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DIGITAL SIMULATION MODEL FOR A TURBOPROP ENGINE

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ABSTRACT

A comprehensive Turboprop Engine model for digital simulation based on the steady state data and transient characteristics has been proposed for a light transport aircraft. The engine and propeller characteristics have been modeled and implemented in Matlab/Simulink environment. The validation has been carried against the flight data and match is found to be satisfactory

Key Words: Engine dynamics, Propeller Dynamics, turboprop engine model

NOMENCLATURE

Ng	Generator Speed (rpm)
N_P	Propeller Speed (rpm)
%Ng	Generator Speed – percentage of rated speed
%N_P	Propeller Speed – percentage of rated speed
Np	Propeller Speed in rps
ρ	Air density in FPS units (computed from atmosphere model)
D	Propeller diameter in feet
V	Velocity in fps
J	Advance Ratio
C_P	Propeller Power coefficient
C_T	Propeller Thrust coefficient

1. INTRODUCTION

The Indian Light Transport Aircraft (LTA) is a twin turboprop multi-role aircraft having cantilever low wings and pusher engines. This aircraft is powered by PT6Aengines at 1200 SHP. The Flight Mechanics and Control Division, NAL is developing a Fixed Base Training Simulator for LTA.

As part of this activity, it is planned to develop a comprehensive Turboprop Engine model for digital simulation based on the steady state data and transient characteristics. This paper presents the schematic of the proposed turboprop engine model, its implementation and validation. The operation of general turboprop engine is briefly explained in the next section.

2. GENERAL TURBOPROP ENGINE OPERATION

The PT6 engine, a lightweight free turbine engine incorporating a reverse flow combustion path, is designed for aircraft propulsion use. It utilizes two counter-rotating turbines; one driving the compressor and the other driving the propeller through a reduction gearbox. The latter turbine is “free” or independent of the compressor turbine.

This design is referred to as “Free Turbine Engine” and has certain advantages,

- During an engine start, only the compressor section of the PT6A engine needs be rotated by the starter-generator. This results in lower starter cranking torque.
- The PT6A engine free turbine design allows the propeller RPM to be reduced and the propeller feathered during ground operation without shutting down the engine. This facilitates fast passenger loading and permits very quiet ground operation.
- Np is independent of Ng
- Compact design

The design of the PT6A engine allows it to be split into two major parts called the power section assembly and the gas generator assembly [1]. The gas generator assembly houses the compressor assembly, combustion chamber and accessory gearbox. The power section assembly houses the two stage power turbines and reduction gear box. Figure 1 shows the schematic of a typical free turbine engine (PT 6A).

The compressor draws air into the engine via an annular plenum chamber, air pressure increases across the compressor axial stages and centrifugal stage and this air is then directed to the combustion chamber. At the correct compressor speed, fuel is

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[+] Scientists, Flight Simulation Group, Flight Mechanics and Control Division introduced into the combustion chamber via fuel nozzles. Spark igniters located in the combustion chamber ignite the air-fuel mixture. The hot gases generated by the combustion are then directed to the turbine area. At this point, ignition is turned off since a continuous flame exists in the combustion chamber.

The hot expanding gases accelerate and cause the compressor turbine to rotate. These expanding gases travel across the different stages of power turbines, which provide rotational energy to drive the propeller shaft. The reduction gear box reduces the power turbine rotation rate to one suitable for propeller operation. Engine shutdown is accomplished by shutting off fuel going to the combustion chamber.

2.1 Power Management

Power management of the engine is handled by a three lever system viz. Power Lever, Propeller Lever and Fuel Condition Lever. Figure 2 shows the power management using the three levers.

Power Lever:

The power lever operation serves to modulate engine power from full reverse thrust to take-off. This lever can be moved fully forward to have maximum power and fully aft for reverse operation. The position at 'IDLE' represents lowest level of power during flight operation. This lever functions as follows:

- Connects to a cam assembly located on the accessory gear box. Cam assembly transmits the power lever movement to the Fuel Control Unit (FCU). FCU controls Ng.
- Controls the compressor speed (Ng) in forward as well as reverse thrust mode.
- Controls the propeller pitch in reverse when the beta valve is engaged.

Fuel Lever:

This lever has three positions viz. shut-off, low idle and high idle. This lever functions as follows:

- Shut-off position stops fuel flow to the combustion chamber and causes the engine to shut down. The shut-off position completely bypasses the FCU.
- Low Idle is the minimum Ng allowed and High Idle is the minimum power used in flight.
- Fuel Lever allows to set Ng from low idle to high idle

  Low Idle speed ranges 50-54% Ng (19,000 to 20,000 rpm approximately)
  High Idle speed ranges 67-71% Ng (25,000 to 26,500 rpm approximately)

Propeller Lever:

This lever has FINE and FEATHER positions. This lever functions as follows:

- Connected to the propeller speed control lever which controls the propeller governor and controls the propeller speed in governing mode. This is achieved by metering the flow of oil into the beta tube. As more oil enters the beta tube, the propeller moves to fine pitch position.
- Allows feathering of the propeller by bypassing the oil flow to the beta tube and dumping it back to the reservoir.

2.2 Gas Generator Model

The steady state engine performance data has been obtained from Engine Performance Program supplied by manufacturer. This performance data includes gas generator rpm, fuel flow rate, Inter Turbine Temperature (ITT) and Shaft Horse Power (SHP) obtained as function of Mach number, Altitude and percentage engine torque for the atmospheric configurations ISA and ISA+15 respectively. These parameters are obtained as a function of Rating Code (RC), Mach number ranging from 0.0 to 0.6 and altitude ranging from 0.0ft to 30000ft. Figure 3 shows the block diagram showing the inputs and possible outputs of Engine Performance Program.

The value of RC in Figure 3 above is varied from 20% in steps of 10% to 100% of the Take-off rating (Rating Code #1 in reference). The gearing relationship between PLA range (Idle to Fully forward comprising take-off, climb and cruise phases) and %Ng, %Torque given below are based on the observations from flight data.

Phase	PLA Range (deg)	%Torque	%Ng
Take-off	30	100%	100%
Cruise	15	40%-60%	85%
Reverse	-15	15%	87%

The dynamics of the %Ng and consequently the SHP developed in the gas generator stage is frequently modeled to have a first order lag with time constant ‘τ1’. We have chosen to introduce this first order lag on the signal RC.

The SHP developed in the gas generator is absorbed by the propeller in the form of power required to turn the propeller.

2.3 Propeller Characteristics

Propeller performance data is available for a blade angle range of (0 - 50 deg) from the propeller manufacturers program. The propeller data is given in the form of power and thrust coefficients [2] as a function of the advance ratio and blade angle.

The advance ratio is denoted by
$J = V / (Np * D)$ (1)

The power coefficient is denoted by
$C_P = (\text{Power}) / (\rho * Np^3 * D^5)$ (2)

The thrust coefficient is expressed as
$C_T = (\text{Thrust}) / (\rho * Np^2 * D^4)$ (3)

In Figures 4a and 4b, we have the Power coefficient (C_P) and thrust coefficient (C_T) data respectively shown as a function of the advance ratio (J) for different propeller blade angle settings. In these figures the blade angle is held constant for each curve and increases from curve to curve as one moves from left to right.

A point on any of these curves in Figure 4a represents the amount of power required to maintain the propeller for a particular pitch angle and advance ratio. Similarly, the corresponding point having same blade pitch angle and advance ratio on Figure 4b, gives the thrust developed by the propeller.

It is noted that the propeller characteristics (Figures 4a-4b) indicate the steady state power required and thrust developed. The propeller system however has an additional degree of freedom in the terms of the pitch angle of the propeller which influences these curves. This degree of freedom is constrained by the PLA in the reverse region by the beta valve as discussed in section 2 above. In the range from flight idle to maximum PLA, it is determined by the automatic pitch control. A summary of this is given below:

Phase	**PLA Range (deg)**	**Blade Angle (deg)**
Take-off	30	--- (under automatic governor control)
Flight Idle	0	11
Reverse	-15	-15

The Propeller Lever can be used to set minimum to maximum propeller RPM setting. This is achieved through the propeller governor. The Propeller Lever can also be used to completely bypass the propeller oil and cause feathering of the propeller with the gas generator running.

Therefore, similar to the approach used in the gas generator model of section 3 above the propeller pitch control dynamics is sought to be modeled as a first order lag. Further, this first order lag with time constant ‘τ2’ is taken to be identical to the feathering time constant.

2.4 Dynamics of Propeller

The propeller and gearbox combined represent rotary inertia which must be overcome by the SHP produced by the exhaust gases from the gas generator acting through the power turbine in order to spool up the propeller RPM. The SHP on the input side is opposed by the instantaneous power absorbed by the propeller at the other end.

$Ppow = C_P * \rho * Np^3 * D^5$ (4)

In the above expression, C_P is obtained from Figure 4a for the instantaneous values of advance ratio J and blade angle β'. As discussed above, the instantaneous blade angle β' lags the steady state blade angle β by the time constant ‘τ2’ explained in the previous section. Before proceeding further, we explain how the steady state blade angle β is obtained.

It is clear that the automatic pitch control mechanism in the propeller is in equilibrium when the SHP developed in the gas generator is fully absorbed in the propeller. Thus steady state value of the blade angle will be such as to cause all of the instantaneous SHP developed in the gas generator to be absorbed in the propeller for the instantaneous value of Advance Ratio (J). Thus, the SHP obtained from EEPP is used to compute propeller power coefficient (C_{P1}). The parameters C_{P1} and J are used as input to propeller performance charts (Figure 4a) to estimate steady state blade angle β.

The propeller thrust coefficient, C_T is obtained from Figure 4b for the instantaneous values of advance ratio J and blade angle β'. The propeller thrust will be computed based on the propeller RPM (during propeller feathering and normal operation) as given below.

$$Thrust_{prop} = C_T * \rho * Np^2 * D^4 \qquad (5)$$

The total thrust will be the sum of propeller thrust and jet thrust (~5% of propeller thrust)

$$Thrust\ (total) = Thrust_{prop} + Thrust_{jet} \qquad (6)$$

Based on the dynamic elements covered in Sections 3, 4 and 5 above, the complete dynamic model of the turboprop engine is presented in Figure 5. Another important aspect which must be covered in a dynamic model is the simulation of engine startup. This is discussed next.

2.4 Engine Startup

During start up, starter generator (SG) will start rotating the engine compressor and engine may be lighted by moving the fuel lever to GI position when Ng > 13%. The burning of fuel-air mixture along with the starter aid will bring the engine quickly to its self sustaining RPM. The SG will be automatically disconnected once the speed of SG reaches (≈ 47-49% Ng). Later, the fuel lever is moved to Flight Idle (FI) position and Ng rises to 70%. As mentioned already, when the fuel lever is at shut off, the fuel flow to combustion chamber is cut off.

3. IMPLEMENTATION AND VALIDATION

The turboprop engine model shown in Figure 5 has been implemented in Matlab/Simulink environment.

3.1 Implementation of Turboprop Engine

The Matlab/Simulink model has been implemented using the engine performance data and propeller performance charts. The engine and propeller time constants are estimated from the flight data. Figure 6 shows the screenshot of simulink model. As explained already, the engine output is used to drive the propeller. The propeller power coefficient and Advance Ratio are used to compute the blade angle based on the propeller performance charts. The logic catering to the propeller FINE and FEATHER positions has been incorporated to select the appropriate blade angle. Based on the blade angle and Advance Ratio, the propeller power and thrust coefficients are computed. The total thrust is computed as the sum of propeller thrust and jet thrust. Next section provides the validation methodology adopted for turboprop simulink model.

3.1 Validation

The flight data covering the take-off and cruise profile of Light Transport Aircraft has been used for the validation. The input parameters to the simulink model are Mach number, altitude and PLA extracted from the flight data. The output parameters such as %Ng, %Torque and %Np are compared. Figure 7 shows the comparison plots of flight and simulink model. The match is found to be satisfactory.

4. CONCLUSION

A comprehensive turboprop engine model for digital simulation has been proposed, implemented and validated. The proposed model is being integrated to the in-house flight simulator facility towards the r simulation of various modes of operation of the normal as well as failure regimes of the engine.

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2. David Allerton, Principles of Flight Simulation, Aerospace Series, John Wiley & Sons Ltd, 2009.

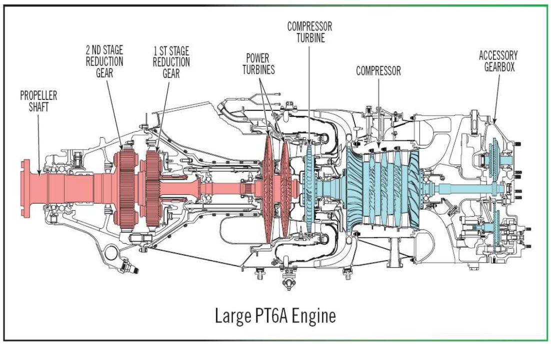

Figure 1. Layout of typical PT6A engine

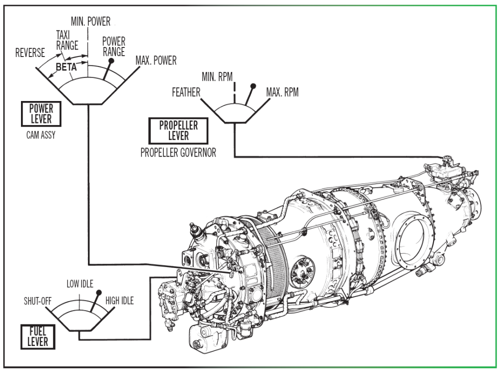

Figure 2. Power Management using three levers

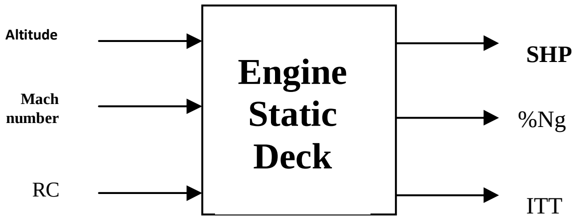

Figure 3. Block Schematic of Engine Steady State Deck

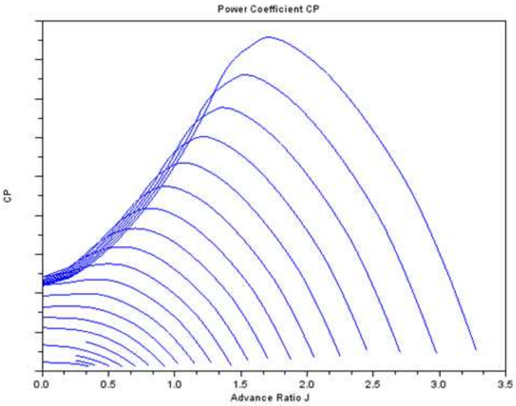

Figure 4a. Power Coefficient Curves for propeller

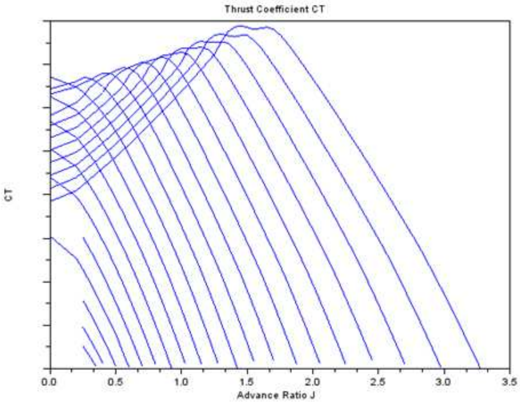

Figure 4b. Thrust Coefficient Curves for propeller

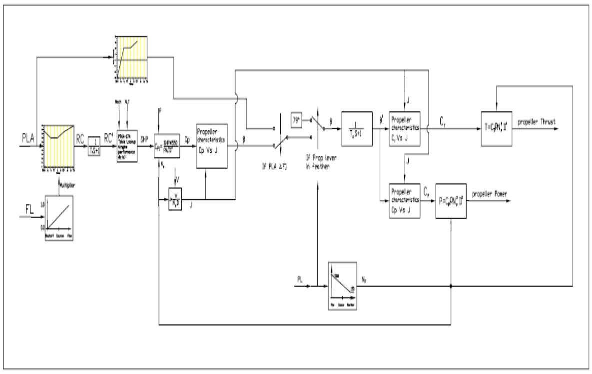

Figure 5. Block Schematic of the comprehensive Engine Model

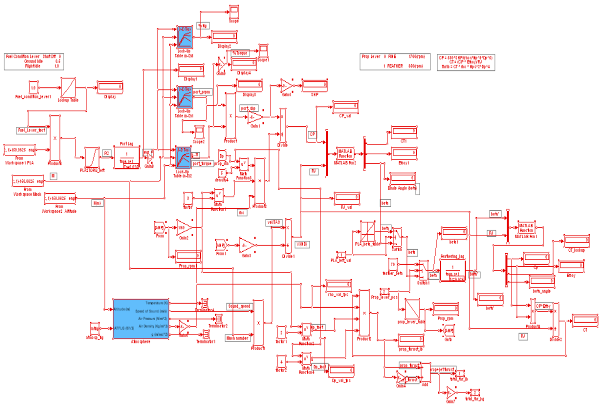

Figure 6. Screenshot of Turboprop engine model in Matlab / Simulink

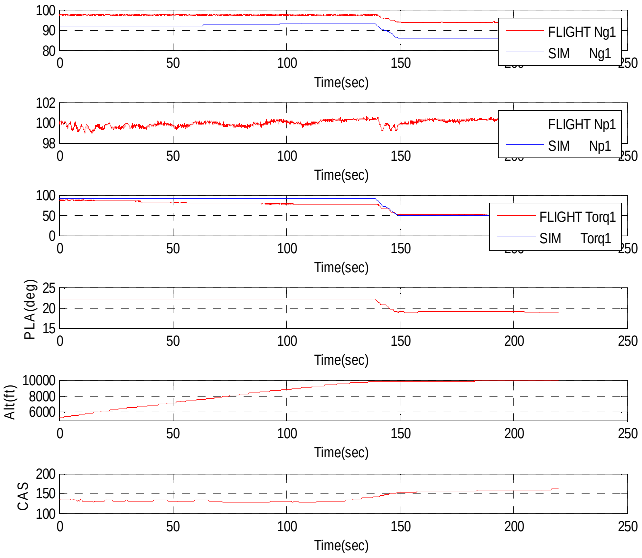

Figure 7. Comparison of engine parameters for flight data and simulink model