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Parametric Study of NACA 4-Series Airfoil Designs for Lift-to-Drag Performance

Fairuz Izzuddin Romli * and Muhammad Naqib Md Nasir

Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

ABSTRACT

Airfoil design has a great influence on the overall flight performance of flying vehicles. In conceptual design stage where design decisions have to be quickly made, having a metamodel that can properly capture the relationship between airfoil design parameters and resultant aerodynamic performance is very useful for the airfoil selection process. In line with this notion, this study is done to perform computational fluid dynamics (CFD) simulation analysis to obtain the effects of varying airfoil design parameters on the resultant lift-to-drag (L/D) performance and establish a mathematical metamodel for this relationship. 140 airfoil designs have been constructed by varying the digits in the NACA 4-series airfoil numbering system and they are analyzed using XFLR5 software at zero-degree angle of attack, Reynolds number of 100,000 and 0.3 Mach with sea level conditions. Using the simulation analysis results, regression analysis is used to form a mathematical metamodel for the effects relationship between the airfoil design variables as described by the NACA 4-series numbering system and the resultant L/D. The maximum thickness of the airfoil design is found to have the highest impact on L/D. Moreover, the metamodel has been shown to have acceptable goodness-of-fit level with R^2 value of 98.81% and prediction error of less than 20%.

Keywords: Airfoil design, NACA, CFD, Lift-to-drag, Regression analysis

I. INTRODUCTION

The aircraft's wing is perhaps the most important part of the aircraft design. This is because the wing section has a great influence on the overall aerodynamic performance of the aircraft and it is also the main contributor to the lift force that enables the aircraft's flight [1]. In the meantime, the heart of the aircraft's wing design is the airfoil, which is the cross-sectional shape of the wing [2]. The choice of airfoil will dictate the shape of the wing and subsequently, the aerodynamic performance of the aircraft. Many studies have been pursued to develop optimal shapes of airfoil for provision of high lift and low drag forces during flight [3]. Due to its great impact to the overall aircraft performance, selection of airfoil for the wing section should be properly made as tailored to the aircraft's operational flight mission requirements.

During the conceptual aircraft stage, airfoil selection can either be made by going through the established airfoil databases or designing custom airfoil shape to suit with the aircraft mission requirements. Some examples of available databases for airfoil designs include the NACA, Selig and also Eppler airfoil series. On the other hand, development of custom airfoil for specific aircraft design is observed in several studies including for a propeller-driven aircraft [4] and an unmanned aerial vehicle [5]. Choosing the existing airfoil design for the aircraft from standard databases may seem to be easier as their aerodynamic characteristics have been already well-established but it can also be hard to find the one that perfectly matches with intended flight mission requirements. On contrary, though developing new custom airfoil involves much greater efforts and longer timeframe, the resultant airfoil design is ensured to be directly tailored to the required aircraft performance.

Today, computational fluid dynamics (CFD) analysis is often applied to estimate aerodynamic characteristics of

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* To whom correspondence should be addressed, E-mail: fairuz_ir@upm.edu.my

airfoils, which in turn determines the performance for the wing and subsequently, the overall aircraft. In short, CFD is a method that uses the techniques from physics, applied mathematics and computer science to model, predict and visualize the fluid flow [6]. As alternative to experimental study in the wind tunnel, CFD simulation is gaining more popularity and importance among researchers since it can provide faster results with a good accuracy of various flow parameters around a body geometry such as airfoil [7]. For instance, applications of CFD in aerospace studies include for the analysis of blended-wing-body aircraft [8], airship [9], unmanned aerial vehicle [10] and tiltrotor aircraft [11]. In recent years, the advancement in computing technology has enabled great improvements in the capabilities and the accuracy of results for numerical simulation analyses such as CFD [12].

Furthermore, metamodeling technique has proven to be a convenient and useful approach in conceptual design stage where many design decisions have to be made within a short time and under lots of design uncertainties. Instead of time-consuming and costly physical experimentation or simulation runs, a mathematical metamodel can be derived to estimate and aid in the product performance evaluation [13]. In general, a metamodel is often viewed as the black-box function or the surrogate model that aptly captures the relationship between input variables to an output variable of interest, which allows instant and cheap approximation of the value of the output variable with any settings of the input variables' value [14]. For example, a metamodel has been used to estimate the aerodynamic lift and drag forces for an airship with variation of design fineness ratio [15]. Moreover, the metamodeling approach has also been used to predict the aircraft's noise emission [16] and to optimize the design of a general aviation aircraft [17].

Since airfoil design selection is a crucial step during the conceptual aircraft design phase, it is beneficial to have a metamodel that relates the main airfoil design parameters to the resultant aerodynamic characteristics. This will help the aircraft designer to make better decisions regarding the airfoil shape to be used for the aircraft's wing according to the required aerodynamic performance. In view of this, the objective of this research is to derive a suitable metamodel that captures the effects of airfoil design parameters to the resultant aerodynamic lift-to-drag (L/D) performance.

II. METHODOLOGY

The first step of the methodology is to identify airfoil design variables to be varied. In order to be consistent with current definition of airfoil parameters, numbering system for NACA 4-series airfoil nomenclature is chosen to be the main reference for the airfoil design variations. As shown in Figure 1, the NACA 4-series airfoils are defined by three main shape design parameters: maximum camber, location of maximum camber and maximum thickness. According to this numbering system, for instance, NACA 2412 airfoil indicates that it has a maximum camber of 2% of the chord length that is located at 40% of the chord length from the leading edge. Meanwhile, the last two digits imply that the airfoil's maximum thickness is 12% of the chord length.

For this study, the aerodynamic analysis is performed through CFD simulations using XFLR5 software. It should be noted that XFLR5 software has been applied in various studies such as for aerodynamic performance analysis of a drone design with winglets [18] and also a modified airfoil design [19]. The simulation capability and the accuracy of analysis results for the XFLR5 software have already been demonstrated in many studies [20].

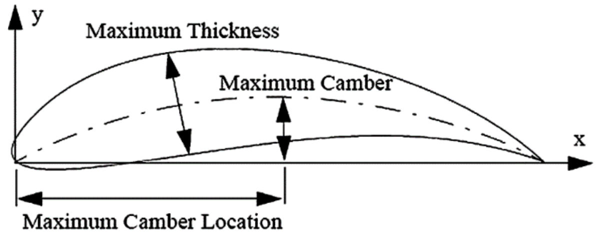


Figure 1 Shape parameters for NACA 4-series airfoils [21]

Moreover, the design of experiments (DoE) approach is used in setting the case runs for the simulation analysis. The application of DoE helps to ensure sufficient analysis data of good quality for the development of the metamodel [22]. Table 1 tabulates the considered number of levels for each of the airfoil shape design parameters for the analysis. Moreover, the simulation analysis in XFLR5 software also requires the setting of Reynolds number and Mach number. It is noted that in aerodynamics system, the values of these two parameters provide an insight into the flow type. It has been indicated that the consideration of Reynolds number is crucial during airfoil selection process due to its effects on aerodynamic characteristics of the airfoil design [23]. For this study, low Reynolds numbers region is of interest and airfoils in this region are often used for design of small unmanned aerial vehicles (UAVs). The Reynolds numbers considered in this study is 100,000. Meanwhile, the default Mach number of 0.3 is used for this study, which is mostly suitable as well for cruise flights of UAVs. The simulation analysis setting is tailored to sea level conditions.

Table 1 Values of considered variables for the simulation analysis

Level	NACA 4-series Numbering		
	1st Digit (MC)	2nd Digit (LMC)	3rd & 4th Digits (MT)
1	1	2	10
2	2	3	15
3	3	4	20
4	4	5	25
5	5		30
6	6		
7	7		

*MC is maximum camber, LMC is location of maximum camber, MT is maximum thickness

For full factorial DoE setup, the total simulation case runs for this study is 140. This means that 140 airfoil shape designs need to be modelled for the simulation analysis. It should be noted that the XFLR5 software is equipped with the airfoil design module, which is used to construct these required 140 airfoils. Figure 2 shows an example model of NACA 3215 airfoil that is created in XFLR5 software.

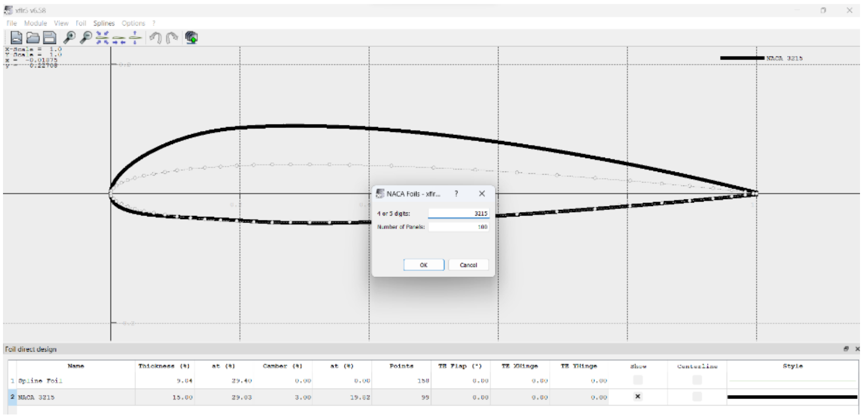
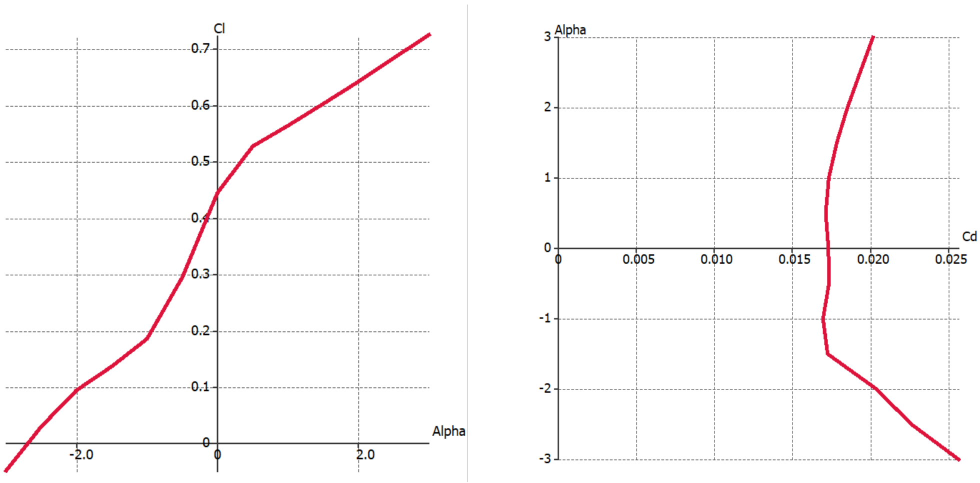


Figure 2 NACA 3215 airfoil design model in XFLR5

Once the airfoil design model is constructed, it is then used for the simulation analysis in XFLR5. In this module, aerodynamic performance of the airfoil design at specified Reynolds number is generated for range of angles of attack as presented in Figure 3 for the NACA 3215 airfoil design.



(a) Lift coefficient versus angle of attack

(b) Drag coefficient versus angle of attack

Figure 3 Simulation analysis results for NACA 3215 airfoil design in XFLR5

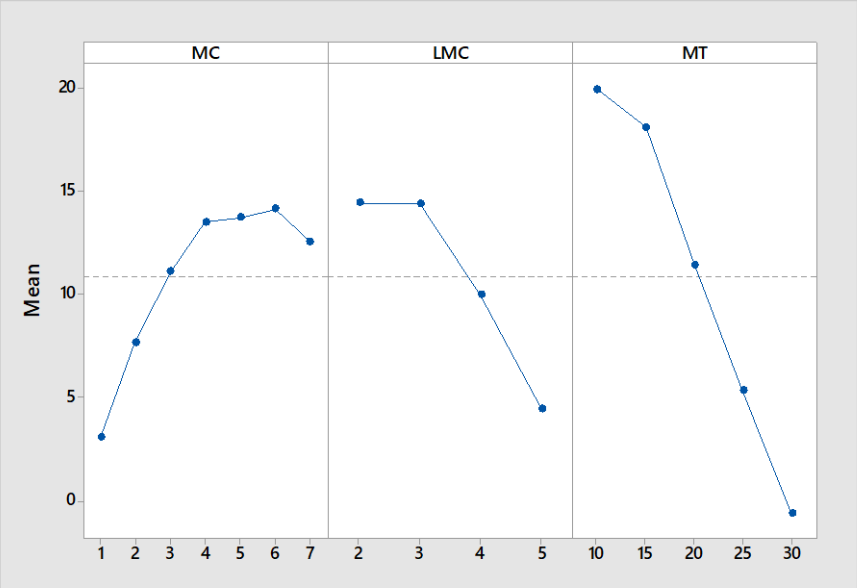
It should be noted that one of the common measures of aerodynamic performance is L/D, whereby a higher L/D is preferred since it implies better aerodynamic efficiency of the flying body. Use of L/D as the primary indicator for aerodynamic efficiency can be observed in various studies such as the performance analysis of compound wing-body aircraft design [24] and effects analysis of flow control on airfoil aerodynamic characteristics [25]. Moreover, in this study, the interest is on the aerodynamic performance at 0° angle of attack, which typically resembles the condition at cruise flight phase. Since cruise is the longest flight phase in typical aircraft mission profile, design of aircraft's wing is often made for cruise conditions. All in all, based on the simulation results in XFLR5, L/D data at 0° angle of attack is collected for all 80 simulation case runs.

The collected simulation data is statistically analyzed to construct the metamodel using MINITAB software. For the metamodeling process, polynomial regression analysis is used to create the metamodel. A polynomial regression model is fitted with the least squares method. Moreover, to ensure that the metamodel has a good predictive capability, several standard goodness-of-fit tests are applied [26].

III. RESULTS AND DISCUSSION

As previously mentioned, 140 different airfoil design models are constructed in this study and they are analyzed in XFLR5 at Reynolds numbers of 100,000, Mach number of 0.3, angle of attack of 0° and sea level conditions. Once all simulation analyses are completed, the results are then imported to MINITAB software for statistical analysis.

The main effects plot is depicted in Figure 4. In short, this is the plot of mean L/D value at each level of the airfoil design variables that is indicative of their relative strength of effects to dictate the L/D value. The mean L/D value is calculated by averaging the L/D values at each level of the parameters. For instance, the mean L/D value at MC = 1 is the average value for all cases with MC = 1, regardless of the values for other parameters. On the other hand, mean L/D value at LMC = 2 is defined as the average L/D value for all cases with LMC = 2, regardless of the value of other parameters.



*MC is maximum camber (1st digit), LMC is location of maximum camber (2nd digit),
MT is maximum thickness (3rd & 4th digits)

Figure 4 Main effects plot for L/D

As can be observed in Figure 4, maximum thickness is shown to have the highest effects on L/D value, which is implied from the difference between the minimum and maximum values of L/D as maximum thickness is varied. In addition, effect of all design variables are approximately linear and also monotonous. The L/D value is increased as maximum camber increases, although near the high end of maximum camber, the value of L/D seems to reduce a bit. In contrast, L/D decreases as location of maximum camber and maximum thickness are increased. Overall, according to the plot, it can be deduced that the most impact to L/D of the airfoil design is obtained by altering the maximum thickness of the airfoil. It is also good to note that a small maximum thickness corresponds to a high L/D on average, which is believed to be possibly due to a lower drag force generated for thinner airfoils.

Analysis of variance (ANOVA) of the DoE method is conducted in MINITAB software to highlight the percent contribution of each airfoil design variable on the variation of L/D value. In other words, a variable is said to be highly significant if it contributes the most to the variation in L/D value. From the ANOVA results, the percent contribution for each airfoil design variable is estimated by dividing its corresponding sum of squares value with the total sum of squares, and multiply it by 100. The results are shown in Table 2 and it can be noted that they are basically in line with previous assertion made based on main effects plot in Figure 4. In brief, the highest contribution towards the L/D variation comes from the maximum thickness of the airfoil with more than 50% contribution. This means that, in term of airfoil design, the most impact to the L/D value can be obtained by changing airfoil's maximum thickness, which is consistent with the conclusion made from previous main effects plot. Additionally, note that the tabulated percent contributions to L/D value in Table 2 only include the main effects. However, higher order and interaction effects are also considered in the development of the final metamodel to increase its effectiveness and goodness of predictability.

Table 2 Percentage contributions of themain effects for L/D from ANOVA results

Variable	% Contribution
Maximum Camber (1st digit)	13.13
Location of Maximum Camber (2nd digit)	15.42
Maximum Thickness (3rd and 4th digits)	54.80

A polynomial regression model is fitted in MINITAB software for the metamodel, which also considers possible higher order terms of the main and interaction effects. The generic polynomial regression model used for constructing the metamodel is presented in Equation (1) whereas Table 3 lists the value for the coefficients for all variable terms in the constructed metamodel. The goodness-of-fit tests are carried out to evaluate the model's capability in predicting and capturing the behaviors of the simulation analysis data. Firstly, the value of coefficient of determination, R^2 for the metamodel is 0.9881, which indicates that 98.81% of the variation in the L/D data values could be explained by the constructed model. This is taken to imply the goodness of the metamodel in fitting of the simulation analysis results data.

$$L/D = a_1MC + a_2LMC + a_3MT + b_1MC^2 + b_2LMC^2 + b_3MT^2 + c_1MC*LMC + c_2MC*MT + c_3LMC*MT + d_1MC^3 + d_2LMC^3 + d_3MT^3 + e_1MC^2*LMC + e_2MC^2*MT + e_3MC*LMC^2 + e_4MC*LMC*MT + e_5MC*MT^2 + e_6LMC^2*MT + e_7LMC*MT^2 + f_1MC^4 + f_2MT^4 + f_3MC^3*LMC + f_4MC^3*MT + f_5MC^2*LMC^2 + f_6MC^2*LMC*MT + f_7MC^2*MT^2 + f_8MC*LMC^3 + f_9MC*LMC^2*MT + f_{10}MC*LMC*MT^2 + f_{11}MC*MT^3 + f_{12}LMC^3*MT + f_{13}LMC^2*MT^2 + f_{14}LMC*MT^3 \quad (1)$$

Table 3 Coefficients of the metamodel for L/D

Coefficients	Value
a_1	-7.71708
a_2	-62.94939
a_3	10.15273
b_1	-4.78446
b_2	15.02387
b_3	-1.06470
c_1	24.47551
c_2	0.94238
c_3	3.41587
d_1	0.30537
d_2	-2.14375
d_3	0.03731
e_1	-0.35535
e_2	0.16947
e_3	-4.12643
e_4	-0.92704
e_5	-0.01960
e_6	-0.34337
e_7	-0.06864
f_1	0.00049
f_2	0.16922
f_3	-0.00040
f_4	-0.01737
f_5	-0.01209
f_6	0.12291
f_7	-0.00550
f_8	0.00151
f_9	0.10600
f_{10}	0.09123
f_{11}	0.00772
f_{12}	-0.00031
f_{13}	-0.00460
f_{14}	0.00754

*MC is maximum camber (1st digit), LMC is location of maximum camber (2nd digit), MT is maximum thickness (3rd & 4th digits)

Another measure of the metamodel's goodness-of-fit is by looking at its residuals. For the regression modeling, good models will have normally-distributed residuals with mean of zero. In addition, the plot of residuals versus fits plot should appear random without visible trend or pattern while the normal probability plot of residuals should be in a straight line. Figure 5 shows the residuals histogram plot of the metamodel and the residuals approximately follow normal distribution with mean of zero. On the other hand, the residuals versus fits plot for the metamodel is shown in Figure 6. There appears to be no obvious trend or pattern visible in the plot, which is a good indication as it implies that the residuals are randomly scattered and no significant term is left out from the final model. Moreover, the normal probability plot of the residuals in Figure 7 shows that the residuals mostly fall on the straight line. On the whole, the residuals of the metamodel are also implying its acceptable goodness-of-fit.

The last goodness-of-fit test for the metamodel that is applied in this study is by using the random cases. For this evaluation, five different random simulation case runs are performed in XFLR5 software and actual L/D values obtained from the simulation analysis are then compared with the predicted values using the constructed metamodel. Variable settings and the comparison of L/D values for the random cases are presented in Table 4. It can be observed that the highest prediction error for the random cases from the use of the constructed metamodel is 16.858%, which is less than 20%. In general, this can be taken as acceptable and demonstrates good predictability of the metamodel for cases outside of the ones used for its fitting. This implies that the constructed metamodel is able to properly capture the underlying relationship between the considered airfoil design variables and L/D.

Nevertheless, it is noted that, since the metamodel has been fitted using simulation data from XFLR5 software, its prediction accuracy is highly dependent on the accuracy of simulation results of the XFLR5 software. In their work, Communier et al. [27] has shown great consistency of the simulation results from XFLR5 to those from wind tunnel tests. Similarly, acceptable accuracy of simulation analysis results from the XFLR5 software to the wind tunnel results is also supported by other researchers such as Guzelbey et al. [28] and Shams et al. [29]. Based on this, it can be also taken that the metamodel has a similar level of accuracy to the XFLR5 software.

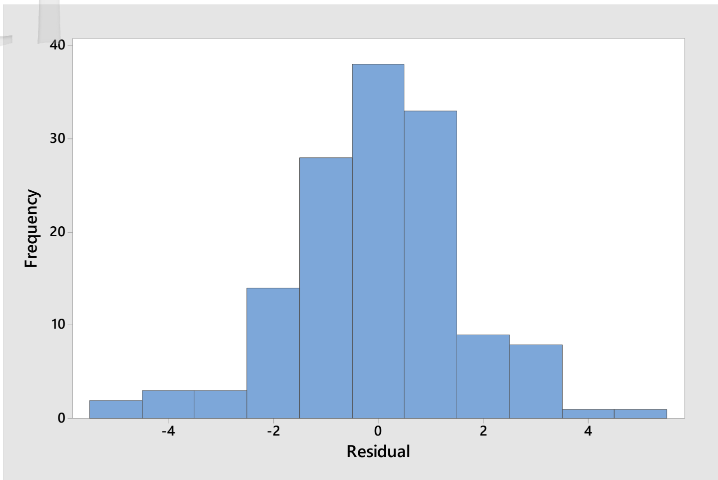


Figure 5 Residuals histogram plot for L/D

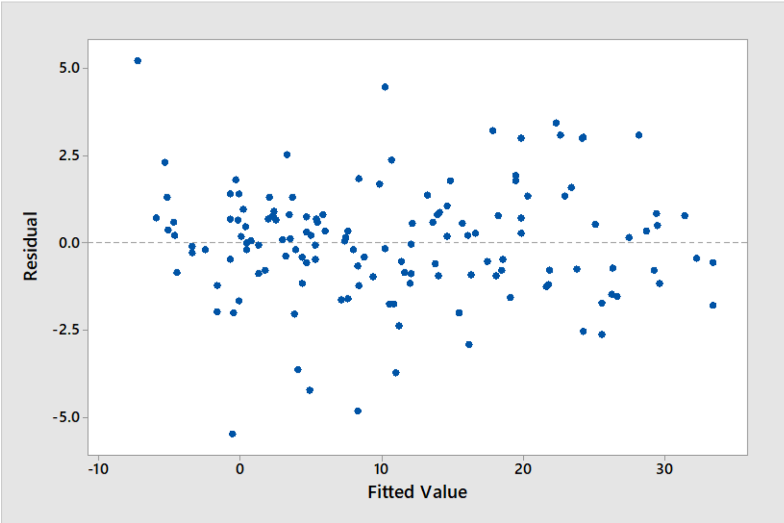


Figure 6 Residuals versus fits plot for L/D

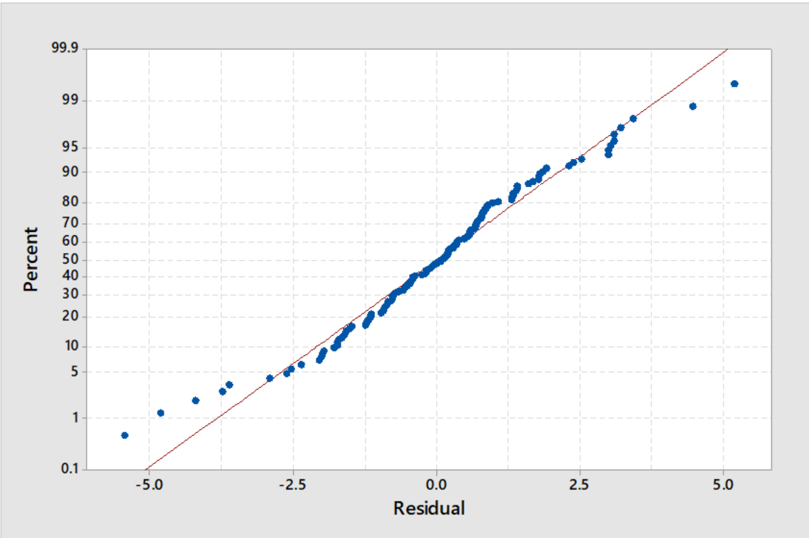


Figure 7 Normal probability plot of residuals

Table 4 Actual versus predicted L/D values for random cases in goodness-of-fit test

Random Case Settings	L/D Value		% Error
	Actual	Predicted	
NACA 2314	22.037	18.322	16.858
NACA 4423	9.494	8.133	14.335
NACA 6218	21.062	21.811	3.556
NACA 5312	30.663	33.182	8.215
NACA 3426	2.015	2.291	13.697

IV. CONCLUSIONS

The selection or design of airfoils for flying vehicles is important to their overall aerodynamic performance. In this study, the metamodeling approach is applied to aid the decision-making process by constructing a metamodel that captures the effects of airfoil design variables to the value of L/D. The airfoil design variables are varied based on the NACA 4-series numbering system that dictates the values for maximum camber, location of maximum camber and also maximum thickness of the airfoil. In total, 140 airfoil designs are modelled and analyzed using XFLR5 software. The collected simulation analysis data is then statistically analyzed using MINITAB software and a regression model is fitted for the metamodel. On the whole, it has been found that the airfoil's maximum thickness is the most prominent design variable that can affect its aerodynamic L/D value. Moreover, the goodness-of-fit for the metamodel has been demonstrated, which corresponds to a R^2 value of 98.81% and prediction error of less than 20% for random test cases.

The findings from this study highlight that the effects of the considered airfoil design variables on L/D value can be aptly captured and modelled using statistical regression method. More simulation data and higher fidelity analysis tool will increase the accuracy and goodness of the model. In future, simulation analysis data for more airfoil designs can be added to fit the metamodel and more variables can also possibly be included into the predictive metamodel to further expand on its applicability, including variables that represent environmental or flow conditions of flights such as Reynolds number, Mach number and air density that are expected to have distinguished effects on L/D performance as well.

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