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CFD Letters

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ISSN: 2180-1363

Optimization of a Blended-Wing-Body Unmanned Aerial Vehicle Design for Maximum Aerodynamic Lift-to-Drag Ratio

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ARTICLE INFO

Article history:
Received 12 September 2022
Received in revised form 11 October 2022
Accepted 13 November 2022
Available online 1 March 2023

ABSTRACT

Although unmanned aerial vehicle (UAV) has found many applications in various fields, its operation has been constrained by its low flight endurance. To date, several design efforts are pursued to improve this performance and one of them is the exploration of blended-wing-body (BWB) design. In this study, parametric study is conducted on the BWB UAV design of Baseline-VII that is developed by Flight Technology and Test Center (FTTC), Universiti Teknologi MARA Shah Alam, Malaysia. The primary goal is to optimize the current Baseline-VII design for maximum lift-to-drag ratio, which in turn implies a higher flight endurance. Three design parameters are considered: inboard wing sweep angle, outboard wing sweep angle and also inboard wing span. A full-factorial design of experiments (DoE) is applied to set the total 27 design case settings for this study, with three different values considered for each design parameter: 10°, 25° and 50° for inboard and outboard wing sweep angles, and 200 mm, 300 mm and 400 mm for the inboard wing span. The computer-aided design (CAD) models for the design cases are constructed using Solidworks and the resultant aerodynamic lift-to-drag ratio is found through computational fluid dynamics (CFD) simulation analysis using ANSYS Fluent. The collected data is then statistically analysed using regression analysis in MINITAB to construct a representative regression model that aptly capture the effects of the varied design parameters on the design aerodynamic lift-to-drag ratio. Based on the results, it has been found that the maximum lift-to-drag ratio for the modified Baseline-VII UAV design is 2.8119, which is obtained with optimal settings of inboard wing sweep angle = 17.2727°, outboard wing sweep angle = 20.9091° and inboard wing span = 400 mm. This is about 28.4% increment of lift-to-drag ratio from the original Baseline-VII design.

Keywords:
Blended-wing-body; lift-to-drag ratio; unmanned aerial vehicles; sweep angle; wing span; parametric study

1. Introduction

Today, the unmanned aerial vehicles (UAVs) have found many operational applications in various fields. This situation is reflected by the increased worldwide numbers of flying UAVs, which has been projected to reach 3.2 million units by 2022 [1]. In conjunction to this, many emerging technologies and revolutionary designs for UAVs have been researched and developed to better match with their mission requirements for different specific usage. For instances, UAVs are used in estimation of forest

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https://doi.org/10.37934/cfdl.15.3.1221

inventory attributes [2], target surveillance [3] and precision agriculture such as production and soil mapping [4], and each of these applications will have their own mission goals and operational needs. However, in spite of their variety of applications, the utilization of UAVs has been greatly constrained by their onboard power supply. Most of UAVs are powered by batteries and the heavy reliance on their internal battery power to successfully perform their operational mission has been limiting the amount of time that they can be deployed [5]. The current batteries do not offer adequate power for long duration flight because of their low energy density, especially when other onboard systems such as cameras and sensors are also operated by the same battery as the UAV's propulsion system. For instance, a relatively high energy density lithium battery is only able to commonly power a flight time of about 20 to 40 minutes [6]. All in all, this limited flight endurance issue becomes a key factor that constrains operational flight range and flight time of current UAVs.

To improve flight endurance of these battery-powered UAVs, several new design researches and technology developments have been pursued. A direct effort to ease this issue is to enhance battery technologies and battery management system that will enable the UAVs to have longer operational flights through having more efficient energy storage and consumption [7]. The new emerging battery technologies are researched and developed to make UAVs lighter, smaller and longer lasting. Among others, these include new batteries such as liquid hydrogen, graphene, super capacitor and biofuel cells [8]. At this moment however, a much superior battery for use of UAVs has yet to be developed. Alternatively, another means to tackle this issue is to enhance the aerodynamic characteristics of the UAV designs. In this case, the flight endurance can be increased by reducing the required energy or power consumption for the UAVs to fly. UAV designs with high lift-to-drag ratio are preferred since they have better potential for increased flight endurance [9]. With this notion, new unconventional design concepts have been explored for UAVs including blended-wing-body (BWB). The BWB design, which integrates or blends the conventional wing and fuselage together into a single design structure, has been shown in many studies to have better aerodynamic characteristics and lower fuel or power consumption due to its reduced wetted area and weight [10]. In Malaysia, the Flight Technology and Test Center (FTTC), Universiti Teknologi MARA Shah Alam is actively researching and also developing small-scale UAVs. Several BWB UAVs have been designed and studied by FTTC over the years, from their first Baseline-I design up until Baseline-IX, which are developed for various operational missions and applications. Figure 1 shows few early design evolutions of BWB UAVs developed by FTTC.

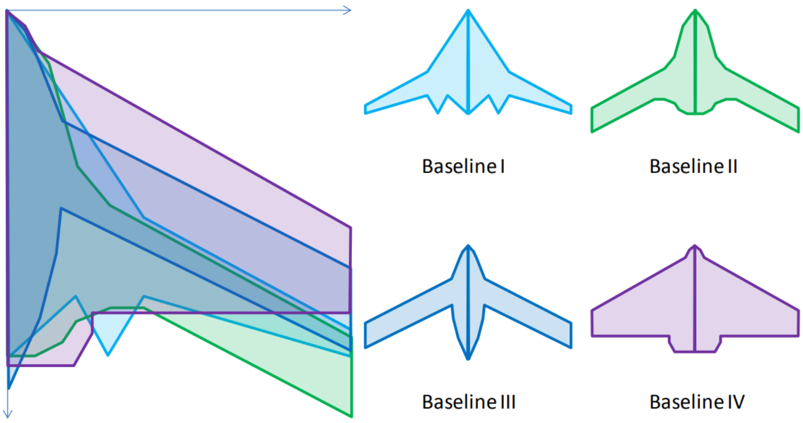

Fig. 1. Examples of BWB UAV designs by FTTC [11]

Of particular interest in this study is Baseline-VII design that is developed by FTTC based on the cranked-wing flying-wing configuration. This BWB UAV design is estimated to have maximum lift-to-drag ratio of 2.19 when cruise flying (*i.e.,* at angle of attack of roughly 0°) [12]. However, it is strongly believed that its aerodynamic performance can be further improved by optimizing its planform shape design. Hence, the main goal of this study is to conduct a parametric design analysis on the Baseline-VII BWB UAV and establish its optimal design settings for the highest maximum lift-to-drag ratio.

2. Methodology

Computational fluid dynamics (CFD) analysis essentially deals with numerical flow simulation and it is governed by several key governing equations that dictate the physics of fluid mechanics and also thermal sciences like continuity, Navier-Stokes and energy equations [13]. In aerospace applications, CFD is a widely applied method to estimate the aerodynamic features or characteristics of objects or vehicle designs. For instances, CFD simulation has been used in analyzing aerodynamic performance of UAV designs [14], airfoil designs [15] and also unconventional flying vehicle designs such as hybrid airships [16]. Furthermore, a parametric study is often applied as part of design optimization process, whereby interested design parameters are varied to capture their effects on the objective function of the optimization [17]. Based on collected data from the parametric study, optimal setting of the interested design parameters that corresponds to the optimum value of the design objective function can be derived. As mentioned before, the aim of this study is to optimize the Baseline-VII BWB UAV design by FTTC with respect to its maximum aerodynamic lift-to-drag ratio. The reference baseline design of this BWB UAV is shown in Figure 2, which also illustrates the considered design parameters for the parametric study: inboard sweep angle, outboard sweep angle and inboard wing span.

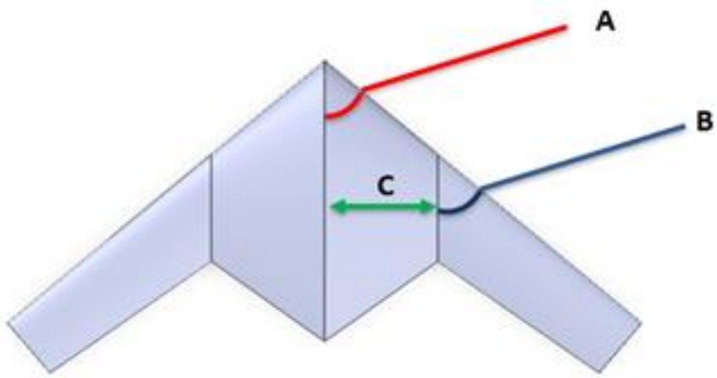

Fig. 2. Design variables for the parametric study: A (inboard sweep angle), B (outboard sweep angle), C (inboard wing span)

Each of the design parameters is varied at three different values for the parametric study: inboard wing sweep (10°, 25°, 50°), outboard wing sweep (10°, 25°, 50°) and inboard wing span (200 mm, 300 mm, 400 mm). To determine the simulation case design settings for these design parameters, design of experiment (DoE) method is used. DoE is often applied in many research studies for experimental or simulation planning to ensure that the data obtained is highly suitable for statistical analysis such as the regression analysis [18, 19]. For this study, based on a full-factorial DoE setup, there are a total number of 27 different design cases. CFD simulation analysis using ANSYS Fluent software is done to obtain aerodynamic lift-to-drag ratio for all these 27 design cases. Using these CFD simulation results, a regression model that aptly captures the effect relationship between the aerodynamic lift-to-drag ratio and the considered design parameters is derived with the statistical analysis software, MINITAB. The regression model is then applied to find the optimal setting of the considered design parameters that corresponds to the highest value of the lift-to-drag ratio for the BWB UAV design.

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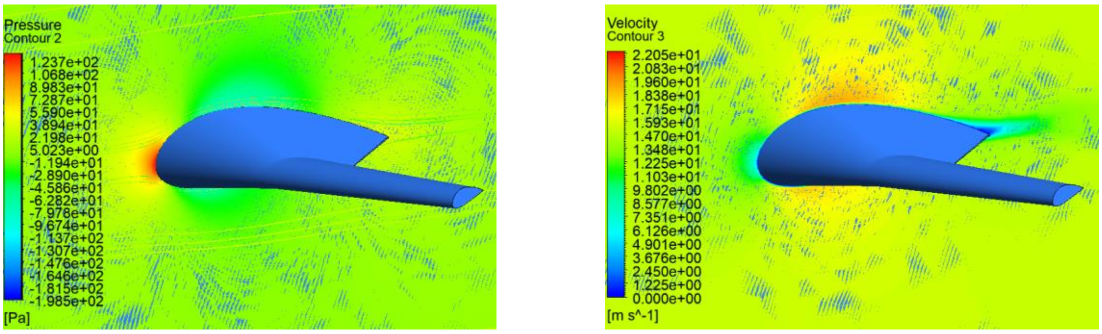
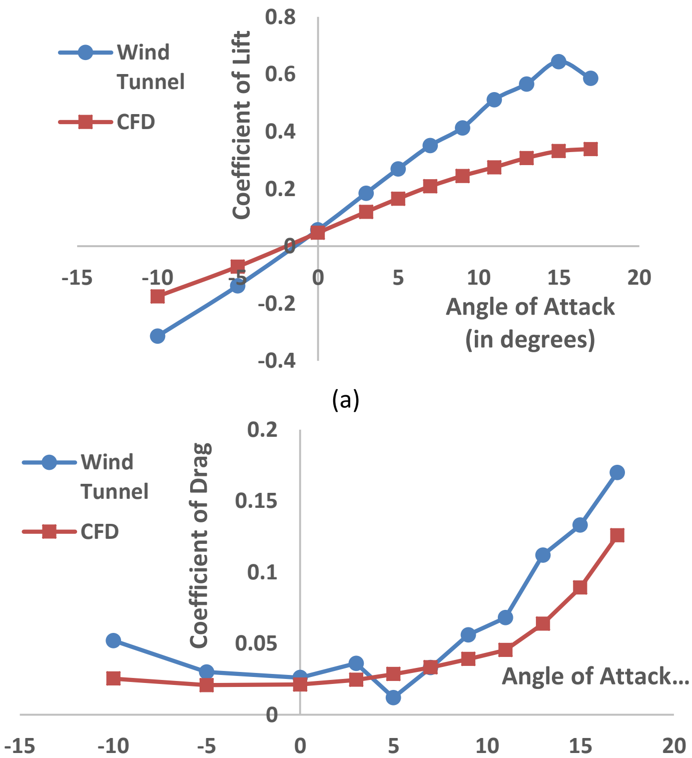
Before the CFD simulation design case runs are conducted, it is common to do an initial test case run to validate the simulation settings and select proper simulation parameters such as meshing and turbulence model. For this study, experimental result from previously conducted wind tunnel test for Baseline-VII UAV design, which has been published by Ahmad *et al.,* [20], is used as the comparative reference for the initial validation study. In this case, the CFD simulation settings are tailored to the wind tunnel test setup in the experimental study, which was done using the wind tunnel facilities at UTM-LST AEROLAB of Universiti Teknologi Malaysia. Moreover, Reynolds number is set to 2.63 x 10^5, and the Spalart-Allmaras turbulence model and tetrahedral mesh are applied for the CFD simulation. Figure 3 shows the CFD simulation results of the constructed CAD model for the current Baseline-VII design. Comparison of results between the CFD simulation and the wind tunnel experimental testing is presented in Figure 4.



(a) (b)

Fig. 3. CFD simulation results for current Baseline-VII design (a) Pressure contour (b) Velocity contour



(a)

(b)

Fig. 4. Comparison of lift and drag coefficients from CFD simulation and reference wind tunnel test (a) Lift coefficient (b) Drag coefficient

It can be observed that the trends for both aerodynamic lift and drag coefficients obtained from the numerical simulation analysis are essentially similar to the outputs from the wind tunnel testing. Errors between the two results are also found to be within an acceptable range. Of particular interest, at approximately 0° angle of attack, which is the main focus of this study for the cruising flight phase, the lift and drag coefficients from the CFD simulation analysis are 0.047 and 0.021, respectively, while values obtained from experimental wind tunnel test are 0.057 and 0.026, respectively. Accordingly, the resultant lift-to-drag ratio value is 2.21 for the CFD simulation and 2.19 for the wind tunnel test, leading to an error of only 0.91%. Overall, based on the results, it is concluded that the CFD simulation settings used are aptly appropriate to represent the conditions of the previous wind tunnel testing and the output results are of acceptable accuracy to the actual values.

In the meantime, Figure 5 shows the results for the conducted mesh study of the CFD simulation. The mesh study, or also known as grid independence test, is commonly done to dictate suitable mesh size and type to be used in the simulation analysis [21]. As previously discussed, the accuracy of the obtained lift and drag coefficient values for the CFD simulation is taken as appropriate and this means that the mesh type used is acceptable for this simulation study. Moreover, it can be taken from the plot in Figure 5 that the values of both lift and drag coefficients converged at number of elements of around 2 million. This becomes the benchmark in terms of number of elements for the meshing, and subsequently also the mesh size, for the simulation study.

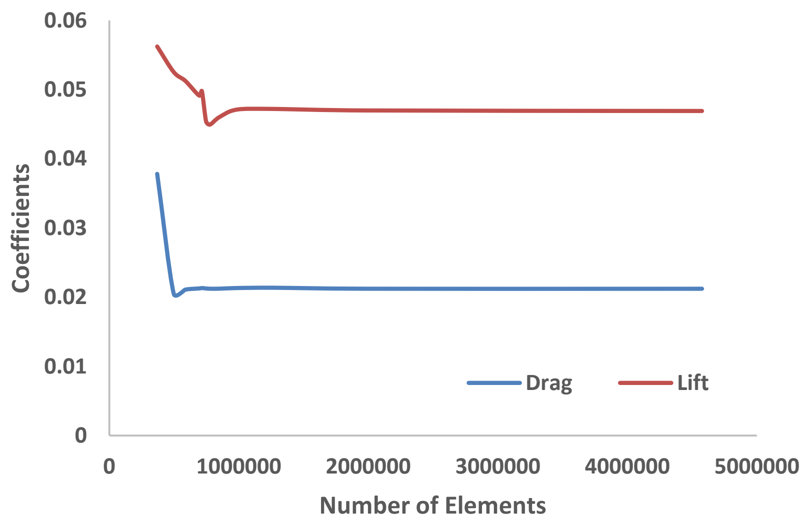


Fig. 5. Mesh convergence study for the CFD simulation analysis

Once the CFD simulation settings have been validated and finalized, simulation runs for 27 design cases of the Baseline-VII can be conducted. Computer-aided design (CAD) models for all 27 simulation case runs of the Baseline-VII design are constructed using Solidworks software and they are imported into the ANSYS Fluent software for the CFD simulation analysis. It should be noted that the resultant modified Baseline-VII BWB UAV design is determined accordingly by the values of inboard wing span, outboard sweep angle and inboard sweep angle such that the total wing area of the original baseline design of Baseline-VII is maintained in all 27 different design variation cases. In general, wing area is an important design feature that has been used for estimation of the operational flight performance, structural empty weight and also volume of traditional wing section. By having similar wing area, this provides a good comparison basis for the effects of the design variations on aerodynamic lift-to-drag ratio without significantly affecting other features of the original BWB UAV design such as weight and available onboard volume. Moreover, since the focus is on the cruise flight, the angle of attack used for the CFD simulation runs is 0°.

3. Results and Discussion

The simulated lift-to-drag ratio from the CFD analysis for all 27 design cases is tabulated in Table 1. It can be seen that it is hard to establish any directly visible trends of effects by just looking at the simulation results. In order to have better understanding of the effects caused by the varying design parameters on aerodynamic lift-to-drag ratio of the modified Baseline-VII design, standard statistical regression analysis is applied. This is a widely-used method for investigating underlying relationships between interested variables, or in other words, to determine the causal effect of one variable to the other. Some examples of similar use of regression analysis method to this study include Japar *et al.,* [22], Ni *et al.*, [23] and Jalasabri *et al.,* [24].

Table 1
Simulation results of lift-to-drag ratio for all 27 design cases

Inboard Wing Span, *b* (mm)	Outboard Wing Sweep Angle, α_o (°)	Inboard Wing Sweep Angle, α_i (°)	Simulated Lift-to-Drag Ratio, *L/D*
200	10	10	1.818
200	10	25	1.911
200	10	50	2.145
200	25	10	1.822
200	25	25	1.913
200	25	50	2.161
200	50	10	1.599
200	50	25	1.709
200	50	50	1.973
300	10	10	2.508
300	10	25	2.613
300	10	50	2.687
300	25	10	2.521
300	25	25	2.648
300	25	50	2.703
300	50	10	2.376
300	50	25	2.482
300	50	50	2.548
400	10	10	2.790
400	10	25	2.770
400	10	50	2.430
400	25	10	2.803
400	25	25	2.759
400	25	50	2.419
400	50	10	2.669
400	50	25	2.633
400	50	50	2.312

The regression analysis in this study is done using MINITAB statistical software and the resultant analysis of variance (ANOVA) table is presented in Table 2. The coefficients for the regression model are tabulated in Table 3 and this model has coefficient of determination, R^2 of 99.84%. A high R^2 value indicates that the regression model appropriately captures the variability of the simulation data very well, which in turn implies on its goodness of fit and predictability. Note that the regression model is fitted up until the third order terms for each main design parameter and all possible interaction cross terms. However, as observed in both Table 2 and Table 3, there are few missing terms that have been eliminated from the final regression model due to their negligible effect on the value of the simulated lift-to-drag ratio.

Table 2
ANOVA table for the regression analysis

Source	DF	SS	MS	F-Value	p-Value
Inboard Wing Span, b	1	0.060	0.060	1.000	0.375
Outboard Wing Sweep Angle, α_o	1	0.008	0.008	0.140	0.730
Inboard Wing Sweep Angle, α_i	1	0.014	0.014	0.240	0.653
b^2	1	0.013	0.013	0.210	0.670
α_o^2	1	0.004	0.004	0.070	0.804
α_i^2	1	0.010	0.010	0.160	0.706
$b*\alpha_o$	1	0.002	0.002	0.030	0.869
$b*\alpha_i$	1	0.005	0.005	0.080	0.798
$\alpha_o*\alpha_i$	1	0.031	0.031	0.510	0.516
b^3	1	0.005	0.005	0.090	0.783
$b^2*\alpha_o$	1	0.001	0.001	0.010	0.931
$b^2*\alpha_i$	1	0.002	0.002	0.030	0.868
$b*\alpha_o^2$	1	0.001	0.001	0.020	0.906
$b*\alpha_i*\alpha_o$	1	0.008	0.008	0.140	0.732
$b*\alpha_i^2$	1	0.002	0.002	0.040	0.861
$\alpha_i*\alpha_o^2$	1	0.014	0.014	0.230	0.659
$\alpha_i^2*\alpha_o$	1	0.014	0.014	0.230	0.659
$b^2*\alpha_o^2$	1	0.000	0.000	0.000	0.952
$b^2*\alpha_i*\alpha_o$	1	0.000	0.000	0.010	0.938
$b^2*\alpha_i^2$	1	0.000	0.000	0.000	0.949
$b*\alpha_i*\alpha_o^2$	1	0.008	0.008	0.130	0.736
$b*\alpha_i^2*\alpha_o$	1	0.008	0.008	0.130	0.740
$\alpha_i^2*\alpha_o^2$	1	0.005	0.005	0.080	0.787
Error	4	0.242	0.061		
Total	27	153.965			

Table 3
Coefficients of the constructed regression model

Term	Coefficient	Term	Coefficient
b	0.032080314	$b*\alpha_o^2$	-0.000005011
α_o	-0.149483522	$b*\alpha_i*\alpha_o$	-0.000012093
α_i	-0.195654482	$b*\alpha_i^2$	-0.000007481
b^2	-0.000107896	$\alpha_i*\alpha_o^2$	-0.000055869
α_o^2	0.001486943	$\alpha_i^2*\alpha_o$	-0.000055773
α_i^2	0.002274532	$b^2*\alpha_o^2$	0.000000004
$b*\alpha_o$	0.000526481	$b^2*\alpha_i*\alpha_o$	0.000000004
$b*\alpha_i$	0.000817992	$b^2*\alpha_i^2$	0.000000004
$\alpha_o*\alpha_i$	0.005816458	$b*\alpha_i*\alpha_o^2$	0.000000072
b^3	0.000000114	$b*\alpha_i^2*\alpha_o$	0.000000071
$b^2*\alpha_o$	-0.000000456	$\alpha_i^2*\alpha_o^2$	0.000000468
$b^2*\alpha_i$	-0.000000876		

Apart from the R^2 value, another means to test the goodness of the constructed regression model is by conducting a random test case. This test can also indicate the goodness of the prediction by the regression model for cases that are not included in its construction. For this study, a random case of inboard wing sweep angle = 13.2323°, outboard wing sweep angle = 15.6566° and inboard wing span = 400 mm is used. The CAD model for this random design case is constructed and the corresponding lift-to-drag ratio is obtained through CFD simulation. Table 4 presents the comparison between the simulated lift-to-drag value and the predicted value using the constructed regression model, and it is observed that the error is just about 0.3%. This further supports the goodness of the fitted regression model.

Table 4
Random test case for the constructed regression model

b (mm)	α_o (°)	α_i (°)	Lift-to-Drag Ratio from CFD Simulation	Predicted Lift-to-Drag Ratio using Regression Model	Error (%)
400	15.6566	13.2323	2.8144	2.8062	0.2914

Since the goodness-of-fit of the regression model has been clarified, it can be used to predict the optimum settings of inboard wing sweep angle, outboard wing sweep angle and inboard wing span that correspond to the maximum lift-to-drag ratio. Using the response optimizer feature in MINITAB as shown in Figure 6, the optimum settings have been found as inboard wing sweep angle = 17.2727°, outboard wing sweep angle = 20.9091° and inboard wing span = 400 mm, and maximum lift-to-drag ratio is 2.8119. In comparison to the maximum lift-to-drag ratio of roughly 2.19 at 0° angle of attack for the current original Baseline-VII UAV design, this is close to 28.4% improvement.

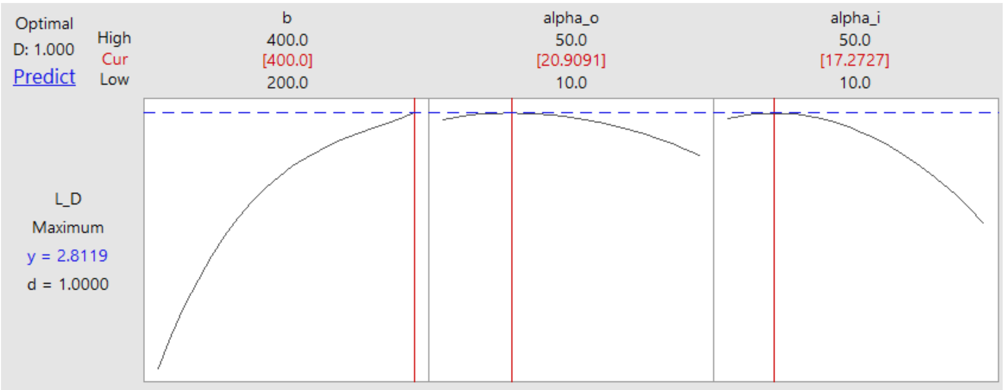


Fig. 6. Optimum settings for maximum lift-to-drag ratio

4. Conclusion

A parametric study is conducted on the current Baseline-VII UAV design to improve its lift-to-drag ratio, which in turn will increase its operational flight endurance. Three design parameters: inboard wing sweep angle, outboard wing sweep angle and inboard wing span, are varied at three different values, leading to a total 27 design cases based on full-factorial DoE settings. CFD simulation analysis using ANSYS Fluent software are conducted on these design cases and the obtained lift-to-drag ratio data is then used in regression analysis using MINITAB software. Based on the optimization result, it is found that maximum lift-to-drag ratio for the modified Baseline-VII UAV design can be potentially improved to 2.8119, an increment of 28.4%. This is achieved by having the inboard wing sweep angle = 17.2727°, outboard wing sweep angle = 20.9091° and inboard wing span = 400 mm.

Acknowledgement
The research was not funded by any grant.

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