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Performance Simulation of a Turboprop Engine in On-design and Off-design Conditions

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Abstract

A performance simulation program for the turboprop engine was developed for performance prediction, development of an EHMS(Engine Health Monitoring Systems)and the flight simulator. characteristics of components including compressors, turbines, power turbines and the constant speed propeller were required for the steady state and transient performance analysis with on and off design point analysis. At on-design condition , the object of analysis is to obtain estimates of the performance parameters such as primarily thrust and specific fuel consumption in terms of design limitations, the flight conditions, and design choices.

Keywords: simulation-turboprop-on-design-off-design

Introduction

A performance simulation program for the turboprop engine has been required for more precise performance prediction and development of the EHMS and the flight simulator. However, because most performance analysis programs of engine manufacturers are proprietary, they are usually not provided to their customers.

A non-linear analog simulation of a J85-13 turbojet engine was developed by Slender, et al.(1972). The study indicated that a mathematical representation using the dynamics inherent in the conservation equations and engine geometry will provide a better simulation than those using component representation and linearized dynamics [1].

TURBOCAL, a digital computer program that simulates the on-design , off-design and transient performance of arbitrary gas turbine configuration was developed by Douglas (1986). This program performed also rig-test analysis of three engines. In order to obtain numerical solution of the dynamic equations for the transient performance simulations, the modified Euler method was used [2].

On-design performance analysis

The configuration of turboprop engine herein investigated in fig.1.

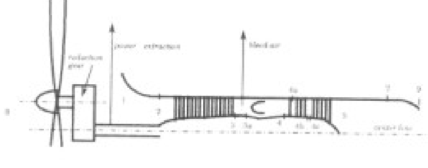

Fig.1 configuration of turboprop engine

Table 1 presents the on-design analysis date which obtain optimum compressor pressure ratio and maximum allowable turbine temperature for off-design analysis.

Table 1 – on-design analysis data[3]

Variable	Quantity
Altitude	7645(m)
Mach Number	0.8
Fuel heating value(hpr)	41865(kj/kg)
Maximum inlet turbine temperature	1778 (k)

To estimate component's characteristics in design point analysis, well known thermodynamic relations were used.

Off-design performance analysis

In off-design point analysis, the following assumptions were considered:

- Gases are assumed to be calorically perfect both upstream and downstream of the burner and values of γ_t , C_{pt} don't vary with throttle setting.
- The air flow passed through the intake, the compressor, and the power turbine must be constant[4].

The importance parameters in off-design analysis which calculated from on-design analysis are optimum compressor pressure ratio and maximum allowable turbine temperature.

Equations

In the steady state performance analysis for on and off design point, the following equations were considered.

$$\tau_\lambda = \frac{c_{pt} T_{t4}}{c_{pc} T_0} \qquad (1)$$

$$\tau_r = 1 + (\delta_c - 1)/\delta_c M_0^2 \qquad (2)$$

$$\tau_c = \pi_c^{(\delta_c - 1)/(\delta_c e_c)} \qquad (3)$$

$$\eta_c = \frac{\pi_c^{(\delta_c - 1)/\delta_c} - 1}{\tau_c - 1} \qquad (4)$$

$$f = \frac{\tau_\lambda - \tau_r \tau_c}{(h_{pr} \eta_b / c_{pc} T) - \tau_\lambda} \qquad (5)$$

Result and discussion

In the following section, the result of on and off-design analysis illustrated in fig.2,3 and 4.In fig.2 optimum compressor pressure ratio obtain in terms of total turbine temperature and specific thrust. In this figure you can see that the compressor pressure ratios of 25 and 20 have the maximum specific thrust. On the other hand in fig.3 obviously illustrate that the pressure ratio of 25 has the lower value of specific fuel consumption than 30. S0 the pressure ratio of 25 is a optimum value.

The variation of compressor pressure ratio versus altitude and Mach Number investigated in fig.4.In according to fig.4,in a specified altitude, the compressor pressure ratio will decrease due to increase the value of Mach Number.

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Conclusion

As can be seen from above charts, to compromise between on-design performance analysis and off-design, the following notes are remarkable:

1. As a result of increment altitude, the compressor pressure ratio and specific fuel consumption increase while specific thrust decrease. So the turboprop engine is suitable for short altitude.

2. The specific thrust will constant and SFC will decrease due to increment of flight Mach Number.

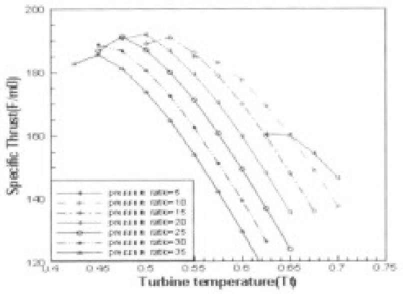

Fig.2 On-design optimum compressor pressure ratio

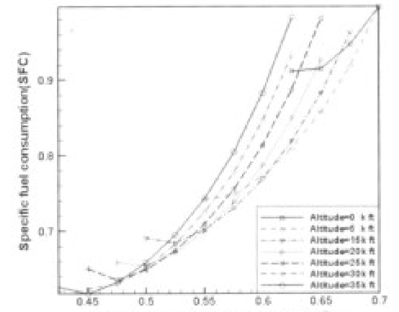

Fig.3 on-design specific fuel consumption

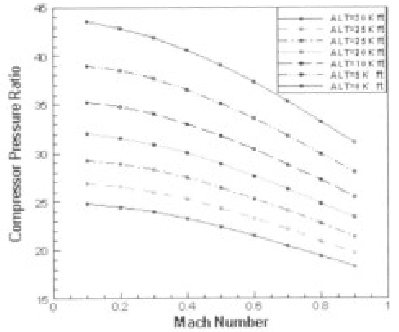

Fig.4 Off-design compressor pressure ratio

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Abstract

The simulation of aircraft is probably one of the most complicated yet exciting field in the engineering world today. A performance simulation program for the turboprop engine(PT6-62), which is the power plant of the first Korean indigenous basic trainer KT-1, was developed for performance prediction, development of an EHMS(Engine Health Monitoring Systems)and the flight simulator[1]. Characteristics of components including compressors, turbines, power turbines and the constant speed propeller were required for the steady state and transient performance analysis with on and off design point analysis. At on-design condition , the object of cycle analysis is to obtain estimates of the performance parameters (primarily thrust and specific fuel consumption) in terms of design limitations(such as maximum allowable turbine temperature and attainable component efficiencies), the flight conditions (the ambient pressure, temperature and Mach number), and design choices(such as compressor pressure ratio, fan pressure ratio, etc.). moreover, at off-design condition, the object of off-design cycle analysis is to determine estimates of an engine's performance over its operating envelope. Then, an engine cycle and its design conditions are selected so, the results of the off-design cycle analysis are used to size the engine. The independent variables in off-design are flight conditions, throttle setting, and nozzle settings. This program which provide by FORTRAN program, investigate some performance parameters such as mass flow rate, compressor pressure ratio, fuel flow rate, specific fuel consumption and turbine inlet temperature versus various altitudes and flight Mach number. The successive substitution method was used to calculate off-design analysis while in on-design condition no iteration required for solution due to all of the design choices are free to be selected by the designer and the engine performance characteristics per unit mass flow are determined for each selected set of choices.

Keywords: *simulation-turboprop-on design-off design*

Introduction

A performance simulation program for the turboprop engine has been required for more precise performance prediction and development of the EHMS and the flight simulator. However, because most performance analysis programs of engine manufacturers are proprietary, they are usually not provided to their customers.

Changduk kong, Jayoung ki and Sukchoo chung investigated the performance simulation of a turboprop engine for basic trainer in 2002.they developed program was evaluated with the performance data provided by the engine manufacturer and with analysis results of GASTURB program[1].

A non-linear analog simulation of a J85-13 turbojet engine was developed by Slender, et al.(1972). The study indicated that a mathematical representation using the dynamics inherent in the conservation equations and engine geometry will provide a better simulation than those using component representation and linearized dynamics[2] .

Saravamuttoo and Maclsaac(1973) used a hybrid computer in order to optimization of thrust. The digital computer was better suited to store and access data such as compressor and turbine characteristics while the analog computer calculated the integration of net torque and numerous multiplication and divisions for the representation of thermodynamic variables[2].

In 1975, the digital computer program , called DYNGEN, was developed by Seller and Daniele. They attempted to simulate the steady state and dynamic performance of a turbojet and turbofan engines[3].

In 1985, TURBOTRANS, which is a generalized modular digital computer code, was developed by Palmer and Yan. This code evaluate the steady state and transient performance simulation of arbitrary gas turbine engines with arbitrary control systems[3].

TURBOCAL, a digital computer program that simulates the on-design , off-design and transient performance of arbitrary gas turbine configuration was developed by Douglas (1986). This program performed also rig-test analysis of three engines. In order to obtain numerical solution of the dynamic equations for the transient performance simulations, the modified Euler method was used [3].

In this research, first of all, the on design cycle analysis evaluated in order to calculate some special data to simulate turboprop engine at off-design cycle analysis. Secondly, the off-design point analysis performed in terms of altitude between sea level to 30000 ft height and flight Mach number between 0 to 0.85.

On-design versus off-design

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During this process of selecting a set of design point parameters for each critical flight conditions, the final engine will always be running off-design and will therefore behave differently at each operating point.

On-design point performance analysis

The configuration of turboprop engine herein investigated in fig.1[4]. As can be seen from fig1 and fig.2, the compressor of this turboprop engine is powered by the high pressure turbine, while the low pressure turbine provides mechanical power to both the propeller and power takeoff. The station numbers, shown in fig.2, of locations indicated in table 1[4].

Table 3-station numbers of locations

Station	Location
0	Far upstream or free stream
1	Inlet or diffuser entry
2	Inlet or diffuser exit-compressor entry
3	Compressor exit
3a	Burner entry
4	Burner exit -nozzle vanes entry-high pressure turbine entry
4a	Nozzle vane exit-coolant mixer 1 exit
4b	High pressure turbine exit-coolant mixer 2 entry
4c	Coolant mixer 2 exit-low pressure turbine entry
5	Low pressure turbine exit
7	Core exhaust nozzle entry
9	Core exhaust nozzle exit

Table 2 presents the on-design analysis date which obtain optimum compressor pressure ratio and maximum allowable turbine temperature for off-design analysis. In order to examine the performance turboprop engine at on-design point with the variation of turbine total temperature ratio range from 0.4 to 0.75, the performance was analyzed with the altitude of 7645 m and flight Mach number 0.8 at 100 % rotational speed of the gas generator. The heating value of the fuel which burn in the combustion chamber is about 41865 kj/kg and the maximum inlet turbine temperature which exit from the combustion chamber is approximately 1778 K.

Table 2 – on-design analysis data[3]

Variable	Quantity
Altitude	7645(m)
Mach Number	0.8
Fuel heating value(hpr)	41865(kj/kg)
Maximum inlet turbine temperature	1778(k)

To estimate component's characteristics in design point analysis, well known thermodynamic relations were used. The following assumptions were used to analyzed on design performance:

- The flow is, on the average, steady.
- The flow is one dimensional at the entry and exit of each component and at each axial station.
- The propeller is driven by the low pressure turbine, which also provides the mechanical power for accessories.

Off-design performance analysis

In off-design point analysis, the following assumptions were considered:

- Gases are assumed to be calorically perfect both upstream and downstream of the burner and values of γ_t , C_{pt} don't vary with throttle setting.
- The air flow passed through the intake, the compressor, and the power turbine must be constant[4].
- The component efficiencies and total pressure ratios don't change from their design values.
- Cooling air fractions are constant.

The performance of a selected design point turboprop engine of the type shown in fig.1 is desired at off-design flight conditions and throttle setting. Since the high pressure turbine drives the compressor, the power balance of the high pressure spool yields the expression for calculating the total temperature ratio of the compressor at off-design conditions. In this code, there are six dependent and four independent as shown in table 3[4].

Table 3-off-design performance variables

component	*Independent variables*	*Constant or known variables*	Dependent variables
Engine	M_0, T_0, P_0	………..	m_0
Diffuser	………..	π_d	………..
Compressor	………..	………..	π_c, τ_c
Burner	T_{t4}	π_b	………..
Coolant mixer1	………..	τ_{m1}	………..
High pressure turbine	………....	π_{th}, τ_{th}	………....
Coolant mixer2	………..	π_{m2}, τ_{m2}	………..
Low pressure turbine	………....	………....	π_{tl}, τ_{tl}
Nozzle	…………	η_{prop}	P_9/P_0
Total number	4	………..	6

The importance parameters in off-design analysis which calculated from on-design analysis are optimum compressor pressure ratio and maximum allowable turbine temperature. An expression for the total temperature ratio of the low pressure turbine yielding minimum thrust specific fuel consumption with all other variables being held constant can be obtain for the case when $P_9 = P_0$ (P_9 will equal P_0 when the exhaust nozzle operates unchoked, which often the case, particularly at cruise)[5].

Effect of variable of altitude on specific thrust

In according to equation 6and 7, from sea level to 11000 m height the temperature of the atmosphere increase by the rate of 0.0065 K per one meter and from this level to 20000 meter height the temperature stay constant to 216.7 K. So, as a result of increase elevation and in according to equation 7 and 8, the pressure of the atmosphere will be decrease[6]. The variation of atmospheric temperature and pressure illustrate in fig.5 and fig.6. So, the rate of specific thrust will be fall as a result of decrease temperature and pressure atmospheric.

The propeller of the turboprop engine

Propeller is one of the essential elements which its produce approximately 90 % total thrust for propulsion. So, the propeller efficiency is an important parameter to evaluate on and off-design points analysis. Generally, the propeller efficiency in terms of Mach number illustrated in fig.3. As can be seen from fig.3, the propeller efficiency will increase linearly to Mach number 0.1, from this point to about Mach number 0.7 its will be constant in the value of 0.82. After that, from Mach number 0.7 to above, the propeller efficiency steadily decrease because of shock wave in a tip of propeller. So, the flight velocity of a turboprop engine should be between 0.1 to 0.7 flight Mach Numbe[7]. In this research the Clark-Y-5868-R6, which has 3 blades[8], used to simulate the performance turboprop engine.

Equations

The on-design equations are developed for the low pressure turbines total temperature ratio giving minimum fuel consumption.

In the steady state performance analysis for on and off design point, the following equations were considered.

C_{pt}, C_{pc} are specific heat of combustion gases and air and T_{t4}, T_0 are maximum allowable turbine temperature and ambient temperature respectively.

$$\tau_\lambda = \frac{c_{pt} T_{t4}}{c_{pc} T_0} \qquad (1)$$

τ_λ is often appropriate to work in terms of design limitations.

$$\tau_r = 1 + (\delta_c - 1)/\delta_c M_0^2 \qquad (2)$$

τ_r, τ_c are as free stream recovery and compressor total temperature ratios respectively. Moreover, δ_c is a specific heats ratio.

$$\tau_c = \pi_c^{(\delta_c - 1)/(\delta_c e_c)} \qquad (3)$$

η_c, π_c, e_c are as compressor efficiency, compressor pressure ratio and compressor polytropic efficiency.

$$\eta_c = \frac{\pi_c^{(\delta_c - 1)/\delta_c} - 1}{\tau_c - 1} \qquad (4)$$

f, h_{pr}, η_b are as fuel-air ratio, fuel heating value and combustion efficiency.

$$f = \frac{\tau_\lambda - \tau_r \tau_c}{(h_{pr}\eta_b / c_{pc}T) - \tau_\lambda} \qquad (5)$$

For altitude between 0 to 11000 (m),

$$T = T_0 - 6.5E - 3 * H \qquad (6)$$

T,H are as temperature and altitude .

For altitude between 11000 (m) to 20000 (m) its given by:

$$T = 216.65K \qquad (7)$$

Moreover, in the range of 0 to 11000 (m) height, the pressure can be evaluated as:

$$\frac{P}{P_0} = \left(\frac{288.15}{288.15 - 6.5E - 3 * H}\right) \qquad (8)$$

And for the range of 11000 (m) to 20000 (m), its given by:

$$\frac{P}{22632} = EXP[(-0.15768E - 3) * (H - 11000)] \qquad (9)$$

Result and discussion

In the following section, the result of on and off-design analysis illustrated in fig.4 to 10. It can be seen from fig4 and fig.5, the temperature of the atmosphere will decrease due to increase altitude by the rate of 0.0065K till the altitude of 15000 m. In this elevation,15000 m to above, the temperature will be constant to about 216.7 K. Moreover, Like temperature, the rate of atmospheric pressure and air density will fall as a result of increase altitude. In fig.6 optimum compressor pressure ratio obtain in terms of total turbine temperature and specific thrust. In this figure you can see that the compressor pressure ratios of 25 and 20 have the maximum specific thrust. On the other hand in fig.7 obviously illustrate that the pressure ratio of 25 has the lower value of specific fuel consumption than 30. S0 the pressure ratio of 25 is a optimum value.

The variation of compressor pressure ratio versus altitude and Mach N umber investigated in fig.8.In according to fig.8, in a specified altitude, the compressor pressure ratio will decrease due to increase the value of Mach Number.

Conclusion

As can be seen from above charts, to compromise between on-design performance analysis and off-design, the following notes are remarkable:

1- In according to fig.8, in a specified altitude the compressor pressure ratio will abate as a result of increase flight Mach Number. Actually, the main reason is that, with reference to equation 2, the temperature ratio of the compressor and hence compressor pressure ratio will decrease because of increment flight Mach Number. So the turboprop engine is suitable for narrow range of flight Mach Number between 0.1 to .7 M0. Moreover, in a specified flight Much Number, the compressor pressure ratio will be proliferate due to reproduce of elevation. The essential reason is that the temperature of the surrounding will be decrease and hence compressor pressure ratio will be augment as a result of increase altitude.

2- As can been from fig.9, at every specified altitude, the specific thrust will be decrease due to increment flight Mach Number. Furthermore, in a specified flight Mach Number, the rate of thrust will be decrement in a reason of increase elevation. Because the thrust has the closely relative to the surrounding temperature.

3- The oscillations of specific fuel consumption (SFC) in terms of Mach Number in a variety altitude illustrated in a fig.10. As a result of increase flight Mach Number and in a specific elevation, the specific fuel consumption (SFC) will be increase while thrust will be decrease. Anymore, in a specific Mach Number, SFC trends to increment because of increase elevation. It is remarkable to say that the fligh Mach Number range between 0<M0<0.11, the rate of specific fuel consumption (SFC) will be constant and it's independent of altitude.

Generally, the turboprop engine is suitable for narrow range of altitude and flight Mach Number. Moreover, it's a good choice for transport materials, because it has high level specific thrust in insignificant flight velocity.

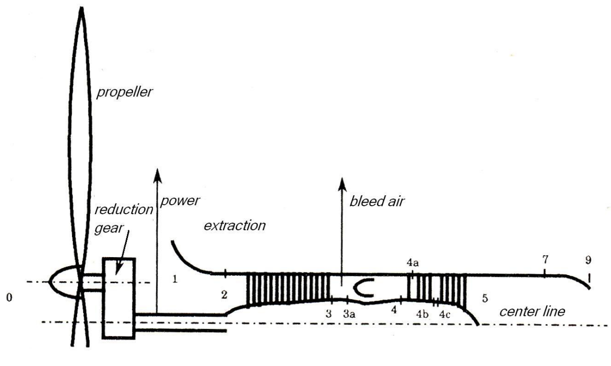

Fig.1 Configuration of Turboprop Engine

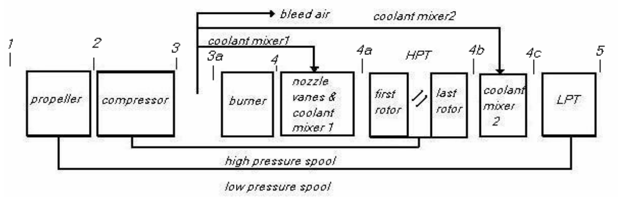

Fig.2 Block Diagram of Turboprop Engine

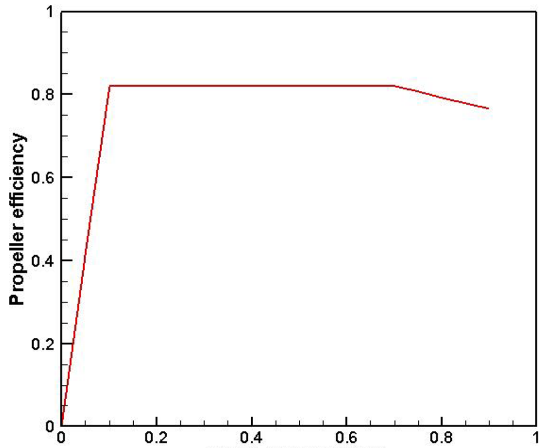

Fig.3 Propeller Efficiency of Turboprop Engine

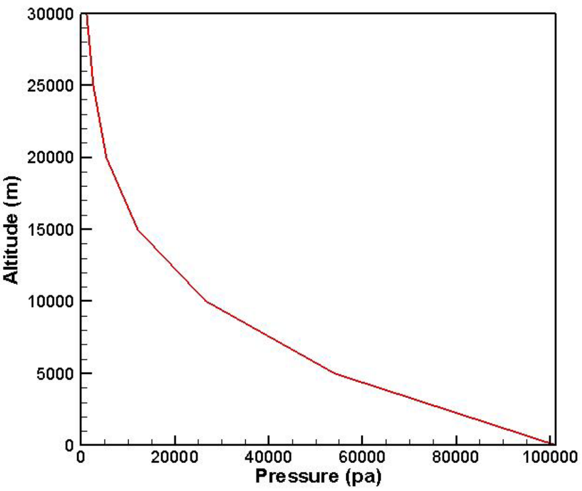

Fig.4 Variation of Pressure Versus Altitude

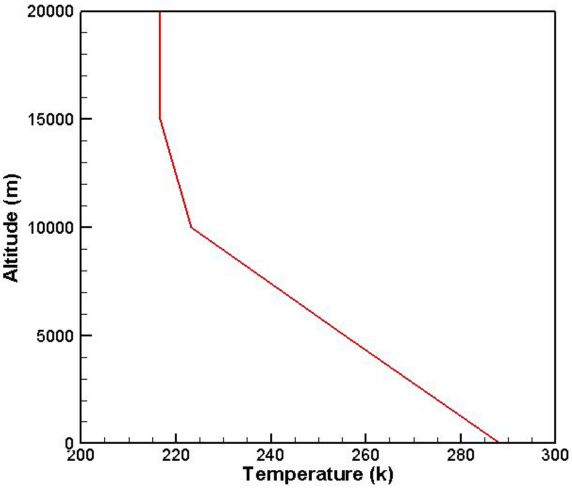

Fig.5 Variation of Temperature Versus Altitude

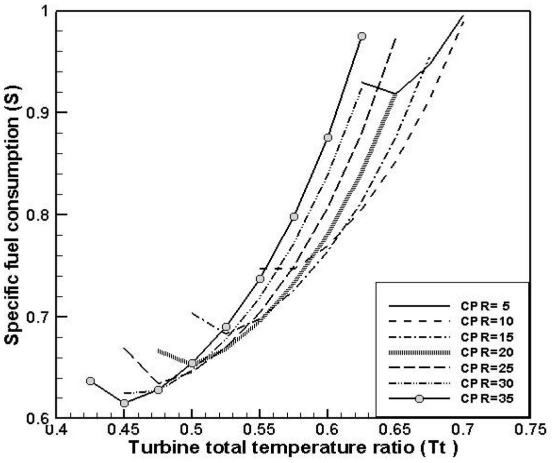

Fig.6 On-Design Specific Fuel Consumption

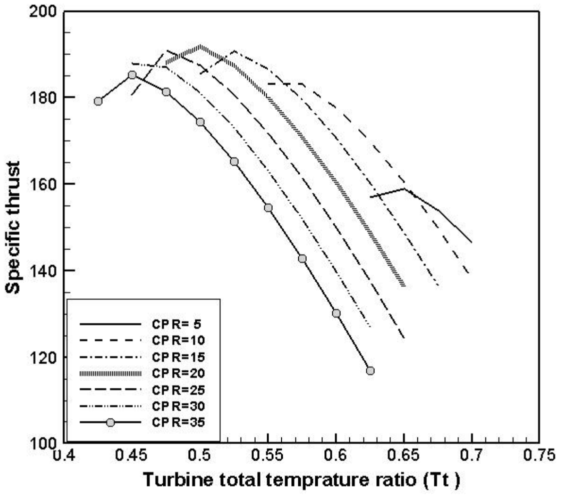

Fig.7 On-Design Specific Thrust

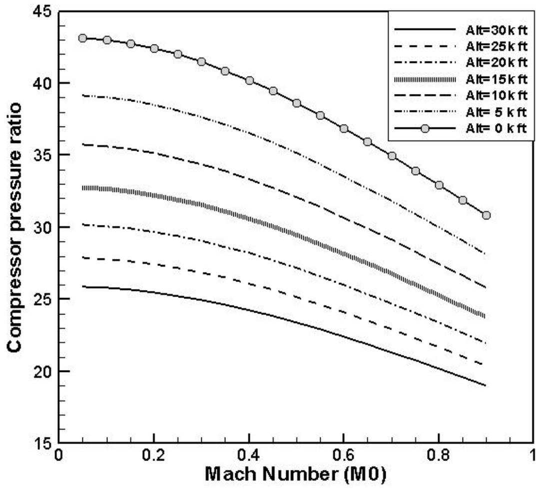

Fig.8 Off-Design Turboprop Compressor Pressure Ratio

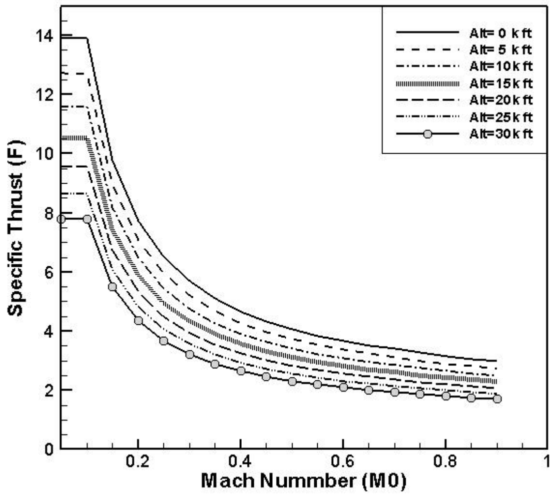

Fig.9 Off-Design Thrust of Turboprop Engine

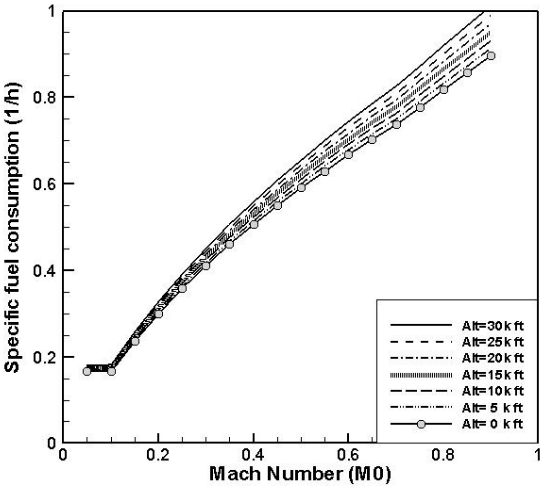

Fig.10 Off-Design Specific Fuel Consumption

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