AIAA SciTech Forum
11–15 & 19–21 January 2021, VIRTUAL EVENT
AIAA Scitech 2021 Forum
10.2514/6.2021-0279

Performance and Stability Analysis of a High Speed Jet using Multi-Disciplinary Approach

S. Salamat[1], I.Arif[2] and H. Raza[3]
[1]*Department of Aerospace Engineering, College of Aeronautical Engineering, National University of Sciences and Technology, Islamabad, Pakistan*

[2]*Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong*

[3]*Department of Mechanical Engineering, Auburn University, Alabama, USA*

In this paper the performance and stability characteristics of a high-speed jet using a multi-disciplinary approach involving advanced analysis tools including Advanced Aircraft Analysis®, aircraft technical manuals, historical trends, empirical relations, regression analysis, CAD software, C++ program, and XFLR® is presented. A unique methodology has been developed by combining and associating these multi-disciplinary tools to analyze the aerodynamic characteristics of a multi-role modern jet aircraft. Initially, a wide range of aircraft characteristics related to its geometry, structure, propulsion system, and weight configurations have been evaluated/identified as the input for the aerodynamic analysis. A methodology is also developed for the classification of airfoil at different wing sections based on the similarity index using C++. The preliminary aerodynamic results are validated by available flight manuals and wind tunnel data for verification of the developed scheme. Subsequently, a detailed aerodynamic, structural, stability (static and dynamic) analysis is carried out to identify all the performance parameters and unknown design variables. The developed scheme using a multi-disciplinary approach can not only provide the detailed characteristics of an existing aircraft but can also be used for further modifications in the aircraft.

I. Introduction

Aircraft are complex machines that are based on the optimum design to perform its desired role and tasks efficiently[1, 2]. Hence, the design process is initiated well before the prototype testing of aircraft. In order to enhance or upgrade the design/performance features of an existing aircraft, it's all geometric, aerodynamics and structural aspects are required to be known to the aerospace engineers. However, due to the confidentiality of aircraft design process, engineers have limited access to complete aircraft performance profiles [3]. Although a well-defined aircraft design and analysis methodology is available in the literature [4, 5], these methods consider some important features relying on historical trends or estimates. Hence, the uncertainty in their applicability still prevails. In order to overcome these limitations, aircraft performance and stability analysis methodology is designed based on a multi-disciplinary approach that involves different advanced tools based on their strengths and applicability. The method could be applied for the analysis of any existing aircraft so that any design modification can be proposed.

For this research, a conventional multirole fighter aircraft is analyzed for calculation of its static/dynamic stability and performance parameters. The scope of this research encompasses computation of aircraft performance parameters such as coefficient of lift, lift curve slope, drag polar, rate of climb, and other performance parameters. The static and

---

[1] Associate Professor, Department of Aerospace Engg, College of Aeronautical Engineering, National University of Science and Technology, H-12 Islamabad, Pakistan.
[2] PhD Researcher, Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong.
[3] PhD Researcher, Department of Mechanical Engineering, Auburn University, Alabama, USA.

dynamic stability characteristics of the aircraft are also analyzed using the design method. The designed approach is validated with available wind tunnel data and flight manuals for verification of the developed scheme.

II. Research Methodology

A comprehensive research framework is designed for the current research as it involves multi-disciplinary tools for the required analysis. One of the most demanding and challenging phases of the research is the identification/estimation / calculation of accurate input parameters for aerodynamic analysis. These inputs are related to aircraft geometrical parameters, weights, propulsion system, etc. For this purpose, data extraction is carried out using the flight / technical manuals, verified aircraft CAD model [6, 7], literature review, and other programming tools such as C++, Matlab®, etc. A methodology is also developed to classify airfoil at different wing and tail sections with the available online databases. Once the initial inputs are ascertained and verified with available Wind Tunnel Testing (WTT) data [6, 8] and literature [9-11], aircraft aerodynamic performance and stability analysis are evaluated using Advanced Aircraft Analysis® [5]. The designed methodology adopted in this research is shown in Figure 1.

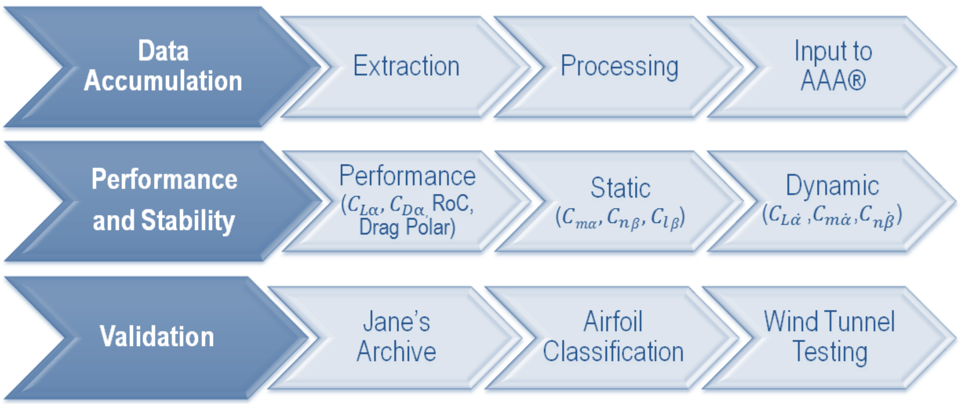

Figure 1. Methodology for Research

III. Input Parameters

The input parameters are initially categorized into four major domains such as aircraft geometric inputs, weight inputs, propulsion system inputs, and structural inputs. Approximately 300 parameters are evaluated/identified based on these domains for subsequent aircraft aerodynamic / performance and stability analysis. Details of inputs identified for each domain are presented below:

A. Geometric Inputs

The inputs related to geometric features require in-depth details of airfoils at different wing and tail sections. Furthermore, geometric details of fins, fuselage, and landing gear are also required. Therefore, the geometric parameters are acquired mainly from technical manuals, however, due to the non-availability of complete geometric dimensions in OEM technical manuals, few geometric features are extracted from verified CAD model as well [6]. For this purpose, available verified CAD model [6, 8] is utilized to extract coordinates using AutoCAD® and CATIA®. The CAD model used for the extraction of all geometric parameters is shown in Figure 2.

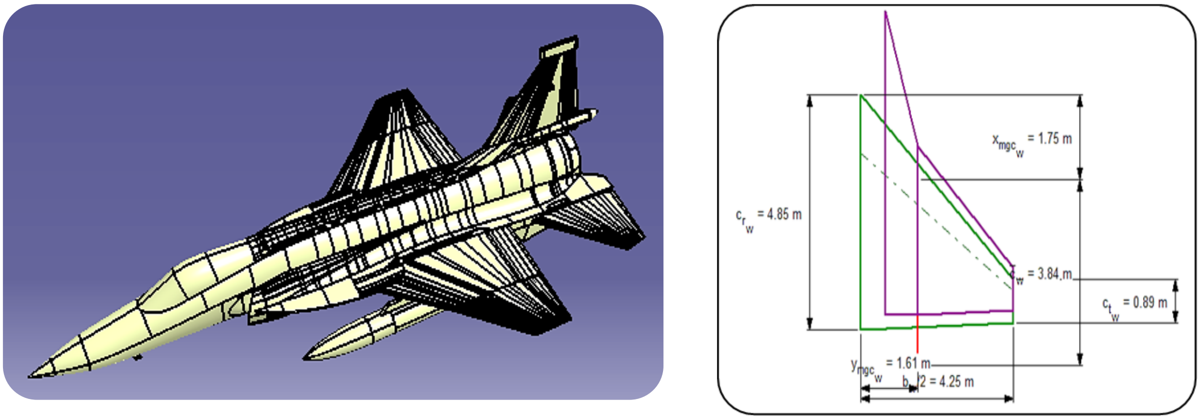

Figure 2. CAD model used to extract coordinates using AutoCAD® and CATIA®

In order to extract accurate external dimensions of the fuselage, 20 sub-stations are generated at prominent locations. Similarly, 05 sub-stations are created on aircraft wings and tails for the same purpose. After providing all the input data of each major component of aircraft, a complete geometry is created (except wingtip launcher) and finalized in AAA®. The complete 3D-view of the aircraft as developed in AAA® (shown in Fig 3) shows good agreement with respect to aircraft external geometric features.

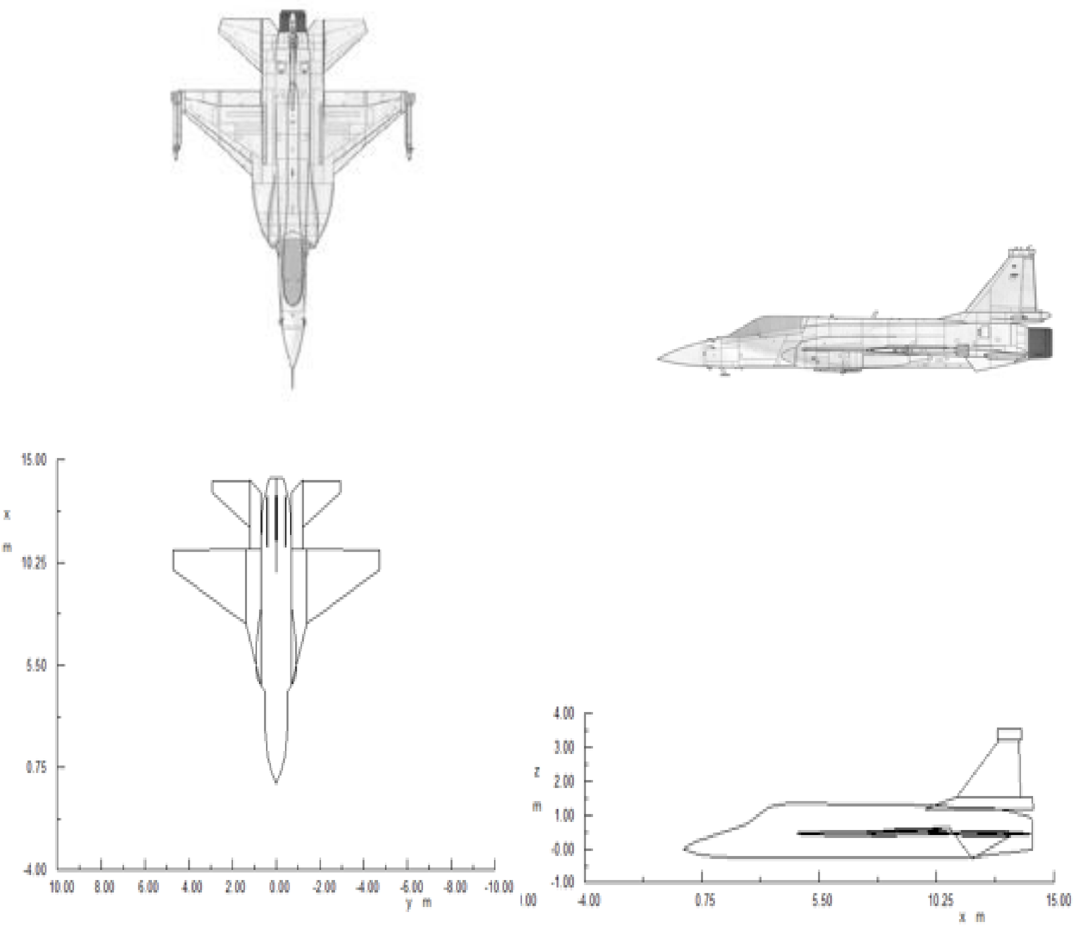

Figure 3. Top and side views of the CAD model of jet aircraft (top row) and developed in AAA® (bottom row)

B. Weight Inputs

Aircraft weight inputs are identified by establishing a generic cruise mission profile for supersonic jet aircraft based on available literature [4]. The selected segments of the mission profile for the calculation of fuel fraction weights are shown in Fig 4. For the cruise segment, design altitude and Mach number are determined from the flight manuals of the aircraft. Each segment of the mission profile is individually analyzed for calculation of mission fuel fraction (MFF) as shown in Table 1. Furthermore, engine operating mode is carefully set at each segment according to the flight manual.

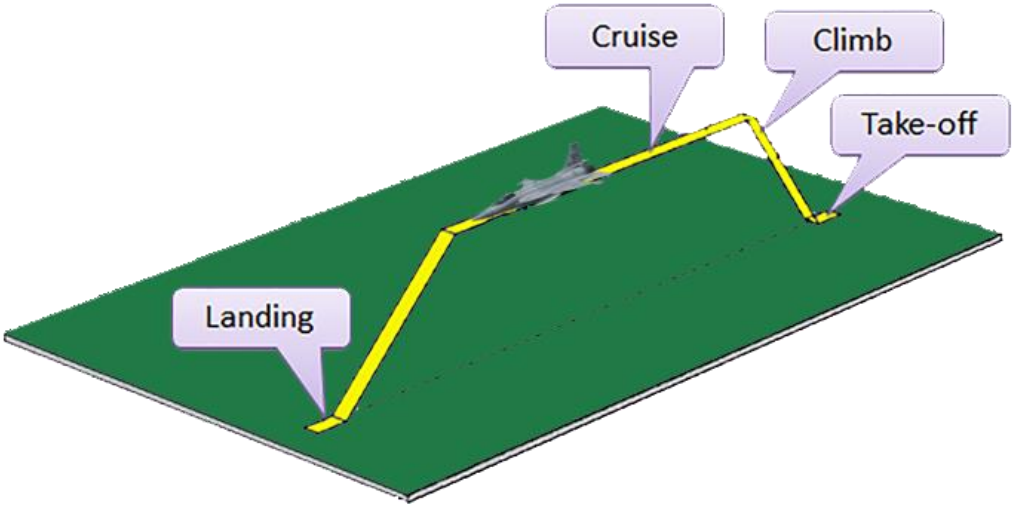

Figure 4. Aircraft Mission Profile

Table 1 Mission Segments

MISSION PHASE	ENGINE MODE	FUEL USED (KG)	MFF
Warm up / Taxi	Idle-Mil	-	-
Acceleration/Take-Off	Max-Mil	370.13	0.99
Climb	Mil	381.01	0.99
Cruise	M=0.82	1340.82	0.78
Landing	-	453.59	0.99

Empty weight and gross take-off weight are analytically calculated using the iterative procedure [4, 12]. The finalized empty (W_E) and take-off (W_{TO}) weights after mission design are given in Table 2. These outputs are further validated with data available in the technical manual. Table 2 shows the calculated weights along with available literature data [10]. A good agreement is observed between the results which validate the current approach to weight estimation.

Table 2 Empty weight and gross take-off weight

PARAMETER	AAA®	REF [10]	DIFF (%AGE)
W_E (N)	62,800	62,900	0.16
W_{TO} (N)	88,000	89,300	1.5

C. Aerodynamic/Structural Inputs

A total of 16 input parameters are identified/evaluated for the aerodynamic/structural domain. Among these inputs, some of the most critical input include prediction of lift curve slope $C_{L\alpha}$ for aircraft wing, horizontal and vertical tail as their corresponding airfoil are unknown. To evaluate $C_{L\alpha_{Wing}}$, both $C_{L\alpha_{root-Wing}}$ and $C_{L\alpha_{tip-Wing}}$ are calculated using Design Foil®. The aspect ratio of the wing is determined from technical manual while taper ratio and quarter chord sweep are both evaluated from the CAD model using CATIA®. Thickness to chord ratio for tip and root airfoil is calculated using XFLR5®. Likewise, several other parameters are also pre-processed by the OEM technical manuals.

D. Propulsion Inputs

The propulsion system is one of the most critical aircraft systems which requires careful consideration in analyzing aircraft performance and stability characteristics. Hence, special emphasis is laid on identifying/evaluating the input parameters related to the propulsion system. The aircraft under study is equipped with RD-93 Turbofan engine. Engine weight and sizing parameters are readily available in OEM manuals, however, the other operational parameters such as components internal temperature and pressure at different operating conditions, engine thrust specific fuel consumption (TSFC), compression ratio, afterburner fuel efficiency, etc are determined from an in-house verified analytical model [13]. The engine on-design and off-design mass flow rates are also determined from OEM manuals, whereas its off-design performance is analyzed through the analytical model. The calculated values of dry thrust and wet thrust at different Mach No are compared with OEM available data and are shown in Fig 5 and 6.

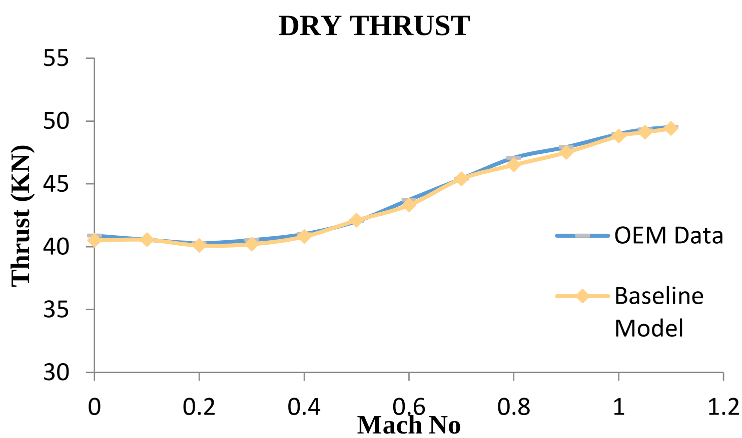

Figure 5. Dry Thrust Comparison of Baseline Model

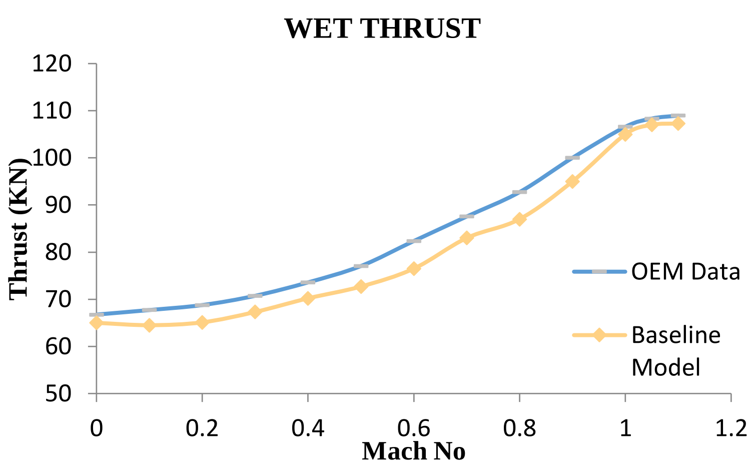

Figure 6. Wet Thrust Comparison of Baseline model

IV. Results and Discussion

Once all the important input characteristics are determined, the aircraft aerodynamic performance and stability characteristics are determined and validated with available data. Salient details of output obtained from the designed methodology are presented in subsequent paragraphs.

A. Aerodynamic Performance

The lift performance ($\boldsymbol{C_{L\alpha}}$) of the aircraft, at the cruise conditions, is shown in Fig 7. Various lift performance parameters such as $\boldsymbol{C_{Lmax}}$, $\boldsymbol{\alpha_{stall}}$ and $\boldsymbol{\alpha_0}$ are also evaluated and listed in Table 3. The $\boldsymbol{C_{Lmax}}$ value for a typical fighter aircraft [14] is also shown as a reference in Table 3.

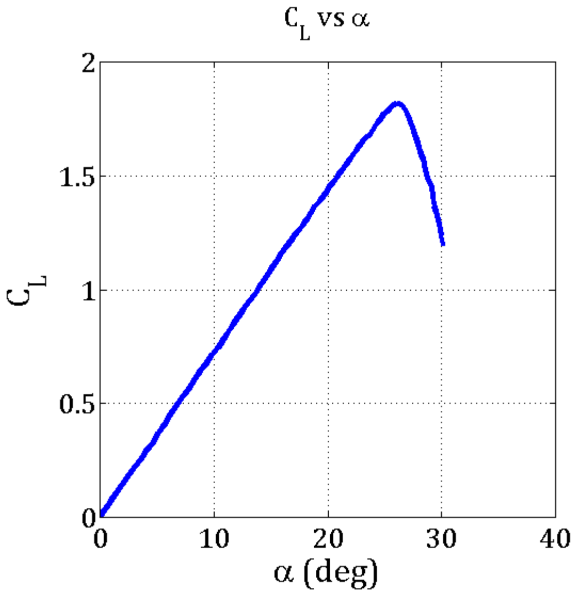

Figure 7. Lift Curve Slope

Table 3 Lift performance at Cruise conditions

Parameter	**Calculated**	**Ref [14]**
$C_{L\alpha}$	0.0633	-
C_{Lmax}	1.81	1.8
α_{max} (deg)	25.1	-
α_0 (deg)	-0.2	-

The drag polar is also calculated for various mission segments according to the aircraft configuration and is shown in Fig 8. Complete aircraft drag is a combination of skin friction drag and pressure drag according to mission segment, where the magnitude of drag of clean aircraft serve as a baseline for other configuration [12]. A typical calculation of zero-lift drag C_{D0} is presented below using Raymer's methodology [14].

$$C_{D0} = \frac{S_{wet}}{S_{ref}} \times C_f \qquad (1)$$

where the ratio of the wetted and reference areas $\frac{S_{wet}}{S_{ref}} = 4$ and friction coefficient $C_f = 0.0038$ [15]. The C_{D0} for clean aircraft is calculated as 0.0144. Similarly, from Fig 8, L/D_{max} and $C_{D\alpha}$ are calculated and compared with available data in literature [14] as shown in Table 4.

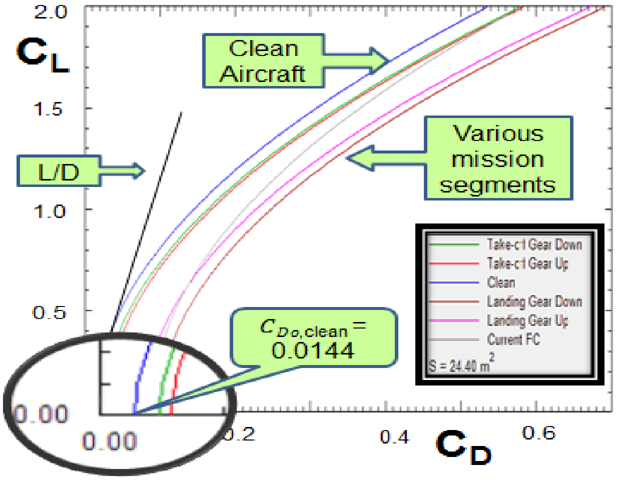

Figure 8. Drag Polar of the aircraft at cruise condition

Table 4 Drag characteristics

Parameter	AAA®	Raymer [14]
$C_{D0_{clean}}$	0.0144	0.0152
$\left(\frac{L}{D}\right)_{max}$	11.5	-
$C_{D\alpha}$	0.0577	0.0625

B. Thrust Performance

Aircraft rate of climb (*ROC*) is considered one of the most important performance parameters [16, 17]. The thrust available (T_A) and thrust required (T_R) at cruise conditions are utilized to estimate the *ROC* of the aircraft. *ROC* is usually calculated by the excess thrust whereas the thrust required vis a vis complete drag of the aircraft for subsequent calculation of *ROC* at cruise condition is obtained analytically using the following analytical relations [5]:

$$T_R = D = \frac{1}{2}\rho_\infty V_\infty^2 S C_D \tag{1}$$

$$D = \frac{1}{2}\rho_\infty V_\infty^2 S C_{D,0} + \frac{2KS}{\rho_\infty V_\infty^2}\left(\frac{W}{S}\right)^2 \tag{2}$$

$$ROC_{max} = \left[\frac{\left(\frac{W}{S}\right)Z}{3\rho_\infty C_{D,0}}\right]^{\frac{1}{2}}\left(\frac{T}{W}\right)^{\frac{3}{2}}\left[1-\frac{Z}{6}-\frac{3}{2\left(\frac{T}{W}\right)^2\left(\frac{L}{D}\right)_{max}^2 Z}\right] \tag{3}$$

where,

$$Z = 1 + \sqrt{1+\frac{3}{\left(\frac{L}{D}\right)_{max}^2\left(\frac{T}{W}\right)^2}} \tag{5}$$

$\left(\frac{W}{S}\right)$ is the wing loading and $\left(\frac{T}{W}\right)$ is the thrust to weight ratio. The thrust required is plotted against velocity at cruise conditions and subsequently compared with analytically calculated results. The difference between thrust required and available thrust at specific cruise conditions, i.e. ROC is plotted against velocity as shown in Fig 9. The difference between the two curves is in close agreement with AAA® results. The maximum ROC computed from AAA® is 24.7 m/s whereas the maximum ROC computed analytically (using $RoC = T_{excess}/Velocity$) is 24.5 m/s.

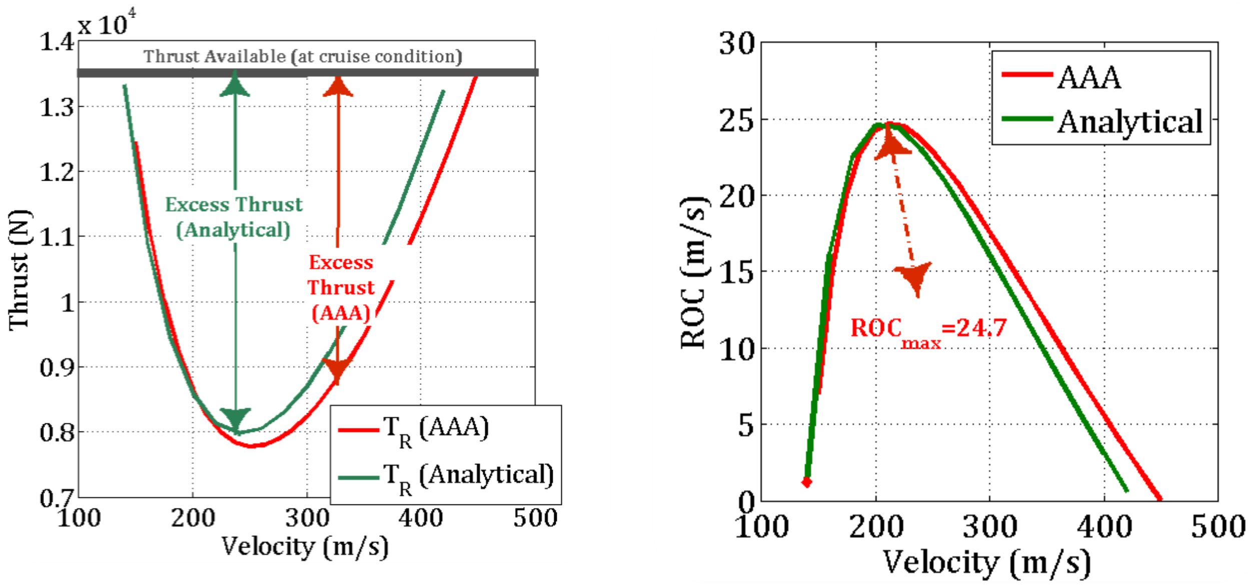

Figure 9. Comparison of Excess Thrust and ROC

C. Range, Take-off, and Landing Performance

Performance parameters such as range (R), take-off (S_{TO}), and landing (S_{LDG}) distances are also calculated using analytical expression [2-4]:

$$R = \frac{2}{c_t}\sqrt{\frac{2}{\rho_\infty}}\frac{C_L^{\frac{1}{2}}}{C_D}\left(W_0^{\frac{1}{2}} - W_1^{\frac{1}{2}}\right) \tag{6}$$

$$S_{TO} = \frac{1.21(\frac{W}{S})}{g\rho_\infty(C_{L\,max})[\frac{T}{W} - \frac{D}{W} - \mu_r\,(1 - L/W)]_{0.7\,V_{LO}}} + 1.1\sqrt{\frac{2}{\rho_\infty}\frac{W}{S}\frac{1}{(C_L)_{max}}} \tag{7}$$

$$S_{LDG} = 1.1\sqrt{\frac{2}{\rho_\infty}\frac{W}{S}\frac{1}{(C_L)_{max}}} + \frac{1.1^2\left(\frac{W}{S}\right)}{(g\rho_\infty(C_L)_{max}\left[\frac{T_{rev}}{W} + \frac{D}{W} + \mu_r\left(1 - \frac{L}{W}\right)\right]_{0.7V_{TD}}} \tag{8}$$

where, c_t is thrust specific fuel consumption, μ_r is the coefficient of rolling friction, V_{LO} is the liftoff velocity, T_{rev} is the absolute magnitude of the reverse thrust, and W_0 and W_1 are the initial and final weights respectively. The calculated parameters are shown in Table 5 along with the comparison with literature [10].

Table 5 Range, Take-off and Landing Performance

PARAMETER	AAA®	REF [10]	DIFF (%AGE)
Range (km)	1927	2037	5.4
TO Distance (m)	310	319	2.8
Landing Distance (m)	762	870	12.4

D. Stability Parameters

Since the performance parameters of the aircraft have been evaluated and are found in good agreement with the literature, the analysis is further extended by analyzing the stability characteristics of the aircraft and the results are compared with the OEM manuals and literature. The analysis of static stability parameters include evaluation of aircraft pitch C_{m_α}, roll C_{n_β}, and yaw C_{n_β} stability as shown in Table 6. The analysis reveals that the aircraft is partially statically unstable in the pitch axis. A positive $C_{N\beta}$ indicates that the aircraft is directionally stable whereas the negative $C_{L\beta}$ indicates lateral stability of the aircraft. The Static Margin of the aircraft is found to be below 5% which depicts that the aircraft is marginally stable with high maneuverability [4].

Table 6 Static Stability parameters of the aircraft

PARAMETER	AAA® OUTPUT	TENDENCY
C_{m_α} (deg^{-1})	- 0. 002	Partial Static Instability
C_{m_0}	- 0. 012	
C_{n_β} (deg^{-1})	0.0002	Stable
C_{l_β} (deg^{-1})	- 0.0132	Stable
$SM\ in\ \%\ of\ x/c$	2.8	Marginal Stable

E. Dynamic Stability Parameters

Dynamic stability parameters are the blueprint of an aircraft's design [18] and could be used to design a realistic flight simulator for the fighter aircraft. Calculation of dynamic stability parameters is not possible through conventional analytical formulae [19]. Hence, AAA® is utilized for the calculation of dynamic stability characteristics of the aircraft. Few of the dynamic stability parameters evaluated in this research are listed in Table 7.

Table 7 Dynamic Stability parameters of the aircraft

PARAMETER	Value	PARAMETER	Value
$C_{L_{\dot\alpha}}$ (deg^{-1})	- 0. 081	$M_{\dot\alpha}$ $(\frac{1}{sec})$	-0.567
$C_{m_{\dot\alpha}}$ (deg^{-1})	- 0. 097	ζ_{SP}	0.665
$C_{n_{\dot\beta}}$ (deg^{-1})	0.0002	$\zeta_{P_{long}}$	0.692
$C_{l_{\dot\beta}}$ (deg^{-1})	- 0.0132	ζ_D	0.259
$C_{y_{\dot\beta}}$ (deg^{-1})	2.8	ζ_α	0.12
$Z_{\dot\alpha}$ $(\frac{m}{sec})$	-0.729	ζ_β	0.08

F. Airfoil Classification

Besides the analysis of performance and stability characteristics, a novel method is developed to identify and classify the airfoil used on the aircraft wing and tails. For the said purpose, AutoCAD® is used to extract the airfoil coordinates from the CAD model of the aircraft. To accomplish this task, a section plane is generated to isolate the wing from required locations, and splines are generated. The random coordinates generated through splines are organized and normalized in a standard format. The extracted root airfoil, mid airfoil, and the tip airfoil can be seen in Fig 10 below.

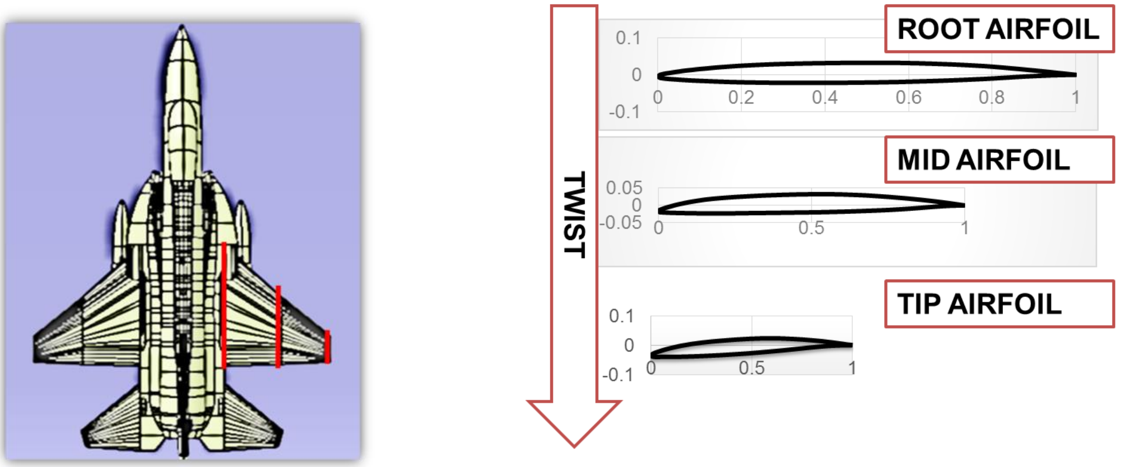

Figure 10. Airfoil classification using AutoCAD®

To identify these airfoils, a C++ program is written based on the similarity index (SI) function which calculates the sum of the differences between the coordinates, and the airfoils with the smallest SI value are obtained. The airfoils are compared with a known comprehensive database, UIUC [20]. The comparison revealed that the aircraft root airfoil is similar to NACA 6-series airfoil 64-206 as shown in Fig 11.

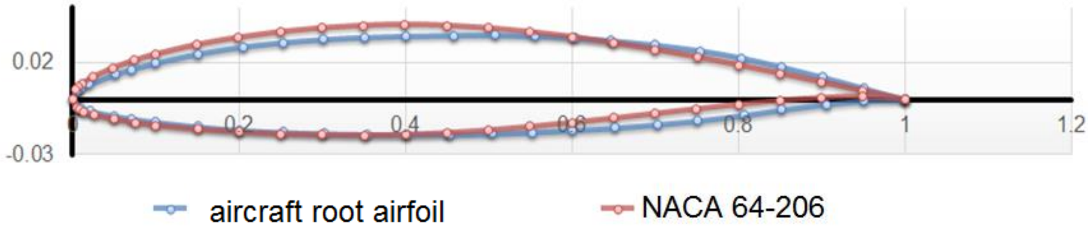

Figure 11. Airfoil classification using AutoCAD®

V. Conclusion

A complete multi-disciplinary approach is developed and tested for analyzing the aerodynamic characteristics of a high-speed jet using analysis tools including AAA®, aircraft technical manuals, historical trends, empirical relations, regression analysis, CAD software, C++ program, and XFLR® is presented. Efforts are made to accurately compute performance and stability parameters for the jet aircraft and validate the results with the available data. Subsequently, a detailed aerodynamic, structural, stability (static and dynamic) analysis is carried out to identify all the performance parameters and unknown design variables. A method to classify the airfoils used on the aircraft wing is also established and presented in this research. The framework using a multi-disciplinary approach can not only provide the detailed characteristics of an existing aircraft but can also be used for further modifications in the aircraft.

Acknowledgments

The authors acknowledge the use of Numerical Analysis Lab (NAL) of the College of Aeronautical Engineering, Risalpur, Pakistan.

References

1. Amadori, K., C. Jouannet, and P. Krus. *A framework for aerodynamic and structural optimization in conceptual design*. in *25th AIAA Applied Aerodynamics Conference*. 2007.
2. Anemaat, W., et al., *A Knowledge-Based Design Framework for Aircraft Conceptual and Preliminary Design.* SAE Transactions, 2006: p. 598-611.
3. Mattingly, J.D., *Aircraft engine design*. 2002: AIAA.
4. Raymer, D., *Aircraft design: a conceptual approach*. 2012: American Institute of Aeronautics and Astronautics, Inc.
5. Roskam, D.J., *Adavnced Aircraft Analysis V3.6*. DAR Corporation.
6. Masud, J., I. Arif, and Z. Toor. *Composite Analysis and Characterization of Exhaust Effects on Aerodynamic Behavior of a Supersonic Aircraft*. in *55th AIAA Aerospace Sciences Meeting*. 2017.
7. Masud, J., O. Khan, and S.M. Hassan. *Intake and Airframe Characterization through Composite CFD*. in *53rd AIAA Aerospace Sciences Meeting*. 2015.
8. Arif, I., J. Masud, and I. Shah, *Computational Analysis of Integrated Engine Exhaust Nozzle on a Supersonic Fighter Aircraft.* Journal of Applied Fluid Mechanics, 2018. **11**(6): p. 1511-1520.
9. Anderson, D., J.C. Tannehill, and R.H. Pletcher, *Computational fluid mechanics and heat transfer*. 2016: Taylor & Francis.
10. Jackson, P., *Jane's All the world Aircraft 2004-2005.* 2016.
11. Cook, M.V., *Flight dynamics principles: a linear systems approach to aircraft stability and control*. 2012: Butterworth-Heinemann.
12. Anderson Jr, J.D., *Fundamentals of aerodynamics*. 2010: Tata McGraw-Hill Education.
13. Arif, I., et al. *Analytical Modelling and Validation of a Turbofan Engine at Design Conditions*. in *AIAA Scitech 2019 Forum*. 2019.
14. Raymer, D.P., *Aircraft Design: A Conceptual Approach and Rds-Student, Software for Aircraft Design, Sizing, and Performance Set (AIAA Education)*. 2006: AIAA (American Institute of Aeronautics & Ast.
15. *Skin Friction Calculation*. Available from: http://adg.stanford.edu/aa241/drag/SkinFrictionCalc.html.
16. Mattingly, J.D., *Elements of propulsion: gas turbines and rockets*. 2006: American Institute of Aeronautics and Astronautics.
17. Sadraey, M.H., *Aircraft design: A systems engineering approach*. 2012: John Wiley & Sons.
18. McCormick, B.W., *Aerodknamics aeronautics and flight.* 1995.
19. Hull, D.G., *Fundamentals of airplane flight mechanics*. Vol. 19. 2007: Springer.
20. RERORT, A.A., *Cooperative Programme on Dynamic Wind Tunnel Experiments for Maneuvering Aircraft.* 1996.