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Analytical Modelling and Validation of a Turbofan Engine at Design Conditions

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In this paper an analytical model designed for a low-bypass turbofan engine (RD-93) at static sea level conditions and its validation with available data by manufacturer has been presented. Due to military confidentiality, comprehensive engine performance data of fighter aircraft engines at different operating conditions is not available with its users. Hence, it is impossible to ascertain certain flow parameters such as pressure and temperature at different engine stations or propose any design modification in existing engine design. A unique approach of thrust matching technique is employed to develop a model which could provide engine characteristic data at all operating conditions. A comprehensive scheme has been developed for modelling and simulation of engine using different analytical methods along with various software packages such as ONX®, PERF®, and GasTurb®. Several validation cases were tested and results were compared with actual engine performance data provided by Original Equipment Manufacturer (OEM). The results obtained agree well with the OEM data and the current available literature. This research forms an integral part of an already conducted and published study by the same author for characterization of exhaust effects on aerodynamic behavior of a supersonic aircraft. The developed analytical model can further be used in proposing design modification / improvements in the engine under study. Also, the approach developed here is equally applicable to various turbofan engines used in fighter aircraft where comprehensive engine performance data is not available with users.

Nomenclature

AB	=	Afterburner
AOA	=	Angle of Attack
BPR	=	Bypass ratio
FPR	=	Fan's pressure-ratio
HPC	=	High-pressure compressor
HPT	=	High-pressure turbine
LPT	=	Low-pressure turbine
OEM	=	Orignial Equipment Manufacturer
P	=	Static Pressure
TSFC	=	Thrust Specific Fuel Consumption

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I. Introduction

Propulsion system of an aircraft is directly responsible for aircraft performance under different flight conditions. Historically, design and testing of propulsion system initiated much before aircraft design due to its criticality. Some of the major design considerations of engines are reliability, durability and flight performance [1]. The development process of engine systems starts before aircraft production as well, hence, successful design of engine become more vital [1]. The technological advancements supported by improved materials, strong structures and new manufacturing techniques have resulted in much better and reliable aero engines which can operate on a vast flight envelope. Furthermore, these improvements have enhanced compressor design pressure ratio, turbine inlet temperature, exhaust jet velocity and overall fuel efficient engines. In the present study, a low bypass turbofan engine RD-93 is studied to develop its analytical model for its application in different research studies.

RD-93 engine is a low bypass turbofan engine with a high thrust to weight ratio. The engine is a light weight turbofan engine which is being used for fighter aircraft (shown in Fig 1). Generally, it is an upgrade variant of originally built RD-33 engine developed by OKB-117 in 1981 [2]. The engine has an excellent flow stability which counters flow disturbances efficiently and in turn helps in better control of aircraft. The engine also offers high rate of thrust and aircraft acceleration which is essentially required for modern fighter aircraft [3].

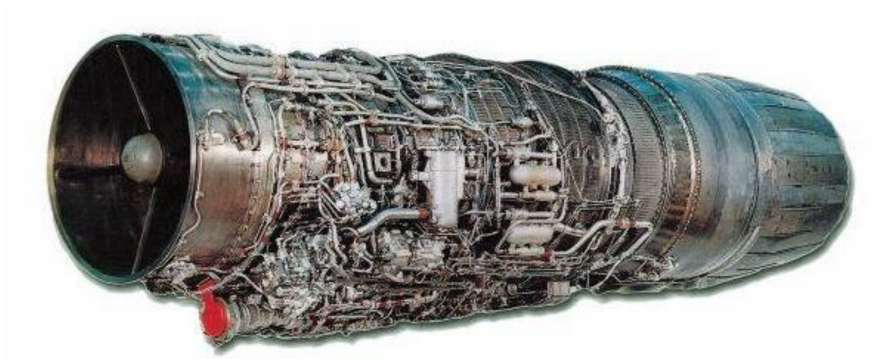

Figure 1. RD-93 TurboFan Engine

The basic aim of designing analytical model of RD-93 is to ascertain certain parameters required for integration of exhaust nozzle in numerical analysis of aircraft [4]. The analysis was carried out at design operating conditions. Thrust matching technique was employed for validation of model for further utility in carrying out numerical analysis of exhaust nozzle with aircraft integration. A comprehensive scheme was developed in accordance with Aircraft Engine Design literature and using software package ONX® and PERF®.

II. Utilization of RD-93 Analytical Model

This work forms an integral part of a study conducted by the same author for characterization of exhaust effects on aerodynamic behavior of a supersonic aircraft [4]. In order to integrate the propulsion system and exhaust nozzle with baseline aircraft for numerical analysis, it was important to ascertain different engine parameters at all flight conditions. Calculation and finalization of boundary conditions is considered one of the most critical step in numerical analysis. Input conditions for intake, exhaust and aircraft are required for each flight condition in order to carry out accurate numerical analysis. It is important to mention that calculation of exhaust nozzle boundary conditions is quite complex and cumbersome as it requires complete details of propulsion system (RD-93). For this purpose, mathematical modelling for RD-93 engine was carried out to ascertain the exhaust nozzle boundary conditions (pressure, temperature, pressure ration etc) at different flow conditions. The designed analytical model can further be utilized in similar studies or proposing any design changes in existing engine.

III. Methodology

For development of analytical model of RD-93 engine, a detailed methodology was devised. Review of literature was carried out as an initial step which included study on different analytical models, detailed turbofan engine characteristics including RD-93, and review of available software and their limitations. The next step is the selection of software package and calculation / estimation of input parameters required for designing the analytical model. This step is one of the most challenging task in designing an analytical model of a military aircraft engine due to military confidentiality and non-availability of individual component performance and efficiency data. The data is extracted using different schemes for each component and are discussed in detail in subsequent sections. The next step is calculation of engine design and off design mass flow rate. Usually, engine design and off design mass flow rate at different flight conditions is not available in technical manuals. However, for RD-93, engine mass flow operating line in accordance with flight speeds was available from OEM data. Engine performance parameters such as thrust, fuel consumption and exit velocity are calculated in the next step. The results are compared with available thrust data. Difference in calculated and actual results are further refined by varying individual component efficiencies and verifying the results at different design and off design conditions. Detailed flow chart of methodology adopted for this research is shown in Fig 2 below:

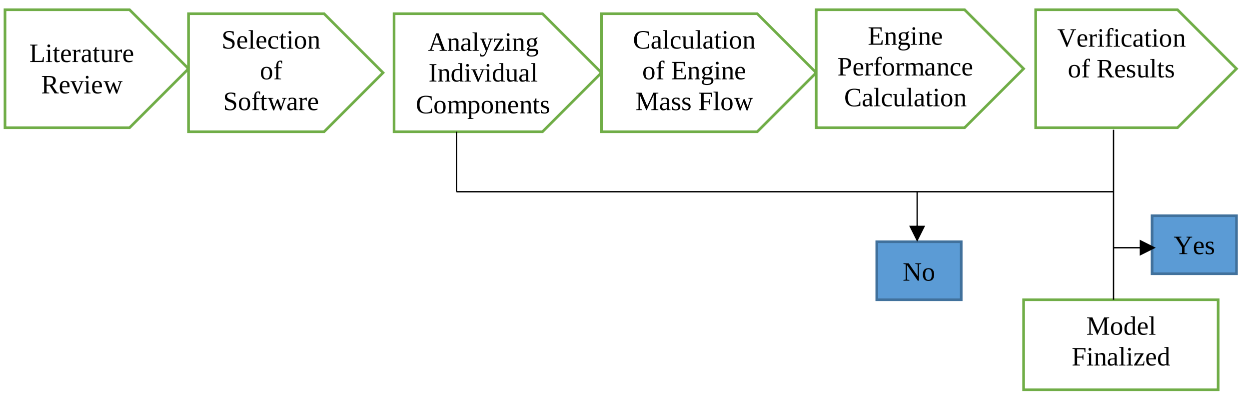

Figure 2. Methodology Flow Chart

IV. Analytical Modeling

RD-93 is a dual-duct, dual-rotator turbofan engine, which has an afterburner shared by inner/outer channel and a fully adjustable supersonic nozzle. It comprises electronic hydro-mechanical fuel control system, lubricating / ventilating system, starting system and parameter-monitoring system, etc. Analytical modeling of engine under study is based on thermodynamic cycle analysis for a typical turbofan engine with afterburner. The analytical model is initially designed at design conditions for baseline model and validated with OEM data.

The tools used for thermodynamic analysis during this research are ONX® and PERF® which is designed by J. Mattingly [5]. The data inputs for RD-93 engine components were ascertained from available technical manual and real time engine operations. Due to unavailability of exact engine parameters at some engine stations, general trends and available literature was consulted for certain inputs, such as components efficiencies. The obtained results are then further improved by iteration of assumed parameters in order to design an analytical model that can predict the engine performance of RD-93 turbofan engine at every condition. Layout of a typical turbofan engine is shown in Fig 3.

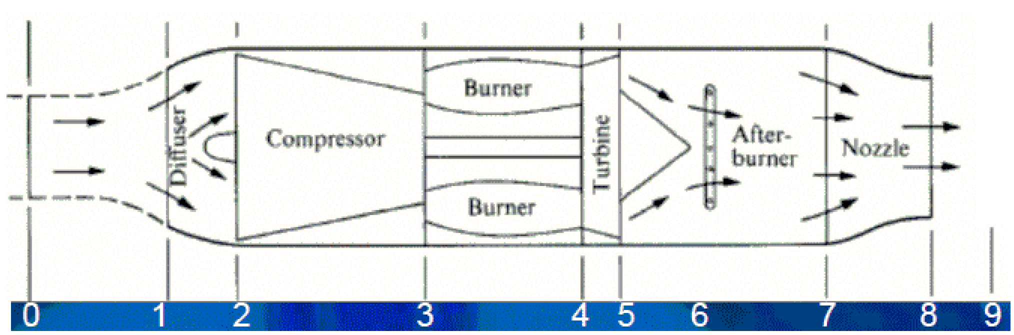

Figure 3. Cutaway of a Typical Turbofan Engine with Mixed Flow Afterburner

A. Overview of RD-93 Engine

Engine under study is a low bypass turbofan engine with an inlet fan with variable guide vanes, three stage low pressure compressor (LPC) and nine stage high pressure compressor (HPC). The air from compressor is extracted for different purposes including environmental control system, cooling of turbine blades etc. During the analytical modelling, the compressor assembly was divided into two parts to differentiate low pressure compressor and high pressure characteristics. The air, after passing through the inlet device and being compressed in the fan is divided in the support housing into dual flow and is directed to the bypass and main ducts. The air supplied to the main duct is compressed additionally in the high-pressure compressor and after this it is forwarded to the combustion chamber. The air supplied to the bypass duct is supplied to the afterburner and to the exhaust nozzle. The compressed air is subjected to combustion in annular combustor. The chemical reactions involved during combustion process is treated as ideal with temperature dependent enthalpies and specific heats. Fuel properties of JP-8 are used and combustion is considered to be complete without any fuel dissociation. RD-93 operates afterburner based on mixed flow exhaust. The bypass air also helps in cooling of afterburner duct which ultimately reduces infra-red signatures. Therefore, characteristics of mixed exhaust nozzle were applied during analytical modelling to accurately predict the exhaust nozzle flow.

B. ONX® and PERF®

ONX ® and Perf ® are engine design and analysis software packages developed by J. Mattingly and are frequently used in educational institutes and mechanical industry [5]. The software can be effectively used to design and analyze aircraft engines for both design and off design conditions.

C. General Assumptions

Some of the considerations and assumptions made during engine simulations [6] were as follows:

1) All calculations were made at sea level conditions

2) The pressure ratio of high pressure compressor and low pressure compressor were already known and used for simulations

3) Combustion chamber pressure losses are not dependent on turbine's characteristics

4) Total pressure loss at combustion process is quite low

5) Efficiencies of combustion chamber and afterburner are constant for all operations

V. Initial Baseline Model of Engine

A. General Characteristics

General characteristics of RD-93 engine were obtained from its available technical manuals. For accurate analytical modelling, the compressor pressure ratio and bypass ratio of engine were fixed at 21 and 0.49 respectively. The fan pressure ratio was kept for optimum configuration according to thrust setting. Turbine inlet temperature (TET) was known from its technical manual and was kept at a reasonable temperature range according to material limitations. Engine design mass flow rate at different flight conditions is generally not available in technical manuals. However, for RD-93, engine mass flow operating line in accordance with flight speeds was available form OEM data. The availability of mass flow rate significantly enhanced the accuracy of analytical model and reduced the percentage error in calculated result. Some of the general characteristics used for current research is shown in Table 1 below:-

Table 1. General Characteristics of RD-93 Engine

S No	Parameter	Value
1	Dry Weight	1055 kg
2	Hi Compressor Pressure Ratio	7:1
3	Low Compressor Pressure Ratio	3:1
4	By Pass Ratio	0.49
5	Turbine Inlet Temperature	>1600 K

B. Mass Flow Rate Estimation

Engine design mass flow rate at different flight conditions is generally unknown in engine technical manuals due to design confidentiality. Due to this limitation, researchers use average mass flow rate or predict / estimate mass flow rates based on generic trends [6]. However, for RD-93 engine, Wind tunnel test data was available with the authors which proved to be quite essential in overall accuracy of analytical model [4, 7]. The available data was in the form of non-dimensional parameter ($m_{act}/m_{theoretical}$) for each flight speed and altitude [4]. The operating line at Mach No 0.6 is shown in Fig 4 below.

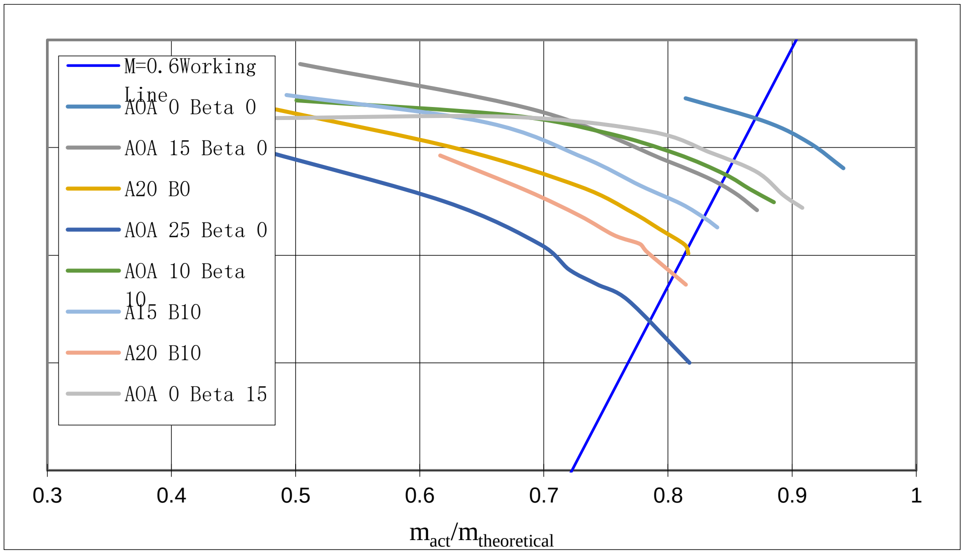

Figure 4. Mass Flow Rate Operating Line at Mach No 0.6

C. Characteristics of Major Components

Details of input considerations for different components of RD-93 engine are presented below:-

1) Intake: The inlet mass flow rates and diffuser parameters were already known from OEM data. Hence, a reliable input was obtained for analytical modelling. Alternatively, pressure recovery was also calculated using following expression:

$$\eta 1 = 1.0 \quad \text{if M} < 1 \tag{1}$$

$$\eta 1 = 1.0 - 0.075 * [(\text{M} - 1)^{1.35}] \quad \text{if M} < 1 \tag{2}$$

2) Compressor: Isentropic efficiency of fan under full after burner condition was considered for analytical model. Pressure ratio for high pressure compressor and low pressure compressor was also known from OEM data. The final temperature of the compressor is calculated from the equation [5]:

$$T_{exit} = T_{in}\left\{1 + \frac{\left(\frac{P_{exit}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{comp}}\right\} \tag{3}$$

3) Combustion Chamber: The annular combustor of RD-93 has specific combustion efficiency which was already known from OEM data. The maximum temperature inside combustion chamber depends upon the type of material and type of combustor. A combustor efficiency of 96% was selected for the analytical model based on the data available in literature on similar type of combustor in turbo fan engine [8, 9].

4) Turbine: For high pressure turbine, the efficiency was selected as 89% and for low pressure turbine an efficiency of 91% was selected for analysis. These efficiencies were based on similar type of engines with similar turbine configuration [5, 10]. Standard cooling parameters were selected for turbine stages as the cooling air is drawn from high pressure compressor for this purpose. The final temperature at turbine exit can be estimated by[5]:

$$T_{exit} = T_{in} * \left\{ 1 - \eta_{turb} * \left[1 - \frac{1}{\left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}}} \right] \right\} \tag{4}$$

5) Afterburner: The performance of afterburner is directly related to the combustion efficiency, temperature limits and pressure losses inside afterburner section. The combustion efficiency of afterburner is generally lower than combustor due to presence of low pressure gases. For this reason, an efficiency of 91% was selected for AB section [5, 11]. The pressure loss is further divided into cold losses and hot losses. The cold loss across afterburner is considered as 5% while the hot loss is considered as 8% of inlet total pressure [12]. The temperature of gases at afterburner exit (nozzle inlet) was cautiously selected keeping in view the material limitations and other engine limitations. Hence, a temperature of 2000K to 2200K was selected for different flow conditions. The specific thrust of the engine was calculated by [5]:

$$\frac{F}{\dot{m}} = \frac{a_o}{g_c} \left[\left(1 + f + f_{AB}\right) \frac{V_9}{a_0} - M_0 + \left(1 + f + f_{AB}\right) * \frac{R_{AB}}{R_c} \frac{T_9}{V_9} \frac{a_0}{T_0} \frac{1 - \frac{P_0}{P_9}}{\gamma} \right] \tag{5}$$

6) Mechanical Losses: The presence of mechanical and thermal losses cannot be neglected in engine analysis. The mechanical losses in power shaft connecting turbine to compressor for turbofan engine can be upto 2-5% which includes losses due to bearings, windage, pumps etc [13, 14]. Although the percent mechanical loss is different for each engine but they can be approximated by the size and type of engine. The mechanical losses are much greater in large engine which are operated by large connecting shafts and gear systems. In military type small engines, these mechanical losses are relatively less due to its small size, but on the other hand military engines are subjected to extreme operating conditions and requirements which can increase the mechanical losses as well. For twin spool engines, the shaft mechanical loss is high and due to high number of compressor stages the windage loss also increases. Hence, for RD-93 engine, the mechanical loss for low pressure compressor is taken as 4% and for high pressure compressor as 3% [13]. For other components, an average of 3% mechanical loss is selected [14, 15].

Individual component efficiencies selected for baseline analytical model is shown in Table 2:

Table 2: RD-93 Engine Components Characteristics

S No	Parameters	Value
1	Fan Efficiency	86%
2	High Pressure Compressor	90%
3	Low Pressure Compressor	88%
4	Combustor	96%
5	High Pressure Turbine	89%
6	Low Pressure Turbine	91%
7	Afterburner	91%
8	Fuel Heating Value	41868 KJ/kg

VI. Performance Prediction of Initial Baseline Analytical Model

The engine performance parameters including dry and wet thrust were calculated using the parameters as mentioned in above sections and were compared with OEM available data. Thrust matching technique was basically used for validation of model, however, thrust specific fuel consumption (TSFC) was also calculated for performance estimation. Due to military confidentiality of RD-93 engine data, only thrust magnitude is presented, while TSFC is not presented in this paper. The calculated values of dry thrust and wet thrust at sea level at different Mach No were compared with OEM available data and are shown in Fig 5 and 6.

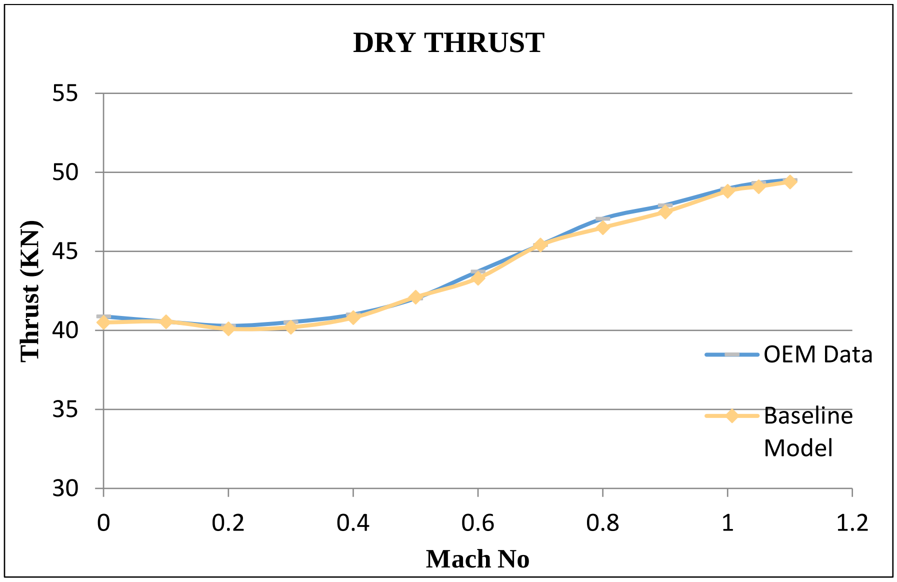

Figure 5. Dry Thrust Comparison of Baseline Model

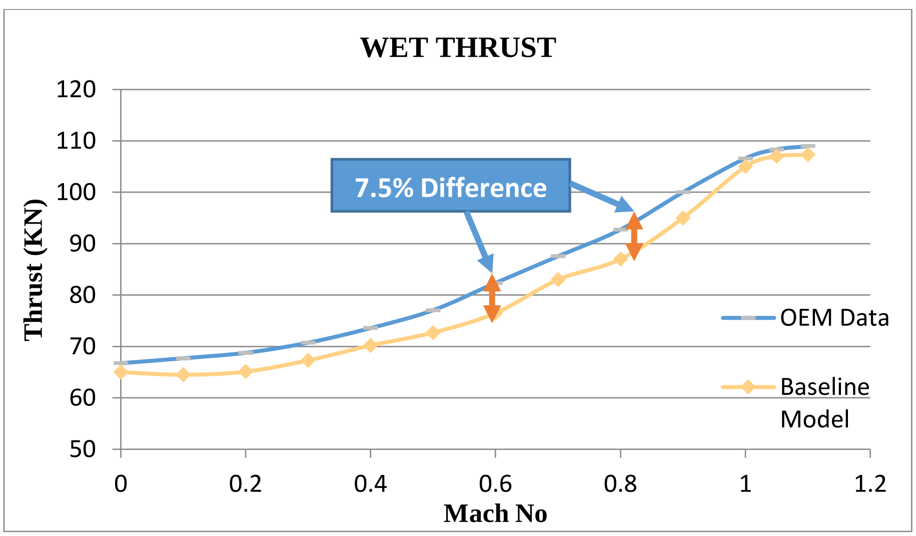

Figure 6. Wet Thrust Comparison of Baseline model

From the above Fig., it can be observed that the values of dry thrust at different Mach No is similar to that of OEM data at all flight speeds. An average of 2% difference is observed between the calculated results and OEM data. However, the difference is much prominent at Afterburner mode. A maximum difference of 7.5% was observed between the calculated and OEM data. Also, the difference in magnitude is significant at subsonic speeds and reduces at supersonic speed. Hence, a refinement in analytical model was required to match engine thrust at both low and high speeds with afterburner operation.

VII. Modifications in Baseline Analytical Model for Better Performance Prediction

In order to further refine the baseline model of RD-93 engine, the component efficiencies and other parameters were refined and their effects on thrust and TSFC were observed. However, slight change in compressor, combustor and turbine efficiencies did not result in any significant change in wet thrust due to involvement of afterburner module. Since the difference in results were mainly observed in AB mode, it was evident that the efficiency, maximum temperature or cooling requirements would play a vital role in modifying the engine wet thrust. Therefore, it was imperative to refine the AB module characteristics to achieve the results which matches with OEM data. Literature on gas turbine engines [12, 16] revealed that AB can enhance engine thrust by 50% but also result in much higher fuel consumption. Similarly for RD-93 engine, use of after burner significantly increases the engine thrust but at the same time increase the fuel consumption as well. Hence, it was evident that the difference in thrust at AB mode obtained by analytical model can be reduced by adjusting the AB module temperatures. Since the temperatures at AB duct can reach upto maximum design limit, therefore it was not feasible to reduce the cooling flow requirements of AB module. Since, the fuel flow rate during AB operation is high along with air flow rate, the volume flow requirement at sea level is easily met. Hence, the AB combustor efficiency can be increased which would further enhance the engine wet thrust. For this purpose, the efficiency of afterburner was increased from 91% to 93% and the temperature limit was kept at maximum i.e 2200K. Engine thrust was calculated again with refined model and results are shown in Fig 7 and 8.

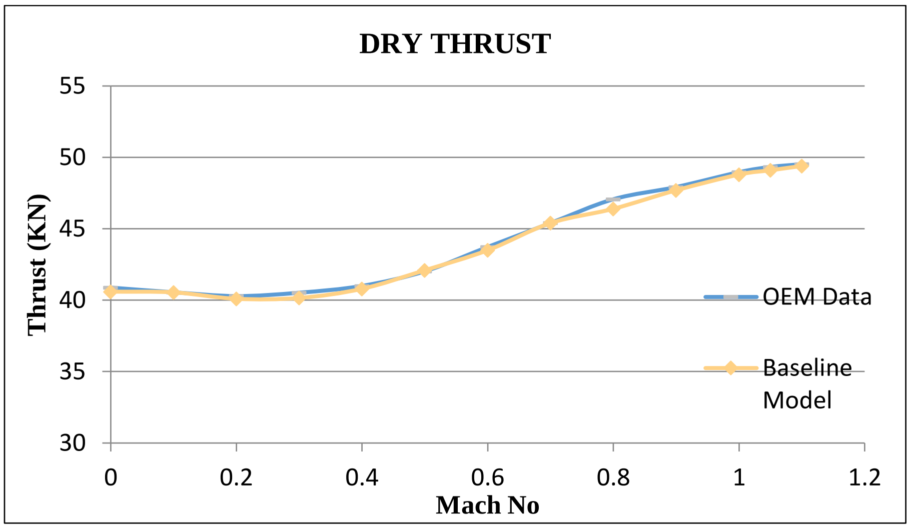

Figure 7. Dry Thrust Comparison of Refined Model

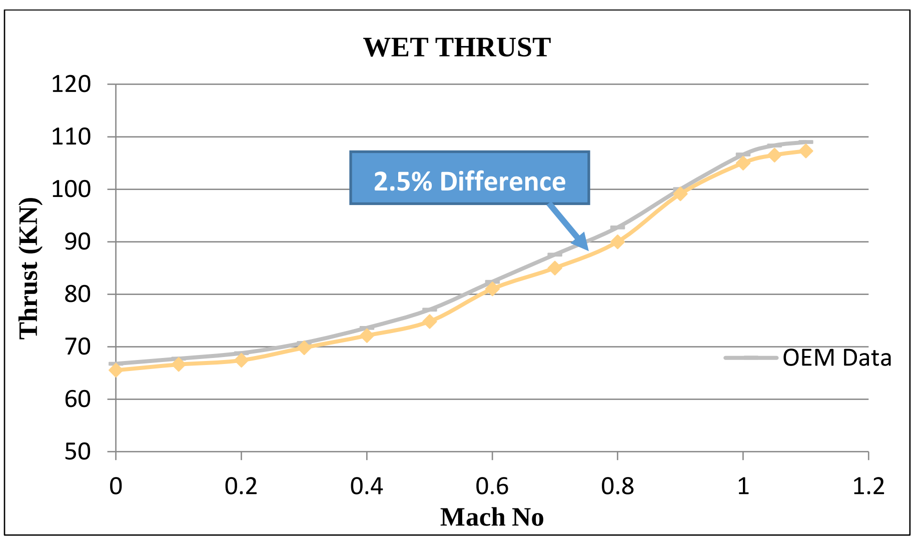

Figure 5. Dry Thrust Comparison of Refined Model

From the above graphs, it can be observed that the dry thrust is not much affected with the changes in baseline model, and the difference in wet thrust is significantly reduced to 2.5%. Hence the refined model provided optimum results at both subsonic and supersonic speed for both dry and wet thrust mode.

VIII. Conclusion

Analytical model of RD-93 engine was successfully designed and verified with OEM available data. The designed model is capable of calculating engine dry and wet thrust and TSFC over a wide range of flight conditions within 2.5% accuracy of manufacturer's data on thrust. The verified model was successfully utilized to obtain boundary conditions for numerical analysis of aircraft with exhaust nozzle [4]. The results obtained from numerical analysis were also validated with Wind Tunnel Data which further verified the accuracy and validitiy of the analytical model developed in this study.

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