AE471A: Conceptual Design of a Twin-boom Fixed-Wing VTOL UAV

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Aim:

To introduce and develop the basic concept of aircraft design and build a platform with conceptual knowledge.

Abstract:

- The design of an aircraft draws on a number of basic areas of aerospace engineering. These include aerodynamics, flight mechanics, propulsion, light-weight structures and control.
- Each of these involves parameters that govern the size, shape, weight and performance of an aircraft.

Preliminary Design	**Conceptual Design**
Redefined sizing of - preferred concept	What drives the design?
Tests	Competing concepts evaluated
Design examined data/ establish parameters	Performance goals established
Some changes allowed	Will it work/meet requirement?
	What does it look like?
	Preferred concept selected

Mission Requirements

- VTOL UAV
- 150 kg MTOW
- 50 kg maximum payload
- 6 hrs endurance
- Maximum speed of 25-30 m/s
- 5 km cruise altitude
- Twin-boomed

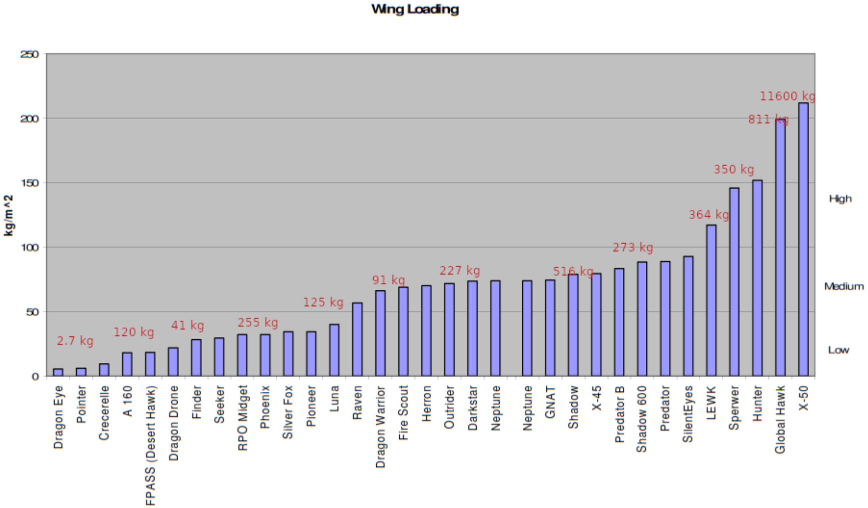
Existing models

UAV	MTOW (kg)	Payload (kg)
Zala 421-20	200	50
Aerostar	230	50
ASN 206	222	50
Primoco	150	30
Kapothaka	130	
AL-150	150	40
H150L XY	130	30
Sojka III	145	
RQ-7 Shadow	170	43
RQ-2 Pioneer	205	
AV-1 Albatross	125	
Yabhon-RX	160	50
ANTEX-M X03	150	30
BAE Phoenix	175	50
IAI Scout	159	38
MiniFalcon II	150	35
BAE Kingfisher 2	121	22
Nearchos	110	
Mastiff	138	37
	158.95	39.64

Airfoil Selection

- Cd shape of the usable Cl region
- Behavior of the drag bucket for laminar airfoils (high Re no)
- Stall behavior - sharp vs gradual
- Pitching-moment coefficient - can drive trim drag
- Compatibility with flaps
- Effectiveness with control surfaces
- Thickness to chord - for structures and internal volume
- Ability to operate over entire flight envelopes (Re, Mach)
- Ease of construction (Thin, cusped trailing edges are hard to build)

UAV	Wingspan (m)	Gross weight (kg)	Wing loading (kg/m^2)
Zala 421-20	6	200	33.33
Aerostar	8.7	230	26.44
ASN 206	6	222	37.00
Primoco	4.9	150	30.61
Kapothaka	4.5	130	28.89
AL-150	8	150	18.75
H150L XY	5.9	130	22.03
Sojka III	4.12	145	35.19
RQ-7 Shadow	4.3	170	39.53
RQ-2 Pioneer	5.15	205	39.81
AV-1 Albatross	5.4	125	23.15
Yabhon-RX	5.8	160	27.59
ANTEX-M X03	7	150	21.43
BAE Phoenix	5.6	175	31.25
IAI Scout	4.96	159	32.06
MiniFalcon II	5.5	150	27.27
BAE Kingfisher 2	4.23	121	28.61
Sigma Nearchos	5.1	110	21.57
Tadiran Mastiff	4.25	138	32.47
	5.55	**158.95**	**28.65**


Wing Loading
kg/m^2
250
200
150
100
50
0
2.7 kg
120 kg
41 kg
255 kg
125 kg
91 kg
227 kg
516 kg
273 kg
364 kg
350 kg
811 kg
11600 kg
High
Medium
Low
Dragon Eye
Pointer
Crecerelle
A 160
FPASS (Desert Hawk)
Dragon Drone
Finder
Seeker
RPO Midget
Phoenix
Silver Fox
Pioneer
Luna
Raven
Dragon Warrior
Fire Scout
Herron
Outrider
Darkstar
Neptune
Neptune
GNAT
Shadow
X-45
Predator B
Shadow 600
Predator
SilentEyes
LEWK
Sperwer
Hunter
Global Hawk
X-50

$$C_{L_{cruise}} = \frac{W/S}{\frac{1}{2}\rho {V_{cr}}^2} = \frac{20 \times 9.8}{\frac{1}{2} \times 0.736 \times 27.5^2} = 0.70$$

$$C_{L_w} = \frac{C_{L_{cruise}}}{0.95} = 0.74$$

$$C_{l_i} = \frac{C_{L_w}}{0.9} = 0.82$$

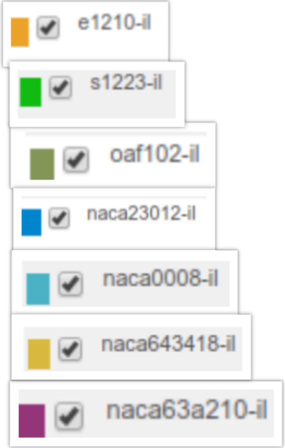
$$C_{L_{max}} = \frac{W/S}{\frac{1}{2}\rho_o {V_s}^2} = \frac{20 \times 9.8}{\frac{1}{2} \times 1.225 \times 23^2} = 1.49$$

$$C_{L_{max_w}} = \frac{C_{L_{max}}}{0.95} = 1.58$$

$$C_{l_{max}} = \frac{C_{L_{max_w}}}{0.9} = 1.66$$

$$C_{l_{max}} = C_{l_{max_{gross}}}$$

$$Re = \rho VL/\mu = 1.24 \times 10^6$$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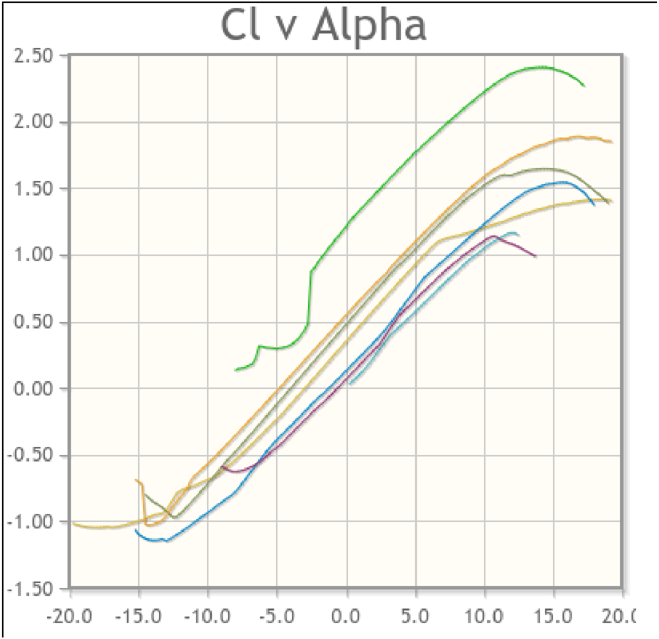
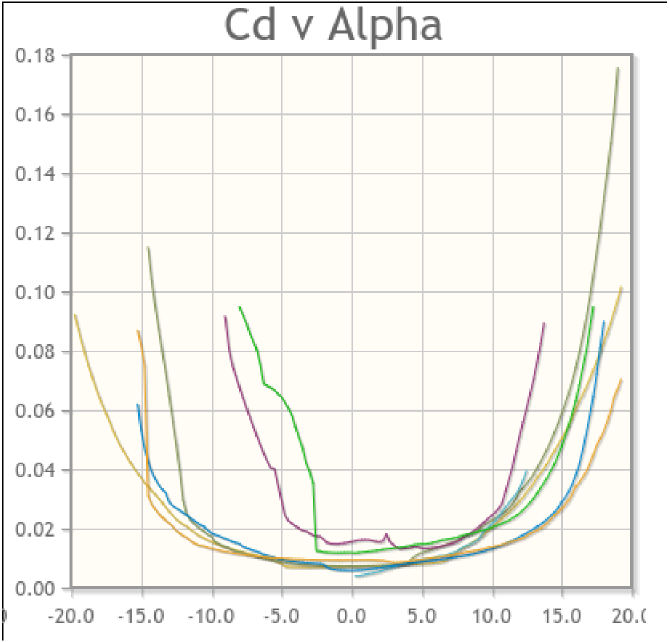


Source:airfoiltools.com



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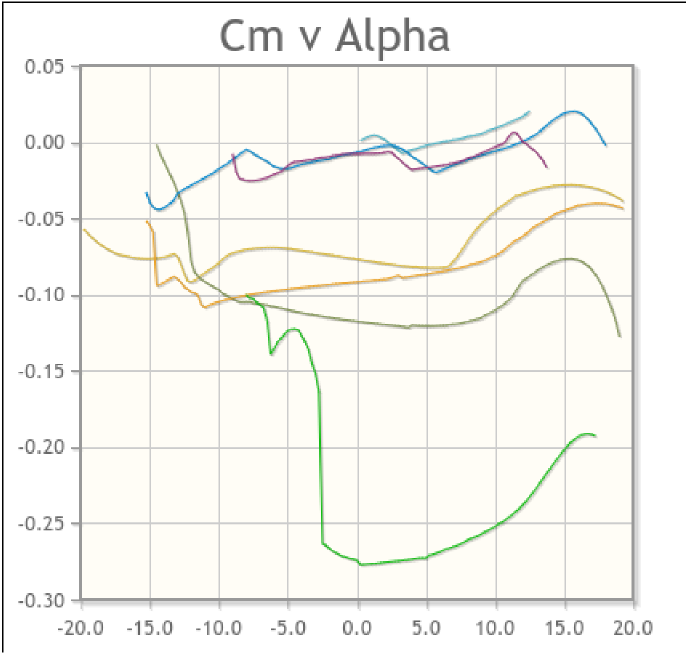


Source:airfoiltools.com

Geometric Sizing

Wing Sizing

NACA 64418 characteristics:

Stall angle stall $\alpha_{stall} = 16^0$

Maximum lift coefficient $C_{L_{max}} = 1.4$

Zero lift angle of attack $\alpha_{L=0} = -3^0$

Airfoil lift curve slope $C_{l_\alpha} = 5.73/$ rad

A trim angle (α_{trim}) of 7^0 and an aspect ratio (AR) of 8 chosen

$$e = 1.78(1 - 0.045AR^{0.68}) - 0.64 = 0.81$$

$$C_{L_\alpha} = \frac{C_{l_\alpha}}{1 + \frac{C_{l_\alpha}}{\pi e AR}} = \frac{5.73}{1 + \frac{5.73}{\pi \times 0.81 \times 8}} = 4.4718 \ /rad$$

$$C_L = C_{L_\alpha}(\alpha_{trim} - \alpha_{L=0}) = 4.4718 \times \frac{180}{\pi} \times (7 - (-3)) = 0.78$$

$$Assume\ span\ of\ 7\ m:$$

$$S = \frac{b^2}{AR} = 7^2/8 = 6.125m^2.$$

$$V=\sqrt{\frac{2\,W_{TO}g}{\rho SC_L}}=\sqrt{\frac{2\times 150\times 9.8}{0.736\times 6.825\times 0.78}}=28.9\ m/s$$

$$\bar{c}=\frac{b}{AR}=7/8=0.875\ m$$

$$Assume\ \lambda=0.68:$$

$$c_r=\frac{2S}{b(1+\lambda)}=1.04\ m$$

$$c_t=\lambda c_r=0.71\ m$$

Recalculating wing area with the inclusion of taper ratio:

$$S=\lambda bc_r+(1-\lambda)b\frac{(c_t+c_r)}{2}=6.825\ m$$

$$V=\sqrt{\frac{2\,W_{TO}g}{\rho SCL}}=27.38\ m/s$$

Horizontal Tail Sizing

$$Assume:$$

$$V_H = 0.6$$

$$\lambda_{HT} = 0.6$$

$$S_{HT} = 1.5\ m^2$$

$$AR_{HT} = \frac{2}{3}AR = \frac{2}{3} \times 8 = 5.33$$

$$V_H = \frac{S_{HT} l_t}{S\overline{c}} = 0.6 = \frac{1.5 l_t}{6.825 \times 0.875}$$

$$\implies l_t = 2.39\ m$$

$$b_{HT} = \sqrt{AR_{HT} S_{HT}} = \sqrt{5.33 \times 1.5} = 2.83\ m$$

$$c_{r_{HT}} = \frac{2 S_{HT}}{b_{HT}(1 + \lambda_{HT})} = \frac{2 \times 1.5}{2.83 \times 1.6} = 0.66\ m$$

$$\overline{c}_{HT} = \frac{2}{3} c_{r_{HT}} \frac{1 + \lambda + \lambda^2}{1 + \lambda} = \frac{2}{3} \times 0.66 \times \frac{1.96}{1.6} = 0.54\ m$$

$$c_{t_{HT}} = \lambda_{HT} c_{r_{HT}} = 0.6 \times 0.66 = 0.398\ m$$

Vertical Tail Sizing
Assumed:
Vertical tail area: $S_{VT} = 0.6\ m^2$
Taper ratio: $\lambda_{VT} = 0.4$
Aspect ratio: $AR_{VT} = 1$

$$V_V = \frac{S_{VT} l_t}{Sb} = \frac{0.6 \times 2.39}{6.825 \times 7} = 0.03$$
$$b_{VT} = \sqrt{AR_{VT} S_{VT}} = \sqrt{1 \times 0.6} = 0.77\ m$$
$$c_{r_{VT}} = \frac{2 S_{VT}}{b_{VT}(1 + \lambda_{VT})} = 1.11\ m$$
$$c_{\bar{V}T} = \frac{2}{3} c_{r_{VT}} \frac{1 + \lambda + \lambda^2}{1 + \lambda} = 0.822\ m$$
$$c_{t_{VT}} = \lambda_{VT} c_{r_{VT}} = 0.4 \times 1.11 = 0.442\ m$$

Table: Design parameters

AR_w	7.18	AR_{HT}	4.79	AR_{VT}	1
b_w	7 m	b_{HT}	2.68 m	b_{VT}	0.77 m
$\bar{c_w}$	0.99 m	$\bar{c_{HT}}$	0.57 m	$\bar{c_{VT}}$	0.82m
c_{r_w}	1.16 m	$c_{r_{HT}}$	0.7 m	$c_{r_{VT}}$	1.11 m
c_{t_w}	0.789 m	$c_{t_{HT}}$	0.42 m	$c_{t_{VT}}$	0.44 m
		l_t	1.86 m		
		V_H	0.415 m		

$$Wingloading = \frac{W_{TO}}{S} = \frac{150 \times 9.8}{6.825} = 21.98\ kg/m^2$$

$$X_{NP} = 0.453\ m$$

$$Assuming\ SM = 10\%,\ X_{NP} - X_{cg} = SM \times \bar{c}$$

$$= 0.365\ m\ from\ the\ wing\ leading\ edge.$$

Drag Polar

$$C_D = C_{D_o} + k{C_L}^2$$
$$C_{D_o} = C_{D_{o_f}} + C_{D_{o_w}} + C_{D_{o_{ht}}} + C_{D_{o_{vt}}} + C_{D_{o_{LG}}} + \dots$$

Wetted Areas

$$S_{wet_{plf}} = 2S_{exp.plf}\left(1 + \frac{0.25(t/c)_r(1+\tau\lambda)}{1+\lambda}\right)$$
$$\tau = \frac{(t/c)_r}{(t/c)_t}$$
$$\lambda_f = \frac{l_f}{D_f}$$
$$S_{wet_{fus}} = \pi D_f l_f \left(1 - \frac{2}{\lambda_f}\right)^{\frac{2}{3}} \left(1 + \frac{1}{\lambda_f^2}\right)$$

Table: Summary of wetted areas

Component	Wetted area (m^2)
Planform	14.26
Fuselage	2.96
Horizontal tail	3.18
Vertical tail	1.27
Booms x 2	1.5
Total	23.17

The correlation $log_{10} S_{wet_{tot}} = c + d\ log_{10} W_{TO}$ (with c = 1.0892 and d = 0.5147 [Roskam]) gives $S_{wet_{tot}} = 22.6\ m^2$ which is close to the total evaluated wetted area of 23.17 m^2.

Zero-lift Drag Coefficient

$$C_{Do_W} = C_{f_w} f_{tc_W} f_M \left(\frac{Swetw}{S}\right)\left(\frac{C_{D_{min_W}}}{0.004}\right)^{0.4}$$

$$C_{f_w} = \frac{0.455}{log10(Re_w)^{2.58}}$$

$$Re_w = \frac{\rho VL}{\mu}$$

$$f_{tc_W} = 1 + 2.7(t/c)_{max} + 100(t/c)^4{}_{max}$$

$$f_M = 1 - 0.08M^{1.45}$$

$$C_{Do_W} = C_{f_w} f_{tc_W} f_M \left(\frac{S_{wet_{plf}}}{S}\right)\left(\frac{C_{D_{min_w}}}{0.004}\right)^{0.4}$$

$$C_{Do_{ht}} = C_{f_{ht}} f_{tc_{ht}} f_M \left(\frac{S_{wet_{ht}}}{S}\right)\left(\frac{C_{D_{min_{ht}}}}{0.004}\right)^{0.4}$$

$$C_{Do_{vt}} = C_{f_{vt}} f_{tc_{vt}} f_M \left(\frac{S_{wet_{vt}}}{S}\right)\left(\frac{C_{D_{min_{vt}}}}{0.004}\right)^{0.4}$$

$$C_{Do_f} = C_{f_f} f_{ld} f_M \left(\frac{S_{wet_{fus}}}{S}\right)$$

$$Re_w = \frac{\rho V L_f}{\mu}$$

$$f_{ld} = 1 + \frac{60}{{\lambda_f}^3} + 0.0025\lambda_f$$

$$C_{Do} = K_c \left[\ C_{Do_w} + C_{Do_f} + C_{Do_{ht}} + C_{Do_{vt}} + \ldots\ \right]$$

$K_c = 1.2$ taken for GA aircraft and RPVs.

Table: Results of Zero-lift drag calculation

Component	C_{Do}
Wing	0.0210
Fuselage	0.00230
Horizontal tail	0.00586
Vertical tail	0.00216
Overall	0.0376

Effects of Installation of SOTM

Model: MicroSat LM - GetSat with dimensions 32x25.5 cm and weight 7.6 kg.

$Source{:}getsat.com$

$$Re_{avg} = \frac{\rho V(L_{fus} + C_{sotm})}{\mu}$$

$$C_f = \frac{0.455}{log_{10}(Re_{avg})^{2.58}}$$

$$C_{D_{O_{sotm}}} = \frac{S_{wet}}{S_{sotm_{theory}}} C_f$$

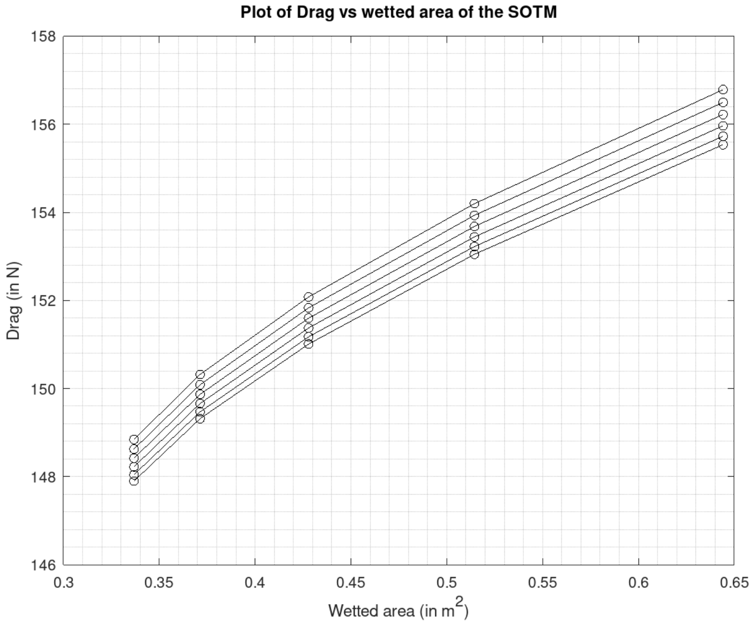
$$e = 1.78(1 - 0.045AR^{0.68}) - 0.64$$

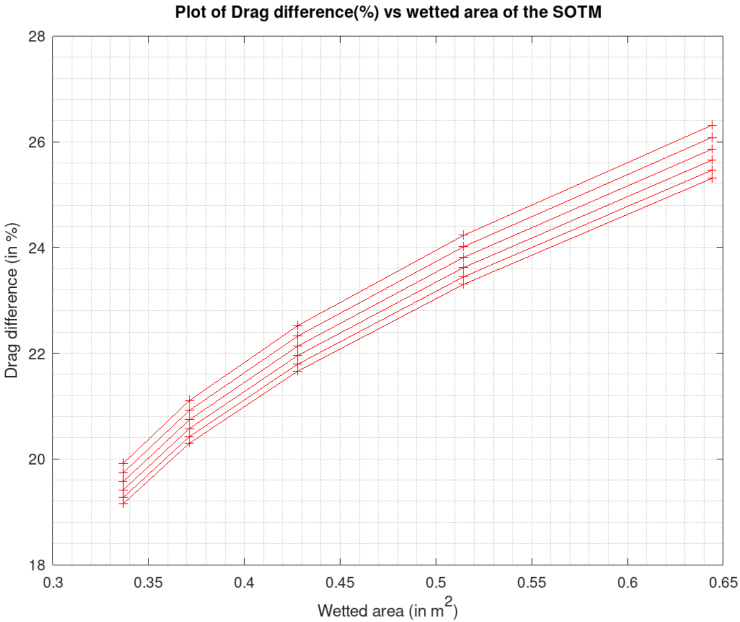
$$k = \frac{1}{\pi e AR}$$

$$C_{D_{new}} = C_{D_0} + C_{D_{O_{sotm}}} + kCL^2$$

$$D_{new} = C_{D_{new}} \frac{1}{2} \rho {V_{cr}}^2 S$$

$$P_{req_{new}} = D_{new} V_{cr}$$


Plot of Drag vs wetted area of the SOTM
158
156
154
152
150
148
146
Drag (in N)
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
Wetted area (in m2)



Plot of Drag difference(%) vs wetted area of the SOTM
Drag difference (in %)
Wetted area (in m2)
28
26
24
22
20
18
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65

Power Plant Selection

$$k = \frac{1}{\pi e AR} = \frac{1}{\pi \times 0.81 \times 8} = 0.049$$

$$C_D = C_{D_o} + k{C_L}^2 = 0.0376 + 0.049 \times 0.78^2 = 0.0659$$

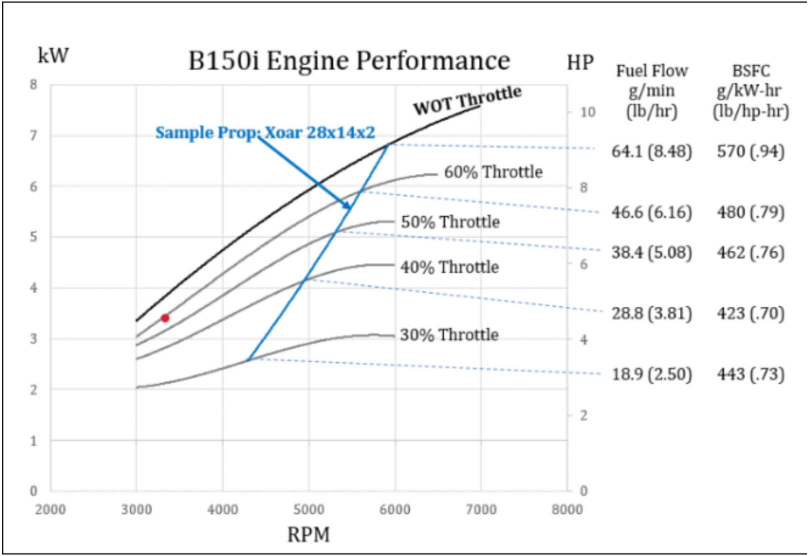
$$D = \frac{1}{2}\rho V^2 S C_D = \frac{1}{2} \times 0.736 \times 27.38^2 \times 6.825 \times 0.0659 = 124.12\ N$$

$$P_{req} = DV = 124.12 \times 27.38 = 3.4\ kW\ or\ 4.56\ hp$$

Chosen powerplant is B150i UAV EFI engine system with BSFC of 470 g/kW-hr (0.78 lb/hp-hr) and weighs 4.3 kg.

Table: Engine characteristics for the fixed-wing mode

Engine type	Force air-cooled 2-stroke twin
Displacement	150 cc (9.15 ci)
Weight	4.3 kg
Power (7000 RPM)	7.5 kW (10 hp)
BSFC (5000-7000 RPM)	470 g/kW-hr (0.78 lb/hp-hr)
Fuel type	Gasoline, 50:1 premix



Source:Power4flight B150i Datasheet

For VTOL mode, thrust loading of 1.4 and climb velocity of 5 m/s was chosen.

$$\frac{T}{W} = 1.4$$

$$V_{climb} = 5\ m/s$$

$$T = 1.4 \times 150 \times 9.8 = 2058\ N$$

$$P_{req} = TV_{climb} = 2058 \times 5 = 10.3\ kW\ or\ 13.8\ hp$$

Chosen powerplant: Hirth 4201 engine

Table: Engine characteristics for the VTOL mode

Engine type	Two cylinder two stroke (opposed)
Displacement	183 cc (11.5 ci)
Weight	5.7 kg
Power (6500 RPM)	11 kW (15 hp)
Dimensions	213 mm x 330 mm x 160 mm
Fuel type	Gasoline, 50:1 premix

Propeller Selection

Rotational speed $N = 3500\ RPM$ at 60% throttle at the cruise altitude of 5 km.

$$THP = \frac{P_{req}}{1000} = 3.4\ kW$$

$$BHP = \frac{THP}{\eta_p} = 4.656\ kW$$

$$Speed\ Power\ Coefficient: C_s = V\left(\frac{\rho}{BHPn^2}\right)^{\frac{1}{5}} = 0.94$$

$$where\ n = N/60$$

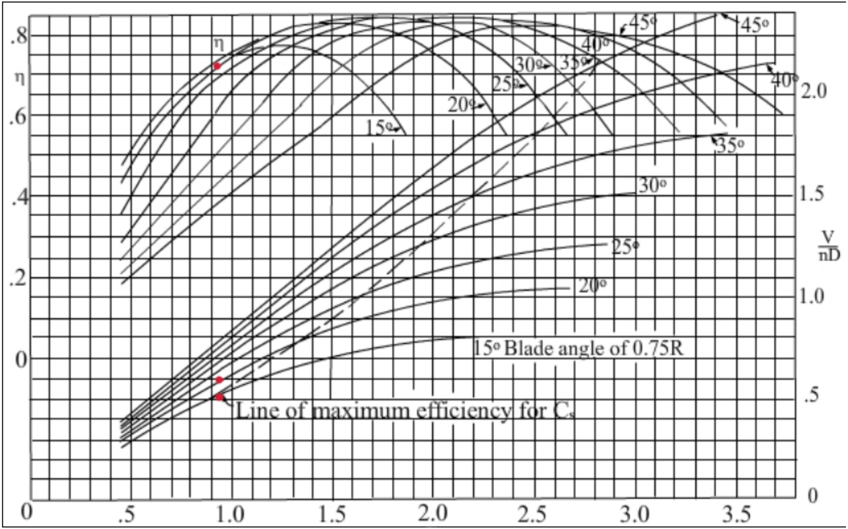
$$Pitchangle\ \beta = 15^0$$

$$Propeller\ efficiency\ \eta_p = 0.73$$

$$Advance\ ratio\ J = 0.5$$

$$Diameter\ d = \frac{V}{nJ} = 0.94\ m\ or\ 36.96\ in$$

$$Pitch = \frac{V}{n} = 0.47\ m\ or\ 18.48\ in$$



Source:NPTEL Airplane Design, Tulapurkara

Xoar 36x18 propellers were thus chosen.

For VTOL mode,

$$Thrust\ generated:\ T = \frac{1}{4}\frac{P\eta_p}{V_{climb}} = \frac{1}{4}\frac{10.3 \times 10^3 \times 0.8}{5} = 412N$$

$$Aerodynamic\ lift\ L_p = T = \frac{1}{2}\rho V_{av}^2 S_p C_{L_p}\ [C_{L_p}\ b/w\ 0.2 - 0.4]$$

$$Propeller\ planform\ area\ S_p = D_p C_p$$

$$Propeller\ aspect\ ratio\ AR_p = D_p/C_p\ [AR_p\ b/w\ 7\ to\ 15]$$

$$Propeller\ diameter\ D_p = K_{np}\sqrt{\frac{2P\eta_p AR_p}{\rho V_{av}^2 C_{L_p} V_{climb}}}$$

$$V_{tip_{climb}} = \sqrt{V_{tip_{static}}^2 + V_{climb}^2}$$

$$V_{tip_{static}} = \frac{D_p}{2}\omega$$

$$\omega = 2\pi n/60 = 2\pi \times 6500/60 = 680.68\ rad/s$$

$$V_{av} = 0.7 V_{tip_{climb}}$$

Through multiple iterations, $D_p = 0.94\ m$ (Two bladed propeller, $K_{np} = 1$)

Weight Estimation

Fuel and Mass Weights

$$W_{TO} = W_{payload} + W_{fuel} + W_{crew} + W_{empty}$$

$$MF_{fuel} = 1 - exp(\frac{-E\ V\ BSFC}{\frac{L}{D}\ \eta_p})$$

$$\frac{L}{D} = \frac{C_L}{C_D} = 0.78/0.066 = 11.82$$

$$\eta_p = 0.7\ (assumed)$$

$$BSFC = 480\ g/kW\text{-}hr$$

$$\Longrightarrow MF_{fuel} = 0.075$$

$$W_{fuel} = 11.25kg$$

$$W_{empty} = W_{TO} - W_{fuel} - W_{payload} - W_{crew} = 88.75\ kg$$

$$MF_{empty} = \frac{W_{empty}}{W_{TO}} = 0.59$$

Table: Summary of preliminary weight estimation results

Maximum take-off weight	150 kg
Fuel weight	11.25 kg
Empty weight	88.75 kg
Maximum payload weight	50 kg
Crew weight	0 kg

Component weights

$$W_{wing} = 0.0038(N_z W_{TO})^{1.06} AR^{0.38} S^{0.25} (1+\lambda)^{0.25} \left(\frac{t}{c}\right)^{-0.14}$$

$$W_{HT} = \frac{3.184\, W_{TO}^{0.887} S_{HT}^{0.101} AR_{HT}^{0.138}}{57.5 t_{root_{HT}}^{0.223}}$$

$$W_{FUS} = 0.5257 F_{MG} F_{NG} F_{Pres} F_{VT} F_{Matl} L_{struct}^{0.3796} (W_{carried} N_z)^{0.4863} \left(\frac{1.3\, V}{100}\right)^{2}$$

Here,
$F_{MG} = 1.07$ assuming the main gear to be on the fuselage
$F_{NG} = 1.04$ assuming the nose gear to be on the fuselage
$F_{Pres} = 1$ as the UAV has an unpressurized fuselage
$F_{VT} = 1$ as the vertical tail weight was not to be included in the fuselage weight.
$F_{Matl} = 1$ as the material factor for a metallic fuselage was 1.
L_{struct} is the structural length of the fuselage in feet.
$W_{carried}$ is the weight of the components carried within the structure in pounds.

Other Weights

$$W_{boom} = 0.14 L_{boom} W_{cant} \ lb$$
$$W_{avion} = W_{avionics} + W_{inst} + W_{comms} + W_{wiring}$$
$$W_{avion} = f_{avion} W_{TO}$$

Gundlach recommends $f_{avion} = 10\%$ for general cases.

Table: Summary of component weight estimation results

Wing weight	21.43 kg
Fuselage weight	12.95 kg
Total empennage weight	14.57 kg
Total boom weight	6.68 kg
Engine weight	4.3+5.7 kg
Avionics weight	15 kg
Total weight	80.63 kg

Control Surface Sizing

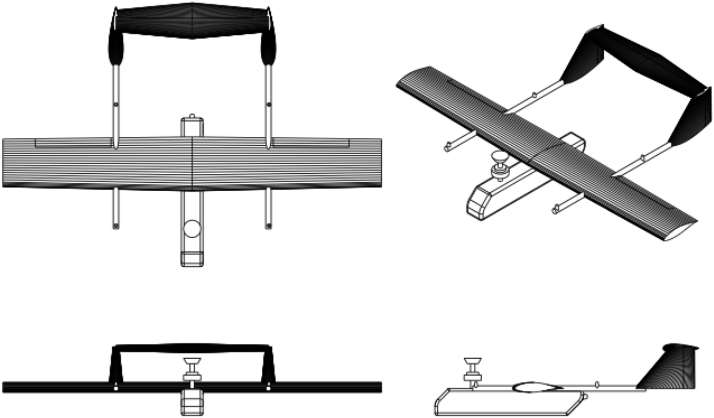
Table: Results of Control Surface Sizing

Control surface	Area (m^2)	Span (m)	Chord (m)
Aileron	0.34	1.40	0.13
Elevator	0.22	2.26	0.11
Rudder	0.09	0.54	0.12

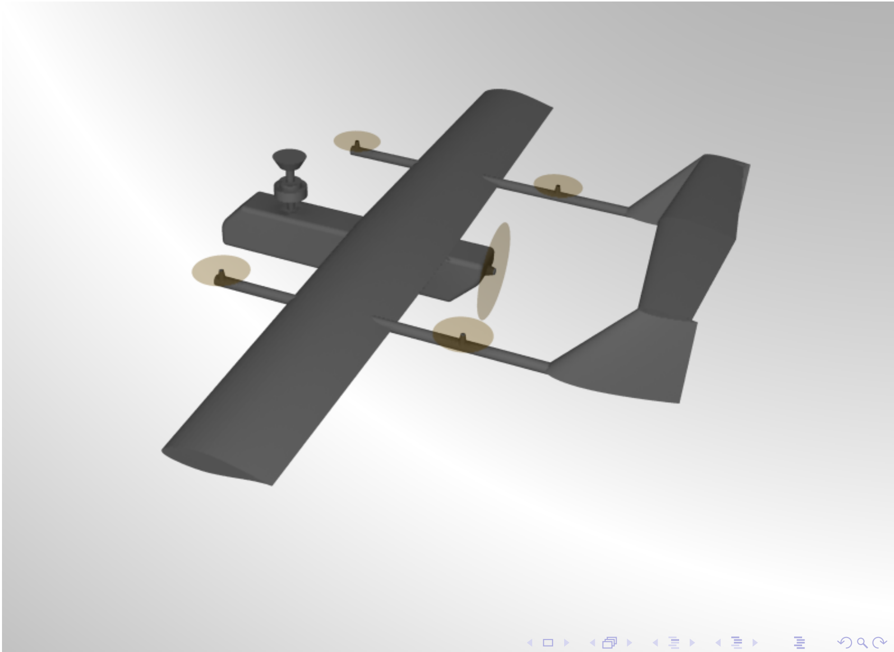
Table: Maximum deflections

Control surface	Maximum deflection +ve (deg)	Maximum deflection -ve (deg)
Aileron	20 (down)	-25 (up)
Elevator	20 (down)	-25 (up)
Rudder	30 (left)	-30 (right)

Orthographic Drawing



Rendered image



Flight Envelope

From CS-VLA 335 regulations, maximum cruise speed cannot be less than

$$V_c = 2.4\sqrt{\frac{W_{TO}g}{S}} = 34.98\ m/s$$

$$Max\ cruise\ speed\ V_{max} = 1.3\,V_c = 45.47\ m/s$$

$$Dive\ Speed\ V_d = 1.4\,V_c = 48.98\ m/s$$

$$For\ the\ wing,\ C_{L_{max_{up}}} = 1.4\ and\ C_{L_{max_{down}}} = -0.9$$

$$Stall\ speed\ V_s = \sqrt{\frac{W_{TO}g}{\frac{1}{2}\rho_{sl}SC_{L_{max_{up}}}}} = 15.74\ m/s$$

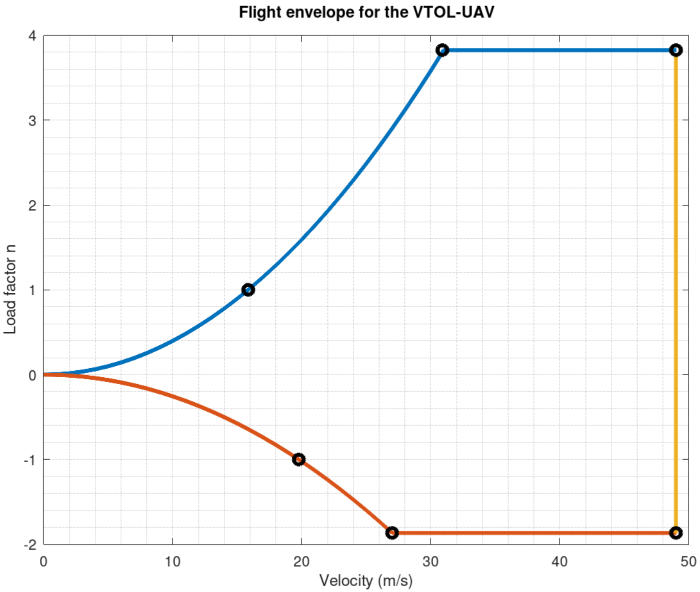
$$Load\ factor\ n = \frac{L}{W} = \frac{\frac{1}{2}\rho_{sl}SC_{L_{max_{up}}}}{W} = 0.004\,V^2$$

$$Taking\ n_{pos} = 3.8\ and\ n_{neg} = -1.9$$

$$Maneuvering\ speed\ V_{man} = \sqrt{n/0.004} = 30.68\ m/s$$

Similar procedure followed for the lower curve

V-n Diagram



Flight envelope for the VTOL-UAV
Load factor n
Velocity (m/s)
4
3
2
1
0
-1
-2
0
10
20
30
40
50

Gust effects

Gust Load factor variation during cruise flight

$$n = 1 + \frac{K_g V_{ge} V_e a \rho S_{wga}}{2 W_{TO}}$$

$$where \;\; V_{ge} = 25, 50 \; ft/s$$

$$a = \frac{2\pi}{1 + \frac{2}{AR}}$$

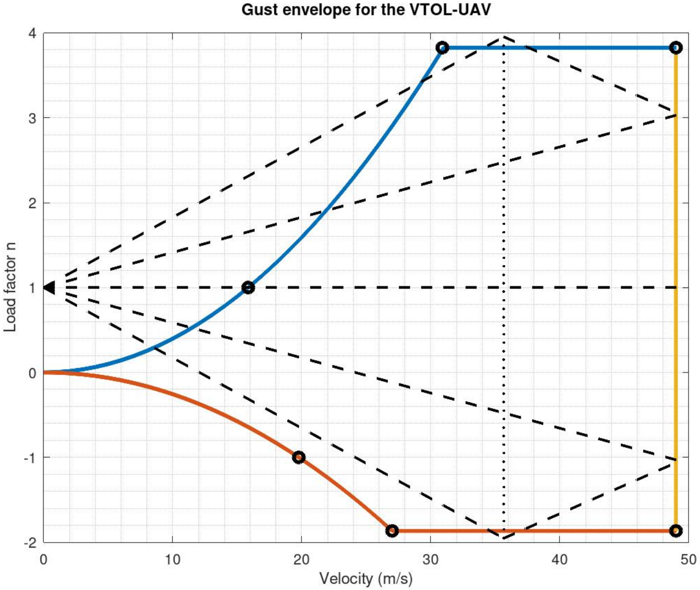
Air vehicle mass aspect ratio

$$\mu_g = \frac{2 W_{TO}}{\rho C_{mgc} a c S_{wga}} = \frac{2 \times 150}{0.736 \times 0.875 \times 5.026 \times 6.825} = 13.4$$

Gust alleviation factor

$$K_g = \frac{0.88 \mu_g}{5.3 + \mu_g} = \frac{0.88 \times 13.4}{5.3 + 13.4} = 0.63$$

Gust V-n diagram



Stability and Control Derivatives

Table: Summary of Longitudinal Stability and Control Derivatives

C_{L_o}	0.1859
C_{D_o}	0.376
C_{m_o}	0.08
C_{L_α}	4.7451
C_{m_α}	-0.4745
C_{L_q}	-3.3237
$C_{L_{\delta_e}}$	0.4732
C_{m_q}	-6.0698
$C_{m_{\delta_a}}$	-0.8642

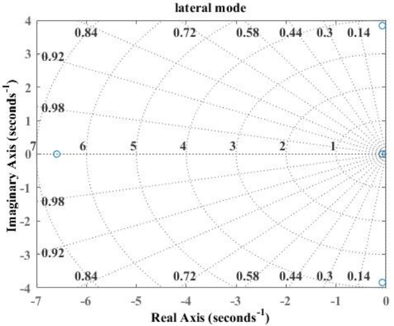
Table: Lateral and Directional Stability and Control Derivatives

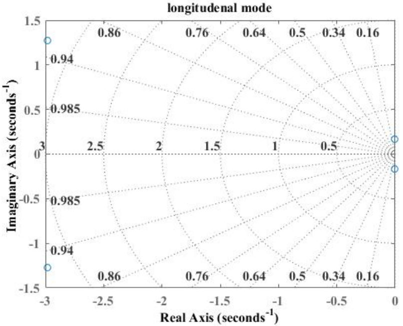
C_{Y_β}	-0.328
C_{l_β}	-0.189
C_{n_β}	0.028
C_{Y_p}	0.027
C_{l_p}	-0.674
C_{n_p}	-0.098
C_{Y_r}	0.224
C_{l_r}	0.195
C_{n_r}	-0.074

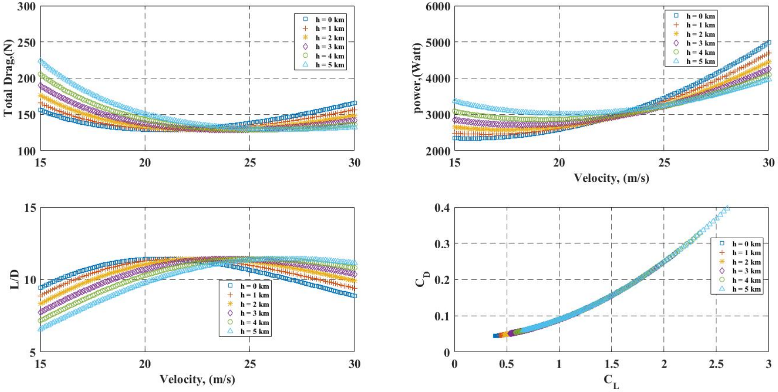
Trim Analysis

Pole	Damping	Frequency (rad/TimeUnit)	Time Constant (TimeUnit)
-2.99e+00 + 1.27e+00i	9.20e-01	3.25e+00	3.35e-01
-2.99e+00 - 1.27e+00i	9.20e-01	3.25e+00	3.35e-01
-4.20e-03 + 1.68e-01i	2.50e-02	1.68e-01	2.38e+02
-4.20e-03 - 1.68e-01i	2.50e-02	1.68e-01	2.38e+02

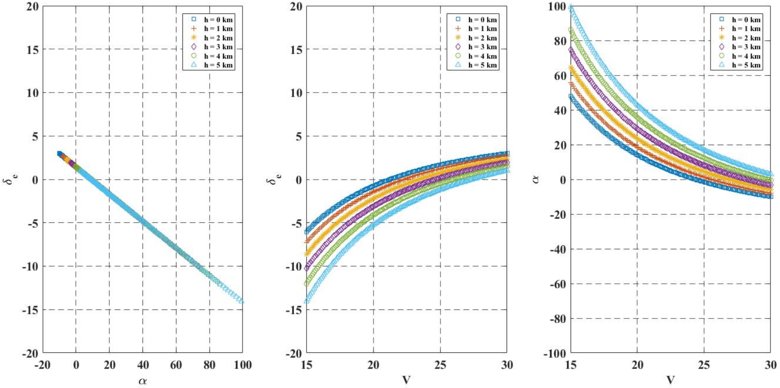
Pole	Damping	Frequency (rad/TimeUnit)	Time Constant (TimeUnit)
-6.59e+00	1.00e+00	6.59e+00	1.52e-01
-8.25e-02 + 3.83e+00i	2.15e-02	3.83e+00	1.21e+01
-8.25e-02 - 3.83e+00i	2.15e-02	3.83e+00	1.21e+01
-8.24e-02	1.00e+00	8.24e-02	1.21e+01


lateral mode
Imaginary Axis (seconds^-1)
Real Axis (seconds^-1)
0.84
0.72
0.58
0.44
0.3
0.14
0.92
0.98
7
6
5
4
3
2
1


longitudenal mode
Imaginary Axis (seconds^-1)
Real Axis (seconds^-1)
0.86
0.76
0.64
0.5
0.34
0.16
0.94
0.985
3
2.5
2
1.5
1
0.5



Total Drag,(N)
power,(Watt)
Velocity, (m/s)
L/D
Velocity, (m/s)
C_D
C_L
h = 0 km
h = 1 km
h = 2 km
h = 3 km
h = 4 km
h = 5 km



h = 0 km
h = 1 km
h = 2 km
h = 3 km
h = 4 km
h = 5 km
δ_e
α
V

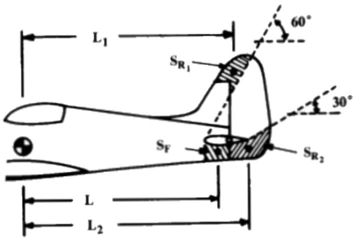
Spin Recovery

Tail Damping Ratio:

$$TDR = \frac{S_F L^2}{S_w\left(\frac{b}{2}\right)^2} = \frac{0.21 \times 2.39^2}{6.825 \times 3.5^2} = 0.0143$$

Unshielded Rudder Volume Coefficient:

$$URVC = \frac{S_{R_1} L_1 + S_{R_2} L_2}{S_w\left(\frac{b}{2}\right)} = 0.0119$$



Source: Aircraft Design, D. Raymer

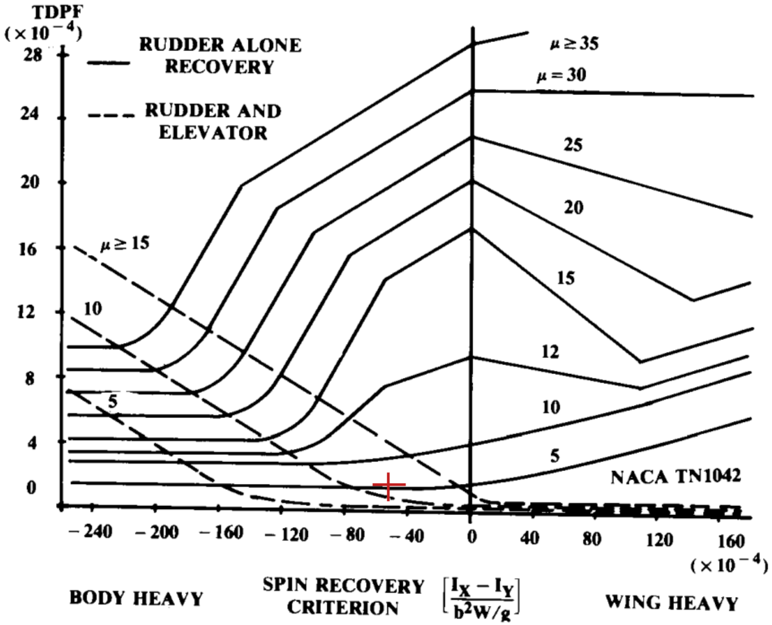
Tail Damping Power Factor:

$$TDPF = (TDR)(URVC) = 0.0143 \times 0.0119 = 1.7 \times 10^{-4}$$

$$\mu = \frac{\left(\frac{W}{S}\right)}{\rho g b} = \frac{150}{6.825 * 0.736 \times 7} = 4.26$$

Inertial Yawing Moment Parameter:

$$IYMP = \frac{I_X - I_Y}{b^2\left(\frac{W}{g}\right)} = \text{-}55 \times 10^{-4}$$



Source:Aircraft Design- A Conceptual Approach, D. Raymer

Sadraey Approach

Transform aircraft mass MoI from body axis to wind axis

$$\begin{bmatrix} I_{xx_w} \\ I_{zz_w} \\ I_{xz_w} \end{bmatrix} = \begin{bmatrix} \cos^2\alpha & \sin^2\alpha & -\sin 2\alpha \\ \sin^2\alpha & \cos^2\alpha & \sin 2\alpha \\ \frac{1}{2}\sin 2\alpha & -\frac{1}{2}\sin 2\alpha & \cos 2\alpha \end{bmatrix} \begin{bmatrix} I_{xx_B} \\ I_{zz_B} \\ I_{xz_B} \end{bmatrix}$$

Determine the rate of spin recovery

$$\dot{R}_{SR} = \frac{\Omega}{t}$$

Calculate the required yawing moment

$$N_{SR} = \left(\frac{I_{xx}I_{zz} - I_{xz}^2}{I_{xx}}\right)_w \dot{R}_{SR}$$

Obtain rudder control derivative after accounting for the new rudder effective area

$$\overline{V}_{V_e} = \frac{l_V S_{V_e}}{bS}$$

$$C_{n_{\delta R}} = -C_{L_{\alpha V}} \overline{V}_{V_e} \eta_V \tau_R \frac{b_{R_e}}{b_V}$$

Check the rudder deflection

$$\delta_r = \frac{N_{SR}}{\frac{1}{2}\rho V_s^2 S b C_{n_{\delta r}}}$$

Sample calculation ($W_{TO} = 150$ kg, Sadraey)

$$Using\ t = 3s\ and\ \Omega = 240^o/sec,$$

$$\dot{R}_{SR} = \Omega/t = 1.39\ rad/s$$

$$C_{n_{\delta R}} = -0.0713$$

$$N_{SR} = 311.26$$

$$\delta_r = \frac{N_{SR}}{\frac{1}{2}\rho {V_s}^2 S b C_{n_{\delta_r}}}$$

$$= \frac{311.26}{0.5\ x\ 0.736\ x\ 20.45^2\ x\ 6.825\ x\ 7\ x\ (-0.0713)}$$

$$= \text{-0.594}\ rad\ or\ \text{-34}^o$$

Parachute Recovery System

Material selection

Ripstop nylon for canopy, weighs 0.045kg/m^2, Spectra for shroud lines and harnesses.

Design

In equilibrium descent phase,

$$W_{recov} = D = \frac{1}{2}\rho {V_T}^2 C_{D,Chute} S_{Chute}$$

$$S_{Chute} = \frac{\pi}{4} {D_{Chute}}^2$$

$$C_{D,Chute} = 0.62 (Assuming\ hemispherical\ canopy)$$

$$D_{Chute} = \sqrt{\frac{8 W_{recov}}{\pi \rho {V_T}^2 C_{D,Chute}}}$$

$$= 14\ m$$

$$W_{canopy} = 0.045 \times S_{Chute} = 6.93kg$$

Assuming a maximum opening shock value of 15g and a safety factor of 1.5, the design maximum load while deploying the parachute is calculated as

$$\begin{aligned} Load_{max} &= 1.5 \times 15g \times W_{TO} \\ &= 33,075.5\ N \end{aligned}$$

Suspension lines of type III paracord (specific weight of 6.59 g/m) made of Nylon Kernmantle rope has a minimum breaking strength of 2440 N.
Minimum of 18 suspension lines could be used.

$$l_{susp} = 1.15 \times D_{Chute} = 1.15 \times 14 = 16.1\ m$$
$$W_{susp} = 18 \times 6.59 \times 10^{-3} \times l_{susp} = 1.91 kg$$

Deployment mechanism: Drogue parachute system

$$\begin{aligned} W_{drogue} &= 0.12(C_D A)_d + (0.28 \times 10^{-3}) q_\infty (C_D A)_d^{3/2} \quad in\ N \\ &= 1.12\ N\ or \\ &= 114.3g \end{aligned}$$

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