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Effect of the wing airfoil shape on the aerodynamics and performance of a jet-trainer aircraft – An optimization approach

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Effect of the wing airfoil shape on the aerodynamics and performance of a jet-trainer aircraft – An optimization approach

K A Othman and A S Mahdi Al-Obaidi *

School of Computer Science and Engineering, Faulty of Innovation and Technology, Taylor's University, Selangor DE, Malaysia

E-mail: abdulkareem.mahdi@taylors.edu.my

Abstract. Among the key factors in developing the performance of military aircraft are its aerodynamic characteristics and performance. This research presents the effect of shape of the wing airfoil on the aerodynamic characteristics and performance of the popular jet trainer aircraft L-39C. The aerodynamic data of different airfoil shapes were used to determine the aerodynamic characteristics and performance of the L-39C for different airfoil shapes in an effort to optimize the aircrafts aerodynamic and performance. NACA 64A012 airfoil is currently used on the L-39C, however, there may exist many airfoils that may have potential to improve the aerodynamic characteristics and hence the aircraft performance. For this purpose, a group of NACA airfoils are selected, namely, NACA 4412, NACA 2415, NACA 64212 and NACA 64215. Each of these airfoil influences the aerodynamic characteristics of the aircraft and hence its performance. For each airfoil, the aircraft performance in terms of thrust required, power required, and rate of climb at different altitudes and airspeeds are calculated and analysed. The airfoil data were calculated at cruising flight at zero angle of attack to reduce the variables that can affect the calculations. The results of the calculation and analysis showed that NACA 4412 has significant results in terms of aerodynamic characteristics although in terms of aerodynamic performance, the NACA 64A012 and NACA 4412 showed lower thrust required and power required. NACA 4412 has a $(C_L)_{max}$ of 1.67, whereas NACA 64A012 has a $(C_L)_{max}$ of 1.336, indicating that the airfoil stalled early at higher altitudes. NACA 4412 also showed better results in terms of aerodynamic characteristics compared to the other selected airfoils although NACA 64A012 shows some variance in the results. NACA 4412 and NACA 64A212 have shown to be promising in aerodynamic characteristics and performance where one has its own benefits over the other. Although in the end, NACA 4412 may be recommended for its aerodynamic characteristics and performance.

1. Introduction

A jet trainer is a plane that is designed and used to teach pilots how to safely operate advanced aircraft where sophisticated modern military aircraft necessitates a high level of piloting proficiency. Single-engine aircraft are commonly used in military training programmes for primary training, while the twin-jet trainers used for transition stages [1]. Primary trainer aircrafts are typically made of simple materials and have a minimal amount of complicated equipment. The transition trainers are significantly more difficult. They are quick and agile, and they can be outfitted with a variety of complex equipment found in combat vehicles. By changing one part of the aircrafts such as the wing or tail, the aerodynamic characteristics of it will be affected highly whether it be its manoeuvrability or climbing rate. Either way making these sorts of changes will have the potential of improving the aircrafts performance depending

on the significance on the change. An example of this would be that if a wing area would be adjusted or altered, it may affect the thrust required of the aircraft to travel at a specific altitude. The wings of course have major effect of the aircraft's performance following the information and figure 1.
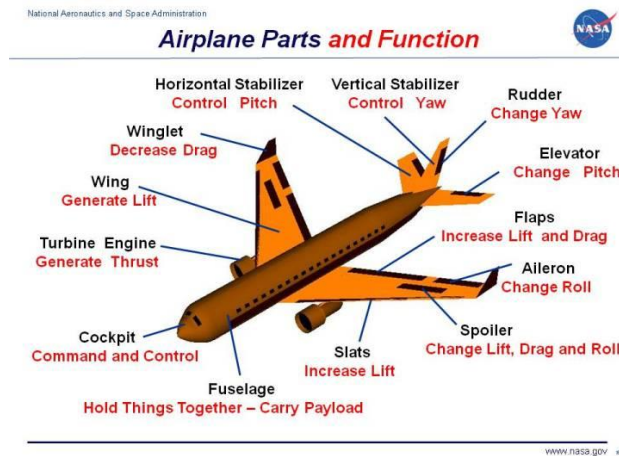

Figure 1. Information on an aircraft's wing [2].

The wings are responsible for most of the lift created by the plane, ensuring that it stays in the air. The thrust generated by the turbine engines mounted beneath the wings is utilised to overcome drag and move the plane forward through the air. Smaller wings at the tail of the plane are used to control and regulate the plane's movement. The horizontal stabiliser and the vertical stabiliser are frequently located in the tail, and their purpose is to keep the plane flying straight by providing stability and the vertical stabiliser prevent yaw, or side-to-side movement of the plane's nose while the horizontal prevents pitch, or upward and downward movement of the nose. The amount of force produced by a wing can be altered by altering the wing's back end and due to the wings' capacity to alter forces, the aircraft can be controlled and manoeuvred easily. As seen from the front of the aircraft, the rudder is the moveable part of the vertical stabilizer that deflects the tail to the left and right while the elevator is the hinged component of the horizontal stabilizer that moves up and down to deflect the tail. The outboard hinged portion of the wing that is utilised to roll the wings from side to side is known as the aileron. With that said, the shape of the wings matter in this case that it can affect the lifts and drags produce from the wings which leads to the airfoil.

The airfoil is defined as the cross-sectional shape of the wing. Its main purpose is to create a lifting force for the aircraft as well as create dragging force [3]. Depending on the aircraft, each different type requires variable types of airfoil whether it requires thin and streamlined for lower drag and lift, or a thicker one for higher drag and lift. Generally, any aircrafts can have a few wing airfoils built that can be fixed that is respect to their fuselage or in any motions which is usually for helicopters [4]. The characteristics are usually predicted based on existing aerodynamic characteristics of a wing airfoil if wingspan is larger respect to the chords, velocity of chord component is higher compared with wingspan component and the Mach numbers are in subcritical although usually the volume of the characteristics is considered to have a huge area of application [5]. Development of wing airfoils inclined to focus on the wing problem from planform effects and went to systematic experiment approach. The test eventually led to the NACA airfoil investigations where it is systemized further by separating the effects of camber and thickness distribution and the test is done with higher Reynold numbers [3].

Most of the airfoils in the NACA family camber sections are attained with the combination of mean line and thickness distribution as well as leading edges and trailing edges are being defined as forward and rearward limits of the mean line. The straight line that connects to the leading and trailing edges is defined as the chord line and the ordinates of the cambered wing airfoil sections are attained by laying off thickness distributions perpendicular to mean lines [4]. Although the NACA family airfoils contains

ones with 4, 5 or 6 digits, it does not affect any differences in performances but only in terms of the airfoil geometry. The numbering for the NACA airfoils is based on each section geometric location where the number is the percentage of the chord from the front which can be seen in figure 2. Example of this is NACA 2412 where the 1st digit 2 shows the airfoil has a maximum camber 2%, 2nd digit 4 is 40% or 0.4 chords from the leading edge and the last two which is 1 and 2 is the airfoil with a maximum thickness of 12% of the chord [6, 7].
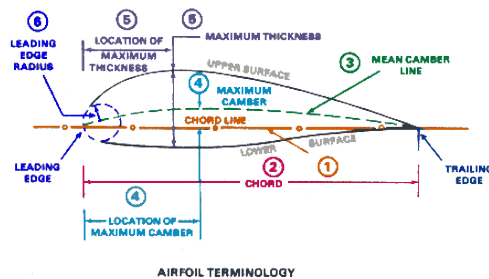

Figure 2. Information on an airfoil [6].

2. Details of L-39C Jet trainer

The L-39C, sometimes known as the "Albatros," (figure 3) is a two-seat single-engine jet training aircraft built by Czech company Aero Vodochody [8]. It has a maximum take-off weight of 4,549 kg and weights roughly 3,565 kg. It is propelled by a turbofan engine that produces 14.7 kN of thrust and has a max speed of 756 km/h. The airstrip has a take-off distance of around 530 m and a landing distance of around 652 m [8]. It has a ceiling service of roughly 11000 m, a rate of climb of 1320 m, and a maximum speed of 700 km/h during steady level flight. The highest Mach number the aircraft is able to reach is an estimate of 0.80. It has a length of 12.13 m and a wingspan of 9.46 m [9]. This aircraft is simple to operate in comparison to other aircraft, requiring only 12 hours of dual training before being allowed to fly solo. The L-39C Albatross is now the most frequent aircraft in military pilot training. The L-39C, which is frequently used as a jet trainer, and the L-39ZA, which is also used in light-attack and training [10], which are the two most common versions of the L-39C. The L-39C was a regular Soviet training plane during the Cold War [11]. Other of L-39C's specifications are listed in tables 1 and 2.
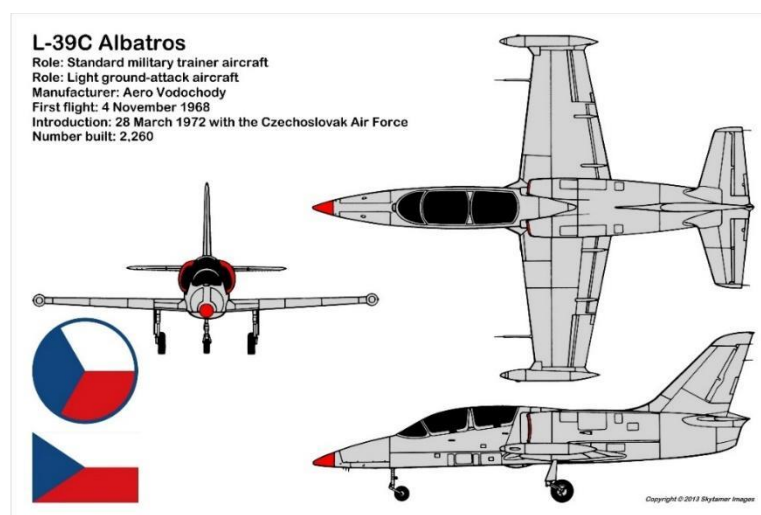

Figure 3. Front, top and side view of the L-39C "Albatros" [12].

Table 1. L-39C characteristics.

General characteristics	Metric
Crew	2
Length	12.13 m
Wingspan	9.46 m
Height	4.77 m
Wing area	18.8 m^2
Weight	3465 kg
Maximum take-off weight	4549 kg
Turbofan engine power	14.7 kN
Airfoil	NACA 64A012

Table 2. L-39C performance characteristics.

Performance of aircraft	Metric	Performance of aircraft	Metric
Engine speed	210 m/s	Range	1100000 m
Take off distance	530 m	Thrust-to-weight ratio	0.37
Landing distance	652 m	Wing loading	250 kg/m^2
Ceiling service	11000 m	Altitude duration	5000 m in 300 s
Mach number	0.8	Ferry range	1750000 m
Maximum speed	194 m/s	Endurance (internal fuel)	9000s
Rate of climb	21 m/s	Endurance (internal and	13800 s

3. Methodology

The research methodology is based on the literature review made where suggested methods of research include the comparison of different aircraft and airfoil models. The 1st half of the research plan was to mainly research multiple jet trainer aircrafts and their airfoils from the available data that exists in other research journal and research centres such as a university. The data that would be used will be from a website source "airfoiltools" which are a compilation of airfoil data from the University of Illinois [13]. There are also other analyses found on the aircrafts with their current airfoils that can be beneficial data in the research based on the literature review and sources.

In the 2nd half, other methods include using the knowledge of aircraft performance, thermodynamics, and fluid dynamics to provide the suitable equations needed to analyse the aircrafts and airfoil. From here, we will be able to focus the main parameters for the research which would be the lift coefficient, C_L and drag coefficient, C_D. The data will then be correlated with the selection criteria suggested from one of the literatures reviews. Most of the aircrafts and airfoil were obtained and verified from a website under the University of Illinois with their correlation [14]. The list of airfoils has been shortlisted based on mainly jet trainers for compatibility with the L-39C and can be seen in table 3 including the aircrafts current airfoil.

Table 3. List of airfoils with respective aircraft [14].

Airfoil	Aircraft
NACA 64A012	L-39C Albatross
NACA 4412	Aeronca 65-TAC Defender
NACA 2415	FMA IA62
NACA 64A212	Aermacchi MB339
NACA 64215	AIDC TCH1 Chung Hsing

3.1 Selection criteria of the airfoil

Considering that the aircraft that is being optimized is a multi-regime aircraft which is what a jet trainer is, it has specific requirements and criteria that it must follow to be able to function appropriately as well as a regulation to avoid being used for other specific purposes in military training. Generally, the airfoil

acceptable design criteria include its convenient shape and thickness of the trailing edge [15, 16, 17]. For a jet trainer, it is quite unusual for leading-edge flaps to be used. Other than that, design acceptability would help solve manufacturing simplicity as well. The aircrafts main operation economy involves the effect of drag. On a horizontal flight, the aircraft would require low drag at $C_L = 0.3$ at Ma = 0.4 and for a sustained turn it is $C_L = 0.4$ at Ma = 0.7 with a load factor n = 4g. This research focuses on a horizontal flight for simplification of the calculation and not involving too many variables. The other requirement would be the lift and drag coefficient ratio, C_L/C_D gradient would be as low as possible. The last part is to consider the lift and drag ratio, L/D and maximum lift coefficient, $(C_L)_{max}$ to be as high as conceivable.

3.2 Calculations for performance and stability
Most of the values that would be used for the calculations are based on the aircrafts general specifications which can be seen in table 4.

Table 4. Albatross L-39C data (Jet Trainer 2-seater Basic and Advanced) [20].

Airfoil	NACA 64A012	Max Lift Coefficient	1.336
Wing span	9.12 m	zero-lift drag coefficient	0.02
Root Chord, m	2.795	Max Take-off weight	4700 kg
Tip Chord, m	1.327	Max Speed	700 km/h
Wing Loading	250.0 kg/m²	Weight, N (Take-off weight: 4700 kg)	46107
Wing Area (S_W)	18.8 m²	Service ceiling	11.5 km
Aspect Ratio	4.4	Rate of climb	22 m/s
Aircraft Height	4.7 m	Thrust	1722.744 kg
Aircraft Length	12.13 m	Max Mach	0.8
Oswald efficiency factor	0.86	Powerplant	Progress AI25-TL turbofan, 16.9 kN

Other than that, the calculation for thrust required, T_R, power required P_R, and rate of climb, V_C will be against different altitudes which would have different density and speed of sound. To again reduce the variables for the calculations, the data would be mostly near the cruising flight altitude along with few other altitudes from 4 km to 14 km. The atmospheric data using the standard atmosphere model is calculated and the results of the atmospheric air properties are shown in table 5. It is important to consider the effect of the altitude (more specifically the density) on the aerodynamic characteristics of the wing (airplane) [18].

Table 5. Atmospheric data [19]

Height (km)	Temperature (K)	Pressure (Pa)	Density (kg/m³)	Speed of Sound (m/s)	Relative Density	Relative Speed of sound
4	262.15	61616.20	0.81896	324.549	0.668	0.954
6	249.15	47152.74	0.65942	316.399	0.538	0.930
8	236.15	35570.61	0.52483	308.034	0.428	0.905
10	223.15	26408.41	0.41235	299.436	0.337	0.880
12	216.65	19328.75	0.31086	295.042	0.254	0.867
14	216.65	14098.25	0.22674	295.042	0.185	0.867

To calculate the thrust required, T_R for the aircraft to move and to relate thrust to airspeed, density and drag coefficient.

$$T_R = D = c_D \frac{1}{2} \rho V_\infty^2 S_W \tag{1}$$

where: D = drag force, ρ = air density, V_∞= aircraft airspeed, S_W= wing area, C_D = Drag coefficient

Power required, P_R can be calculated by multiplying trust with airspeed,

$$P_R = T_R \times V = \frac{1}{2} \rho V_\infty^3 S_W c_D \tag{2}$$

The thrust available is 16.8 kN, which is calculated at full throttle. Due to the limited mass flow rate at higher altitudes, the thrust varies with altitude because the powerplant is a turbofan,

$$T_A = 16.8 \times \frac{\rho}{\rho_0} \tag{3}$$

where: ρ_0 = density at 0 altitude

At different speeds, the power available, P_A, can be calculated from T_A using the same formula as P_R,

$$P_A = T_A \times V \tag{4}$$

The excess power required for level flight, or rate of climb (ROC), V_C, can be defined as the excess power divided by the weight of the aircraft,

$$V_c = \frac{P_A - P_R}{W} \tag{5}$$

4. Results and Discussion

4.1 Data comparison of NACA 64A012

To ensure the legitimacy of the data obtained from the website airfoiltools, the data of the L-39C's airfoil of NACA 64A012 [13] was compared with the new data obtain from the resource to make ease of comparison. Note that the values were also taken at different Reynold number, Re which may cause the data to be slightly different each other. The comparison can be seen in figure 4. It can be observed from this figure that the data compared is proven to be similarly close to each other despite having different Re. The data obtained from the research thesis [20] was tabulated at $Re = 3 \times 10^6$ while the airfoiltools were tabulated at $Re = 1 \times 10^6$ as that was the highest available data that was able to be obtained. This shows that the data obtain through airfoiltools contains minor errors in data and differences in value.
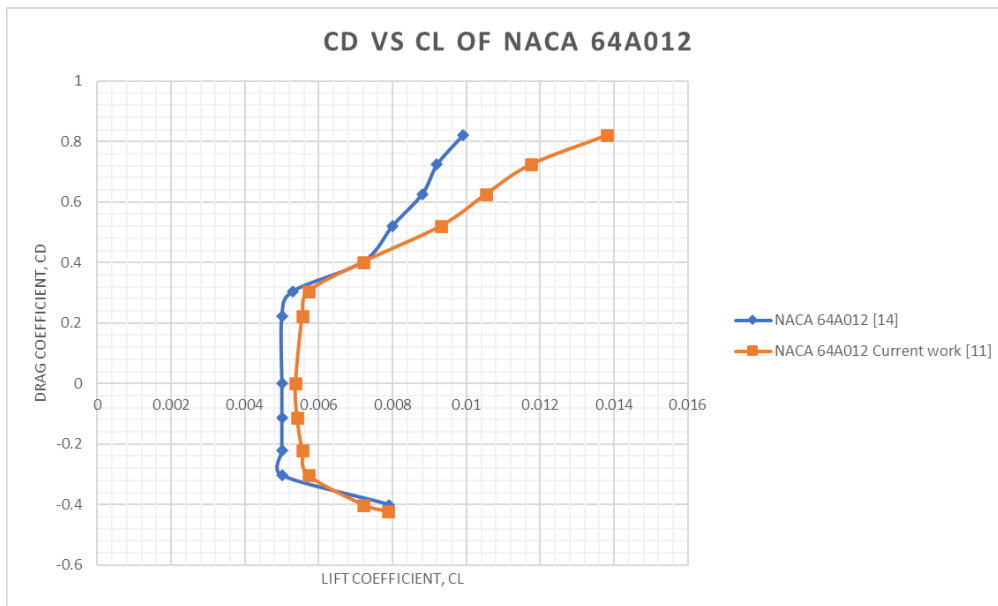
Figure 4. Comparison between 64A012 polar diagram
obtained in this study with the data obtained from [13, 20].

4.2 Aerodynamic characteristics of the airfoils
As mentioned in the details above, the airfoils being compared are NACA 4412, NACA 2415, NACA 64A212 and NACA 64215 along with the current L-39C airfoil NACA 64A012 to see how big of a difference each airfoil has in terms of characteristics and performance. Majority of the data is against the angle of attack from -4 to 15.75 to not overload the results and the range also shows the $(C_L)_{max}$ for most of the airfoils.

Figure 5 shows the lift coefficient, C_L of the airfoils against the angle of attack, α. The airfoil with the highest C_L is NACA 4412 while NACA 64A012 has the lowest based on the α. NACA 64A212, 2415 and 64215 has somewhat similar values of C_L although NACA 64215 has slightly lower values than the other two. The $(C_L)_{max}$ for NACA 4412 is shown to be 1.67 whereas NACA 64A012 is 1.336 showing that the airfoil stalled early at higher α.
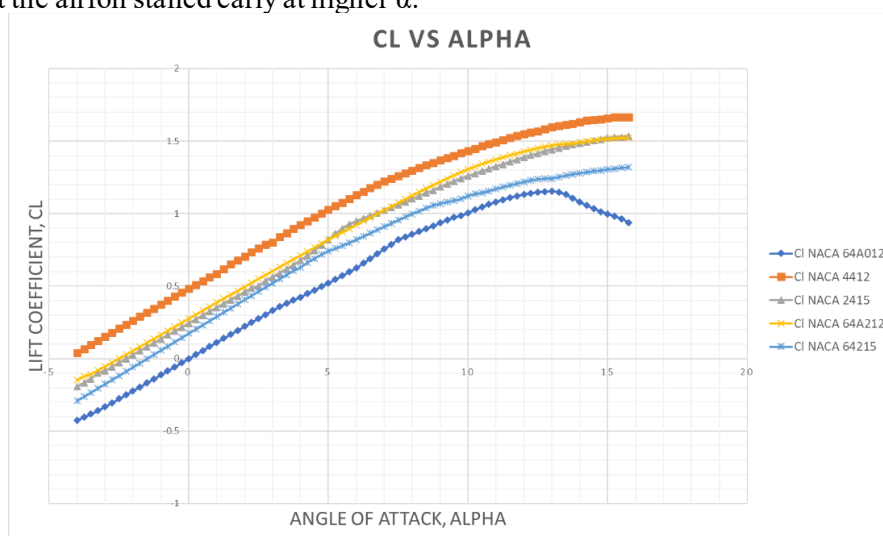

Figure 5. Lift coefficient, C_L, against angle of attack, α, for the selected airfoils.

Figure 6 shows the drag coefficient, C_D of the airfoils against the angle of attack, α. The airfoil with the highest C_D is NACA 64A012 the higher the α while NACA 64215 has the lowest with α however, the rest of the airfoils have somewhat similar values in the middle although NACA 64A212 had the highest early on. The $(C_D)_{min}$ for NACA 64A012 is 0.00537 where NACA 64215 is 0.00627 which is higher than the other.
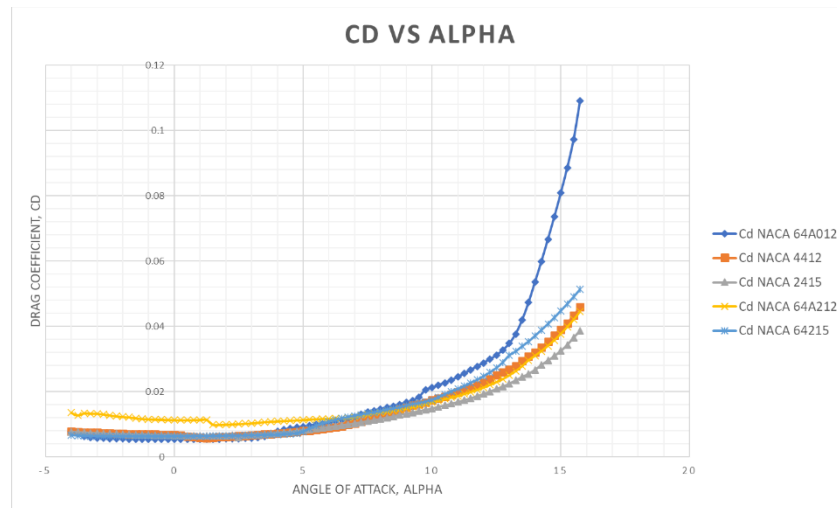

Figure 6. Drag coefficient, C_D, against α of the selected airfoils.

Figure 7 shows the lift coefficient, C_L of the airfoils against the drag coefficient, C_D. NACA 64A012 is seen to have a higher C_D with lower C_L while the rest has lower C_D with a somewhat higher C_L. NACA 4412 is shown to have the highest value of C_L at increasing but lower C_D value.
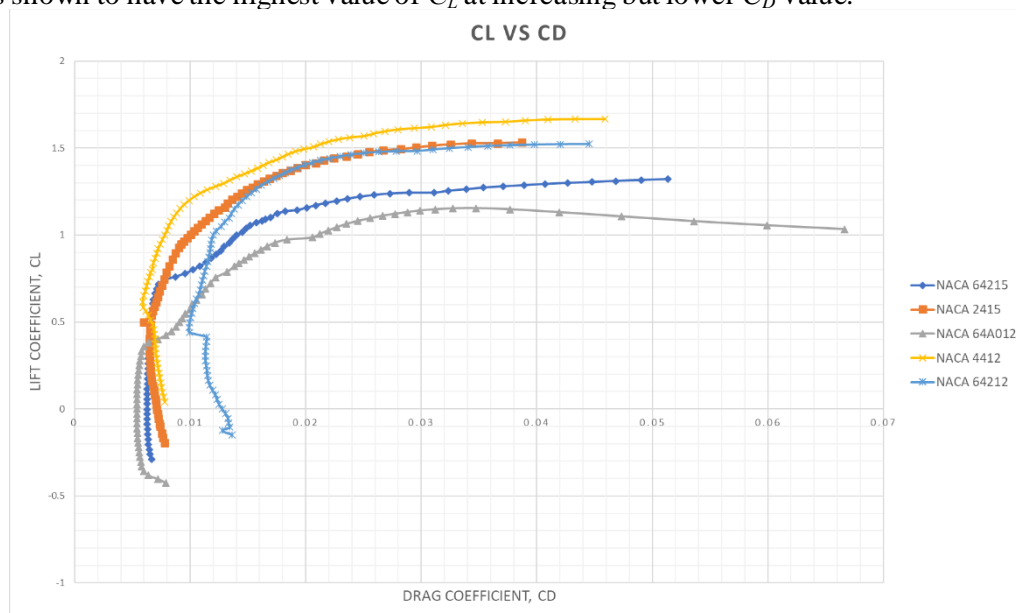

Figure 7. Lift coefficient, C_L, against Lift coefficient, C_D, the selected airfoils.

Figure 8 shows the lift and drag coefficient ratio, C_L/C_D against the angle of attack, α. NAC 4412 shows promising results with a higher C_L/C_D at the beginning and became the same with the other airfoils after while NACA 64A012 had the overall lowest C_L/C_D. $(C_L/C_D)_{max}$ value for NACA 4412 is 129.373

which is the highest among the other airfoils while NACA 64A012 is 61.9083 which is the lowest compared with the others.
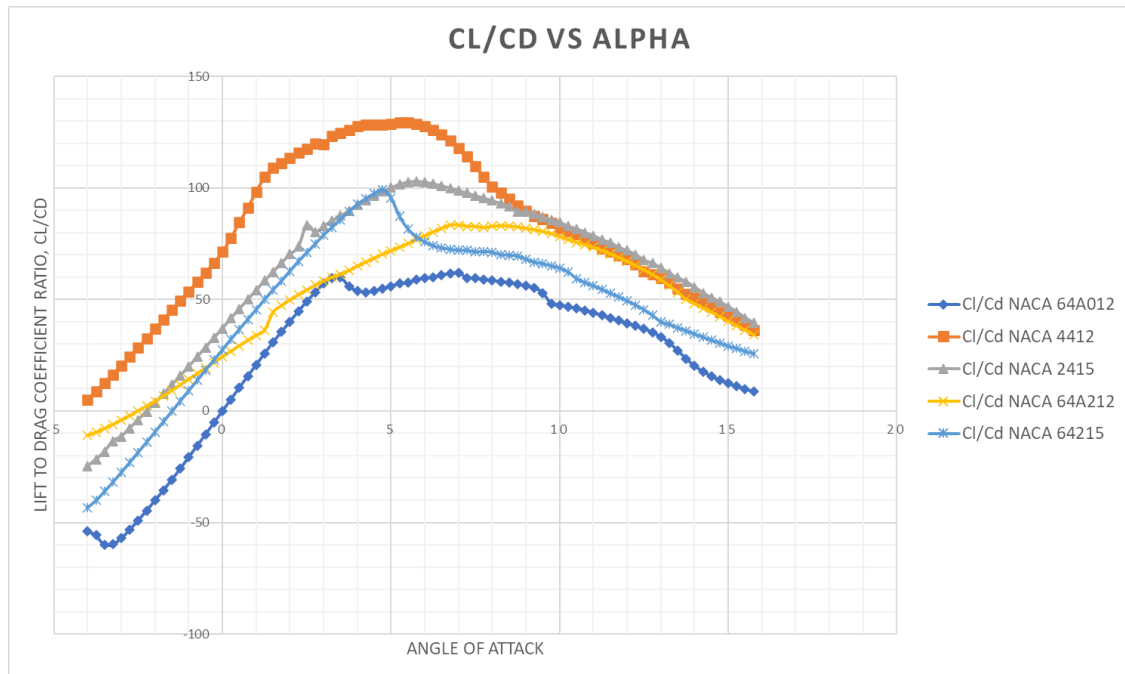

Figure 8. Lift-to-drag ratio C_L/C_D against α of the selected airfoils.

4.3 Aerodynamic performance of Airfoil

Below are the calculated data of thrust required, T_R, power required P_R, and rate of climb, V_C compared and calculated at different level of altitude which has variable density and speed of sound. The calculations were made at the assumptions of small thrust angle approximation (STAA), where the C_D and C_L of the airfoil are at $\alpha = 0°$ at horizontal flight. Another value was also considered kept constant was the airspeed at Ma = 0.4 which was one of the recommended values for a jet trainer at horizontal flight.

From figures 9, 10 and 11 all showed similar results corresponding with one another whereas the altitude goes higher up, the values of T_R, P_R, and V_C decreases with their respective airfoils. NACA 64A212 is shown to have the highest value of T_R, P_R, and V_C while NACA 64A012 shows the lowest although approaching 14 km altitude is somewhat like the others. NACA 4412, 2415 and 64215 shows to similar values to each other overall showing that they only require the same values.
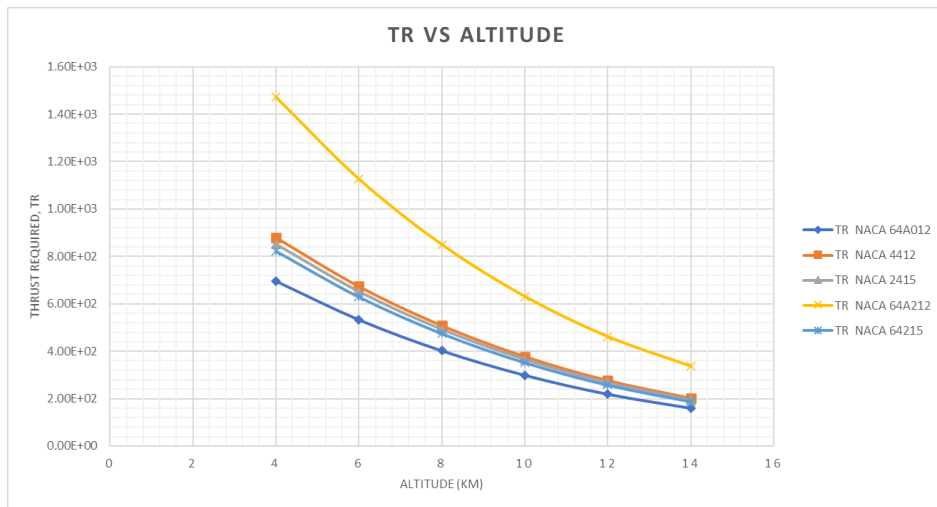
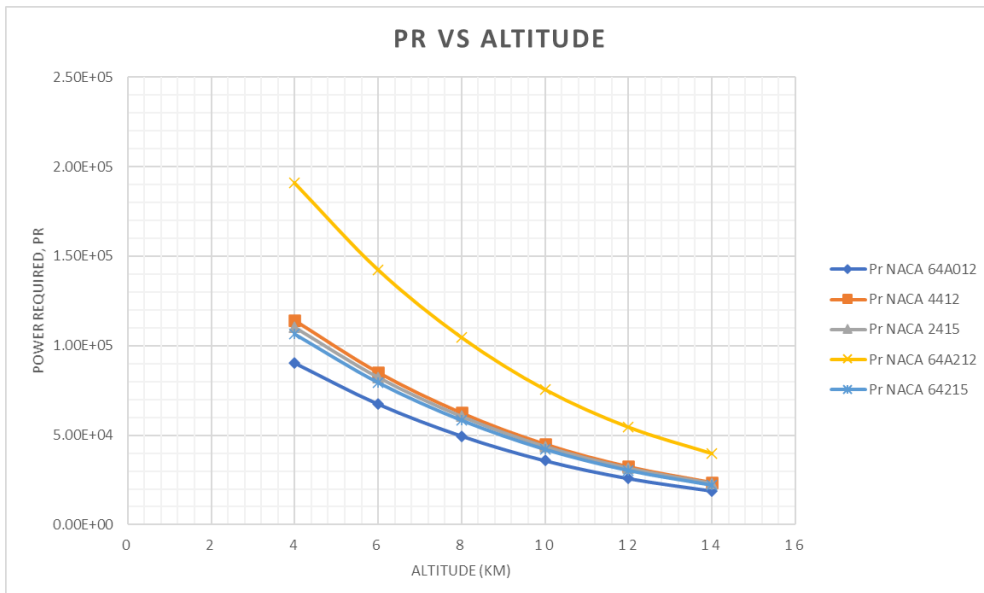**Figure 9.** Thrust required, T_R, against altitude for the selected airfoils.

Figure 10. Power required, P_R, against altitude for the selected airfoils.
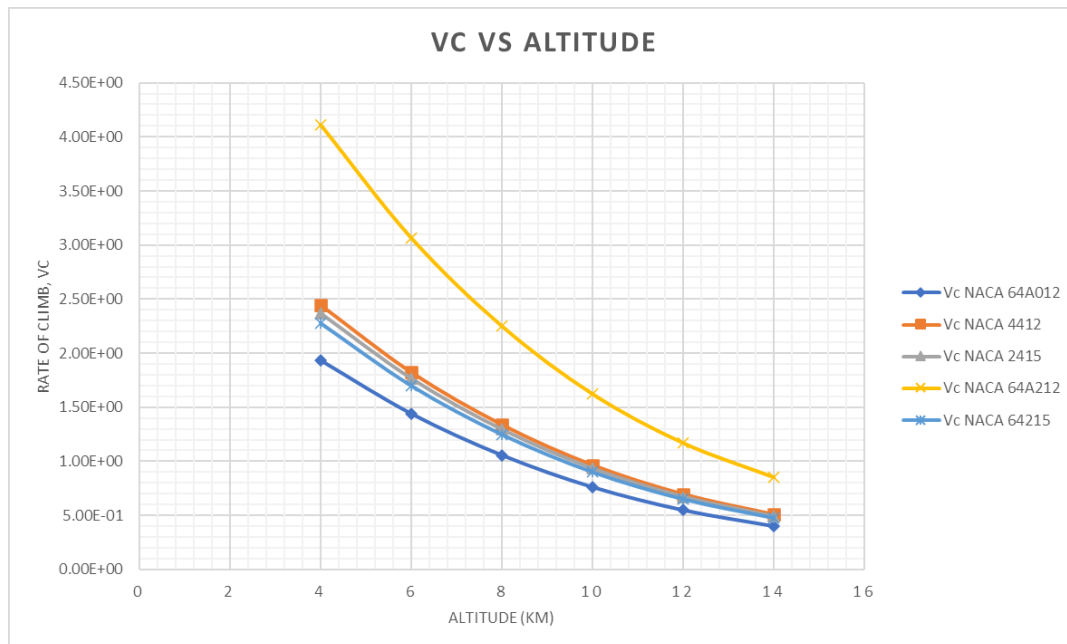
Figure 11. Rate of climb, V_C, against altitude for the selected airfoils.

5. Conclusion

This research presented promising values for the options of optimizing the L-39C aircraft with different results. The results have shown that several of these airfoils selected have the potential to increase the aerodynamic performance and characteristics and satisfy the suggested criteria for a better airfoil for a jet trainer aircraft. Both are NACA 4412 and NACA 64A212 which results have shown to be promising in aerodynamic characteristics and performance. Despite that the data was collected at a lower Re value, the results shown to be promising with a few adjustments needed. Nevertheless, the research shows to be a useful reference for future uses for airfoil analysis and aircraft optimization along with the knowledge and data obtained. This can also be expanded towards more variety of airfoils that may have potential with L-39C.

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