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PRELIMINARY AERODYNAMIC WING DESIGN OPTIMISATION FOR WING-IN-GROUND EFFECT AIRCRAFT

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Abstract

Wing-in-Ground (WIG) effect aircraft have become an interesting concept in the context of reducing the environmental footprint and increasing the speed of coastal transport. However, obtaining an efficient wing shape in a cost-effective manner is an elusive goal in the early stages of any aircraft design. In this work, a multi-objective wing planform optimisation methodology is proposed by combining a parametric shape modeller OpenVSP, a low fidelity solver VSPAERO and Non-dominated Sorting Genetic Algorithm (NSGA-II) to support the preliminary design of wing-in-ground effect aircraft. Methodology is demonstrated by performing three different wing planform optimisations ranging from planar wing optimisation to nonplanar wingtip optimisation by improving both lift to drag ratio and static height stability characteristics of a wing planform in ground effect. The analysis of the Pareto optimal solutions suggests that when employing the Vortex Lattice Method (VLM) for aerodynamics and stability derivatives computation, the optimiser converged to drooped wing type configuration which enhances both aerodynamic efficiency and static height stability characteristics of wing-alone configuration.

Keywords: Wing-in-Ground Effect, Multi-objective, Wing Planform Optimisation, Aircraft Design, NSGA-II

1. Introduction

A Wing-in-Ground (WIG) effect craft flies in close proximity of ground and uses the ground effect to enhance its aerodynamic efficiency [1]. When combined with an electric propulsion system, a WIG craft has the potential to become an efficient platform for the next generation coastal transport vehicles. Unlike conventional aircraft, aerodynamic characteristics of a WIG craft are strongly affected by the presence of ground, hence stability problems arise when a WIG craft is perturbed by a gust. Therefore it is necessary to maintain static stability in both pitch and height directions. Staufenbiel [2] and Irodov [3] derived the static height stability condition for a conventional WIG configuration.

To maintain adequate pitch and height stability margin, the Russian third-generation Ekranoplan series used a rectangular wing planform with a large horizontal tailplane outside the ground effect. However, these larger tails require an additional support system, which can create significant drag and increases the maximum take-off weight and power requirements of the WIG craft. On the other hand, Lippich showed that a tapered sweep forward wing with anhedral offers more stability than a rectangular planform and utilized smaller horizontal tail stabilizers to achieve the required static height stability [4]. Over the recent years, aerodynamic shape optimization has seen rapid development [5, 6, 7]. Wing planform optimisation considering only aerodynamics could yield better designs but it may come at the expense of a decrease in static height stability margin for a WIG craft. Therefore it is essential to include the parameters that define the planform such as half span, taper ratio, sweep, twist and dihedral in optimisation to obtain an optimum wing planform that satisfies both aerodynamic and static height stability requirements of a WIG craft.

Lee et. al. [8] performed three dimensional wing optimisation by considering lift coefficient, aerodynamic efficiency and static height stability condition as objectives. Sectional shapes are parametrized using Bezier curves and considered only two planform parameters such as chord ratio and sweep angle as design variables. Even though the design shows better performance, the considered planform

parametrization is not sufficient to generate large planform variations in optimization, thus affecting the optimal solution.
For conventional aircraft, nonplanar wings have been shown to reduce the induced drag beyond planar wings [6, 7]. However, only few examples are available in the literature to better understand whether nonplanar wings could satisfy the stability requirements of WIG craft. Furthermore including nonplanar wing deformation in the shape optimisation process may increase the likelihood of multi-modality in the design space [9], hence global optimisation algorithms are preferred than gradient-based optimisation algorithms in the early stages of the aircraft design process. Therefore, in this work, multi-objective wing planform optimisation is performed using Non-dominated Sorting Genetic Algorithm-II (NSGA-II) [10], in which the planform parameters are optimized by minimizing the stability derivatives that influence the static height margin and by maximizing the aerodynamic efficiency of the wing.
Aircraft design process is a multi-disciplinary process, hence consistent CAD models need to be shared among disciplines. In this work, OpenVSP is used as a geometry tool in the design process [11]. OpenVSP allows geometries to be parametrized at various levels ranging from traditional planform alterations using parameters such as aspect ratio, taper ratio, twist and sweep to local surface changes using CST parametrisation method [12]. OpenVSP version 3.26.1 is utilized for this study. Low fidelity methods are preferred in early stages of the aircraft design process which allow fast calculations, and unconventional optimised designs can be obtained within short periods of time [7, 13]. In this work, VSPAERO tool is considered for the aerodynamic analysis. VSPAERO is an open source aerodynamic analysis solver developed by NASA and integrated with OpenVSP to support the conceptual design stage of an aircraft. VSPAERO can perform aerodynamic analysis using a Vortex Lattice Method (VLM) or a panel method and in this work aerodynamic calculations were performed using the VLM method.
In this work, multi-objective planar and nonplanar wing planform optimizations have been performed to investigate the influence of nonplanar wing geometries on the aerodynamics and longitudinal static height stability characteristics of a WIG vehicle. An OpenMDAO-based multi-objective optimisation framework has been developed to integrate a geometry modelling tool, VLM-based aerodynamics and stability derivatives computation module with post-optimality analysis to select a best compromise solution from the set of non-dominated optimal solutions obtained using NSGA-II.
Section 2.1 discusses the planar and nonplanar parametrization of the baseline wing considered in this work. Aerodynamics and longitudinal static height stability of a WIG craft are presented in Section 2.2 and Section 2.3 respectively. Multi-objective wing planform optimisation problem formulation is presented in Section 2.3.1. VSPAERO solver validation is presented in Section 2.4. Optimisation results are presented and discussed in Section 3.

2. Methodology

A brief summary of the optimisation framework employed in this work is presented here. The framework can be broken down into five major components: wing planform parametrization, panel discretisation, Vortex Lattice Method (VLM) solver, stability derivatives evaluation and the optimiser.

2.1 Geometry Parametrization

In this work, optimisation of a wing planform is performed for ground effect aircraft. A NACA six series airfoil shape is used and cross-sectional shape remains fixed throughout the design process, hence thickness-to-chord ratio of the wing sections are unaltered in the optimisation. A rectangular wing planform is considered as a baseline geometry and parametrized using OpenVSP geometry tool. In order to understand the influence of planform parameters on the aerodynamic efficiency and longitudinal static stability of the WIG design, wing planform optimisation has been performed using three different set of parametrization. Design variables considered in three different cases are shown in Figure 1.

2.1.1 Case-1: Planar Optimisation

In this case, wing geometry is parametrized using one segment and wing planform is defined by five parameters: span (b), root chord (c_r), tip chord (c_t), sweep (β) and twist (γ). Planar deformations are only considered in this case, hence dihedral angle is not included in Case-1. To achieve smooth variation of chord along the spanwise direction, the blending tool in openVSP is used to parametrize the segment. The blending tool provides enhanced control over sweep and dihedral angles of the leading and trailing edges of a wing section. In addition to that, the user can also control the continuity of the planform leading and trailing edge curves (LE/TE) across various segments. For this work, the tip section is set to free hence the tip section is unconstrained and leading edge of the root section is set to ANGLES with default values for sweep/dihedral and strength. Trailing edge of the root section is set to LE_ANGLES hence tangent at the root section of the trailing edge planform curve match with the tangent at the leading edge planform curve. Design variables considered in this case are shown in Figure 1a.

2.1.2 Case-2: Nonplanar Wing Optimisation

In this case, the baseline wing is divided into two segments. Similar to Case 1, the geometry of each segment is parametrized using the blending tool. The inner segment is defined using four planform variables: root chord $(c_{r,1})$, tip chord $(c_{t,1})$, sweep (β_1) and twist (γ_1). Similarly, the outer wing segment is defined using four design variables: tip chord $(c_{t,2})$, sweep (β_2), twist (γ_2) and dihedral angle (Γ_2). Segment continuity is maintained by aligning the tip chord of the inner segment $(c_{t,1})$ with the root chord of the outer wing segment $(c_{t,1} = c_{r,2})$. In optimisation, the total span of the wing is taken as design variable, hence span of the inner and outer wing segment is maintained as 30% and 70% of the total span of the wing respectively. The dihedral angle of the inner wing segment is not considered as a design variable hence remains as planar throughout the optimisation. To include nonplanar geometries in the design space, dihedral angle of the outer wing segment is taken as a design variable. Figure 1b shows the list of design variables for Case-2.

2.1.3 Case-3: Nonplanar Wingtip Optimisation

As in Case-2, the baseline wing is divided into two segments and a blending tool is employed to parametrize each segment. However, the span of the outer wing is reduced to 30% of the total span and dihedral (Γ_2) of the outer wing is taken as a design variable hence nonplanar wingtip configurations can be achieved in the design space. A sample deformation of the wingtip is shown in Figure 1c.

2.2 Aerodynamics of Wing-in-Ground Effect

Ground effect augments the lift and reduces the induced drag acting on a finite wing [14]. The induced drag coefficient $(C_{D,i_{IGE}})$ and lift coefficient $(C_{L_{IGE}})$ of a wing in ground effect can be written as [15],

$$C_{D,i_{IGE}} = \Phi_L^2 \Phi_D C_{D,i_\infty}, \tag{1}$$

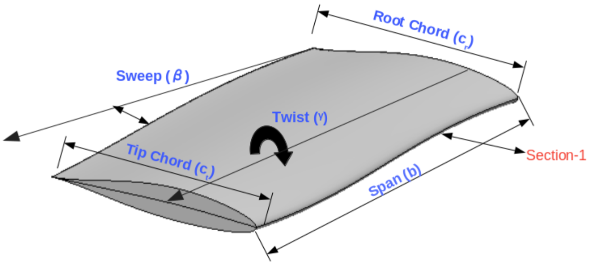
$$C_{L_{IGE}} = \Phi_L C_{L_\infty}. \tag{2}$$

where C_{D,i_∞} and $C_{L,\infty}$ are the induced drag coefficient and lift coefficient in out of ground effect, Φ_L and Φ_D are the ground effect coefficient for lift and drag respectively. These coefficients describe how the lift and induced drag of a wing are affected by the ground effect. Ground effect coefficient for lift (Φ_L) can be defined as the ratio of coefficient of lift of the wing evaluated in ground effect $(C_{L,IGE})$ at some height (H) above the ground to the coefficient of lift of the same wing evaluated outside the ground effect $(C_{L,\infty})$. It can be written as,

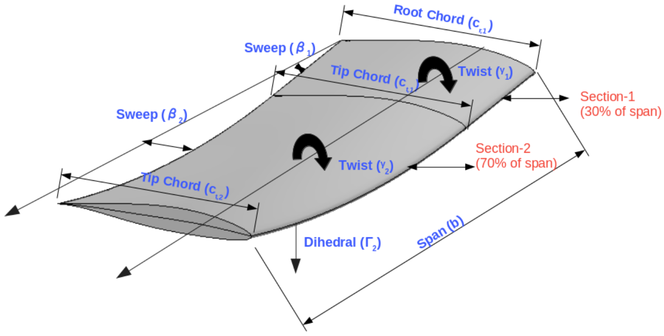
$$\Phi_L = \frac{C_{L,IGE}}{C_{L,\infty}} \tag{3}$$

Similarly, ground effect coefficient for drag (Φ_D) can be defined as the ratio of induced drag coefficient to the square of the lift coefficient of the wing evaluated in ground effect divided by the same ratio of the wing evaluated outside of the ground effect. It can be written as,

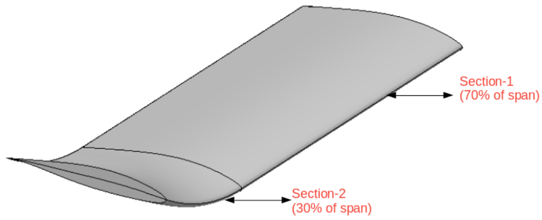
$$\Phi_D = \frac{(C_{D,i}/C_L^2)_{IGE}}{(C_{D,i}/C_L^2)_\infty} \tag{4}$$



(a) Case-1



(b) Case-2



(c) Case-3

Figure 1 – Parametrization of the baseline wing with design variable definitions

In out of ground effect flight, Φ_L and Φ_D are equal to one. Figure 2a shows the values of ground effect coefficient obtained using Equation 3 and Equation 4 as a function of ratio of wing height from ground to wing span (H/b) for the baseline rectangular wing shown in Figure 1a. VSPAERO is used to compute the required aerodynamics quantities.

In close proximity to the ground, flow around a wing is forced to be parallel to the ground thus trailing wing tip vortices are disrupted. As a result, intensity of the downwash is reduced thus reducing the induced drag and increasing the effective angle of attack of the wing, hence the lift. This can be clearly seen in Figure 2a. Furthermore, if the aircraft flies extremely close to ground $(H/b < 0.3)$, airflow between the lower surface of the wing and ground is compressed to form an air cushion which further enhances the lift. Figure 2 shows the calculated aerodynamic performance and ground effect coefficient of the baseline rectangular wing as a function of H/b. When compared to the same wing operating outside the ground effect, for values $H/b < 1$, ground effect enhances the lift-to-drag ratio.

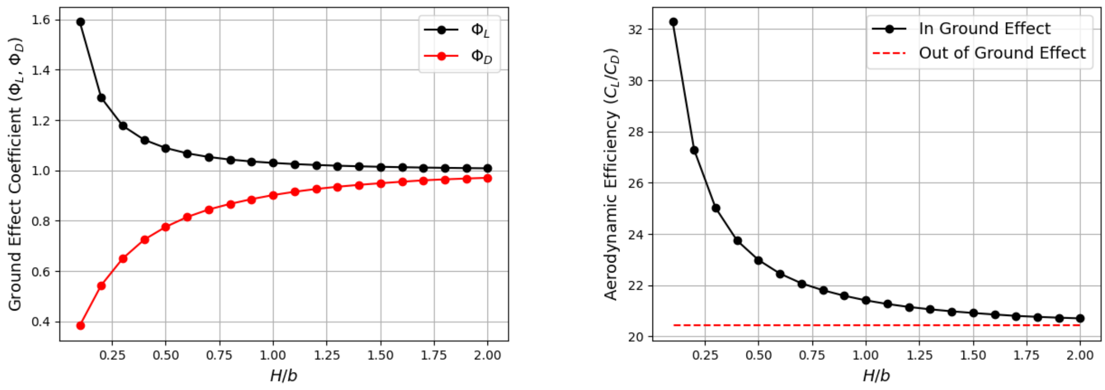
2.3 Longitudinal Static Stability

In close proximity of the ground, aerodynamic characteristics such as lift (C_L) and moment (C_M) coefficients of a WIG craft are strongly affected by the presence of ground, hence these coefficients are depends on both angle of attack (α) and flying altitude (H) [1]. Mathematically this can be written as,

$$\begin{aligned} \delta C_L &= C_{L,\alpha}\delta\alpha + C_{L,h}\delta h \\ \delta C_M &= C_{M,\alpha}\delta\alpha + C_{M,h}\delta h \end{aligned} \tag{5}$$

Here C_L and C_M represents coefficient of lift and moment computed in ground effect. Subscript $_{IGE}$ is omitted for clarity. Stability of a WIG craft can be determined based on the derivative of lift and moment with respect to angle of attack (α) and height ratio $(h = H/\bar{c})$ where $\bar{c}$ is the mean aerodynamic chord. These can be written as,

$$C_{L,\alpha} = \frac{\partial C_L}{\partial \alpha},\; C_{L,h} = \frac{\partial C_L}{\partial h},\; C_{M,\alpha} = \frac{\partial C_M}{\partial \alpha},\; C_{M,h} = \frac{\partial C_M}{\partial h} \tag{6}$$



(a) Ground effect coefficient vs H/b

(b) Aerodynamic efficiency vs H/b

Figure 2 – Influence of ground effect coefficient and aerodynamic efficiency on ratio of distance from ground to wingspan (H/b) for the baseline wing

Like conventional aircraft, WIG craft should create a pitch down moment in response to a sudden increment in α such that,

$$C_{M,\alpha} < 0 \tag{7}$$

where $C_{M,\alpha}$ is the variation of pitch with respect to angle of attack. In addition to that, a WIG craft should also need to satisfy longitudinal static stability in the vertical direction. Hence stable cruise can be achieved without active correction to the ground clearance. According to Staufenbiel [2], the static height stability condition is given as,

$$\begin{aligned} HS &= C_{L,h} - \left(\frac{C_{M,h}}{C_{M,\alpha}} C_{L,\alpha}\right) < 0 \\ &= C_{L,h} - M_R C_{L,\alpha} < 0 \end{aligned} \tag{8}$$

where $M_R = \frac{C_{M,h}}{C_{M,\alpha}}$ is the moment ratio. In close proximity of the ground, the $C_{L,h}$ term is negative hence it offers a stabilizing effect. On the other hand, the moment ratio is negative for a statically stable aircraft $(M_R < 0)$ and offers destabilizing influence in Equation 8 and heavily depends on $C_{M,\alpha}$. The absolute value of $C_{M,\alpha}$ depends on tail volume ratio (V_H), tail efficiency (η_T) and static margin (SM), hence the adverse moment ratio term can be minimized by incorporating a large horizontal tail unit placed out of ground effect. However, the main wing is in ground effect, hence it is important to $C_{L,h}$ and its absolute value depends on the flying altitude, airfoil shape and wing planform. In this study, wing planform is only considered hence minimizing $C_{L,h}$ term (or maximising $|\,C_{L,h}\,|$) is taken as an objective function instead of HS as given in Equation 8.

2.3.1 Optimisation Formulation

In this work, two conflicting objective functions are considered: maximising aerodynamic efficiency (C_L/C_D) and minimizing the stability derivative term $C_{L,h}$, which has the most stabilizing effect on the static height stability. The mathematical formulation of a three dimensional wing planform optimisation is defined as follows:

$$\begin{aligned} &\text{Objective Function:} && \text{Max}\left(\frac{C_L}{C_D}\right),\ \text{Min}\ C_{L,h} \\ &\text{subject to} && C_L = C_L^* \\ & && 0.5\mathscr{V}^* \le \mathscr{V} \le 1.5\mathscr{V}^* \\ & && \delta_l \le \delta \le \delta_u \\ &\text{Case-1} && \delta_1 = [\alpha, \gamma, \beta, c_r, c_t, b] \\ &\text{Case-2} && \delta_2 = [\alpha, \gamma_1, \beta_1, c_{r,1}, c_{t,1}, \gamma_2, \beta_2, c_{t,2}, \Gamma_2, b] \\ &\text{Case-3} && \delta_3 = \delta_2 \end{aligned} \tag{9}$$

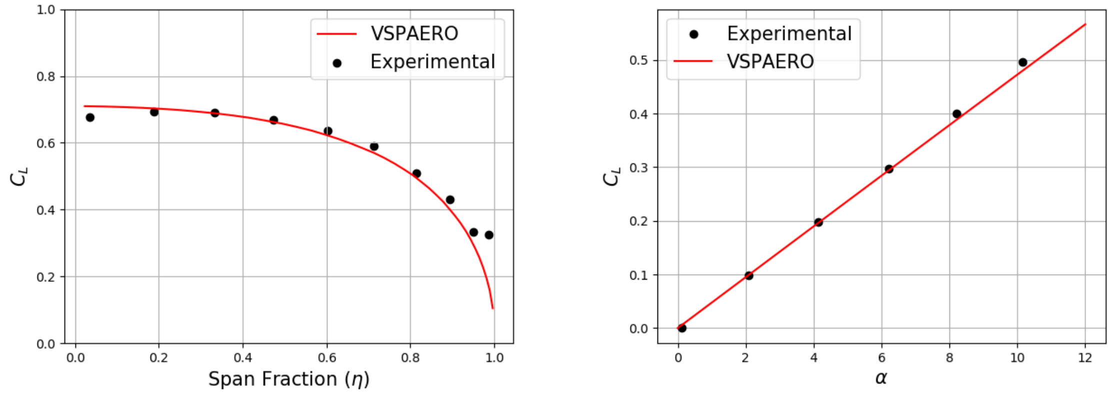
Category	Name	Lower Limit	Upper Limit	Units
Objective Function	max C_L/C_D	-	-	
	min $C_{L,h}$	-	-	
Case-1: Variables	AOA (α)	-3	3	Degrees
	Twist (γ)	-5	5	Degrees
	Sweep (β)	0	5	Degrees
	Root chord (c_r)	0.5	2	Ref. units
	Tip chord (c_t)	0.5	2	Ref. units
	Span (b)	0.5	3	Ref. units
Case 2: Variables	α	-3	3	Degrees
	γ_1	-5	5	Degrees
	β_1	0	5	Degrees
	$c_{r,1}$	0.5	2	Ref. units
	$c_{t,1}$	0.5	2	Ref. units
	γ_2	-5	5	Degrees
	β_2	0	5	Degrees
	$c_{t,2}$	0.5	2	Ref. units
	Γ_2	-10	10	Degrees
	b	0.5	3	Ref. units
Case 3: Variables (Other variables are same as Case 2)	Γ_2	-30	30	Degrees

Table 1 – Bounds for the design variables

Here, C_L^* is the design lift coefficient; δ is a design variable vector for each optimisation case; α represents the angle of attack; c_r, c_t represents root and tip chord respectively; γ and β represent twist and sweep angle respectively; Γ is the dihedral angle; and $\mathscr{V}$ is the baseline wing volume, subscripts 1 and 2 in the design variables represent inner and outer wing segments respectively. In this work, we want to consider solely the influence of aerodynamics and stability on the wing design for WIG craft. Hence structural related requirements such as wing root bending moment are not considered in this work. Bounds on the design variables considered in all the three cases are shown in Table 1. All the optimizations have been performed under the cruise condition of $\frac{H}{b_0} = 0.5$, where b_0 is the span of the baseline wing and subsonic flow conditions are used with freestream Mach number 0.1.

2.4 VSPAERO Solver Validation

Capabilities of VSPAERO in calculating subsonic aerodynamic quantities are assessed using two wing-alone configurations whose experimental results are available in the literature [16]. The first case is an unswept rectangular wing designed using NACA 0012 airfoil with an aspect ratio of 5.9. The second case is a trapezoidal wing designed using NACA 64A010 airfoil with taper ratio of 0.5, aspect ratio of 3 and a sweep of $45°$. Figure 3a compares computed spanwise lift distributions for case 1 at angle of attack $\alpha = 8$ degrees with experimental data. Computed results are reasonably consistent with the experimental data in the mid span region and only small deviations are found at the root and tip of the wing. Figure 3b compares computed lift coefficient for a range of angles of attack with experimental data. For small angles of attack, VSPAERO matches with experiential data, but viscous effects are neglected thus the computed results deviate from experimental data for regions close to higher angle of attack. Agreement between VSPAERO and experimental results indicates that VSPAERO can be used in the early stages of the aircraft design process where capturing



(a) Half span lift distribution for case 1 at $\alpha = 8^\circ$

(b) Lift curve for case 2

Figure 3 – Comparison between experimental results and VSPAERO for various wing cases

Parameters	Category	Value
Population	Case-1	50
	Case-2	70
	Case-3	70
Generation	Case-1	30
	Case-2	50
	Case-3	50
Crossover Rate	-	0.6
Mutation Rate	-	0.2

Table 2 – Parameters for NSGA-II

approximate solutions quickly is of more importance than obtaining a detailed investigation using a RANS-based solver.

2.5 OpenMDAO Framework

In this work, an OpenMDAO-based optimisation framework has been developed to integrate aerodynamics and stability modules with pyOptSparse-driver library to drive the design process [17]. Top level OpenMDAO API reads a user input file and defines an objective function, design variables, constraint functions and calls multiple external modules for optimisation. These modules are: OpenVSP-based CAD module for geometry generation, VSPAERO with VLM method for computing aerodynamic quantities and stability module for computing required stability derivatives. In VSPAERO, ground effect computations were performed using the method of images.

2.5.1 Optimiser

Including nonplanar wing deformation in the shape optimisation process may increase the likelihood of multimodality in the design space, hence global optimisation algorithms are preferred than gradient-based optimisation algorithms. In a multi-objective optimisation problem, the optimal solution is not unique hence an optimiser converges to a set of nondominated potential optimal solutions called Pareto optima. Therefore, in this work, the NSGA-II algorithm is used to solve the multi-objective wing planform optimisation problem given in Equation 9. NSGA-II is an evolutionary algorithm and employs efficient non-dominated ranking procedure to obtain different levels of Pareto frontier. In the initial generations, the optimiser assigns more selection pressure towards the less violated constraints. Once solutions reach the feasible region, NSGA-II guides the search towards the direction of the Pareto optimal region. Table 2 summarizes the optimisation parameters used in NSGA-II.

2.5.2 Post Optimality Analysis

Finding a best compromise solution in a set of Pareto optimal solutions is necessary in the multi-objective optimisation problem. In this work, fuzzy based set theory is used to assign member function value to each Pareto optimal solution and a solution which has the maximum membership value is selected as the best compromise solution [18]. For each non-dominate solution k, membership function for a minimization of ith objective function is defined as,

$$MF_i^k = \begin{cases} 1, & f_i < f_i^{min} \\ \frac{f_i^{max} - f_i}{f_i^{max} - f_i^{min}}, & f_i^{min} < f_i < f_i^{max} \\ 0 & f_i \geq f_i^{max} \end{cases} \tag{10}$$

Normalized member function value is then obtained as,

$$MF^k = \frac{\sum_{i=1}^{M} MF_i^k}{\sum_{k=1}^{y} \sum_{i=1}^{M} MF_i^k} \tag{11}$$

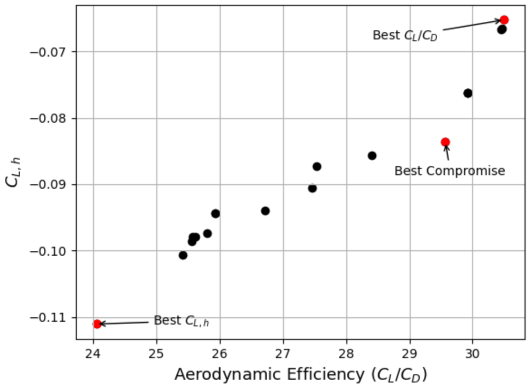
where y is the number of non-dominated solution and M is the number of objective function.

3. Results and Discussion

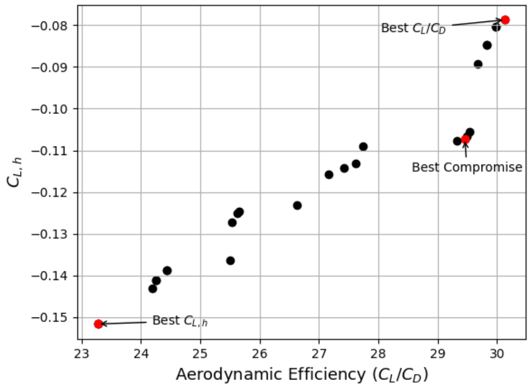
Unlike out-of-ground effect aircraft, a WIG vehicle has to satisfy the static height stability condition to achieve steady cruise flight. However, it is difficult to satisfy both aerodynamic and stability requirements simultaneously. Therefore in this work, multi-objective planform optimisation has been performed using the NSGA-II optimisation algorithm coupled with the low-fidelity aerodynamic analysis solver VSPAERO. The OpenVSP parametric geometric modeller has been employed as a geometry tool. To understand the design requirements of a WIG craft, the baseline rectangular wing planform has been parametrized using three different sets of planform design variables and multi-objective optimisation has been performed independently. In Case-1, the design space doesn't include non-planar geometries and planform optimisation has been performed using a single wing segment. In both Case-2 and Case-3, the wing planform is divided into two segments, the span of the outer wing corresponds to 70% and 30% of the overall span respectively. Nonplanar shape variations are included in the design space by changing the dihedral angle of the outer wing segment, whereas the dihedral angle of the inner wing segment remains fixed in the optimisation. The design lift coefficient considered in this work is $C_L = 0.4$, which is moderately lower than the normal cruise lift coefficient and is handled using an inequality constraint in the optimisation.

Figure 4 shows the Pareto plot for the three optimisation cases. The best compromise solution for each case obtained using post optimality analysis is also highlighted in Figure 4. Diversity in the resultant Pareto plot can be further improved by increasing the number of population and generation for each case in NSGA-II. Figure 5 shows the optimised planform geometries obtained using all the three optimisation cases. Planform shapes shown in the left corresponds to the best L/D ratio, the best compromise solutions are shown in the middle and the best $C_{L,h}$ shapes are shown in the right side. From an aerodynamics points of view, we see very similar trends, to minimize induced drag the optimiser converges to the largest possible wingspan, hence in all the best L/D designs, the span of the wing is close to the upper limit. Furthermore, the optimiser tapered the wing to optimise the spanwise wing loading and converged to a slender configuration for the best L/D designs and the low aspect ratio (short and wide) wing configurations for better stability characteristics. Best compromise solutions fall between the slender and low aspect ratio configuration.

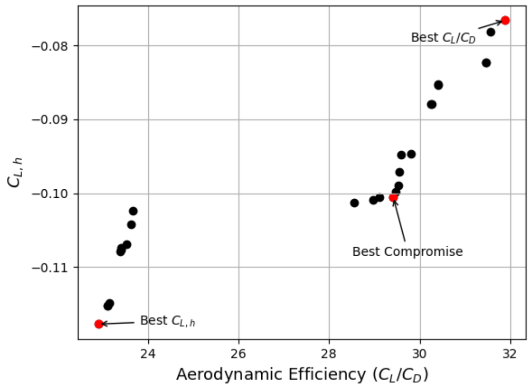
Nonplanar wing tip optimisation has the potential to increase the lift to drag ratio beyond what is achievable with the planar (Case-1) and nonplanar wing planform (Case-2) optimisation. However, wings with large wingspans lead to larger moments and stresses hence structural analysis will be included in future to minimize the wing root bending moment. On the other hand, the optimiser converged to smaller aspect ratio wings to improve stability characteristics at the cost of decreasing the aerodynamic efficiency. In terms of stability, nonplanar wing offers better stability than planar wings. In particular, changing dihedral angle of the 70% of the span (Case-2) made it possible to achieve best minimum value of $C_{L,h} = -0.15$. Figures 6, 7, and 8 show the performance characteristics



(a) Case-1

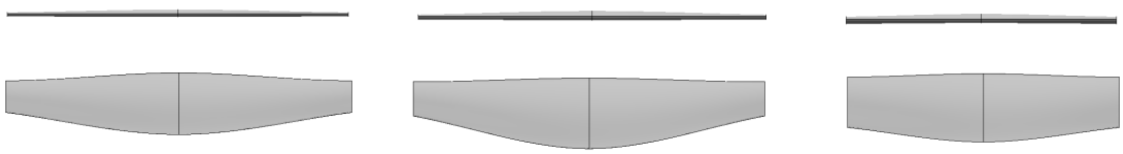


(b) Case-2

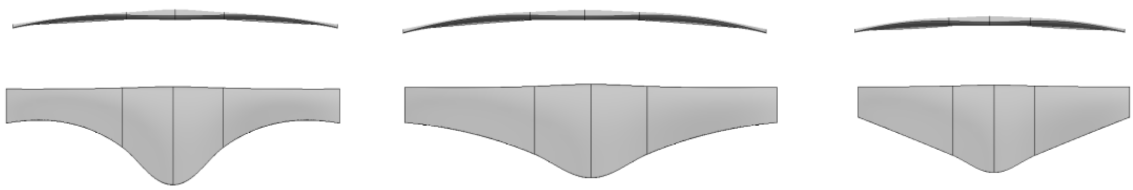


(c) Case-3

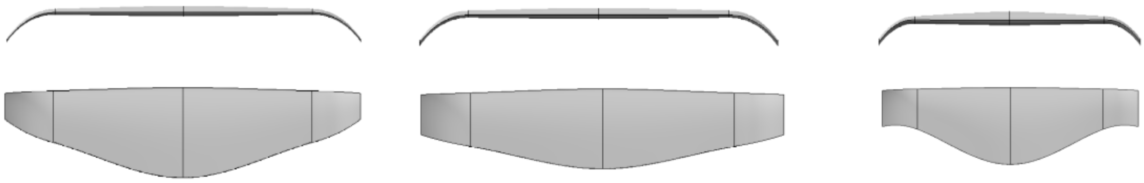
Figure 4 – Pareto optimal plot for all the three optimisation cases



(a) Case-1



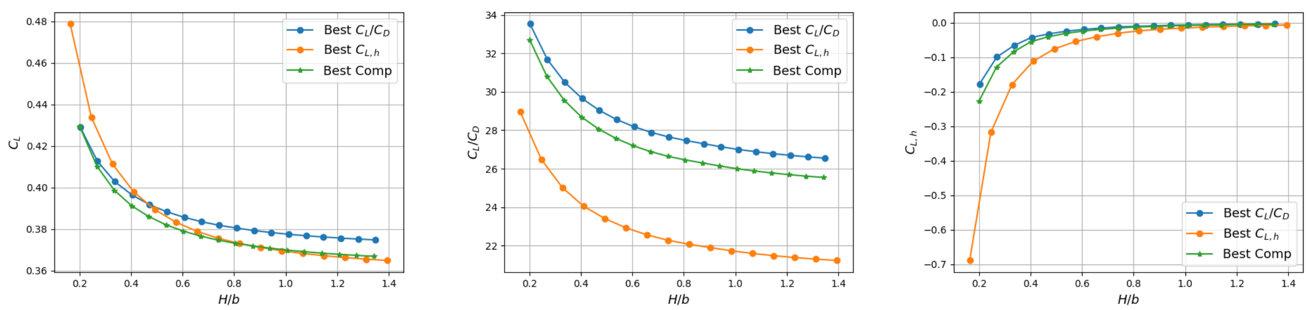
(b) Case-2



Best L/D *Best Compromise* *Best $C_{L,h}$*

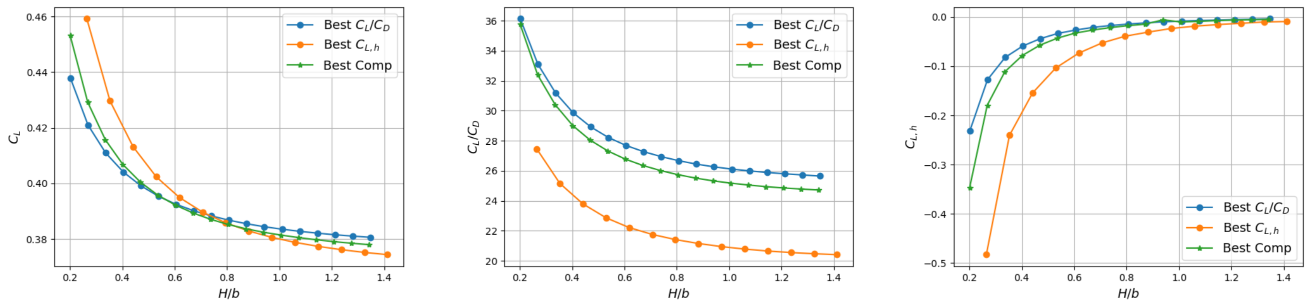
(c) Case-3

Figure 5 – Optimized planform shapes obtained from all the three cases. Left side shapes corresponds to best L/D ratio, right side shapes corresponds to best $C_{L,h}$, shapes in the middles corresponds to best compromise solution



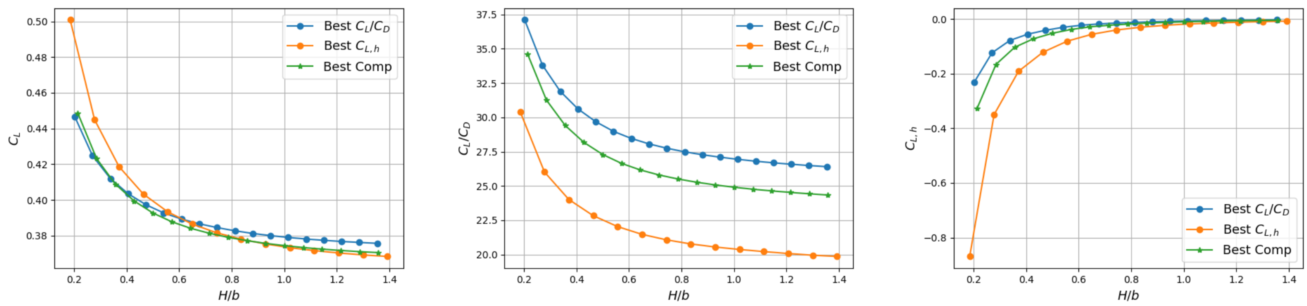
(a) C_L vs H/b (b) C_L/C_D vs H/b (c) $C_{L,h}$ vs H/b

Figure 6 – Performance characteristics of Case-1 optimum shapes



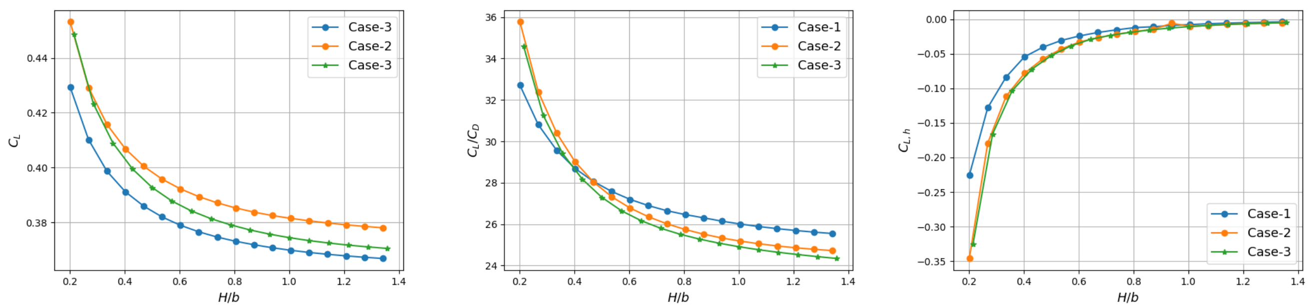
(a) C_L vs H/b (b) C_L/C_D vs H/b (c) $C_{L,h}$ vs H/b

Figure 7 – Performance characteristics of Case-2 optimum shapes



(a) C_L vs H/b (b) C_L/C_D vs H/b (c) $C_{L,h}$ vs H/b

Figure 8 – Performance characteristics of Case-3 optimum shapes



(a) C_L vs H/b (b) C_L/C_D vs H/b (c) $C_{L,h}$ vs H/b

Figure 9 – Performance characteristics of the best compromise designs

of optimum wing planform shapes shown in Figure 5 over a wide range of height ratio H/b. Although the low AR wing is less efficient aerodynamically, it increases $C_{L,h}$ hence it is better suited to enhance static height stability of a WIG craft. In general, low AR wings have low $C_{L,max}$ and high stall angle of attack α_{stall} and requires high angle of attack before stabilizing moments begin to drop.

Nonplanar wings with anhedral configurations create additional lift by creating a dynamic air cushion called RAM pressure under the wing surface hence C_L value increases rapidly in close proximity to the ground hence increasing $C_{L,h}$. This can be clearly seen in Figure 5b, thus anhedral wing configurations improve the longitudinal static height stability characteristics of a WIG vehicle. Similar design configurations can also be found in the Lippich-type WIG vehicle, Airfish 3 and Airfish 8 [4]. However, this configuration may exhibit poor stall characteristics, as presence of ground not only increases the pressure on the wing's lower surface but may also increase the pressure gradient along the streamwise direction on the wing's upper surface. Hence, when a WIG craft operates at a higher angle of attack, stall may begin in the mid span and spreads to tip and root portion of the wing [19].

In Case-3, the optimiser converged the wing's spanwise camber in the downward direction compared to traditional wings which may be raised to have a winglet. Wings with a downward spanwise camber are called drooped wings. As similar to Case-2, the effect of RAM pressure is also evident when flying closer to the ground hence Case-3 exhibits similar stability characteristics. However, from an aerodynamics point of view, drooped wings experience the opposite of the Case-2 configuration, where the lift is reduced along the span hence there is a large reduction in drag towards the tip. This results in better lift to drag ratio than Case-1 and Case-2 configurations. Previous wing planform optimisation studies for out-of-ground effect aircraft showed similar performances [7, 20]. Best compromise solutions have negligible differences in span when compared with best L/D designs, however changes in the chord distribution and nonplanar deformation have a significant effect on $C_{L,h}$. Performance characteristics of the best compromise solution for each case are shown in Figure 9. When compared with non-planar wing planform (Case-2), winglet down configuration (Case-3) shows better trade off between L/D ratio and $C_{L,h}$ over a wide range of height ratio H/b.

4. Conclusion and Future Work

In this work, a multi-objective nonplanar wing design optimisation methodology is presented for wing-in-ground effect aircraft. A set of Pareto optimal solutions are obtained which improves both aerodynamics and stability characteristics of a WIG craft. An open-source vortex-lattice method (VLM) flow solver VSPAERO is utilised to compute aerodynamics and stability characteristics. OpenVSP is used as a geometry modeller to handle both planar and nonplanar shape variations in the design space.

Starting from a rectangular wing, the NSGA-II optimiser can generate a set of non-dominated potential optimal solutions with improved aerodynamics and longitudinal static height stability characteristics of a wing alone configuration. With a large enough design space and VLM based inviscid analysis model, NSGA-II optimiser converged to drooped type wing configuration. Results presented here have shown the benefits of drooped wing type configuration to enhance both L/D ratio and stability derivatives $(C_{L,h})$ for ground effect application. The framework developed in this work is a first step in constructing a high fidelity multi-disciplinary optimisation framework applicable to conceptual and preliminary design phases of WIG aircraft for future coastal transportation. In future work, the current framework will be extended to handle gradient-based multi-objective wing planform optimisation to include both aerodynamics and stability characteristics of a WIG craft.

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7. Copyright Statement

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