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ASE 367K FLIGHT DYNAMICS
Fall 2024

HOMEWORK 5
Due: 2024-10-18 at 11:59pm via Canvas

Problem 1

If someone gave you the values C_{D_0} and κ for the drag polar $C_D = C_{D_0} + \kappa C_L^2$, the value T_A for the thrust available, the value W for the weight, and the value S for wing area of a jet powered aircraft flying straight and level at an altitude with air density ρ, explain how you would compute the minimum and maximum speeds at that altitude.

Problem 2

If $\dot{h}_0$ is the minimum sink rate of an aircraft in steady straight gliding flight, what would be the minimum sink rate of the same aircraft in a steady gliding turn, $\dot{h}(\phi)$, be in terms of $\dot{h}_0$ and the bank angle, ϕ?

Problem 3

Compute the range assuming:

i. The aircraft cruises at Mach 0.8 and maintains a constant altitude.
ii. The aircraft cruises at Mach 0.8 and maintains a cruise climb.

for a jet aircraft at an initial cruise altitude of 35,000 ft. (i.e., the altitude at the beginning of the cruise phase) with an initial cruise mass of 78,000 kg (i.e., the mass at the beginning of the cruise phase), **20,000 kg of useable fuel,** and the following characteristics:

$$C_{L_0} = 0.2$$
$$\frac{dC_L}{d\alpha} = 5.7296 \quad [rad^{-1}]$$
$$C_{D_0} = 0.016$$
$$\kappa = 0.048$$
$$S = 125 \quad [\mathrm{m}^2]$$
$$c_T = 3.552\text{x}10^{-5} \quad \left[\frac{kg}{N\cdot s}\right]$$
$$T = 216{,}000 * (P/P_0) \quad [\mathrm{N}]$$

where P is the pressure at the altitude in question, and P_0 is the pressure at sea-level.

Problem 4

Consider an aircraft that is symmetric about its xz-plane. Suppose that the total angular momentum of the aircraft in its body frame is given by:

$$\boldsymbol{h}_B = \mathbb{I}_B \boldsymbol{\omega}_B + \boldsymbol{h}'_B$$

where $\boldsymbol{h}'_B = \left(h'_x, h'_y, h'_z\right)^T$ accounts for the angular momentum of the aircraft's rotors in the body frame and is assumed to be constant. In terms of the components of $\boldsymbol{\omega}_B = (p, q, r)^T$, the components of $\dot{\boldsymbol{\omega}}_B = (\dot{p}, \dot{q}, \dot{r})^T$, the non-zero components of $\mathbb{I}_B$ (i.e., I_{xx}, I_{yy}, I_{zz}, etc.) and the components of $\boldsymbol{h}'_B$, derive equations for the body-frame components of the moment acting on the aircraft, L, M and N.

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① $C_D = C_{D_0} + kC_L^2$

C_{D_0}, k, T_A, W, S and ρ given

Jet flying straight level

Find minimum and maximum speeds at that altitude.

Thrust available:

$$T_{avail} = C_D \bar{q} S = C_{D_0}\left(\tfrac{1}{2}\rho V^2 S\right) + \frac{2\varepsilon W^2}{\rho V^2 S}$$

C_L

Solve for V, which V satisfies the T_{avail} equation.

$$0 = \tfrac{1}{2} C_{D_0} \rho S V^2 - T_{avail} + \frac{2\varepsilon W^2}{\rho V^2 S}$$

$$= \tfrac{1}{2} C_{D_0} \rho S V^4 - T_{avail} V^2 + \frac{2\varepsilon W^2}{\rho S}$$

$$X = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$= \frac{T_{avail} \pm \sqrt{T_{avail}^2 - 4\left(\tfrac{1}{2} C_{D_0}\cancel{\rho S}\right)\left(\frac{2\varepsilon W^2}{\cancel{\rho S}}\right)}}{2\left(\tfrac{1}{2} C_{D_0} \rho S\right)}$$

$$= \frac{T_{avail} \pm \sqrt{T_{avail}^2 - 4 C_{D_0} \varepsilon W^2}}{C_{D_0} \rho S}$$

or

$$= \frac{\frac{2}{C_D \rho S} T_{avail} \pm \sqrt{\frac{4 T_{avail}^2}{C_{D_0}^2 \rho^2 S^2} - 4\left(\frac{4\varepsilon W^2}{C_{D_0}(\rho S)^2}\right)}}{2}$$

∗ If we solve for x, we get two numbers. This is where Thrust available line crosses the Drag polar curve. The lower value is the minimum speed, and the higher value is the maximum speed

$$=\frac{\frac{2T}{C_{D_0}\rho S} \pm \sqrt{\frac{4T^2}{C_{D_0}^2\rho^2 S^2} - 4\left(\frac{4\varepsilon W^2}{C_{D_0}\rho^2 S^2}\right)}}{2}$$

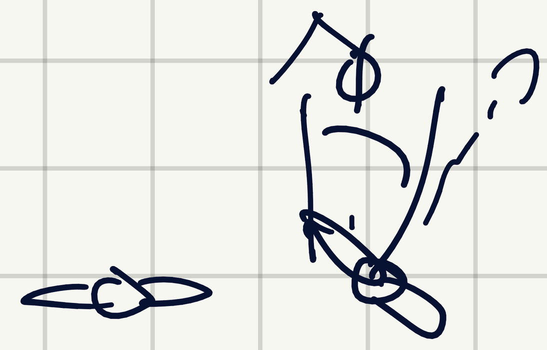
$$=\frac{\frac{\cancel{2}T}{\cancel{C_{D_0}}} \pm \cancel{2}\sqrt{\frac{T^2}{\cancel{C_{D_0}^2}} - 4\,\frac{\varepsilon W^2}{\cancel{C_{D_0}}}\cdot\frac{C_{D_0}}{\cancel{C_{D_0}}}}}{\cancel{2}\rho S}$$

$$=\frac{T \pm \sqrt{T^2 - 4\varepsilon W^2 C_{D_0}}}{\rho S C_{D_0}} \quad \checkmark$$

(2)

$$w = L = \dot h$$

$$w\cos\gamma = L\cos\phi = \dot h(\phi)$$



V

$$W\cos\gamma = L = \dot h$$

$$W\cos\gamma = L\cos(\phi) \Rightarrow \dot h(\phi)$$

$$\dot h(\phi) = \dot h_0 \;\dots\dots$$

$\downarrow$

$\dot h$ in the lecture

$$L = C_L \tfrac{1}{2}\rho V^2 S = W\cos\gamma \qquad D = C_D \tfrac{1}{2}\rho V^2 = -W\sin\gamma$$

$$V = \sqrt{\frac{2W\cos\gamma}{C_L \rho S}} \qquad \sin\gamma = -\frac{D}{W}$$

$$\dot h = V\sin\gamma$$

$$= -\sqrt{\frac{2W\cos\gamma}{C_L\rho S}}\left(\frac{D}{W}\right)$$

$L = W\cos\gamma$

$$= -\sqrt{\frac{2W\cos\gamma}{C_L\rho S}}\,\frac{L}{W}\left(\frac{D}{L}\right) \qquad \frac{\cancel{W}\cos\gamma\, D}{\cancel{W}\, L}$$

$$= -\sqrt{\frac{2W\cos\gamma}{C_L\rho S}}\cos\gamma\left(\frac{1}{L/D}\right)$$

$$= -\sqrt{\frac{2W\cos^3\gamma}{\rho S}}\left(\frac{C_D}{C_L^{3/2}}\right)$$

if $\cos\gamma \sim 1$

$$= -\sqrt{\frac{2W}{\rho S}}\left(\frac{C_D}{C_L^{3/2}}\right)$$

$$\dot h_0 = -\sqrt{\frac{2W}{\rho S}}\,\frac{4C_{D_0}}{\left(\sqrt{\frac{3C_{D_0}}{\varepsilon}}\right)^{3/2}}$$

$\uparrow$

where $\dfrac{d\dot h}{dC_L} = 0$.

$$\dot h_0 = -\sqrt{\frac{2W}{\rho S}}\,\frac{4C_{D_0}}{\left(\frac{3D_0}{\varepsilon}\right)^{3/4}}$$

$$= -\sqrt{\frac{2W}{\rho S}}\,\frac{4\varepsilon^{3/4}}{3}\,C_D^{1/4}$$

$$L\cos\mu = W$$

$$L\cos\phi = W\cos\gamma = \tfrac{1}{2}\rho V^2 S C_L \cos\phi$$

$$L = \frac{W\cos\gamma}{\cos\phi} = \frac{\rho V^2 S C_L \cancel{\cos\phi}}{2\cancel{\cos\phi}}$$

$$= \tfrac{1}{2}\rho V^2 S C_L$$

$$D\cos\phi = W\cos\gamma$$

$$V = \sqrt{\frac{2W\cos\gamma}{\rho S C_L \cos\phi}}$$

$$\dot{h} = V\sin\gamma$$

$$= -\sqrt{\frac{2W\cos\gamma}{\rho S C_L \cos\phi}}\ \frac{D}{W}$$

$$L\cos\phi = W\cos\gamma$$

$$L = \frac{W\cos\gamma}{\cos\phi}$$

$$= -\sqrt{\frac{2W\cos\gamma}{\rho S C_L \cos\phi}}\ \frac{D}{W}\frac{L}{L}$$

$$= -\sqrt{\frac{2W\cos\gamma}{\rho S C_L \cos\phi}}\ \frac{D\cancel{W}\cos\gamma}{\cancel{W}L\cos\phi}$$

$$= -\sqrt{\frac{2W\cos\gamma}{\rho S C_L \cos\phi}}\ \cos\gamma\,\frac{D}{L\cos\phi}$$

$$= -\sqrt{\frac{2W\cos^3\gamma}{\rho S\ \cos^3\phi}}\ \frac{C_D}{C_L^{3/2}}$$

if $\cos\gamma \sim 1$

$$= -\sqrt{\frac{2W}{\rho S\cos^3\phi}}\ \frac{C_D}{C_L^{3/2}}$$

$$= -\frac{1}{\cos^{3/2}\phi}\sqrt{\frac{2W}{\rho S}}\ \frac{C_D}{C_L^{3/2}}$$

$$\boxed{= \frac{\dot{h}_0}{\cos^{3/2}\phi}}$$

3

i) $Mach = \frac{V}{V_s} = 0.8\ Mach$

$h_i = 35{,}000\,ft \qquad m_i = 78{,}000\,kg \qquad m_f = 58{,}000\,kg$

<u>Constant altitude</u> Jet

$$\frac{dr}{dm} = \frac{\dot{r}}{\dot{m}} = \frac{V}{-C_T T} = -\frac{V}{C_T D}$$, since $T = D$ for Cruising, $L = W$ for constant altitude

V const

$$= -\left(\frac{L}{W}\right)\frac{V}{C_T D}$$

$$dr = -\frac{L}{D}\frac{V}{C_T m g}\,dm$$

$$Range = R = \int_0^R dr = -\int_{W_i}^{W_f}\left(\frac{L}{D}\right)\left(\frac{V}{C_T g}\right)\frac{dm}{m}$$

C_L

$$= -\int_{W_i}^{W_f}\frac{C_L}{C_D}\left(\frac{1}{C_T g}\right)\sqrt{\frac{2}{C_L \rho S}}\,\frac{dm}{m^{1/2}}$$

$$= \frac{\sqrt{C_L}}{C_D}\left(\frac{2}{C_T g}\right)\sqrt{\frac{2}{\rho S}}\left(m_i^{1/2} - m_f^{1/2}\right)$$

$$C_L = C_{L_0} + C_{L_\alpha}\alpha + \overset{0}{\cancel{C_{L_{i_t}} i_t}} + \overset{0}{\cancel{C_{L_{\delta e}}\delta e}}$$

$$C_D = C_{D_0} + K C_L^2$$

$$R = \frac{\sqrt{C_L}}{C_{D_0} + K C_L^2}\left(\frac{2}{C_T g}\right)\sqrt{\frac{2}{\rho S}}\left(\ ''\ \right)$$

$$C_{L\,start} = \frac{2(78000\ kg)(9.81)}{125 m^2\ \rho\ V^2} = 0.2 + 5.7296\alpha_{start}$$

$$C_{L\,end} = \frac{2(58000)(9.81)}{125\ \rho\ V^2} = 0.2 + 5.7296\alpha_{end}$$

$$\frac{1}{2}\rho V^2 S\ C_L = W$$

$$\frac{1}{2}\rho V^2 (125) C_L = 78000(9.81)$$

$$\frac{1}{2}\rho V^2 C$$

Tropopause

Temp 3° per 1000ft

$$Mach = \frac{V}{a} = \frac{1}{\sqrt{\gamma R T}}$$

660 mph

a)

$$L = W = \frac{1}{2}\rho V^2 S C_L = mg$$

$$C_L = C_{L_0} + C_{L_\alpha}\alpha$$

$$C_D = C_{D_0} + kC_L^2$$

$$\dot{m} = -C_T T_R$$

$$T_R = D = \frac{1}{2}\rho V^2 S C_D$$

$$\dot{m} = -C_T \frac{1}{2}\rho V^2 S\left(C_{D_0} + k\left(\frac{mg}{\frac{1}{2}\rho V^2 S}\right)^2\right)$$

$$\frac{dt}{dr}\left(\frac{dm}{dt}\right) = -C_T\left(\frac{1}{2}\rho V^2 S C_{D_0} + k\frac{m^2g^2}{\frac{1}{2}\rho V^2 S}\right)\frac{1}{V}$$

$$\frac{dm}{dr} = -\frac{C_T}{V}(\;''\;)$$

$$\frac{1}{(\;''\;)} = \frac{-C_T}{V}dr$$

$$\frac{dm}{\frac{1}{2}\rho V^3 C_{D_0} + \frac{km^2g^2}{\frac{1}{2}\rho V^2 S}} = -\frac{C_T}{V}dr$$

$$\int_{m_1}^{m_2} \frac{1}{-C_T}\left(\frac{dm}{\frac{1}{2}\rho V S C_{D_0} + \frac{2km^2g^2}{\rho V^3 S}}\right) = \int_{r_1}^{r_2} dr = Range$$

Personal Notes

Constant altitude & constant Mach

* To maintain constant altitude, α or C_L is adjusted. Thrust is also reduced to prevent accelerating. Velocity kept const.

* For Cruise Climb, typically, velocity is changed to maintain a constant mach. Velocity needs to change since speed of sound changes as altitude changes. C_L and C_D are changed, since C_L needs to be adjusted to account for loss of fuel and C_D depends on speed that changes as I said. However, the ratio C_L/C_D is kept constant. $L = W$ is always true for cruise climb. We are not looking for accelerated climb. For b), V is constant, since speed of sound is constant for tropopause. C_L and C_D should change accordingly.

$C_T = 3.552 \times 10^{-5}$

air density: $\rho = 0.38035$ kg/m³

Speed of Sound: $a = 295.046$ m/s @ 35000 ft

$m_1 = 78000$ kg

$m_2 = 58000$ kg

$V = a \cdot Mach = 295.046 \cdot 0.8$ m/s

$S = 125\ m^2$ $\quad C_{D_0} = 0.016$ $\quad k = 0.048$ $\quad g = 9.7737\ m/s^2$ @ 35000 ft

MATLAB

Range = 3580.67 km

$$L = W = \frac{1}{2}\rho V^2 S C_L \qquad D = \frac{1}{2}\rho V^2 S C_D = T$$

$$C_L = \frac{2W}{\rho V^2 S}$$

$$\dot{m} = -C_T T$$

$$= \frac{-C_T}{2}\rho V^2 S\left(C_{D_0} + K\left(\frac{2W}{\rho V^2 S}\right)^2\right)$$

$$\frac{dm}{dr} = \frac{-C_T}{2}\rho V S\left(C_{D_0} + K\left(\frac{2W}{\rho V^2 S}\right)^2\right)$$

$$\frac{dm}{dr} = -C_T\left(\frac{1}{2}\rho V S C_{D_0} + \frac{1}{2}\rho V S \frac{K 4 m^2 g^2}{\rho^2 V^4 S^2}\right)$$

$$= -C_T\left(\frac{1}{2}\rho V S C_{D_0} + \frac{2 m^2 g^2 K}{\rho V^3 S}\right)$$

$$dr = \frac{1}{\frac{-C_T}{2}\rho V S C_{D_0} + \frac{2 K m^2 g^2}{\rho V^3 S} C_T} dm$$

b) $R = \int_{w_i}^{w_f} \left(\frac{L}{D}\right)\left(\frac{V}{C_T g}\right)\frac{dm}{m}$

$$R = -\left(\frac{L}{D}\right)\left(\frac{V_{cruise}}{C_T g}\right) \ln(m)\Big|_{m_i}^{m_f}$$

$$= \left(\frac{L}{D}\right)\frac{V_{cruise}}{C_T g}\ln\left(\frac{m_i}{m_f}\right)$$

$$= \left(V_{cruise}\frac{C_L}{C_D}\right)\left(\frac{1}{C_T g}\right)\ln\left(\frac{m_i}{m_f}\right)$$

$$\Rightarrow \frac{\partial R}{\partial C_L} \propto \frac{\partial\left(\frac{V_{cruise} C_L}{C_D}\right)}{\partial C_L} = \frac{\partial\left[\frac{V_{cruise} C_L}{(C_{D_0}+\varepsilon C_L^2)}\right]}{\partial C_L} = 0$$

maximize R.

$$V_{cruise} = \sqrt{\frac{2W}{C_L \rho S}} \Rightarrow$$ Assume $\sqrt{\frac{2W(t)}{\rho(h)S}} = \text{constant}$

for cruise climb

$$\sqrt{\frac{2W}{\rho S}}\ \frac{\partial\left[\frac{\sqrt{C_L}}{C_0+\varepsilon C_L^2}\right]}{\partial C_L} = 0$$

Let $C_L^{1/2} = x$, $C_L = x^2$

$$0 = \frac{\partial}{\partial x}\left[\frac{x}{C_{D_0}+\varepsilon x^4}\right] = \frac{(C_{D_0}+\varepsilon x^4) - x(4\varepsilon x^3)}{(C_{D_0}+\varepsilon x^4)^2} = \frac{C_{D_0}-3\varepsilon x^4}{(C_{D_0}+\varepsilon x^4)^2}$$

$$\Rightarrow C_{D_0} = 3\varepsilon x^4$$

$$C_{D_0} = 3\varepsilon C_L^2$$

$$C_{D_{MR}} = C_{D_0} + \frac{C_{D_0}}{3} = \frac{4}{3}C_{D_0}$$

$$C_{L_{MR}} = \sqrt{\frac{C_{D_0}}{3\varepsilon}}$$

$$= \sqrt{\frac{0.016}{3(0.048)}}$$

$$= \frac{1}{3}$$

$$\cancel{V_{cruise-climb} = \sqrt{\frac{2W(t)}{C_{L_{MR}}\,\rho(h)\,S}} = a(h)\, M_{cruise-climb}}$$

$\rho(35000\,ft)$

$= 7.38\,(10^{-4})$ slugs$/ft^3$

$= 0.3803$ kg/m³

~~$a(h)$ = constant for altitude 35000ft ~ 70000ft~~

$$\cancel{V_{cruise-climb} = \sqrt{\frac{2(78000)(9.81)}{\frac{1}{3}(0.3803)(125)}} = a(h)\ 0.8}$$

$$\cancel{a(h) = 660\text{ mph} = 295.046\text{ m/s}}$$

b) $V_{cruise-climb} = a(h)(0.8)$

$= 295.046\,(0.8)$

$= 236.0368$ m/s

$V_{cruise-climb}$ = constant for this case to keep Mach 0.8 and $a(h)$ doesn't change.

$$L = W = \frac{1}{2}\rho V^2 S C_L \quad \text{for cruise}$$

$$C_{L_{init}} = \frac{2mg}{\rho S V^2}$$

$$= \frac{2(78000)(9.81)}{0.3803(125)(236.0368)^2}$$

$$= 0.5778$$

$$C_{D_{init}} = C_{D_0} + kC_L^2$$

$$= 0.016 + 0.048(0.5778)^2$$

$$= 0.032$$

$$R = 236.0368\left(\frac{0.5778}{0.032}\right)\left(\frac{1}{3.552\times10^{-5}(9.81)}\right)\ln\left(\frac{78000}{58000}\right)$$

$$= 3654.52\text{ km}$$

④

$$\bar{h}_B = I_B \bar{\omega}_B + \bar{h}'_B$$

Assume $\dot{\bar{h}}'_B = 0$, constant

$$\dot{\bar{h}}_B = \cancel{\dot{I}_B}^{\,0}\, \bar{\omega}_B + I_B \dot{\bar{\omega}}_B + \cancel{\dot{\bar{h}}'_B}^{\,0}$$

$$= I_B \dot{\bar{\omega}}_B$$

$\bar{h}'_B$ = constant means the rotor is attached to the Body, so the angular momentum of rotors respect to the Body doesn't change.

$$\bar{h}_B = H_I^B \bar{h}_I$$

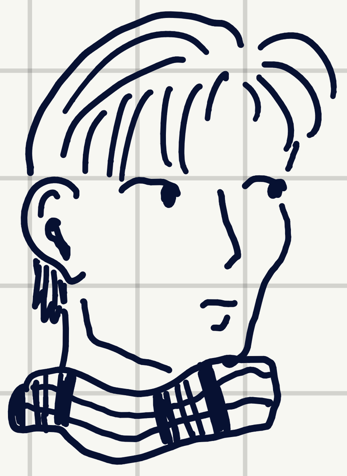
$$\dot{\bar{h}}_B = H_I^B \dot{\bar{h}}_I + \dot{H}_I^B \bar{h}_I$$

$$= H_I^B M_I - (\omega_B \times \bar{h}_B) \qquad \omega_B \times = \tilde{\omega}_B$$

$$= M_B - \tilde{\omega}_B \bar{h}_B$$

$$= M_B - \tilde{\omega}_B (I_B \omega_B + \bar{h}_B')$$

$$I_B \dot{\bar{\omega}}_B = M_B - \tilde{\omega}_B I_B \omega_B$$



$$M_B = I_B \dot{\bar{\omega}}_B + \tilde{\omega}_B (I_B \omega_B + \bar{h}_B')$$

$$= \begin{bmatrix} I_{xx} & 0 & -I_{xz} \\ 0 & I_{yy} & 0 \\ -I_{xz} & 0 & I_{zz} \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix}$$

$$+$$

$$\begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \begin{bmatrix} I_{xx} & 0 & -I_{xz} \\ 0 & I_{yy} & 0 \\ -I_{xz} & 0 & I_{zz} \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

$$+$$

$$\begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \begin{bmatrix} h'_x \\ h'_y \\ h'_z \end{bmatrix}$$

$$M_B = \begin{bmatrix} L \\ M \\ N \end{bmatrix} = \begin{bmatrix} I_{xx}\dot{p} - I_{xz}\dot{r} - r\bar{h}'_y - rqI_{yy} + q\bar{h}'_z - I_{xz}qp + I_{zz}qr \\ I_{yy}\dot{q} - p\bar{h}'_z + I_{xz}p^2 - I_{zz}pr + r\bar{h}'_x + I_{xx}rp - I_{xz}r^2 \\ I_{zz}\dot{r} - I_{xz}\dot{p} + p\bar{h}'_y + I_{yy}pq - q\bar{h}'_x - I_{xx}qp + I_{xz}qr \end{bmatrix}$$

$$L = \frac{1}{2}\rho V^2 S C_L = W$$

lift coeffient

air density

Surface area

Level = Cruise flight

$$D = \frac{1}{2}\rho V^2 S C_D = \text{Thrust}$$

Force

$$\dot{m} = C_T T$$

thrust

fuel

what rate/thrust

V, S, ρ

$C_{D_0}, K \quad C_T$

m_i, m_f

$$\dot{m} = C_T\left(\frac{1}{2}\rho V^2 S C_D\right)$$

$$C_D = C_{D_0} + K C_L^2$$

$$\dot{m} = C_T T$$

Range = Rsm

$$\frac{\cancel{dt}}{dr} \cdot \frac{dm}{\cancel{dt}} = C_T T \frac{dt}{dr}$$

$$\frac{dr}{dt} = V$$

$$\frac{dm}{dr} = C_T T \frac{1}{V}$$

$$\int dr = \int_{m_i}^{m_f} \frac{V}{C_T T}\, dm$$

$$\frac{V}{C_T D} \cdot \frac{L}{L}$$

$$\boxed{L = W}$$

$$\frac{L}{D} \cdot \frac{V}{C_T L}$$

$$= \frac{L}{D} \cdot \frac{V}{C_T mg}$$

V, C_T, m_i, m_f, g

$mg = \frac{1}{2}\rho V^2 S C_L$

$C_L = \frac{2mg}{\rho V^2 S}$

$C_{L_{init}} = \frac{2 \cdot 78000(9.81)}{(0.3805)(239)^2(125)}$

$C_D = C_{D0} + K C_L^2$

$= 0.016 + 0.048(C_L^2)$

$$\int dr = \int_{m_i}^{m_f} \frac{L}{D} \frac{V}{C_T mg} \, dm$$

$$= \int_{''}^{''} V \frac{C_L}{C_D} \frac{1}{C_T g m} \, dm$$

$$C_L = \frac{2mg}{\rho V^2 S}$$ m_i, m_f

$m_i \; m_f$

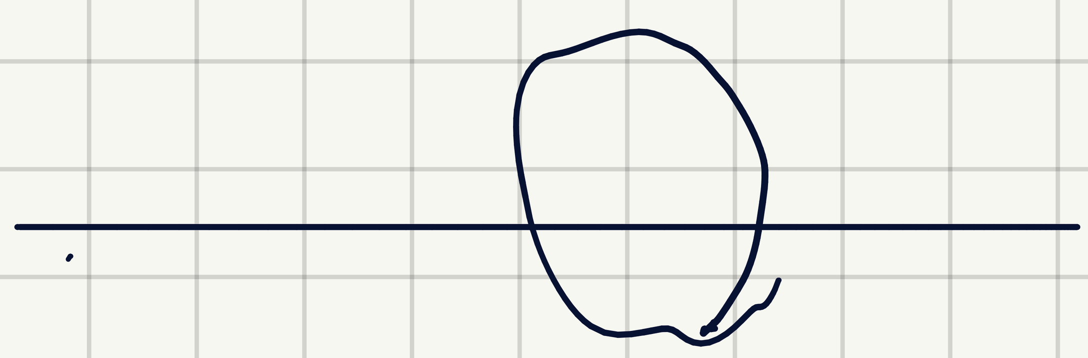
$C_{L_{init}}, C_{L_{final}}$

$C_{D_{init}}, C_{D_{final}}$

C_L

$L = W = \frac{1}{2}\rho V^2 S C_L$

$D = T = \frac{1}{2}\rho V^2 S C_D$

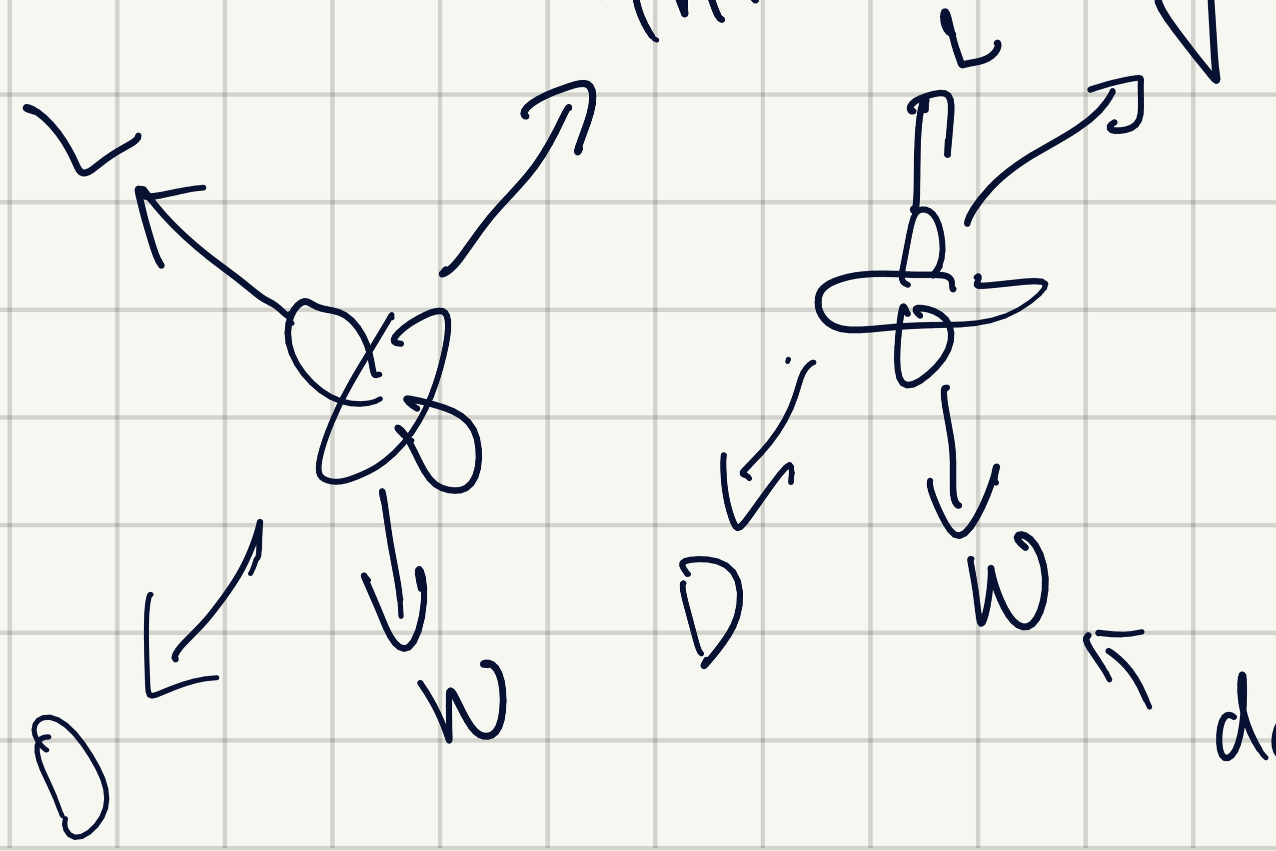


$\frac{L}{D}$ = constant for cruise flight

$\frac{C_L}{C_D}$ = changes b/c altitude changes

→ V

Thrust constant



decreases

$L \neq W$

$L = W$?