Sensitivity and Design Point Analysis of RD-93 Engine at Static Sea Level using Numerical Propulsion System Simulation

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Abstract – **The design and prototyping of jet engines is an extremely costly and laborious task. An alternative to at this is the development of variants of existing engines for enhanced performance which requires detailed modeling of engine in mathematical environment for precise evaluation of performance parameters. This paper presents mathematical modelling and sensitivity analysis of performance of RD-93, a low bypass turbofan engine, towards design parameters including pressure ratio of turbomachinery components, bypass ratio and critical temperatures. The effect of varying the efficiency of engine components on performance of overall engine is estimated using numerical environment of Numerical Propulsion System Simulation (NPSS). The results of performed analysis can serve as a guide for further parametric cycle analyses of low bypass turbofan engines.**

Keywords – mathematical modelling, low bypass turbofan, numerical propulsion system simulation, pressure ratio, bypass ratio

I. Introduction

Gas turbine engines are an integral part of modern industries and act as primary power source of ground as well as aeronautical mechanical systems. With the growing energy crisis and strict adherence to emission control regulations, techniques to improve efficiency and performance of turbine engines are of supreme interest. The study of effect of each component on the overall performance of gas turbine engine can act as a guideline for future parametric studies of jet engines. With advances in technology, variable cycle engines and other sophisticated cycles are being developed to improve efficiency and reduce carbon emissions. The cost of the development of the propulsion system rises substantially with the complexity, making the design process highly dependent upon mathematical modelling and simulation tools. This dependence of aerospace industry on computer codes has led to development of some high-fidelity numerical modeling and simulation environments for performance estimation of overall engine and individual components. Modeling the new variants of existing engines in numerical environment, prior to prototyping has become a common practice in gas turbine industry. Numerical Propulsion System Simulation (NPSS) is a C++ based, object oriented [1] software package developed by NASA in collaboration with US aero-propulsion industry [2]. NPSS provides the freedom of zooming into individual components, allowing a multi-fidelity analysis of the propulsion systems [3].

The selection of a specific engine cycle for any aircraft depends upon the thrust requirement of the aircraft at the critical flight conditions. The evaluation of thrust requirement is influenced by the geometry of the aircraft as well as its design mission, which results in identification of a unique propulsion system which meets the thrust and weight requirement while exhibiting good performance over complete flight envelop [4]. Most of the modern military aircrafts are incorporated with low bypass turbofan engines to meet their thrust requirements [5]. The turbofan engine primarily consists of a fan or a low pressure compressor followed by the core section and a bypass duct. The bypass duct constitutes the bypass stream; whereas the core consists of high pressure compressor, burner, high pressure and low pressure turbines. The flow form the core and the bypass ducts is mixed in the mixer and fed to an augmentor in military engines for additional thrust, and then expanded to the ambient pressure using nozzle [6]. Low bypass turbofan engines combine the high thrust output of turbojet engines with the fuel economy of turbofans. Since design of a unique engine for every aircraft developed is extremely expensive and laborious task, the modification of existing engines is usually employed to fulfill the thrust requirement. The initial step in the development of a new variant is the sensitivity analysis of the performance parameters of the engine

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towards the design parameters. This paper presents the sensitivity analysis of performance of RD-93 towards the design parameters i.e. fan pressure ratio, high pressure compressor pressure ratio, bypass ratio, turbine inlet temperature and after-burner exit temperature using a numerical model. The effect of increasing the efficiency of individual components on the Thrust and Thrust Specific Fuel Consumption (TSFC) of the engine is also presented for comparative study.

Choi, Lee and Yang in [7], presented performance analysis of F-100 PW-229 using GasTurb. The authors used design point parameters available in open literature for the analysis and selected component efficiencies by random search method and compared the output parameters at design point with [8]and [9] and the results exhibit the difference of less than one percent in thrust and fuel flow.

Larsson, Grönstedt, and Kyprianidis presented sensitivity of geared and open rotor turbofan engines towards the component efficiencies in [10]. The engine used for the analysis has low overall pressure ratio which makes the block fuel more sensitive to low pressure system.

H R Patel presented a model to compare the effects of varying fan pressure ratio and bypass ratio on the performance parameters of variable cycle engine in [11]. The study also presented a comparison of performance of variable cycle engine with F-119. The author concluded that the variable cycle engine has superior performance compared to F119.

In this paper, a mathematical model for evaluation of the effect of variation of all the critical design parameters on the performance of a low bypass turbofan engine is presented. The influence of the variation of component performance on the overall engine performance is also quantified in the current study.

Design of a mixed flow, after-burning turbofan engine is a complex process involving a huge number of input parameters. At design point, Thrust and TSFC are the significant performance parameters, the values of which depend upon the design parameters, design limitation and component efficiencies [12]. The laws of conservation of mass, energy and momentum are employed to solve the engine cycle using Reynold's Transport theorem, the Thrust of a mixed flow, afterburning turbofan can be given by,

$$\frac{\partial}{\partial t}(m\,V) = \frac{\partial}{\partial t} \oiiint \rho V\, \partial Vol + \oiint (\rho V)(V.\hat{n})\, dA$$

The number of input parameters of each component used in NPSS for the analysis of a turbofan engine is enormous. Inlet conditions i.e. ambient Mach, altitude, temperature and pressure recovery, compressor and fan pressure ratios, efficiencies and spool speeds, burner exit temperature and efficiency , turbine efficiencies, and nozzle type, just to mention a few. However, the performance of engine is substantially affected by only a few parameters. When developing variant of an existing engine, the effect of these critical parameters on performance of engine is analyzed.

This paper presents the magnitude of improvement or deterioration in performance of RD-93 at design point, when the design parameters are varied from the baseline values. RD-93 is a Russian low bypass, mixed flow turbofan, developed by Kilmov to power JF-17 Thunder aircrafts produced by China in collaboration with Pakistan Aeronautical Complex [13]. With improvement in technology, the efficiencies of the individual components generally increases. Mattingly classifies this increase in efficiencies of engine components with time as technology levels. This paper also encompasses the influence of technology level on Thrust and TSFC of RD-93 at design point. Although the model presented in the current study is developed for RD-93, the general process is applicable to a wide category of low bypass, mixed flow turbofan engines.

II. Engine Architecture

NPSS is an object oriented software package, based on C++ which follows the hierarchy of assemblies, elements, sub-elements, sockets, functions and tables. Fluid link ports are used to connect subsequent elements aerodynamically and shaft link ports are used to connect elements mechanically. Modelling of a propulsion cycle in NPSS starts with the definition of a thermodynamic package. "all Fuel", "CEA", "FPTF", "GasTbl", "ING" and "Janaf" are the thermodynamic packages available in NPSS [14]. "all Fuel" thermodynamic package is used for the modelling of RD-93 in NPSS, which contains both gas and fuel properties. Next step in modeling is the specification of flight condition at which engine is to be designed, using Flight Conditions element. Flow from Flight Conditions enters Inlet element and the pressure of the flow is reduced because of the non-isentropic effects. Flow from Inlet element proceeds to a Compressor element named Fan where it is compressed to higher pressure by design fan pressure ratio. Flow from the outlet of fan is split into two streams in turbofan cycles using Splitter element which has single fluid input and two fluid outlet ports. The flow from one outlet of splitter is passed to core of the engine, i.e. to the high pressure compressor (HPC) where it is compressed to higher pressure. The flow from the other outlet is fed to the bypass duct using a Duct element. The high pressure flow from outlet of HPC is fed to a Bleed element where secondary flow for cooling of high pressure turbine blades is extracted from the primary flow. A percentage of the secondary flow extracted from Bleed element is also used for environment control system of the aircraft which is modeled as a flow sink in NPSS. Rest of the primary flow is drawn into the Burner element where fuel is also introduced through a separate port. Element named FuelStart is used to feed the fuel to the fuel port of the burner. Input variables of the burner element are pressure loss, efficiency and exit temperature of the gases. The high temperature flow is fed to Turbine element named HPT which is coupled mechanically to high pressure compressor using a shaft element. The pressure of the high energy flow is dropped during the work extraction process by the turbine. Flow from HPT then enters into another Turbine element named LPT, which is connected to Fan using low pressure shaft. Secondary flow is drawn from HPC at sixty percent work rise and a bleed element which is essentially the exit of the high pressure compressor, and is introduced to both turbine elements for cooling purpose. After low pressure turbine, a Mixer element named Mixer is added in the model. The mixer element has a two fluid input ports and a fluid output port. Flow from the engine core i.e. exit of the low pressure turbine and the flow from the bypass duct are mixed before introduction to the augmentor using mixer. The static pressures of both the inputs to the mixer must be equal to satisfy the Kutta condition, which states that the two merging flow streams cannot support a static pressure jump, i.e. $P_{16} = P_{6A}$ [15]. Flow from the mixer outlet enters a burner element named After-burner, which like primary burner has a fluid input and a fuel input port. The combustion in the afterburner is carried out at relatively lower total pressure, which decreases the efficiency of the element. Therefore, the amount of the fuel used by the secondary burner element is higher for than the primary burner. The outlet port from the augmentor exit is connected to the inlet of a Nozzle element which can be either convergent or De Laval type depending upon the input value of the Type switch of the element. For RD-93 modeled in the paper, the nozzle element used is a variable area convergent divergent nozzle which expands the incoming high pressure flow to the ambient pressure for all flight conditions. The condition of full expansion at all flight conditions is achieved by varying the throat and the exit area of the CD nozzle [16]. The flow is terminated at the engine exit using a Flowend element, which is added to the model at the exit of the nozzle element.

Following simplified equations are used by NPSS for calculation of component parameters at design point:

$$P_{02} = \eta_{PR} \pi_{diffuser} P_a$$

Where,

$$\eta_{PR} = \begin{cases} 1 & \text{for } M \leq 1 \\ 1 - 0.075(M-1)^{1.35} & \text{for } 1 < M < 5 \end{cases}$$

Pressure ratio of fan and compressor are known at design point.

Using work balance to find the outlet temperature of turbine,

$$m_{HPC}\,(1+f)\,C_p\,(T_{04} - T_{045}) = m_{HPC} C_p\,(T_{025} - T_{03})$$

Where,

$$f = \frac{\left(\frac{T_{04}}{T_{03}}\right) - 1}{\frac{Q}{C_p T_{03}} - \frac{T_{04}}{T_{03}}}$$

Finally, TSFC is given by,

$$TSFC = Thrust/W_{fuel}$$

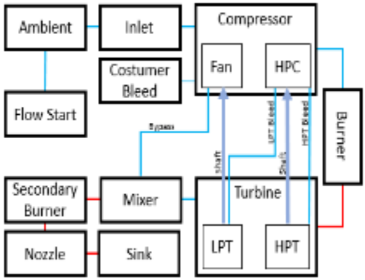

Fig. 1. Engine Architecture

TABLE I. INPUT PARAMETERS

Parameter	Value
Altitude (m)	0
Mach	0
Mass flow rate (kg/s)	75.5
OPR	21
FPR	3
BPR	0.49
TIT (K)	1530
ABET (K)	2056
HPT Bleed	10% of mass flow rate
LPT Bleed	6% of mass flow rate
Customer bleed (kg/s)	0.28

III. ASSUMPTIONS

The following assumptions are made for modelling of a turbofan engine in NPSS environment:

- Design point is taken as static sea level
- Flow throughout the engine is considered steady
- Flow at the entrance and exit of axial components is one dimensional
- Flow area at the exit of combustion chamber is constant
- Flow in the stator of turbine is choked
- Combustor exit temperature does not affect the pressure loss in combustor
- The efficiencies of primary and secondary burner are independent of flight conditions
- Turbo machinery maps used for the analysis are scaled versions of generic maps of fan, HPC, HPT and LPT
- Component efficiencies (η_{fan}, η_{HPC}, η_{HPT} and η_{LPT}) are constant
- Flow through the bypass duct and mixer is considered isentropic [12] [17]

IV. Sensitivity Analysis:

A. *Sensitivity:*

Thrust and TSFC, as previously discussed, are the main parameters that describe the performance of an engine. Though all engine parameters affect their values, it is still pertinent to study how strong or weak a function they are of design parameters. Sensitivity analysis is a simple way of studying the dependence of thrust and TSFC on the chosen design parameters, it also can tell which input parameters are important in reconciling the model with reality[18]. More generally, sensitivity of a parameter towards an input can be defined as the percentage change in that parameter with small change in the input parameter. If a change in component parameter i results in a change in performance parameter j then the sensitivity S_{j-i} can be written as,

$$S_{j-i}=\frac{(j_{max}-j_{min})/j_{min}}{(i_{max}-i_{min})/i_{min}}$$

Greater the value of S_{j-i}, greater will be the dependence of the parameter j on i.

In the following sections, the effects of selected engine design parameters and component efficiencies on thrust and specific fuel consumption of the engine are presented. The component design parameters that are to be varied include bypass ratio, fan pressure ratio, compressor pressure ratio, maximum turbine inlet temperature, maximum afterburner exit temperature and the bleed flows whereas the component efficiencies under consideration are that of the turbomachinery components, and combustion efficiencies of both primary and secondary burner. Even though other parameters undoubtedly contribute to the performance of the engine, a preliminary study ruled them rather ineffective compared to the chosen parameters.

B. *Component Parameters:*

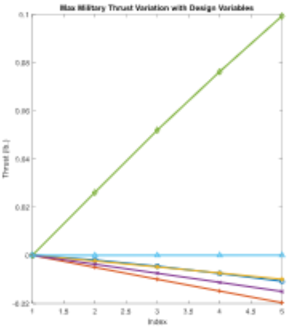

Fig. 2. Sensitivity of military thrust towards design parameters

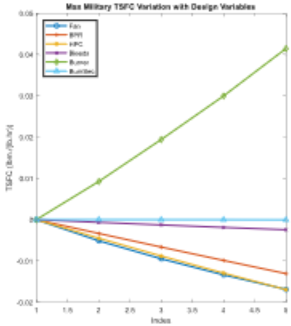

Fig. 3. Sensitivity of military TSFC towards design parameters

First the component design parameters were varied from their baseline values by certain amounts ensuring convergence over the range of values. From Figure 2-3, it is evident that in military conditions, the major contributor to the values of thrust and TSFC is maximum turbine inlet temperature which results in a substantial increase in thrust and TSFC of the engine. This effect is understandable since in order to increase T4, more fuel flow into the combustor is required which results in an increase in thrust as the flow entering the nozzle is at a higher temperature, hence greater kinetic energy. The increased mass flow of fuel also contributes positively towards the thrust as well as TSFC. Increasing burner temperature also corresponds to an increase in combustion efficiency[19], thus a relatively greater increase in thrust is observed compared to TSFC. On the other hand, increasing the bypass ratio of the engine results in a decrease in both parameters since smaller flow goes through the core and thus is easier to heat but results in lower nozzle exit temperatures, hence compromising thrust. The bleed flows affect the engine in a similar manner[18]. Increasing fan and compressor pressure ratio however results in decrease in thrust and TSFC, this is mainly because at higher pressures, the air entering into the combustion chamber is at a higher temperature and less fuel is required to achieve the same T4, thus lowering the exit mass flow rate resulting in a decrease in thrust as well as fuel consumption. Table II tabulates the values of sensitivity of thrust and TSFC as described,

Table II. Sensitivity of Military Performance to Design Parameters

Component	TSFC	Thrust
Fan	-0.1605	-0.1022
Bypass Ratio	-0.1243	-0.1871
High Pressure Compressor	-0.1608	-0.0944

Bleeds	-0.0233	-0.1425
Burner	0.6698	1.6058

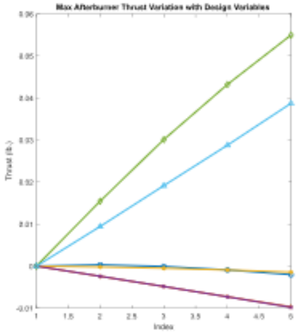

Fig. 4. Sensitivity of max afterburner thrust towards design parameters

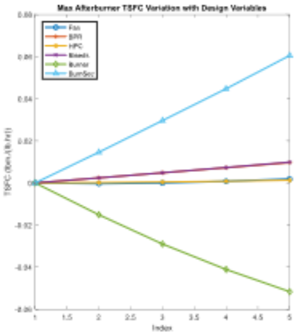

Fig. 5. Sensitivity of max afterburner TSFC towards design parameters

Initiating the afterburner alters the sensitivity significantly as can be seen in Fig 4-5. The afterburner, in this case, shows a similar trend to that of the primary burner in the first case and is due to similar reasons. Variation of bypass ratio in afterburner operation contributes positively to the specific fuel consumption of the engine. In military operations, since the air entering the mixer was not heated afterwards, it resulted only in addition to the thrust and had no effect on the fuel consumption. However, in afterburner operations the air which is at a lower temperature and pressure, has to be heated to the same T7 which requires addition of more fuel. Also, combustion at lower pressure is inefficient and adds to the fuel consumption causing the SFC to increase. Since the mass leaving the engine is still at a lower pressure, it expands to the atmosphere relatively quickly and is unable to transfer as much kinetic energy as it is possible in a higher pressure case, thus a decrease in thrust is observed. The effect of HPC and Fan pressure ratio is similar to that observed in military operation. These effects are quantified in Table III.

TABLE III. SENSITIVITY OF AFTERBURNER PERFORMANCE TO DESIGN PARAMETERS

Component	TSFC	Thrust
Fan	0.0197	-0.0191
Bypass Ratio	0.0934	-0.0918
High Pressure Compressor	0.0139	-0.0134
Bleeds	0.0947	-0.0930
Burner	-0.8484	0.8876
Afterburner	0.9985	0.6318

C. Component Efficiencies:

Extending the sensitivity analysis to component efficiencies, a significant impact on thrust and TSFC of the engine with variation in component efficiencies can be observed. Here, increasing the burner efficiency results in a significant decrease in TSFC while the effect on thrust is relatively negligible. The predominant effect on thrust is due to changing HPC efficiency which can be prescribed to lower HPT power extraction requirement, a similar trend is seen when changing fan efficiency. These results are evident in Fig 6-7 and Table IV.

TABLE IV. SENSITIVITY OF MILITARY PERFORMANCE TO COMPONENT EFFICIENCIES

Component	TSFC	Thrust
Fan	-0.2535	0.5239
High Pressure Compressor	-0.2663	0.6879
Burner	-0.9561	-0.0610
High Pressure Turbine	-0.4684	0.4864
Low Pressure Turbine	-0.2720	0.2779

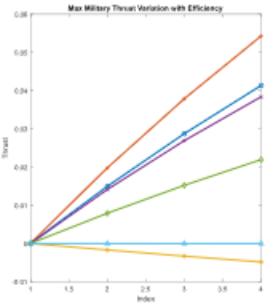

Fig. 6. Sensitivity of military thrust towards efficiencies

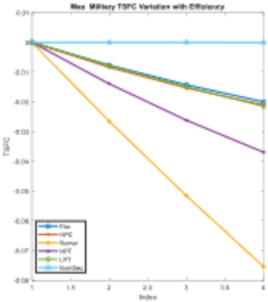

Fig. 7 Sensitivity of military TSFC towards efficiencies

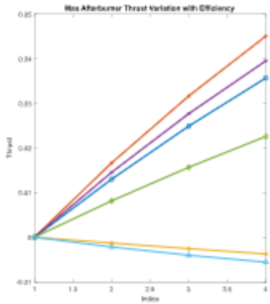

Fig. 8. Sensitivity of max afterburner thrust towards efficiencies

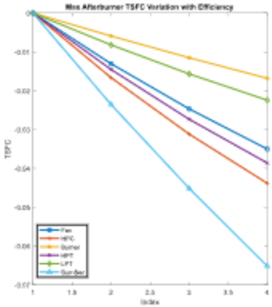

Fig. 9. Sensitivity of max afterburner TSFC towards efficiencies

Similar trends can be observed in afterburner operation with the additional burner behaving in a similar manner to the primary burner. The behavior of all components is as expected i.e. with increasing efficiency the specific fuel consumption falls while the thrust increases linearly over the range tested, except for burner due to reasons discussed previously. These results can be seen in Fig 8-9 and Table V.

TABLE V. SENSITIVITY OF AFTERBURNER PERFORMANCE TO COMPONENT EFFICIENCIES

Component	TSFC	Thrust
Fan	-0.4405	0.4521
High Pressure Compressor	-0.5515	0.5711
Burner	-0.2159	-0.0434
High Pressure Turbine	-0.4859	0.5009
Low Pressure Turbine	-0.2823	0.2863
Afterburner	-0.7815	-0.0540

V. FUTURE WORK

The assumptions considered during this analysis were a product of topic at hand and the accuracy of the results required. However, further improvements in the engine model within 1-D analysis, can be made by considering the variability of performance of the compressor under different flight conditions where the actual performance departs significantly from the map results, this may be due to change in geometry structural or thermal load, for which new maps would be required. Similarly, combustion maps could be used instead of constant pressure loss, to determine the performance of the combustion chamber under varying flight conditions and variable geometries (resulting from the change in temperatures and pressures within the chamber), which may result in ranges of combustion efficiencies rather than the conservative constant value considered in this study.

The design point of the analysis can be deviated from static sea level which will result in different values of performance parameters, though the trends of the sensitivity analysis should not differ by changing the design point.

The transient analysis of the cycle can be performed in future to further elaborate the performance variation with time. In this study, however flow through each component and the analysis is carried out in steady state.

VI. CONCLUSION:

With the growing demand of high power output coupled with low carbon emissions, the need of development of sophisticated gas turbine cycles is increasing. The development and prototyping of new engine cycles is extremely expensive and time consuming process, therefore mathematical and numerical alternatives are being employed by the aerospace industry for performance evaluation of engine cycles. In this paper the effect of variation of engine design parameters and component efficiencies on the performance parameters of a low bypass turbofan engine were presented using NPSS.

The results suggest that the thrust and TSFC in military operation of engine is most sensitive towards the exit temperature of primary burner. While in after-burner operation, the thrust of engine is a strong function of the primary burner's exit temperature, however TSFC is most affected by the secondary burner's exit temperature because of the lower efficiency with which the secondary combustor operates.

The results of sensitivity analysis of engine component efficiency suggest that the military thrust is a strong function of high pressure compressor efficiency and military TSFC is dependent strongly upon the combustion efficiency of the primary burner. While in after-burner operation, the efficiency of high pressure compressor affects the thrust the most, and TSFC is affected substantially by efficiency of secondary burner.

In this study, the dependencies of engine components and design parameters were studied and reasons for these behaviors were presented. Such analyses highlight the operation of the engines as a whole in terms of specific components and thus can be used for academic as well as professional purposes.

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