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STABILITY ANALYSIS AND CONTROL-SURFACE OPTIMIZATION OF ADELTA-WING FIXED-WING UAV

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ABSTRACT

Delta-wing flying wings are attractive for small UAVs because they are structurally simple and carry no tail, but the same absence of a tail leaves a single pair of elevons responsible for trim, pitch control and roll control, and it ties static stability to the wing planform. This paper studies how far that single control pair can be sized down before the airframe loses either its stability or its controllability. We build a compact, reproducible model of a 4.5 kg, 1.6 m span delta UAV with a 55° leading-edge sweep: a Helmbold lift slope combined with the Polhamus leading-edge-suction analogy for vortex lift, strip-theory elevon effectiveness, a four-state longitudinal model and a four-state lateral-directional model. Static margin, short-period and phugoid behavior are examined as the centre of gravity moves, and the elevon layout (chord fraction, inboard and outboard station) is then optimized with differential evolution against approach-trim, roll-rate, pitch-authority and hinge-moment requirements. For a 4 % MAC static margin the optimized layout needs 0.083 m² of elevon area, 41 % less than an initial full-span layout, and lowers the hinge moment by 49 %. The study also shows that approach-trim authority, not short-period behavior, caps the usable static margin at roughly 5 % MAC for a section pitching moment of +0.03, and that this ceiling moves by about one percentage point for every 0.01 of reflex. All aerodynamic inputs are engineering estimates; the results are a design-level trade study and not a substitute for wind-tunnel or flight data.

Keywords: Delta Wing, Flying Wing, UAV, Static Margin, Elevon, Control Allocation, Vortex Lift, Differential Evolution, Flight Dynamics.

1 INTRODUCTION

A tailless delta is hard to beat on paper. It has low wetted area for its span, a deep root that is easy to build in foam or composite, and a leading-edge vortex that keeps the wing flying at angles of attack where a straight wing would already have stalled [2], [4], although the unsteady behavior of that vortex on less slender wings is more complicated [20]. The price is paid in the flight-control department. Without a horizontal tail, the wing has to supply its own pitch stability, the trailing-edge elevons have to trim the nose-down or nose-up moment of the whole vehicle, and the same two surfaces must also roll the aircraft. Every degree of elevon travel that goes into trim is a degree that is no longer available for maneuvering, and every extra square centimeter of elevon adds mass, servo load and hinge moment [1], [21].

Most of the open literature on tailless aircraft treats these questions one at a time. Kwiek showed that elevon deflection changes the stability derivatives of a small tailless UAV by more than a change in Mach number does, so it cannot be left out of a longitudinal dynamic-stability analysis [5]. Kania et al. recently quantified how winglet size moves the lateral-directional modes of a tailless configuration, with trim deflection and L/D tracked alongside [6]. On the control side, the control-allocation literature has developed good tools for distributing a commanded moment over redundant surfaces [10], [11], with applications to rhomboid-wing and flying-wing UAVs [7]–[9]. Flight-derived and early analytical work on tailless deltas [12], [13] and on the static and dynamic behavior of flying wings [22], [21] establishes what the derivatives look like, and yaw control of a tailless aircraft has been treated separately [18]. What is harder to find is a study that starts from the other end: given a fixed delta planform, how small can the elevons be made, and where should they sit, if the aircraft is still to trim at approach speed, roll at a useful rate and keep an acceptable static margin?

That is the question this paper takes on. We make three contributions. First, we assemble a self-contained analysis model for a small delta UAV that captures the features that matter most for this question: nonlinear vortex lift, a lift-weighted elevon moment arm, trim-induced loss of lift, and the coupling of elevon area to hinge moment. Second, we use it to map static margin, short-period and phugoid behavior against centre-of-gravity position. Third, we optimize the elevon layout and show how the achievable static margin is capped by approach trim authority and by the amount of reflex built into the wing sections.

We want to be upfront about what this paper is and is not. The vehicle is a representative design chosen for this study, not a specific airframe we tested. The aerodynamic coefficients come from established empirical methods and are labelled as assumptions wherever they appear. The conclusions are therefore trends and trade-offs that should hold for this class of aircraft, and the absolute numbers should be re-derived with wind-tunnel, panel-method or CFD data before they are used for a real build.

2 VEHICLE AND AERODYNAMIC MODEL

2.1 Configuration

The vehicle is a delta flying wing with a 55° leading-edge sweep, measured from the lateral axis, a 1.60 m span and a root chord of 1.143 m. Two small tip fins provide directional stability, and a pair of trailing-edge elevons provides pitch and roll control. Fig. 1 shows the planform with the initial and optimized elevon layouts discussed in Section V-C. With the delta planform, the reference quantities follow directly:

$$S = \frac{bc_r}{2}, \quad AR = \frac{b^2}{S}, \quad \bar{c} = \frac{2}{3}c_r, \quad x_{\bar{c}} = \frac{c_r}{3} \quad (1)$$

which gives $S = 0.914 \text{ m}^2$, $AR = 2.80$, a mean aerodynamic chord of 0.762 m, and a wing loading of 48.3 N/m^2 . Table I lists the assumed vehicle data. Centre-of-gravity position is expressed as a fraction h of the mean aerodynamic chord measured from its leading edge, which is the convention used throughout.

Table 1: Assumed Vehicle and Model Parameters

Parameter	Value	Parameter	Value
Mass, m	4.5 kg	Vortex-lift constant, K_v	2.0
Span, b	1.60 m	Potential-lift centre, h_p	0.32
Root chord, c_r	1.143 m	Vortex-lift centre, h_v	0.50
Wing area, S	0.914 m^2	Section moment, C_{m0}	+0.030
Aspect ratio	2.80	Zero-lift drag, C_{D0}	0.022
I_{xx} , I_{yy} , I_{zz}	0.31, 0.28, 0.55 $\text{kg}\cdot\text{m}^2$	Oswald-type factor, e	0.70
Tip fins (total)	0.05 m^2 , $a_v = 2.2$	Viscous flap factor	0.85
α_{stall} (assumed)	25°	$C_{L\text{max}}$	1.35

2.2 Lift and Pitching Moment

The lift-curve slope is estimated from the Helmbold expression using the half-chord sweep $\Lambda_{1/2}$ [16]:

$$C_{L\alpha} = \frac{2\pi AR}{2 + \sqrt{4 + AR^2 (1 + \tan^2 \Lambda_{1/2})}} \quad (2)$$

For this planform it gives $C_{L\alpha} = 2.94$ per radian. At moderate and high angles of attack a delta wing carries an extra lift contribution from the leading-edge vortex. We use the leading-edge-suction analogy of Polhamus [2]–[4], in which the suction force that would exist on an attached-flow wing is rotated normal to the wing and counted as lift:

$$C_L(\alpha) = K_p \sin \alpha \cos^2 \alpha + K_v \cos \alpha \sin^2 \alpha \quad (3)$$

with K_p taken equal to the Helmbold slope. K_v depends on aspect ratio and leading-edge shape, and a blunt leading edge reduces it. We use $K_v = 2.0$ as a representative value and test its effect in Section V-E. Fig. 2(a) shows that with these constants the vortex term supplies about 24 % of the lift at the assumed 25° stall angle.

The two lift components act at different chord wise positions. We place the potential lift at $h_p = 0.32$ and the vortex lift further aft at $h_v = 0.50$ of the mean chords; both are assumptions informed by the aft shift of vortex-lift loading on slender wings. The wing pitching moment about the centre of gravity is then

$$C_m(\alpha, h) = C_{m0} - C_{L,p}(h_p - h) - C_{L,v}(h_v - h) \quad (4)$$

where $C_{L,p}$ and $C_{L,v}$ are the two terms of the lift equation. C_{m0} is the zero-lift moment of the wing, which can be made positive by using reflexed sections or by adding twist; we return to its importance later. In the linear range the static margin is

$$SM = h_p - h, \quad C_{m\alpha} \approx -C_{L\alpha} SM \quad (5)$$

Because the vortex lift acts aft of h_p , the effective margin grows with angle of attack. At the nominal cruise condition, we find $-C_{m\alpha}/C_{L\alpha} = 0.054$ MAC against a linear margin of 0.040, a modest but useful reminder that the neutral point of a delta is not fixed.

2.3 Elevon Effectiveness and Moment Arm

Each elevon is modeled, following classical thin-airfoil and strip-theory practice [17], as a plain trailing-edge flap occupying a constant fraction E of the local chord between the span stations η_i and η_o (fractions of the semi-span). The chord at station η is $c(\eta) = c_r(1 - \eta)$. Thin-airfoil theory gives the flap effectiveness parameter

$$\tau = 1 - \frac{\theta_f - \sin \theta_f}{\pi}, \quad \theta_f = \arccos(2E - 1) \quad (6)$$

and we multiply it by a viscous factor of 0.85, so that $\tau_v = 0.85 \tau$. The lift increment of the symmetric pair is

$$C_{L\delta} = C_{L\alpha} \tau_v \frac{S_{aff}}{S}, \quad S_{aff} = b \int_{\eta_i}^{\eta_o} c(\eta) d\eta \quad (7)$$

where S_{aff} is the wing area spanned by the elevons. The lift generated by a deflected flap does not act at the quarter-chord. Using the thin-airfoil flap moment, its centre of pressure sits at $x/c = 0.25 - c_{m\delta}/C_{L\delta}$ of the local chord. Weighting that position over the span gives an effective elevon arm x_e , and the pitching moment derivative is

$$C_{m\delta} = -C_{L\delta} \frac{x_e - x_{cg}}{\bar{c}} \quad (8)$$

This is where the planform matters. On a delta, the trailing edge is straight, but the leading edge is swept, so an elevon placed outboard sits much farther aft of the centre of gravity than one placed near the root. Outboard elevons therefore produce more pitching moment per unit of lift they add or remove. That is useful when the elevons must be deflected up to trim, because the lift they destroy is what limits approach.

2.4 Trim and Drag

For steady level flight at speed V , the angle of attack α and the symmetric elevon deflection δ_e must satisfy lift equal to weight and zero net pitching moment:

$$C_L(\alpha) + C_{L\delta} \delta_e = \frac{W}{qS}, \quad C_m(\alpha, h) + C_{m\delta} \delta_e = 0 \quad (9)$$

We solve this nonlinear pair numerically for every flight condition. The drag model is a parabolic polar with an elevon penalty that grows with deflection and elevon area:

$$C_D = C_{D0} + K C_L^2 + 0.6 \frac{S_e}{S} \sin^2 \delta_e, \quad K = \frac{1}{\pi e AR} \quad (10)$$

The elevon coefficient of 0.6 is an engineering approximation based on the normal-force drag of a deflected plate, not a measured value. The assumed stall angle gives $C_{L\max} = 1.35$, a stall speed of 7.7 m/s, and an approach speed of $1.3 V_s = 10.0$ m/s, corresponding to $C_L = 0.80$.

3 DYNAMIC STABILITY MODEL

3.1 Longitudinal Dynamics

We linearize the longitudinal equations of motion about each trimmed condition using stability axes [14], [15]. Of the dimensional derivatives, the pitch-damping term deserves a comment, because a delta has a long, thin chord distribution and the usual tail-based approximations do not apply. We evaluate it by integrating the local lift contribution along the span, assuming the local lift acts at the local quarter chord shifted so that the planform average coincides with h_p :

$$C_{m_q} = -\frac{2C_{L\alpha}}{S\bar{c}^2} \int_{-b/2}^{b/2} c(y) [x_{ac}(y) - x_{cg}]^2 dy \quad (11)$$

The state vector is (u, w, q, θ) and the elevon enters through the lift and moment derivatives of Section II-C:

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} X_u & X_w & 0 & -g \\ Z_u & Z_w & V + Z_q & 0 \\ 0 & M_w & M_q & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} 0 \\ Z_\delta \\ M_\delta \\ 0 \end{bmatrix} \delta_e \quad (12)$$

We neglect the downwash-lag term $C_{m,\dot{\alpha}}$. For a tailless wing there is no tail to lag, so its contribution is small, but this is an approximation and it slightly overestimates the short-period frequency.

3.2 Lateral-Directional Dynamics

The lateral model uses the states (v, p, r, ϕ) with the standard side-force, rolling-moment and yawing-moment derivatives. The tip fins provide $C_{n\beta}$ and most of C_{nr} : with total fin area 0.05 m^2 , lift slope 2.2 per radian and a sidewash efficiency of 0.9, the fins give $C_{n\beta} = 0.035$ per radian. The dihedral effect is estimated as $C_{l\beta} = -0.25 C_{L\alpha}$, roll damping from strip theory as $C_{lp} = -C_{L\alpha}/12$, and the other cross-derivatives from simple trends. These lateral values are the least certain part of the model and are used only to check that the optimized elevons do not do anything unreasonable to the lateral modes, not as predictions of the aircraft's handling.

3.3 Roll Authority

For a differential deflection δ_a (right elevon down, left elevon up by the same amount), strip theory gives the rolling-moment derivative and the steady roll rate of the roll-subsidence mode:

$$C_{l\delta_a} = \frac{2C_{L\alpha} \tau_v}{Sb} \int_{y_i}^{y_o} c(y) y dy, \quad p_{ss} = -\frac{C_{l\delta_a}}{C_{lp}} \delta_a \frac{2V}{b} \quad (13)$$

The same elevon is also loaded in hinge moment, which we estimate from the elevon chord and an assumed hinge-moment slope of -0.5 per radian:

$$H = |C_{h\delta}| \delta q_{max} \int_{y_i}^{y_o} [E c(y)]^2 dy \quad (14)$$

4 ELEVON OPTIMISATION

4.1 Problem Statement

The design variables are the elevon chord fraction E , the inboard station η_i and the outboard station η_o , with the nominal centre of gravity fixed at $h = 0.28$ (a 4 % MAC static margin). We minimize the elevon area, which is a proxy for mass, servo demand and trim-induced drag, subject to the six requirements in Table II:

$$\min_{E, \eta_i, \eta_o} \frac{S_e}{S} \quad \text{subject to} \quad g_k(E, \eta_i, \eta_o) \geq 0, \quad k = 1, \dots, 6 \quad (15)$$

Table 2: Design requirements used as optimization constraints

No.	Requirement	Limit	Evaluated at
g1	Elevon deflection to trim at approach	$\leq 20^\circ$	$C_L = 0.80$, CG 0.03 MAC forward of nominal
g2	Angle of attack at approach trim	$\leq 22^\circ$	same
g3	Steady roll rate for 12° differential deflection	≥ 120 deg/s	18 m/s
g4	Pitch acceleration per 10° of elevon	≥ 15 rad/s ²	18 m/s
g5	Hinge moment per elevon at 15°	≤ 1.0 N·m	28 m/s
g6	Elevon chord at outboard end	≥ 50 mm	geometry

These limits are our own design requirements, fixed before the optimization was run. The approach case is deliberately the demanding one. We assume the payload can shift the centre of gravity 3 % MAC forward of nominal, which adds nose-down trim demand that the elevons must overcome at the highest lift coefficient of the flight envelope.

4.2 Solution Method

The problem is non-convex because the trim solution is nonlinear and the elevon moment arm depends on the layout. We use differential evolution [19] with a population of 20 per variable, 120 generations and a penalty function:

$$J_p = \frac{S_e}{S} + 50 \sum_k \max(0, -g_k) \quad (16)$$

with each constraint normalized by its limit. For the nominal case we ran five random seeds; all five converged to the same layout (elevon area identical to four decimal places), which gives some confidence that the optimum is global within the search bounds. The static-margin sweeps in Section V-D use a single seed per point, so isolated points on those curves should be read with that in mind.

5 RESULTS AND DISCUSSION

5.1 Aerodynamics and Trim

Fig. 2 shows the lift curve and the moment about the centre of gravity at three CG positions. The moment curves bend downward with increasing lift, which is the signature of the aft-moving vortex-lift centre. In trimmed level flight at 18 m/s the aircraft flies at $C_L = 0.24$ and $\alpha = 3.5^\circ$, with a trimmed lift-to-drag ratio of 7.5. The best L/D is 8.3 near 14 m/s.

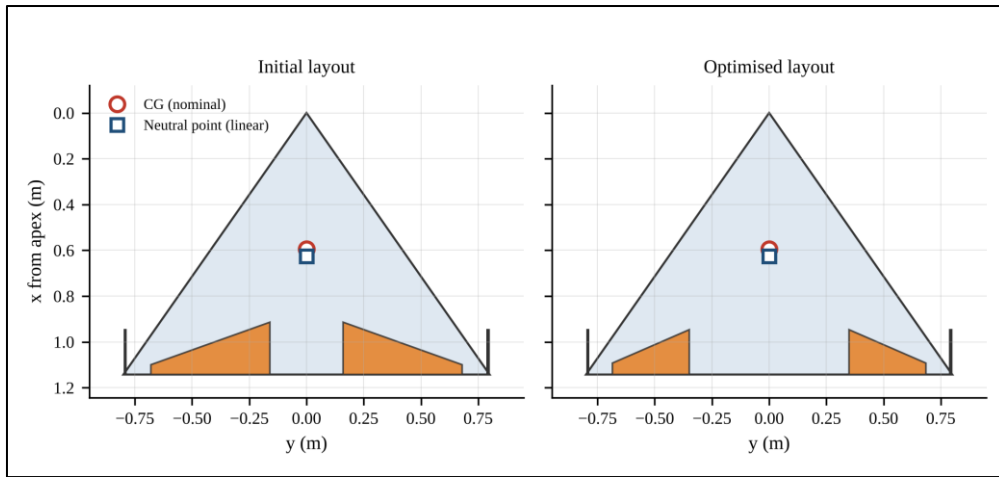


Figure 1: Initial and optimised elevon layouts on the delta planform, with the nominal CG and the linear neutral point.

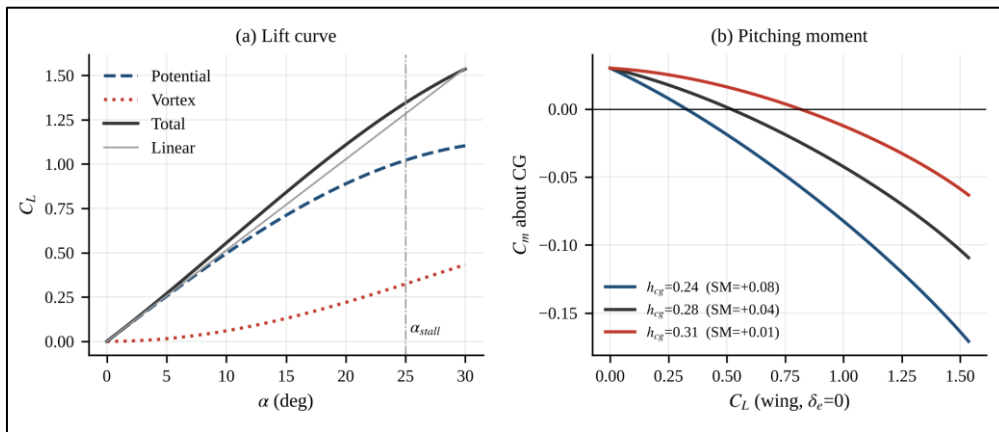


Figure 2: (a) Lift-curve components and (b) pitching moment about the CG for three CG positions.

Fig. 3 shows the trim deflection and trimmed L/D as the CG moves. The trim elevon angle at cruise is positive (trailing edge down) because the reflexed sections give a nose-up zero-lift moment that the elevons must partly cancel. At 18 m/s the trim deflection is +4.0°, +6.7° and +8.5° for $h = 0.25, 0.28$ and 0.30 . What is interesting is how little this costs: the best L/D changes from 8.37 to 8.23, under 2 %, across that CG range. Cruise efficiency therefore gives the designer very little reason to push the CG aft; the CG choice should be driven by stability and by approach trim, which is what the rest of the study examines.

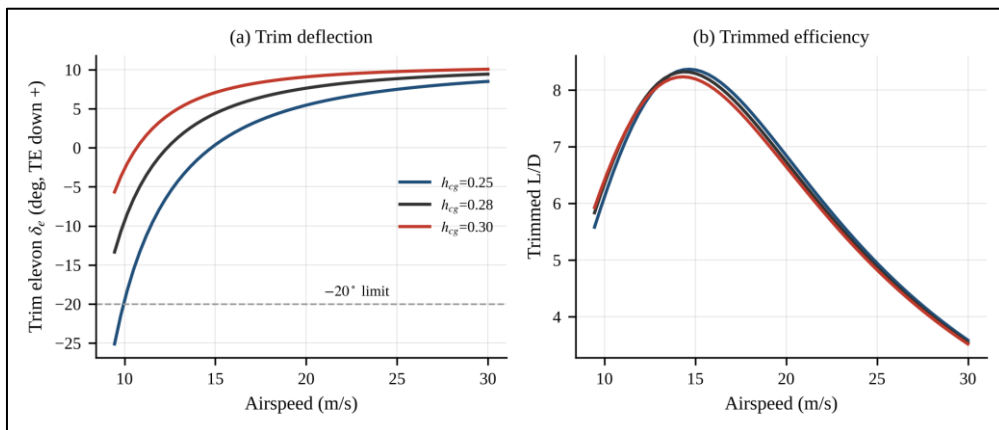


Figure 3: (a) Trim elevon deflection and (b) trimmed lift-to-drag ratio against airspeed for three CG positions (optimised elevons).

The steep rise in required up-elevon at low speed on the left of Fig. 3(a) is the central difficulty of a delta flying wing. As the speed falls, the aircraft has to fly at a higher lift coefficient; the nose-down moment from the vortex lift grows; the

elevons must go up to balance it; and going up removes lift from the wing, which forces the angle of attack up further. At the 10 m/s approach speed of this aircraft, the most forward CG shown is already near the 20° trim limit.

5.2 Static Margin and Dynamic Modes

Table III lists the main derivatives and modes at the nominal condition (18 m/s, SM = 4 %, optimized elevons). The short-period mode has $\omega = 10.8$ rad/s and $\zeta = 0.55$, which is well damped. The phugoid has a period of 9.6 s and $\zeta = 0.077$. As a sanity check, Lanchester's approximation $\zeta \approx 1/(\sqrt{2} L/D)$ gives 0.094, and $\omega \approx g\sqrt{2}/V$ gives 0.77 rad/s, so our model is within about 20 % of the classical estimates for both values.

Table 3: Derivatives and modes at 18 m/s, 4 % static margin (optimised elevons)

Longitudinal	Value	Lateral-directional	Value
$C_{L\alpha}$ (per rad, at trim)	3.15	$C_{y\beta}$	-0.158
$C_{m\alpha}$ (per rad)	-0.169	$C_{l\beta}$	-0.061
C_{mq}	-0.452	$C_{n\beta}$	0.035
$C_{L\delta}$ (per rad)	0.494	C_{lp}	-0.262
$C_{m\delta}$ (per rad)	-0.181	C_{nr}	-0.032
Short period: ω, ζ	10.8 rad/s, 0.55	Roll time constant	0.089 s
Phugoid: T, ζ	9.6 s, 0.077	Dutch roll: ω, ζ	4.8 rad/s, 0.084
L/D (trimmed)	7.52	Spiral: time to double	100 s

The lateral results show what we expect of a tailless aircraft with small fins. Dutch roll is lightly damped ($\zeta = 0.08$) and the spiral mode is slightly divergent, with a time to double of about 100 s. Neither is caused by the elevons, but both would call for a yaw damper or larger fins on a real vehicle. Given the uncertainty on the lateral derivatives, we treat this as a flag for follow-up rather than a finding.

Fig. 4 shows how the longitudinal modes move with static margin. Increasing the margin raises the short-period frequency steadily, while damping falls: ζ_{sp} changes from 0.59 at 3 % to 0.43 at 10 %, and ω_{sp} from 10.0 to 14.7 rad/s. Within the 3–10 % range the short period stays above $\zeta = 0.35$, so the dynamics alone would allow a much larger margin than 4 %. The phugoid is almost insensitive to the margin, because it is governed mainly by L/D.

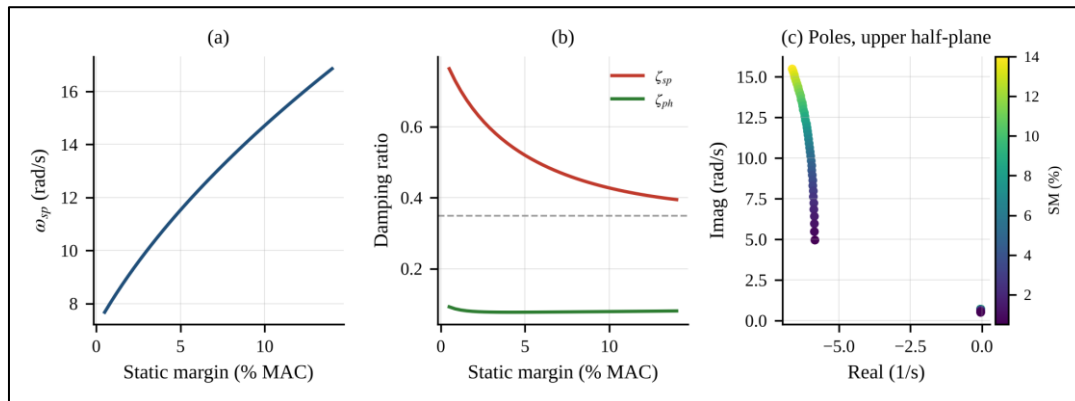


Figure 4: Longitudinal modes against static margin at 18 m/s: (a) short-period frequency, (b) short-period and phugoid damping, (c) pole locations coloured by static margin.

5.3 Optimized Elevon Layout

Only 1.6 % of 2,500 random layouts satisfied all six requirements at the nominal CG (Fig. 5), so the feasible region is narrow. The optimizer finds it reliably. Table IV compares the optimized layout with an initial layout ($E = 0.25$, $\eta_i = 0.20$, $\eta_o = 0.85$) that a designer might draw first.

Table 4: Initial And Optimized Elevon Layouts At The Nominal Cg ($S_m = 4 \% \text{ Mac}$)

Quantity	Initial	Optimised
Chord fraction E	0.250	0.304
Span stations $\eta_i - \eta_o$	0.20 – 0.85	0.44 – 0.86
Elevon area S_e (both sides)	0.141 m ² (15.4 % of S)	0.083 m ² (9.0 % of S)
Approach trim deflection (g1)	20.03°	20.00°
Approach angle of attack (g2)	20.3°	17.3°
Steady roll rate, 12° (g3)	221 deg/s	154 deg/s
Pitch accel. per 10° (g4)	19.6 rad/s ²	15.6 rad/s ²
Hinge moment at 15°, 28 m/s (g5)	0.70 N·m	0.36 N·m
Outboard-end chord (g6)	43 mm	50 mm
Trimmed L/D at 18 m/s	7.47	7.52
All requirements met	No	Yes

The optimized elevons are shorter in span and are moved outboard: each span 0.34 m from $y = 0.35$ m to 0.68 m, with a chord of 196 mm at the inboard end tapering to the 50 mm minimum at the outboard end. Their area is 41 % smaller, and the hinge moment is 49 % lower. The initial layout is not far from passing: its approach trim deflection of 20.03° only just exceeds the limit, and it fails the minimum-chord requirement. The real benefit of the optimizer is that it does the same job with far less surface. It does this by moving the area to where its moment arm is largest. Because the trimming demand is mostly pitching moment, an outboard, aft elevon needs less lift change to produce the same moment, which also costs less wing lift and therefore less angle of attack.

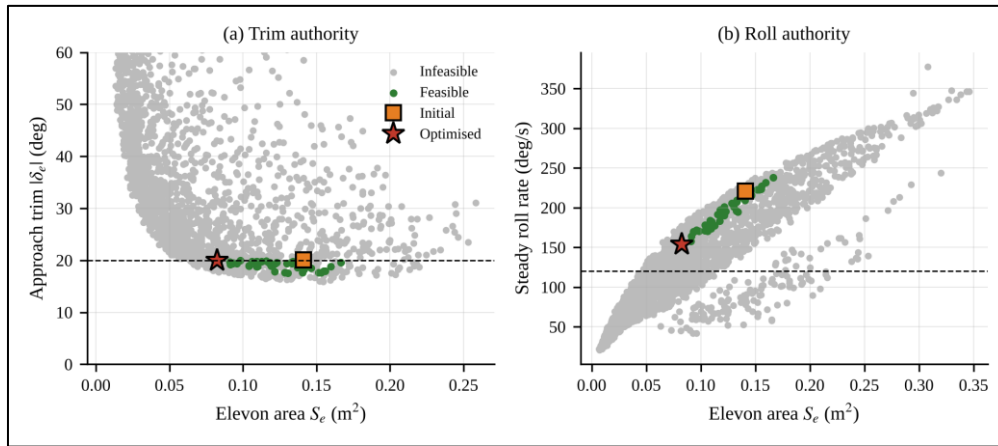


Figure 5: Random layouts at the nominal CG: (a) approach trim deflection and (b) steady roll rate against elevon area. Dashed lines are the requirements; green points satisfy all six.

At the optimum, g1 (approach trim) and g6 (minimum outboard chord) are active, and g4 (pitch authority, 15.6 against 15 rad/s²) is close to active; only the roll-subsidence rate and the hinge moment have real margin. The roll-rate result needs a caveat. The 154 deg/s in Table IV is the quasi-steady roll-subsidence value. In the coupled simulation of Fig. 6(c), the 12° differential deflection gives a peak roll rate of 134 deg/s, reaching 45° of bank in 0.41 s, but the lightly damped Dutch roll ($\zeta = 0.08$) makes the rate oscillate, and it dips to roughly 90 deg/s, below the 120 deg/s requirement, before recovering. The initial layout oscillates in the same way, between about 192 and 125 deg/s. So g3 as defined is optimistic for this aircraft; a yaw damper or larger fins would be needed to realize the quasi-steady rate in a maneuver. The pitch response to a 2° up-elevon step has a peak rate of 14.2 deg/s against 17.6 deg/s for the initial layout (Fig. 6), which is a reduction of about 19 %. That is a real cost, and it is what the g4 requirement exists to bound.

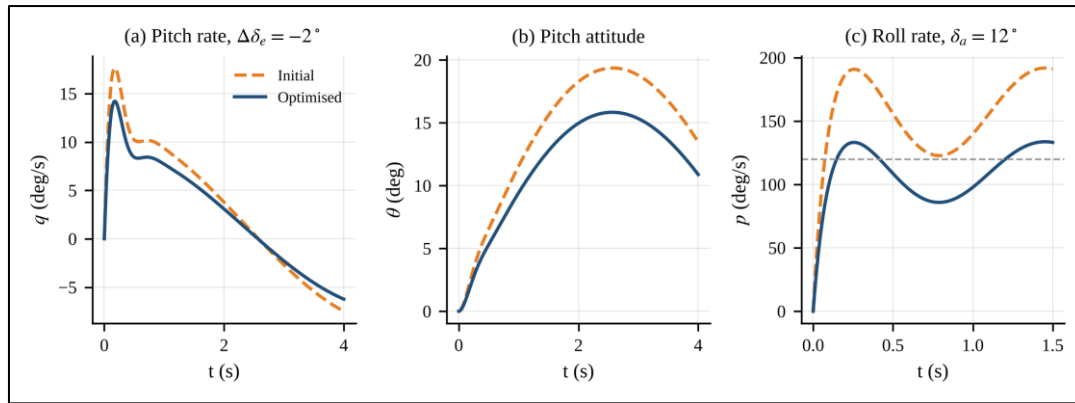


Figure 6: Time responses at 18 m/s and 4 % margin: (a) pitch rate and (b) pitch attitude for a 2° trailing-edge-up step, (c) roll rate for a 12° differential step.

5.4 How Far Can the Static Margin Go?

The optimum is not only a function of the layout. Fig. 7 repeats the optimization across static margins from 2 % to 8 % and for four values of the section moment C_{m0} . For the baseline $C_{m0} = 0.03$, feasible designs exist up to a margin of about 5 %, and the minimum elevon area rises sharply as that limit is approached, from about 0.08 m^2 at 4 % to 0.14 m^2 at 5 %. Beyond it, no layout in the search space meets all requirements. With less reflex, the ceiling falls to 3 % ($C_{m0} = 0.02$) and 2 % ($C_{m0} = 0.01$); with more it rises to 6 % ($C_{m0} = 0.04$). That is close to one percentage point of static margin for every 0.01 of zero-lift moment.

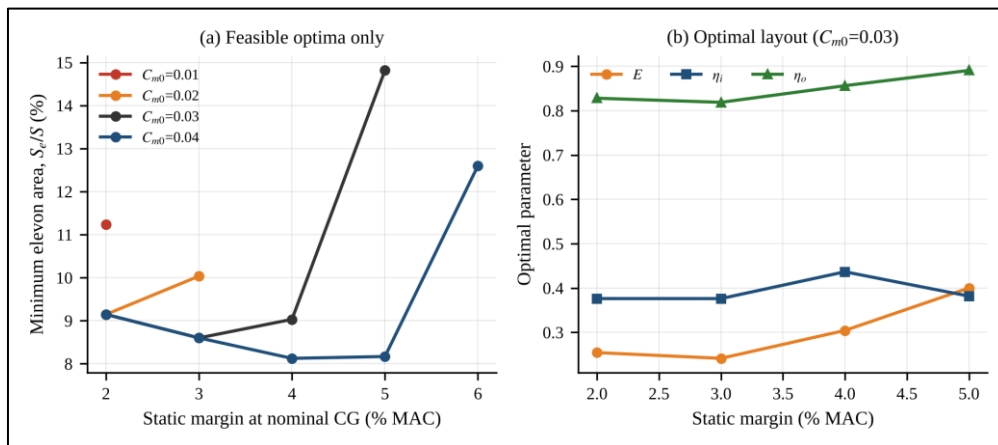


Figure 7: (a) Minimum feasible elevon area against static margin for four section pitching moments; missing points are infeasible. (b) Optimal layout parameters for $C_{m0} = 0.03$.

This result is worth taking away. The short-period analysis in Section V-B says that a static margin of 10 % would be perfectly pleasant to fly. The trim analysis says it cannot be reached at this reflex level. The binding limit on static margin for this delta is therefore the ability of the elevons to balance the aircraft at approach, not its dynamic stability. A designer who has more margin to spare than the elevons can support should look at reflex and twist before looking at larger control surfaces, because extra elevon area runs into the hinge-moment and lift-loss limits that Fig. 5 shows.

5.5 Sensitivity to Modeling Assumptions

Because several inputs are assumed, we reran the nominal optimization with each of three of them perturbed. Table V gives the result.

Table 5: Sensitivity of the nominal optimum to assumed inputs ($\text{sm} = 4\%$)

Case	$S_e \text{ (m}^2\text{)}$	Change	$\eta_i - \eta_o$	E	Feasible
Baseline	0.083	—	0.44 – 0.86	0.30	Yes
$K_v = 1.5$	0.074	-10%	0.38 – 0.81	0.23	Yes
$K_v = 2.5$	0.108	+31%	0.42 – 0.88	0.37	Yes
$h_v = 0.45$	0.074	-10%	0.38 – 0.81	0.23	Yes
$h_v = 0.55$	0.143	+73%	0.37 – 0.89	0.40	No
$\tau_v \text{ factor} = 0.75$	0.116	+41%	0.41 – 0.88	0.38	Yes
$\tau_v \text{ factor} = 0.95$	0.065	-21%	0.46 – 0.84	0.27	Yes

Among the cases that remain feasible, the required area moves by roughly -21% to $+41\%$, which is a reminder that absolute elevon sizing from a model of this kind should not be trusted to better than tens of percent. The layout, however, is stable: η_i stays between 0.37 and 0.46 and η_o between 0.81 and 0.89. The outboard placement and the preference for a moderate chord fraction are therefore robust conclusions, while the exact area is not. In the case with the vortex-lift centre moved further aft ($h_v = 0.55$) the optimizer pushed the chord fraction to its upper bound of 0.40 and still slightly violated the trim limit, so no feasible design was found at that margin. That is consistent with the ceiling discussed above, and shows that the ceiling depends on how far aft the vortex lift acts.

5.6 Limitations

Readers should keep the following in mind. The aerodynamic model is built from empirical correlations, not from panel, CFD or wind-tunnel data, and leading-edge suction analogy results degrade once vortex breakdown begins, which we handle only through the assumed 25° stall angle. The elevon effectiveness is linear in deflection and does not include the loss that occurs at large deflections or in separated flow. The lateral derivatives are rough estimates, and the lightly damped Dutch roll they produce means the quasi-steady roll-rate requirement is not fully realized in the coupled simulation. Pitch-axis flexibility, servo dynamics and actuator rate limits are not modeled. The optimizer is stochastic and was run with one seed outside the nominal case. Finally, the vehicle is a representative design, not a built aircraft, so nothing here has been verified in flight. Each of these is a reason to treat the numbers as design guidance and to confirm them with higher-fidelity analysis.

6 CONCLUSIONS

We built a compact stability and control model for a delta-wing flying-wing UAV, including vortex lift, a lift-weighted elevon moment arm and trim-induced lift loss, and used it to study both the dynamics and the sizing of the elevons. The main findings are as follows.

- For a 4% static margin the optimized elevons need 0.083 m^2 , 41% less area than a full-span initial layout and with 49% lower hinge moment, while meeting the approach-trim, quasi-steady roll-rate, pitch-authority and hinge-moment requirements (the coupled roll response is limited by the lightly damped Dutch roll). The optimum places shorter elevons outboard.
- The short-period mode is well damped ($\zeta = 0.55$) across the $3\text{--}10\%$ margin range, so dynamic stability does not limit the margin. Approach trim authority does: the maximum feasible margin is about 5% for $C_{m0} = 0.03$ and moves roughly one point per 0.01 of C_{m0} .
- Cruise L/D varies by under 2% across the CG range studied, so the CG position should be selected on stability and trim grounds and not on efficiency.
- Absolute elevon area is sensitive to assumed vortex-lift and flap-effectiveness inputs (about -21% to $+41\%$ among feasible cases, and no feasible design at all when the vortex-lift centre moves aft to 0.55 of the chord), while the outboard layout is robust. The trends are therefore more reliable than the numbers.

Natural next steps are to replace the empirical aerodynamics with panel-method or CFD derivatives for the same planform, to add control-allocation logic that splits pitch and roll demands between the two elevons under saturation, to model vortex breakdown and elevon stall, and to validate the model on a flown or wind-tunnel-tested airframe.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

There is no conflict of interest to be disclosed.

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