Chapter 2

An Alternative Airfoil Design and Analysis for a Small Commercial Aircraft with Inverse Design Method

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Abstract

Airfoil is one of the most import design criteria in aircraft design. It directly affects the performance and stability against to the air conditions. They have special shapes to perform the pressure differences at the top and bottom edge, making the aircraft to fly stable. However, flow analysis may be performed at different compressible flow regimes, such as subsonic, transonic, supersonic, or hypersonic regimes. So, it is vital to design the airfoil and wings with respect to the operational altitude, stall characteristics and stability criteria.

In this study, the NACA3512 airfoil model has been analysed by using the Raytheon's Beechcraft 1900D commercial aircraft. To do this, its performance parameters have been used for the airfoil performance analysis. In the first part of the analysis, a hybrid methodology to validate the stability results, then they have been used to determine the performance characteristics of the aircraft. During the analysis, satisfactory results have been obtained, however to provide a better stability to the aircraft, novel studies are going to be conducted.

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1. Introduction

Airfoil is the most important element of the aircraft. The main function of airfoil is to generate lift force. For an aircraft, it has also a function to give the direction using flaps, ailerons to control pitching, yawing and rolling. In order to design an airfoil, there are two methods that are Direct Analysis Method and Inverse Analysis Method, widely used. The analyses related with air vehicles aerodynamics have been performed to improve performance and reduce cost of design air vehicle by applying some optimization and analysis methods. The following paragraphs are mentioned previous studies for air vehicles design and aerodynamic analysis.

The aerodynamic analysis using wind tunnel test for unmanned air vehicles (AUVs) wings design were carried out to determine aerodynamic parameters that are lift, drag and pitching moment at low aspect ratio and low Reynolds numbers by Gabriel and Mueller (2004). The other AUV design study was proposed by Shelton et al. (2006). The study demonstrated the performance of active and passive winglets in point of aerodynamics design and the results of methods were compared each other.

In order to increase aerodynamic performance, active and passive flow control methods are applied for air vehicle wings. Zhen et al. (2011) presented passive flow control study for an AUV wings using rectangular, triangular and curve-edge vortex generators (VGs). The results showed that the lift coefficient increased when the VGs were placed at near the separation point on the wing. The active flow control study was proposed to supress the flow separation for a wing using synthetic jet actuators (Amitay et al., 2001).

In the design problem, optimization methods are applied to obtain reasonable results in point of energy efficiency and cost of the designed vehicle. In the aerodynamic design, it is difficult to find high lift conditions for wings due to flow physics and determination of the design parameters. Pehlivanoğlu (2019) proposed optimization study to design high lift system for airfoil using Particle Swarm Optimization (PSO). The inverse design of airfoils was improved using Bezier curve and Vortex elements method was used to perform flow-field analysis (G.S. and Lal, 2018). Barrett et al. (2006) proposed airfoil design using inverse design method and optimization was applied to reduce design parameters. Elliott and Peraire (1997) presented the aerodynamic design by applying optimization and using unstructured mesh for a business jet. Garabedian and McFadden (1982) analysed and designed the supercritical swept wing and improved formula for finding wave drag. One another aerodynamic design study was carried out for two-dimensional transonic airfoil shape and the solution was achieved by combined Newton method and integral boundary layer analysis due to viscous effect (Giles and Drela, 1987). Selig and Maughmer (1992) also presented inverse airfoil design and performed the flow solution using incompressible potential flow with direct integral boundary layer method. Gopalarathnam and Selig (1998) presented multipoint airfoil design using method of two-dimensional panel method. Using control theory, the airfoil design was performed by Jameson and Reuther (1994). The aim of the study was also extended the Euler equations to solve three-dimensional complex shape. Kim et al. (2004) presented design study to obtain high-lift airfoil configuration using three airfoil design variables and the solutions were performed for compressible flow using Reynolds-Average Navier-Stokes (RANS) equations with Spalart-Allmaras turbulence model. It was concluded that the lift coefficient maximized and lift to drag ratio also increased for the two airfoil designs.

The design of morphing airfoil was proposed to perform the topology optimization at supersonic flow and the evolutionary design method was used that it provided the unique topologies for designing bio-inspired aircraft system (Hodson et al., 2019). The similar study related with inverse airfoil design using genetic algorithm with new parameterization shape methods was carried out and the computational time was also reduced by about half (Jahangirian and Shahrokhi, 2009). The study was proposed to design airfoil using inverse airfoil code that is called PROFOIL by Jepson and Gopalarathnam (2005). This formulation can prevent the stall formation by constraining the speed of aircraft and accounting the lift coefficient. Nili-Ahmadabadi et al. (2010) focused on inverse design method for 2D incompressible viscous flow using flexible string algorithm. The improved design algorithm gave reasonable results in point of robustness, and it can be used for commercial flow analysis. Papadimitriou and Giannakoglou (2013) presented aerodynamic design by analysing third-order sensitivity and two-dimensional airfoil shape design was performed to validate it. Poole et al. (2015) also proposed airfoil design using independent design variables of airfoil and performing the metric-based mathematical derivation. Tang et al. (2007) performed the new study to find optimum shape design for airfoil using the adjoint method and a formulation that is derived from game theory. Another inverse design problem was carried out for subsonic and transonic flow regime using Elastic Surface Algorithm and it was observed that the used algorithm was effective for an airfoil design and it also increased the convergence rate (Safari et al., 2014). The study for inverse and direct design problem of transonic airfoil was implemented using multi-objective Genetic Algorithm by Vicini and Quagliarella (1997).

In the previous study, there are few studies performed using DATCOM code that is embedded in MATLAB. In our study, the performance of an aircraft at cruise flight is analysed by using Inverse Analysis Method. During analysis, apart from the analytical methods, the aerodynamic performance of the designed airfoil is compared and proved with numerical methods by using MATLAB and XFLR5 analysis software.

2. Methodology

Aircraft wing design is based on principals such that improved stability, conceptual design criteria and design limitations of the aircraft. Such include the lift (c_L), drag (c_D) and pitching moment (c_M) coefficients, Lift over Drag Ratio (c_L/c_D), stall angle (α), multimodal and vibrational analysis for various loads onto it. The main checkpoints for the aircraft wing design are, the operational altitude (h) and Mach number (M). While airfoil profile directly affects the lift (L) and drag forces (D), it is also important to provide improved stability for the take-off, cruise, and landing flights.

As the first part, aerofoils are designed with droplet model, which represents to the geometry of them. It is important to design their geometry with respect to the detection of lift and drag forces firstly, to perform the flight operations, and then finding the pitching moment coefficient to determine the stability of the aircraft.

According to the droplet model, an aerofoil is the function of position, so the main concepts of aerofoil design are defined and sketched in Figure 1:

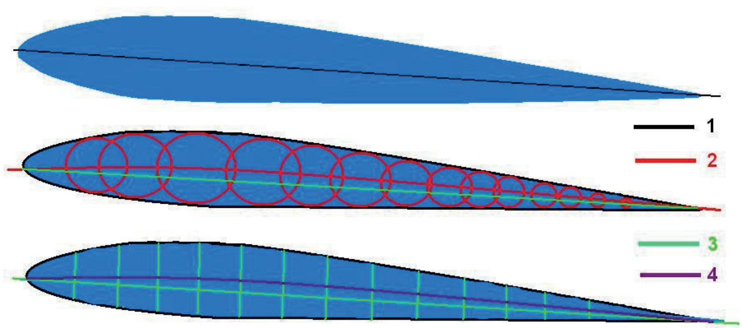

Figure 1: Main Concepts of Aerofoil Design (1: Chord Line, 2: Camber Line, 3: Length, 4: Midline) (NACA airfoil, n.d)

In this study, NACA 4-digit aerofoil model has been used for the aerodynamic design and analysis processes. The meaning of 4 digit is revealed in Figure 2.

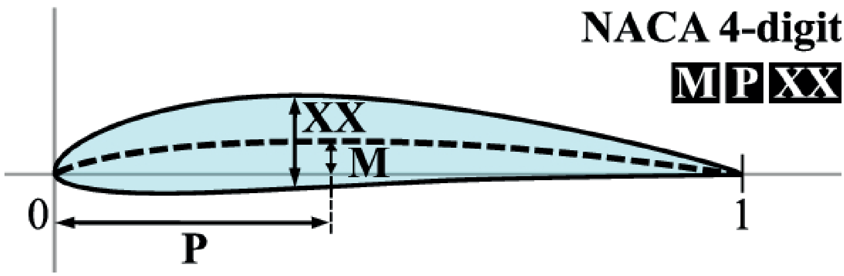

Figure 2: NACA 4-Digit Aerofoil Model Nomenclature (Arias-Rosales and Osorio-Gómez, 2020)

Where,

M: Maximum camber of the hundredths of chord

P: Location of the maximum camber

XX: Maximum thickness in hundredths of chord

According to the model, if the camber line is parallel to the main chord line, then the aerofoil models are considered to be symmetrical. For symmetrical aerofoils, the thickness model is represented in Equation 1.

$$y_t = 5t[0.2969\sqrt{x} - 0.1260x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4] \quad (1)$$

Where

y_t: Vertical Position of the Aerofoil

x: Horiontal Position of the Aerofoil with respect to 0 to 100%

t: Percentage of the Maximum Thickness Value

The leading edge is considered to be a cylinder of a chord-normalized radius of,

$$r = 1.1019t^2 \quad (2)$$

And finally the upper (x_u, y_u) and lower (x_l, y_l) coordinates are represented below as,

$$x_u = x_l = x, \qquad y_u = y_t, \qquad y_l = -y_t \quad (3)$$

For asymmetric (cambered) aerofoils, the position equations become,

$$y = \begin{cases} \frac{m}{p^2}(2px - x^2), & 0 \le x \le p \\ \frac{m}{(1-p)^2}((1-2p) + 2px - x^2), & p \le x \le 1 \end{cases} \quad (4)$$

Where,

m: the Maximum Camberness Ratio

p: the Location of Maximum Camberness

For the cambered aerofoils, the upper and lower coordinates become,

$$x_u = x - y_t \sin(\theta), \qquad y_u = y_c + y_t \cos(\theta), \quad (5)$$

$$x_l = x + y_t \sin(\theta), y_u = y_c - y_t \cos(\theta),$$

Where,

$$\theta = \arctan\left(\frac{dy_c}{dx}\right)$$

$$\frac{dy_c}{dx} = \begin{cases} \frac{2m}{p^2}(p - x), & 0 \le x \le p \\ \frac{2m}{(1-p)^2}(p - x), & p \le x \le 1 \end{cases}$$

(Equation 7)

To detect the aircrafts performance parameters, one can use lift coefficient (c_l) characteristics are inspected with respect to the angle of attack (α). A typical lift coefficient-angle of attack curve is sketched in Figure 3.

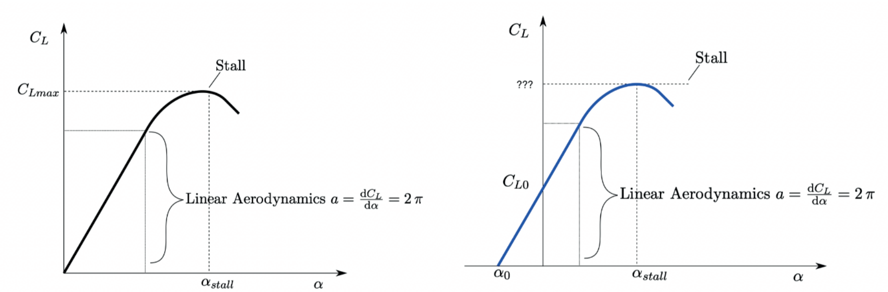

Figure 3: Lift Coefficient-Angle of Attack Curve for Symmetric (Left) and Cambered (Right) (Assumed Knowledge, Retrieved from Aircraft Flight Mechanics by Harry Smith, 2022)

Hence the symmetric curves give 0 lift coefficient for the 0° angle of attack, cambered aerofoils are employed because their zero-lift force occurs in negative angle of attack values. Using linearized region until the stall angle, the lift coefficient can approximately be found as,

$$\frac{dc_l}{d\alpha} \approx 2\pi \tag{8}$$

By taking the integral, then

$$c_l = 2\pi(\alpha - \alpha_0) \tag{9}$$

After that the lift and drag forces can be determined by,

$$L = c_l\left(\frac{1}{2}\rho v^2\right)A \tag{10}$$

$$D = c_d\left(\frac{1}{2}\rho v^2\right)A \tag{11}$$

Where,

L: Lift Force (N)

D: Drag Force (N)

c_l: Lift Coefficient

c_d: Drag Coefficient

ρ: Density of Outside Medium (kg/m^3)

v: Aerofoil Speed (m/sec)

As a starting point of the analysis, Beechcraft 1900D aircraft has been selected for the performance analysis of the wing design. The aircraft's itself has been shown in Figure 4 and Its performance data has been tabulated in Table 1. (Beechcraft 1900D Airplane Flight Manual)

Figure 4: Raytheon Beechcraft 1900D (Beechcraft 1900, n.d.)(Beech 1900 Airliner)

Table 1: Beechcraft 1900D Performance Data (Raytheon: Beechcraft 1900D Passenger Specifications and Performance, 2010)

Crew	1 (2 for airline operations)
Capacity	19 passengers
Length	57 ft 8 in (17.62 m)
Wingspan	57 ft 9 in (17.64 m)
Height	15 ft 5 in (4.72 m)
Empty Weight	10434 lb (4732 kg)
Useful Load	6356 lb (2882 kg)
Max. Takeoff Weight	17120 lb (7764 kg)
Powerplant	2 × Pratt & Whitney Canada PT6A-67D turboprops. 1279 HP (955 kW) each
Fuel Capacity	4484 lb
Fuel Type	Jet A recommended. also others usable
Cruise Speed	280 knots (518 km/h 322 mph) at 20000 ft (6100 m)
Range	707 km with 19 passenger payload (439 mi)
Ferry Range	2.306 km (1432 mi)
Service Ceiling	25.000 ft (7620 m)
Rate of Climb	2.615 ft/min (797 m/min)
Avionics	Rockwell Collins EFIS-84 Electronic Flight Instrument System

3. Analysis

Utilizing the performance parameters, the maximum cruise speed at 20000 ft has been limited to 518 km/hr, corresponding the Mach number of $M \leq 0.3$. So, to improve the airfoil design, 2 cases have been considered.

Case 1: In the cruise flight analysis, the maximum Reynolds Number (Re) for the boundary to turbulence is approximately 500000.

Case 2: If the Mach number for cruise flight is less than or equal to the 0.3, then the flow model of air is considered to be incompressible. Otherwise, it is valid for the air to be compressible.

Combining the considerations with aircraft's performance data, the analysis has been shown in Figure 5.

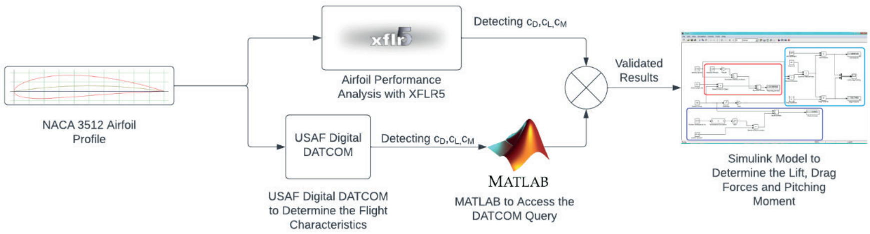

Figure 5: The Developed Model to Detect the Gliding Parameters

Using the Beechcraft 1900S' performance parameters, Reynolds Number at the trailing edge have been determined as 8.80x10^6, so the flow is turbulent. Then the Mach number of the aircraft at its operational altitude (5000 m for the cruise flight) have been determined as approximately 0.40, resulting the flow as compressible. To analyse its gliding performance, Vortex Lattice Method (VLM)-based analyses have been conducted via XFLR5 software. The cruise flight parameters have been tabulated in Table 2.

Table 2: Cruise Flight Parameters of the Aircraft at 5000 m Altitude

Geopotential Altitude Above Sea Level, *h (m)*	Temperature, T *(°C)*	Acceleration of Gravity, *g (m/s²)*	Absolute Pressure, P *(*10⁴ N/m²)*	Density, ρ *(10⁻¹ kg/m³)*	Dynamic Viscosity, μ *(*10⁻⁵ N.s/m²)*
5000	-17.47	9.791	5.405	7.364	1.628

After that the first part of the analysis, the computer-aided airfoil model has been sketched in Figure 6.

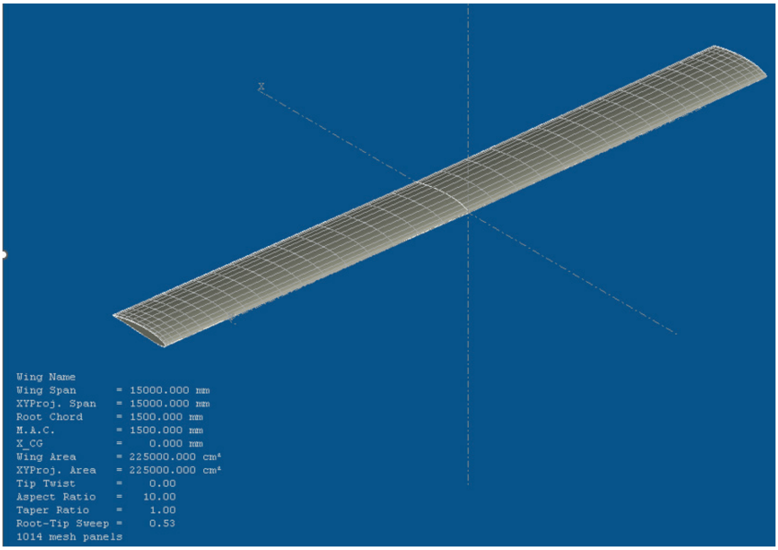

Figure 6:NACA3512 Airfoil CAD Model of Performance Parameters

Then the analyses with Mach number of 0.4 and the Reynolds Numbers ranging from 8x106 to 8.5x106 with XFLR5 have been revealed in Figure 7.

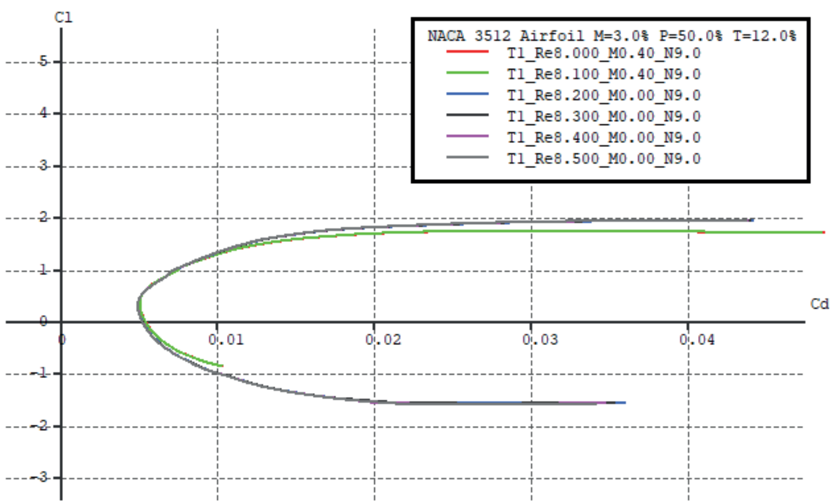

Figure 7: Lift-to-Drag Ratio Graph for 0 Degrees Angle of Attack

In the first analysis, the minimum Lift-over-Drag Ratio have been determined as 80. Then the lift coefficient-angle of attack graph has been plotted in Figure 8.

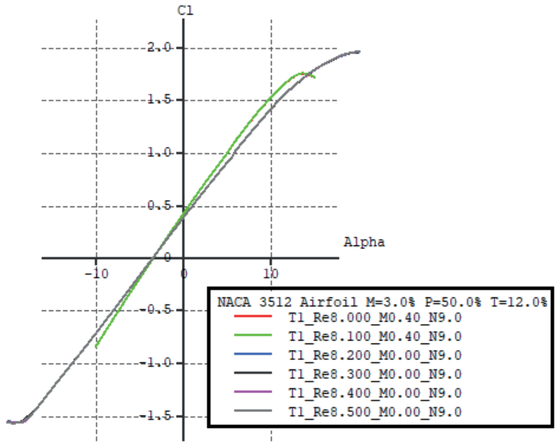

Figure 8: Lift Coefficient-Angle of Attack Graph for NACA 3512 Aerofoil

With respect to the graph, the stall angles for the aerofoil have been determined as 13 degrees. To determine the stability of the aerofoil, Pitching Moment-Angle of Attack graph has been plotted in Figure 9.

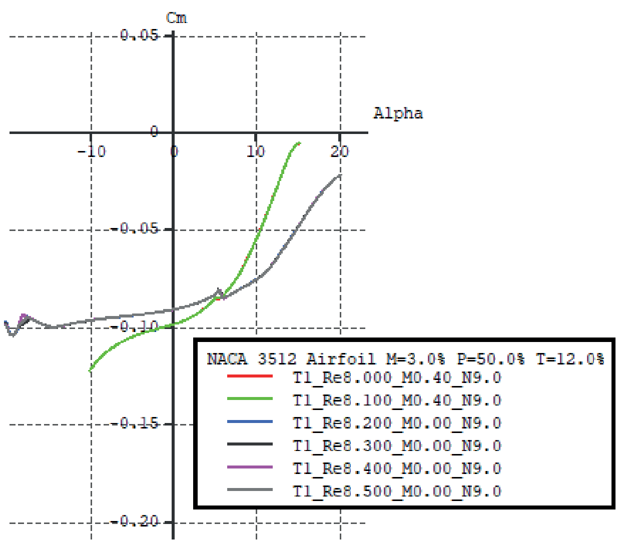

Figure 9: Pitching Moment-Angle of Attack Graph for NACA3512 Airfoil

At that analysis, the pitching moment coefficients have been determined as negative values, in which it has a direct effect in the design process.

At the second part of the analysis, the gliding parameters of NACA3512 airfoil have been performed utilizing DATCOM database and MATLAB. c_L-α graph have been sketched in Figure 10.

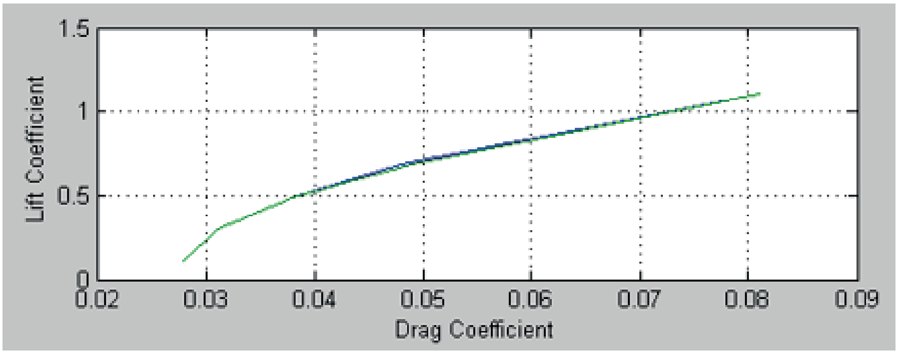

Figure 10: MATLAB-DATCOM Lift-over-Drag Graph for NACA3512 Airfoil

As the second part of the analysis, the developed MATLAB-DATCOM database has determined the minimum Lift-over-Drag ratio as approximately 80, having similar results with XFLR5.

As the final part of the analysis, the Lift and Drag forces for the cruise flight have been determined in the developed Simulink software. The simulation has been sketched in Figure 11.

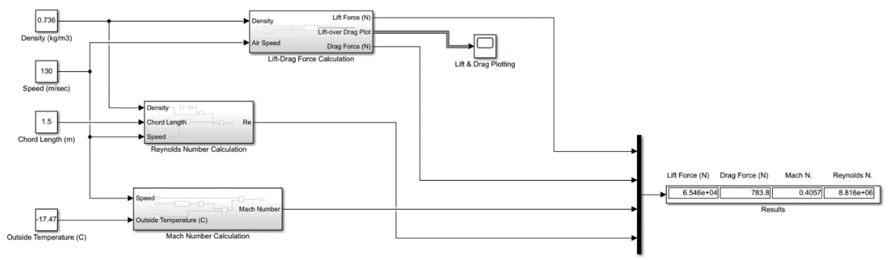

Figure 11: Simulink Model to Detect Gliding Parameters of NACA3512 Airfoil

After the successive analysis for the cruise flight, flight parameters and changes have been tabulated in Table 3.

Table 3: Comparison of Original Airfoil and NACA3512 Airfoil for Raytheon Beechcraft 1900D

	With Original Airfoil	**With NACA3512 Airfoil**	**Change (%)**
Lift Force (N)	76165	65460	-12.91
Stall Angle (Degrees)	10	13	+30

4. Results and Discussion

In this study, a hybrid methodology has been designed to detect the performance parameters for the Raytheon's Beechcraft 1900D commercial aircraft. To do this, inverse optimization methods have been used.

In order to perform the analyses, firstly the performance parameters of the aircraft at cruise flights have been determined. As the flow regime is turbulent at the trailing edge and the Mach number during its cruise flight, the air flow has been determined as compressible, however it has also determined as subsonic flow. So, Vortex Lattice Method-based methods gives satisfactory results for subsonic flows, then the first analysis have been conducted with XFLR5 software. In the first analyses, the minimum Lift-over-Drag Ratio has been determined as 80. Then, DATCOM-based second analysis has been held, which corresponds to give the similar results with the first analysis part. Then the validated results have been analysed via developed Simulink model.

At the end of the analysis, there exist differences between the original airfoil and NACA3512 airfoil, such that the lift force has decreased by approximately 13%, on the other hand, stall angle has been decreased by 30%. As pitching moment point of view, the results have been obtained as negative, which corresponds to the demand for the changes in the structural design of the aircraft. Utilizing the study, further studies are going to be held by means of artificial intelligence.

5. Conclusion and Further Studies

In this study, a new aerofoil design for lower Mach numbers have been analysed to detect the low-speed aerodynamic characteristics. To perform this, the aerofoil profile has been applied to the Raytheon's Beechcraft 1900D. The performance characteristic of NACA 3512 aerofoil has firstly been determined utilizing Vortex Lattice Method (VLM) via XFLR5. After determining required aerodynamic parameters, then it has been examined under the Digital DATCOM database. Next the analysis results have been integrated by the Simulink simulation to detect the gliding characteristics and performance parameters.

Consequently, this study reveals the potential to create a generalized model to detect the performance parameters for an aircraft at any desired speed. To overcome this, a deep learning-based model for parameter estimation is going to be created for the further studies.

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