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Design of Channel Wing using Lifting Line Theory and Particle Swarm Optimization

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ABSTRACT

The present work studies the optimization of the channel wing design to increase the lift coefficient. The model of the channel wing is constructed using the lifting line theory (LLT), which has been validated through a cross-validation study against experimental wind tunnel results. This model is then applied as the fitness function for the design optimization process, which is performed using the particle swarm optimization (PSO) method. For this study, several design parameters of the channel wing are considered to be varied to obtain their optimal settings. Based on the results of the optimization process, it has been found that the optimal channel length should constitute approximately 28.7% of the semi-wing span with a taper ratio of 0.63. Compared with the original CCW-5, the optimized channel wing has a higher lift coefficient (+48.65%), which holds significant potential for short takeoff and landing. The optimization results also suggest to have a slight twist in the channel wing along with a considerable amount of wing incidence angle. Furthermore, the case study involving a 20% increase in parameters indicates that wing span, length from the root chord to the channel and wing setting angle positively affect the lift coefficient.

Keywords: Channel wing, Short takeoff and landing, Wing design, Lifting line theory, Design optimization

I. INTRODUCTION

Unlike conventional straight-wing aircraft designs that rely on the airfoil in the generation of the lift force, the channel wing aircraft design concept creates a strong low-pressure region in the channel to enhance lift generation. Subsequently, this enables channel wing aircraft to have several advantages including shorter take-off and landing distances, higher lift generation at low speeds and lower noise [1]. The typical channel wing aircraft, as depicted in Figure 1, is an aircraft design that has a straight wing and also an arc wing, whereby the propeller is mounted on the latter wing [2]. Despite the additional weight due to the intricate structures of the channel wing, the improved performance of the aircraft is usually taken as a good trade-off for it. In 1953, the Custer Channel Wing-5 (CCW-5) aircraft completed its maiden flight, demonstrating several impressive capabilities such as taking off in 3 seconds with a taxiing distance of about 30.5 meters and flying in the velocity range of 35 km/h to 354 km/h [3].

Figure 1 Example of channel wing aircraft design [4]

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Since then, many research studies have been pursued and conducted to improve the flight performance of the channel wing design.

An extensive wind tunnel investigation involving the channel wing that is integrated with the modern pneumatic circulation control airfoil and slot advancements has been conducted [5]. The findings of this research demonstrate a decrease in drag as compared to the original channel wing design, alongside improved controllability in power-off scenarios and a boost in the lift coefficient, reaching 8.5. However, it is also concluded in the study that subsequent testing, evaluation and development are needed to address the issues of stability and control. Besides that, substantial alterations in lift and drag efficiency can also result from making some design geometric adjustments including the propeller's placement, the gap between the propeller tips and the length of the blowing slot arc.

Meanwhile, another study is conducted to analyze the influence of the propeller's positioning on the aerodynamics of the channel wing [6]. In this study, computer simulation analysis is performed with varying channel depth, space left around the simplified wing, the chordwise position of the propeller and shape of the propeller. The focus was on the aerodynamic performance of the wing and the operational efficiency of the propeller. It has been found that different designs based on the combination of the varying parameters led to dissimilar performance results. For instance, the wing's aerodynamic performance is good when it is designed with a large embedding depth and has a small gap around it but the propeller's efficiency is degraded [6]. This highlights the complex interaction between the wing design and the position of the propeller, and the proper settings of these parameters are required to have good overall design performance. The effects of different channel wing designs and positions of the propeller are also presented and discussed in several other conducted research studies [7-9]. In another research, a rectangular channel wing design is built and tested in the wind tunnel to investigate the impacts of changing angle of attack (AOA) on lift and drag at 8m/s airspeed, the relative AOA between the duct and the wing, and also the AOA of the airfoil section that supports the motor and spans of the duct [10]. The results have demonstrated that, by having appropriate ducts around the propellers, the channel wing aircraft design could achieve very good take-off and landing performance.

Today, the advancement of computational simulation tools has made it possible to study and analyze engineering design performance without having to conduct physical experimentation. The accuracy of such simulated analyses is also acceptable and close to the actual experimentation. In the case of channel wing studies, experimental methods can be expensive and time-consuming to build the design models for the physical tests, especially when conducting parametric studies where the design parameters are varied throughout the interested design space. Specifically, the use of computational fluid dynamics (CFD) simulation tools can facilitate the exploration of different channel wing designs through the alteration of the wing's geometry. CFD simulation analysis has been widely accepted in engineering fields as an alternative to experimental wind tunnel testing, which is reflected by its utilization in many studies. For instance, CFD simulation has been applied in the study of the effects of wing sweep angles on the lift-to-drag ratio performance [11], the effects of varying airship design parameters to its aerodynamic performance [12] and the effects of the blended-wing body design parameters to its aerodynamics performance [13]. Furthermore, simulation analysis has made it easier for researchers to conduct detailed studies on design improvements. This is because it allows them to quickly analyze many different designs in less time and with less effort than traditional physical testing. As a result, it helps in optimizing designs more efficiently. The collected simulation data can then be used to develop the mathematical or numerical model that is the essential part of design optimization methods. For example, the application of simulation analysis in the design optimization process has been demonstrated in research studies for the design of airfoils [14] and aircraft structures [15]. Alternatively, a numerical model for the objective function of the design optimization process could also be derived from established analytical theories. For instance, optimization for the engine of launch vehicles used standard empirical mathematical models of the propulsion system [16] while a composite wing design was optimized based on theoretical aeroelastic models of the wing [17].

There are several convincing reasons to study the channel wing. One of the main reasons is that theoretically, the "speed of air" concept works, supported by Bernoulli's principle, which illustrates how faster air movement has lower pressure and this pressure difference creates lift. Additionally, previous research on channel wings has demonstrated feasible lift advantages. However, despite efforts, its acceptance within aviation remains limited due to its unconventional nature. Safety concerns, insufficient testing and data, regulatory compliance, and performance uncertainties are primary reasons for this skepticism. Safety concerns might arise not just from maneuverability but also from structural aspects. The fact that a strut has to be attached on top of the channel to hold the engine might cause geometric nonlinearity on the wing. This happens because the stiffness properties change significantly when the wing experiences high deflection on both sides of the strut [18]. Notably, the CCW-5, a modification of the Baumann B-250 Brigadier, significantly increased in weight by about 60% from the original aircraft.

Taking advice from previous research studies, this study aims to optimize the geometric parameters of the channel wing to obtain the highest lift coefficient. The goal is to determine the percentage increase in lift coefficient in comparison with the CCW-5 aircraft. Part of the objective includes modifying the lifting line method so that it can be adapted to a channel wing. The modified mathematical model is then used in the design optimization process, where the particle swarm optimization (PSO) method is applied [19]. It should be noted that the PSO method has been used in the optimization of transport aircraft wings to maximize the range of the wing, the data provided suggests that the PSO algorithm consistently discovers the best possible solution for the given problem [20]. This indicates its suitability to be chosen for this study. In this study, the limitations encountered mirror the constraints associated with the application of the lifting line theory. Firstly, the two-dimensional nature of the study cannot capture the three-dimensional flow phenomena that occur in real-world applications. Secondly, assumptions on the developed model include incompressible fluid, frictionless flow, irrotational flow, inviscid flow and steady-state flow. Thirdly, the study is limited to a certain range of wing sizing.

II. METHODOLOGY

The optimization process starts by modifying the mathematical model of the lifting line theory for the channel wing. The constructed model essentially relates the wing design parameters that will be varied in the optimization stage with the aerodynamic performance of the aircraft. Once the model is validated, it is used for the design optimization process with the PSO method. The optimal setting of the considered wing design parameters is determined from the PSO results. Specifically, the objective function or interested aerodynamic performance parameter for the optimization study is the lift coefficient. In this sense, the mathematical model based on lifting line theory relates the resultant lift coefficient of the channel wing aircraft with different settings of a few geometric design parameters of the channel wing. Figure 2 shows the flowchart of the modeling and simulation process in optimizing the Channel Wing.

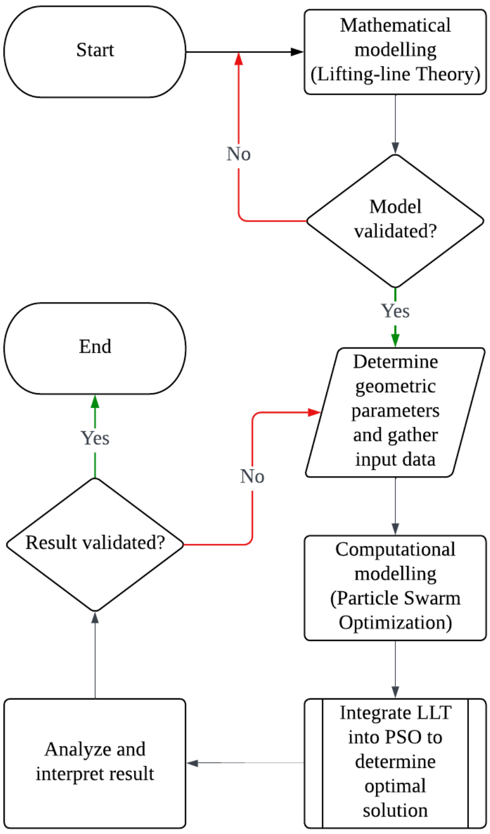

Figure 2 Overall methodology of this study

2.1 Mathematical Modelling

The lifting line theory is a simplified aerodynamic theory that is mainly applicable to straight wings and does not predict stall [21]. To adapt the lifting line theory for a channel wing, it is essential to consider the influence of the channel. Figure 3 depicts the anticipated lift distribution of the power-on channel wing. Note that, due to potential difficulties associated with stability, performance and safety, as well as the channel wing's natural ability to produce a significant lift that also leads to higher lift-induced drag and reduced maximum speed, opting for tapered channel wing design seems like a prudent strategy for mitigating these drawbacks (refer to Figure 7). In this case, the adaptation of the lifting line method for the channel wing is based on the framework developed for arbitrary wings within the lifting line theory where the representation of vortex strengths along the span is depicted through a Fourier sine series comprising N terms [22].

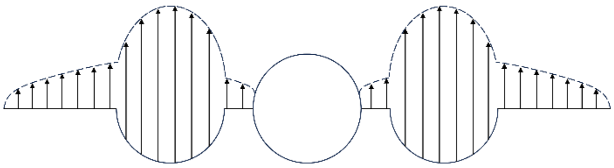

Figure 3 Expected lift distribution of the power-on channel wing

In the lifting line method – special case: arbitrary wings, the parameters may include wing span, root chord, tip chord, angle of attack, zero-lift angle of attack and lift curve slope [22]. For a channel wing, the lift curve slope, $C_{l\alpha}$ varies across different segments of the channel, where steeper segments should have lower values of $C_{l\alpha}$. To calculate the airfoil's $C_{l\alpha}$ for any segment, the steps are depicted in Figure 4. First, the distance from the segment to the center of the channel is calculated, which serves as the base length for the right-angled triangle. Secondly, the angle θ_1 between the segment and the center of the channel is determined. Knowing that θ_1 equals θ_2, it is now possible to obtain the $C_{l\alpha}$ at any segment using the resultant force formula as shown in Equation (1).

$$F_{1_y} = F_1 \sin\theta \rightarrow Segment\ C_{l_\alpha} = C_{l_{\alpha\,(mid)}} \sin\theta \qquad (1)$$

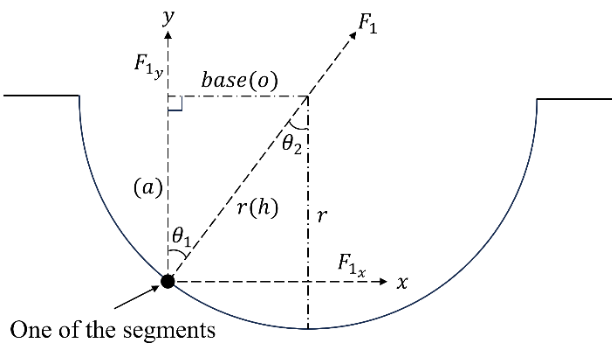

Figure 4 Free body diagram on the channel

In the power-off configuration, the value of $C_{l\alpha}$ at the middle of the channel is the same as that of the wing. However, in the case of power-on configuration, the lift curve slope value in the channel has to be adjusted to be higher than that of the wing to accommodate the engine effect. Moving on, one of the limitations of the lifting line method is that it does not account for the presence of the fuselage. To enhance the realism of the lifting line method, the wing geometry is reduced to account for the fuselage. Firstly, the lift is assumed to be entirely generated by the wing, meaning the fuselage region is assumed to have zero lift coefficient. Secondly, the fuselage is treated as a wall by simply removing the width of the fuselage [22]. This is illustrated in Figure 5, which shows how the influence of the fuselage can be considered within the framework of the lifting line method. As a result of this, the wing span, wing area, aspect ratio and taper ratio will all be reduced. Hence, the channel wing will need to achieve steeper AOA to produce the necessary lift coefficient for a specific flight situation.

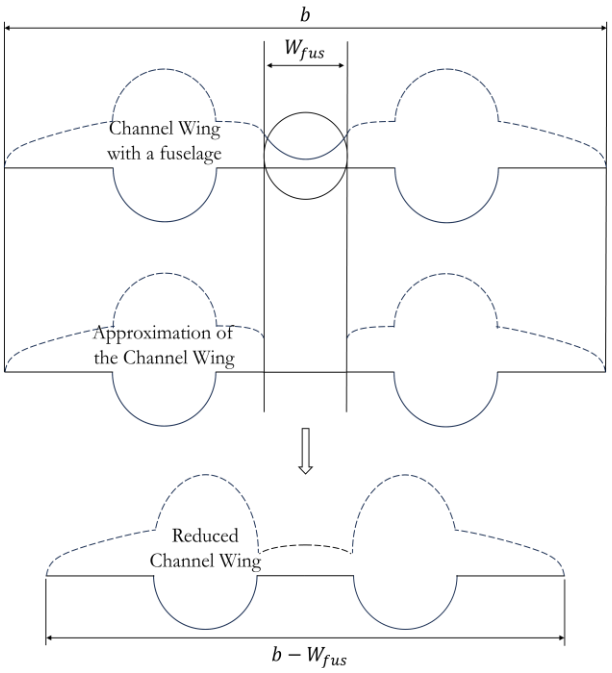

Figure 5 Accounting for a fuselage in the lifting line method

2.2 Model Validation

To validate the modified lifting line method used in this study, cross-validation is done with published work by P. M. Keane and A. J. Keane [10]. The reference work involves testing the lift and drag characteristics of the entire channel wing aircraft configuration in the Mitchell wind tunnel at the University of Southampton. The specifications of the model used are presented in Table 1. In essence, these design parameters are also the variables to be used in the design optimization process later.

The validation is conducted at an airspeed of 8 m/s (given) and air density of 0.736 kg/m^3 (assuming the aircraft is flying at an altitude of 5000m). According to the reference paper, the channel wing's zero-lift AOA is around -7. The zero-lift AOA value used in the lifting line method is assumed lower because the paper did not mention the airfoil used for the wing and based on the picture shown in the paper, the aircraft wing inside the wind tunnel has a rather curved shape together with the flap, which is known to increase lift generation in low speed.

Table 1 Reference's model specification

Parameter	Value	Unit
Wing span, b	7.15	ft
Root chord, C_r	0.92	ft
Tip chord, C_t	0.92	ft
$X1$	0.48	ft
$X2$	0.96 + X1	ft
Twist angle, α_t	0.00	°
Wing setting angle, i_w	0.00	°

Note. X1 is the length from the root chord to the channel and X2 is the length from the root chord to the end of the channel. Refer to Figure 7. Some values are assumed.

Besides, it was proven that with the flap deflected 60°, the NACA 4412 has its zero-lift AOA lowered to -16 [23]. The conducted wind tunnel test on the power-off channel wing in another study has shown that the collected data on the lift curve slope closely resembled the lift performance data of a straight wing with the same NACA 4412 airfoil, which is the airfoil applied for the wing cross-section [24]. Regarding the power-on configuration, accounting for the engine's effect within the framework of the lifting line theory can be quite complex, for simplification, the $C_{l\alpha}$ of the power-on configuration is increased to account for the engine effect. The reference paper mentioned that the lift was improved by 60% when the power was on. Therefore, for the power-off configuration, the constants are assumed as follows: zero-lift AOA=-13°, $C_{l\alpha}$=2π, $C_{l\alpha\text{-}channel(mid)}$=2π. For power-on configuration, the constants are assumed as follows: zero-lift AOA=-13°, $C_{l\alpha}$=10, $C_{l\alpha\text{-}channel(mid)}$=15. The comparison data is plotted in Figure 6, where the reference data (lift coefficient) is taken from Figure 17 of the reference paper, which is converted from lift. It should be noted that the lifting line theory usually falls short in accuracy when the aspect ratio of the reference wing is lower than 5 [25]. The reference model has an aspect ratio of 7.77.

As can be observed in Figure 6, the findings from the conducted cross-validation work have demonstrated a high degree of alignment for both power-off and power-on configurations between the results of the modified lifting line model in this study and the results of the referenced work. On the whole, this is taken to indicate the advantage of the modified lifting line method to represent the channel wing aircraft and therefore it can be confidently used for the next design optimization process.

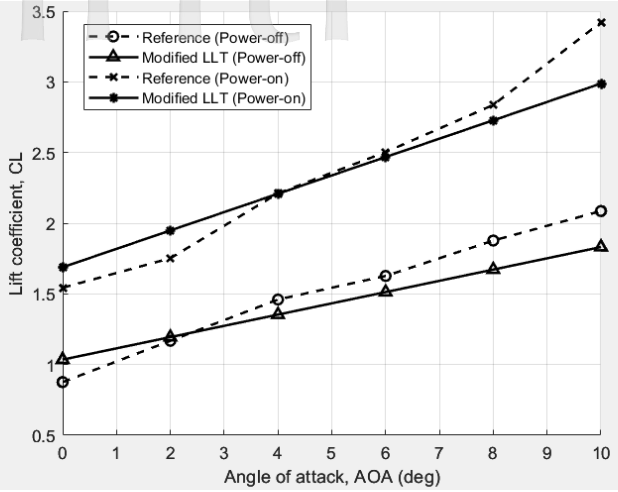

Figure 6 Comparison of the reference model and modified lifting line method

2.3 Geometric Parameters and Particle Swarm Optimization

After the lifting line model is defined and validated to represent the aerodynamic behavior of the channel wing aircraft, the next step is to determine the geometric parameters to be varied and analyzed for the optimization process. As stated before, available design parameters for this purpose are previously listed in Table 1 since they need to be linked to the lifting line model. Table 2 lists the parameters and their range of values, which define the effective design solution space to be explored through the optimization process. The considered parameters are also illustrated in Figure 7. The base values of geometric parameters refer to the CCW-5 specification, which has a wingspan of 41 ft, root chord of 6 ft, channel length (propeller diameter) of 7 ft and gross weight of 5400 lb [26]. Assuming tip chord = 3 ft, wing setting angle=0°, twist angle=-0.1°, zero-lift AOA=-4°, $C_{l\alpha}$=2π, $C_{l\alpha\text{-}channel(mid)}$=2π, fuselage's width=6 ft, air density=0.002378 slug/ft^3. Note that in the design optimization process, the channel wing model adopts the NACA 4412 airfoil and thus refers to the value of -2.7 ° for the zero-lift AOA. The original CCW-5 uses a combination of NACA 4418 and NACA 4412, which is expected to have better performance [26].

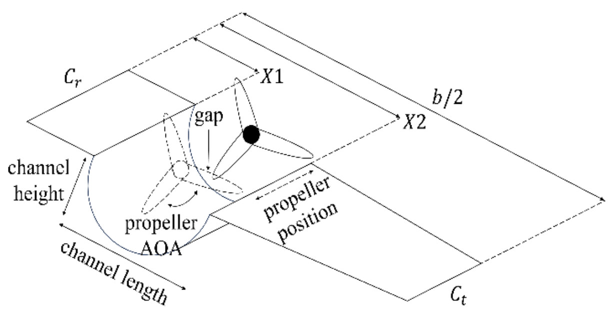

Figure 7 Channel wing geometric parameters

Considering the promotion of elliptical lift distribution and also the lift-generating effect of the channel, the channel should be positioned before the half of the wing's semi-span to reduce the bending moment and the wing's mass moment of inertia around the x-axis, leading to improved lateral control. As previously stated, the design optimization process of channel wing aircraft for this study is performed using the PSO method. The original PSO algorithm is presented by Equation (2) and Equation (3) [27].

$$v_{id} = v_{id} + c_1 rand()(p_{id} - x_{id}) + c_2 rand()\left(p_{gd} - x_{id}\right) \quad (2)$$

$$x_{id} = x_{id} + v_{id} \quad (3)$$

The optimization algorithm is run until the stop condition is met, it is either the desired lift coefficient or the maximum number of iterations is reached.

Table 2 Constraints on the values of geometric parameters for the optimization process

Parameter	Minimum	Maximum
Wing span, b	41 ft – 10%	41 ft + 10%
Root chord, C_r	6 ft – 10%	6 ft + 10%
Tip chord, C_t	TR ≥ 0.4	TR ≤ 0.8
$X1$	≥ 20% of semi-span	≤ 25% of semi-span
$X2$	$X1$ + 20% of semi-span	≤ 50% of semi-span
Twist angle, α_t	0°	4°
Wing setting angle, i_w	-0.3°	-3°

III. RESULTS AND DISCUSSION

Once the particle swarm optimization algorithm meets the termination criteria, the optimization process is stopped. The optimum settings of the channel wing design parameters, which correspond to the highest lift coefficient, are then established based on the obtained optimization results. In this study, the optimal or highest value of the lift coefficient is found to be 0.55. Table 3 tabulates the optimal settings for the considered channel wing aircraft design parameters.

With the best geometric parameter values in hand as shown in Table 3, the lift distribution plot for the channel wing can be generated as depicted in Figure 8. Derived from the results, it is evident that the ideal channel length should make up approximately 28.7% of the semi-wing span, with a taper ratio of 0.63. In comparison to the initial CCW-5 power-off configuration, the CCW-5 model produces a lift coefficient of 0.37 at airspeed of 288 ft/s. By comparison, the optimized result yields a higher lift coefficient of 0.55 (+48.65%) that is produced at a lower speed of 251 ft/s.

Table 3 Optimal settings of design parameters

Parameter	Value	Unit
Wing span, b	36.9	ft
Root chord, C_r	5.4	ft
Tip chord, C_t	3.4	ft
X1	4.4	ft
X2	9.7	ft
Wing setting angle, i_w	4	°
Twist angle, α_t	-3	°

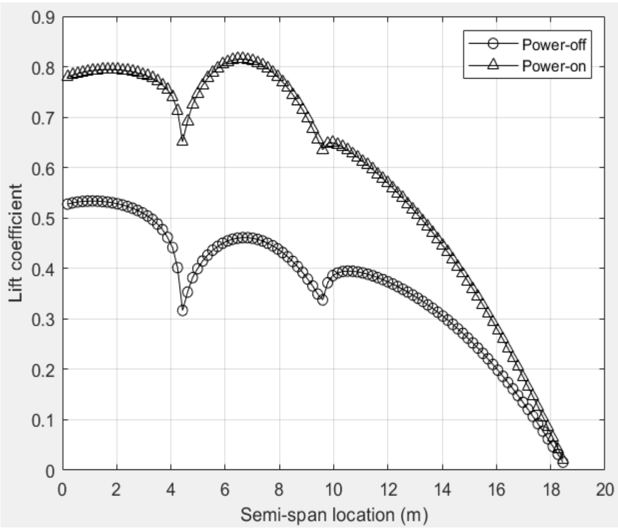

Figure 8 Channel wing lift distribution

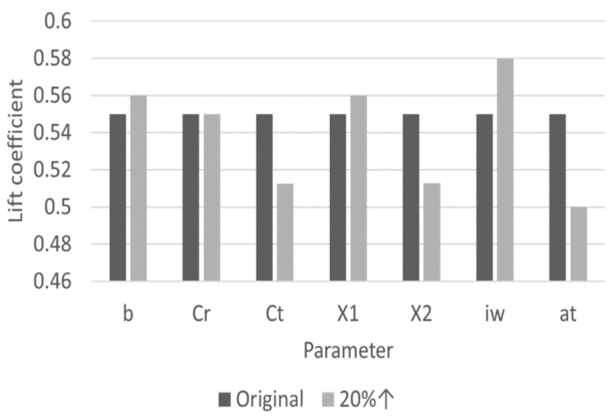

Figure 9 Result of the sensitivity case study

To comprehend the significance of each of the design parameters, a sensitivity study is conducted by increasing each value by 20% to observe its impact on the lift coefficient. Analyzing these parameters is crucial when optimizing an aircraft wing because it aids in identifying critical parameters, enhancing optimization efficiency, enabling trade-off analysis, mitigating risks and validating the design, ensuring optimal performance and resource allocation. The result is shown in Figure 9. It can be observed that, in response to a 20% increase in value, wingspan (b), length from the root chord to the channel (*X1*) and wing setting angle (i_w) demonstrate an increase in the lift coefficient.

On the whole, the summary of the findings from the sensitivity case study is listed as follows:

- Increasing the wing span alters the aspect ratio. Higher aspect ratios typically result in decreased induced drag, which is closely tied to lift production. This reduction in induced drag can enhance the aerodynamic efficiency of the wing, potentially leading to a higher lift coefficient. Likewise, tilting the wings nose up/backward (increase AOA) could increase the lift coefficient by directing the airflow downward.
- When the base of the wing is made wider (i.e. the root chord), there might not be a noticeable change in lift. The root chord primarily affects how lift is distributed across the wing and other factors often matter more in increasing the lift.
- Increasing the size of the root chord can create more drag due to its larger size, which could cancel out any extra lift.
- For engine size (i.e. channel length), a bigger engine can disrupt how the air flows over the wing. This can reduce the lift compared to the drag and may make the plane less efficient because it adds more weight.
- When the twist angle of the wing is increased, it can change how the air moves around it and this possibly can lead to less lift. The twist angle is vital for getting the wing to work well, but too much twist can cause problems with how the air flows over the wing.

IV. CONCLUSION

The present work optimizes the wing geometry of the channel wing using the lifting line method and particle swarm optimization method. The cross-validation has shown the reliability of the modified lifting line model in calculating the lift coefficient for a channel wing. Additionally, the result implies that the optimized channel wing exhibits a substantial increase in lift coefficient when compared to the conventional CCW-5 design. The result showed that the optimized channel wing in comparison to the original CCW-5 has a 48.65% increase in lift coefficient and the optimal channel length is estimated to be around 28.7% of the semi-wing span, with a taper ratio of 0.63. The optimization results also recommend introducing a slight twist to the channel wing in addition to a fair amount of wing incidence angle. Lastly, a conducted design sensitivity study involving a 20% increase in parameters reveals that wing span, length from the root chord to the channel (*X1*), and wing setting angle have a positive impact on the value of the lift coefficient. Future research should focus on the stability and control of the channel wing aircraft.

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