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Prediction of drag coefficient of a hybrid body design of aircraft

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Abstract. *This study presents a design of a quintessential hybrid body aircraft, a blended NACA 4414 airfoil winged body. The Design of Elements approach, via Response Surface Methodology (RSM), is used to evaluate the influence of frontal area, chamber angle and materials on the drag coefficient. The Analysis of Variance (ANOVA) is carried out to find the influences of the same. In order to minimize the simulations, a model in RSM, Central Composite Design (CCD) is used. The results of the same are verified via Computational Fluid Dynamics (CFD) simulations.*

Moreover, combinations of shape memory polymers with composites and graphene nano powder are proposed, for light-weighting and enhanced mechanical properties. A comparison of said materials with commercially used aluminum alloys is done. It is found that the lowest drag coefficient is achievable at a frontal area of 1625 m^2 with an angle of attack of –10° and with a material combination of carbon fiber reinforced polymer, glass fiber reinforced polymer, and 10% graphene nano powder by weight.

Keywords: *finite element analysis; ANOVA; hybrid design aircraft; computer aided design; drag reduction.*

1. Introduction

The significant increase in fossil fuel consumption over the last few decades has created a demand for energy sustainability. This is due to the extensive usage of airplanes for both military and civilian purposes [1]. The aviation industry is an indispensable constituent for the global development of a country. It encompasses the transport of goods and people and thus, the economy and societal value of that country. It paves the way for commerce, trade, tourism, etc. This priority leads to the question of the impact of the aviation industry on other deciding factors such as the environment. The global fuel consumption by commercial airlines reached 95 billion gallons in 2019. This was before it plummeted to almost half the reported fuel consumption due to the COVID-19 pandemic [2]. Fuel economy is the underlying basis behind this project and fuel consumption, including its increasing costs, is still among the major concerns in the aircraft industry. Furthermore, it is estimated to achieve zero emissions by the global aviation industry by 2050 [3]. Aircraft and aerospace technology are evolving. The need to have sustainable development with cleaner and greener use of resources has led to the exploration of many opportunities in this field. Several intricate details, however, have to be addressed to achieve 100% sustainability. Some of these issues include reduction of fuel burn, size, capacity of the aircraft, increase in efficiency and reduction in emissions. Many people have come up with ways to address these problems. [4] Rhea et al. suggested that aerodynamic shape and structural design optimizations maximize the performance at a single flight condition may result in designs with unacceptable off-design performance; [5] Christoper et al. commented on tweaking parameters of the aircraft engine to reduce fuel burn. The aviation industry has not been able to incorporate these solutions into the existing models for various reasons. Some of these reasons include, the safety factors such as emergency exit routes, crash absorbers underneath the fuselage to protect the passengers in case of a crash, the width of airport hangers, and so on.

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Following the revelation of the configuration's enormous potential above traditional fixed-wing aircraft, interest in the design of the hybrid wing body has surged substantially in recent years [6]. The BWB's (blended wing body) aerodynamic advantages come from the integration of its fuselage and wings, which results in a low wetted surface area to volume ratio and lower interference drag. In comparison to a traditional arrangement, this reduces total drag and increases the L/D ratio [7]. With weight reduction, moreover, it aims to reduce fuel burn from 45–50% and thereby increase the overall efficiency.

Usage of optimal materials is paramount for fuel savings as materials are directly related to lightweight. The use of high-performance materials such as composites and structural optimization using computer-aided engineering approaches have been typical light-weighting implementations, with production enabled by advanced manufacturing methods [10]. Shape memory polymers and their composites (SMPs and SMPCs) are a novel family of smart materials that can respond to specific environmental stimuli and recall their original shape. To trigger the deformation of SMPs and SMPCs, a variety of stimulus mechanisms are used. The most prevalent of which being thermal- and electro-responsive components and structures [11]. In comparison to SMAs or ceramics, SMPs offer a far higher degree of deformation and a broader range of variable mechanical properties, in addition to their inherent advantages of being cheap, lightweight and quick to produce. Polymers, in specific, have further advantages in that they may be made biocompatible, non-toxic and biodegradable [12].

This literature reviews various combinations of shape memory polymers and composites incorporating nano graphene powder dealing a genre of materials that is inclusive of shape memory polymers, nanomaterials and composites. Shape Memory Polymer Composites (SMPCs), as explained by Wilson et al, combine the mechanical properties of composite materials with the shape memory polymer's functional characteristics. The incorporation of Nano-fillers in the SMP matrix can improve the mechanical characteristics of Shape Memory Polymer Nano-Composites (SMPNCs) and structural portions in industrial components as required [13]. From the simulations carried out by Yang [14], it can be seen that the angle of attack or the chamber angle directly influences the drag coefficient. It was found that the drag coefficient increases as the angle of attack increases. Moreover, from the equation of coefficient of drag, it can be inferred that it depends on the frontal area of the aircraft. The design of experiment (DOE), as a statistical method, has been widely applied in different fields of science and industry, especially to support the design, development and optimization of products and processes [16]. It consists of a set of applied statistical methods for systematically classifying and quantifying cause-and-effect relationships between variables and outputs in the researched process or phenomenon, with the goal of determining the settings and conditions under which the process can be optimized [16].

Following this, Analysis of Variance (ANOVA) is performed to find the extent of influences of the said parameter on the output variable. The statistical process of analysis of variance (ANOVA) is used to compare the means of several samples. It can be regarded as a multi-group version of the t-test for two independent samples. The goal is to see if there are any significant differences in class means, which is done by the analysis of variances [17]. The ANOVA test of the hypothesis is based on a comparison of two independent estimates of the population variance [18].

This research proposes a conceptual aircraft design comprising a hybrid body with a lifting fuselage design for boundary-layer ingestion to lower drag. Moreover, current innovations with regard to the design of the aircraft do not follow the airport norms, making them unsafe to fly. This work aims to address that issue. The findings based on the work of Chapman et al [8], are used as a reference for this paper. Chapman et al [8] modelled a hybrid body aircraft using the NACA 4414 airfoil and calculated it's drag coefficient. The profile is created using the GUI available at Airfoil Tools and a bespoke NACA 4414 airfoil [9]. The maximum camber is 4.3 percent at 40 percent chord length from the leading edge of the airfoil, the airfoil thickness is 14 percent chord length, and there are 200 points formed in space.

Taking frontal area and angle of attack as two key parameters and a combination of materials, from the literature, Computational Fluid Dynamics (CFD) analysis is performed to simulate the airplane under moving conditions against air, mimicking a real-life scenario. Influencing parameters are chosen based on the literature review and combinations yielding minimum drag coefficient values are presented. A number of material combinations consisting of SMPs and NCs are listed and recommended in this research. Furthermore, in order to investigate the influences of frontal area, chamber angle and materials, Response Surface Methodology (RSM) is used, which is one of the Design of Experiments (DoE) approaches, in order to decide the number of CFD simulations to be performed [15].

2. Methods

2.1. Modelling and Simulation

The steps involved in modeling and analysis are explained in Fig. 1. First, a hybrid body design aircraft is created using Solidworks software. The main aim of the designing process is to address the shortcomings of the previous designs.

The aircraft (Fig. 2) is designed in such a way to adhere to the airport specifications. The dimensions are 25 m high, 70 m long, and 60 m wide. Since this design is inspired by delta wing aircraft, the entire flight follows the NACA4412 airfoil. The literature [19] suggest that the NACA4412 has a bottom section which is almost flat. This prevents the negative ground effect, which leads to a better lift to drag ratio. In other words, it helps countermand the drag forces. For the analysis, the fuselage and wings are

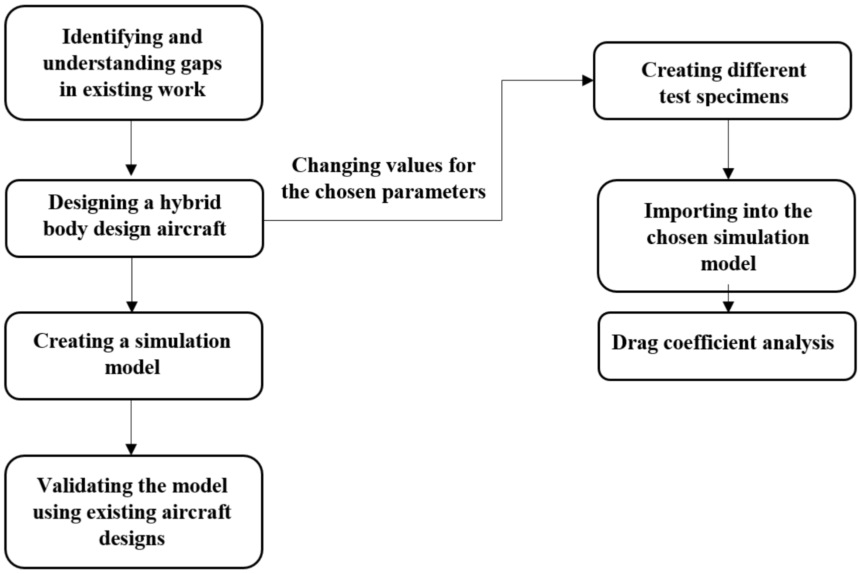

Fig. 1. Finite Element Analysis procedure

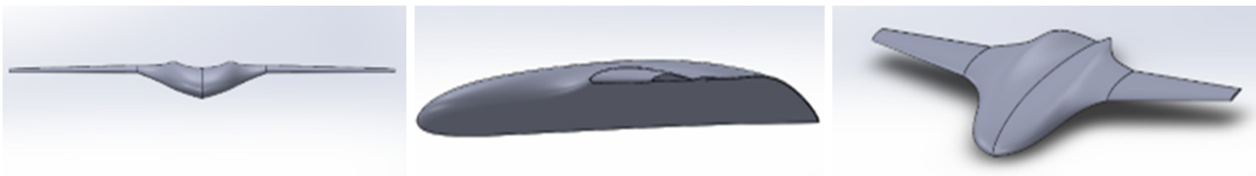

Fig. 2. Proposed Hybrid body design *a*) Front view *b*) Side view *c*) Isometric view

taken into consideration. As per Fig. 1, a simulation model is created. This model is validated using existing commercial aircraft – Boeing 737-700 and Airbus A319 [20].

There are several kinds of drag forces that act on an aircraft. They are wave, skin-friction, form, interference and trim drag forces. Additional drag forces are also generated by components of aircrafts such as fuselage, wings, spoilers, struts, landing gears and so on. Wave drag is usually caused by shock waves on the airfoil. This form of drag is not considered in calculating the drag coefficient in this case. Skin-friction drag, on the other hand, occurs due to the shear flow in the thin boundary layer close to the surface of the airfoil. Separated flow makes the boundary layer thick which in turn produces Form drag. Flow of fluid also causes interference drag. Mutual influence of flow around adjacent and neighboring components is responsible for interference drag.

Drag coefficient and drag force [21] can be calculated as follows:

$$\Delta C_{Do} = C_{fe} * FF * Q_c \frac{S_{wet}}{S_W} \tag{1}$$

Where, C_{Do}= Zero drag, C_{fe}= Skin-friction coefficient, S_{wet}= Wetted area, S_W= the wetted area of the component, FF= form factor, and Q_C= interference factor.

For a laminar flow,

$$C_{fe} = \frac{1.328}{\sqrt{\text{Re}}} \tag{2}$$

Whereas for a turbulent flow,

$$C_{fe} = \frac{0.455}{\left(\log \text{Re}\right)^{2.58} \cdot \left(1 + 0.144 + M^2\right)^{0.65}} \tag{3}$$

Where M =Mach number and Re = Reynolds number. Since this paper primarily focuses on fuselage and wings, one can calculate the $S_{W,\ Fuselage}$ and $S_{W,\ wing}$ as:

$$S_{W,Fuselage} = \pi d_f l_f \left(0.5 + 0.135 \cdot \frac{l_n}{l_f}\right)^{\frac{2}{3}} \cdot \left(1.015 + \frac{0.3}{\lambda_F^{1.5}}\right) \tag{4}$$

$$S_{W,wing} = 2 S_{\exp} \left(1 + 0.25 \left(t/C\right)_r \cdot \frac{1 + \tau\lambda}{1 + \lambda}\right) \tag{5}$$

where:
$d_f =$ Fuselage diameter, ($d_f =$ Fuselage circumference /π)
$\lambda_f =$ Fuselage fineness ratio, $\lambda_f = l_f / d_f$,
$l_n =$ The distance from the aircraft nose in x direction to the start of the cylindrical part of the fuselage,
$l_f =$ The length of the fuselage,

$(t/C)_r =$ Ratio of the thickness of the wing airfoil to the chord length,
$S_{exp} =$ Exposed wing area,
$\tau =$ Ratio of relative airfoil thickness,
$\lambda =$ Taper.

$$DragForce = \frac{1}{2} C_D A_1 \rho v^2 \quad (6)$$

$$C_D = \Delta C_{Do} + k C_L^2 \quad (7)$$

$$\Delta C_{Do} = C_{Do} + \Delta C_{D(wings)} \quad (8)$$

Where:
C_D = Drag Coefficient,
A_1 = Frontal Area or the area that is projected,
P = density of fluid,
v = relative velocity between the fluid and the material,
k = Correction factor, $k = \frac{1}{\pi A e}$,
e = Oswald factor,
C_L = Lift coefficient of wings.
When the angle of attack changes, the equation for drag coefficient takes a parabolic form. As the angle of attack inches closer to the maximum angle, the equation becomes as mentioned in equation (9):

$$C_D = \Delta C_{Do} + k_1 (C_L - C_{L\min})^2 + k_2 (C_L - C_{L\min})^4 \quad (9)$$

Equations 1–9 are taken from [21]. Weight of the material used also influences the drag force and drag coefficient. From this, one can infer that drag coefficient and drag force are dependent on the frontal area, angle of attack and the material used. Thus, the above-mentioned parameters are used to perform the analysis.

Table 1 suggests that the error is less than 5% showing the validation of chosen simulation model. The same simulation model is used to analyze the drag coefficient of the proposed model. The initial analysis gives an inference that the drag coefficient of the proposed model is 0.023. Ansys FLUENT is used to perform the analysis. Meshing is done at element size – 0.1 mm (Fig. 4).

Several simulation analyses are run by using different permutations and combinations of parameters like frontal area, material and angle of attack obtained from the DOE (Designs of Experiment) approach.

Table 1. Validation of the simulation model with existing aircraft designs

Aircraft Model	Actual Drag coefficient	Observed drag coefficient
Boeing 737-700	0.029	0.031
Airbus A319	0.031	0.030

Reynolds- Averaged Navier-Stokes (RANS) procedure is used as it gives best results irrespective of the computational power. All calculations are carried out with appropriate enclosures at cruising speed of 150 m/s at an altitude of 10,000 m above sea level (Fig. 3) [22]. In order to achieve high accuracy, second order is chosen for pressure, density, momentum and energy [23].

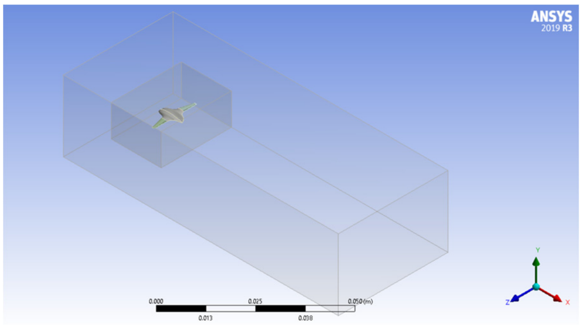

Fig. 3. Enclosures around the aircraft

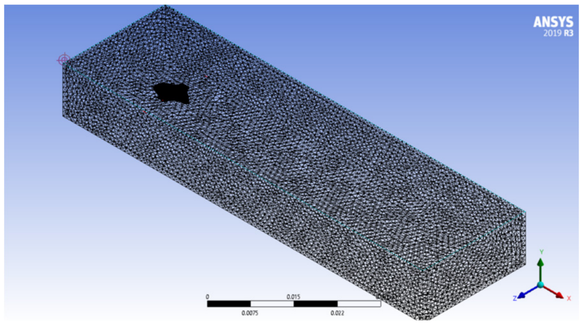

Fig. 4. Post meshing with element size 0.0001 m

3. Results and Discussion

3.1. Design of Experiments and Optimization

Five levels are considered for each parameter. The DOE approach is used to find different permutations and combinations of material, frontal area and angle of attack to perform the analysis. The central composite design (CCD) (Fig. 5) of the Response Surface Methodology (RSM) is used in the DOE approach. CCD is efficient as it provides information on total error and variable effects. It is represented by the combination of 20 points with 6 axial and 8 corner points. Each of the five levels is labeled as –2, –1, 0, 1 and 2. This is done to have a rotatable design.

Table 2 represents the parameter levels used for DOE. The DOE table (Table 3) is used to determine the number of simulations to be performed. Sample models are created and the analyses are performed in accordance with the sample models. After the analysis, ANOVA (Table 4) is performed using the MINITAB software to understand the influences of the input parameters on the response parameter, i.e., drag coefficient. A regression equation is then obtained. The equation helps to understand the relationship among the variables.

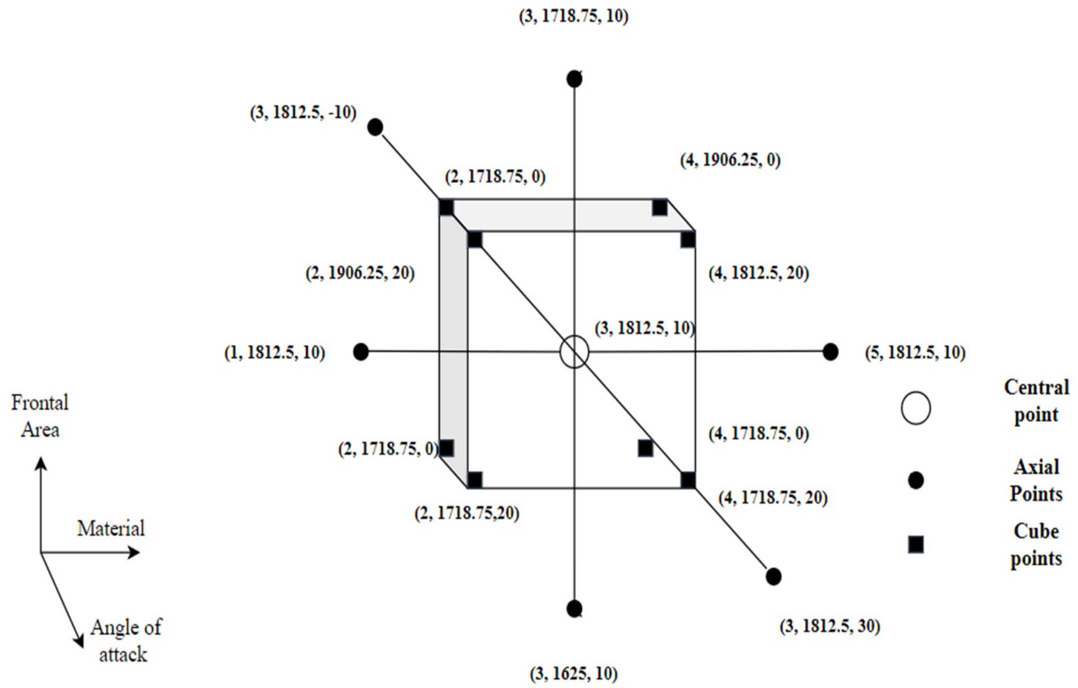

Fig. 5. Central Composite Design

Table 2. Parameter Levels

Symbol	Parameter	Level				
		–2	–1	0	1	2
X1	Material	1	2	3	4	5
X2	Frontal Area (m^2)	1625	1718.75	1812.5	1906.25	2000
X3	Angle of attack (°)	–10	0	10	20	30

Where,
1= Glass Fiber Reinforced Polymer (GFRP) (45%) + Carbon Fiber Reinforced Polymer (CFRP) (45%) + Graphene Nano Powder (10%)
2= Acrylonitrile Butadiene Styrene plastics (ABS) (45%) + CFRP (45%) + Graphene Nano Powder (10%)
3= Poly Lactic Acid (PLA) (45%) + CFRP (45%) + Graphene Nano Powder (10%)
4= Aluminium alloy 2024,
5= Aluminium Alloy 2014

Table 3. Table showing different combinations and drag coefficient

Standard Order	Run Order	Material	Frontal Area(m^2)	Angle of Attack (°)	Actual Drag Coefficient
1	1	2	1,718.75	0	0.024
2	2	4	1,718.75	0	0.028
3	3	2	1,906.25	0	0.028
4	4	4	1,906.25	0	0.032
5	5	2	1,718.75	20	0.028
6	6	4	1,718.75	20	0.032
7	7	2	1,906.25	20	0.032
8	8	4	1,906.25	20	0.036
9	9	1	1,812.5	10	0.022
10	10	5	1,812.5	10	0.034
11	11	3	1,625	10	0.026
12	12	3	2,000	10	0.034
13	13	3	1,812.5	–10	0.03
14	14	3	1,812.5	30	0.034
15	15	3	1,812.5	10	0.03
16	16	3	1,812.5	10	0.03
17	17	3	1,812.5	10	0.03
18	18	3	1,812.5	10	0.03
19	19	3	1,812.5	10	0.03
20	20	3	1,812.5	10	0.03

Table 4. Analysis of Variants (ANOVA) results

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	0.000366	0.000122	57.42	0.000
Material	1	0.000138	0.000138	64.95	0.000
Frontal Area	1	0.000189	0.000189	88.94	0.000
Angle of attack	1	0.000039	0.000039	18.38	0.001
Error	16	0.000034	0.000002		
Lack-of-Fit	11	0.000034	0.000003	*	*
Pure Error	5	0.000000	0.000000		
Total	19	0.000400			

3.2. Regression Equation

The obtained regression equation is a second order polynomial. Corresponding values of Material, frontal area and angle of attack are substituted in the regression equation.

Table 5 shows the value of drag coefficient obtained from the regression equation along with the error percentage.

$$Drag\ Coefficient = -0.04553 + 0.002938A \\ +0.000037B + 0.000156C$$

Where, A= Material; B= Frontal Area and C= Angle of attack. To validate and understand it's compatibility, the regression model is tested and compared to the results obtained from the FEA analysis. The calculated error in drag coefficient between the former and the latter is observed to be less than 5%. This shows the legitimacy of the regression equation. The main effects plot (Fig. 6) is plotted to find the impact of each input parameter on the drag coefficient. The graph suggests that drag coefficient increases significantly with increase in Frontal area and the angle of attack. Of all materials, Glass Fiber Reinforced Polymer (GFRP) (45%) + Carbon Fiber Reinforced Polymer (CFRP) (45%) + Graphene Nano Powder (10%) offer the least drag. The corresponding contour plots are also plotted as shown in Figs. 7–9. The contour plots show the influence of the material, frontal area and angle of attack on drag coefficient.

Table 5. Error analysis between FE simulation model and regression model

Standard Order	Run Order	Material	Frontal Area (m^2)	Angle of Attack (^{o})	Actual Drag Coefficient	Drag coefficient from regression	Error percent (%)
1	1	2	1,718.75	0	0.024	0.024	0
2	2	4	1,718.75	0	0.028	0.029	3.57
3	3	2	1,906.25	0	0.028	0.029	3.57
4	4	4	1,906.25	0	0.032	0.033	3.12
5	5	2	1,718.75	20	0.028	0.027	3.57
6	6	4	1,718.75	20	0.032	0.033	3.12
7	7	2	1,906.25	20	0.032	0.033	3.12
8	8	4	1,906.25	20	0.036	0.037	2.77
9	9	1	1,812.5	10	0.022	0.023	4.54
10	10	5	1,812.5	10	0.034	0.035	2.94
11	11	3	1,625	10	0.026	0.025	3.84
12	12	3	2,000	10	0.034	0.035	2.94
13	13	3	1,812.5	–10	0.03	0.029	3.33
14	14	3	1,812.5	30	0.034	0.035	2.94
15	15	3	1,812.5	10	0.03	0.031	3.33
16	16	3	1,812.5	10	0.03	0.031	3.33
17	17	3	1,812.5	10	0.03	0.031	3.33
18	18	3	1,812.5	10	0.03	0.031	3.33
19	19	3	1,812.5	10	0.03	0.031	3.33
20	20	3	1,812.5	10	0.03	0.031	3.33

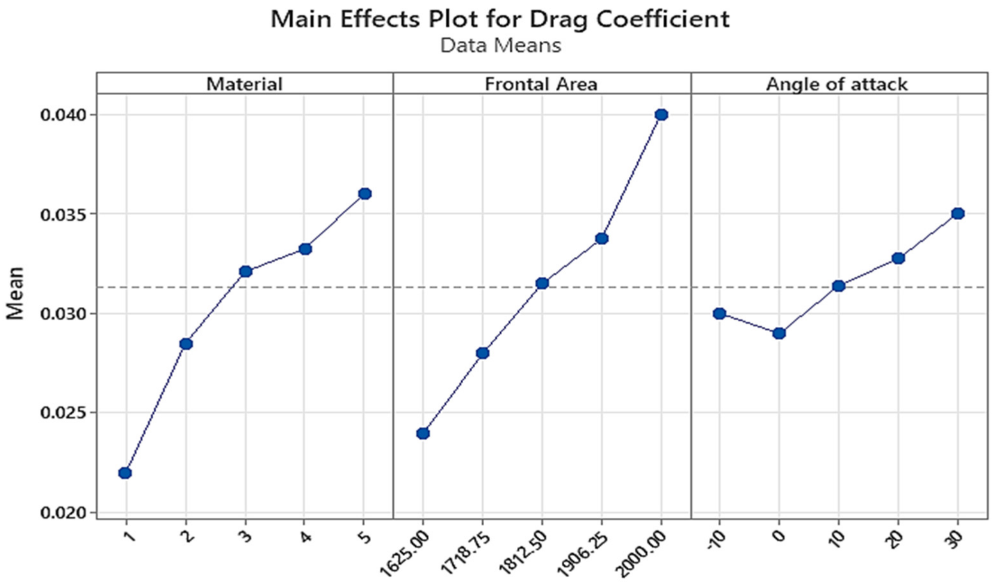

Fig. 6. Main Effects plot showing influences of different parameters on drag coefficient

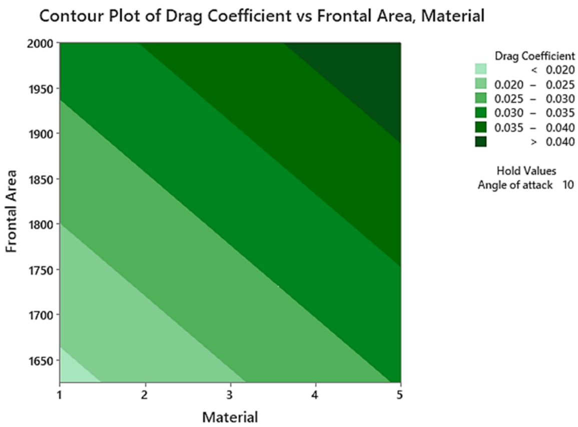

Fig. 7. Influences of Material and Frontal Area on the drag coefficient

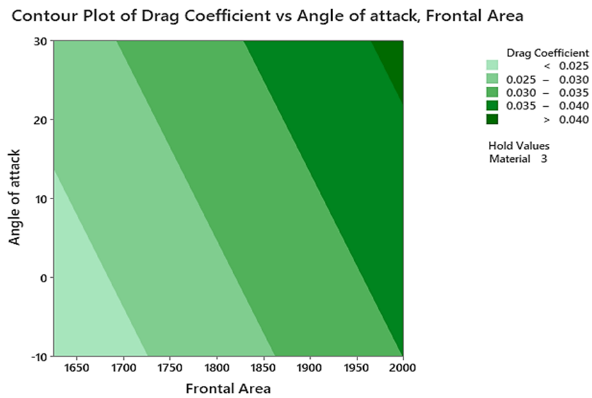

Fig. 9. Influences of Angle of attack and frontal area on the drag coefficient

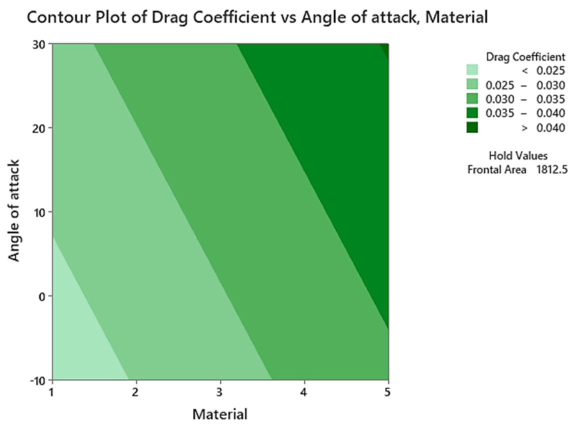

Fig. 8. Influences of angle of attack, material on the drag coefficient

3.3. Multiple Response Prediction

To identify the optimal combination of input parameters to achieve minimum drag coefficient, the response optimization study is performed. This can be done to single or multiple responses. Fig. 10 shows the optimization plot. MINITAB software is used to perform this. Table 6 suggests that Glass Fiber Reinforced Polymer (GFRP) (45%) + Carbon Fiber Reinforced Polymer (CFRP) (45%) + Graphene Nano Powder (10%), 1625 m^2 frontal area, and -10^o angle of attack are the optimal parameters. To confirm the results obtained, the FEA analysis is performed with the parameters mentioned in Table 6. The corresponding result is 0.018. Error analysis between the Optimization Result (0.017) (Table 6) and the Finite element analysis (0.018) is observed to be 5.56% (Table 7). This proves that the optimized model is legitimate.

Table 6. Response optimization results

Variable		Value		
Material		Glass Fiber Reinforced Polymer (GFRP) (45%) + Carbon Fiber Reinforced Polymer (CFRP)(45%) + Graphene Nano Powder (10%)		
Frontal Area		1625 m^2		
Angle of attack		–10°		
Response	Fit	SE Fit	95% CI	95% PI
Drag Coefficient	0.01683	0.00149	(0.01288, 0.01917)	(0.01130, 0.02075)

Table 7. Error analysis between optimized drag coefficient and observed drag coefficient from finite element analysis

Optimal drag coefficient (response optimization)	Observed drag coefficient (FEM)	Error
0.017	0.018	5.56

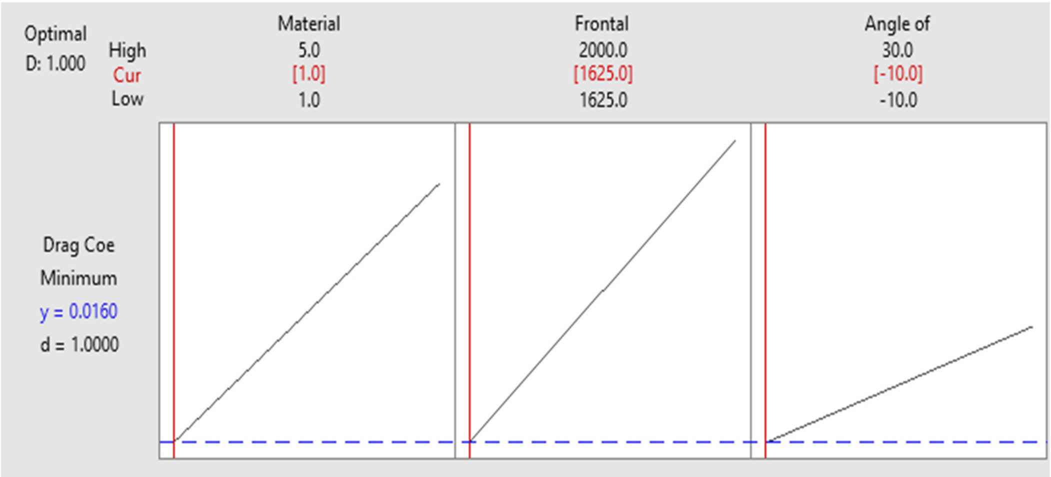

Fig. 10. Response optimization of different parameters

4. Conclusions

The finite element analysis to estimate the drag coefficient of the proposed hybrid body design aircraft is carried out. After validating the simulation model with already existing designs and literature result, the influence of parameters like material, angle of attack and frontal area are investigated using the DOE and ANOVA approach. Based on the former, 20 combinations of the above-mentioned parameters are tested and drag coefficients are estimated. ANOVA is used to obtain the regression equation, which is then validated by comparing the results obtained from the equation to the one obtained from the finite element analysis. The optimization study is then performed to find the optimal combination of material, angle of attack and frontal area. Glass Fiber Reinforced Polymer (GFRP) (45%) + Carbon Fiber Reinforced Polymer (CFRP)(45%) + Graphene Nano Powder (10%) proved to be best material, whereas 1625 m^2 is the optimal area. The regression equation helps to avoid repeating a similar experiment to predict the drag coefficient. This helps in saving lot of time to optimize the drag coefficient in all future designs.

List of Abbreviations

ANOVA- Analysis of Variance
CCD - Central Composite Design
RSM- Response Surface Methodology
DOE- Design of Experiments
GFRP - Glass Fiber Reinforced Polymer
CFRP- Carbon Fiber Reinforced Polymer

Declarations

Availability of data and material: Not applicable

Competing Interests: The authors declare no competing interest.

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Прогнозування коефіцієнта опору гібридної конструкції кузова літака

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Анотація. *У цьому дослідженні представлено проєкт літака з гібридним корпусом, який є квінтесенцією літака зі змішаним крилом NACA 4414, що складається з крила та планера. Для оцінки впливу лобової площі, кута камери та матеріалів на коефіцієнт лобового опору застосовано метод розрахунку елементів за допомогою методології поверхні відгуку (RSM). Для виявлення впливу цих факторів використовується дисперсійний аналіз (ANOVA). Для того, щоб мінімізувати симуляції, використовується модель в RSM, центральна композиційна конструкція (CCD). Результати моделювання перевіряються за допомогою комп'ютерної гідродинаміки (CFD).*

Крім того, запропоновано комбінації полімерів з пам'яттю форми з композитами та нанопорошком графену для полегшення ваги та покращення механічних властивостей. Проведено порівняння цих матеріалів з комерційно використовуваними алюмінієвими сплавами. Встановлено, що найнижчий коефіцієнт лобового опору досягається при лобовій площі 1625 м^2 *з кутом атаки –10 ° і з комбінацією матеріалів з полімеру, армованого вуглецевим волокном, полімеру, армованого скловолокном, і 10% графенового нанопорошку за вагою.*

Ключові слова: *аналіз скінченних елементів, дисперсійний аналіз (ANOVA), гібридна конструкція літака, комп'ютерне проектування, зменшення лобового опору.*