ad}}{2} \qquad (12)$$

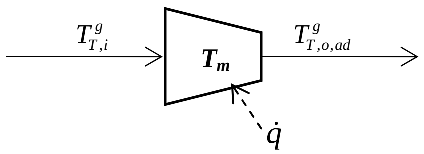


Figure 2: Gas temperature crossing a component

where

$T^g_{T,i}$ : Inlet gas total temperature

$T^g_{T,o,ad}$ : Adiabatic outlet gas total temperature

Given

$$\Theta = T^m - T^g_{T,av}$$

and

$$\int \frac{d\Theta}{\Theta} = -\int \frac{h \cdot A^m}{m^m \cdot C^m} \cdot dt$$

we have then

$$\frac{T^m - T^g_{T,av}}{T^m_n - T^g_{T,av}} = e^{-\frac{h \cdot A^m \cdot t}{m^m \cdot C^m}}$$

where $T^m_n$ is initial metal temperature.

We define the term $\frac{h \cdot A^m}{m^m \cdot C^m}$ as thermal time constant $t_{cm}$ which is about 5 seconds for a 200kg mass engine and 40 seconds for a 2 tonnes mass engine [4]. We have then

$$T^m = T^g_{T,av} - (T^g_{T,av} - T^m_n) \cdot e^{-\frac{t}{t_{cm}}} \qquad (13)$$

At the exit of a component, the total air temperature of the gas $T_{ig}$ is calculated by using its adiabatic total air temperature.

$$T^g_T = T^g_{T,o,ad} - \frac{\dot{q}}{Cp \cdot \dot{m}} \qquad (14)$$

$\dot{m}$ : Mass flow crossing component

$Cp$ : Gas specific heat

### 2.5 COMBUSTION CHAMBER MODEL

Total temperature ($T_{T5}$) and pressure ($P_{T5}$) at the exit of combustion chamber are calculated by equations expressed below. From equation (8), we develop

$$\frac{dT_{T5}}{dt} = \left(\dot{m}_{41} \cdot H_4 - \dot{m}_5 \cdot H_5\right) \cdot \frac{R_5 \cdot T_{T5}}{C_{V5} \cdot P_{T5} \cdot V_{CB}} - \frac{T^2_{T5} \cdot R_5}{P_{T5} \cdot V_{CB}} \cdot \left(\dot{m}_{41} - \dot{m}_5\right)$$

We have then

$$\frac{dT_{T5}}{dt} = \frac{R_5 \cdot T_{T5}}{P_{T5} \cdot V_{CB}} \begin{pmatrix} \dfrac{\left(\dot{m}_{41} \cdot H_4 - \dot{m}_{5air} \cdot H_{5air} + \dot{m}_f \cdot LHV\right)}{C_{V5t}} \\ -T_{T5} \cdot \left(\dot{m}_{41} - \dot{m}_5\right) \end{pmatrix} \qquad (17)$$

$m_f$ : Fuel flow rate (*kg/s*)

$LHV$ : Fuel lower heating value (*J/kg*)

$V_{CB}$ : Combustor volume (*m$^3$*)

The gas total temperature at time t ($T_{T5t}$) is given as:

$$T_{T5t} = T_{T5,t-1} + \left(\frac{dT_{T5}}{dt}\right) \cdot \Delta t \qquad (18)$$

where $T_{T5t}$, $T_{T5t-1}$ is total temperature at time t and t-1 respectively.

The total pressure ($P_{T5t}$) at time t is calculated by the state equation:

$$P_{T5t} = \rho_{5t} \cdot R_{5t} \cdot T_{T5t}$$

or more accurately by equation (19) proposed by WALSH [4]

$$P_{T5t} = \left(1 + \frac{\gamma_5 - 1}{2} \cdot M^2_{5t}\right)^{\frac{1}{\gamma_5 - 1}} \cdot \rho_{5t} \cdot R_{5t} \cdot T_{T5t} \qquad (19)$$

Variation of gas density with time and gas density ($\rho_{5t}$) at time t are calculated by equations (20) and (21) respectively.

$$\frac{d\rho_5}{dt} = \frac{\dot{m}_{41t} - \dot{m}_{5,t} + \dot{m}_{ft}}{V_{CB}} \qquad (20)$$

$$\rho_{5t} = \rho_{5,t-1} + \left(\frac{d\rho_5}{dt}\right) \cdot \Delta t \qquad (21)$$

### 2.6 TRANSIENT SHAFT POWER AND ROTATIONAL SPEED

Unbalanced shaft power due to acceleration or deceleration of a double spool turbojet engine, for example, are expressed as

for high pressure rotor

$$\Delta PWhp = \dot{m}_5 \cdot \left(H_5 - H_6\right) - \frac{\dot{m}_3 \cdot \left(H_4 - H_3\right)}{\eta_{mhp}} \qquad (22)$$

for low pressure rotor

$$\Delta PWlp = \dot{m}_{6m} \cdot \left(H_{6m} - H_7\right) - \frac{\dot{m}_2 \cdot \left(H_3 - H_2\right)}{\eta_{mlp}} \qquad (23)$$

where $\eta_{mhp}$, $\eta_{mlp}$ are respectively mechanical efficiency for high and low pressure rotor.

Shaft power *PW* in function of angular speed is given as

$$PW = \Gamma \cdot \omega$$

and then, by using equations (1) and (2), we have

$$I \cdot \dot{\omega} = \Gamma_{tur} - \Gamma_{com} = \frac{\Delta PW}{\omega}$$

$$\left(\frac{\pi}{30}\right)^2 \cdot I \cdot N \cdot \frac{dN}{dt} = \Delta PW$$

Rotor acceleration rate and rotation speed at time t are calculated by

$$\frac{dN}{dt} = \frac{900 \cdot \Delta PW_{t-1}}{\pi \cdot I \cdot N_{t-1}} \qquad (24)$$

$$N_t = N_{t-1} + \left(\frac{dN}{dt}\right) \cdot \Delta t \qquad (25)$$

### 3. MODEL APPLICATION FOR GAS TURBINE

Matlab, GUIs and its mathematic tools are used in this work in order to model and calculate the operations and the performances of aircraft gas turbine engine. GUIs allow the users creating graphic interfaces in the form of windows composed by elements. In a graphic interface window, the communication with the users is generally established using objects such as list box, check box, push button, static or edit texts.

The program is made in order to calculate operations and performance of many configurations of aircraft gas turbine engines. In the program, gas turbine engines are separated in two principle types:

- Single spool engine
- Double spool engine

In each type of engine, the users can choose then that the engine

- has an afterburner or not
- functions with which type of nozzle
- and is turbojet or turbofan (separate or mixed stream)

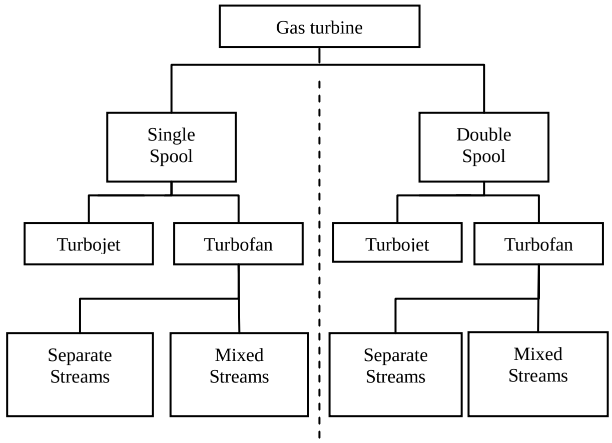

Figure 5: Engine configuration diagram

The program also composes in two parts: Principle programs and Sub-programs. In the principle programs, there are three calculating modules for the on design, the off design and the transient operations. The sub-programs are created for drawing curves of compressor and turbine characteristic maps from data given by the users and for, optionally; calculating nozzle losses, due to boundary layer, friction etc.

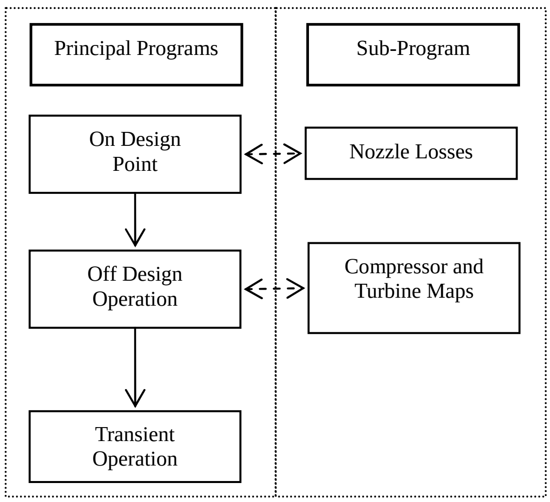

Figure 6: Schematic Diagram of the program

### 4. COMPOSITION OF PROGRAMMING AND EXAMPLE

The programming is separated in 2 principle parts:

- Graphical user interface creating part
- Calculating part

The users can communicate with the calculation programmes via the graphic interfaces created by using GUIs. Through graphic windows with interactive commands, the users enter numerical data of the engine of which they want to carry out the calculation, such as atmospheric and flight condition, combustor exit total temperature, thrust etc. After having entered the data necessary to calculation of the cycle and points of operation, these values are sent to the calculation programs which compose in three parts:

- Operating point calculation part
- Operating line calculation part
- Transient performance calculation part

Aircraft gas turbine engine cycle calculation begins with the operating point calculation. The user enters numerical data through a panel such as figure 7 and then click over the button "EXECUTE" in order to launch the calculation.

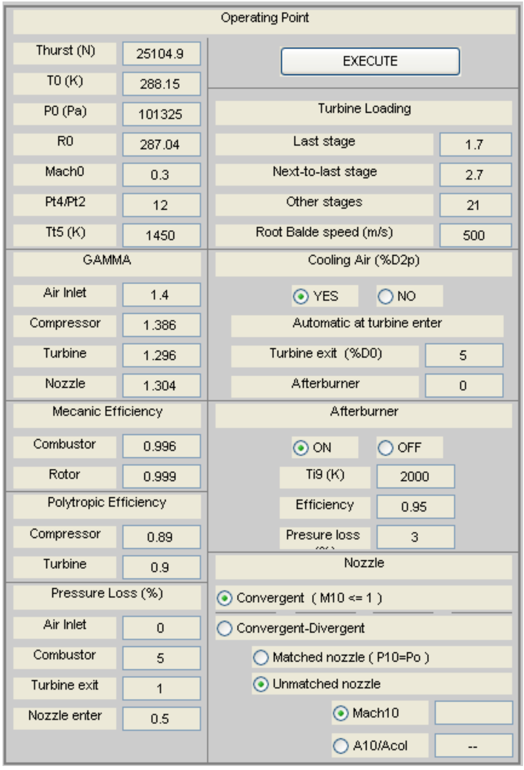

Figure 7: Data Panel for Operating Point calculation

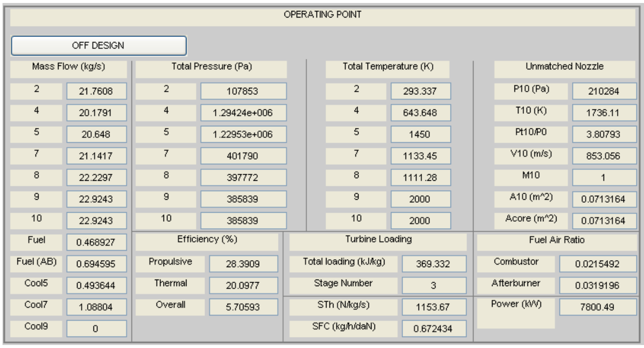

Figure 8: Result Panel

Figure 8 represents the results of the operating point calculation. The values displayed in this panel are mass flow, total temperature and pressure at each position in the engine, efficiencies, thrust etc.

The operating line calculation is launched by clicking at the upper right button called "OFF DESIGN". Another panel (Figure 9), displaying again the value of operating point as reference point, appears. Through the panel, the user enters number of point of the operating line and step value of rotation speed. This panel has buttons (on the top) which link to sub-programs for creating compressor and turbine maps.

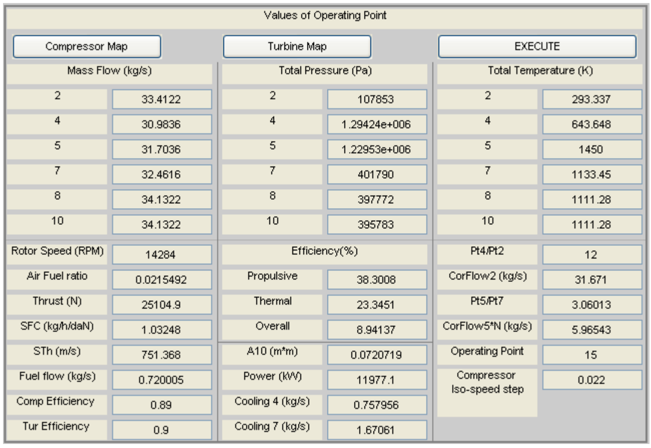

Figure 9: Data Panel for Operating Line calculation

Figure 10 is an example of data compressor panel. The user gives values of compressor map such as pressure ratio, corrected mass flow and efficiency of each iso-speed line.

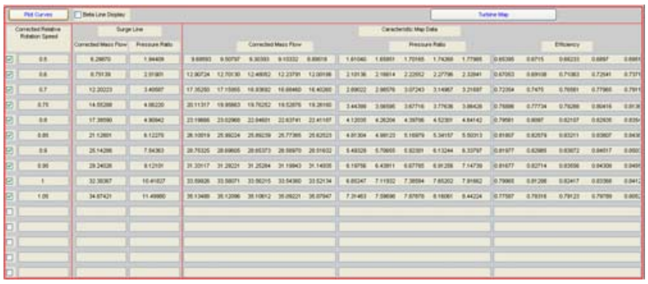
Figure 10: Panel for entering compressor map data

After finishing creating compressor and turbine maps, the calculation can be executed. The results are displayed values of important parameters of each point on the operating line in form of table with slide bar (Figure 11) and there is the button for lunching the transient performance calculation on the bottom left.

The operating line, plotting in compressor and turbine maps as cross-marker lines, is also presented in others graphic windows (Figure 12).

In order to execute the transient performance, the values of parameters, such as fuel flow and time variation, volumes, rotor moment of inertia etc., should be specified in data panel (Figure 13).

When the calculation is finished, the results of the calculation are appeared on the screen in the same format as the operating line calculation. The transient operating line is also plotted in the compressor and turbine maps (Figure 14).

## 5. CONCLUSION

The program created in this work by using Matlab for calculating and visualizing graphic results, is for analysis of on design, off design and transient operation of single and double spool aircraft gas turbine engines, with in-line compressor, with/without afterburner and with convergent or convergent-divergent nozzles. The program uses the aero-thermodynamic equations for modelling the calculation. For the transient model, this program takes into account the effect of intercompnent volumes and also the heat transfer effect Because of the powerful of Matlab, the program is easy to access to the core of the program and then modify the model by the user and made for the user easy to understand and utilize.

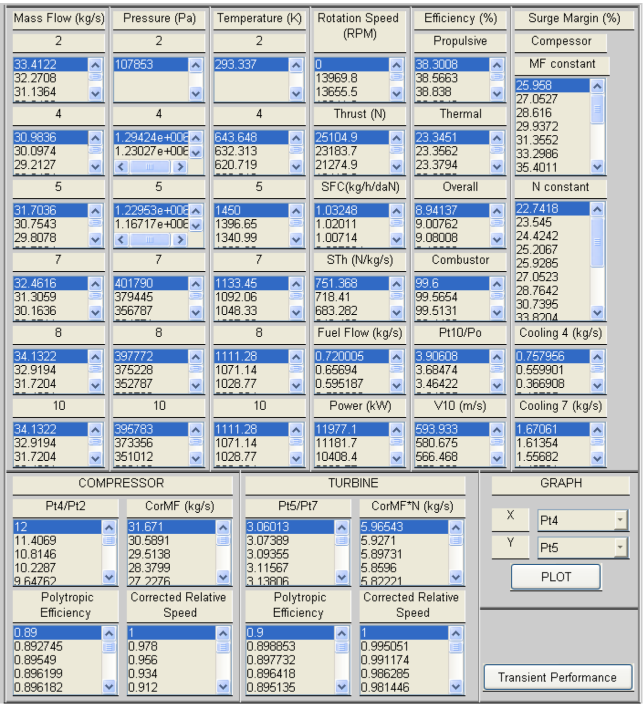


Figure 11: Operating Line

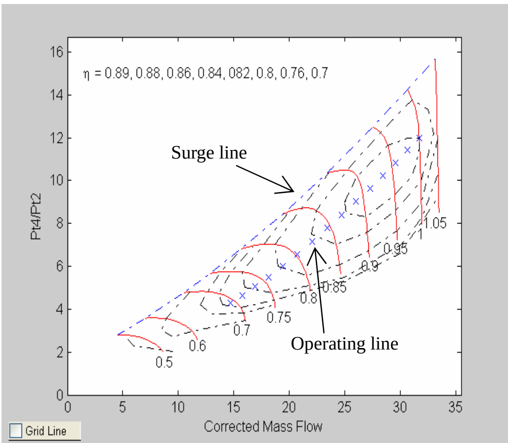


Figure 12a: Steady-state operating line on a compressor map

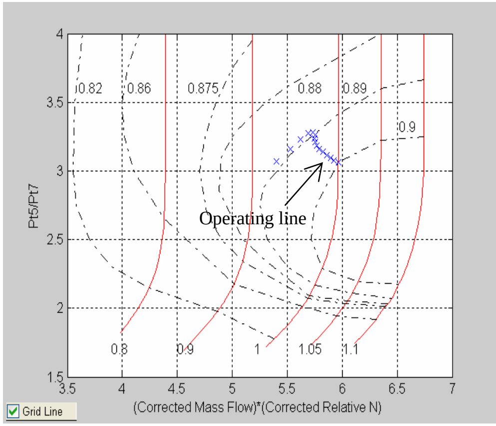


Figure 12b: Steady-state operating line on a turbine map

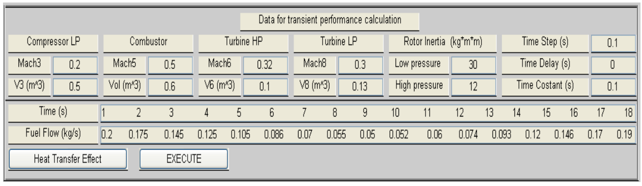


Figure 13: Data Panel for Transient Performance calculation

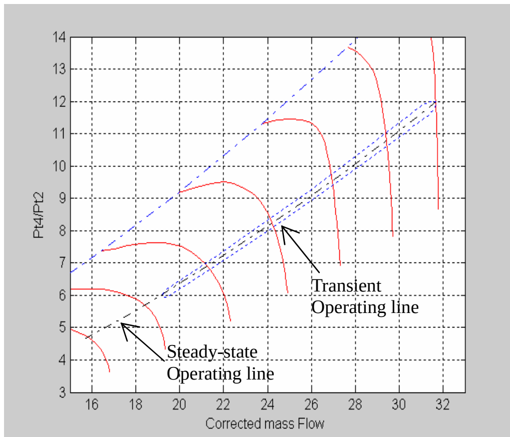


Figure 14a: Transient operating line on a compressor map

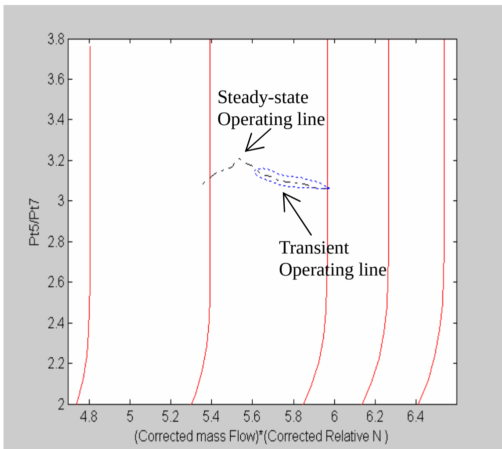


Figure 14b: Transient operating line on a turbine map

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