

Aircraft Flight Modeling During the Optimization of Gas Turbine Engine Working Process

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Abstract. The article describes a method for simulating the flight of the aircraft along a predetermined path, establishing a functional connection between the parameters of the working process of gas turbine engine and the efficiency criteria of the aircraft. This connection is necessary for solving the optimization tasks of the conceptual design stage of the engine according to the systems approach. Engine thrust level, in turn, influences the operation of aircraft, thus making accurate simulation of the aircraft behavior during flight necessary for obtaining the correct solution. The described mathematical model of aircraft flight provides the functional connection between the airframe characteristics, working process of gas turbine engines (propulsion system), ambient and flight conditions and flight profile features. This model provides accurate results of flight simulation and the resulting aircraft efficiency criteria, required for optimization of working process and control function of a gas turbine engine.

1. Introduction

Economic and aircraft performance characteristics are usually used as optimization criteria during the selection of working process parameters of gas turbine engine. Mathematical models of these characteristics of various detail levels are described in [1, 2].

Following criteria are most widely used: payload mass, take-off mass of the aircraft, total weight of the propulsion system and required fuel, specific fuel consumption of aircraft, cost of aircraft operation per hour, cost of transportation, net profit per operation hour, reduced cost of transportation, flight range. All these criteria are influenced (directly or indirectly) by the fuel mass onboard.

Most approaches to optimization of the working process parameters of gas turbine engine use the statistic correlation between the SFC at the rated conditions, SFC at off-design modes of operation and the fuel consumption for a given flight range [1]. The purpose of this paper is to provide a method of aircraft flight simulation, providing the interconnection between the propulsion system control program, working process parameters of engine and the aircraft efficiency criteria.

2. Problem setting

Flight conditions influence the working process parameters of gas turbine engine according to the general laws of joint operation of engine components. The value of thrust of the propulsion system to the external drag of the aircraft ratio determines the change in airspeed or flight trajectory. The external drag of an aircraft depends on its aerodynamic characteristics and control parameters and can be calculated for a given climb/descent program or for a specified flight trajectory. Control program of



propulsion system determines the aircraft movement parameters along the flight trajectory, flight time, amount of fuel required for the flight and, ultimately, the values of the criteria characterizing the efficiency of the aircraft operation during the given mission. Therefore, the aircraft flight model, taking the interconnection between the engine working process parameters and aircraft behavior into the account is required to provide the correct results of engine working process optimization.

3. Aircraft flight modeling

This aircraft flight model may be developed using the system of differential equations describing the dynamics of the aircraft during the flight. The initial data for this model include take-off mass of the aircraft, aerodynamic and geometric characteristics of the airframe; programs of climbing and descending; altitude of cruising; initial airspeed and coordinates of the aircraft, areas of the characteristic sections of gas turbine engine, performance maps of engine components, control program of engine.

The results of flight simulation include the aircraft parameters variation along the flight trajectory, flight time, fuel consumption per flight, the values of the aircraft performance criteria.

It is necessary to take into account the fact that the flight of aircraft is often a multi-stage process. For example, the scheme of the flight of a subsonic transport (or passenger) aircraft includes the following main stages (figure 1): takeoff; climb; cruising; descending; waiting for landing; pre-landing maneuvering; landing.

Engine operation during the take-off and landing, waiting and pre-landing maneuvering is determined by safety requirements and operational requirements, usually these modes are extreme for engine.

Engine operation during climbing and descending is also regulated, but the engine parameters are not constant and change along the altitude due to variation of ambient conditions.

Engine mode of operation during the cruising changes in a wide range and is determined by the thrust value required for the horizontal flight at a given airspeed.

As the aircraft flight is described in a variety of ways according to the flight stage, modeling of these stages is performed separately. The results of modeling are sequentially transferred as the initial data to the next stages of flight.

Climbing. Airspeed change along the altitude is usually considered initial data. The mode of engine operation is supposed to be constant (nominal mode). This flight stage ends as the aircraft reaches the given altitude of cruising. Flight trajectory is determined by the engine control function (thrust changes according to the ambient conditions).

Cruising. Cruising begins as the aircraft reaches the corresponding altitude and finishes as it reaches the descending point. The engine mode of operation may either change in accordance to the aircraft weight, or be estimated to provide constant airspeed. Horizontal flight conditions provide the means for calculating the angle of attack at each point of cruising. The flight profile may include additional climbing and cruising stages as the weight of aircraft decreases.

Descending. This stage of flight is identical to the climbing stage, except for the idle mode of engine operation.

4. Mathematical model of flight

Aircraft flight is described by three groups of equations: dynamic equations of aircraft motion, kinematic equations and weight change as a result of fuel consumption.

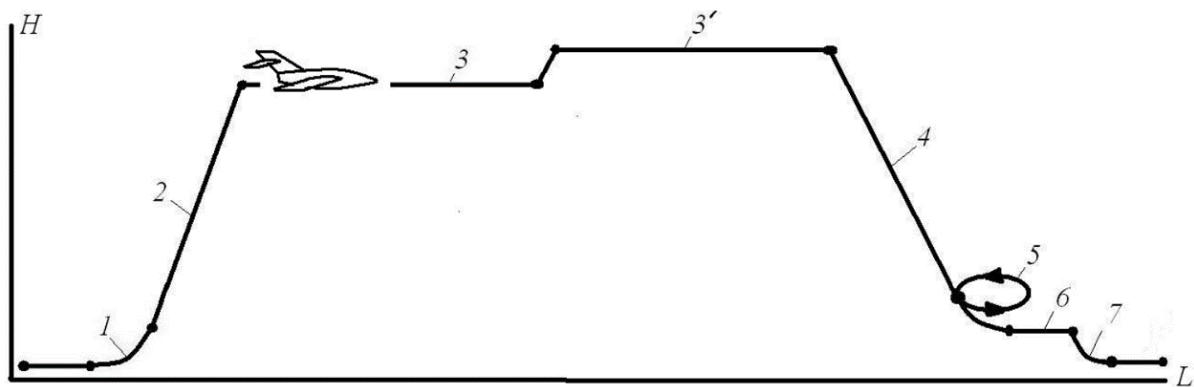


Figure 1. Typical flight profile of a transport aviation aircraft: 1 – takeoff; 2 – climb; 3, 3' – cruising; 4 – descending; 5 – waiting for landing; 6 – pre-landing maneuvering; 7 – landing.

Dynamic equations of aircraft motion relative to the ground (neglecting the wind velocity) include [3, 4, 5]:

$$\left. \begin{aligned} M_A \dot{V}_f &= P_{\text{ef.ps}} \cos(\alpha + \varphi_{th}) \cos \beta - X_a - M_A g \sin \Theta; \\ M_A V_f \dot{\Theta} &= P_{\text{ef.ps}} [\sin(\alpha + \varphi_{th}) \cos \gamma_a + \cos(\alpha + \varphi_{th}) \sin \beta \sin \gamma_a] + Y_a \cos \gamma_a - \\ &- Z_a \sin \gamma_a - M_A g \cos \Theta + 2M_A \varpi_z V_f \cos \varphi \sin \Psi + M_A V_f^2 \frac{\cos \Theta}{R_{\text{earth}} + H}; \\ -M_A V_f \cos \Theta \dot{\Psi} &= P_{\text{ef.ps}} [\sin(\alpha + \varphi_{th}) \times \sin \gamma_a - \cos(\alpha + \varphi_{th}) \sin \beta \cos \gamma_a] + \\ &+ Y_a \sin \gamma_a + Z_a \cos \gamma_a + 2M_A \varpi_z V_f \times (\sin \varphi \cos \Theta - \cos \varphi \cos \Psi \sin \Theta) - M_A V_f^2 \cos^2 \Theta \sin \Psi \frac{\text{tg } \varphi}{R_{\text{earth}} + H}. \end{aligned} \right\} \quad (1)$$

Coriolis and centrifugal force (associated with ground curvilinearity) for airspeeds less than 1000 m/s are usually not taken into the account.

Flight without aircraft roll and sideslip is described by:

$$\gamma_a = 0; \quad (2)$$

$$\beta = 0; \quad (3)$$

$$Z_a = 0. \quad (4)$$

With the above mentioned assumptions, the equations system (1) takes the following form:

$$\left. \begin{aligned} M_A \dot{V}_f &= P_{\text{ef.ps}} \cos(\alpha + \varphi_{th}) - X_a - M_A g \sin \Theta; \\ M_A V_f \dot{\Theta} &= P_{\text{ef.ps}} \sin(\alpha + \varphi_{th}) + Y_a - M_A g \cos \Theta. \end{aligned} \right\} \quad (5)$$

Following equations describe the kinematics of motion and aircraft weight change as a result of fuel consumption:

$$\left. \begin{aligned} \dot{H} &= V_f \sin \Theta; \\ \dot{L} &= V_f \cos \Theta; \\ \dot{M}_A &= -G_{\text{fuel.ps}}. \end{aligned} \right\} \quad (6)$$

As the flight stages are usually described with their corresponding distances, use of flight range L as a phase variable is reasonable (figure 1). Thus, the differential equations system of the aircraft flight may be described as follows:

$$\left. \begin{aligned} \frac{dV_f}{dL} &= \frac{1}{M_A V_f \cos \Theta} \left[P_{\text{ef,ps}} \times \cos(\alpha + \varphi_{th}) - X_a - M_A g \sin \Theta \right]; \\ \frac{d\Theta}{dL} &= \frac{1}{M_A V_f \cos \Theta} \left[P_{\text{ef,ps}} \times \sin(\alpha + \varphi_{th}) + Y_a - M_A g \cos \Theta \right]; \\ \frac{dH}{dL} &= \text{tg } \Theta; \\ \frac{dt}{dL} &= \frac{1}{V_f \cos \Theta}; \\ \frac{dM_A}{dL} &= \frac{-G_{\text{fuel,ps}}}{V_f \cos \Theta}. \end{aligned} \right\} \quad (7)$$

The resulting system of differential equations include the airframe parameters (external drag X_a , lifting force Y_a , angle of attack α) and propulsion system parameters (effective thrust $P_{\text{ef,ps}}$, fuel consumption $C_{\text{fuel,ps}}$). These parameters depend on the control functions of aircraft and engine and may be calculated using the individual sub-models, having their own hierarchy (figure 2).

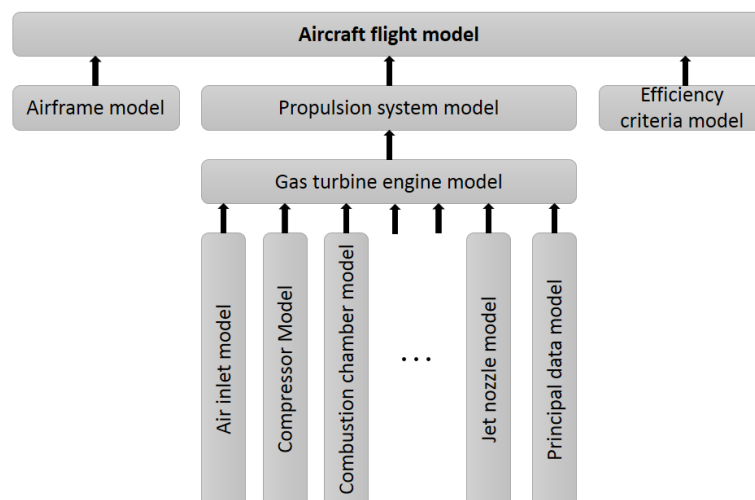


Figure 2. Structure of the mathematical model of aircraft flight.

The mathematical model of gas turbine engine is described in detail in [4] and the mathematical model of criteria.

5. Mathematical model of aircraft

The mathematical model of the aircraft provides the values of lifting force Y_a and external drag X_a as a function of geometrical parameters, aerodynamic characteristics and flight conditions [6, 7, 8]:

$$Y_a = c_{ya} \frac{k}{2} p_H M_f^2 S_w; \quad (8)$$

$$X_a = c_{xa} \frac{k}{2} p_H M_f^2 S_w. \quad (9)$$

Aerodynamic characteristics of the airframe are usually described by the following functional relations [5]: a) $c_{ya} = f(\alpha, M_f)$, b) $c_{xa} = f(c_{ya}, M_f)$: (figure 3).

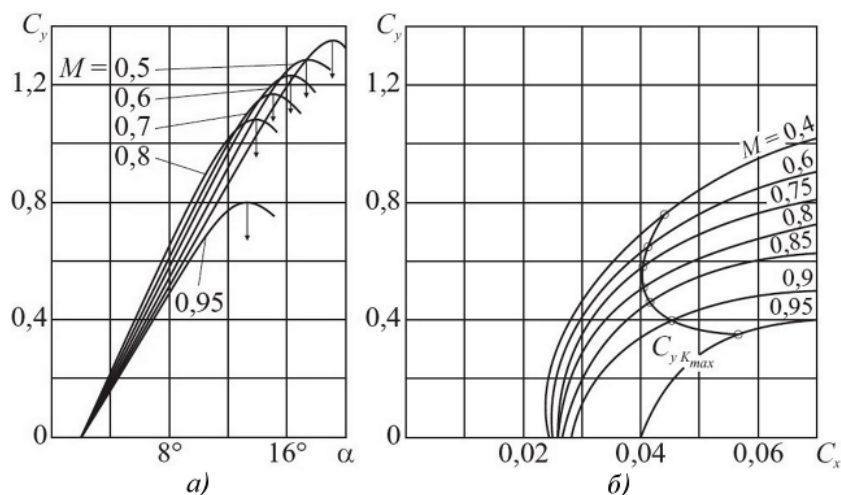


Figure 3. Aerodynamic characteristics of airframe.

6. Conclusions

The described above mathematical model of aircraft flight provides the functional connection between the airframe characteristics, working process of gas turbine engines (propulsion system), ambient and flight conditions and flight profile features. This model provides accurate results of flight simulation and the resulting aircraft efficiency criteria, required for optimization of working process and control function of a gas turbine engine [9, 10].

7. Nomenclature

- SFC – specific fuel consumption;
- M_A – mass of aircraft;
- V_f – airspeed;
- $P_{ef.ps}$ – overall effective thrust of propulsion unit;
- α – attack angle;
- β – sliding angle;
- γ_a – rolling angle;
- φ_{th} – angle between the thrust vector and aircraft axis;
- X_a – drag force;
- Y_a – lifting force;
- Z_a – side force;
- c_{xa} – lift coefficient;
- c_{ya} – drag coefficient;
- g – free fall acceleration;
- Θ – угол наклона траектории;
- ϖ_z – угловая скорость вращения земли;
- Ψ – угол пути;

- R_{earth} – radius of Earth;
- H – flight altitude;
- $G_{fuel,ps}$ – fuel consumption rate;
- L – flight range;
- t – flight time;
- k – adiabatic index of ambient air;
- p_H – ambient pressure;
- M_f – ambient Mach number;
- S_w – wing area.

Acknowledgments

This work was supported by the Ministry of education and science of the Russian Federation in the framework of the implementation of the program of increasing the competitiveness of Samara University among the world's leading scientific and educational centers for 2013-2020 years.

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