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Fuel Control Unit Modeling and Fuel-Property Compensation for Jet A-1 and TS-1 Operation in a PT6A Turboprop Engine Using MATLAB Simulink

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Abstract—This paper presents a reduced-order MATLAB Simulink model of the fuel control unit of a PT6A turboprop engine for evaluating the transient response of the engine when operated with Jet A-1 and TS-1 aviation turbine fuels. The study focuses on the functional connection between fuel properties and engine-level variables rather than on detailed hydro-mechanical hardware design. The proposed model represents the fuel control unit as a set of equivalent computational blocks, including power-lever command scheduling, gas-generator speed feedback, compressor-discharge pressure correction, minimum and maximum fuel-flow limits, acceleration and deceleration rate limits, a first-order pump and metering-valve lag, and a fuel-property compensation block. The engine is represented by a zero-dimensional thermodynamic model that includes compressor pressure rise, combustor energy balance, free-turbine speed response, gearbox speed reduction, propeller-shaft power, and propeller-shaft efficiency. Jet A-1 and TS-1 are compared through their lower heating values, with Jet A-1 used as the reference fuel and TS-1 considered both without and with lower-heating-value compensation. Simulation results show that the response curves of the two fuels are close because both fuels belong to the kerosene family. However, without compensation, TS-1 produces a lower final shaft power, approximately 558.63 kW compared with 562.30 kW for Jet A-1. When lower-heating-value compensation is applied, the TS-1 fuel-flow command increases slightly and the shaft power, compressor-discharge pressure, and speed responses are restored close to the Jet A-1 baseline. The results indicate that TS-1 can be considered a feasible substitute from an engine-level thermodynamic perspective, provided that fuel quality, fuel-system condition, and the control schedule are verified before operational use.

Keywords—PT6A; fuel control unit; Jet A-1; TS-1; lower heating value; MATLAB Simulink; transient response; turboprop engine

I. INTRODUCTION

The PT6A is a free-turbine turboprop engine widely used in aviation because of its reliability, modular construction, and stable operation over a broad range of flight and ground conditions. In this engine architecture, useful power is extracted by the free turbine and transmitted through a reduction gearbox to the propeller shaft. Therefore, the fuel schedule must not only provide the thermal energy required by the gas generator, but also support stable free-turbine and propeller-shaft operation.

The fuel control unit (FCU) is the main device that links the pilot's power command with the actual fuel mass flow entering the combustor. In a real PT6A-type hydro-mechanical system, the FCU combines power-lever input, compressor-discharge pressure, gas-generator speed feedback, acceleration limiting, deceleration limiting, and temperature protection. These functions prevent flameout, hot start, overtemperature, overspeed, and poor acceleration behavior. For simulation purposes, the detailed hydro-mechanical components can be replaced by equivalent mathematical blocks while preserving their control role.

In fuel logistics and operational planning, Jet A-1 and TS-1 are both relevant aviation turbine fuels. Although they are both kerosene-based fuels, their lower heating value, density, viscosity, volatility, and low-temperature behavior may differ from batch to batch. The lower heating value directly affects the thermal power introduced into the combustor. If the same fuel mass flow is used for a lower-heating-value fuel, a slight reduction in combustor outlet temperature and shaft power may occur. This paper therefore investigates whether an FCU compensation block can reduce the performance difference between Jet A-1 and TS-1 at the system-model level.

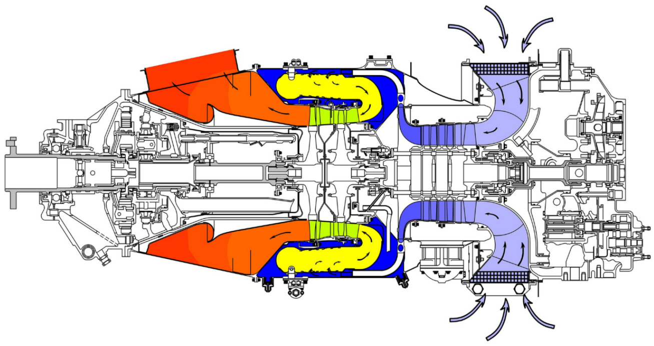

Fig. 1. Simplified PT6A engine architecture used as the system-model reference.

II. MODEL BASIS AND NUMERICAL METHOD

The proposed simulation framework consists of two coupled parts: a reduced thermodynamic model of the PT6A and a functional model of the FCU. The thermodynamic model calculates the evolution of compressor-discharge pressure, combustor outlet temperature, free-turbine speed, propeller-shaft speed, shaft power, and shaft efficiency. The FCU model calculates the commanded and delivered fuel mass flow from the power-lever input and engine feedback variables.

The compressor is represented by an overall pressure ratio calibrated to the reference model. In the reduced representation, the axial and centrifugal compressor sections are not resolved geometrically; instead, their effect is introduced through the compressor pressure ratio as a function of normalized speed. The combustor is modeled by an energy balance in which the lower heating value of the fuel is the main fuel-dependent parameter. The free turbine and gearbox are represented through a speed response and a fixed reduction ratio, allowing propeller-shaft speed and shaft power to be estimated at the engine-system level.

Three fuel-control cases are simulated. The first case uses Jet A-1 as the reference fuel. The second case uses TS-1 without lower-heating-value compensation, meaning that the FCU does not intentionally increase fuel flow to offset the lower energy content. The third case uses TS-1 with lower-heating-value compensation. In this case, the fuel command is multiplied by the ratio between the reference lower heating value and the actual fuel lower heating value.

TABLE I. FUEL LOWER HEATING VALUES USED IN THE SIMULATION

Fuel	LHV (MJ/kg)
Jet A-1	42.80
TS-1	42.50

III. FUEL CONTROL UNIT STRUCTURE

The FCU is represented as a set of computational blocks that correspond to the main functions of a hydro-mechanical fuel controller. The power-lever block converts the pilot's command into an initial fuel-flow demand. The speed-feedback block compares the actual gas-generator speed with a reference value and corrects the fuel command. The pressure-correction block accounts for compressor-discharge pressure and therefore links the fuel schedule to the working state of the compressor. The limiter block constrains fuel flow within minimum and maximum values and applies acceleration and deceleration rate limits. The fuel-property compensation block modifies the command according to lower heating value and, in more detailed extensions, density and viscosity. Finally, the pump and metering-valve lag block represents the finite dynamic response of the fuel system.

This structure is suitable for MATLAB Simulink because each physical function can be implemented using standard blocks, including lookup tables, summing junctions, gains, saturation blocks, rate limiters, first-order transfer functions, and MATLAB Function blocks. The model is not intended to replace manufacturer calibration data. Instead, it provides a research-level tool for evaluating how fuel properties influence engine trends and how fuel scheduling may reduce the resulting differences.

TABLE II. FUNCTIONAL FCU BLOCKS REPRESENTED IN THE SIMULINK MODEL

Block	Function
Power-lever schedule	Converts pilot command into requested fuel flow.
Speed feedback	Corrects the command using gas-generator speed error.
Pressure correction	Links fuel flow with compressor-discharge pressure.
Fuel-flow limiter	Prevents flameout, overfueling and excessive acceleration.
LHV compensation	Offsets Jet A-1 and TS-1 energy-content differences.
Pump/valve lag	Represents dynamic delay of pump and metering valve.
Combustor	Converts fuel energy into gas-temperature rise.

IV. MATHEMATICAL FORMULATION

The FCU and engine-level dynamics are represented by the following reduced equations. Equation numbers are provided consecutively as recommended by the template.

$$e_N = N_{g,\mathrm{ref}} - N_g \qquad (1)$$

Gas-generator speed error.

$$\dot{m}_{f,\mathrm{cmd}} = \dot{m}_{f,0} + K_N e_N + K_P\left(P_3 - P_{3,\mathrm{ref}}\right) \qquad (2)$$

Reduced FCU fuel command.

$$\dot{m}_{f,\mathrm{LHV}} = \dot{m}_{f,\mathrm{cmd}} \frac{LHV_{\mathrm{ref}}}{LHV} \qquad (3)$$

Lower-heating-value compensation.

$$\dot{m}_{f,\mathrm{out}} = \mathrm{sat}\left(\dot{m}_{f,\mathrm{LHV}}, \dot{m}_{f,\mathrm{min}}, \dot{m}_{f,\mathrm{max}}\right) \qquad (4)$$

Fuel-flow saturation.

$$\tau_f \frac{d\dot{m}_{f,\mathrm{out}}}{dt} + \dot{m}_{f,\mathrm{out}} = \dot{m}_{f,\mathrm{LHV}} \qquad (5)$$

First-order pump and metering-valve lag.

$$\frac{d\dot{m}_{f,\mathrm{out}}}{dt} \le R_{\mathrm{acc}}, \qquad \frac{d\dot{m}_{f,\mathrm{out}}}{dt} \ge -R_{\mathrm{dec}} \qquad (6)$$

Acceleration and deceleration rate limits.

$$C_B = \rho V_B c_p \qquad (7)$$

Effective thermal capacitance of the combustor control volume.

$$C_B \frac{dT_3}{dt} = \dot{m}_a c_p (T_2 - T_3) + \dot{m}_f\left(LHV - c_p T_3\right) \qquad (8)$$

Combustor energy balance.

$$\pi_c = \frac{p_2}{p_1} \qquad (9)$$

Overall compressor pressure ratio.

$$N_{\mathrm{prop}} = \frac{N_{\mathrm{FT}}}{i_g} \qquad (10)$$

Propeller-shaft speed after reduction gearbox.

$$P_{\mathrm{shaft}} = \omega_p M_l \qquad (11)$$

Propeller-shaft power.

$$\eta_p = \frac{P_{\mathrm{shaft}}}{\dot{m}_f LHV} = \frac{\omega_p M_l}{\dot{m}_f LHV} \qquad (12)$$

Propeller-shaft thermal efficiency.

TABLE III. MAIN SYMBOLS USED IN THE MODEL

Symbol	Meaning
α_PLA	power-lever command
ṁ_f	fuel mass flow (kg/s)
N_g	gas-generator speed
P_3, p_2	compressor-discharge pressure
LHV	lower heating value
τ_f	fuel-system time constant
T_2, T_3	compressor and combustor outlet temperatures
π_c	compressor pressure ratio
N_FT, N_prop	free-turbine and propeller-shaft speeds
P_shaft, η_p	shaft power and shaft efficiency

V. RESULTS AND DISCUSSION

The fuel-flow response shows that all cases follow the same general acceleration schedule. Fuel mass flow initially follows the command increase and then approaches a steady value near the nominal operating point. In the TS-1 case with lower-heating-value compensation, the final fuel flow is slightly higher than in the Jet A-1 case. This is physically consistent because a lower-heating-value fuel must be supplied at a slightly higher mass flow to maintain the same thermal power input.

The combustor outlet temperature response shows only small differences among the cases. TS-1 without compensation produces a lower final temperature than Jet A-1 because the total chemical energy introduced into the combustor is lower. When lower-heating-value compensation is applied, the TS-1 temperature response nearly matches the Jet A-1 baseline, indicating that the compensation block effectively restores the combustor energy input.

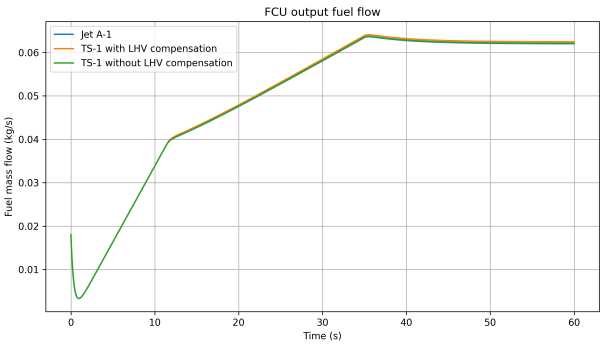

Fig. 2. FCU output fuel-flow response for Jet A-1 and TS-1 cases.

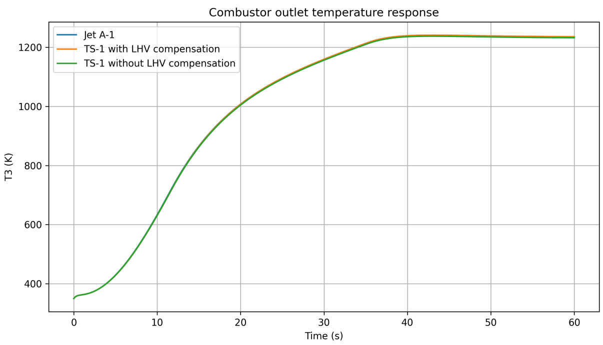

Fig. 3. Combustor outlet temperature response.

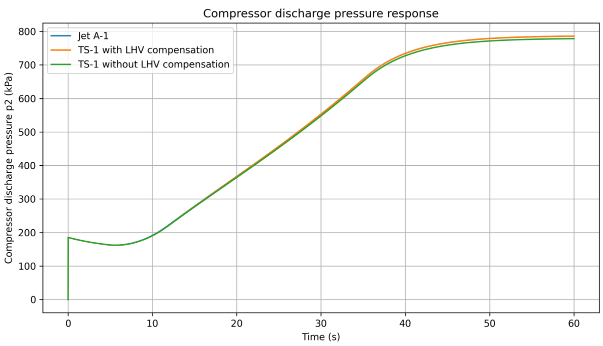

Fig. 4. Compressor-discharge pressure response.

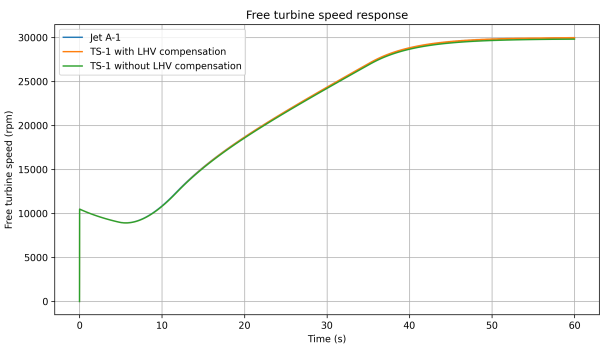

Fig. 5. Free-turbine speed response.

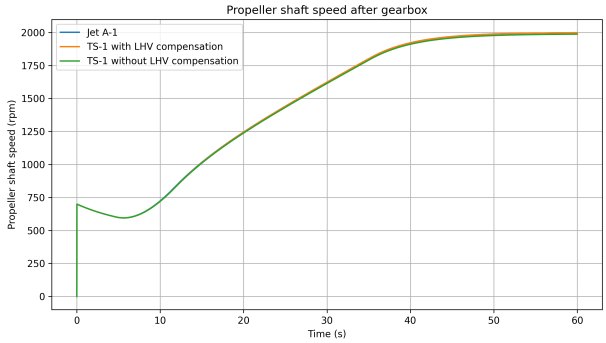

Fig. 6. Propeller-shaft speed after gearbox.

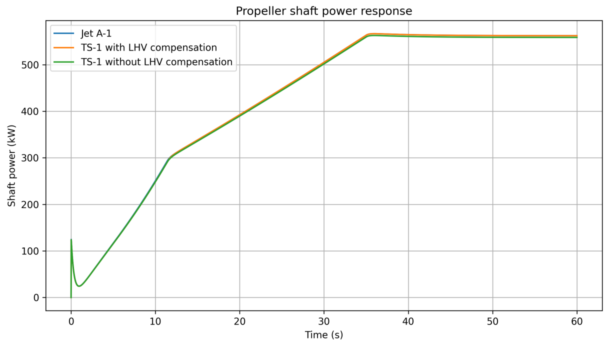

Fig. 7. Propeller-shaft power response.

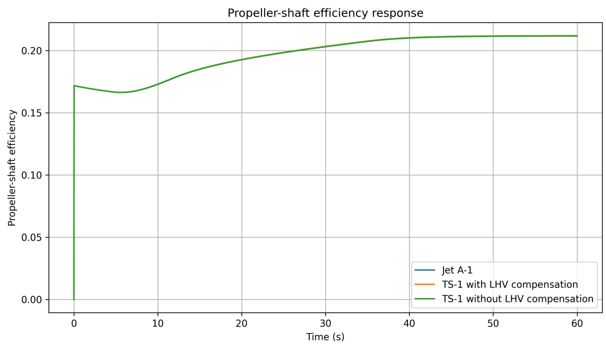

Fig. 8. Propeller-shaft efficiency response.

The compressor-discharge pressure, free-turbine speed, and propeller-shaft speed responses show similar trends. Without compensation, TS-1 leads to slightly lower final values because less thermal power is available for the turbine and compressor spool. With compensation, the TS-1 response is close to Jet A-1, demonstrating that the FCU can be used in the model to reduce fuel-induced deviations in engine operating variables.

The propeller-shaft power result provides the clearest operational comparison. Jet A-1 reaches approximately 562.30 kW in the final state, whereas TS-1 without compensation reaches approximately 558.63 kW. This difference is small but relevant for high-power operating conditions. With lower-heating-value compensation, the TS-1 case returns to approximately 562.30 kW. The propeller-shaft efficiency remains nearly unchanged across the cases, which suggests that the primary effect in this reduced model is not a change in cycle efficiency but a change in the fuel energy supplied to the combustor.

TABLE IV. FINAL SIMULATION VALUES

Case	Fuel flow (kg/s)	Power (kW)	ηp
Jet A-1	0.062018	562.30	0.211839
TS-1 no comp.	0.062116	558.63	0.211608
TS-1 comp.	0.062456	562.30	0.211839

VI. CONCLUSION

A MATLAB Simulink-compatible reduced-order model of the PT6A fuel control unit was developed to evaluate the effect of Jet A-1 and TS-1 on transient engine response. The FCU was modeled through functional blocks representing power-lever scheduling, speed feedback, compressor-discharge pressure correction, fuel-flow limits, acceleration and deceleration limits, lower-heating-value compensation, and first-order pump and metering-valve lag. This structure captures the main control functions required for engine-level fuel-schedule analysis.

The simulation results indicate that Jet A-1 and TS-1 produce close thermodynamic responses because both fuels are kerosene-based and have similar lower heating values. However, when TS-1 is used without compensation, the lower heating value leads to a modest reduction in combustor outlet temperature, compressor-discharge pressure, rotational speed, and propeller-shaft power. The final propeller-shaft power decreases from approximately 562.30 kW for Jet A-1 to approximately 558.63 kW for uncompensated TS-1. When the FCU includes lower-heating-value compensation, the TS-1 fuel-flow command increases slightly and the final shaft power, pressure, and speed responses are restored close to the Jet A-1 reference values.

From an operational perspective, TS-1 may be considered a feasible substitute for Jet A-1 in cases where fuel logistics require an alternative fuel, provided that the fuel batch meets the applicable aviation-fuel specification and the fuel system is in acceptable technical condition. Nevertheless, actual operational approval must also consider density, viscosity, water content, particulate contamination, storage stability, fuel-nozzle condition, FCU calibration, and validation with engine test data. The present model is therefore most appropriate for preliminary trend analysis and for developing a more complete Simulink-based digital tool for PT6A fuel-system studies.

ACKNOWLEDGMENT

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