

Article

Computational Simulation of PT6A Gas Turbine Engine Operating with Different Blends of Biodiesel—A Transient-Response Analysis

Camilo Bayona-Roa *, J.S. Solís-Chaves , Javier Bonilla , A.G. Rodríguez-Melendez and Diego Castellanos

Universidad ECCI, Cra. 19 No. 49-20, Bogotá 111311, Colombia; jsolisc@ecci.edu.co (J.S.S.-C.);

jbonillap@ecci.edu.co (J.B.); rodriguez.anderson@ecci.edu.co (A.G.R.-M.);

diegocastellanos1234@hotmail.com (D.C.)

* Correspondence: cbayonar@ecci.edu.co

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Abstract: Instead of simplified steady-state models, with modern computers, one can solve the complete aero-thermodynamics happening in gas turbine engines. In the present article, we describe a mathematical model and numerical procedure to represent the transient response of a PT6A gas turbine engine operating at off-design conditions. The aero-thermal model consists of a set of algebraic and ordinary differential equations that arise from the application of the mass, linear momentum, angular momentum and energy balances in each engine's component. The solution code has been developed in Matlab-Simulink® using a block-oriented approach. Transient simulations of the PT6A engine start-up have been carried out by changing the original Jet-A1 fuel with biodiesel blends. Time plots of the main thermodynamic variables are shown, especially those regarding the structural integrity of the burner. Numerical results have been validated against reported experimental measurements and GasTurb® simulations. The computer model has been capable to predict acceptable fuel blends, such that the real PT6A engine can be substituted to avoid the risk of damaging it.

Keywords: gas turbine engine; two-spool turboprop engine; PT6A engine; aero-thermal model; Matlab-Simulink; bio-diesel; start-up transient

1. Introduction

The necessary thrust that is required for an aircraft to provide lift is commonly supplied by a heat engine. In particular, a gas turbine engine can convert heat energy into mechanical energy by involving the flow of air passing through several thermo-fluidic processes within its components. One of the most important features of gas turbine engines is that, contrary to reciprocating engines, separate sections of the engine are devoted to the intake, compression, combustion, power conversion and exhaust processes. This also means that all processes are performed simultaneously and that they are strongly coupled between them. Hence, the conceptual description of the gas turbine engine's response is complex; it involves the approximation from very different engineering disciplines: Aerodynamics, Thermodynamics, Heat Transfer, Structural Analysis, Materials Science and Mechanical Design.

Remarkably, in all those fields the mathematical modeling of a gas turbine engine is constructed by applying the mass, energy and momentum balances over the most representative solid and fluid elements of the engine. These balances have to do with the air crossing through the gas turbine engine's stages and its interaction with the rotatory solid components. The overall result of this modeling process gives a set of several partial differential equations whose solution is the spatial and temporal

description of the air through the engine's stages and the performance of the engine. Since there are not any exact solutions due to the geometry complexity and temporal dependence, we rely entirely on numerical methods to find an approximated numerical solution.

The level of numerical resolution of each component is also important: a great level of detail in the description may also be computationally expensive. Selecting one or other may be based on the objectives of the simulation and the given computational resources. In a turboprop engine modeling, for example, the complex geometric description of the rotary components makes it hard to generate a full spatial solution, namely a discrete spatial mesh for Computational Fluid Dynamics (CFD). Considering the dynamic rotatory movement of the components raises—even more—the model complexity and the computational cost. Trying to couple the engine's components in the CFD simulation is a problem that may not be solvable with actual computational methods and power.

And that is our particular motivation in the present work: to simulate the overall engine performance. We are also restricted by the computational resources at hand, which are a personal computer. These requirements typically lead to neglect a very detailed spatial description of the airflow, preferring an integrated definition of each engine stage to what is referred to as a lower-dimensional model. This approach defines space-averaged values at each engine's component and the partial differential equations arising from the balance equations turn to ordinary differential equations that can be solved numerically in an affordable way. The important aspect is that this spatially-simplified approach is capable to represent the engine's operation giving accurate physical solutions that arise from the balance equations.

Precisely, we are interested in computational simulations capable of representing the PT6A turboprop gas turbine engine performance when a change in the operating fuel occurs. Specifically, the evaluation of the transient state of the engine at the start-up procedure, when the temperature in the burner reaches its maximum and can significantly affect the combustion chamber. Testing a gas turbine operating with fuel compositions is costly and time-consuming but also leads to performance degradation of the manufactured engine. Instead, the tests that can be achieved with computational models like those in References [1–4] which are inexpensive and fast when used for new designs, predicting the system's integrity and calculating real-time responses. In this sense, a wide range of computer engines have been implemented and reported in the literature: from systematic models in References [5–9], to the detailed component design of engine parts in References [10–15]. Because of the previously supported reasons, we opt for an integrated representation of the engine as an assembly of components to what is commonly referred to as a Common Engineering Model (CEM). These components—inlet, fan, compressors, combustion, turbine, shafts and nozzle—are abstracted in the computational model as blocks—or objects—, having connections between them and therefore, being able to model the various propulsion systems, such as multi-spool or turbo-fan type of engines.

We restrict our survey to engine models based on physical descriptions of the engine components. Those range from simulation tools used by the gas turbine production and control industry [16], steady and transient performance simulations of power gas turbines in References [17,18] and general gas turbine software such as DYNGEN [19], TERTS [20], GSP [21], Gasturbolib [22], GasTurb® [23], among others. Academic research has exploited the architectures given by Matlab-Simulink® [22] and Modelica® [24], where different engine types can be created in a visual interface approach. However, most of these works simulate the steady-state thermodynamic cycle of the engine without describing the dynamic behavior of the air that crosses the stages of the engine and nearly all are linearized versions that do not work far from the linearization point—like when the engine operates with blends of biodiesel fuel. Instead, the coupled non-linear version of the equations are solved with the Newton-Raphson method but it requires the computation of the Jacobian and may not converge to the actual numerical solution at all operating regimes. The particular methods that we are interested in, are the ones that do not require an extensive iterative process to obtain the numerical solution of the set of algebraic and differential equations. Those arrange the equations in such a way that the output values can be obtained from the input variables. This is consistent with the flow of air through the

engine components: the input variables are referred to the entering flow conditions, while the output solved variables are the exiting flow.

The thermal performance prediction of gas turbine engines operating with biodiesel has barely been reported in References [25,26] using these computational techniques. The opposite is true for reciprocating engines operating with biodiesel blends, for which performances and emissions predictions have been extensively carried out. What was reported for the steady simulations of gas turbine engines indicated that the modified lower heating value of biodiesel fuels had a significant influence on thrust, fuel flow, and specific fuel consumption at every flight condition and all mixing ratio percentages. Those preliminary results are encouraging and motivate the present research in gas turbine engine technology. Chiefly, for substituting the source of jet fuel from fossil-based fuel to biomass-based, which could reduce the environmental impact and energy consumption of gas turbines.

Our computational approach for the transient response simulation of a gas turbine engine operating with blends of biodiesel is similar to the ones in References [7,20,22,27], where aero-thermodynamical descriptions of gas turbine engines have been done. In contrast to those approaches, we consider the gas dynamics, which are the application of the mass, momentum and energy balances at every component of the gas turbine engine. Especially at the compression and turbine sections, where a stage-by-stage thermo-fluidic description is done for high-fidelity purposes. Another key aspect of the present work has to do with the solution algorithms and the development of the model in a flexible programming architecture, which makes it possible to create the specific configuration of the PT6A turboprop engine but also enables the future extension of the engine model. We formulate each engine component using a separate block, in which the mass, momentum and energy equations give the solution of the dynamical variables. The complete engine is the composition of blocks resulting in a block diagram. Matlab-Simulink® offers the capability of coding those blocks and connecting them to configure any gas turbine engine. It also gives the possibility of using a graphical interface which is more user-friendly, but the relevant feature of this software is that it makes possible to generate source code in C language to generate a much faster executable program. Block diagrams make also possible to link the engine software to control devices, with the capability of driving input/output signals for data acquisition and control. All these features being relevant in the on-live prediction of the gas turbine engine.

The remaining parts of this article are organized in the following order. In Section 2, the real operational gas turbine engine is described: we reproduce a generic version of the Pratt-Whitney PT6A engine. Simultaneously, we present the theoretical description of the thermodynamic processes occurring inside each engine's components. The simulation of different scenarios are given in Section 3. The scenarios include the validation of our model with the reported experimental data of the engine's steady operation, the subsequent steady operation with blends of biodiesel and the transient engine response at the start-up procedure to determine the engine's structural integrity and deterioration. Finally, in Section 4 some conclusions close the article.

2. The PT6A Engine Model

A generic version of the Pratt-Whitney PT6A-65 "Medium" engine, including the labeling of its parts, is displayed in Figure 1. In general, gas turbine engines consist of: an air inlet, a compression section (including the compressor and diffuser), a combustion section (combustion chamber), a turbine section, an exhaust section and an accessory section (for necessary systems). The theoretical description of the thermodynamic processes occurring in these components is Brayton's cycle. But the dynamic simulation of the engine's behavior must account for non-equilibrium conditions, which is the case of the start-up procedure of the engine. The Brayton's model must, therefore, be complemented with the actual design of the turbo-machinery of the engine's stages.

We develop a gas-dynamical model for describing the thermo-fluidic phenomena present in each gas turbine engine's component. For doing so, we apply the fluid's continuity balance for every component of the engine. Especially those with transient mass storage, namely the combustion

chamber where compressible effects of the air are relevant and for the coupling of mass fluxes between consecutive components. We also apply the fluid's momentum balance at the core flows in the compressor and turbine stages. Fluid's energy balance accounts for the combustion chamber heat addition and the compression and expansion processes. The mechanical energy equation is also applied to the rotor stages, including the inertial and frictional losses terms of the rotor shaft, to model the mechanical coupling between the moving components. Since our model focus on describing the primary flow-path components and avoids the description of the structural behavior of the solid parts of the engine—which are not essential in the engine's operation. We also neglect the heat transfer between the solid metal components and the gas in the energy balance equation. As reported in previous works such as Ref. [18], some other non-flow-path components affect the ability to maintain the operation conditions and accounting for them can be significant to obtain accurate simulations. This is the case of the combustion model, the fuel system or the external loads related to the propeller. Although we acknowledge the importance of these systems, we exclude the engine-inlet or engine-outlet integration (to reproduce the inlet and outlet flows), the engine-aircraft integration (to reproduce structural analysis), the engine-environment integration (for adverse weather and pollution) and those control systems.

The application of the balances to the engine's components results in a 0-dimensional model representing the operation at transient state. This “aero-thermal” model is usually confined to the normal operating range of the engine but in the present work it is aimed at giving the engine response at off-design operating conditions. A practical approach to numerically solving the 0-dimensional model is to implement it in Matlab-Simulink® software [28], which possess a graphical user interface for building algebraic block diagrams that give solution to the governing differential equations. Hence, we present the global block diagram of the governing equations in Figure 2, where the engine model is represented at a component level. An extended explanation of each engine's component and how we represent it, will be developed through the following paragraphs. Moreover, each component's block diagram will be presented through the detailed explanation of each sub-system. We list inputs, parameters, variables and outputs for every block diagram.

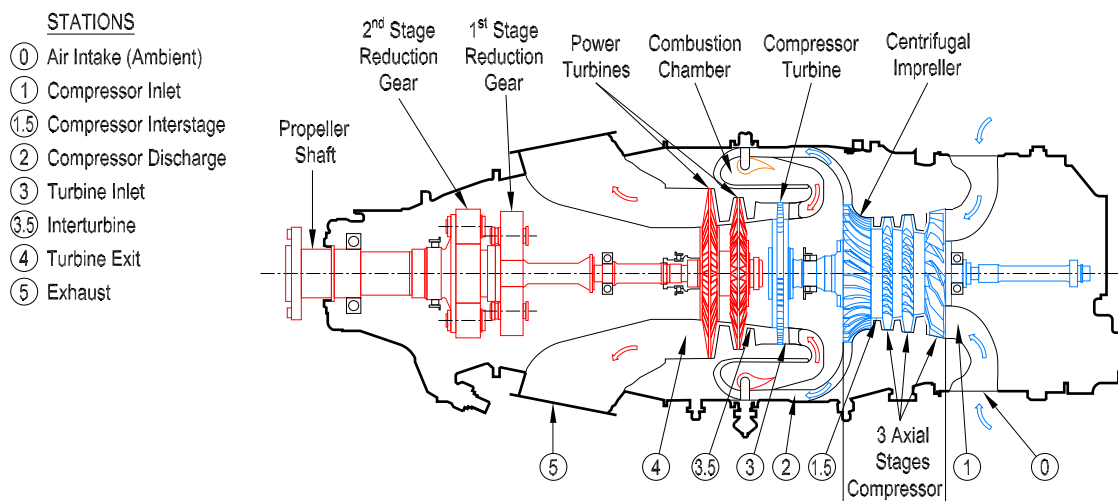


Figure 1. Cross section and stations of the Pratt-Whitney PT6A-65 engine.

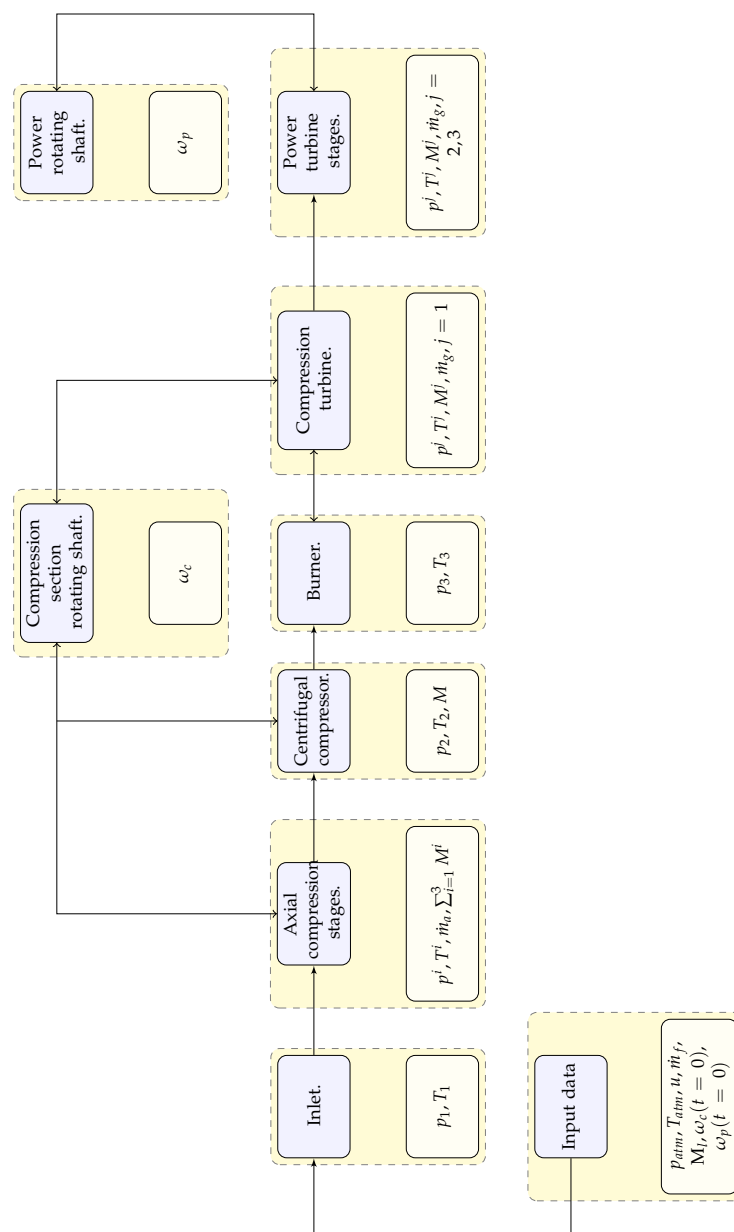


Figure 2. Flow chart of the PT6A-65 engine's model.

2.1. Air Inlet

One of the main characteristics of this gas turbine engine is that it is mounted backward in the nacelle in most aircraft installations. This feature makes that the airflow is directed inside the components of the engine in the same direction as the aircraft's displacement. Another consequence is that the intake is located at the rear part of the engine and therefore, the air passes through the exterior of the aircraft (and the engine itself) before entering to the intake. The PT6A-65 design cares for guiding the intake air to the engine using ducts that avoid facing the exhaust gases: since the typical requirement is to provide laminar and clean air into the compressor—so that, it can operate at maximum efficiency—the inlet duct changes smoothly from opposing the direction of the airflow to the axially forward direction of the aircraft's speed.

We define the inlet component as to be the intake air conditioner: even though our model is restricted to an on-ground operation, with no rarefying processes of the atmospheric air entering into the engine, we extend the possibility of the operation of the model during in-flight operation