SIMULATION OF TWIN SPOOL TURBOJET ENGINE

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ABSTRACT

Simulation of performance of gas turbine engine fitted in fighter class aircraft is tried both for steady and transient operations. Performance of the engine is calculated for the inputs of air and fuel mass flow rates, altitude conditions and throttle positions for sea level and combinations of varying Mach number and altitude conditions. Methodology consists of usage of a series of equations for various modules of engine and all are sequentially evaluated to get the output namely thrust, specific fuel consumption and station values like pressures and temperatures. Dynamic simulation consists of varying the throttle position, when the engine is on ground and obtaining various performance parameters of the engine as outputs. In order to do this a series of equations are developed in order to arrive at the transfer function of the spools of the engine. For estimating the stability of the engine step inputs in the form of fuel flow rate for HP spool and exit area variation for LP spool are tried and found to be as per the expectations.

1. INTRODUCTION

Gas turbine engines have come into existence replacing piston engines because piston engines could not be operated at higher altitudes and higher forward Mach numbers. Despite the fact that gas turbine engines are seriously inefficient compared to piston engines, this aspect is overlooked and many modifications were carried out on turbojets to improve the efficiency aspects.

As, thrust to weight ratio improves, the generation of engines is also parallely raised. This paved the way for twin spool turbojet engine with afterburner. Engines for application in fighter class aircrafts are always in the developmental phase to meet the avaracious demands of the pilot. While doing so, simulation of the engine performance occupies a large chunk of developmental exercise. Since fighter class engines demand for transient dynamics due to deep throttle requirements, it is necessary to carry out the simulation for transient dynamics also.

In order to carry out the static simulation a series of equations, which are available in open literature is used barring aside afterburner performance. The static simulation that is carried out on the engine is covered by the boundary conditions like ISA sea level static, various RPM conditions of the engine, variations in altitude and Mach number combinations. The platform that is used for calculation is Matlab and the results that are obtained are compared with the information available in gas turbine literature.

As said earlier, since dynamic simulation is also to be carried out, a set of equations are derived and used for this purpose. Both afterburner operations and altitude and Mach number combination are safely neglected because the error accumulation in the dynamic simulation is observed to be prohibitive. Transient dynamics since requires transfer functions for identifying the response, an attempt is made by using step input for both LP and HP RPMs. The step input is fuel flow rate for HP spool while variation in exhaust area for the LP spool [8]. Crossover frequencies are also required in order to identify the stability of the engine either during acceleration or deceleration, for locating the margin availability.

For carrying out the above, Simulink platform is exhaustively used to arrive at the requirements mentioned above. Simulation of the engine has given a confidence of versatility of doing the same exercise for any type of configured engines following turbojet configuration.

2. GAS TURBINE ENIGNE

The gas turbine is also an internal combustion engine that uses air and fuel as the working fluid. The engine extracts chemical energy from the fuel and converts it to finally mechanical energy for using it in turbine unit to drive the compressor and propeller, which, in turn, propel the airplane [6].

2.1 THEORY OF OPERATION

The basic principle of the airplane turbine is identical to any and all engines that extract energy from the burning of

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chemical fuel. The basic four steps for any internal combustion engine are:

1. Intake of air.
2. Compression of the air.
3. Combustion, where fuel is injected (if it was not drawn in with the intake air) and burned to convert the stored energy.
4. Expansion and exhaust, where the converted energy is put to use.

In the turbine engine, however, these four steps occur at the same time but in different axial locations. As a result of this fundamental difference, the turbine has engine sections called:

1. The diffuser
2. The compression section
3. The combustion section (the combustor)
4. The turbine and
5. The exhaust section

2.2 TURBOJET ENGINE

A jet engine in which a fan is driven by a turbine provides extra air to the burner and gives extra thrust [6].

3. STABILITY

Dynamics system consists of static and dynamic stability. Unless static stability is ensured, dynamic stability cannot be incorporated. Classical examples for static stability are a ball on a concave, convex and plane on surface. In the case of dynamic stability it is necessary to ensure the frequency response by Laplace transform and locations of poles and zeros. The poles, for a dynamic stability should locate in the left half of the h-s plane. In this case depending upon the location of the pole in the left half of the plane convergent and divergent stabilities could be identified. This process is followed in this paper for identifying the stability of the system-engine.

4. MATHEMATICAL MODELING FOR STATIC

Turbojet engine used for analysis for this project is meant for fighter class applications. As it is known, an engine is developed from a gas generator and its basic elements are compressor, combustion chamber and turbine. Addition of interface elements likes diffuser at the front and exhaust nozzle at the rear constitutes the basic single shaft engine.

Steady state of the engine is defined as the rpm of the spools continues to run in the same rpm for a long period as long as the throttle is kept in the same quadrant. In order to do this, it is necessary that the torque generated by the turbine module should equate the torque requirement of the compressor. This therefore has to be brought under a system of curves for various operating condition of the engine [8].

Torque produced by turbines

$$Q_{TH} = \frac{J \times m_g \times c_p \times T_4 \times \eta_{TH}}{2\pi N_H}\left[1 - \left(\frac{1}{\pi_{TH}}\right)^{\frac{\eta_g - 1}{\eta_g}}\right]$$

(1)

$$Q_{TL} = \frac{J \times m_g \times c_p \times T_5 \times \eta_{TL}}{2\pi N_L}\left[1 - \left(\frac{1}{\pi_{TL}}\right)^{\frac{\eta_g - 1}{\eta_g}}\right]$$

(2)

Torques required by the compressor is

$$Q_{CH} = \frac{\dot{m}_a \times T_2 \times R \times \gamma}{(\gamma - 1) \times 2\pi N_H \times \eta_{CH}}\left(\pi_{CH}^{\frac{\gamma - 1}{\gamma}} - 1\right)$$

(3)

$$Q_{CL} = \frac{\dot{m}_a \times T_1 \times R \times \gamma}{(\gamma - 1) \times 2\pi N_L \times \eta_{CL}}\left(\pi_{CL}^{\frac{\gamma - 1}{\gamma}} - 1\right)$$

(4)

The stable operation of the engine depends upon many parameters like pressures and temperatures at various stations, air mass flow and fuel mass flow rates, expansion and compression ratios, RPM of the spools etc… As being done in any other simulation exercise of the power plants [3], continuity of air mass flow and gas mass flow are maintained, RPM of the spools are maintained.

5. MATHEMATICAL MODELING FOR DYNAMICS

Jet engines of fighter class aircrafts encounter deep throttling depending upon the requirements of the pilot, who has given the responsibility of defending the air space. Engines encountering deep throttles also have lesser steady state ratings depending upon the type of sorties. The engines before fitment on aircrafts require testing in order to prove the performance both during steady and transient ratings as prescribed by the designer and endorsed by airworthiness agencies. All parameters measured in the engine as given in testing technology need to be written the limits along with its timings. It is necessary to identify the tracing of the engine on the compressor characteristics map which is having abscissa as non-dimensional mass flow parameter, while the ordinate

as pressure ratio. In the field of X and Y axes, masked are the throttle transients or throttle characteristics and compressor characteristics for each other non-dimensional RPM.

Aspiring for a mathematical model to represent transient dynamics of a twin spool engine, following conditions are to be met:

a) Continuity of air mass flow.
b) Torque balance between the compressor and turbine.
c) RPM balance between low and high pressure spools.

In order to achieve the above, there are control parameters and controllable parameters along with control laws of the engine [11].

Control parameter is one which can be controlled by the pilot by the single movement of the throttle. This can in turn varies some more of the control parameters depending upon the boundary condition of the engine: controllable parameters are the manifestations of the engine in terms of RPM of the spool/spools, thrust of the engine, temperature and pressures at various locations both axially and circumferentially along the engine stations.

Control laws are the ones which are applied on the engine by using the control parameters and these laws are the ones which meets the requirement as stipulated by the aircraft designer.

5.1 ENGINE MODEL

Considering the acceleration and deceleration of a twin spool turbojet engine, it can be written as the torque balance between the compressor and turbine however this also depends upon the polar moment of inertia of the rotors. Thus for an acceleration for both the spools,

$$\frac{\pi J_{LF}}{30} \text{ x } \frac{dN_{LF}}{dt} = M_{T_{LF}} - M_{C_{LF}} \tag{5}$$

Similarly,
$$\frac{\pi J_{HF}}{30} \text{ x } \frac{dN_{HF}}{dt} = M_{T_{HF}} - M_{C_{HF}} \tag{6}$$

Using algebraic manipulation, the engine transfer function can be for LP spool and HP spool independently,

$$\bar{n}_{HF} = \frac{K_{C_{LF}} X \tau_{n_{HF}} X s + \left(K_{C_{LF}} + K_{C_{HF}} X K_{1_{n_2}}\right) X \bar{m}_f + K_{1_A} X \left(\tau_{n_{HF}} X s + 1\right) X A_7}{\tau_{n_{LF}} \times \tau_{n_{HF}} X s^2 + \left(\tau_{n_{LF}} + \tau_{n_{HF}}\right) X s + \left(1 - K_{1_{n_2}} X K_{2_{n_1}}\right)} \tag{7}$$

Similarly,

$$\bar{n}_{HF} = \frac{K_{C_{HF}} X \tau_{n_{LF}} X s + \left(K_{C_{HF}} + K_{C_{LF}} X K_{2_{n_1}}\right) X \bar{m}_f + K_{1_A} X K_{2_{n_1}} X A_7}{\tau_{n_{LF}} X \tau_{n_{HF}} X s^2 + \left(\tau_{n_{LF}} + \tau_{n_{HF}}\right) X s + \left(1 - K_{1_{n_2}} X K_{2_{n_1}}\right)} \tag{8}$$

An attempt is made to carry out the transient dynamic of the engine using the above formula as applicable to sector of the dynamics of the engine.

Initially the trials are made for ISA SLS condition wherein the dynamic simulation is carried out for idle to max and vice versa; cruise to max rpm and vice versa; 90% to max rpm and vice versa etc.

Since the dynamics of the engine for the transfer function obtained has matched for unit step signal. In all the above cases the results of the dynamics obtained are placed at results and analysis.

6. RESULTS AND ANALYSIS

6.1 STEADY STATE

Gas turbine engine simulation has become part and parcel of design and development for abinitio design engines. For carrying out this process normally two types of simulations are carried out in a gas turbine engine. They are static and dynamic simulations which are carried out to extract the performance data during steady and transient ratings.

Table 6.1 Input Parameters

INPUT PARAMETERS				
THROTTLE ANGLE	MACH NUMBER	ALTITUDE		AIR MASS FLOW RATE
		P_{S_0}	T_{S_0}	
100%	0.0	1.033	288.0	65.2
96%	0.0	1.033	288.0	61.8

| 89% | 0.0 | 1.033 | 288.0 | 56.4 |
| 42% | 0.0 | 1.033 | 288.0 | 24.0 |

altitude 3 km the Mach number is opened at 0.5 and 0.86 and these all Tables 6.3 to 6.6 are represented below.

During steady ratings the throttle is kept steady and the performance thus obtained from this engine is evaluated.

All the inputs and outputs performance data for ISA, SLS condition Table 6.1 and 6.2 thus obtained for the steady state simulation is discussed.

Table 6.2 Output Parameters

OUTPUT PARAMETERS	
TORQUE AT HIGH SPOOL RPM (j/kgk)	TORQUE AT LOW SPOOL RPM (j/kgk)
2.3761*10^9	1.74888*10^9
4.9713	4.0000
4.5391	3.9251
1.6993	2.2009

In this work also the steady simulation of the engine constitute sea level static followed by opening up of altitude 3 km and 4.5 km for a given Mach numbers are 0.5, for a given

Table 6.3 Input and output parameters for altitude 3000 condition is placed at given Mach no 0.5

INPUTS					
MACH = 0.5, PS_0 = 0.708, TS_0 = 266.2					
OUTPUTS					
RPM	OPR	LPR	HPR	FMFR	THRUST
100%	8.9	3.0506	2.9175	1.0400	3.134×10^3
94%	7.2	2.7379	2.6298	0.4	3.1382×10^3
89%	5	2.2731	2.1996	0.2	2.5571×10^3

94%	3.8	1.9761	1.9230	0.2	10^3
89%	3.9	2.0025	1.9476	0.2	2.5376×10^3

Table 6.4 Input and output parameters for altitude 4500 condition is placed at given Mach no 0.5

INPUTS					
MACH = 0.5, PS_0 = 0.579, TS_0 = 256.3					
OUTPUTS					
RPM	OPR	LPR	HPR	FMFR	THRUST
100%	8.8	3.0330	2.9014	1.0400	2.7290×10^3
					$2.7564 \times$

Table 6.5 Input and output parameters for altitude 3000 condition is placed at given Mach no 0.5

INPUTS					
MACH = 0.5, PS_0 = 0.708, TS_0 = 266.2					
OUTPUTS					
RPM	OPR	LPR	HPR	FMFR	THRUST
100%	8.9	3.0506	2.9175	1.0400	3.134×10^3

94%	7.2	2.7379	2.6298	0.4	3.1382 x 10^3
89%	5	2.2731	2.1996	0.2	2.5571 x 10^3

Fig. 6.1 plotted the work required by the compressor in terms of joules/kg k and this is plotted against the HP spool rpm of the engine. The requirement of work is also more or less linear in nature except for a minor non linearity from 96 to 100%. It is obvious that the engine produces maximum thrust in the sensible rpm range of 92 to 100% of the dry max condition, which in turn depends upon the pressure ratio of the HP spool of the compressor. As the pressure ratio is increased naturally the work requirement is also more. This representation is also more or less as per the requirement of the compressor in any proven engine.

Table 6.6 Input and output parameters for altitude 3000 condition is placed at given Mach no 0.86

INPUTS					
MACH = 0.86, PS_0 = 0.708, TS_0 = 266.2					
OUTPUTS					
RPM	OPR	LPR	HPR	FMFR	THRUST
100%	8.9	3.0506	2.9175	1.0400	2.7484x 10^3
94%	7.5	2.7955	2.6839	0.5	3.2530 x 10^3
89%	4.9	2.2498	2.1780	0.2	2.5283 x 10^3
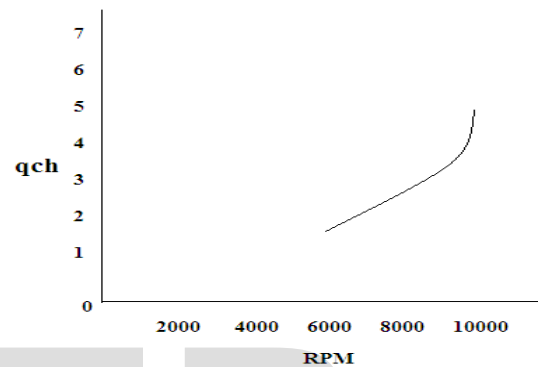
Fig. 6.1 qch Vs RPM of the spool

Fig.6.2 indicates the work requirement of the LP compressor from idle to max rating of the engine. X-axis indicates the spool RPM while the Y-axis indicates the work required in terms of J/Kg K. As it has happened for the HP spool, a similar trend is shown for LP compressor also. Here again from the sensible rpm value namely 96% to dry max rating of the engine, a small non linearity is shown which is absent in the lesser rpm regime. The work requirement of the compressor has to be the minimum most as far as possible to cater the case of design of turbine module.
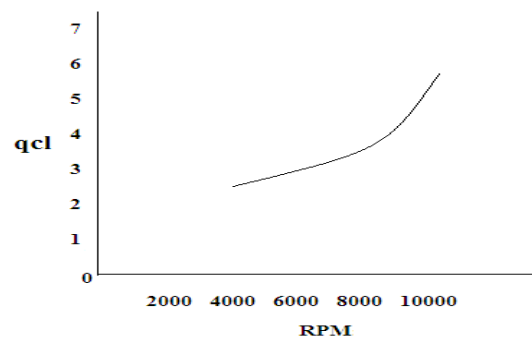
Fig.6.2 qcl Vs RPM of the spool

6.2 TRANSIENT STATE

This part explains the dynamic performance analysis carried out on the engine used for static analysis. As mentioned elsewhere in the report since the engine undergoes deep throttling quite often, it is mandatory to identify the characteristics during the transient simulation of the engine. It is customary that the transient dynamics of the engine should have idle to max and vice versa, cruise to max and vice versa, 96% to max vice versa etc. Although the engine is provisioned with afterburner the simulation either maximum to afterburner or idle to afterburner is not carried out for want of appropriate dynamic equations.

In almost all the cases during the dynamics of the plant, the control factors become the input to identify whether the system or the plant encounter a divergence or oscillatory phenomenon or convergence which is much desired. In this case the transfer function is derived (the procedure is explained in mathematical modeling for dynamics) and then manipulated to have the response of either the low pressure spool RPM or high pressure spool RPM vis-à-vis the plant dynamics. As usual although three test signals are available only the unit step function is used to capture the NL or NH response. In order to create the step input signal for the response of the plant, fuel flow rate is used for identifying NH response, while exhaust nozzle area variation is used for NL response. In all cases of response study, the same methodology is used. It could be seen from the Fig. 6.3 and 6.5 the response of NL is much lower than the response of NH spool because of its resistance offered by the gear box from the mechanical sense the plots are placed in Fig. 6.4 and 6.6. Here the transfer function is derived for the engine taking into consideration the steady state whether it is for NL and NH response. A mux is used to compare the step signal and the response and the same in depicted in the scope. The input and response function (numerator of the transfer function 0.002 s+0.89 and denominator of the transfer function 0.14 s^2+ 0.76 s+ 1.0) as captured is placed in Fig. 6.4 for the LP spool.

The plant although is a non linear continuous operation, due to the assumptions made and the derivations there of, the plant is made linear time invariant.
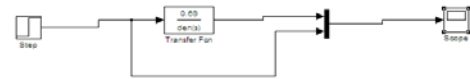
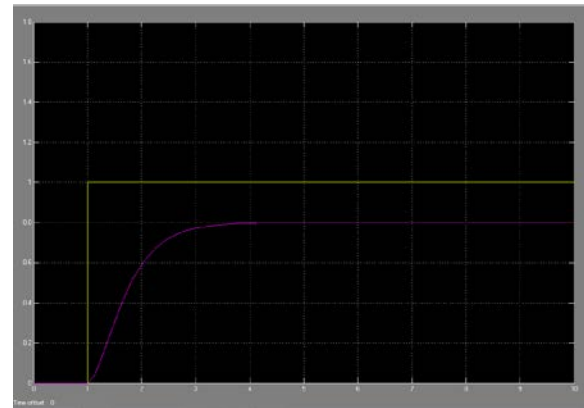Fig.6.3 Transfer function for low pressure spool RPM

Fig.6.4 Response of LP spool for unit step function

Here the transfer function is derived for the engine taking into consideration the steady state whether it is for NL and NH response. A mux is used to compare the step signal and the response and the same in depicted in the scope. The input and response function (numerator of the transfer function 0.00054 s+0.91 and denominator of the transfer function 0.14 s^2+ 0.76 s+ 1.0) as captured is placed in Fig. 6.6 for the HP spool.

The plant although is a non linear continuous operation, due to the assumptions made and the derivations there of, the plant is made linear time invariant.
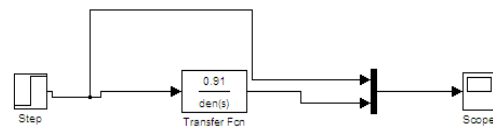

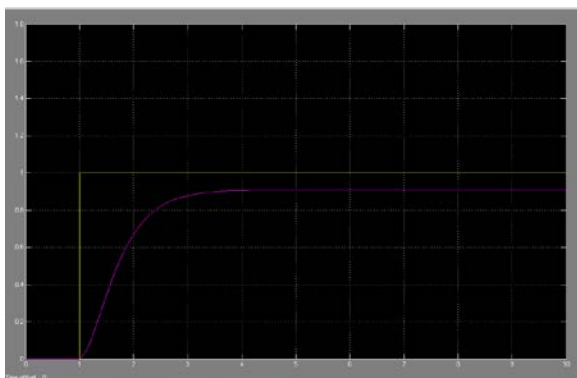Fig.6.5 Transfer function for high pressure spool RPM

Fig. 6.6 Response of HP spool for unit step input

7.   CONCLUSION

Most of the engines which are under development have a variety of simulation works namely system simulation, hardware in loop system (HILS) and IRON BIRD which consists of overall engine and aircraft software. The exercise performed now is a very preliminary work however gives an idea how to do the simulation work for an aircraft engine consisting of various modules. It has been observed that unless all the mathematical equations are available and software interfaced, it is not possible to carry out a simulation work. For that matter irrespective of transient dynamics due to non-availability of performance equations, a set of equations is derived and used to establish a stability of the engine. In fact the transfer function is derived for the engine and step input in terms of fuel mass flow rate and exhaust area variation has given stability characteristics of the overall engine.

ACKNOWLEDGEMENT

LIST OF ABBREVIATION

FMFR	Fuel Mass Flow Rate
HPR	High Pressure Ratio
JPT	Jet Pipe Temperature
LPR	Low Pressure Ratio
OPR	Overall Pressure Ratio
HILS	Hardware in Loop System
RPM	Revolution per Minute
LPT	Low Pressure Turbine
HPT	High Pressure Turbine

IST OF SYMBOLS

ε	Radius of the Circle with -1+j0
$\bar{n}$	Nominal RPM
S	Laplace transform
$\bar{\dot{m}}_f$	Nominal Fuel Flow Rate
$\bar{A}_7$	Nominal Area of Exhaust Nozzle
π_{CL}	LPC pressure ratio
π_{CH}	HPC pressure ratio
π_{TL}	LPT pressure ratio
π_{TH}	HPT pressure ratio
J	Mechanical Equivalent of Heat

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