On-design and off-design simulation of the performance of a Micro Turbofan Engine using LabVIEW and GSP

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Abstract— This paper presents the on-design and off-design simulation of a twin spool micro turbofan engine that is expected to produce in the range of 4 kN performed using Gas Turbine Simulation Programme (GSP 11®) and LabVIEW. There is a huge gap in the availability of micro gas turbine engines in the thrust range around 4 kN to power UAVs and drones. This analysis brings out the feasibility of thrust generation using a micro turbofan engine so as to fill the gap. The engine is analyzed for four different mass flow rates, Mach numbers ranging from 0.3 to 0.8 with the operating altitude between 5000 m to 9000 m. The net thrust produced for compressor pressure ratio of 3.5 and bypass ratio 1.5 is in the range of 4.6 to 7.3 kN at a mass flow rate of 36 kg/s which satisfies the expected design requirement of the engine. Also, the maximum turbine inlet temperature is less than 1100 K so that there is no need for a new material required in combustor and in turbine where the high temperature exists. The outcomes of this analysis form a strong base for further analysis, design and fabrication of micro turbofan engine to propel future Medium Altitude Long Endurance (MALE) Unmanned Aerial Vehicles (UAVs).

I. INTRODUCTION

There has been a constant thrive to develop new propulsion systems to increase the endurance and range of Unmanned Aerial Vehicles that are presently hindered by the limitations of the battery operated propulsion methods. Gas turbine engines in the micro scale are being developed as a reasonable substitute in place of battery systems to propel UAVs. In recent times, Turbofan engines are preferred over turbojet engines to develop high thrust while the specific fuel consumption is less as compared to turbojet engines. It is found that by compromising a bit on the energy required to drive the fan, turbofan engine yields higher thrust per amount of fuel used. In these lines, the use of simulation software goes handy in determining the performance of these engines even before they are manufactured. Commercial software like GasTurb, GSP, Perf, etc., has been widely used in the gas turbine industry to model and simulate these engines. This move saves valuable cost and time spent to manufacturing and testing of the main components of the turbofan engine E.g. Fans, compressors, turbines. The on-design and off-design analysis forms the basis of thermodynamic analyses of these engines providing vital data to predict the performance of the gas turbine engines with reasonable accuracy. This paper deals with the on-design and off-design analysis of a micro turbofan engine that is expected to develop a thrust in the range of 4 kN that can be used to propel MALE UAVs. The outcomes of the analysis will play a major role in the future design of micro turbofan engines for MALE UAV propulsion.

II. LITERATURE BACKGROUND

During the recent years there has been an increasing interest on studies in micro range Turboprop engines suitable for UAV propulsion. Some of the research findings relevant to the present study are presented below.

Mofid Gorji et al performed the Turbofan engine performance to determine the thrust, thrust specific fuel consumption and thermal, propulsive and the overall efficiencies of turbofan engine at high pressure and low pressure compressor pressure ratio, exit temperature pressure from high pressure compressor, combustor inlet temperature, corrected inlet mass flow rate of compressor and fan and bypass ratio. Turbofan engine performance graphs as well as the constraint functions that are controlled by the controller based on flight Mach number and in various heights were accurately drawn. Andrew Dankanich and David Peters carried out detailed studies on the Bypass Ratio of a turbofan engine as a Function of Thrust and Fuel Flow in which they concluded that the specific fuel consumption decreases as bypass ratio increases due to which the propulsive efficiency also increases. The increase in efficiency enables large savings on fuel and thus has a large impact on the global economy and environment. Shufan Zhao et al estimated the requirements of a Turbofan engine for high altitude Carrier-Based UAV propulsion. The required thrust
is calculated for different altitudes from 9 to 13km. The weight estimation method from flight profile was used to calculate the weight of UAV in each stage and thereby obtaining the SFC requirements. Then an attempt is made to design the engine to meet the requirements. The results show that required thrust decreases from 11.916 kN to 9.0576 kN with increase in altitude from 9 to 13 km. The SFC should be less than 0.0565 kg/N.h. But simulation of the engine in GSP software yielded higher SFC. In 2011, Rahman et. al conducted a thermodynamic analysis of gas turbine power plant by varying different parameters. The result shows that the thermal efficiency of the engine is strongly influenced by compression ratio, ambient temperature, air-fuel ratio and the isentropic efficiencies of the components. With rise in ambient temperature and the air to fuel ratio, the thermal efficiency and power output decreases linearly. With increase in ambient temperature and air to fuel ratio, the specific fuel consumption and heat rate increase linearly. Higher the compression ratio and lower the ambient temperature leading to efficiency, high power and low specific fuel consumption.

Elzahaby et.al have investigated the performance of a Micro Gas turbine engine using empirical relations and experimental test rig. The performance of the compressor and combustion chamber were predicted using this model. The prediction on performance of the engine based on Thrust and fuel consumption is found to be more accurate. Dinesh Kumar and Gupta have conducted a parametric and performance analysis of turbojet engine using CFD and MATLAB. The study analyses the effect of temperature, pressure and mass flow rates on the performance of the engine. The variation of these input parameters provides a systematic analysis of the jet engine from ambient to the exhaust. The result shows different parameters plotted across the axis of the engine.

However, the detailed on-design and off-design of a micro turbofan engine is not available in the reported literature. Hence, the present study aims at performing the complete analysis and of a micro turbofan engine and to determine the performance of the engine at various input parameters like mass flow rate, altitude, Mach number and pressure ratio and bypass ratios.

III. SIMULATION STUDIES ON TURBOFAN ENGINE

Simulation studies are performed to understand the thermodynamic changes of the working fluid mainly air and products of combustion as it flows through the engine. It is normally performed in two stages namely, On-design and Off-design analysis. On-design analysis (also known as design point or parametric analysis) determines the engine performance at different flight conditions and design choices and limits. The Off-design analysis which is also known as engine performance analysis or transient analysis determines the performance of a specific engine at all flight conditions and throttle settings. In a Turbofan engine, air is taken in through an opening in the front of the engine which is compressed to 3 to 12 times its original pressure in the compressor. Fuel is added to the air and burnt in the combustion chamber to raise the temperature of the fluid mixture to about 1,400 °F to 1,500 °F. The resulting hot air is passed through a turbine, which drives the compressor and fan the exhaust gasses passes through a nozzle outlet where thrust is produced because of the reactive forces of the exit stream. The main components of a turbofan engine are, a) Inlet Duct b) Fan c) Fan nozzle d) Compressor e) Combustion chamber f) Turbine and g) Core Exhaust Nozzle.

A. On-design performance simulation of Turbofan Engine using LabVIEW

Parametric analysis of a twin spool turbofan engine is performed using LabVIEW, (a systems engineering software for applications that require test, measurement, and control with rapid access to hardware and data insights). The analysis is conducted for various pressure ratios of the compressor, Mach number of inlet flow as well as altitudes of operation. The Pressure ratio in the analysis ranges from 1.5 to 5, the Mach number from 0.3 to 0.8 and the altitude of operation in the range 5000 m to 9000 m. The results of the analysis are shown below. The bypass ratio is varied from 0.5 to 2.5. The block diagram of the Turbofan engine simulated using LabVIEW is shown in Fig 1.

![Fig 1 Block diagram of the LabVIEW simulation of Turbofan Engine](image)

a) Effect of Compressor Pressure Ratio

The compressor pressure ratio is one of the main parameters that affect the thrust generated in the turbofan engine. The pressure ratio in the study is varied from 1.5 to 4 and the variation of thrust and SFC is simulated using the LabVIEW software model. The same parameters are studied at varying Mach numbers in the range of 0.3 to 0.9. Also, the propulsive, thermal and overall efficiency of the engine under varying inlet conditions is also simulated. Fig 2, shows the variation of thrust generated in the engine at various pressure ratios in the compressor.
It is seen that the thrust produced by the engine increases as the compressor ratio increases. The thrust produced ranges from 140 N per unit mass of flow rate to 310 N per unit mass of flow rate.

Fig. 3 shows the variation of SFC in the engine at various pressure ratios in the compressor. It is evident from the simulation that the SFC decreases with increase in compressor pressure ratio. Hence the fuel consumed at higher pressure ratio is less leading to increased efficiency of the engine. It is seen that the SFC reduces from 0.29 kg/N.h to 0.14 kg/N.h as the compressor pressure ratio increases from 1.5 to 4. The LabVIEW simulation is performed to estimate the propulsive efficiency of the turbofan engine. Fig.4, shows the variation in the propulsive efficiency of the turbofan engine for various compressor pressure ratio.

It is evident from Fig 4, that the propulsive efficiency increases till a particular compressor pressure ratio and then decreases a little after which there is no change in the efficiency with increase in compressor pressure ratio. The maximum propulsive efficiency of the turbofan engine is found to be 80% for a compressor pressure ratio of 2 and the minimum efficiency of 73% if is found to be the pressure ratio of 4.

Fig 5, shows the variation of thermal efficiency with respect to change in compressor pressure ratio. It is confirmed from the figure that the thermal efficiency increases as the compressor pressure ratio increases. The maximum thermal efficiency of the turbofan obtained is 21% for a compressor pressure ratio of 4 and the minimum efficiency of 5.8% if is found corresponding to the pressure ratio of 1.5. Similarly, Fig 6, shows the variation of overall efficiency of the turbofan engine with respect to change in compressor pressure ratio. The maximum overall efficiency is found to be 14.5% at the compressor pressure ratio of 4.
b) Effect of Mach Number

The Mach number of the inlet air entering into the engine is another important parameter that affects the performance of the turbofan engine as it operates at various altitudes. The Mach number in the study is varied from 0.2 to 0.8 and the variation of thrust and SFC is simulated using the LabVIEW software model. Also, the propulsive, thermal and overall efficiency of the engine under varying inlet conditions is also simulated. Fig. 7, shows the variation of thrust generated in the engine at Mach number of the inlet flow.

Fig. 7 Variation of Thrust produced for various Mach Number

Fig. 7 & 8, shows the variation of thrust and SFC at various inlet Mach number of the engine. The thrust generated decreases as the Mach number of the inlet flow increases and the SFC increases as the inlet Mach number increases. The thrust generated is found to be maximum, while the SFC is found to be minimum at lower Mach number of operation of the turbofan engine.

The variation of Propulsive and thermal efficiency of the engine for various Mach number is shown in Figs 9 & 10 as below.

Fig. 8 Variation of SFC at various Mach Number

Fig. 9 Variation of Propulsive efficiency with Mach Number

Fig. 10 Variation of Thermal efficiency with Mach Number
It is evident from Figs 9 & 10, that the propulsive and thermal efficiency of the engine with increase in Mach number. The maximum propulsive efficiency of the turbofan engine is found to be 80% at Mach 0.8 and the maximum thermal efficiency of 14% at the Mach number of 0.8.

B. Off-design performance simulation of Turbopfan Engine using GSP

NLR’s Gas turbine Simulation Program (GSP-11), an off-line component-based modeling environment for gas turbines which is widely used to perform the steady state simulation of the engine is used to perform the off-design analysis. GSP is a powerful tool for performance prediction and off-design analysis with respect to variables such as ambient (flight) conditions, installation losses, certain engine malfunctioning (including control system malfunctioning), component deterioration and exhaust gas emissions. The transient response of the engine is studied by varying the fuel inlet to the engine to check the performance of the engine at various engine operating conditions. This enables the control engineers to develop proper control mechanisms to see that the engine delivers the required thrust at all throttling conditions.

a) Transient response of the Turbopfan engine

![Fig. 11 Transient response of the turbofan engine at various fuel conditions](image)

Fig 11 shows the transient response of the engine at various fuel inlet conditions. The fuel is increased and then decreased to know the performance of the engine at various throttle conditions. It is seen that, the engine readily responds to the change in inlet fuel flow and stabilizes in less than 2 seconds when accelerated as well as decelerated.

b) Compressor Map

The compressor map is a graph that describes a particular compressor’s performance characteristics, including efficiency, mass flow range, boost pressure capability, and turbo speed. The compressor map and the turbine map obtained for various inlet conditions in the study for a Turbopfan engine using GSP are shown below in Figs 12 & 13.

![Fig. 12. Compressor Map of the Turbofan Engine](image)

The turbine map obtained from the analysis is shown in Fig 13. The turbine map is orientated differently than the compressor map with the pressure/expansion ratio on the horizontal axis and the corrected flow on the vertical axis. As the burnt gases that are at a high pressure entering the turbine expands to a lower pressure in a turbine, turbines are also known as expanders. The turbine efficiency is also shown in the turbine map.

c) Turbine Map

![Fig. 13. Turbine Map of the Turbofan Engine](image)

IV. CONCLUSION

The on-design and off-design performance simulation of a twin spool Turbopfan engine intended to produce thrust in the range of 4 kN is analysed using LabVIEW and GSP software. The important results and conclusions are given below:

The compressor pressure ratio and the inlet Mach number have the same effect on the thrust generated by the engine. As the compressor pressure ratio and the Mach number of inlet air flow increases, the thrust produced by the engine also increases. Similarly, as the compressor pressure ratio and inlet Mach number increases, the SFC of the engine decreases. Hence, the Propulsive, thermal and overall efficiency of the engine is found to increase as the inlet Mach and compressor pressure ratio increases. It is concluded that the increase in efficiency of the engine will
enable economic operation of UAVs as well as increase the range and endurance of the engine to a great extent. The outcomes of the study will be very vital in the design and operation of micro turbofan engines for UAV propulsion in the near future.

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