Mehanika leta letala

- sposobnosti
- stabilnost, krmljivost

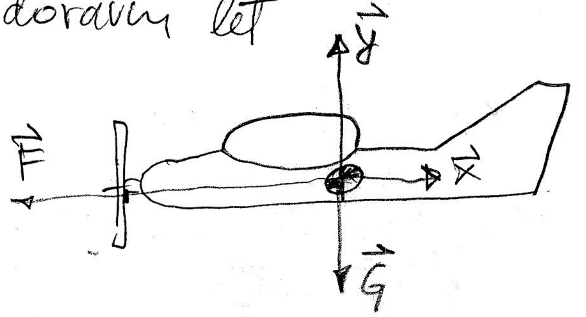
① letalo kot masna točka

• m

$$\Sigma \vec{F} = m \cdot \vec{a}$$

- stacionarni režim
- nestacionarni

Vodoravni let



$$F - X = 0$$
$$Y - G = 0$$

$$Y = \frac{1}{2} \rho v^2 \cdot A \cdot C_y = m \cdot g$$

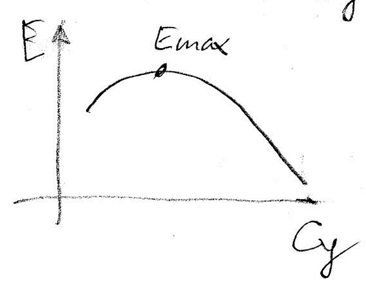
$$\boxed{v_{min} = \sqrt{\frac{2}{\rho} \cdot \frac{mg}{A} \cdot \frac{1}{C_{y\,max}}}}$$

obtežba krila

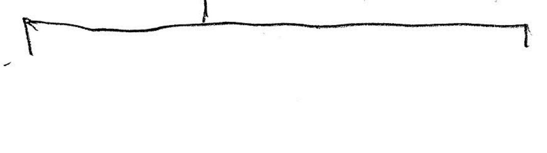
$$F = X = \frac{1}{2} \rho v^2 \cdot A C_x = \frac{1}{\cancel{2}} \cancel{\rho} \cdot \cancel{A} \cdot C_x \cdot \frac{\cancel{2}}{\cancel{\rho}} \frac{mg}{\cancel{A}} \cdot \frac{1}{C_y}$$

vlečna sila $\boxed{F = \frac{C_x}{C_y} \cdot mg = \frac{mg}{E}}$

$$E = \frac{C_y}{C_x}$$



Koeficient upora



C_x

- zavisi od vzgona
  - koef. induciranega upora — C_{xi}
  - koef. valovnega upora — C_{xv}
- koef. profilnega upora — C_{xpy}
- ne zavisi od vzgona
  - viskozni — C_{xp}
  - tlačni — C_{xtl}
  - $\underbrace{C_{xp} \quad C_{xtl}}_{X_p}$
  - valovni upor
  - interfer. upor — $C_{x\,int}$

$M > 0{,}7$

$$C_x = \underbrace{C_{xp}}_{\text{profilni}} + \underbrace{C_{xi}}_{\text{inducirani}}$$

$$= C_{xp} + \frac{1+\delta}{\pi \cdot \lambda} \cdot C_y^2$$

zavisi od oblike krila, $\delta = 1$ za eliptično krilo

$$C_x = K_1 + K_2 \cdot C_y^2 \quad \text{— v splošnem}$$

$$F = \frac{C_x}{C_y} \cdot mg$$

$$\frac{C_x}{C_y} = \underbrace{\frac{K_1}{C_y}}_{C_{x\,prof.}} + \underbrace{K_2 \cdot C_y}_{C_{x\,ind}}$$

$$\frac{d\left(\frac{C_x}{C_y}\right)}{dC_y} = -1 \cdot \frac{K_1}{C_y^2} + K_2 = 0$$

$$C_y = \sqrt{\frac{K_1}{K_2}} \quad \text{pri } E_{max}$$

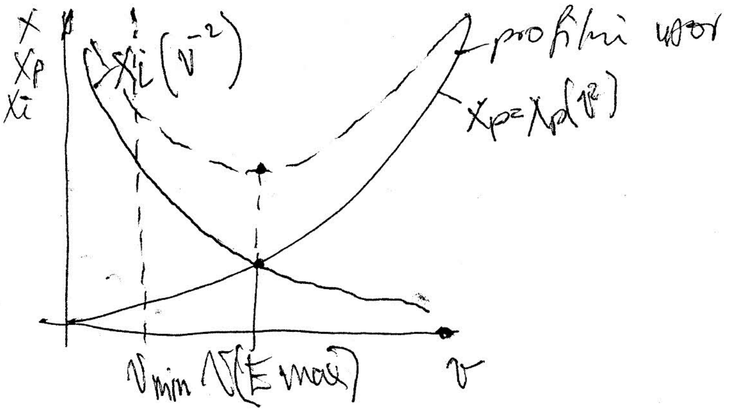
$$C_y = \sqrt{\frac{C_{xp}}{1+\delta}\,\pi\lambda} \Rightarrow \boxed{\frac{1+\delta}{\pi\lambda} \cdot C_y^2 = C_{xp}}$$

$$\boxed{C_{xi} = C_{xp} \text{ pri } E_{max}}$$

$$F = X_p + X_i$$

$$V_{E\,max} = \sqrt{\frac{2}{\rho} \cdot \frac{mg}{A}} \cdot \sqrt[4]{\frac{K_2}{K_1}}$$

$$X_p = \frac{1}{2} \rho V^2 \cdot A \cdot C_{xp}$$



$$X_p = m \cdot g \cdot \left(\frac{C_x}{C_y}\right)_p = mg \cdot \frac{K_1}{\sqrt{\frac{K_1}{K_2}}}$$

$$X_p = m \cdot g \cdot \sqrt{K_1 \cdot K_2} \quad \text{profilni upor pri max. finesi}$$

$$X_i = m \cdot g \cdot \left(\frac{C_x}{C_y}\right)_i = mg \cdot K_2 \cdot C_y$$

pri max. finesi

$$X_i = m \cdot g \cdot K_2 \sqrt{\frac{K_1}{K_2}} = mg\sqrt{K_1 K_2}$$

pri max. finesi je ind. upor = prof. uporu

$$X_i = \cancel{K_2 \cdot C_y}$$

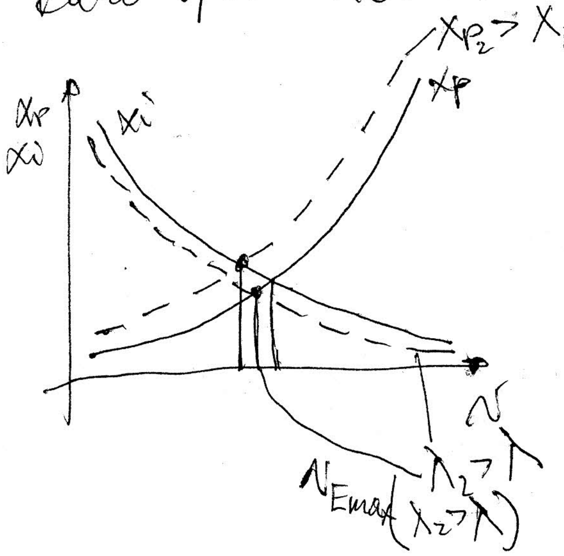
$$\frac{1}{2}\rho v^2 \cdot C_y \cdot A = m \cdot g$$

$$C_y = \frac{mg}{\frac{1}{2}\rho v^2 \cdot A}$$

$$X_i = m \cdot g \left(\frac{C_x}{C_y}\right)_i = mg \cdot K_2 \cdot C_y = \frac{(mg)^2 K_2}{\frac{1}{2}\rho A v^2}$$

$$C_{y_{Emax}} = \sqrt{\frac{C_{x0}}{1+\delta} \cdot \pi \lambda}$$

Kako vpliva vitkost

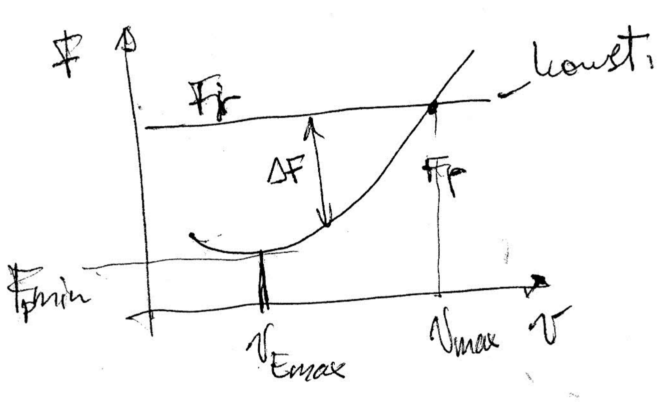


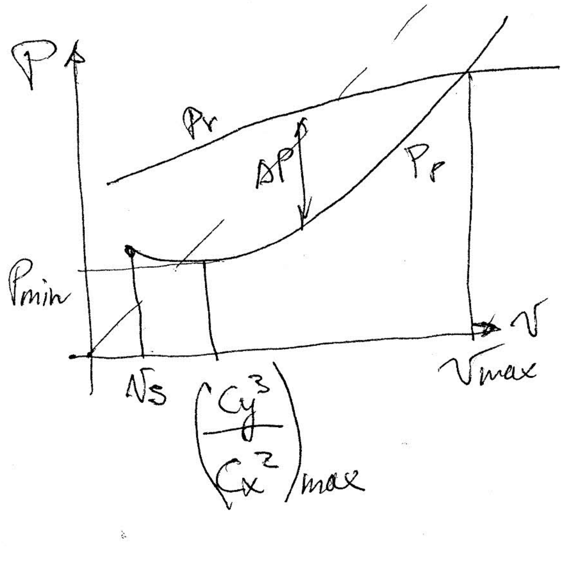
$\lambda = C_{xi} \quad X_i$

$\lambda < \lambda_2 = C_{xi_2} \quad X_{i_2} < X_i$

- Večja vitkost manjši ind. upor

$$P_p = F_p \cdot v$$





P_{min} →

razpoložljiva sila = konst

količnik dvigonja

- Vpliv višine na P-D za sile (Penojev diagram)

Potrebna vlečna sila

$$F_p = \frac{mg \cdot C_x}{C_y} = \frac{mg}{E}$$

konst

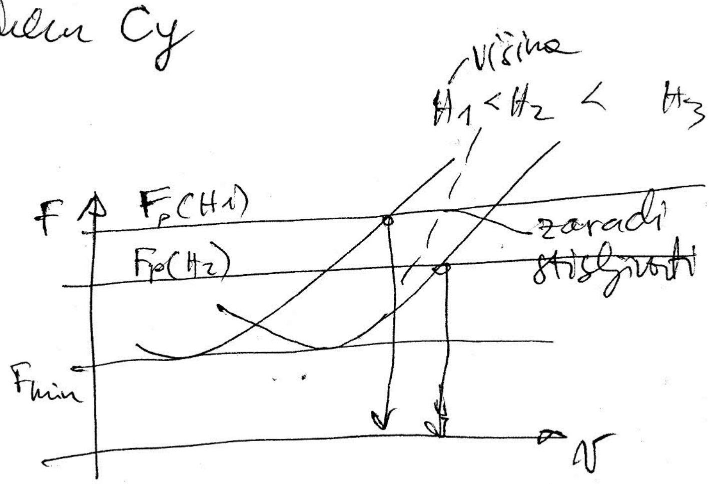
E konst - letimo pri enakem C_y

$$\boxed{\frac{1}{2}\rho v^2} \boxed{C_y} A = m \cdot g$$

konst. konst.

konst. indicirano hitrost

$$v_{TAS} = v_{TAS_0} \sqrt{\frac{\rho_0}{\rho(H)}}$$



v_{TAS} - z višino narašča

v_{zvoka} - z višino pada $f(T)$

$M = \frac{v_{TAS}}{v_{zvoka}}$ - se povečuje

narašča, pada

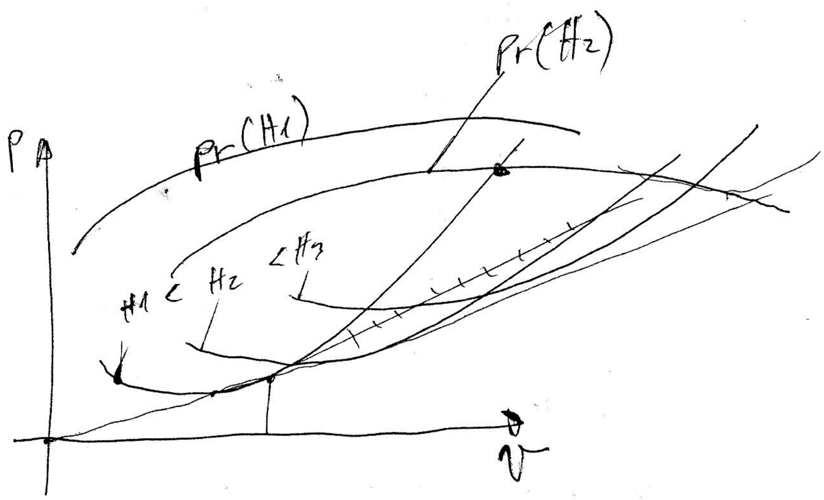
večja temp. razlika - večja razpoložljiva moč

Penojev diagram za višino

Vpliv višine na P-D za moči

$$P_p = F_p \cdot v_{TAS} = F_p \cdot v_0 \sqrt{\frac{\rho_0}{\rho_H}}$$

$$v_{TAS} = v_0 \cdot \sqrt{\frac{\rho_0}{\rho}}$$



$$P_m(H) = P_{m0} \cdot \frac{1}{\eta_m} \left[\frac{\rho(H)}{\rho_0} - (1 - \eta_m) \right]$$ - motorja

mehanski izkoristek

$P_r = P_m \cdot \eta_{elise}$ - razpoložljiva moč

Omejitve horizontalnega leta

$P_r \geq P_p$ – potrebna

razpoložljiva

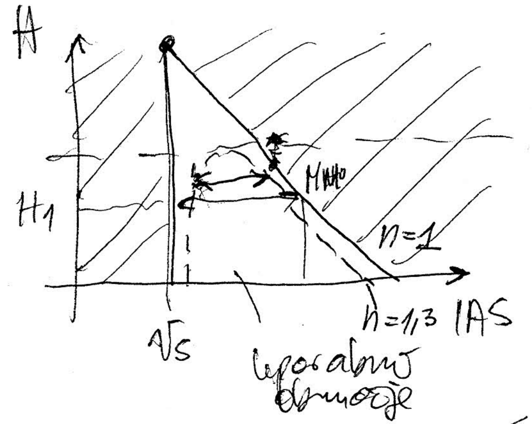
Omejitve za min hitrost

$V_{min} = V_s$ porušitev vzgona pri velikih vpadnih kotih

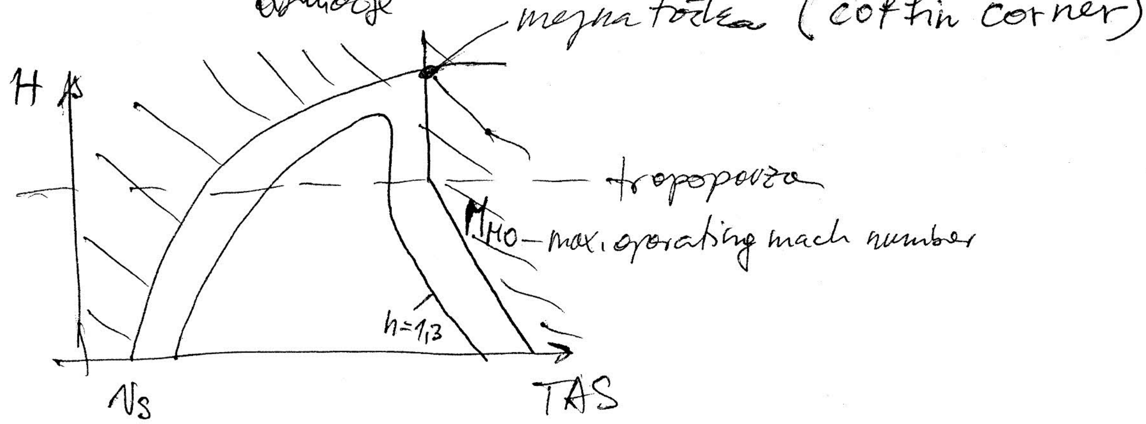
V_{MO} – z shock stall | porušitev vzgona zaradi tlačnih skokov

maksimum operativna hitrost

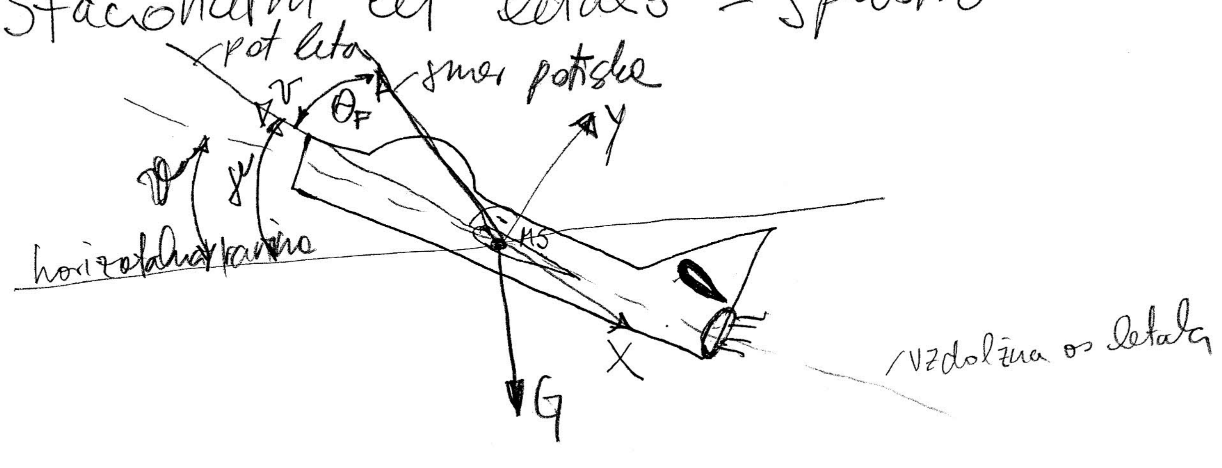
M_{MO} – maksimalno operativno machovo število



z višino machovo št. narašča



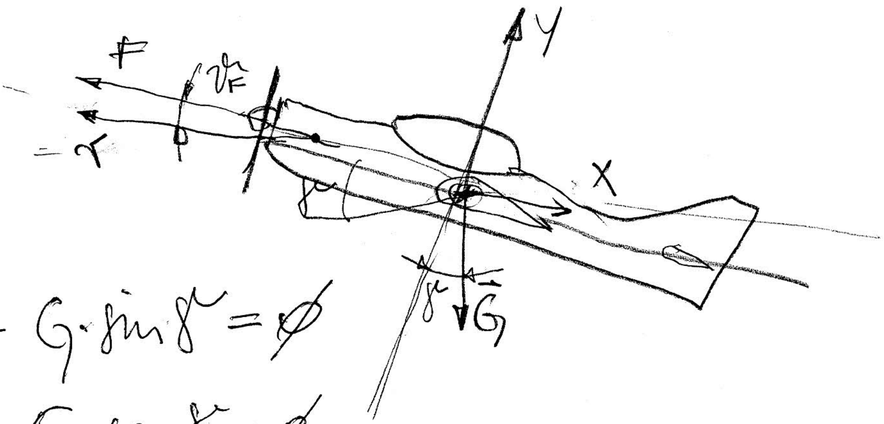
Stacionarni let letalo – splošno



Klasična letala

ϑ – zmeren

γ – zmeren



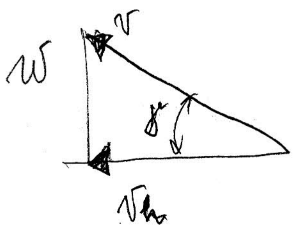
$$F \cdot \cos\vartheta_F - X - G \cdot \sin\gamma = 0$$

$$F \cdot \sin\vartheta_F + Y - G \cdot \cos\gamma = 0$$

$$\vartheta_F = 0$$

$$F = X + G \cdot \sin\gamma$$

$$Y = G \cdot \cos\gamma$$



$$E = \frac{Y}{X}$$

$$f = \frac{F}{G}$$

$$f = \frac{F}{G} = \frac{X}{G} + \sin\gamma$$

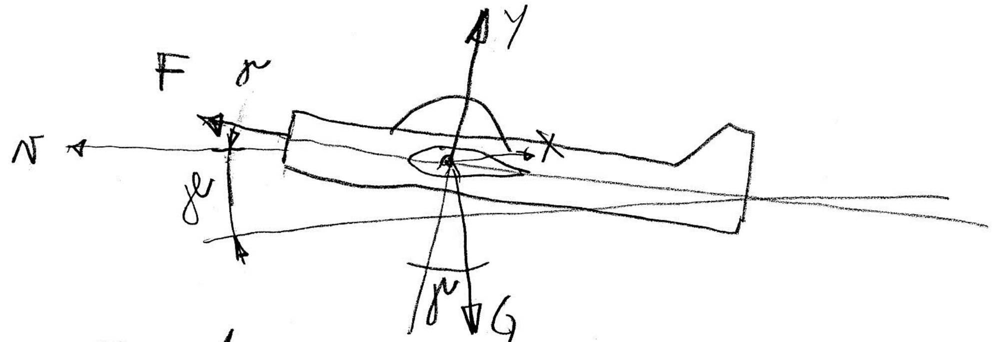
$$f = \frac{F}{G} = \frac{X}{Y} \cdot \cos\gamma + \sin\gamma$$

$$\boxed{f = \frac{1}{E}\cos\gamma + \sin\gamma}$$

horizont. let $\gamma = 0$

$$f = \frac{F}{G} = \frac{1}{E}$$

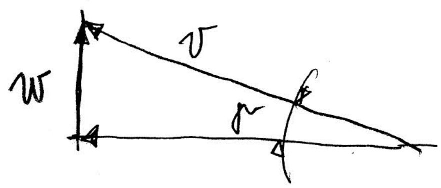
$$F = 0$$



$$\frac{E}{G} = \frac{1}{E} \cdot \cos\gamma + \sin\gamma$$

vzpenjanje $\quad F = X + G \cdot \sin\gamma \;\Big|\cdot v$

$$F \cdot v = X \cdot v + G \cdot v \cdot \sin\gamma$$



$$w \cdot G = (F - X) \cdot v$$

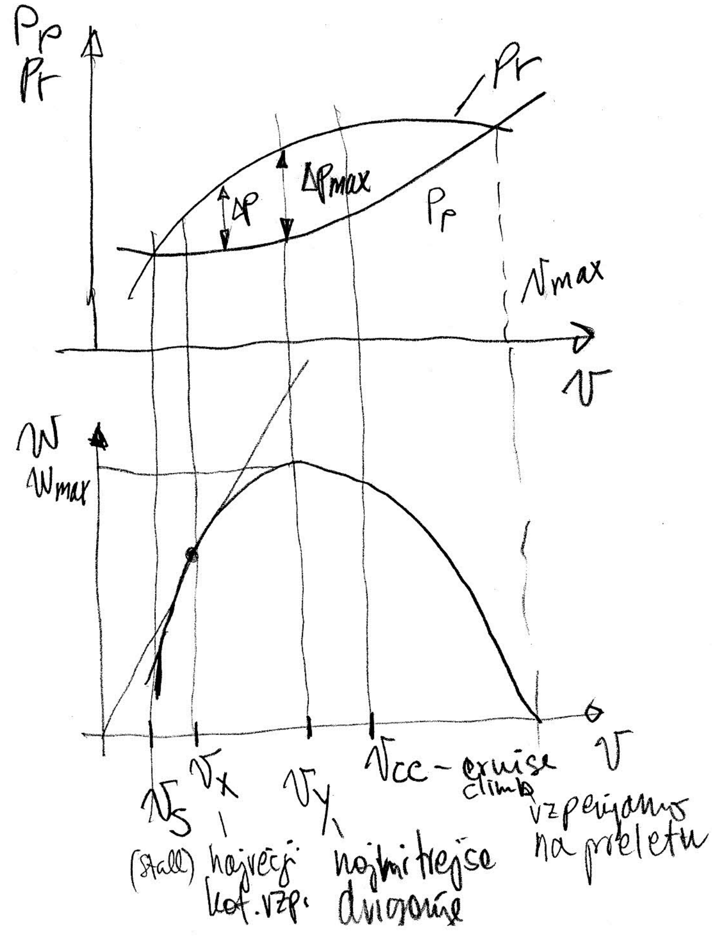
razpoložljiva

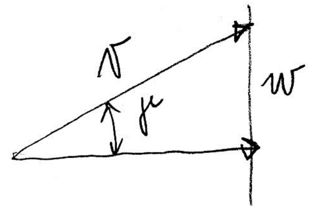
$$w = \frac{F \cdot v - X \cdot v}{G} = \frac{P_r - P_p}{G}$$ potrebna

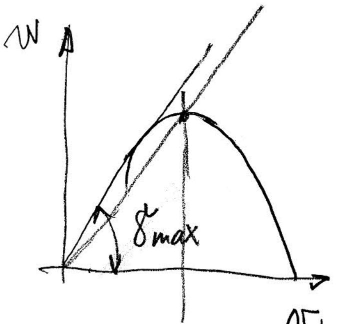
pot. en.

$$w \cdot m \cdot g = m \cdot g \frac{dh}{dt} = \frac{d(mgh)}{dt} = \frac{d(E_p)}{dt} =$$

$$= P_r - P_p$$



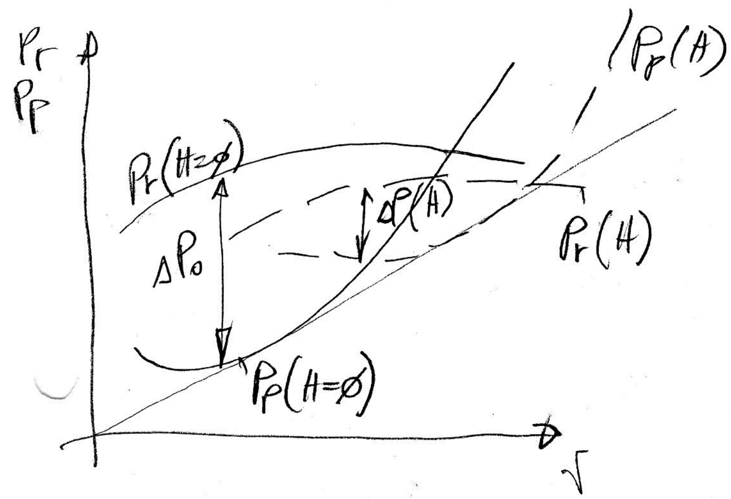


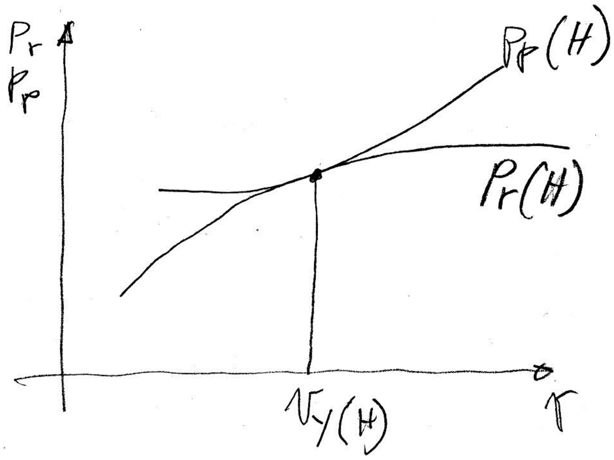


$v_h = v \cdot \cos\gamma$

kot direktno odčitamo

$$P_m(H) = P_{m0} \cdot \frac{1}{\eta_m} \cdot \left[\frac{\rho(H)}{\rho_0} - (1-\eta_m)\right]$$

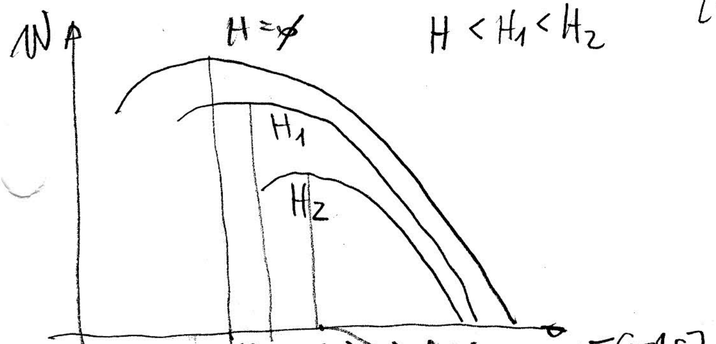


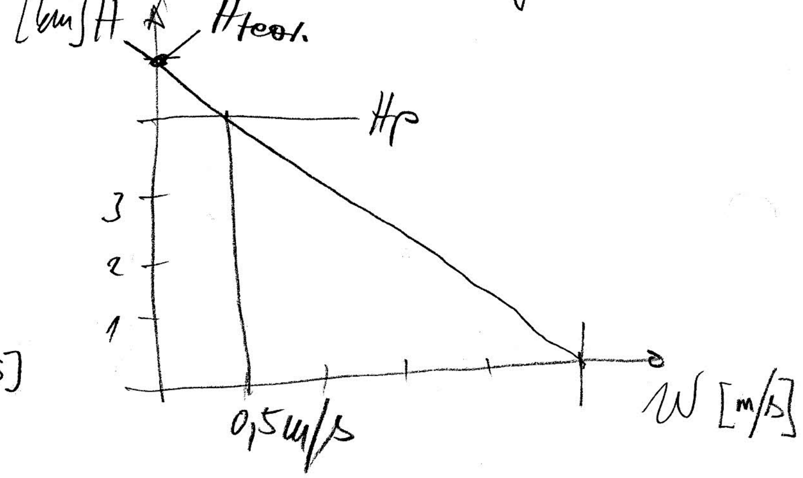


$$v_y(H) = v_{y0}\sqrt{\frac{\rho_0}{\rho(H)}}$$

teoretičen vrhunec leta

$$P_r = P_p \Big|_{v_y}$$

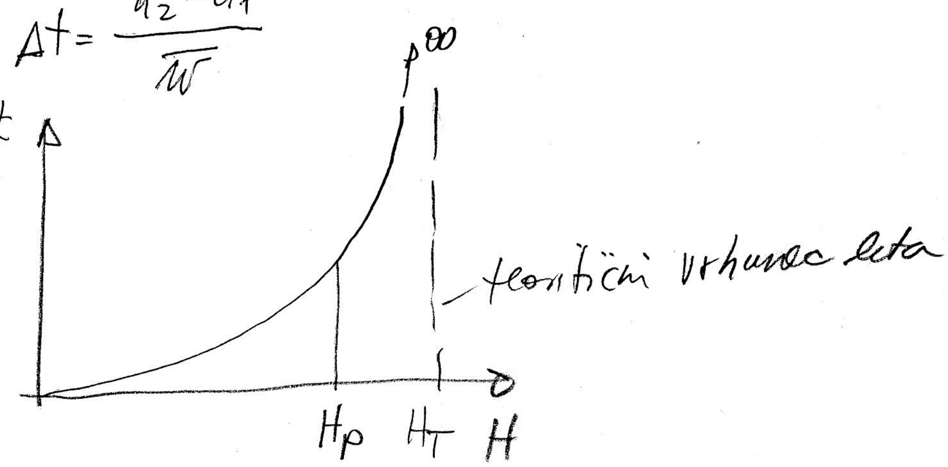




$$w(H) = \frac{dh}{dt} \qquad \Delta t = \frac{h_2 - h_1}{w}$$

$$\int_0^t dt = \int_{h_1}^{h_2} \frac{dh}{w(H)}$$

$$t = \int_0^H \frac{dh}{w(H)}$$



Dolet in čas trajanja leta

RPM ↓
↑ MP - manifold pressure } manjša poraba goriva

kvadratno pravilo

Primer: 2500 RPM
25 inHg

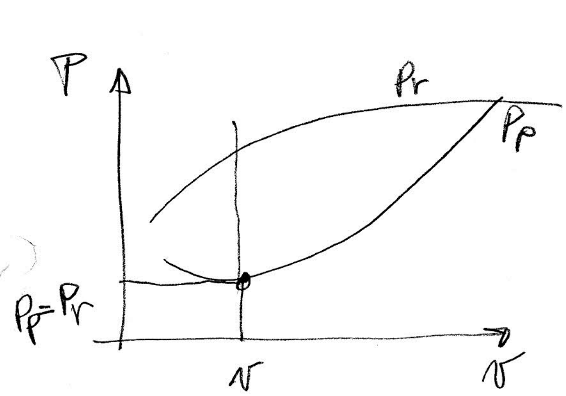
Breguet

Zmanjševanje mase s porabo goriva 10–20% točnost ocen

ni upoštevano spreminjanje hitrosti

$\frac{\text{Dolet}}{t}$ = podaljšani dolet

na določeni višini brez rezerve



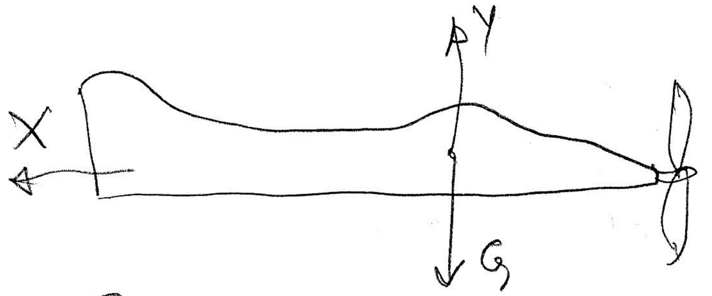
$c \left[\frac{kg}{kWh}\right]$ poraba

P_m - moč motorja

η - izkoristek elise

m_g - masa goriva

m_0 - celotna masa (gorivo, prtljaga, potniki)



$$P_r = P_m \cdot \eta = P_p = X \cdot v \Rightarrow P_m = \frac{X \cdot v}{\eta}$$

zmanjšanje mase zaradi porabe goriva

$$-dm = c\, P_m \cdot dt$$

$$-\frac{dm}{dt} = c \cdot \frac{X \cdot v}{\eta}$$

dolet propelerskega letala

$$-\frac{dm}{dt} = c \cdot \frac{1}{2} \rho v^2 A \cdot C_x \cdot \frac{v}{\eta}$$

$$\frac{1}{2} \rho v^2 A \cdot C_y = m \cdot g$$

$$-\frac{dm}{dt} = c \cdot \cancel{\frac{1}{2}} \cancel{\rho} \cdot \cancel{A} \cdot \frac{C_x}{\eta} \cdot v \frac{mg}{\cancel{\frac{1}{2}} \cancel{\rho} \cancel{A} C_y}$$

$$-\frac{dm}{dt} = \frac{c}{\eta} \frac{C_x}{C_y} \cdot m \cdot g \cdot v$$

$$v \cdot dt = ds = -\frac{\eta}{c} \cdot \frac{C_y}{C_x} \cdot \frac{1}{g} \cdot \int_{m_0}^{m_0 - m_g} \frac{dm}{m}$$

$$S = -\frac{\eta}{c \cdot g} \cdot \frac{C_y}{C_x} \cdot \ln\left(\frac{m_0}{m_0 - m_g}\right)$$

Maximalni dolet

S_{max} : v_{S}^{o} $\left(\cancel{\frac{C_y}{C_x}}\right)$ $\left(\frac{C_y}{C_x} = E\right)_{max}$

$\eta \uparrow$

$\downarrow c$ – spec. poraba goriva

po teh enačbah
ρ – gostota ni pomembna
optimalni dolet se ne more določiti po teh enačbah

Trajanje leta propelerskoga letala

$$-\frac{dm}{dt}=\frac{cX\cdot v}{\eta}=\frac{c}{\eta}\cdot mg\frac{c_x}{c_y}\cdot\sqrt{\frac{mg}{\frac{1}{2}\rho A}}\sqrt{\frac{1}{c_y}}=$$

$$X=\frac{m\cdot g}{E}=m\cdot g\frac{c_x}{c_y}$$

$$=\frac{c}{\eta}\frac{1}{\sqrt{\frac{1}{2}\rho A}}\cdot(mg)^{3/2}\cdot\frac{c_x}{c_y^{3/2}}$$

$$-\frac{3}{2}+\frac{2}{2}\ \frac{1}{2}$$

$$\int_0^t dt=-\frac{\eta}{c}\cdot\sqrt{\frac{\rho A}{2g^3}}\cdot\frac{c_y^{3/2}}{c_x}\cdot\int_{m_0}^{m_0-m_g}m^{-3/2}\,dm$$

$$t=+\frac{\eta}{c}\sqrt{\frac{\rho A}{2g^3}}\cdot\frac{c_y^{3/2}}{c_x}\left(-2\right)\cdot\left(m^{-1/2}\right)\Big|_{m_0}^{m_0-m_g}$$

$$\int_{m_0}^{m_1}m^{-3/2}dm=-\frac{2}{3}\cdot m^{1/2}\Big|_{m_0}^{m_1}\ ✓$$

$$t=\frac{\eta}{c}\sqrt{\frac{2\cdot\rho\cdot A}{g^3}}\,\frac{c_y^{3/2}}{c_x}\left(\frac{1}{\sqrt{m_0-m_g}}-\frac{1}{\sqrt{m_0}}\right)$$

t_{max} : v_t : $\left(\frac{c_y^{3/2}}{c_x}\right)_{max}$ količnik dvigonja

$\eta\uparrow$

$c\downarrow$

$m_g\uparrow$

$\rho\uparrow \Rightarrow H=\emptyset$

A

Breguet za reakcijski motor

$c\left[\frac{kg}{kNh}\right]$

$-dm = c \cdot F \cdot dt$

$F = X = \frac{1}{2}\rho v^2 \cdot A \cdot C_x = mg \cdot \frac{C_x}{C_y}$

- trajanje leta

$$\int_0^t dt = -\frac{dm}{c \cdot F} = -\frac{1}{cg} \cdot \frac{C_y}{C_x} \int_{m_0}^{m_0 - m_g} \frac{dm}{m}$$

$$t = \frac{1}{cg} \cdot \frac{C_y}{C_x} \cdot \ln\left(\frac{m_0}{m_0 - m_g}\right)$$

t_{max} : v_t pri $\left(\frac{C_y}{C_x}\right)_{max}$ $\qquad \rho$ - gostota ni pomembna

$c \downarrow$

$m_g \uparrow$

- dolet

$$F = X = \frac{1}{2}\rho v^2 A C_x = mg \frac{C_x}{C_y} = \frac{1}{2}\rho A C_x \cdot v \sqrt{\frac{mg}{\frac{1}{2}\rho A C_y}}$$

$$-dm = c \sqrt{\frac{1}{2}\rho A g} \frac{C_x}{\sqrt{C_y}} \cdot \sqrt{m}\, v \cdot dt$$

$$v \cdot dt = ds = -\frac{1}{c}\sqrt{\frac{2}{\rho g A}} \cdot \frac{\sqrt{C_y}}{C_x} \cdot \int_{m_0}^{m_0 - m_g} \frac{dm}{\sqrt{m}}$$

$$S = -\frac{1}{c}\sqrt{\frac{2}{\rho A g}} \cdot \frac{\sqrt{C_y}}{C_x} (+2)\sqrt{m}\Big|_{m_0}^{m_0 - m_g} =$$

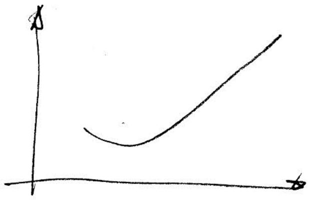
$$S = \sqrt{\frac{2}{\rho g A}} \cdot \frac{1}{C} \frac{\sqrt{C_y}}{C_x} \left[\sqrt{m_0} - \sqrt{m_0 - m_g}\right]$$

S_{max} : $\left(\frac{\sqrt{C_y}}{C_x}\right)_{max}$ (tekina hitrost)

$c \downarrow$

$m_g \uparrow$

$\rho \downarrow \Rightarrow H \uparrow$



$\left.\frac{C_x}{C_y}\right|_{max}$

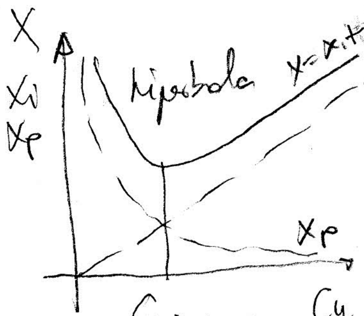
$$\left(\frac{C_y}{C_x}\right)_{max} = E_{max} \Rightarrow C_{xi} = C_{xp}$$

$$X = X_i + X_p = 2X_i = 2X_p$$

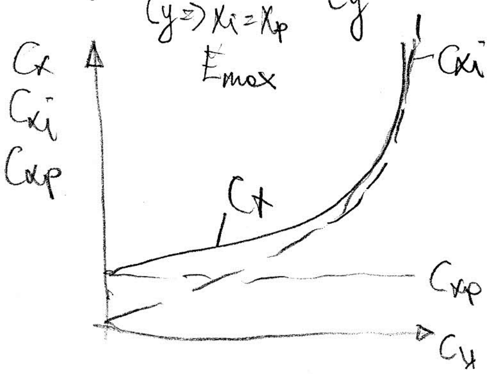
$$X_p = \frac{1}{2}\rho v^2 A \cdot C_{xp} = f(v^2) = mg \cdot \frac{C_{xp}}{C_y} = \underline{f\left(\frac{1}{C_y}\right)}$$

$$Y = \frac{1}{2}\rho v^2 \cdot A \cdot C_y = m \cdot g$$

$$X_i = \frac{1}{2}\rho v^2 \cdot A\, C_{xi} = mg \frac{C_{xi}}{C_y} = mg \cdot \frac{1+\delta}{\pi\lambda} C_y = f(C_y)$$



$$X_i = 2 \cdot (mg)^2 \frac{1+\delta}{\pi\lambda} \cdot \frac{1}{\rho A} \cdot \frac{1}{v^2} = f\left(\frac{1}{v^2}\right)$$



Povezava med C_{xp}, C_{xi}

$$P_{rop} = P_p\Big|_{min} \sqrt{\frac{2}{\rho}\frac{(mg)^3}{A}} \cdot \left(\frac{C_x}{C_y^{3/2}}\right)_{min}$$

$$\left(\frac{C_y^{3/2}}{C_x}\right)_{max}$$

potrebna moč

$$P_p = F_p \cdot v = X \cdot v = (X_p + X_i) \cdot v$$

$$P_p = \frac{1}{2}\rho A \cdot C_{xp} v^3 + 2 \cdot \frac{(mg)^2}{\rho A} \cdot \frac{1+\delta}{\pi \cdot \lambda} \cdot \frac{1}{v}$$

$$\frac{\partial P_p}{\partial v} = \frac{1}{2}\rho \cdot A C_{xp} \cdot 3 \cdot v^2 - 2\,\frac{(mg)^2}{\rho A}\,\frac{1+\delta}{\pi \cdot \lambda} \cdot \frac{1}{v^2} =$$

$$= \frac{1}{2}\rho A v^2 \left(3 C_{xp}\right) - \frac{4 \cdot (mg)^2}{(\rho A)^2 \cdot v^4} \cdot \frac{1}{2}\rho A v^2 \cdot \frac{1+\delta}{\pi\lambda}\Big) =$$

$$v^2 = \frac{2mg}{\rho A \cdot C_y} =$$

$$\left(\frac{\frac{1}{2}\rho A \cdot v^2}{m \cdot g}\right)^2 = \frac{1}{C_y^2}$$

$$= \frac{1}{2}\rho A v^2 \Big[3 C_{xp} - \underbrace{\left(\frac{1+\delta}{\pi\lambda} \cdot C_y^2\right)}_{C_{xi}}\Big] = \emptyset$$

$$= \quad 3 C_{xp} = C_{xi}$$

$$C_{xp} = \frac{1}{3} C_{xi}$$

čimmanjši inducirani upor

najdaljši čas

$$\frac{\sqrt{C_y}}{C_x}\Bigg|_{max}$$

$$C_x = C_{xp} + \frac{1+\delta}{\pi\lambda} C_y^2 = C_{xp} + K C_y^2$$

$$\frac{d\left(\frac{\sqrt{C_y}}{C_{xp} + K C_y^2}\right)}{dC_y} = \frac{\frac{1}{2} \cdot C_y^{-\frac{1}{2}} \cdot (C_{xp} + K C_y^2) - 2 \cdot K \cdot C_y \cdot \sqrt{C_y}}{(C_{xp} + K C_y^2)^2} = \emptyset$$

$$\frac{1}{2}C_{xp}+\frac{1}{2}K C_y^2-2K C_y^2=\emptyset \Big|\cdot 2$$

$$C_{xp}=3K\cdot C_y^2=3C_{xi}$$ ~~naj~~ večje hitrosti

$$C_{xi}=\frac{1}{3}C_{xp}$$

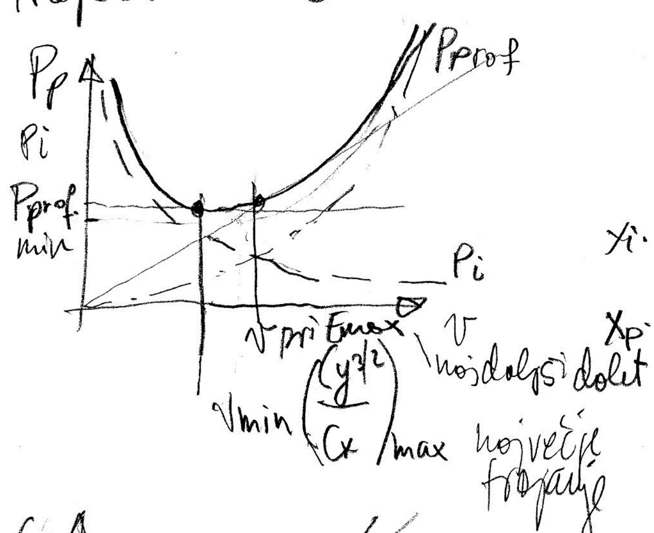
$$\left.\frac{C_y}{C_x}\right|_{max}=E_{max} \Leftrightarrow C_{xi}=C_{xp}$$

$$\frac{C_y}{C_{xp}+\frac{1+\delta}{\pi\cdot\lambda}\cdot C_y^2}=\frac{\cancel{C_y}}{2\cdot\frac{1+\delta}{\pi\cdot\lambda}\cdot C_y^{\cancel{2}}}=\frac{1}{2\frac{(1+\delta)}{\pi\lambda}\cdot\sqrt{\frac{\pi\lambda}{1+\delta}C_{xp}}}$$

$$C_{xp}=\frac{1+\delta}{\pi\lambda}\cdot C_y^2 \qquad =\frac{1}{2}\sqrt{\frac{\pi\lambda}{1+\delta}\cdot\frac{1}{C_{xp}}}$$ samo od geometrije je odvisno

$$C_y=\sqrt{\frac{\pi\lambda}{1+\delta}\cdot C_{xp}}$$

Propelrska letala

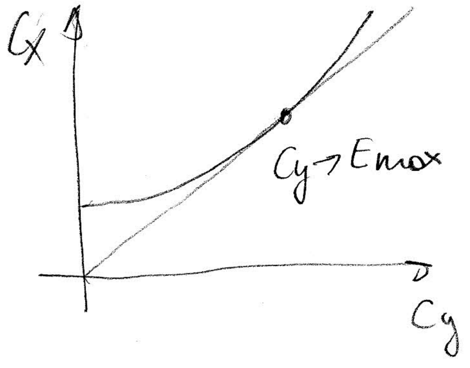


$$X_i=f\left(\frac{1}{v^2}\right)$$

$$X_p=f(v^2)$$

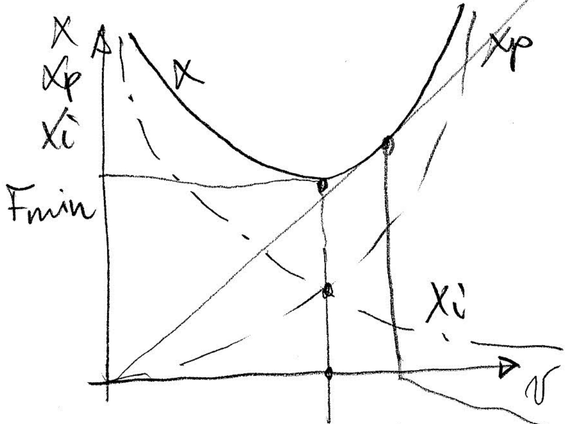
$$X_i\cdot v=P_i=f\left(\frac{1}{v}\right)$$

$$X_p\cdot v=P_{prof}=f(v^3)$$



Reakcijska letala

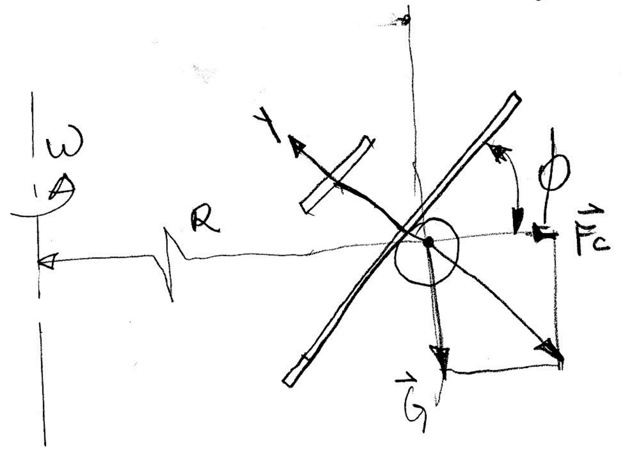
F_{min} = min. potisna sila



v pri E_{max} najdaljše trajanje

$\left(\frac{\sqrt{C_y}}{C_x}\right)_{max}$ – najdaljši dolet reakcijskih letal

Sposobnosti letala v zavoju



d'Alambert

$\sum \vec{F} + \vec{F_v} = 0$ $\quad \sum F_H + F_v = -Y \cdot \sin\phi + F_c = 0$

$\vec{F_v} = -m\vec{a}$ $\quad \sum F_H + F_v = Y \cdot \cos\phi - G = 0$

$F = X = \frac{1}{2}\rho v^2 A \cdot C_x$ $\quad n \cdot G = Y = \frac{G}{\cos\Phi} = \frac{1}{2}\rho v^2 A \cdot C_y$

$$n = \frac{Y}{G} = \frac{1}{\cos\Phi}$$

$F = X = \frac{1}{2}\rho v^2 \cdot C_x$

$F = \frac{G}{\cos\Phi} \cdot \frac{C_x}{C_y} = n \cdot (mg) \cdot \frac{1}{E} = (n \cdot g) \cdot m \cdot \frac{1}{E}$

$$P_{P_z \atop zavoj} = F_P \cdot v = n \cdot g \cdot m \cdot \frac{C_x}{C_y} \sqrt{\frac{2n \cdot mg}{\rho A \cdot C_y}}$$

$$P_{P_z \atop zavoj} = \sqrt{\frac{2(mg)^3}{\rho A}} \cdot \frac{C_x}{C_y^{3/2}} \cdot n^{3/2} =$$

$$P_{P_z} = P_P \cdot \sqrt{n^3}$$

v zavoju hor. let

$$F_C = \sqrt{Y^2 - G^2} = G\sqrt{n^2-1}$$

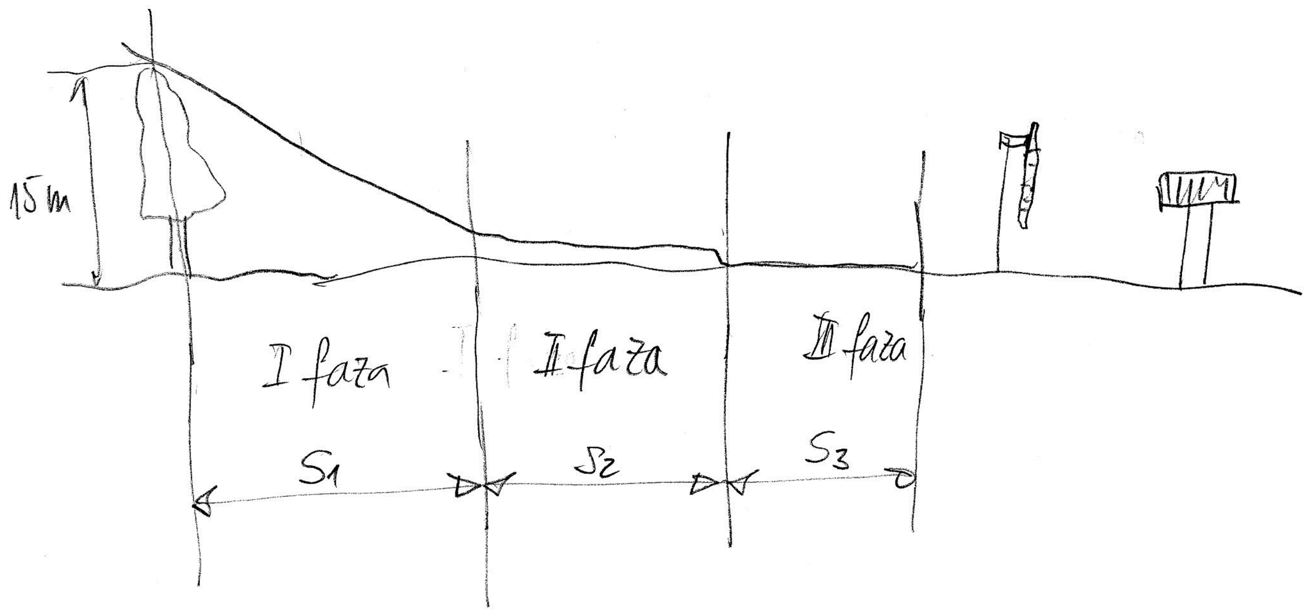
$$F_C = m \cdot \frac{v^2}{R} = m \cdot \omega^2 \cdot R = m \cdot \omega \cdot v = ma$$

$$\frac{mv^2}{R} = mg\sqrt{n^2-1}$$

$$R = \frac{v^2}{g\sqrt{n^2-1}}$$

$$\omega = \frac{v}{R} = \frac{g\sqrt{n^2-1}}{v}$$

Pristanek letala



I faza - spuščanje

$F = \varnothing$

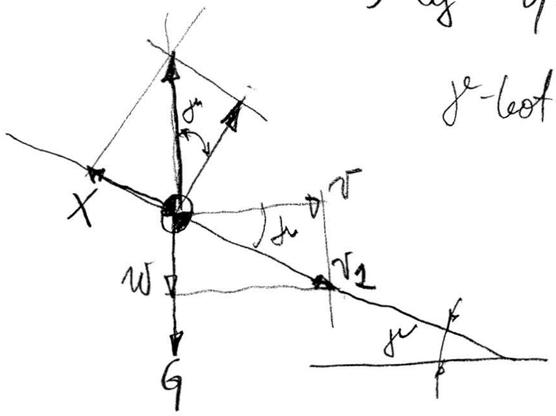
hitrost prihoda v_1

1,6 - Pitts

a) $1{,}3 - 1{,}4 \cdot v_{so}$

b) $C_y \approx 0{,}8\, C_{y\,max}$ - rezerva

γ - kot spuščanja

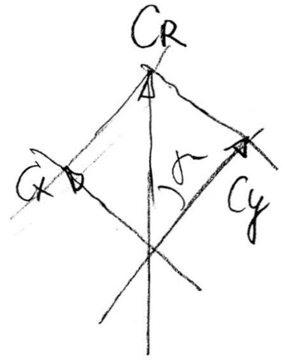


$$Y = G \cdot \cos\gamma$$

$$X = G \cdot \sin\gamma$$

$$\frac{1}{2}\rho v^2 A \cdot C_y = m \cdot g \cdot \cos\gamma$$

$$\frac{1}{2}\rho v^2 A \cdot \frac{C_y}{\cos\gamma} = m g$$



$$v_1 = \sqrt{\frac{2 \cdot m g}{\rho A \cdot C_R}}$$

$$C_R^2 = C_x^2 + C_y^2$$

$$\operatorname{tg}\gamma = \frac{C_x}{C_y} = \frac{w}{v} = \frac{1}{E} = \frac{\Delta H}{S_1}$$

$$w = v_1 \cdot \sin\gamma$$

$v = v_1 \cdot \cos\gamma \approx v_1$ za majhne kote

t_1 - čas spuščanja

$$t = \frac{\Delta H}{w} = \frac{15\,m}{w}$$

$$S_1 = t_1 \cdot v = \frac{\Delta H \cdot v}{w}$$

čelni veter

čelni +, hrbni -

$v_g = GS = v - v_v$ - čelni veter

$S_1 = t_1 \cdot v_g = t_1(v - v_v)$

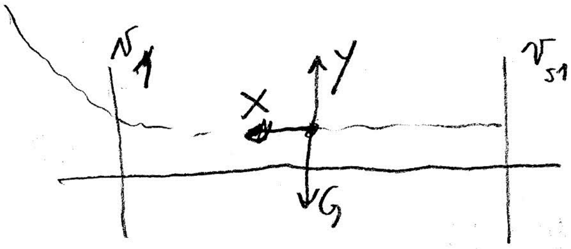
TALNI EFEKT

$\phi = \dfrac{(16h/b)^2}{1+(16h/b)^2}$

h - višina
b - razpon

REDUKCIJA INDUCIRANEGA UPORA

II faza pristanka



$F = \emptyset$

$\frac{1}{2}\rho v^2 \cdot C_y \cdot A = m \cdot g$

$v^2 \cdot C_y = \text{konst}$

$\Downarrow$

C_x

$\Sigma F_x = -X = m \cdot a = m \cdot \dfrac{dv}{dt}$

$X = -m\dfrac{dv}{dt} \cdot \dfrac{ds}{ds} = -m \cdot v\dfrac{dv}{ds} = \frac{1}{2}\rho v^2 A C_x$

$ds = \dfrac{-2m}{\rho A} \cdot \dfrac{1}{C_x} \cdot \dfrac{dv}{v}$

$C_x = f(v)$

$\overline{C_x} = \frac{1}{2}\left[C_x(v_1) + C_x(v_{s1})\right]$

$$ds = \frac{-2m}{\rho A} \cdot \frac{1}{C_x} \cdot \frac{dv}{v}$$

$$S_2 = -\frac{2m}{\rho A}\frac{1}{C_x} \cdot \ln v \Big|_{v_1}^{v_{s1}}$$

$$S_2 = \frac{2m}{\rho A}\frac{1}{C_x} \cdot \ln\frac{v_1}{v_{s1}} \doteq \frac{2m}{\rho A}\frac{1}{C_x}\ln(1{,}3 \div 1{,}4)$$

v primeru čelnega vetra v_v

$$X = -m\cdot\frac{dv}{ds}\cdot\frac{ds}{dt} = -m\,(v-v_v)\cdot\frac{dv}{ds} = \frac{1}{2}\rho v^2 A c_x$$

$$\int_0^{s_2} ds = \int_{v_1}^{v_{s1}} \underbrace{-\frac{2m}{\rho A}\cdot\frac{1}{c_x}\cdot\left(\frac{1}{v}-\frac{v_v}{v^2}\right)}_{I} dv$$

$$I_1 = -\frac{2m}{\rho A}\cdot\frac{1}{c_x}\cdot\int_{v_1}^{v_{s1}}\frac{dv}{v} = \frac{2m}{\rho A}\cdot\frac{1}{c_x}\cdot\ln\frac{v_1}{v_{s1}}$$

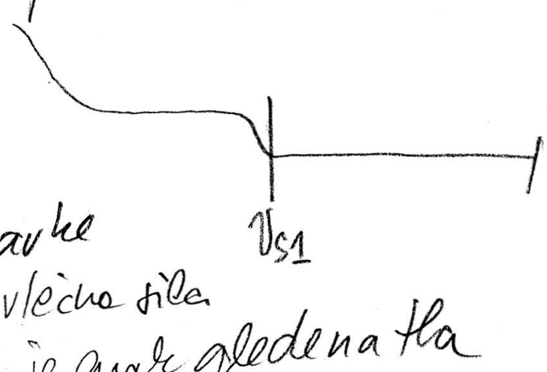
$$I_2 = \frac{2m}{\rho A}\cdot\frac{1}{c_x}\cdot v_v\cdot\int_{v_1}^{v_{s1}}\frac{dv}{v^2} = \frac{2m}{\rho A}\,\frac{v_v}{c_x}\cdot(-1)\left(\frac{1}{v_{s1}}-\frac{1}{v_1}\right)$$

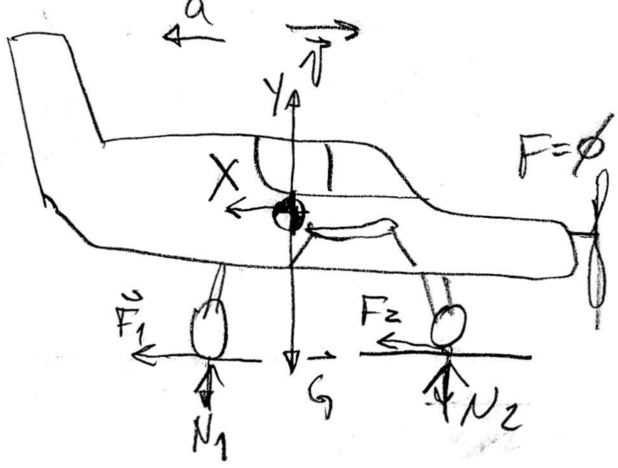
čelni veter

$$s_2 = \frac{2m}{\rho A}\,\frac{1}{c_x}\cdot\left[\ln\frac{v_1}{v_{s1}} - v_v\left(\frac{1}{v_{s1}}-\frac{1}{v_1}\right)\right]$$

$$s_2 = \frac{2m}{\rho A c_x}\,\ln\frac{v_1}{v_{s1}} - v_v\cdot t_2$$

III faza pristanka





1) predpostavke
$F=\emptyset$ vlečna sila
2) položaj je enak glede na tla
3) μ = konst

$\Sigma F_y = \emptyset: \; Y + (N_1 + N_2) - G = \emptyset$

$\Sigma F_x = \emptyset: \; -X - F_{tr_1} - F_{tr_2} = m \cdot a$

$F_{tr_1} - F_{tr_2} = \mu (N_1 + N_2) = (G - Y) \cdot \mu$

$$\frac{1}{2}\rho v^2 A \cdot C_x + \mu \left(m \cdot g - \frac{1}{2}\rho v^2 A C_y\right) = -m \cdot a = -m \cdot \frac{dv}{dt}\frac{ds}{ds}\Big|_{v_v = \emptyset} =$$

$$= -mv \frac{dv}{ds} \quad \Big| \frac{1}{m}$$

$$\mu \cdot g + \frac{\rho A}{2m}\left(C_x - \mu \cdot C_y\right) \cdot v^2 = -v \frac{dv}{ds} = a + bv^2$$

$a = \mu \cdot g$

$b = \frac{\rho A}{2m}\left(C_x - \mu \cdot C_y\right)$

$$\int_0^{S_3} ds = \int_{v_{s1}}^{\emptyset} \frac{v\,dv}{a + bv^2} = -\frac{1}{2b}\int \frac{dz}{z}$$

$z = a + bv^2$

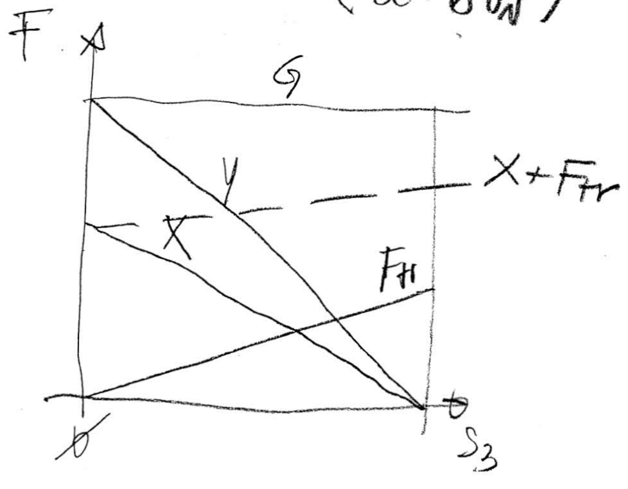
$dz = 2b\,dv \cdot v$

$v\,dv = \frac{dz}{2b}$

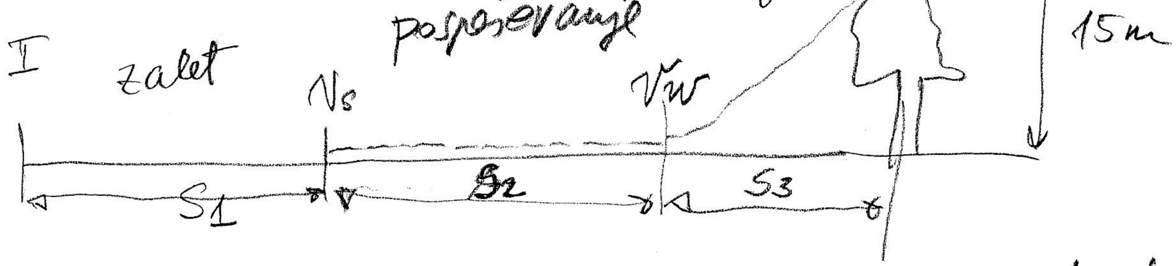
$$S_3 = \frac{1}{2b}\ln\left(\frac{a + bv_{s1}^2}{a}\right)$$

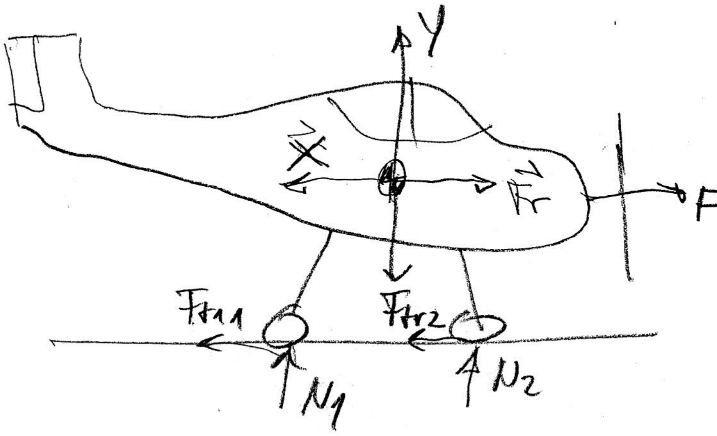
ocena za primer čelnega vetra

$$S_3 = \frac{1}{2b}\ln\left(\frac{a + bv_{s1}^2}{a + bv_N^2}\right)$$



Vzlet





predpostavke
- enak položaj letala
- μ = konst
- $F_r = F_0 - \sigma v^2$

koeficient $\sigma > 0$

$$F_x = 0: \quad F_{tr} = F_{tr1} + F_{tr2} = \mu \cdot (G - Y)$$

$$F_r - X - F_{tr} = m \cdot a$$

brez vetra

$$F_0 - \sigma \cdot v^2 - \frac{1}{2}\rho v^2 A C_x - \mu\left(mg - \frac{1}{2}\rho v^2 A C_y\right) = ma = m\frac{dv}{dt}\frac{ds}{ds} \quad \Big| \cdot \frac{1}{m}$$

$$\frac{F_0}{m} - \mu \cdot g - \left[\frac{\sigma}{m} + \frac{\rho A}{2m}\left(C_x - \mu \cdot C_y\right)\right] v^2 = \frac{v\,dv}{ds} = a - bv^2$$

$$a = \frac{F_0}{m} - \mu \cdot g$$

$$b = \frac{\sigma}{m} + \frac{\rho A}{2m}\left[C_x - \mu C_y\right]$$

$$\int_0^{s_1} ds = \int_0^{v_{s1}} \frac{v\,dv}{a - b v^2} = -\frac{1}{2b}\int \frac{dz}{z}$$

$$z = a - bv^2$$

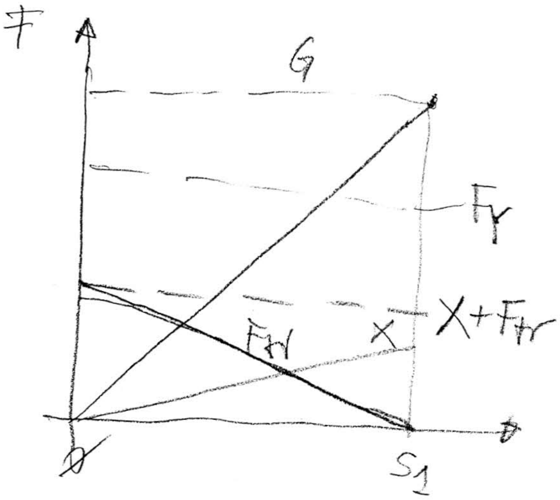
$$v\,dv = -\frac{1}{2b}\,dz$$

$$S_1 = \frac{1}{2b} \ln\left(\frac{a}{a - b v_{S1}^2}\right)$$

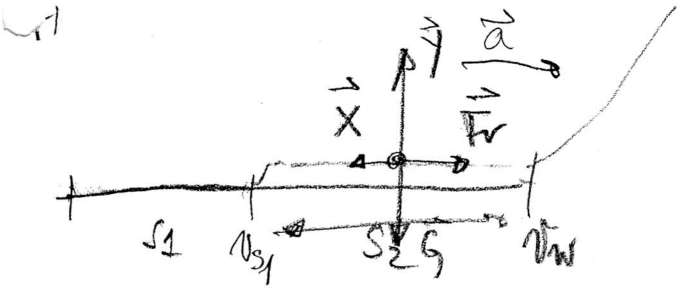
ocena za v_v – veter

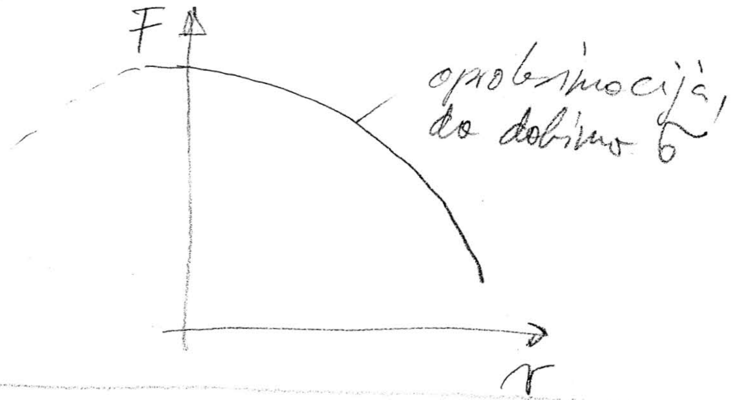
$$S_1 = \frac{1}{2b} \ln\left(\frac{a - b v_v^2}{a - b v_{S1}^2}\right)$$

klonec



Pospeševanje
II faza





$$Y = G$$

$$\underbrace{Fr - X}_{F(v)} = m \cdot a$$

$$\frac{1}{2} \rho v^2 C_y = m \cdot g$$

$$v^2 \cdot C_y = \text{konst}$$

$$a = \text{konst} = \bar{a} = \frac{1}{2}\left(\frac{a(v_w) + a(v_{S1})}{2}\right)$$

$$a = \frac{dv}{dt} = \text{konst}$$

$$v = v_0 + a \cdot t$$

$$s = \cancel{s_0} + v_0 \cdot t + \frac{a t^2}{2}$$

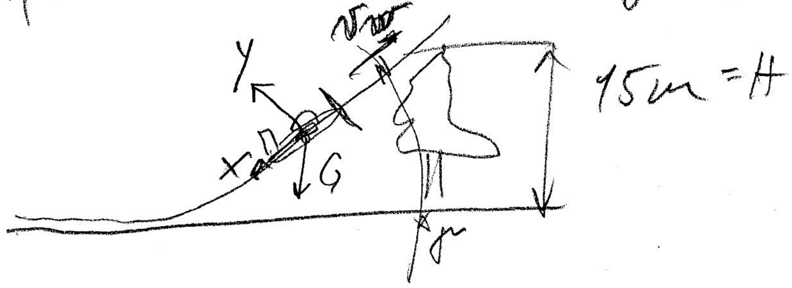
$$s_2 = v_{S1} t + \frac{\bar{a} \cdot t^2}{2}$$

$$t = \frac{v_w - v_{S1}}{a}$$

veter v_v

$$S_2 = \left(v_{s1}\cdot t + \frac{a t^2}{2}\right) - v_v\cdot t$$

III faza – hitrost vzpenjanja



$$Y - G\cdot\cos\gamma = 0$$

$$F - X - G\cdot\sin\gamma = 0 \quad \Big|\cdot v$$

$$F_r\cdot v_w - X\cdot v_w = m\cdot g\cdot v_w\cdot\sin\gamma$$

$$P_r - P_p = m\cdot g\cdot w$$

$$w = \frac{P_r - P_p}{G}$$

$$t_3 = \frac{H}{w}$$

$$S_3 = v_w\cdot\cos\gamma\cdot t_3 \approx v_w\cdot t_3$$

veter v_v

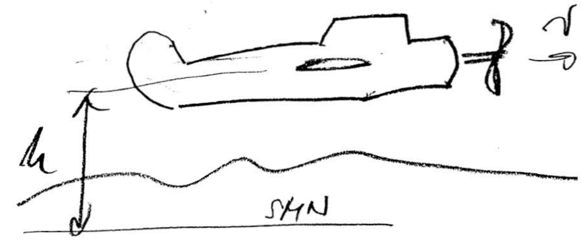
$$S_3 = \underline{(v_w - v_v)}\cdot t_3$$

Energijska metoda – za določanje sposobnosti letala

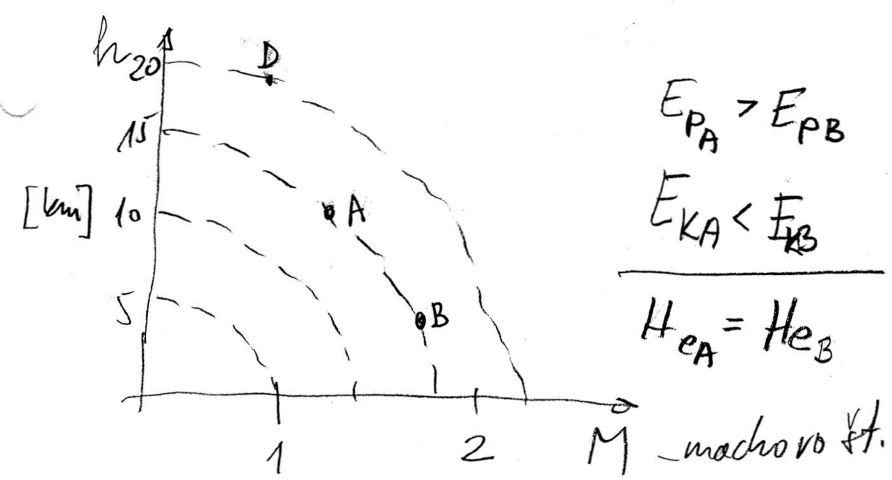
$$E = E_p + E_k$$

$$E = mgh + \frac{1}{2} m v^2$$

$$H_e = \frac{E}{G} = h + \frac{v^2}{2g}$$



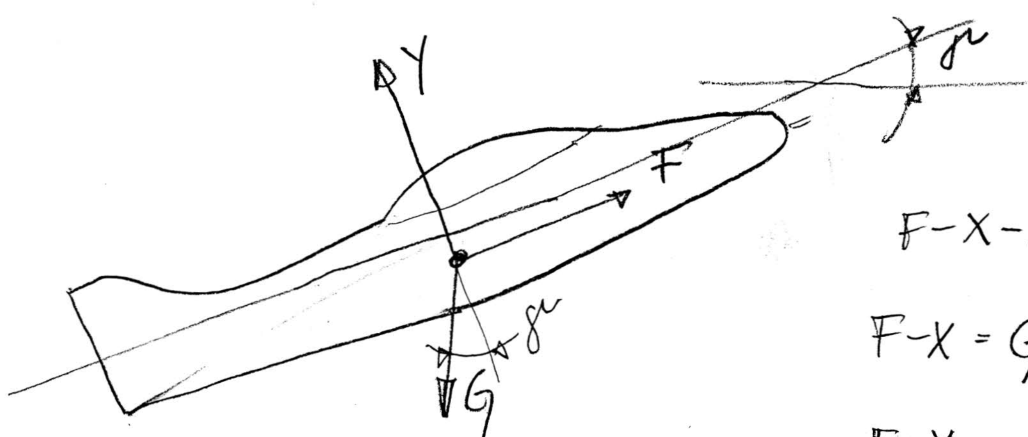
$H_e = h + \frac{v^2}{2g}$ – energijska višina = specifična energija



$$E_{pA} > E_{pB}$$

$$E_{kA} < E_{kB}$$

$$H_{eA} = H_{eB}$$



$$F - X - G \cdot \sin\gamma = m \cdot a$$

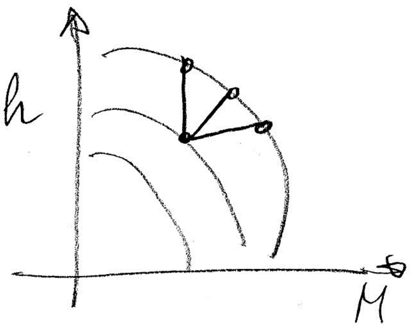
$$F - X = G \cdot \sin\gamma + m \cdot a \quad \Big| \frac{v}{G}$$

$$\frac{F-X}{G} \cdot v = \frac{P_r - P_p}{G} =$$

$$\underline{P_P} = v \cdot \sin\gamma + \frac{v}{g} \cdot \frac{dv}{dt} = P_s$$ – specifična rezerva moči

$$V = v \cdot \sin\gamma = \frac{dh}{dt}$$

$$P_s = \frac{dh}{dt} + \frac{v}{g}\cdot\frac{dv}{dt} = w + \frac{v}{g}\cdot\frac{dv}{dt}$$

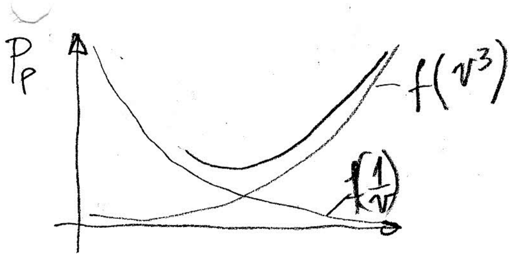


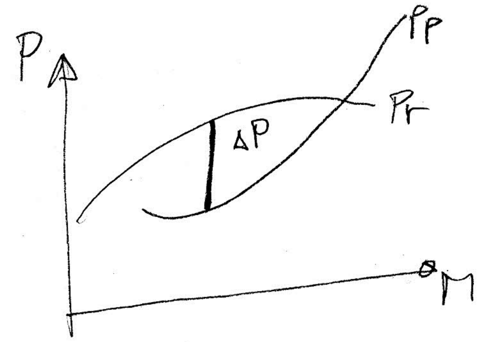
$$H_e = h + \frac{1}{2}\frac{v^2}{g}$$ – energijska višina

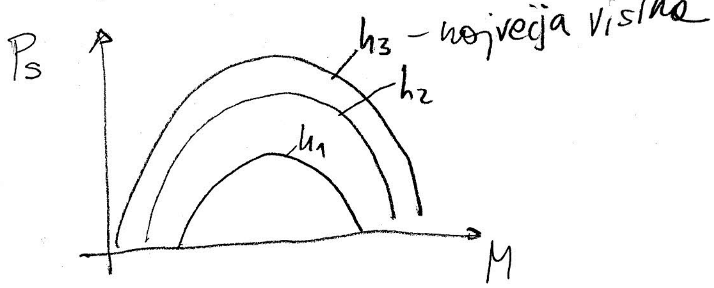
$$\frac{dH_e}{dt} = \frac{dh}{dt} + \frac{v}{g}\frac{dv}{dt}$$

$$P_s = \frac{dH_e}{dt}$$ sprememba energijske višine v enoti časa je enako specifični rezervi moči

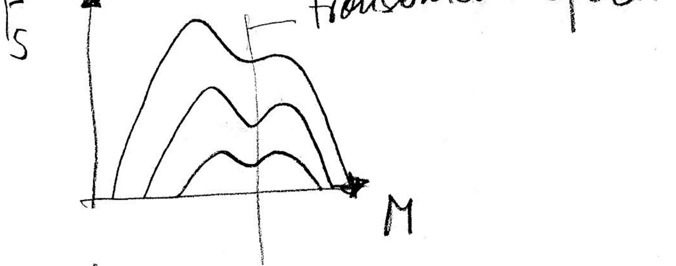
za h-konst

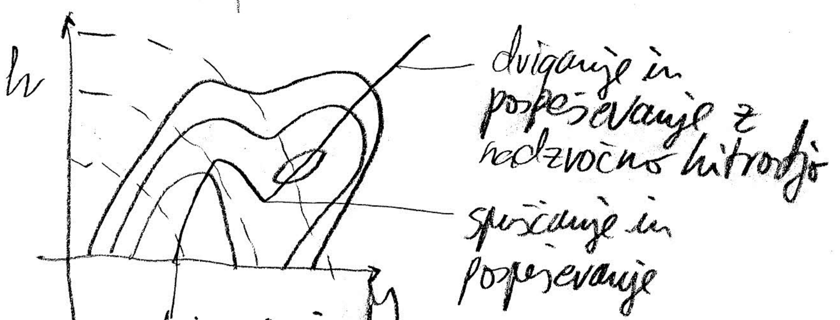






Nadzvočne hitrosti



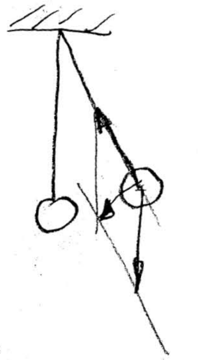


ABICNOS

ordinatni sistem vezan na letalo

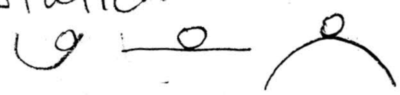
valjanje – roll
sukanje – Yaw
vrtenje okrog prečne osi – pich (prevračanje)

Ravnotežje $\Sigma F = \phi$
$\Sigma M = \phi$

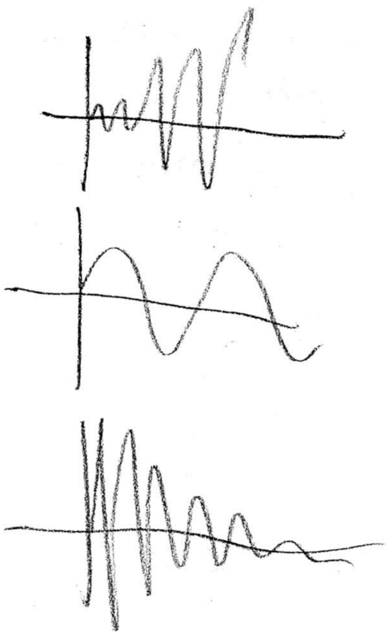


sile in momenti, ~~vračajo~~ ki težijo k vračanju sistema k prvotnem stanju

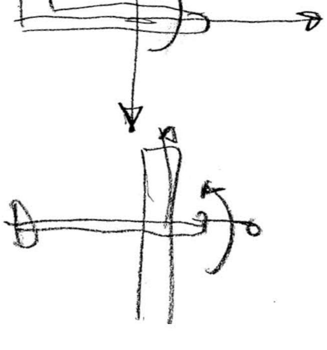
Statična stabilnost



Dinamična stabilnost



Statična stabilnost je potrebni pogoj za dinamično stabilnost



translacija po x in y – vzdolžno gibanje

prečno gibanje

odhod 2-3 maj pred FS
3 maj - Pilatus
4 maj - Emmen
5 maj - sobota

sukanje - smerna stabilnost

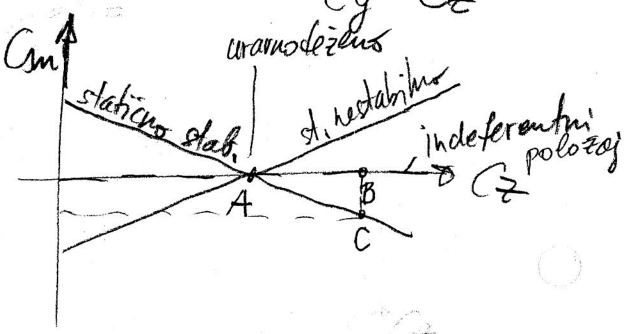
Vzdolžna statična stabilnost letala

Ravnotežje u, w, θ - okrog prečne osi

$\Sigma F_x = 0$

$\Sigma F_z = 0$

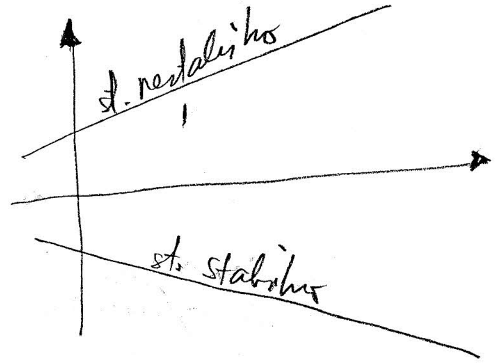
$\Sigma M_y = 0$; $C_m = 0$

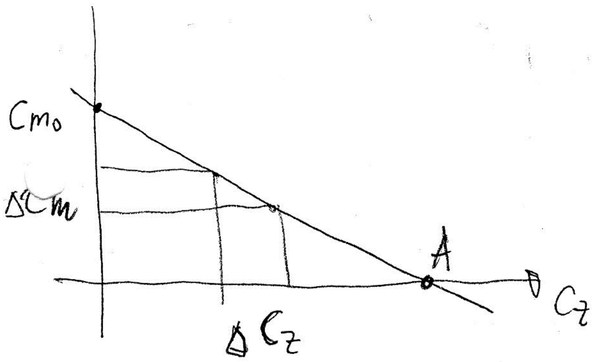


A - ravnotežje

$M > 0$ dviga nos
$M < 0$ spušča nos

$C_y \Rightarrow C_z = a \cdot (\alpha_g - \alpha_n)$





Ravnotežje, stabilno

$C_{m_A} = 0$ $\qquad \dfrac{dC_m}{dC_z} < 0$

$C_{m_0} > 0$ $\qquad \dfrac{dC_m}{dC_z} < 0$

konfiguracija
- samo krilo

ni ravnotežja (ne more leteti)

$c_{m_0} < \phi$

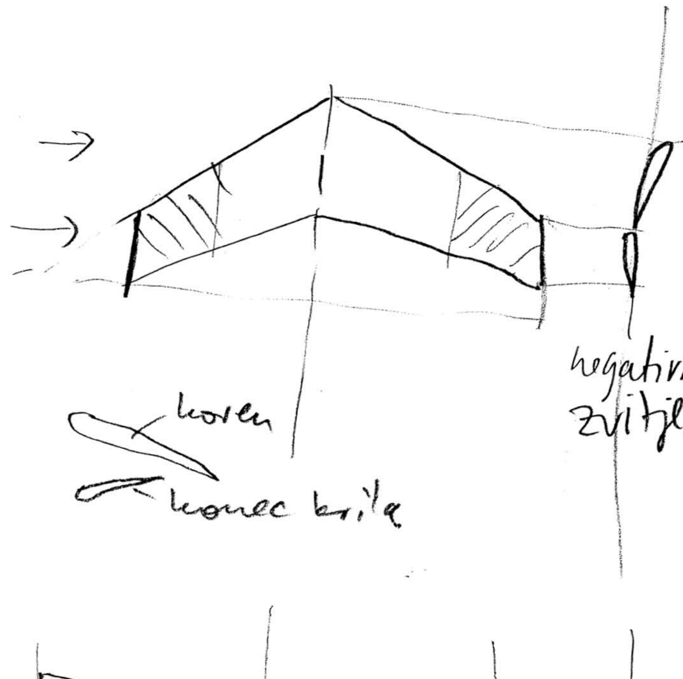
ravnotežje samo pri $c_z = \phi$

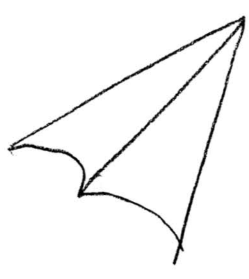
$c_{m_0} = \phi$

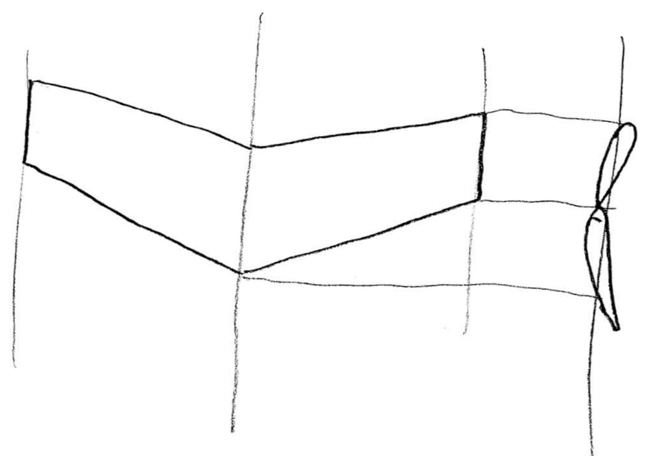
lahko dosežemo ravnotežje

$c_{m_0} > \phi$

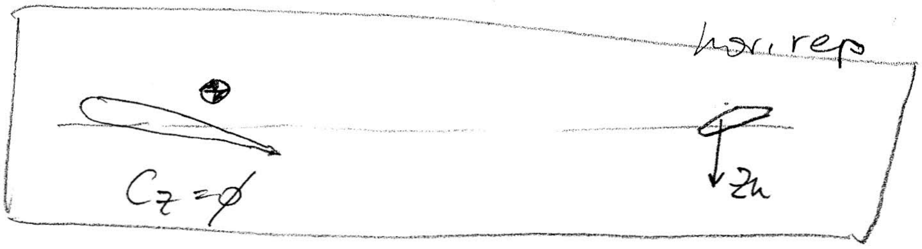
b) krilo s puščico
- $-$ naprej upognjena
- $+$ nazaj upognjena



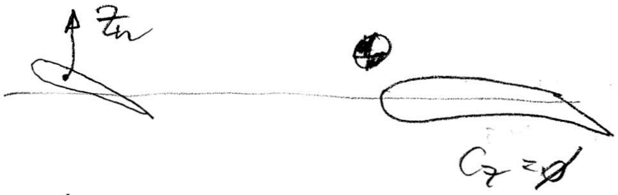




- krilo + hor. površine
- klasična konfiguracija

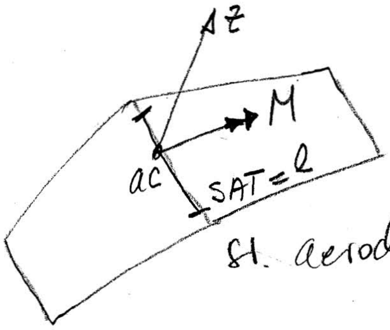


- račman



predpostavke — ~~vzgon~~ prispevek vzgona letala samo krilo

- Moment krila okrog momega središča MS

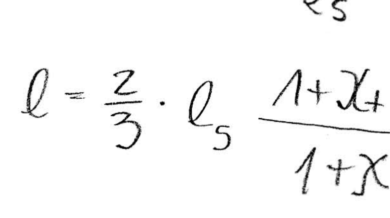


st. aerodinamična tetiva

geometrijska tetiva
$$l_g = \frac{A}{b}$$

$$M = \frac{1}{2}\rho v^2 A \cdot C_m \cdot l_{SAT} =$$
$$= \frac{1}{2}\rho v^2 \int_{-b/2}^{b/2} l \cdot dy \cdot C_m \cdot l$$
$$= l_{SAT} = l = \frac{1}{A} \cdot \int_{-b/2}^{b/2} l^2 \cdot dy$$

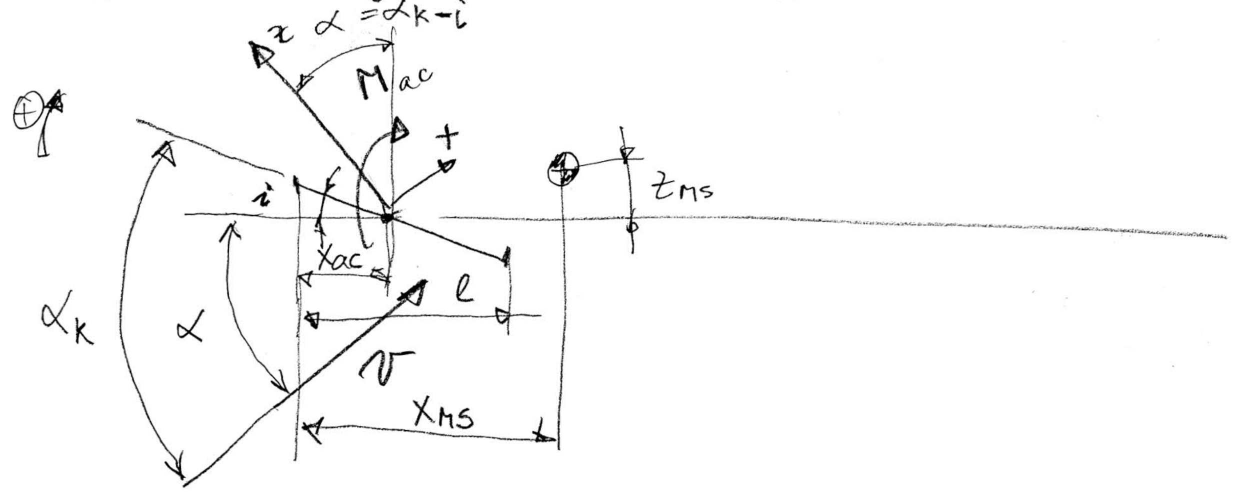
trapezno krilo



zoženje $\lambda = \frac{l_k}{l_s}$

$$l = \frac{2}{3} \cdot l_s \frac{1+\lambda+\lambda^2}{1+\lambda}$$

i - konstrukcijski ali nastavni kot krila



$$\sum M_{KMS} = Z\cdot\cos(\alpha_K - i)(X_{MS} - X_{ac}) + Z\cdot\sin(\alpha_K - i)\cdot Z_{MS} -$$

$$- X\cdot\cos(\alpha_K - i)\cdot Z_{MS} + X\cdot\sin(\alpha_K - i)\cdot(X_{MS} - X_{ac}) + M_{ac} =$$

$\alpha_K - i$ - majhen kot

$\cos(\alpha_K - i) \approx 1$

$\sin(\alpha_K - i) \approx \alpha_K - i$

$Z \gg X$; $d(X_{MS} - X_{ac})$

$$\sum M_{KMS} = Z\cdot d + (Z\cdot(\alpha_K - i) - X)\, Z_{MS} + M_{ac}$$

Z_{MS} - majhen

$$\sum M_{KMS} = Z\cdot d + M_{ac} \quad \Big| : \tfrac{1}{2}\rho v^2 A\cdot l$$

$$C_{mK} = C_Z \frac{d}{l} + C_{mac} = \boxed{C_Z\cdot(h - h_{ac}) + C_{mac}}$$

$$C_{mK} = C_Z\cdot\left(\frac{X_{MS}}{l} - \frac{X_{ac}}{l}\right) + C_{mac}$$

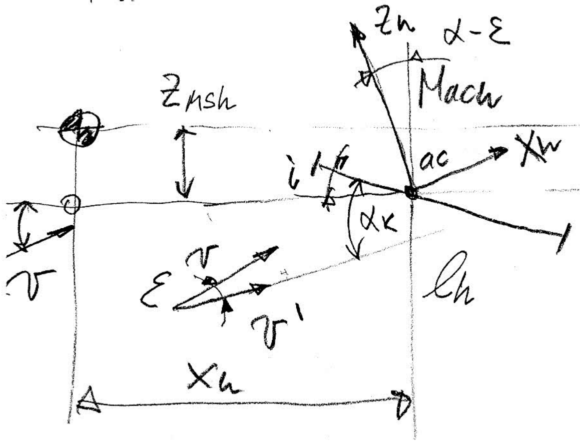
$$h = \frac{X_{MS}}{l}$$

$$h_{ac} = \frac{X_{ac}}{l}$$

Moment H-repa okrog MS

indeks h

ε – kot odklona toka zaradi vzgona krila



$$\Sigma M_{hMS} = -Z_h \cdot \cos(\alpha-\varepsilon) \cdot X_h + Z_h \cdot \sin(\alpha-\varepsilon) \cdot Z_{MSh}$$
$$- X_h \cdot \cos(\alpha-\varepsilon) \cdot Z_{MSh} - X_h \cdot \sin(\alpha-\varepsilon) \cdot X_h + \cancel{M_{ach}}$$

$$\cos(\alpha-\varepsilon) \approx 1$$
$$\sin(\alpha-\varepsilon) \approx \alpha \cdot \varepsilon$$
$$Z > Z_h \gg X_h$$

$$\Sigma M_{hMS} = -Z_h \cdot X_h = -\tfrac{1}{2}\rho v'^2 \cdot A_h \cdot C_{zh} \cdot X_h \quad \Big| : \tfrac{1}{2}\rho v^2 A \cdot l$$

$$C_{mh} = -\left(\frac{v'}{v}\right)^2 \cdot \frac{A_h \cdot X_h}{A \cdot l} \cdot C_{zh}$$ relativni volumen hor. repa

$$\eta = \frac{1/2\,\rho v'^2}{1/2\,\rho v^2} = \frac{v'^2}{v^2}$$

$$\bar{V}_h = \frac{A_h \cdot X_h}{A \cdot l}$$

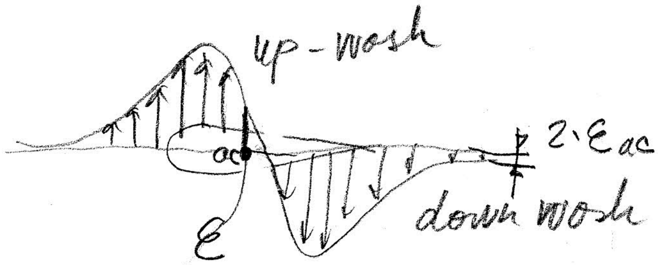
$$\boxed{C_{mh} = -\eta \bar{V}_h C_{zh}}$$

simetričen profil

$$C_{zh} = a_h \cdot \alpha_h$$

$$\alpha_h = \alpha - \varepsilon + i_h$$

$$\alpha_h = \alpha_k - i - \varepsilon + i_h$$



$$\varepsilon = 2 \cdot \frac{C_z^{krilo}}{\pi \lambda_{krilo}}$$

$, + \frac{d\varepsilon}{d\alpha} \cdot \alpha_{ka}$ – aerodinamični vpadni kot krila

izborjeva vrsta

$\alpha_{ka} = \alpha_k - \alpha_{n=N}$

$$\frac{d\varepsilon}{d\alpha} = 2 \cdot \frac{a}{\pi \cdot \lambda}$$

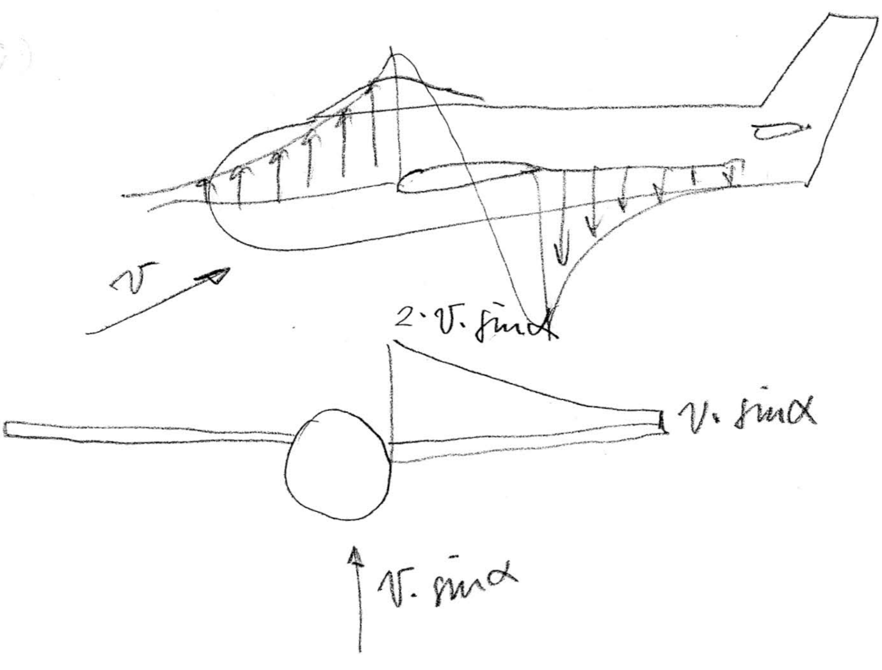
$$C_{mh} = -\eta \cdot \overline{V}_h \cdot a_h \cdot \left(\alpha_k - i - \varepsilon_0 - \frac{d\varepsilon}{d\alpha} \cdot \alpha_{ka} + i_k\right)$$

$\alpha_k \rightarrow \alpha_{ka} + \alpha_{n=n}$

$$C_{mh} = -\eta \overline{V}_h \cdot a_h \cdot \left(1 - \frac{d\varepsilon}{d\alpha}\right) \cdot \alpha_{ka} - \eta \overline{V}_h \cdot a_h \cdot \left(\alpha_h - i - \varepsilon_0 + i_k\right)$$

$\frac{a}{a}$

$$\boxed{C_{mh} = \underbrace{-\eta \overline{V}_h \frac{a_h}{a} \cdot \left(1 - \frac{d\varepsilon}{d\alpha}\right) \cdot C_z}_{f(C_z)} + \underbrace{\eta \cdot \overline{V}_h \cdot a_h \left(i + \varepsilon_0 - \alpha_h - i_h\right)}_{= konst}}$$



$$C_{mTR} = C_{MTRO} + \left(\frac{dC_l}{dC_z}\right.$$

$C_{mac} + C_z \cdot \frac{d}{e} - \eta \cdot \bar{V}_h \cdot C_{zh} + C_{mtro} + \left(\frac{dC_m}{dC_z}\right)_{tr}$

$C_m = C_{mac} + C_z \cdot \frac{d}{e} - \eta \cdot \bar{V}_h \cdot \frac{a_h}{a}\left(1 - \frac{d\varepsilon}{d\alpha}\right) C_z + \eta \bar{V}_h \cdot a_h$

$C_{mtro} + \left(\frac{dC_m}{dC_z}\right)_{tr} C_z$

$$\boxed{C_m = C_{m0} + \left(\frac{dC_m}{dC_z}\right) \cdot C_z}$$ celotno letalo

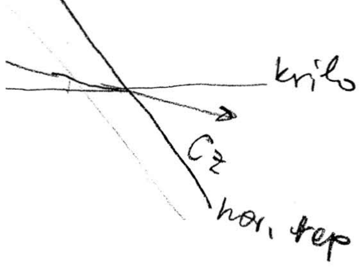
$\cancel{C_{m0} = \frac{dC_m}{dC_z} \cdot C_z}$

$\frac{dC_m}{dC_z} = \frac{d}{e} - \eta \bar{V}_h \cdot \frac{a_h}{a}\left(1 - \frac{d\varepsilon}{d\alpha}\right)$

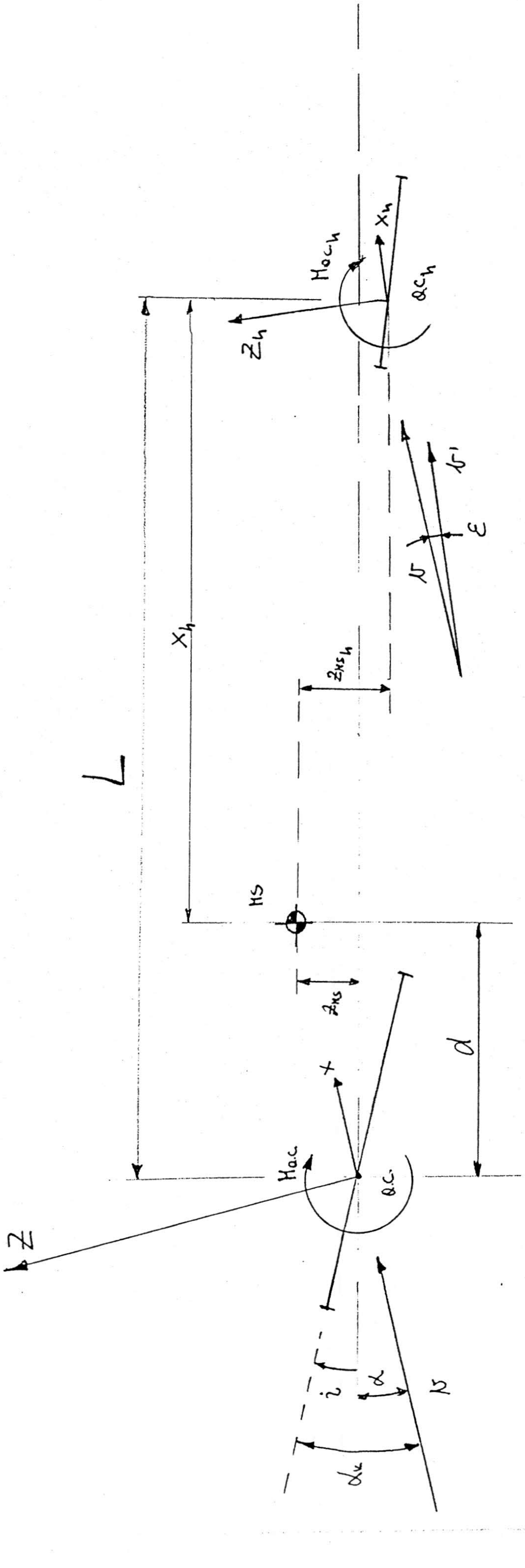
$C_{m0} = C_{mac} + C_{mtro} + \eta \bar{V}_h \cdot a_h \cdot (i + \varepsilon_0 - \alpha_i - i_h)$

$$\boxed{C_m = C_{m0} + \frac{dC_m}{dC_z} \cdot C_z = C_{mk} + C_{mh} + C_{mtr} = 0}$$

$\frac{dC_m}{dC_z} < 0$ za vzdolžno statično stabilno letalo



SK 6a



Vzdolžna stat. stabilnost letala

$$C_m = C_{mk} + C_{mtr} + C_{mh}$$

$$\frac{\partial C_m}{\partial C_z} = \frac{d}{l} + \left(\frac{\partial C_m}{\partial C_z}\right)_{tr} - \eta \bar{V}_h \frac{a_h}{a}\cdot\left(1-\frac{d\varepsilon}{d\alpha}\right)$$

letalo na meji stabilnosti

$$\frac{dC_m}{dC_z} = 0 \qquad \frac{d}{l} = h - h_{ac}$$

$h_{NT} = N_0$

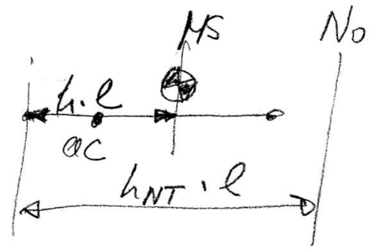
nevtralne točke

$$h_{NT} = N_0 = h_{ac} - \left(\frac{\partial C_m}{\partial C_z}\right)_{tr} + \eta \bar{V}_h \cdot \frac{a_h}{a}\left(1-\frac{d\varepsilon}{d\alpha}\right)$$

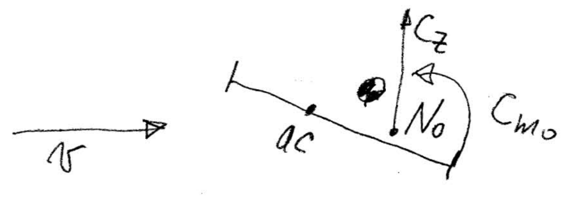
na meji stabilnosti

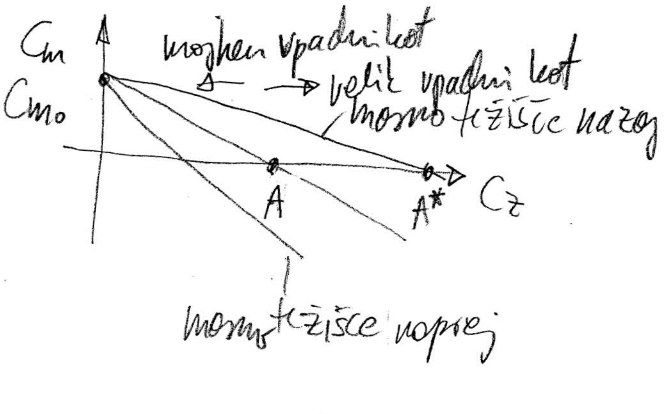
$$\frac{dC_m}{dC_z} = h - h_{NT}$$

$$C_m = C_{m0} + (h - h_{NT})\cdot C_z$$



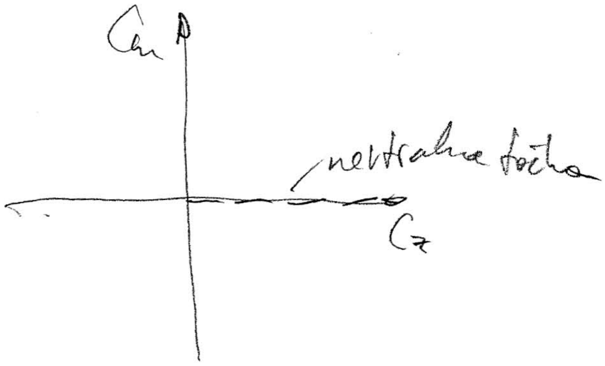
40-50% tetive – leži NT



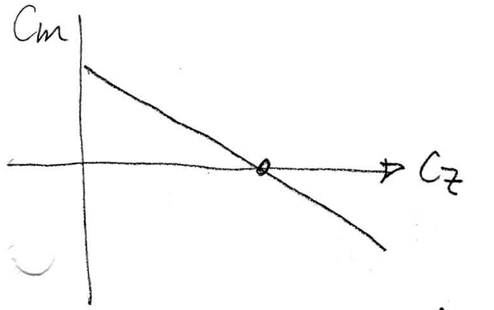


Počasneje letite, manj stabilno bo letalo

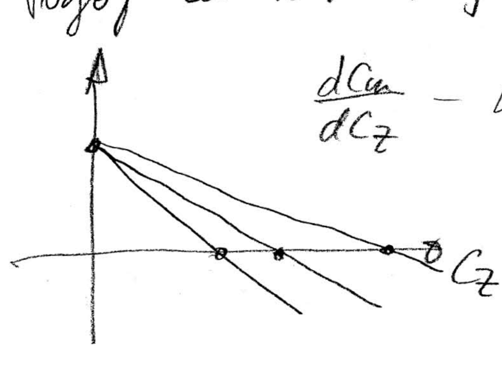
sprememba masnega središča vpliva na stabilnost pri zmoji, kar ni željeno



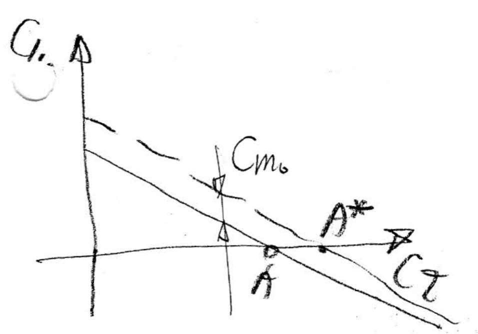
Krmarjenje letala okrog prečne osi.



Pogoj za ravnotežje je koef. momenta ∅

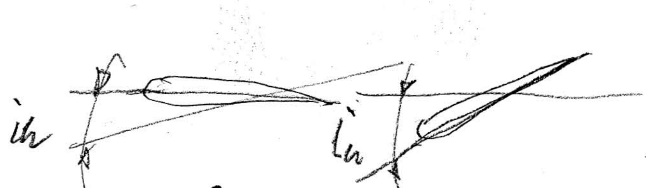


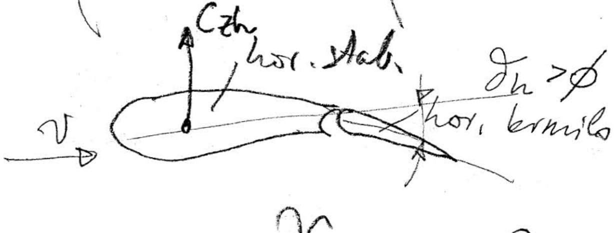
$\frac{dC_m}{dC_z}$ – ni dobro, hitreje letimo bolj stabilno je letalo, če premikamo nevtralno točko s premikanjem težišča



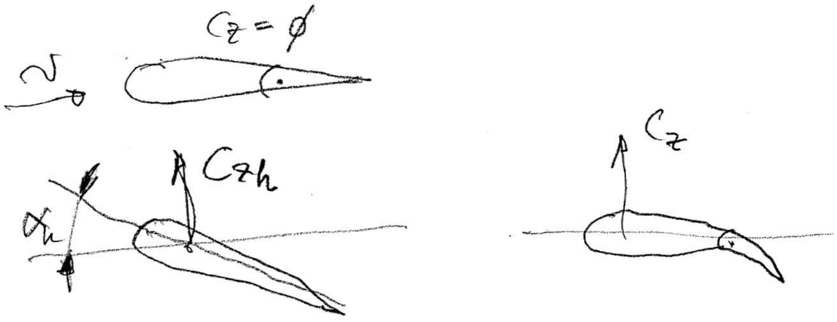
moment, ki ni odvisen od vzgona

$$C_{m0} = C_{mac} + C_{m0tr} + \underbrace{\eta \bar{V}_h a_h \left(\varepsilon_0 + i - \alpha_n - i_h\right)}_{\text{edina varianta, da spreminjamo konstr. vpadni kot hor. repa}}$$





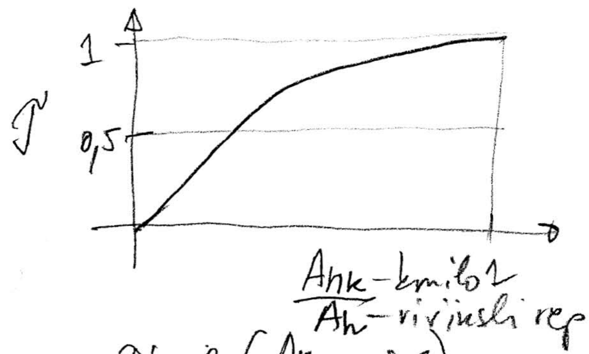
$$\Delta C_{zh} = \frac{\partial C_{zh}}{\partial \delta_h}\delta_h = \frac{\partial C_{zh}}{\partial \alpha_h} \cdot \overset{\tau}{\frac{\partial \alpha_h}{\partial \delta_h}} \cdot \delta_h \; ; \; \Delta C_{zh} = a_h \cdot \overset{\text{učinkovitost višinskega krmila}}{\tau} \cdot \delta_h$$



$\Delta C_z = a_h \cdot \alpha_h$

$\Delta C_z = a_h \cdot \tau \cdot \delta_h$

$\Delta \alpha_h = \tau \cdot \Delta \delta_h$



$\tau = f\left(\frac{A_{hk}}{A_h}, \delta_h\right)$

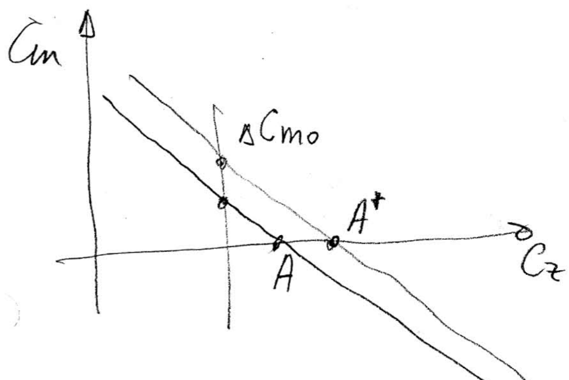
$\Delta C_{zh} = a_h \cdot \tau \cdot \delta_h$

$\Delta C_{mh} = -\eta \, \bar{V}_h \cdot a_h \cdot \tau \cdot \delta_h$

na nos je Θ

$C_{m0} = C_{mk} + C_{m0tr} + \eta \cdot \bar{V}_h \cdot a_h (\varepsilon_0 + i - \alpha_h - i_h$

$\uparrow \tau \cdot \delta_h$



spremeni se $\frac{\partial C_m}{\partial C_z} \cdot C_z$ in

odklon ni enak momenta oz. obratno

Potreben odklon krmila

$C_m = C_{mk} + C_{mtr} + C_{mh}$

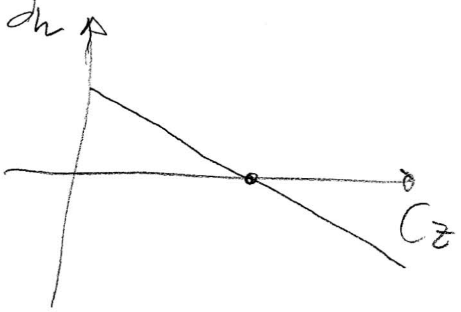
$C_m = C_{m0} + \frac{\partial C_m}{\partial C_z} \cdot C_z + \frac{\partial C_m}{\partial \delta_h} \cdot \delta_h = \phi$

$\Delta C_{mh} = -\eta \cdot \bar{V}_h \cdot a_h \cdot \tau \cdot \delta_h$

$\frac{\partial C_m}{\partial \delta_h} = -\eta \cdot \bar{V}_h \cdot a_h \cdot \tau$

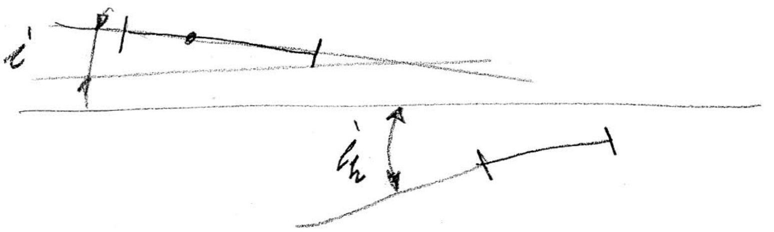
odklon

$$\delta_h = -\frac{\overset{>0}{C_{m0}} + \overset{<0}{\frac{\partial C_m}{\partial C_z}}\cdot C_z}{\underset{<0}{\frac{\partial C_m}{\partial \delta_h}}} \approx A - B\cdot C_z$$

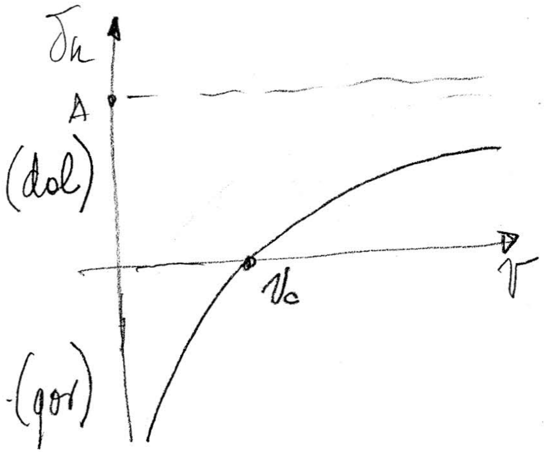


$$C_{m0} = C_{mac} + C_{m0_{tr}} + \eta\cdot \bar{V}_h \cdot a_h \cdot (\varepsilon_0 + i - \alpha_n - i_h)$$

$$\frac{\partial C_m}{\partial C_z} = h - h_{NT}$$



vzdolžni dieder



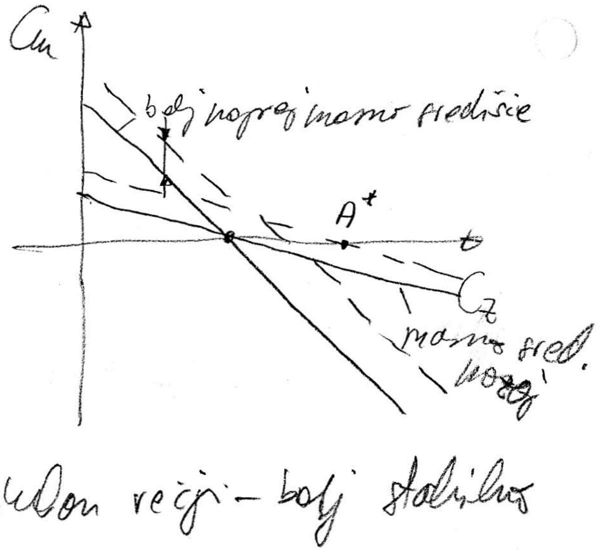
$$m\cdot g = \frac{1}{2}\rho v^2 A\cdot C_z$$

$$C_z = \frac{2mg}{\rho A}\cdot\frac{1}{v^2} = K\cdot\frac{1}{v^2}$$

$$\delta_h = A - B\cdot K\cdot\frac{1}{v^2}$$

$$\delta_h = -\frac{C_{m0} + \frac{\partial C_m}{\partial C_z}\cdot C_z}{\frac{\partial m}{\partial \delta_h}} =$$

$$\frac{\partial C_m}{\partial C_z} = h - h_{NT}$$

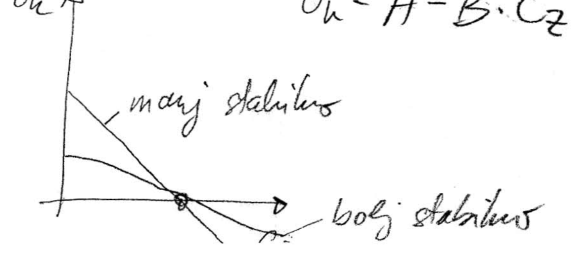


nazaj manj stran

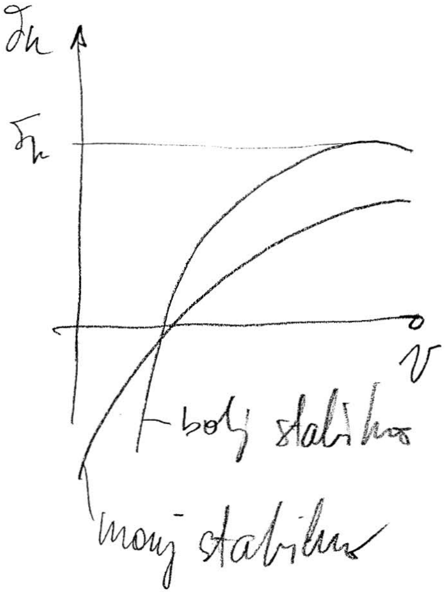
naprej bolj stran

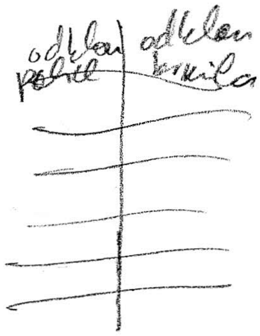
naklon večji – bolj stabilno

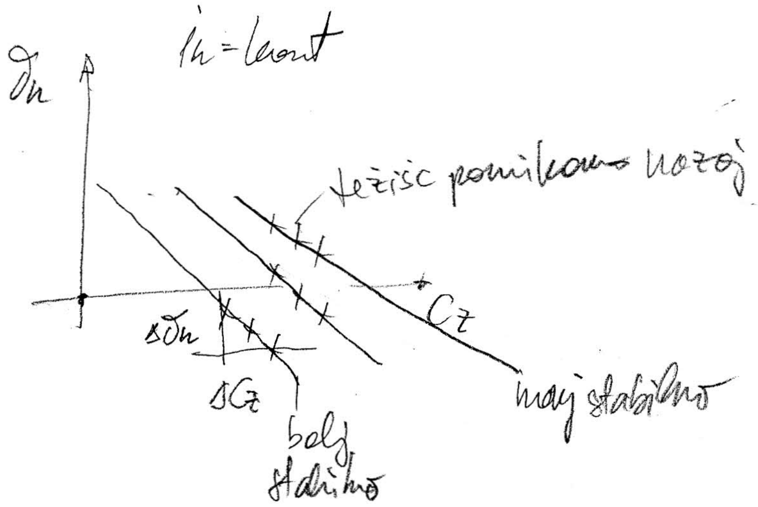
$$\delta_h = A - B\cdot C_z$$



Nastavni kot višinskega repa



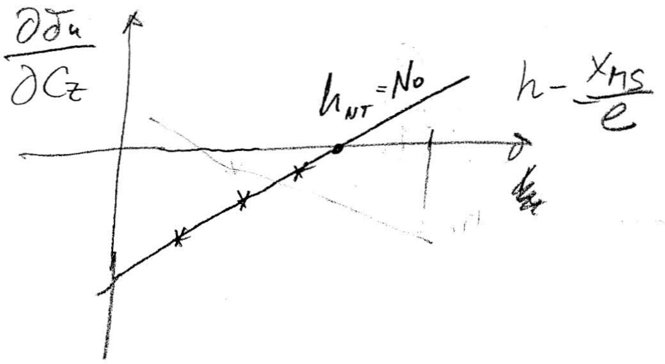




$\delta_h =$

$$\delta_h = -\frac{C_{m0} + \frac{\partial C_m}{\partial C_z} \cdot C_z}{\frac{\partial C_m}{\partial \delta_h}} = -\frac{\frac{\partial C_m}{\partial C_z}}{\frac{\partial C_m}{\partial \delta_h}}$$

$$\left.\frac{\partial \delta_h}{\partial C_z}\right|_{MS=NT} = \varnothing$$



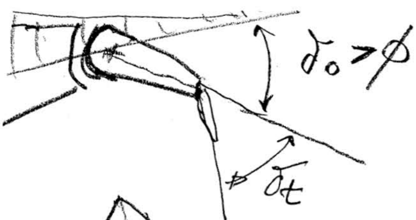
Skrajna sprednja lega

$V_{min} \div V_{max}$

Šarnirni moment – moment okrog tečaja višinskega krmila

— šarnirne os.

$\downarrow$ š ⊕ pozitivno smer šarnirnega momen



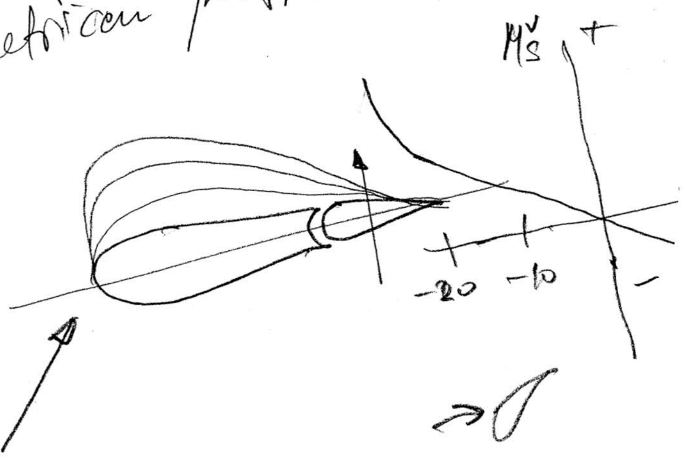
$$\frac{M_{\check{s}}}{\frac{1}{2}\rho v^2 \cdot \underbrace{A_K \cdot l_K}_{\text{krmila}}}$$

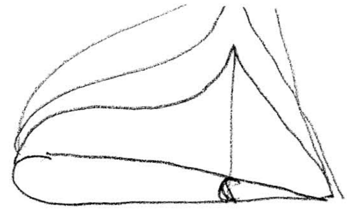
$) \alpha_n, \delta_n, \delta_t$

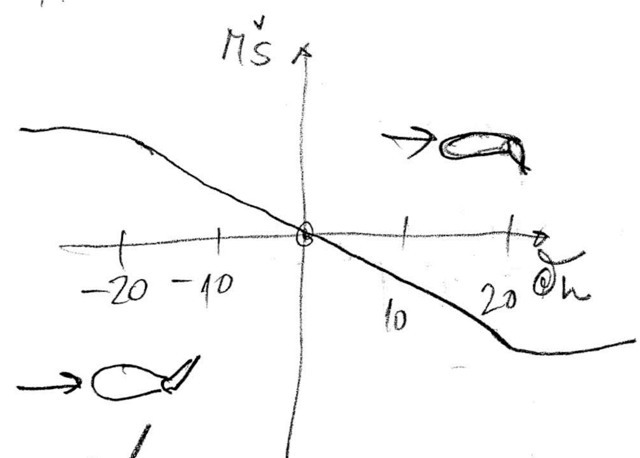
$$C_{m\check{s}} = C_{m\check{s}0} + \frac{\partial C_m}{\partial \alpha} \cdot \alpha_n + \frac{\partial C_m}{\partial \delta_n} \delta_n + \frac{\partial C_{m\check{s}}}{\partial \delta_t} \cdot \delta_t$$

$$C_{m\check{s}} = b_0 + b_1 \cdot \alpha_n + b_2 \cdot \delta_n + b_3 \cdot \delta_t$$

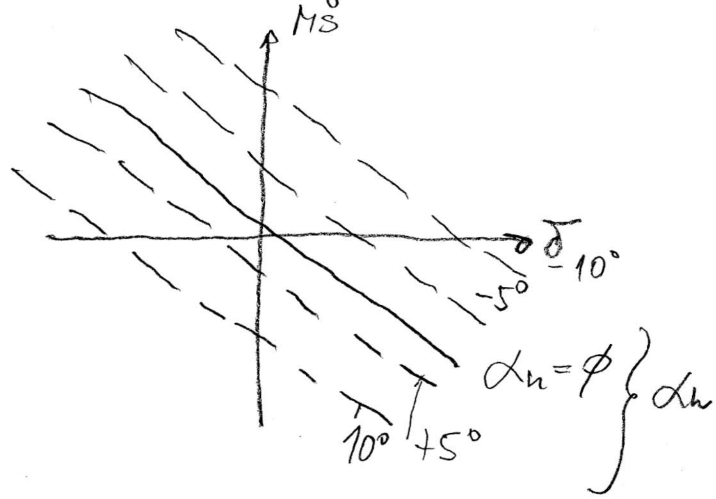
$b_0 = \emptyset$ za simetričen profil







Krivulje šarnirnega momenta



Vzdolžna statična stabilnost pri spuščeni palici

$C_{M\check{S}} = 0$

$b_0 = 0$

$\delta_t = 0$ trimer neodklonjen

$C_{m\check{S}} = b_1 \cdot \alpha_h + b_2 \cdot \delta_h = 0$

$\delta_{h\,leb} = -\frac{b_1}{b_2} \cdot \alpha_h$

lebdenje višinskega krmila

$C_{zh} = a \cdot \alpha_h + a \cdot \tau \cdot \delta_h$

$a \cdot \alpha_h + a \cdot \tau \left(-\frac{b_1}{b_2}\right) \alpha_h$ za lebdenje krmila

$C_{zh} = a \cdot \underbrace{\left(1 - \frac{b_1}{b_2} \cdot \tau\right)}_{} \cdot \alpha_h$

F- faktor spuščenega krmila

Spuščeno krmilo

$$C_{zh} = a_h^* \cdot \alpha_h$$

$$a_h^* \cdot a_h \cdot F$$

$$C_{mh} = -\eta \cdot \bar{V}_h \cdot C_{zh}$$

lebdenje krmila

$$C_{mh} = -\eta \cdot \bar{V}_h \cdot a_h \cdot F \alpha_h$$

Letalo

$$C_m = C_{mw} + C_{m_{tr}} + C_{mh}$$

$$= C_{m0} + \frac{\partial C_m}{\partial C_z} \cdot C_z$$

lebdenje $\quad C_m = C_{m0}' + \frac{\partial C_m'}{\partial C_z} \cdot C_z$

$$C_{m0}' = C_{ac} + C_{m0tr} + \eta \cdot \bar{V}_h \cdot a_h \cdot F \left(\varepsilon_0 + i - i_w - \alpha_h\right)$$

dodano

$$\frac{\partial C_m'}{\partial C_z} = \frac{d}{l} + \left(\frac{\partial C_m}{\partial C_z}\right)_{tr} - \eta \bar{V}_h \cdot \frac{a_h}{a} F \left(1 - \frac{\partial \varepsilon}{\partial \alpha}\right)$$

$$\frac{\partial C_m'}{\partial C_z} = 0 = h_{NT}' - h_{ac} + \left(\frac{\partial C_m}{\partial C_z}\right)_{tr} - \eta \bar{V} \frac{a_h}{a} F \cdot \left(1 - \frac{\partial \varepsilon}{\partial \alpha}\right)$$

nevtralna točka
pri spuščeni palici

$$h_{NT}' = h_{ac} - \left(\frac{\partial C_m}{\partial C_z}\right)_{tr} + \eta \bar{V}_h \cdot \frac{a_h}{a} \cdot F \left(1 - \frac{d\varepsilon}{d\alpha}\right)$$

$$\frac{\partial C_m'}{\partial C_z} = h - h_{NT}' =$$

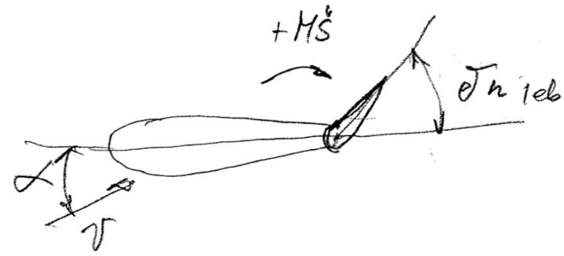
$$C_m = C_{m0}' + (h - h_{NT}') \cdot C_z$$

$$C_m = C_{m0}' + (h - h_{NT}')\cdot C_z$$

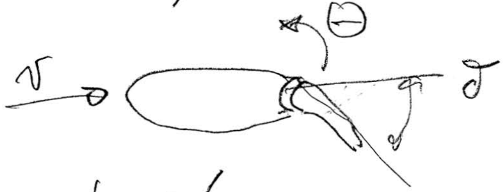
$$F = 1 - \frac{b_1}{b_2}\cdot\tau$$

$$b_1 = \frac{\partial C_m}{\partial \alpha_h}$$

$$b_2 = \frac{\partial C_m}{\partial \delta_h}$$



$b_1 < 0$



$b_2 < 0$

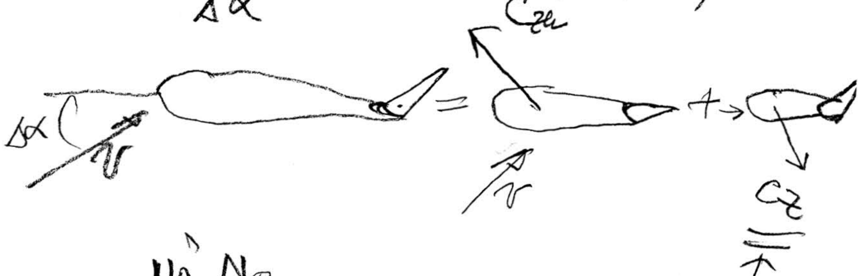
zahteva – redno bolj vlečemo palico

$$F = 1 - \frac{b_1}{b_2}\tau < 1$$

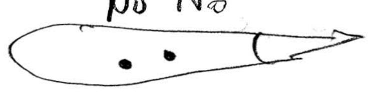
F – zmanjšuje vzdolžno statično stabilnost letala

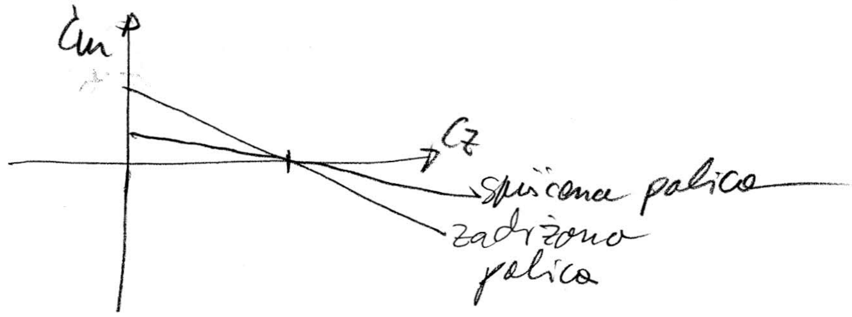
1 $\Delta\alpha$

vrača letalo v prvotni položaj

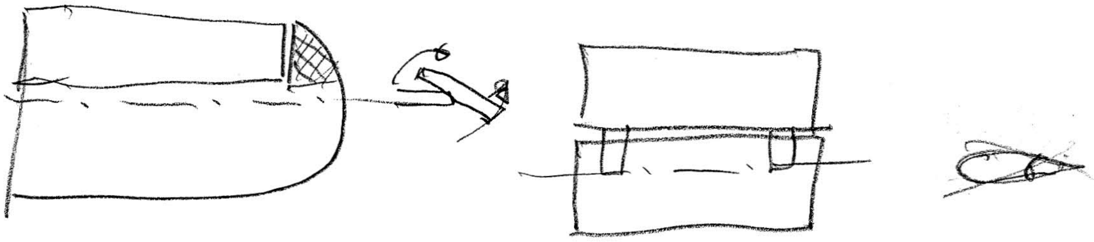


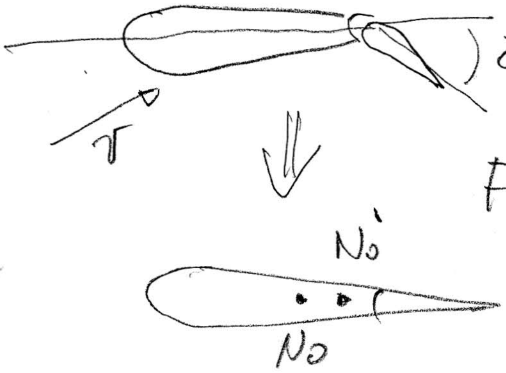
zato se zmanjša stabilno





aerodinamična kompenzacija





δ_h eb – odklon proti toku

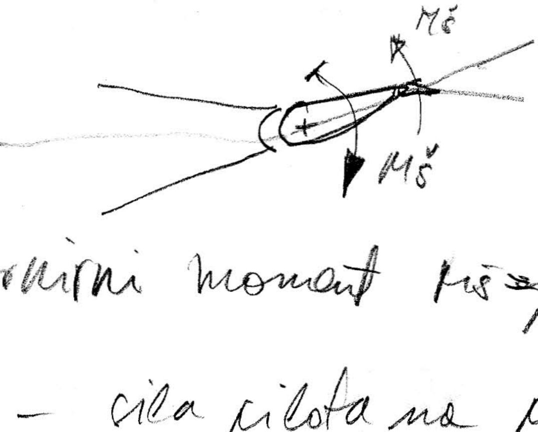
$F > \phi$

Povraten krmilni sistem

h_{NT} – ~~mali~~ ~~se~~ dimenz. na spuščeno palico

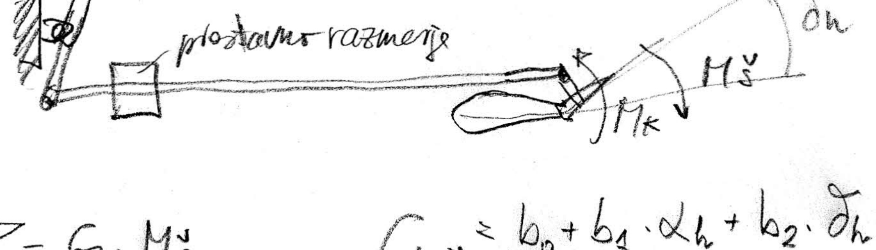
Nepovratni krmilni sistem

h_{NT}



aerodinamični šarnirni moment $M_š \neq \phi$

KRMILNE SILE – sila pilota na palico



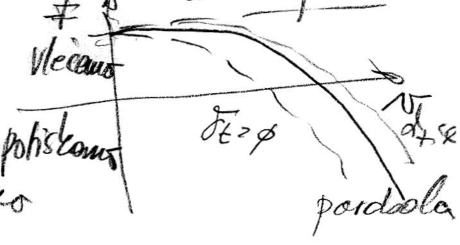
navzdol $\delta_h > \phi$
navzgor $\delta_h < \phi$

$P = G \cdot M_š$

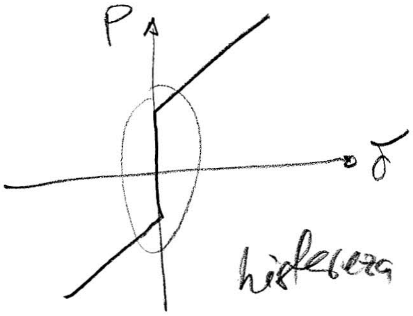
prestavno razmerje

$C_{mš} = b_0 + b_1 \cdot \alpha_h + b_2 \cdot \delta_h + b_3 \cdot \delta_t$

$M_š = \frac{1}{2} \rho v^2 A_k \cdot l_k \cdot C_{mš}$



s trimerjem lahko odklanjamo krmila

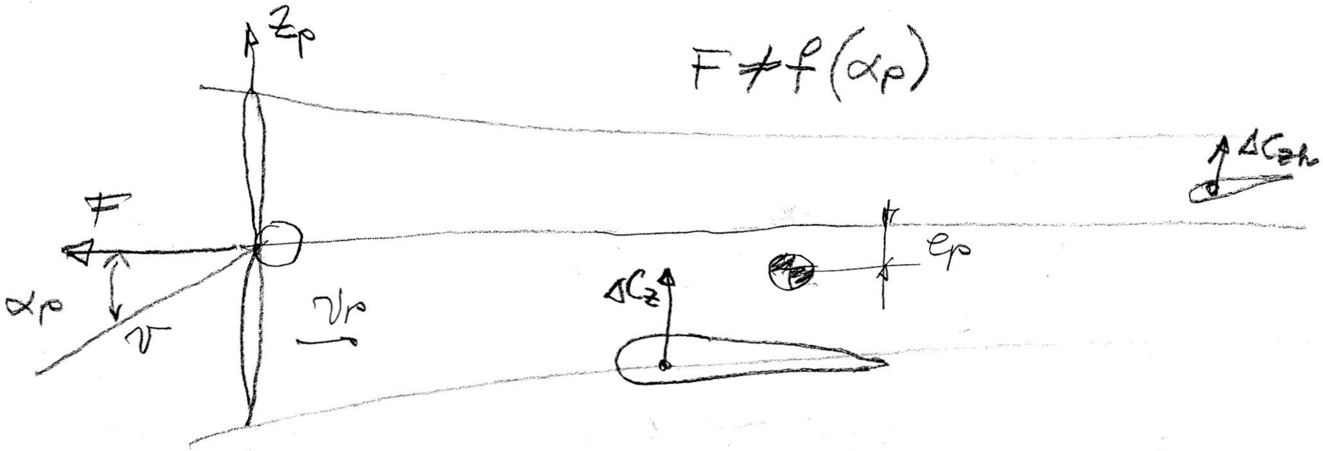


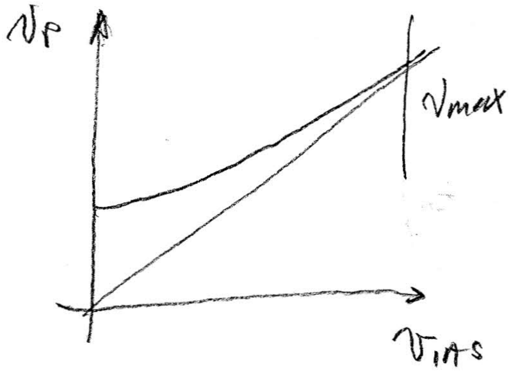
histereza zaradi trenja

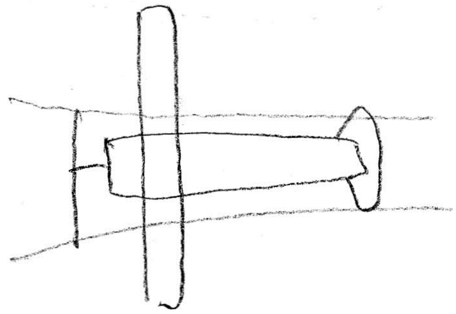
Vpliv pogona:

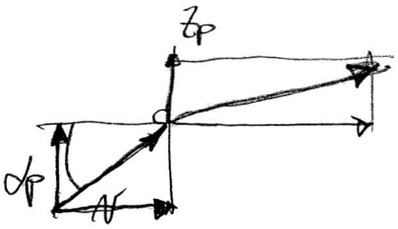
propelerska letala

$F \neq f(\alpha_p)$







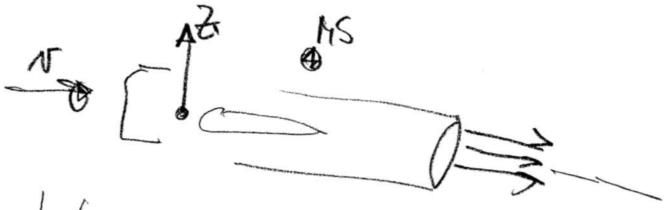


$z_p = f(\alpha_p)$

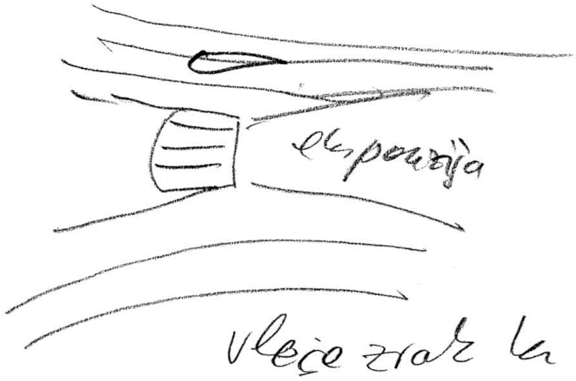
prop. destabilizira pred MS

prop za masnim središčem stabilizira letalo

Reakcijski pogon

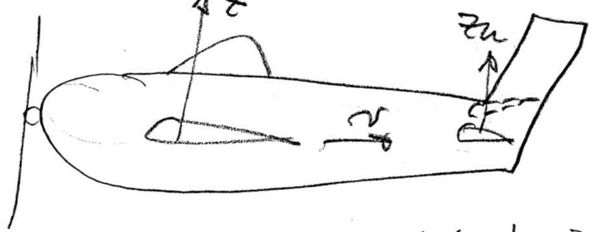


tok ne vpliva na povečanje vzgona krila



vleče zrak k izpuhu

Elastična struktura



rep odkloni ne vzgon
upadni kot VR se zmanjša

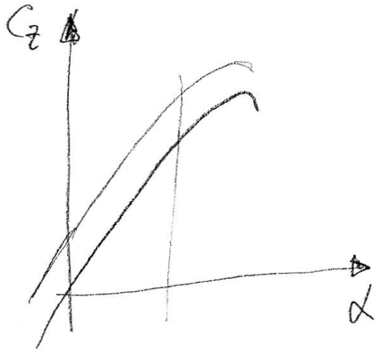
$$\Delta\alpha = k \cdot z_h$$

$$C_{zh} = a_h \cdot \left(\alpha - \varepsilon_0 + i_h - k \cdot z_h\right)$$

$$Z_h = \frac{1}{2}\rho v^2 A_h \cdot C_{zh}$$

$$C_{zh} = \frac{a_h}{1 + \frac{1}{2}\rho v^2 A_h \cdot k} \cdot \left(\alpha - \varepsilon_0 + i_h\right)$$

zmanjšuje gradient vzgona in statično stabilnost

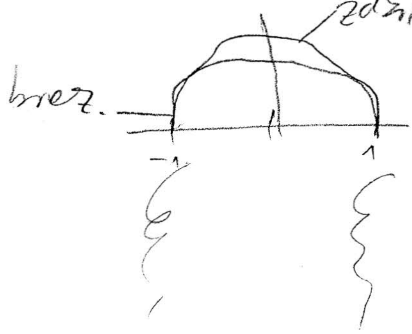


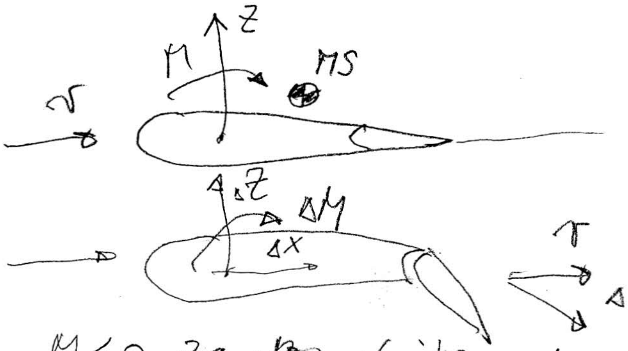
$$C_{m_x} = \underline{C_{mac}} + \frac{d}{l}\cdot \underline{C_z}$$

$$\frac{dC_{m_x}}{\partial C_z} = \phi + \frac{d}{l}$$ enako kot brez zakrilc

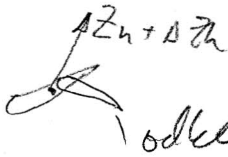
nova ravnotežna lega

$\varepsilon \to$ Hrep





M<0 za poz. vzdolžnost



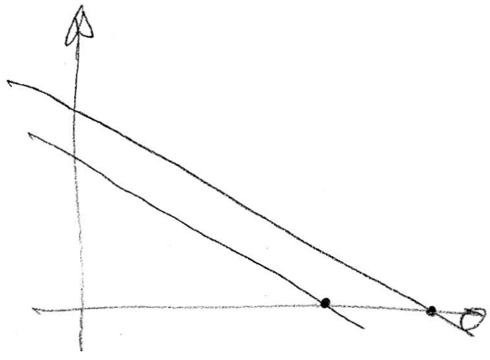
odklon zakrilca navzdol

M na nos

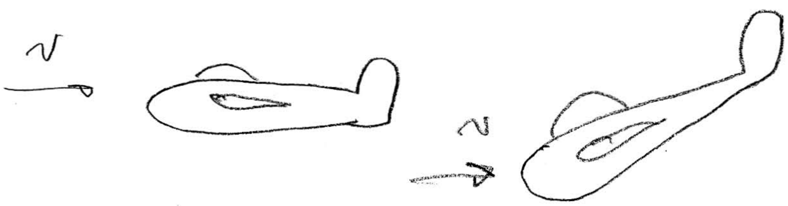
Z_L na rep

X na nos

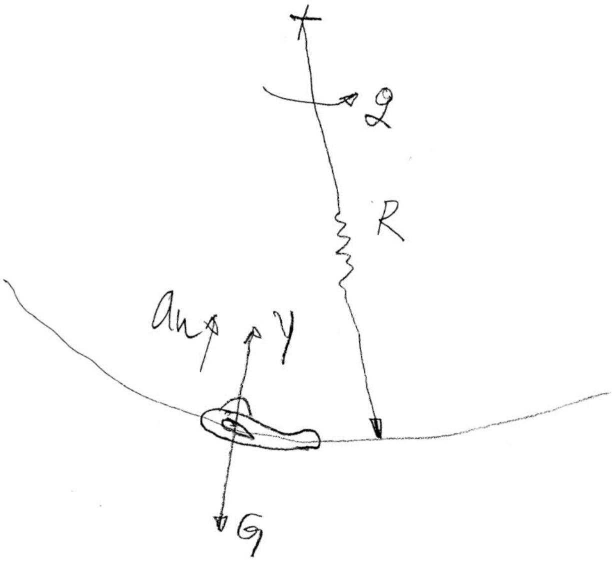
ε na ~~nos~~ rep



enaka hitrost



...mevritanja



$\Sigma F + \Sigma F_i$

$Y - G - m$

$a_n = (n-1)$

$n-1$ – faktor

n – faktor

...⇒ $Y = n \cdot G$

$Y = n \cdot G \Rightarrow n = \frac{Y}{G}$

$\rho =$

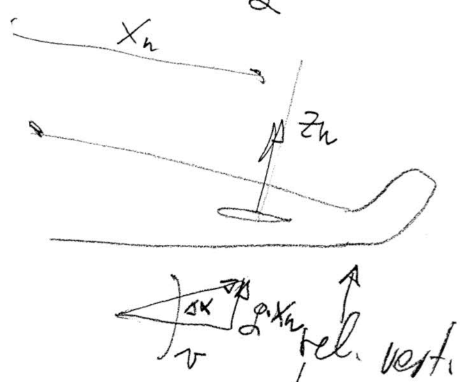
ia obrag ozi ρ

$a_n = \omega^2 \cdot R \cdot \frac{v^2}{R} = \omega \cdot v$

$v = \omega \cdot R$

$a_n = \rho \cdot v = (n-1) \cdot g$

$\rho = \frac{(n-1) \cdot g}{v}$



rel. verti komponenta hitrosti

$\bar{v}$

v manevru NT za NT pri hor. letu

z_n

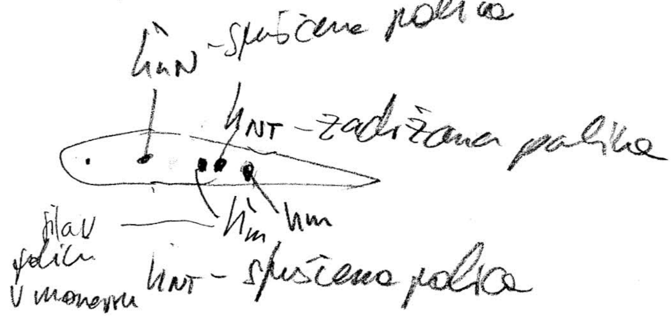
$n - n_m$ – merilo potrebnega odklona višinskega krmila za povečanje faktorja obr...

...enega 1

manjši ko je $h - h_m$ - manjše sile so potrebne za krmiljenje na palici

$$h - h_m = \frac{\Delta \delta_h}{\Delta g}$$

$$h - h_m \Rightarrow \frac{\Delta P}{\Delta g}$$

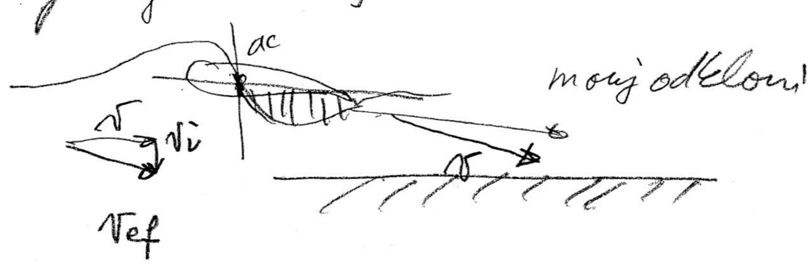


Dovoljeno potovanje masnega središča

Skrajno sprednja lega – potrebna sila na palici za ravnotežje, potreben odklon ali potrebna sila

$\Rightarrow \delta_h$

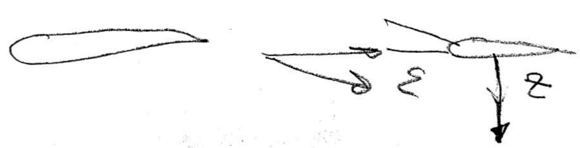
- Pristajalna konfiguracija. je kriterij
- Talni efekt



$$\alpha_{ef} = \alpha - \alpha_i$$

geometr. ; zmanjša

do b/2
brez talnega efekta



$$\varepsilon = \frac{180}{\pi} \cdot \frac{c_y}{\pi \cdot \lambda} \text{ v ac.}$$

pri repu
$\varepsilon = 2 \cdot \varepsilon_{ac}$
Izven talnega efekta

V talnem efektu

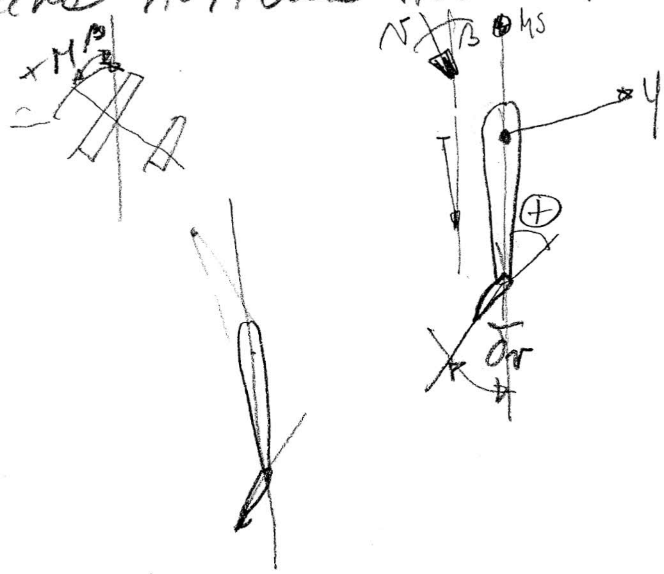
$$\varepsilon = \frac{180}{\pi} \cdot \frac{c_y}{\pi \cdot \lambda}$$

polovica

smerno ~~stabilnost~~ in prečna statična stabilnost letala

$v_j = p_1 v$

valjanje
sukanje
prevračanje



$\frac{v}{u} = \beta$

$$C_n = \frac{N}{\frac{1}{2}\rho v^2 A \cdot b}$$

$$\frac{dN}{d\beta} > 0$$

Vzgon vertikalnega repa

$$Y_v = \frac{1}{2}\rho V_v^2 \cdot A_v \cdot C_{yv}$$

$$C_{yv} = a_v \cdot \alpha_v + a_v \cdot \tau_v \cdot \delta_v$$

$$N_v = -Y_v \cdot X_v$$

$$\overline{V_v}$$

$$C_v = \frac{-\frac{1}{2}\rho V_v^2 A_v \cdot X_v \cdot C_{yv}}{\frac{1}{2}\rho v^2 A \cdot b} = -\left(\frac{V_v}{v}\right)^2 \left(\frac{A_v X_v}{A \cdot b}\right) \cdot C_{yv}$$

$$C_{nv} = -\eta_v \cdot \overline{V_v} \cdot C_{yv}$$

$\alpha_v = -\beta + \sigma$ – odklon toka

$$C_n = C_{nv} + C_{nsr}$$

$$\frac{\partial C_n}{\partial \beta} = \frac{\partial C_{nv}}{\partial \beta} + \frac{\partial C_{nt1}}{\partial \beta}$$

$$\sigma = \frac{\partial \sigma}{\partial \beta} \cdot \beta$$

$$C_{yv} = a_v \cdot (-\beta + \sigma + \tau_v \cdot \delta_v)$$

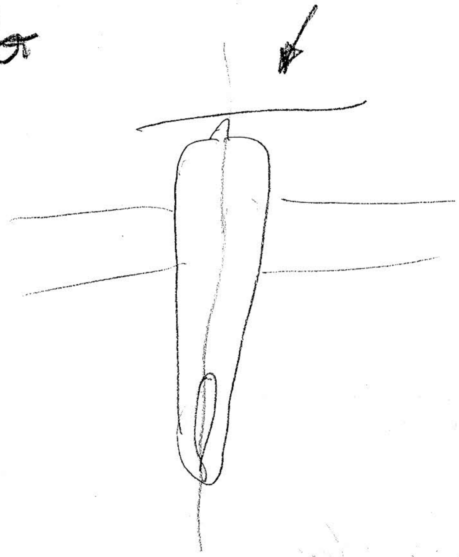
$$\frac{\partial C_{yv}}{\partial \beta} = a_v \cdot \left(-1 + \frac{\partial \sigma}{\partial \beta}\right)$$

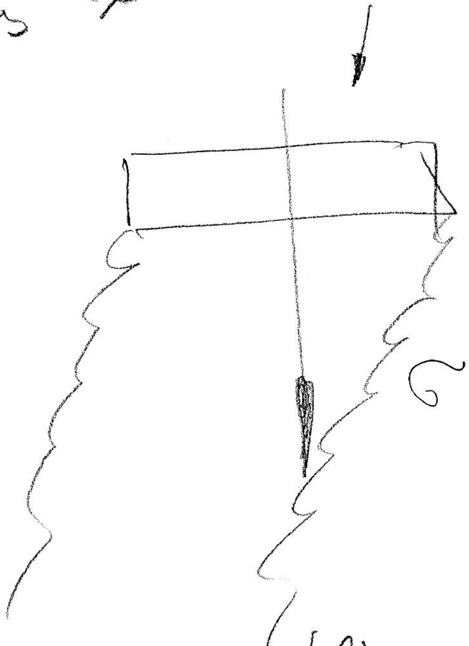
$$\frac{\partial C_n}{\partial \beta} = \eta_v \cdot \bar{V}_v \cdot a_v \left(1 - \frac{\partial \sigma}{\partial \beta}\right) + \left(\frac{\partial C_n}{\partial \beta}\right)_{tr} > \emptyset$$

smernik stabilizira ~~letalo~~

weathercock stab.

$$\frac{\partial C_n}{\partial \beta} < \emptyset$$





σ

krilo ne vpliva na vertikalno stabilnost

MS — malo vpliva

$C_n = \emptyset$

$$C_n = \emptyset = C_{nv} + C_{ntr}$$

$$C_{nv} = -\eta \cdot \bar{V}_v \cdot a_v \cdot \left(-\beta + \sigma + \tau_v \cdot \delta_v\right) + \underbrace{C_{ntr}}_{\text{malo}} = \emptyset_{\delta_v}$$

$$\beta = \tau_v \cdot \delta_v$$

šarnirni moment $C_{Hv} = b_1 \cdot \alpha_v + b_2 \cdot \delta_v$

spuščeno krmilo $\delta_{v_{leb}} = -\frac{b_1}{b_2} \cdot \alpha_v$

$$C_{Yv} = \underbrace{a_v \cdot \alpha_v \cdot \left(1 - \tau \frac{b_1}{b_2}\right)}_{F_v}$$

faktor spuščenega krmila za smernik

displacement control - rep
rate controls - krilca

$\bar{V}_h = \frac{A_h \cdot x_h}{A \cdot l}$ 0,3 ÷ 0,8

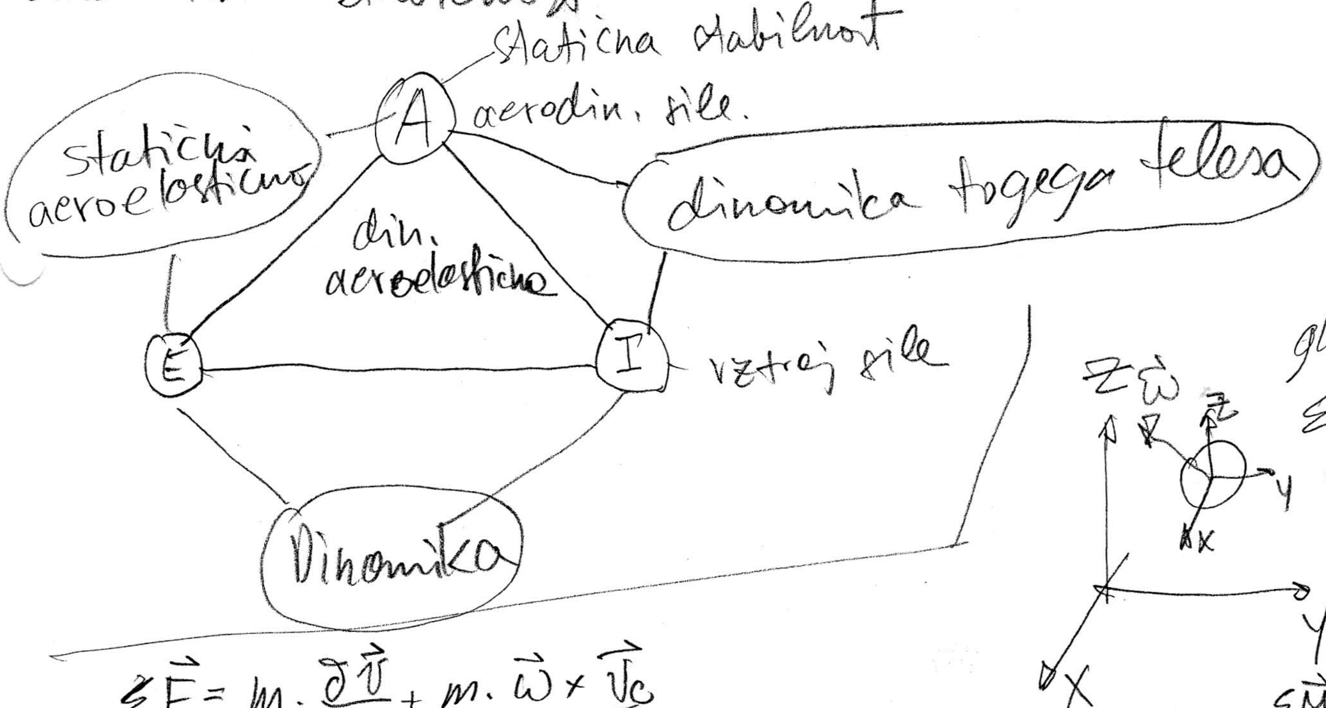
$V = \frac{A_v x_v}{A \cdot b}$ 0,045 - 0,06

$V_{krilc} = \frac{A_k y_k}{A \cdot b}$ 0,03 - 0,045

če je izpolnjena statična stab. je tudi dinamična
za manjša letala

handling qualities

Dinamična stabilnost



globalni k.s.

$\Sigma \vec{F} = m\vec{a} = m \cdot \frac{d\vec{v}}{dt}$

$\Sigma \vec{F} = m \cdot \frac{\partial \vec{v}}{\partial t} + \underbrace{m \cdot \vec{\omega} \times \vec{v}_c}_{\text{eulerjeva en.}}$

vrt. koef.

$\Sigma \vec{M} = J \cdot \vec{\alpha} = \frac{dI}{dt}$

$\frac{\partial v_c}{\partial t} = \frac{\partial v_{cx}}{\partial t}\vec{i} + \frac{\partial v_y}{\partial t}\vec{j} + \frac{\partial v_z}{\partial t}\vec{k}$ 3E + 3E + $\underbrace{3E}_{\text{za vezavo}}$ + 3E + 3E

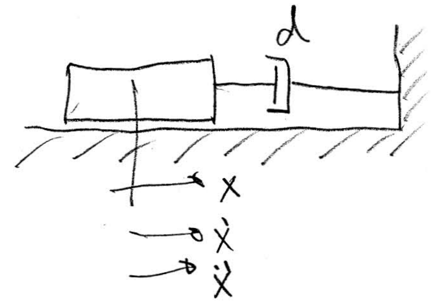
$\Sigma \vec{M} = \frac{\partial \vec{L}}{\partial t} + \vec{\omega} \times \vec{L}$

15E, ki so med seboj
vezane

- Stabilnost pri zadržani palici
- stabilnost pri spuščeni palici
- stabilnost z avtopilotom
- odziv letala na turb.
- inverzni problem – znana pot in iščemo kako je potrebno odklanjati krmila

Rešitev: – direktna integracija
 – numerično reševanje

– linearizacija ⇒ linearna dinamika



$$\Sigma F = m \cdot a = -d \cdot v$$

$$m\ddot{x} + d\dot{x} = 0$$

$$\dot{v} + \frac{d}{m} \cdot v = 0$$

$$v = e^{\lambda t}$$

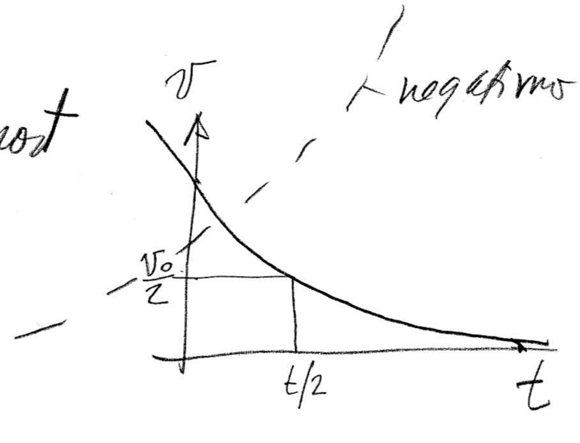
$$\dot{v} = \lambda \cdot e^{\lambda t}$$

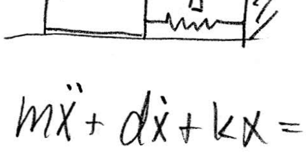
$$e^{\lambda t}\left(\lambda + \frac{d}{m}\right) = 0$$

$$\lambda = -\frac{d}{m}$$ – lastna vrednost

$$v(t) = v_0 \cdot e^{-\frac{d}{m} \cdot t}$$

negativno dušenje





$$m\ddot{x} + d\dot{x} + kx = 0$$

$$\ddot{x} + \frac{d}{m}\dot{x} + \frac{k}{m}x = 0$$

$$\ddot{x} + 2\delta\omega_0\dot{x} + \omega_0^2 x = 0$$

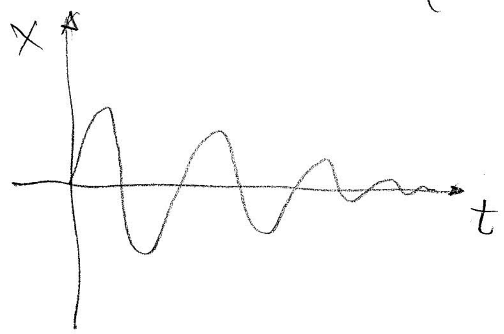
$$\omega_0 = \sqrt{\frac{k}{m}}$$

$$\delta = \frac{d}{d_{kr}}, \quad d_{kr} = 2\sqrt{km}$$

$$\omega_D = \omega_0 \cdot \sqrt{1-\delta^2}$$

$d < d_k$ - oscilatorno gibanje

$x(t) = A \cdot e^{-\delta \omega_0 t} \cdot \sin(\omega_0 t + \phi)$ - p.z. duš.



$d \geq d_{kr}$

Vzd. gib.

fugoidna - dolgo periodično slabo dušeno nihanje

kratko periodična

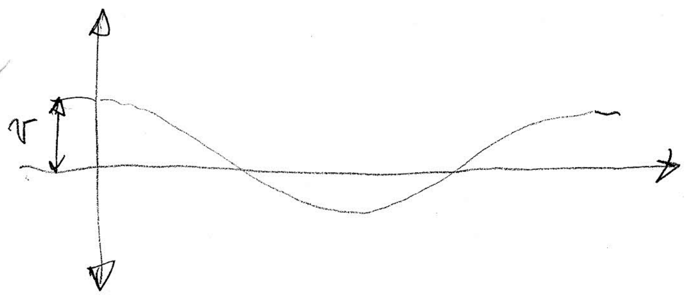
Fugoidna oblika:

u, α, ϑ

sprememba vpadnega kota majhna - samo sprememba hitrosti

dušenje majhno $= E_m =$ konst mehansko en.

$$E_m = E_k + E_p$$



$$E_m = \frac{1}{2} m V_0^2 = \frac{1}{2} m V^2 + mgz$$

$$V_0^2 - V^2 = 2gz$$

$$\Sigma F = m \cdot \ddot{z} = Y - G$$

$$G = \frac{1}{2} \rho V_0^2 A C_y = K \cdot V_0^2$$

$$Y = \frac{1}{2} \rho V^2 A \cdot C_y = K \cdot V^2$$

$K = m$

$$m \ddot{z} = K (V^2 - V_0^2)$$

$$m \ddot{z} + K 2gz = \phi$$

$$\ddot{z} + \frac{mg}{V_0^2} \frac{2g}{m} \cdot z = \phi$$

$$\ddot{z} + \frac{2g^2}{V_0^2} \cdot z = \phi$$

$$\omega_0 = \sqrt{2} \cdot \frac{g}{V_0}$$

$$T_0 = \frac{2\pi}{\omega_0} = \sqrt{2} \pi \cdot \frac{V_0}{g} \quad (20 \text{ sec} - 2 \text{ min})$$

2-3 nihaje, da se ampl. zmanjša na polovico
zelo majhno dušenje

$V_0 = 45\ m/s$

$T_0 = 20$ sek

Kratkoperiodična nihanja - periodična oblika

$$\Sigma M = I_y \cdot \ddot{\vartheta}$$

$$M\alpha(\alpha, q, \delta_h, \dot{\alpha})$$

$$M = M_0 + \frac{\partial M}{\partial \alpha}\alpha + \frac{\partial M}{\partial \dot{\alpha}}\dot{\alpha} + \frac{\partial M}{\partial q} q + \frac{\partial M}{\partial \delta_h}\delta_h$$

$\delta_h = \phi$ zadržana palica

$$I_y \cdot \ddot{\vartheta} - \frac{\partial M}{\partial \dot{\alpha}}\dot{\alpha} - \frac{\partial M}{\partial q} q - \frac{\partial M}{\partial \alpha}\cdot \alpha = \phi$$

$$\alpha = \vartheta$$
$$\dot{\alpha} = \dot{\vartheta}$$

$$\ddot{\alpha} - \left(\frac{1}{I_y}\cdot\frac{\partial M}{\partial \dot{\alpha}} + \frac{1}{I_y}\cdot\frac{\partial M}{\partial q}\right)\cdot\dot{\alpha} - \frac{1}{I_y}\cdot\frac{\partial M}{\partial \alpha}\cdot\alpha = \phi$$

$$Z_\alpha = \frac{1}{m}\cdot\frac{\partial Z}{\partial \alpha}$$

$$\frac{1}{I_y}\cdot\frac{\partial M}{\partial q} = M_q$$

$$\ddot{\alpha} - (M_{\dot{\alpha}} + M_q)\cdot\dot{\alpha} - M_\alpha \cdot \alpha = \phi$$

$$\ddot{x} + 2\delta\cdot\omega_0\cdot\dot{x} + \omega_0^2\cdot x = \phi$$

$$\boxed{\omega_0 = \sqrt{-M_\alpha}} \Rightarrow \boxed{\delta = \frac{-(M_\alpha + M_q)}{2\cdot\sqrt{-M_\alpha}}}$$

$$2\delta\omega_0 = -(M_{\dot{\alpha}} + M_q)$$

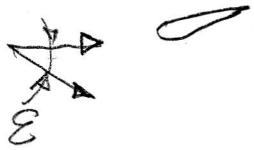
$\omega_0 = \sqrt{-M\alpha}$

$M\alpha = \frac{1}{I_y} \cdot \frac{\partial M}{\partial \alpha} \propto \frac{\partial C_m}{\partial \alpha} \approx \frac{\partial C_m}{\partial C_z}$

$\frac{\partial C_m}{\partial C_z} < \phi$ večji ko je člen, frekvenca višje

$\delta, M\dot{\alpha}, M_q$

$M\dot{\alpha}$ – upoštevamo časovni zamik ~~prit~~ spremembe toka na repu

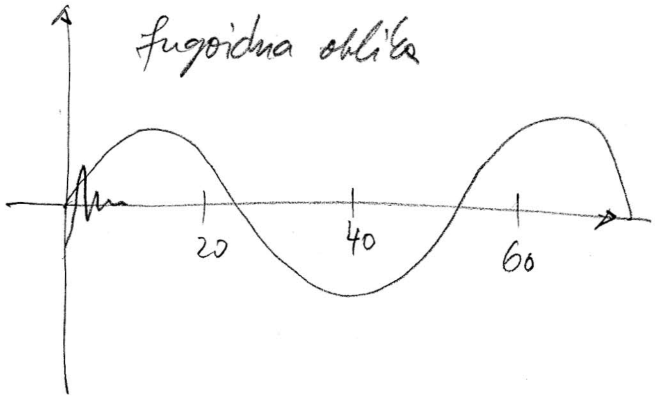


$M_q = \frac{1}{I_y} \cdot \frac{\partial M}{\partial q} < \phi$

$T_h \uparrow \rightarrow \delta \uparrow$ q – rotacija

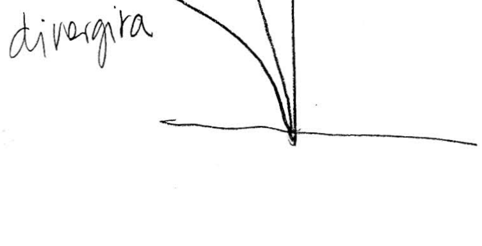
$\Delta z_h = \Delta\alpha_h \cdot a_h$

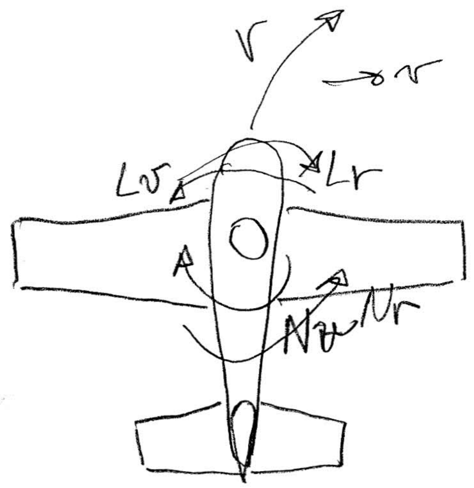
$\Delta\alpha \propto \frac{q \cdot l}{v}$ model viskoznega dušenja



2. Aperiodična oblika → spiralna oblika, oblika valjanja

1. Spiralna oblika – aperiodična oblika





V lom popravlja nagib

L_v – moment valjanja zaradi bočnega drsenja

$L_v = \frac{1}{I_x} \cdot \frac{\partial L}{\partial v}$ – učinek V loma ~~oz~~ diedra

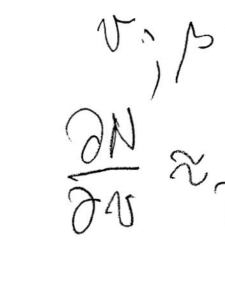
L_R – moment valjanja zaradi sukanja

N_v – moment sukanja zaradi bočnega drsenja

v, β – smerna stabilnost

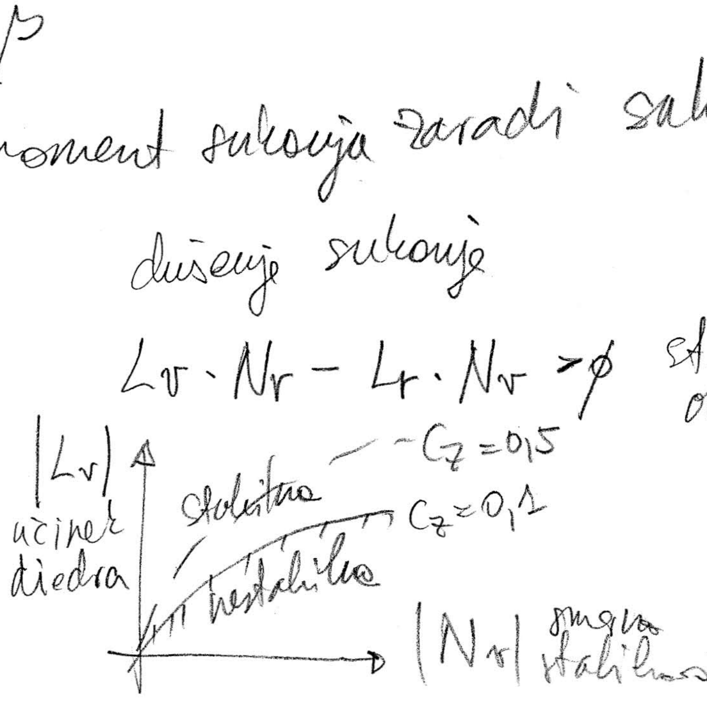
$$\frac{\partial N}{\partial v} \approx \frac{\partial C_n}{\partial \beta}$$

N_r – moment sukanja zaradi sukanja

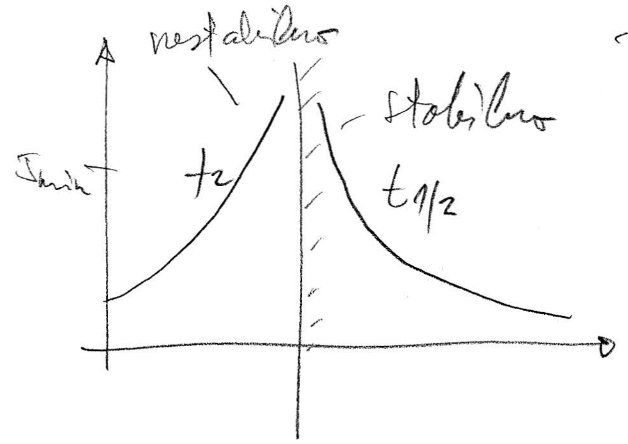


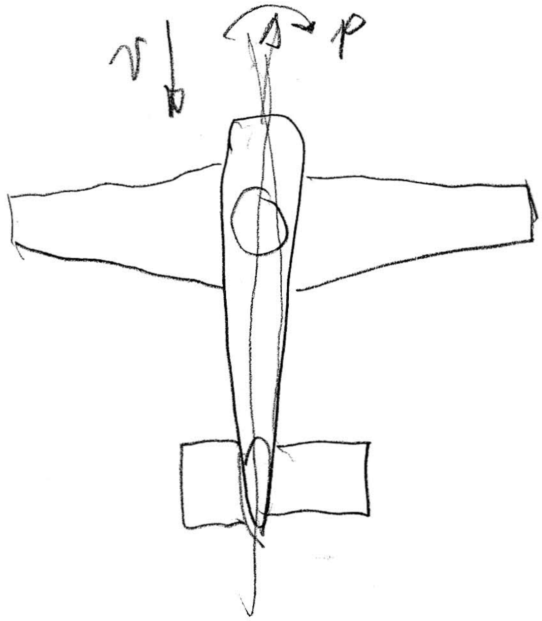
dušenje sukanja

$L_v \cdot N_r - L_r \cdot N_v > 0$ stabilnost spiralne oblike

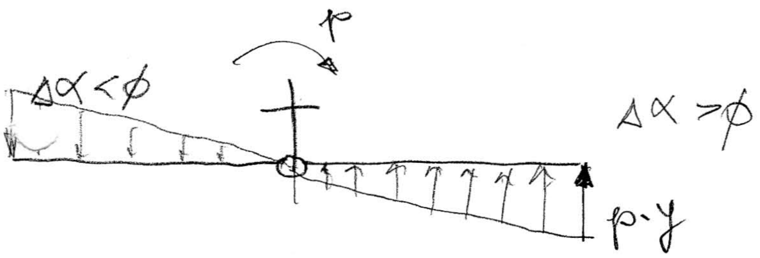


$v\downarrow$ (mala) ali $C_z\uparrow$ (velika) spiralna oblika bolj nestabilna





Oblika valjanja



$$\Sigma L = I_x \cdot \ddot{\phi}$$

$$I_x \cdot \ddot{\phi} - \frac{\partial L}{\partial p} \cdot \dot{\phi} = \phi$$

$$\dot{\phi} = p$$

$$\ddot{\phi} = \dot{p}$$

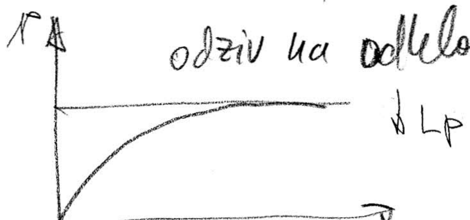
$$\dot{p} - \left(\frac{1}{I} \cdot \frac{\partial L}{\partial p}\right) \cdot p = \phi$$

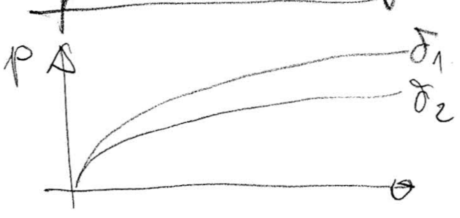
L_p – dušenje valjanja

$$x = x_0 \cdot e^{\lambda t}$$

$$p = p_0 \cdot e^{L_p \cdot t} \qquad t_{1/2} \approx 0{,}5\ s$$

odziv na odklon palice



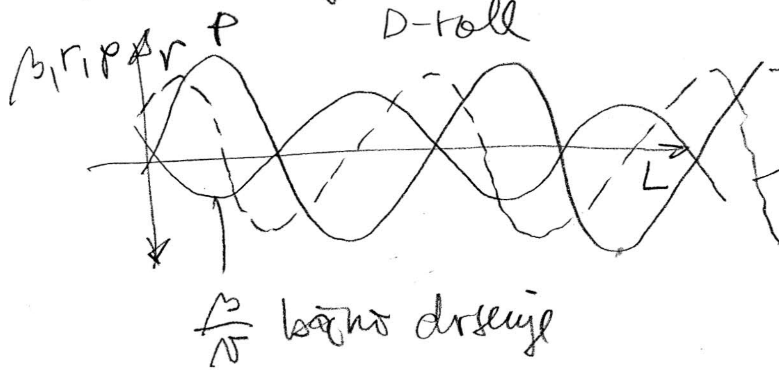


večji ko je razpon
večje je dušenje valjanja

Dutch Roll mode

– bočno drsenje, sukanje, valjanje
– dušenje veliko – oscilatorna oblika

$p\downarrow$ – če je valjanje malo – snaking
polna noga: nos krožno zaniha

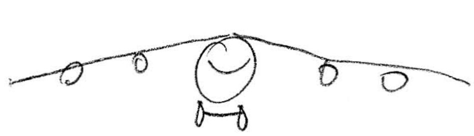


L_v – učinek diedra
N_v – smerna stabilnost

<u>Učinek diedra</u>: L_v

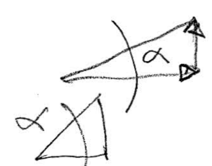
$$\frac{\text{roll}}{\text{yaw}} = \frac{\text{valjanje}}{\text{sukanje}} = \frac{p}{r}\uparrow$$ valjanje poveča

N_v – zmanjša $\frac{p}{r}\downarrow$, poveča dušenje



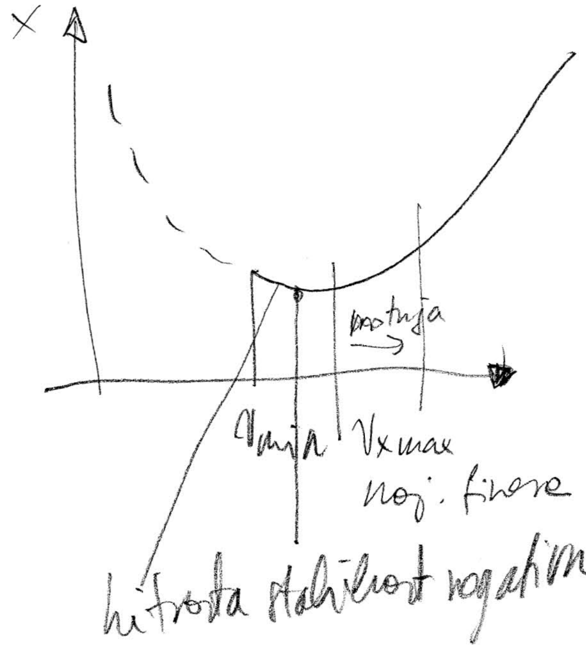
neprijetna za pilota D-roll
yaw damper

mala hitrost



dušilno dušenje
L_p – dušenje valjanja
N_r – dušenje sukanja
M_q – dušenje prevračanja

– dušilni faktor zmanjša



① $v > v_{Emax}$

manjka 1 predavanje

stabilizator

$$C_{M\check{s}} = b_0 + \underbrace{b_1 \cdot \alpha + b_2 \cdot \delta}_{b_{12} = \phi} + b_3 \cdot \delta_t$$

$$C_{M\check{s}} = b_3 \cdot \delta_t$$

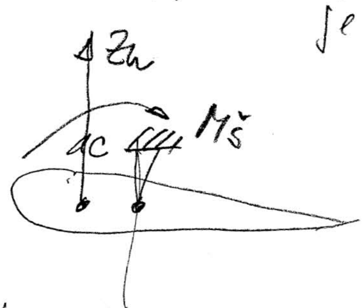
$$\delta_t = \delta_{t0} + G_1 \cdot \alpha$$

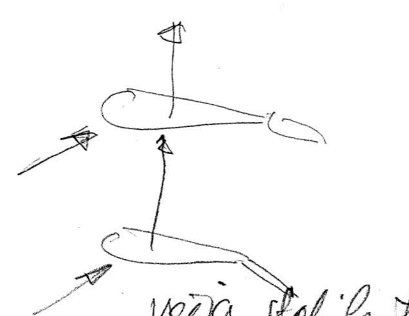
Ravnotežje $C_{M\check{s}} = \phi$

$$\delta_t = \phi = \delta_{t0} + G_1 \cdot \alpha \Rightarrow \alpha = -\frac{\delta_{t0}}{G_1}$$

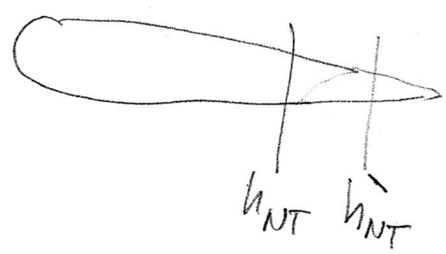
kot trimerja

$h_{NT} = \grave{h}_{NT}$ nevtr. točka pri zadržani palici je nevtr. točka pri spuščeni palici.

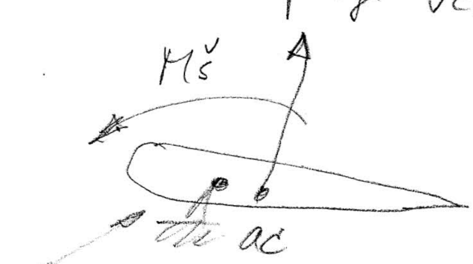




$\grave{h}_{NT}$ za h_{NT}

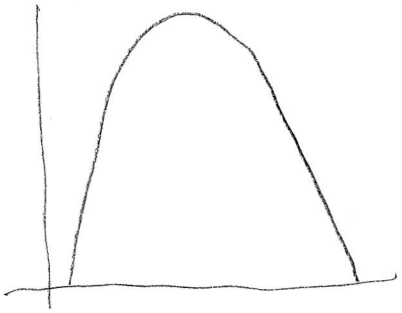


za ac. vpetje večjo stabilnost pri spuščeni palici



$\grave{h}_{NT}$ pred h_{NT}

Vrij = Sveder

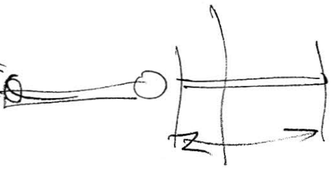


Porke
Frank Gooden

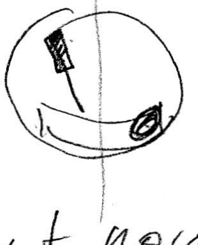
- racman – najprej porušitev vzgona kor. krmila
- omejitev hoda viš. krmila

SVEDER

- Avtorotativno vrtenje okrog vertikalne osi, ko je vpadni kot nad kritičnim
- Rotacijska os je blizu masnega središča



- hitrost se stabilizira
- obremenitve do 2g
- indikacija kontrolnega leta



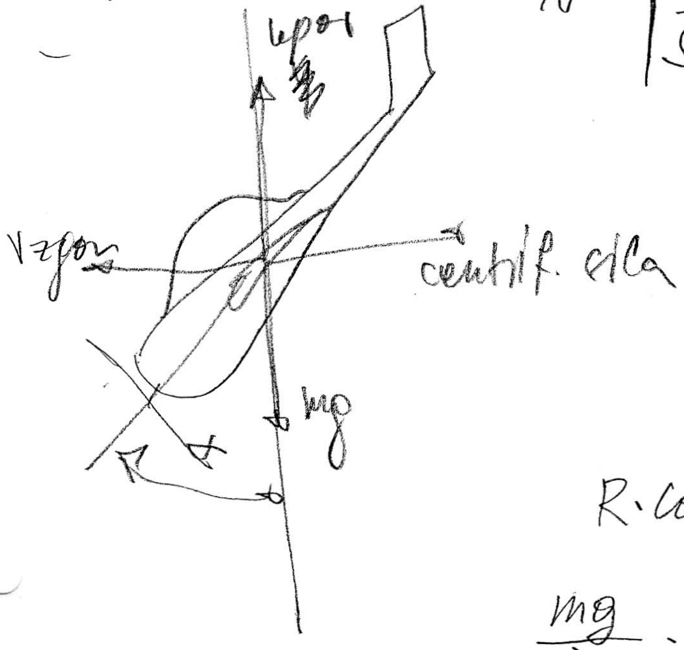
Spuščanje v spirali – hitrost narašča
– obremenitev narašča
– ni bočnega drsenja

- nenadno povečanje sukanja

360° – 1–2 sek

jadralna let. 3–10 sek

Sveder:
- hrbtni
- pravilni



$$mg = R \cdot \sin\alpha = \frac{1}{2}\rho v^2 A \cdot C_R \cdot \sin\alpha$$

$$v = \sqrt{\frac{2}{\rho} \cdot \frac{mg}{A} \cdot \frac{1}{C_R \cdot \sin\alpha}}$$

$$C_R = C_{y\,max}$$

$$v > v_{min}$$

$$R \cdot \cos\alpha = m \cdot \omega_s^2 \cdot r_s$$

$$\frac{mg}{\sin\alpha} \cdot \cos\alpha =$$

$$r_s = \frac{g}{\omega_s^2} \cdot ctg\,\alpha$$

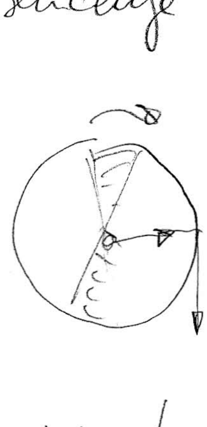
$I_x = A$

$I_y = B$

$A > B \Rightarrow \frac{B}{A} < 1$

vedno najprej palico nasprotno nogo, potem višinsko krmilo v nevtralo

senčenje površin



v desnem kovitu bo moment zmanjševal vpadni kot letala → odvzamemo plin

krilca v nevtralo

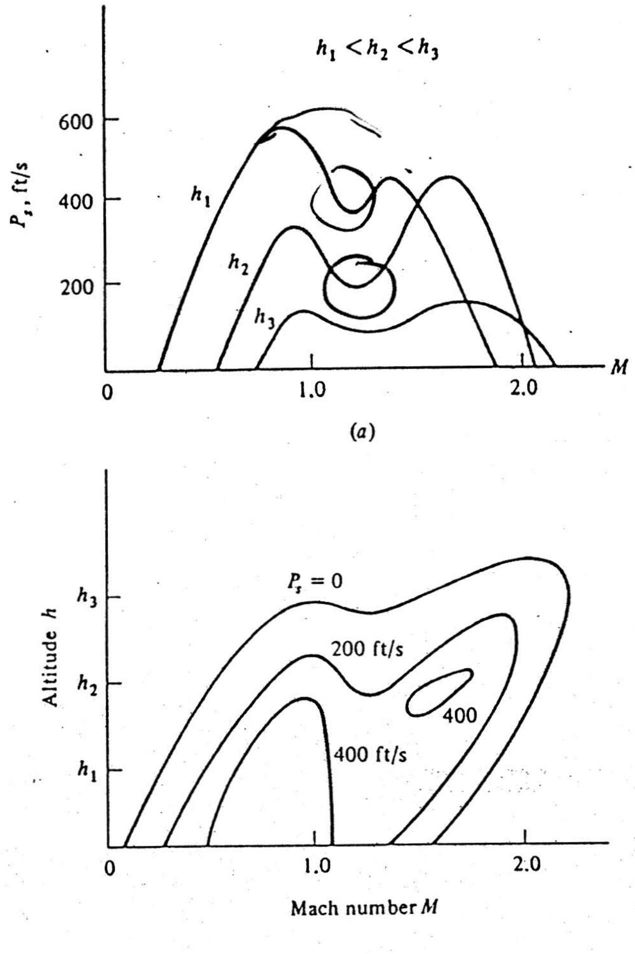


Figure 6.53 Specific excess powe contours for a supersonic airplan

čas za prehod iz enega v drug energijski nivo

$$dt = \frac{dH_e}{P_s} \Rightarrow \Delta t = t_2 - t_1 = \int_{H_{e_1}}^{H_{e_2}} \frac{dH_e}{P_s}$$

$$\Delta t_{min} \Leftrightarrow P_{s\,max}$$

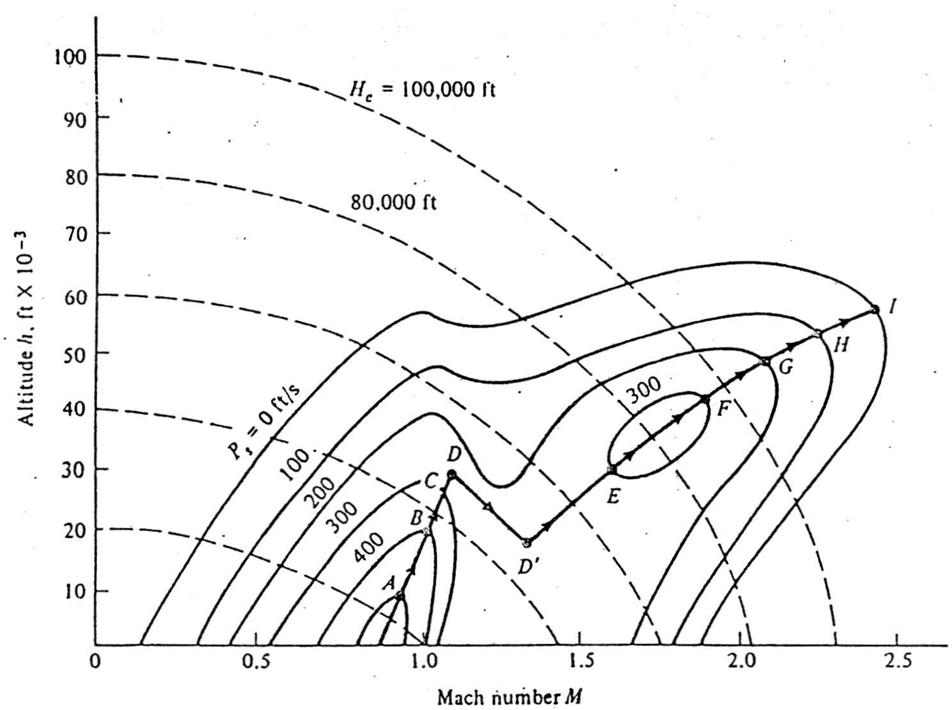


Figure 6.54 Overlay of P_s contours and specific energy states on an altitude–Mach number map. The P_s values shown here approximately correspond to a Lockheed F-104G supersonic fighter. Load factor $n = 1$. $W = 18{,}000$ lb. Airplane is at maximum thrust. The path given by points A through I is the flight path for minimum time to climb.

(i) $$P_s = \frac{P_r - P_p}{G} = \frac{dh}{dt} + \frac{V}{g}\cdot\frac{dV}{dt}$$

=> rezervo moči lahko porabimo za vzpenjanje $\left(\frac{dh}{dt}\right)$, pospeševanje $\left(\frac{dV}{dt}\right)$ ali kombinacijo obojega

$$H_e = h + \frac{V^2}{2g}$$

(ii) $$\frac{dH_e}{dt} = \frac{dh}{dt} + \frac{V}{g}\cdot\frac{dV}{dt}$$

(i) + (ii) => $$\boxed{P_s = \frac{dH_e}{dt}}$$

(2) (1)

Specifično rezervo moči je enako | spremembi energijske višine v enoti časa

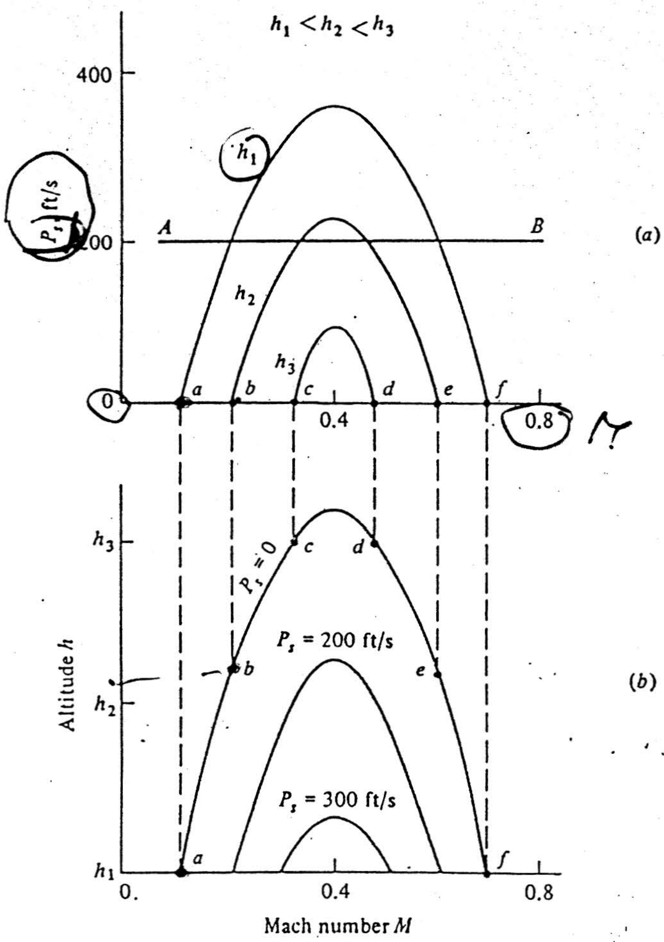


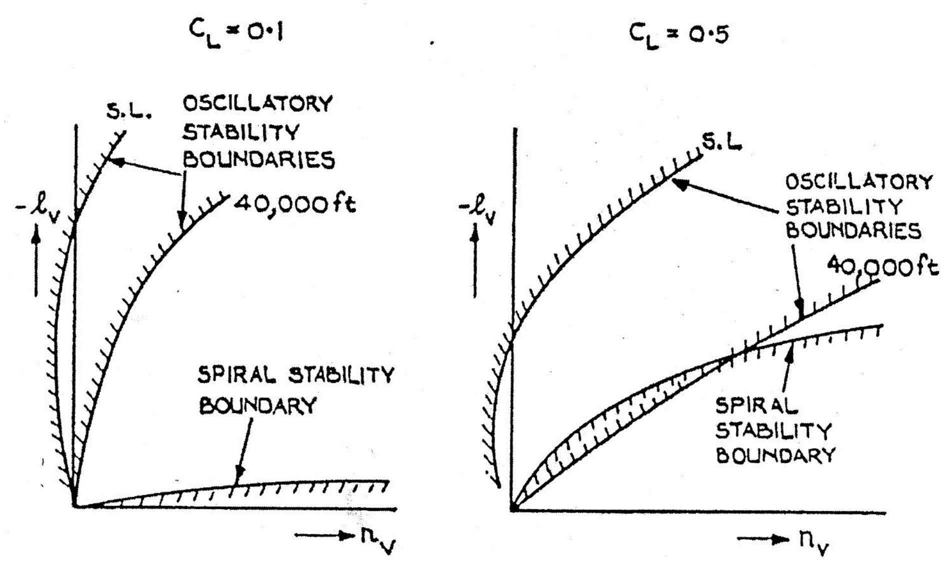
Figure 6.52 Construction of the specific excess power contours in the altitude–Mach number map for a subsonic airplane below the drag-divergence Mach number. These contours are constructed for a fixed load factor; if the load factor is changed, the P_s contours will shift.

- Increase in equivalent airspeed increases frequency of Dutch Roll motion
- At higher altitudes damping of the Dutch Roll motion reduces considerably (yaw damper)

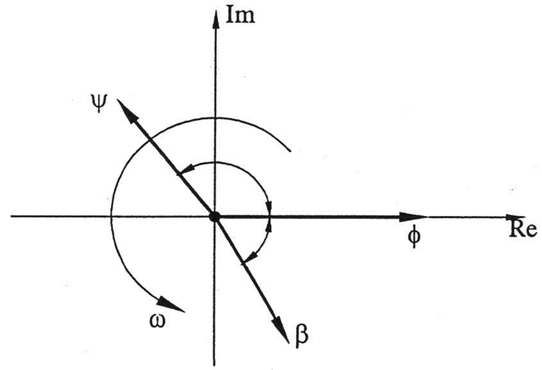
Effects on Dutch Roll motion

- *Increase in dihedral stability*
    - slightly increase frequency
    - decrease damping
    - increase roll/yaw ratio

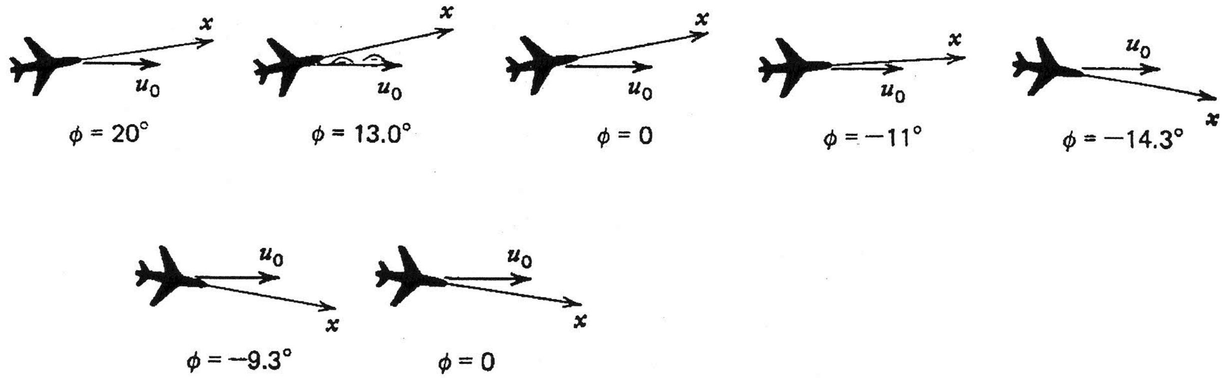
- *Increase in weathercock stability*
    - increase frequency
    - increase damping
    - decrease roll/yaw ratio



Oscillatory and spiral stability boundaries



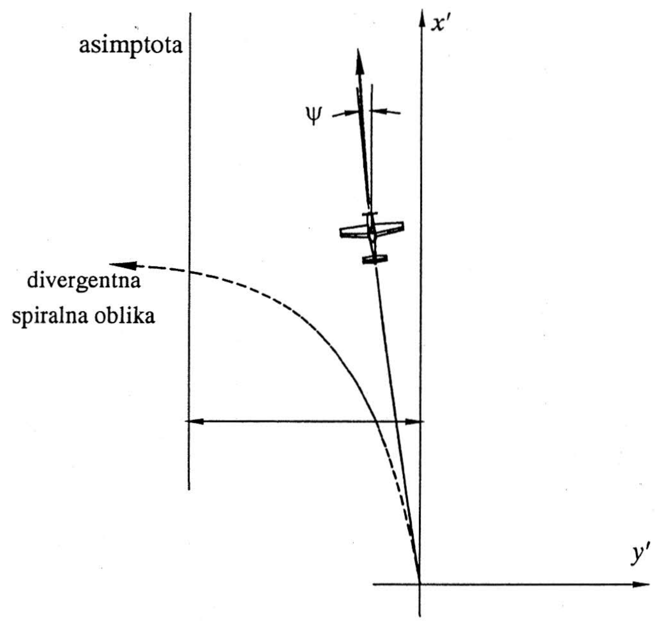
Vector diagram of Dutch Roll mode



Sketch of Dutch Roll motion

Gibanje letala pri Dutch-roll obliki. Naj se letalo zasuka v desno. Ob zasuku letalo bočno drsi v levo, tako da smer leta ostane premočrtna. Pri sukanju v desno se letalo začne tudi valjati v desno. Med tem, ko se letalo še valja v desno, se začne letalo sukati levo in bočno drseti v desno itn.

- effect of fin and dihedral
- increase in airspeed (decrease of AOA) increases stability of the spiral mode
- CG position does not effects the damping of the mode
- spiral divergence vs. directional divergence



Dutch Roll oscillation

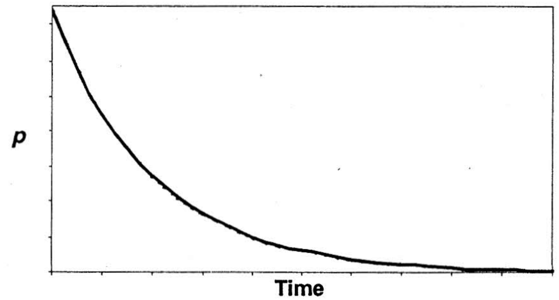
- Dutch Roll motion consists of a relatively short period oscillations, which may be either damped or divergent, involving rolling yawing and sidesliping motions
- roll/yaw ratio is important characteristic of Dutch Roll because it affects the pilot‘s assessment of the handling qualities
- *snaking* – the motion consists mainly of yawing

Airplane Lateral–Directional Dynamic Stability

– 2 aperiodic modes and oscillatory mode

Roll mode

- very heavily damped, almost pure single DOF rolling motion
- damping is reduced with decrease in airspeed and increase in altitude
- CG position has no effect on roll motion
- it is very important to determine the roll response characteristic of the airplane



Variation of roll rate *p* with time for pure rolling motion

Spiral motion

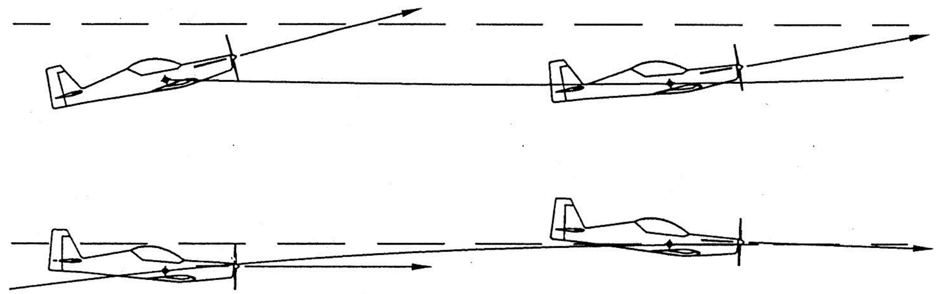
- usually weakly damped motion in bank and yaw, with negligible sideslip
  – approximately a correctly banked turn of increasing radius; the airplane flies along a slightly curved path and approaches initial heading
- often this mode is unstable; the path of motion of the airplane is then a tightening spiral
  – approximately a correctly banked turn of decreasing radius (*graveyard spiral*)
- due to large time to double/half the amplitude, there is no quantitative standard of spiral stability; however, time to double the amplitude should exceed 20 sec

Phugoid motion summary:

- the motion is approximately one of constant total energy, the raising and falling corresponding to an exchange between the kinetic and the potential energy
- change of angle of attack is negligible – velocity of airplane is approximately tangent to the path
- long period and lightly damped mode
- moving CG back lowers static stability and consequently reduces frequency of the phugoid mode
- increase in equivalent airspeed reduces frequency of the phugoid mode
- at higher altitude the damping of the phugoid mode is reduced

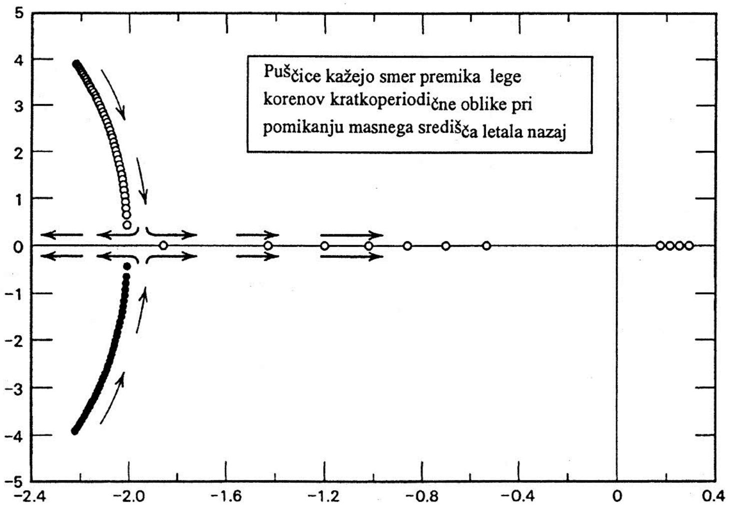
Short-period motion summary:

- the motion is approximately pure oscillatory pitch motion of the airplane
- negligible speed variation, short period and highly damped motion
- as for the phugoid mode, shifting the CG back lowers static stability (aerodynamic stiffness) and therefore reduces frequency of the short-period motion
- damping and frequency of the short-period mode are proportional to the equivalent airspeed
- with increasing altitude the damping of the short-period mode is reduced
- motion should be considerably damped in order to prevent PIO

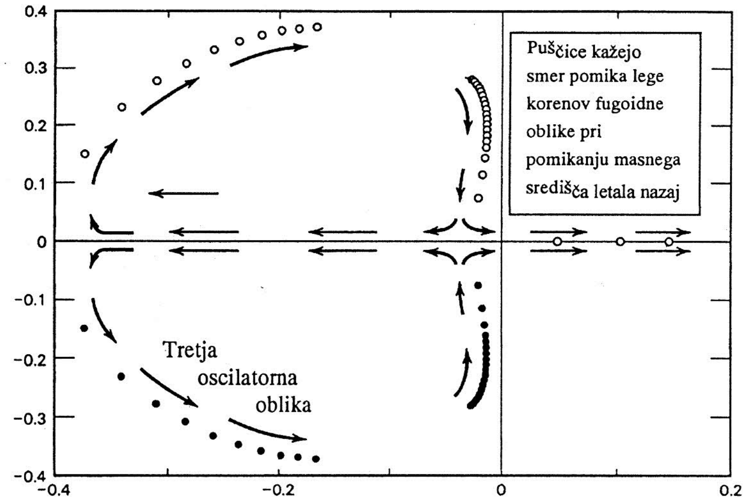


Short-period motion path

- Root locus plot



Root locus plot of short-period motion

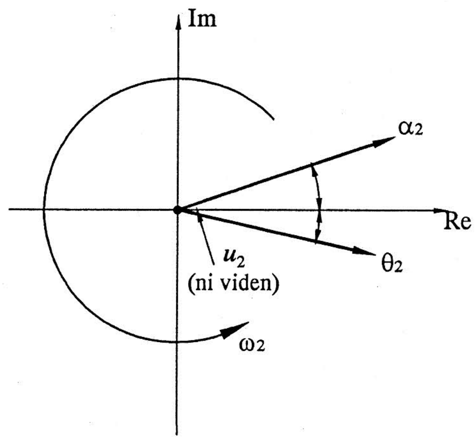


Root locus plot of phugoid motion

Phugoid mode

- change of angle of attack is negligible ($\Delta\alpha \approx 0$) – velocity of airplane is approximately tangent to the path
- the motion is approximately one of constant total energy, the raising and falling corresponding to an exchange between the kinetic and the potential energy
- long period ($T \approx$ 2min) and lightly damped mode ($N_{half} = 2$)

Short-period mode

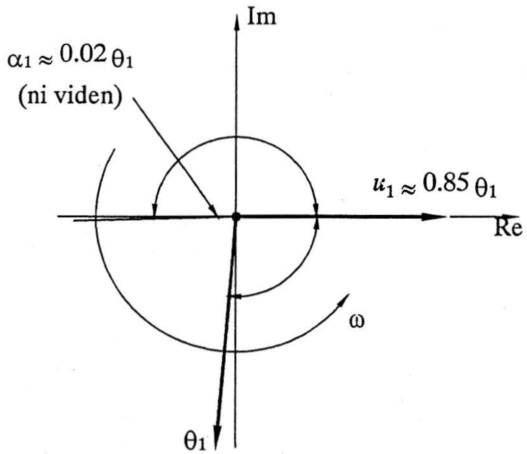


Vector diagram of short-period mode

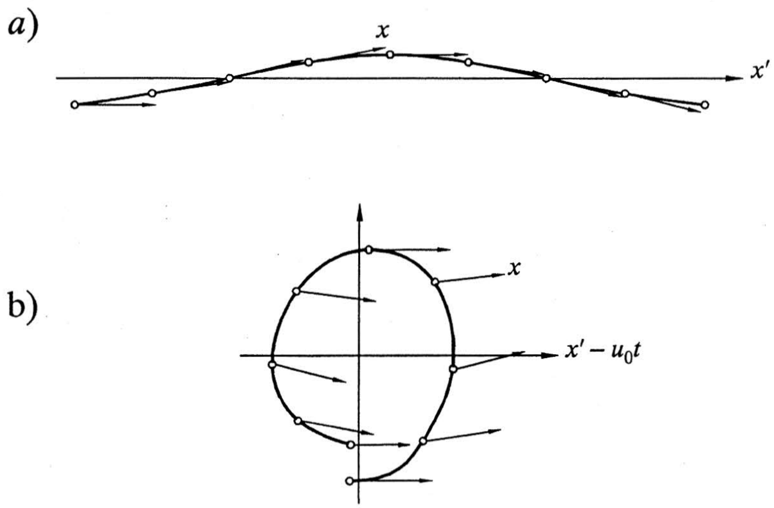
- negligible speed variation ($\Delta u \approx 0$)
- the motion is approximately pure oscillatory pitch motion of the airplane
- short period ($T \approx$ 3sec) and highly damped mode ($N_{half} = 0.2$)

Airplane Longitudinal Dynamic Stability – 2 oscillatory modes

Phugoid mode



Vector diagram of phugoid mode



Phugoid motion path in (*a*) fixed reference frame (*b*) moving reference frame

Small disturbance theory

$$\Delta F = \left(\frac{\partial F}{\partial u}\right)_0 u + \left(\frac{\partial F}{\partial \dot{u}}\right)_0 \dot{u} + \cdots + \left(\frac{\partial F}{\partial \Delta \dot{\delta}_v}\right)_0 \Delta \dot{\delta}_v + \left(\frac{\partial F}{\partial \Delta \ddot{\delta}_v}\right)_0 \Delta \ddot{\delta}_v$$

Stability derivatives

$$X_u = \frac{1}{m}\left(\frac{\partial X}{\partial u}\right)_0 \quad \ldots \quad Y_y = \frac{1}{m}\left(\frac{\partial Y}{\partial v}\right)_0 \quad \ldots \quad Z_w = \frac{1}{m}\left(\frac{\partial Z}{\partial w}\right)_0 \quad \ldots$$

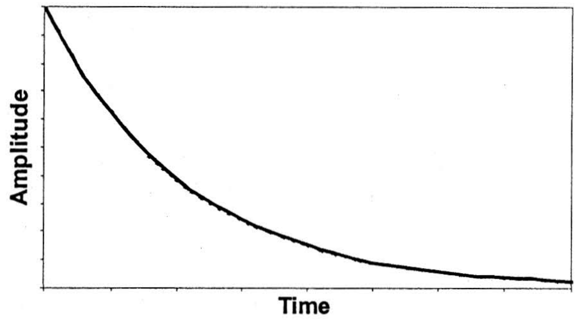
$$L_p = \frac{1}{I_x}\left(\frac{\partial L}{\partial p}\right)_0 \quad \ldots \quad M_w = \frac{1}{I_y}\left(\frac{\partial M}{\partial w}\right)_0 \quad \ldots \quad N_r = \frac{1}{I_z}\left(\frac{\partial N}{\partial r}\right)_0 \quad \ldots$$

Linearised system of equations:

- eigenvalues, eigenvectors

Aperiodic motion

- first order linear differential equation

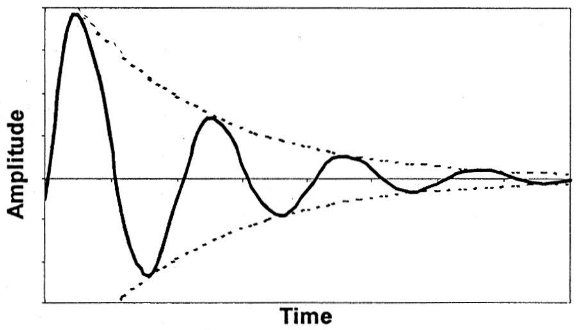


Oscillatory motion

- second order linear differential equation

$$\ddot{x} + \frac{d}{m}\dot{x} + \frac{k}{m}x = 0$$

$$\ddot{x} + 2\delta\omega_0\dot{x} + \omega_0^2 x = 0$$



- **PIO**

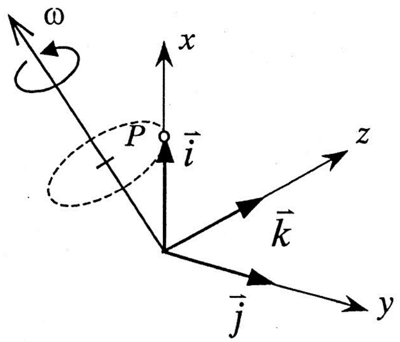
Rigid Airplane Dynamic Stability

Equations of motion for rigid airplane (6 DOF)

- for inertial reference frame

$$\vec{F} = m\frac{d\vec{v}_c}{dt} \qquad \vec{G} = \frac{d\vec{h}}{dt}$$

- for airplane-fixed reference frame

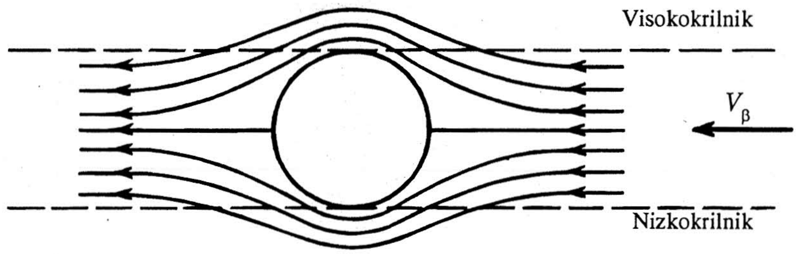


$$\frac{d\vec{i}}{dt} = \vec{v}_P = \vec{\omega} \times \vec{i}$$

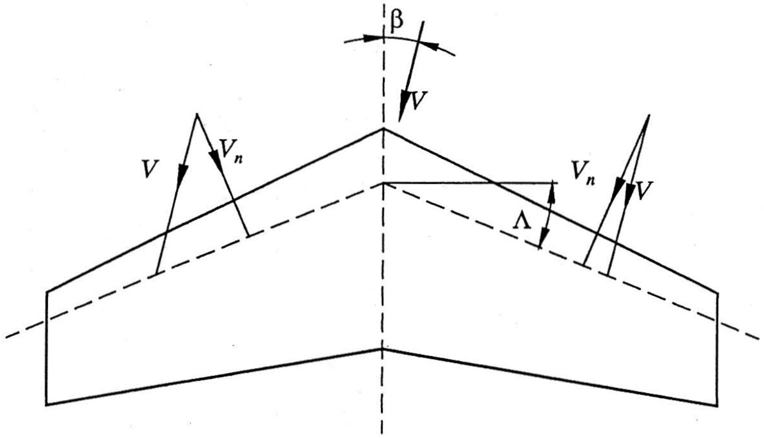
$$\vec{F} = m\frac{\delta\vec{v}_c}{\delta t} + m\vec{\omega} \times \vec{v}_c \qquad \vec{G} = \frac{d\vec{h}}{dt} + \vec{\omega} \times \vec{h}$$

Symmetrical airplane assumption

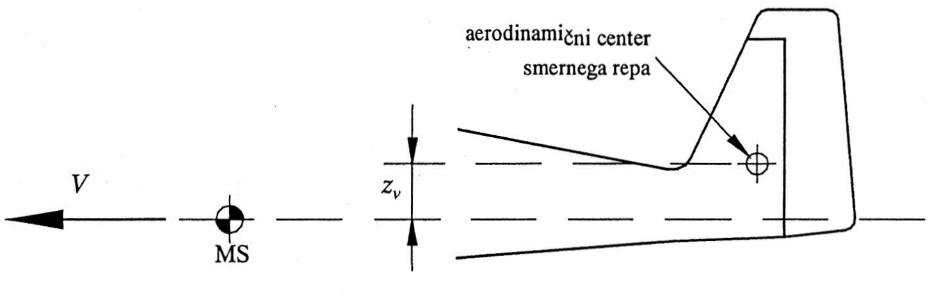
- longitudinal dynamic stability (pitch)
- lateral-directional dynamic stability (roll-yaw)



Vpliv trupa na učinek diedra - $C_{l\beta}$

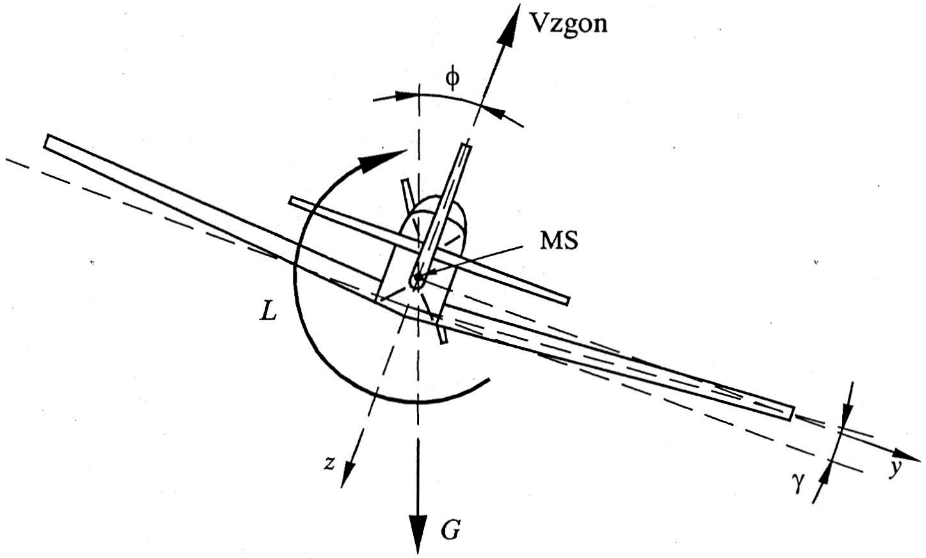


Vpliv puščice krila na učinek diedra

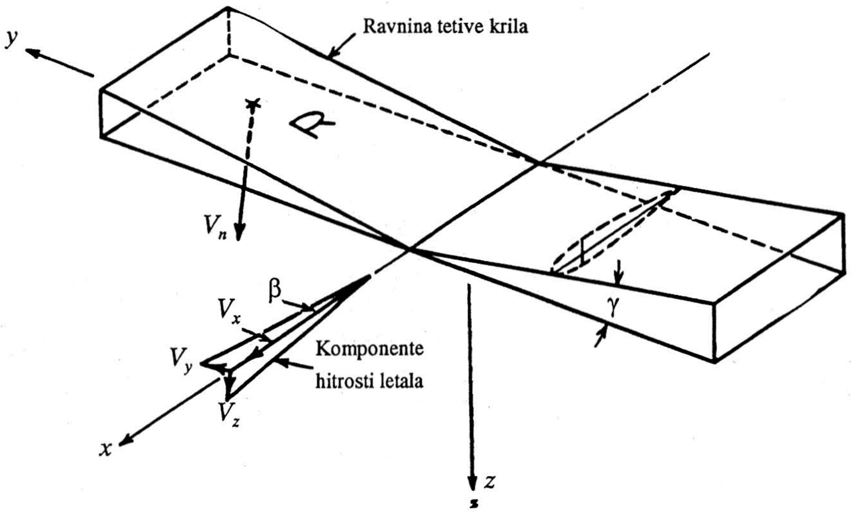


Vpliv smernega repa na $C_{l\beta}$

Airplane lateral static stability



Sile na letalo v nagibu



Vpliv diedra oz. V-loma krila na vpadni kot krila

The forward C.G. limit

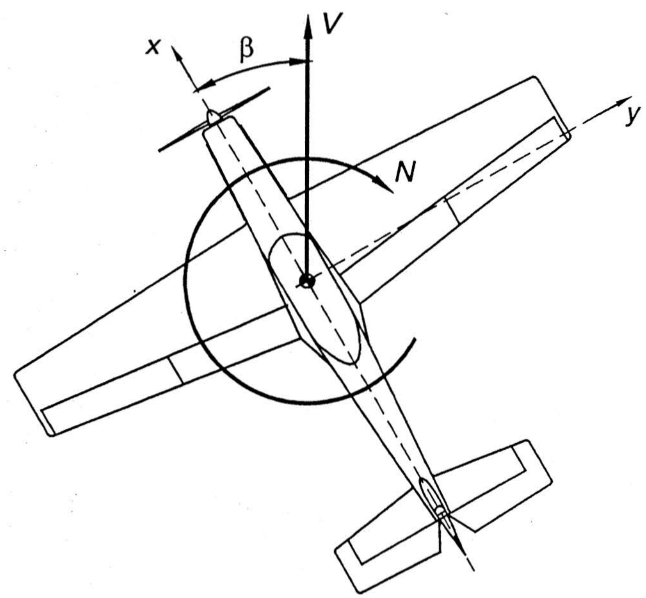
As the C.G. moves forward, the stability of the airplane increases and larger control movements and forces are required to maneuver the airplane. The forward C.G. limit is therefore based on the control considerations and may be determined by one of the following requirements:

1. the stick-force per *g* should not exceed a specific value,
2. the stick-force gradient at trim, dP/dV, shall not exceed a specified value,
3. the stick-force required to land, from a trim at the approach speed, shall not exceed a specified value and
4. the elevator angle required to land shall not exceed maximum up elevator.

Airplane directional static stability

Sideslip

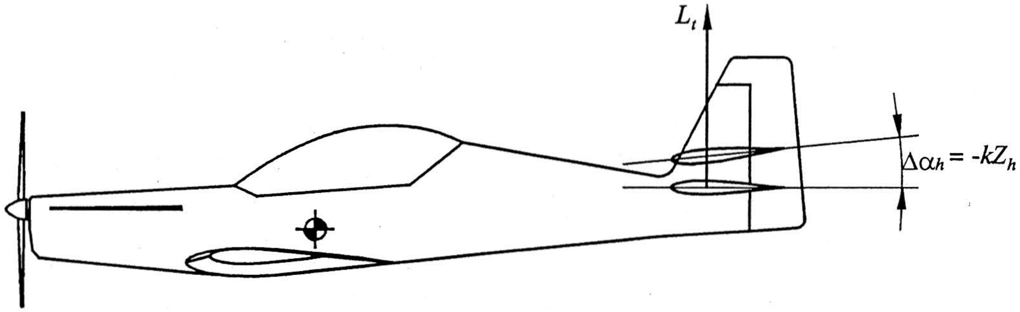
$$\frac{\partial C_n}{\partial \beta} > 0$$



Longitudinal manoeuvring stability

Effect of thrust on

Effect of elasticity of structure on longitudinal stability

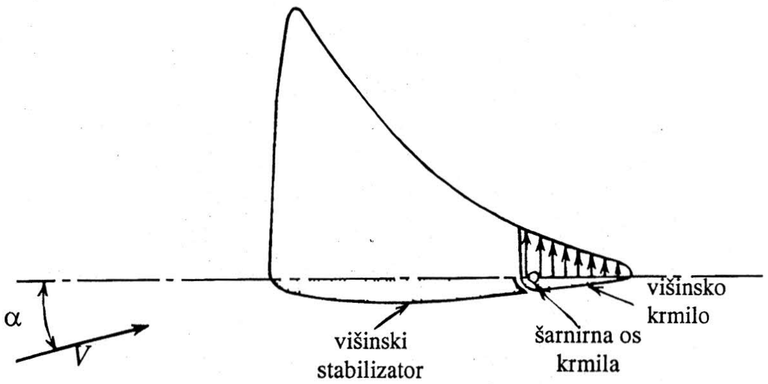


Sprememba vpadnega kota višinskega repa pri deformaciji trupa

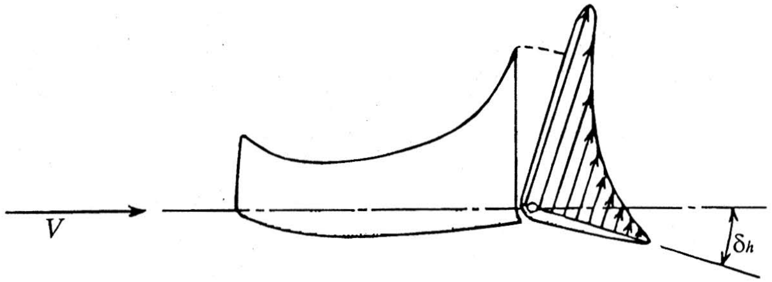
The aft C.G. limit

The permissible aft C.G. limit is determined by the stability considerations. It is based on the location of the stick-free neutral point h'_n when manual controls are employed, and on the stick-fixed neutral point h_n if the elevator control is irreversible. Conservative practice is to keep the aft limit a small distance forward of the computed relevant neutral point due to the effects of wing flaps, the propulsive system, aeroelastic deformation and to provide safe handling characteristic.

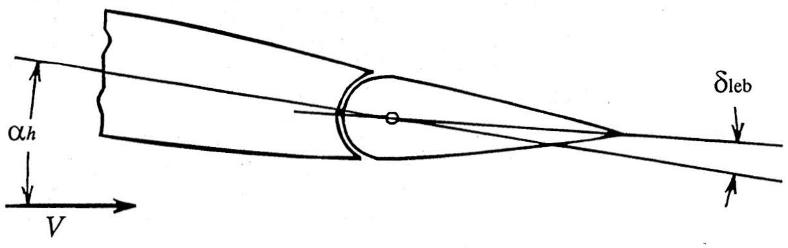
a)



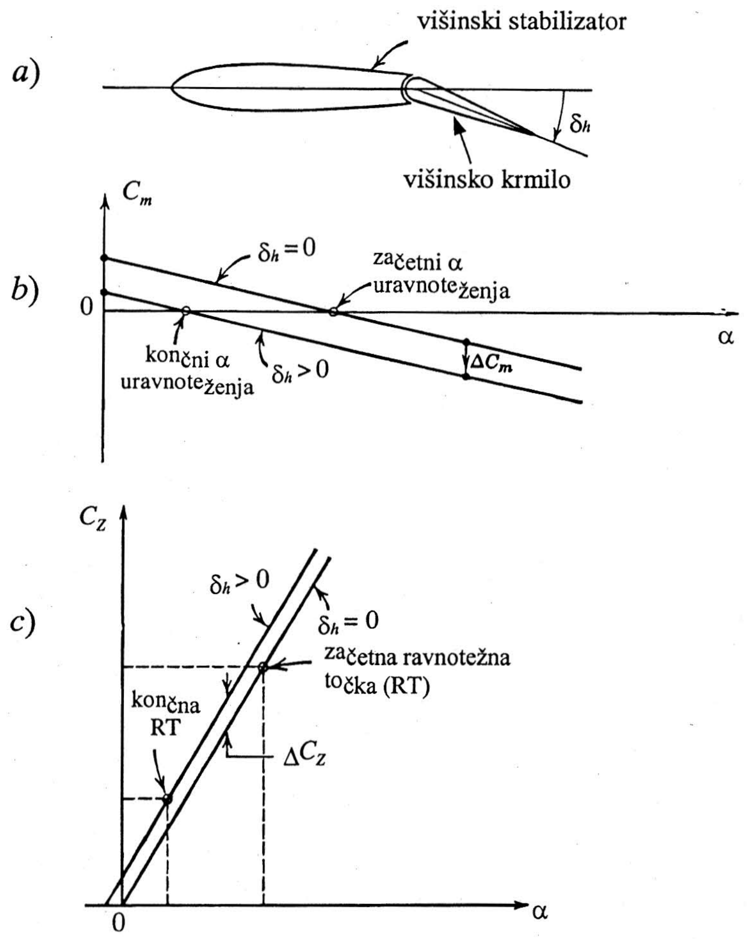
b)



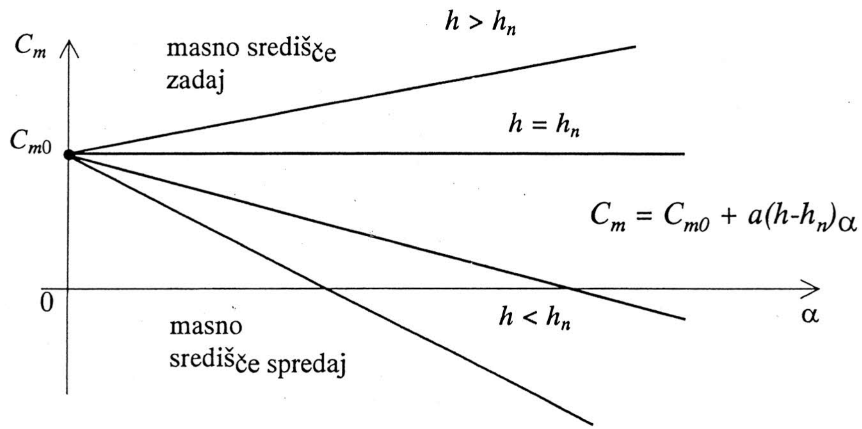
Porazdelitev normalne sile na višinskem repu pri:
a) spremembi vpadnega kota α ob $\delta_h = 0$; *b*) odklonu krmila δ_h ob $\alpha = 0$



Floating elevator

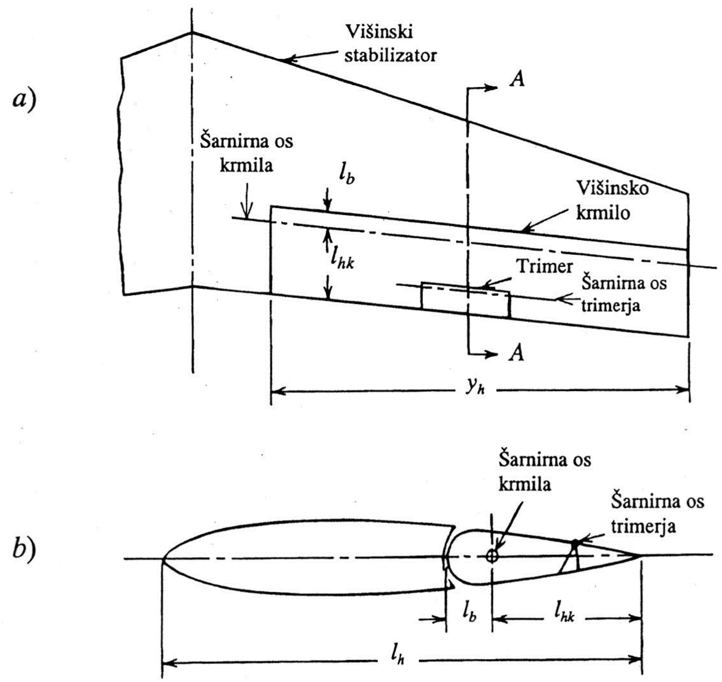


Vpliv odklona višinskega krmila na C_m in C_Z: *a*) pozitiven odklon krmila, *b*) diagram C_m - α, *c*) diagram C_Z - α

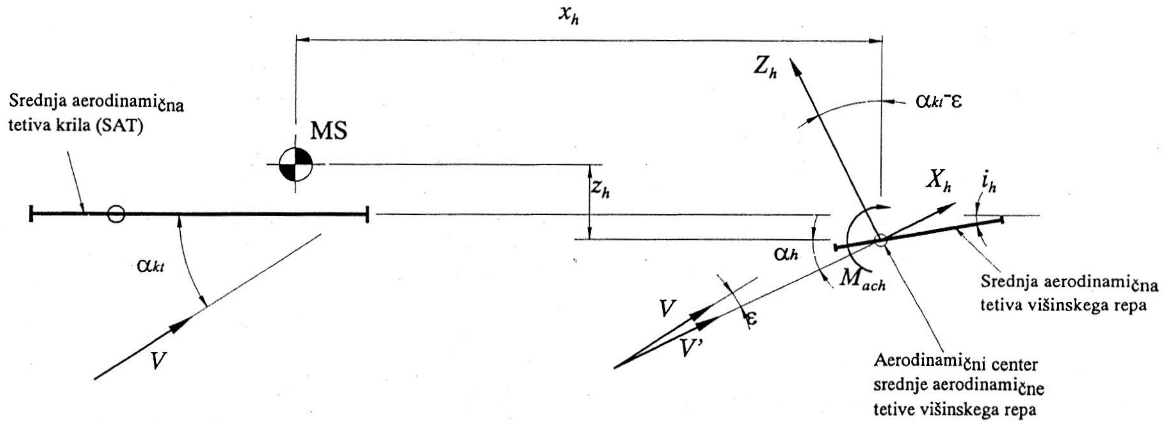


Vpliv lege masnega središča na gradient količnika momenta

Pitch control



Tail contribution



$$C_{mh} = -\eta \overline{V}_h a_h \alpha_h = -\eta \overline{V}_h a_h (\alpha - i_k - \varepsilon + i_h)$$

Pitch moment of complete airplane

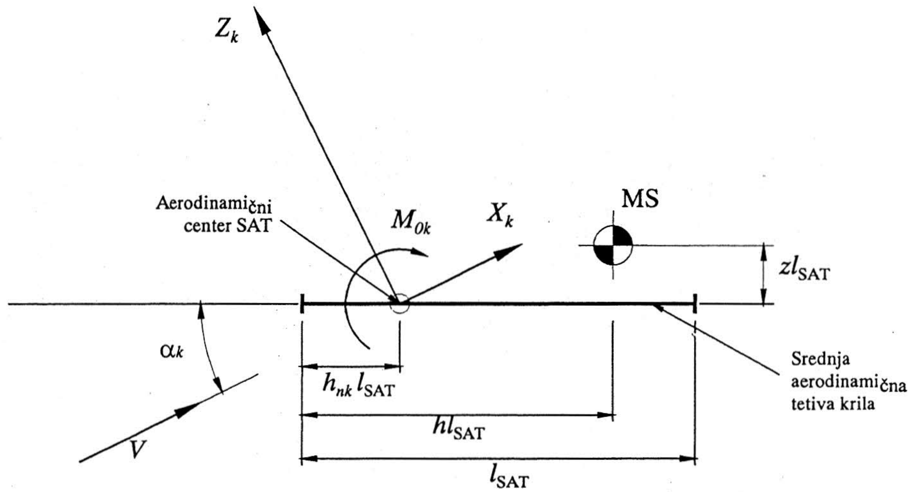
$$C_m = C_{m\,fus} + C_{m\,a.c.} + a\alpha(h - h_{a.c.}) - \eta \overline{V}_h a_h (\alpha - i_k - \varepsilon + i_h) + C_{m\,F} + C_{m\,D}$$

Balance or equilibrium: $C_m = 0$

Static stability: $\dfrac{\partial C_m}{\partial C_z} < 0$ or $\dfrac{\partial C_m}{\partial \alpha} < 0$

Neutral point: $N_0 = h_n$

$$\frac{\partial C_m}{\partial \alpha} = a(h - h_n)$$



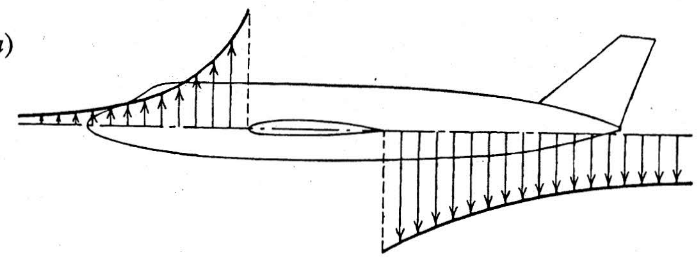
$$\sin\alpha_k \cong \alpha_k\,,\quad \cos\alpha_k \cong 1$$

$$C_{mk} = C_{m\,a.c.} + C_Z\left(h - h_{a.c.}\right)$$

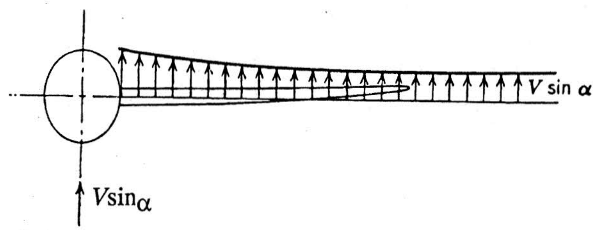
$$C_{mk} = C_{m\,a.c.} + \alpha a\left(h - h_{a.c.}\right)$$

Fuselage contribution

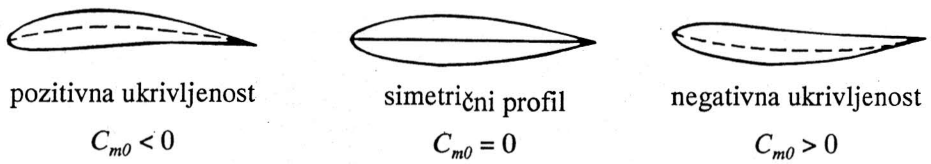
a)

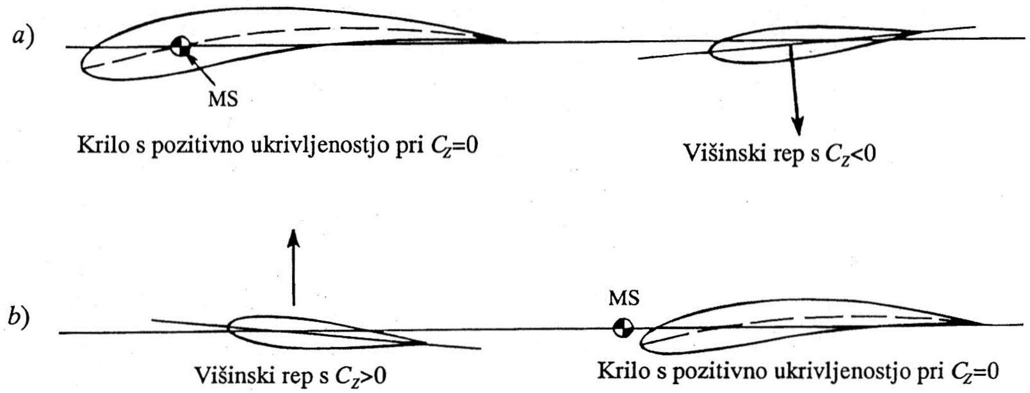


b)

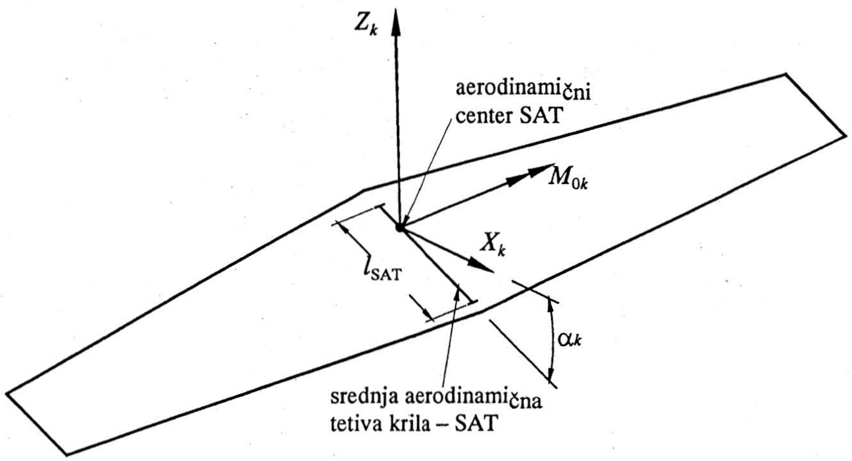


Possible arrangement of wing and tail surfaces





Wing contribution

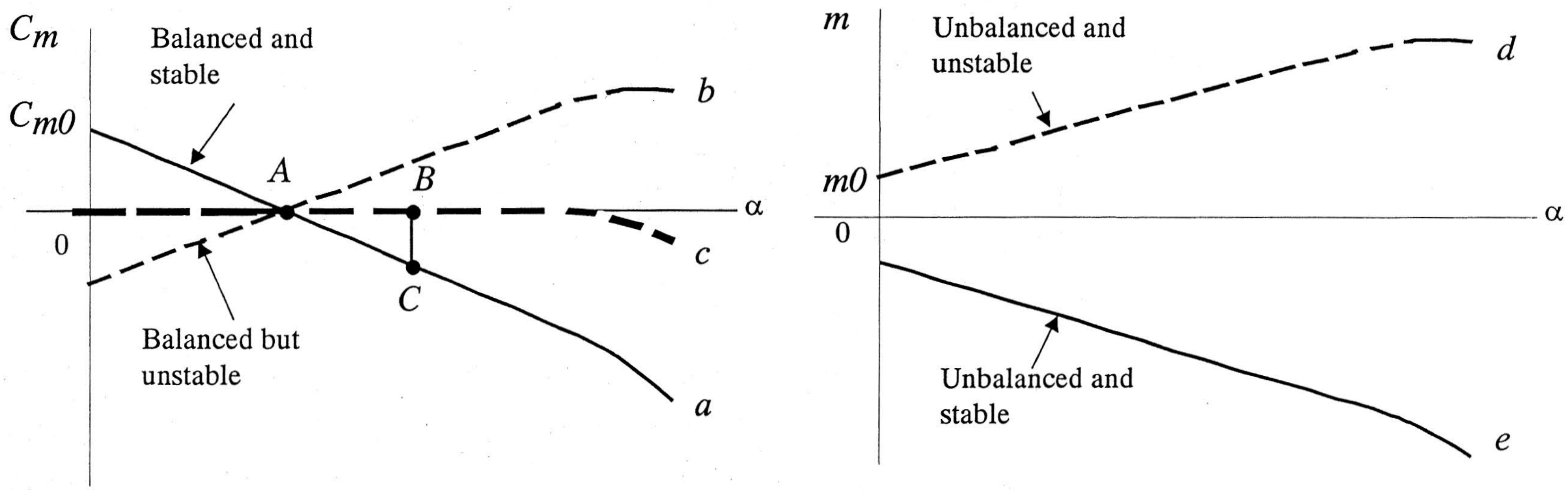


Stability and control are analysed in three planes:

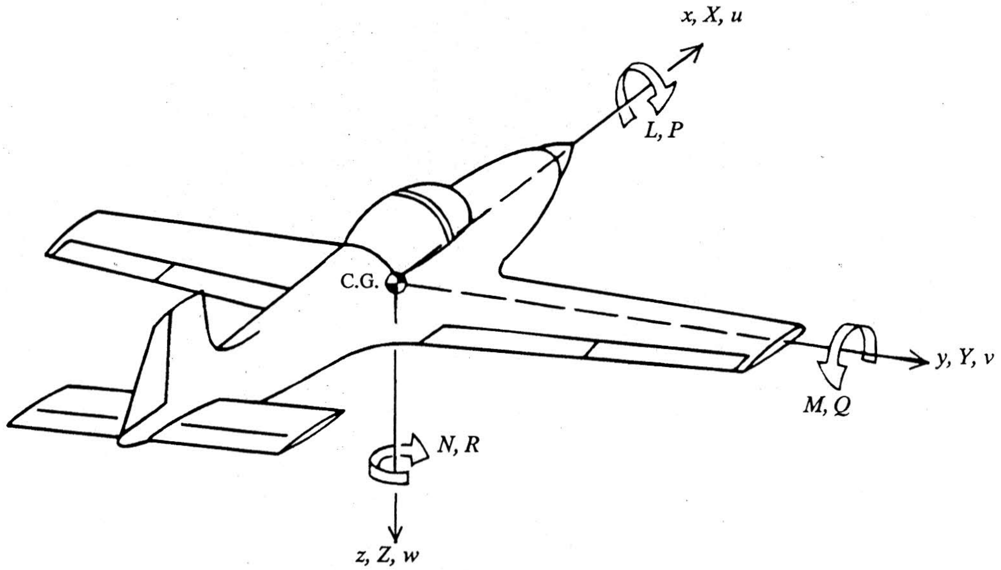
MOTION	STABILITY
Pitch	Longitudinal
Yaw	Directional
Roll	Lateral

Airplane longitudinal static stability

- pitch motion



System of axes



vrtenje okrog:

vzdolžne osi *valjanje* (ang. roll; nem. rollen)

okrog navpične osi *sukanje* (ang. yaw; nem. gieren)

prečne osi !? (ang. pitch; nem. nicken)

axis	Linear velocities	Aerodynamic forces	Angular velocities	Aerodynamic moments	Moment of inertia	Angular displacements
Ox	u	X	p	L	I_x	ϕ
Oy	v	Y	q	M	I_y	θ
Oz	w	Z	r	N	I_z	ψ

Dynamic stability

Dynamic stability is concerned with the subsequent behaviour of a body which possesses static stability. The motion consists of either oscillations about the equilibrium position or aperiodic motion. There are once again three possibilities:

- a body is dinamically *stable* when the amplitude reduces with time
- a body is statically *unstable* when the amplitude increases with time
- a body possesses *neutral* when the amplitude remains constant

Airplane stability

- airplane is designed mainly from performance considerations, but it must also posses acceptable handling characteristics, if necessary achieved by arificial methods
- motion of rigid airplane can be represented as translation along and rotation about three mutually perpendicular axes
- airplane must be controllabe
- stability and control are closely related

Assumptions

- rigid airplane

- conventional arrangement of surfaces

Airplane Stability

Definitions:

Equilibrium

A body is in static equilibrium when it is in a state of rest of uniform motion in a straight line and the forces actiong on it are balanced out.

The definition can be extended to cover those bodies in uniform motion in a curved path. Ther is, in these cases, a resultatn force ana an acceleration towards the centre of the curved path, but they can be considered as cases of dynamic equilibrium.

Stability is property of the equilibrium state and there are two types of stability to consider, static stability and dynamic stability.

Static stability

Static stability is concerned with the forces and moments produced by a small disturbance from the condition of equilibrium. It determines whether or not the body will ***intially*** tend to return, of its own accord, towards the equilibrium condition, once the disturbance is removed.

- a body is statically *stable* when it **tends** to return to the equilibrium position
- a body is statically *unstable* when it **tends** to diverge further away from the equilibrium position
- a body possesses *neutral* static stability when it remains in the disturbed position

degree of static stability possessed by a body:

$$\frac{\text{Restoring effect produced as a result of the disturbance}}{\text{Magnitude of the disturbance}}$$

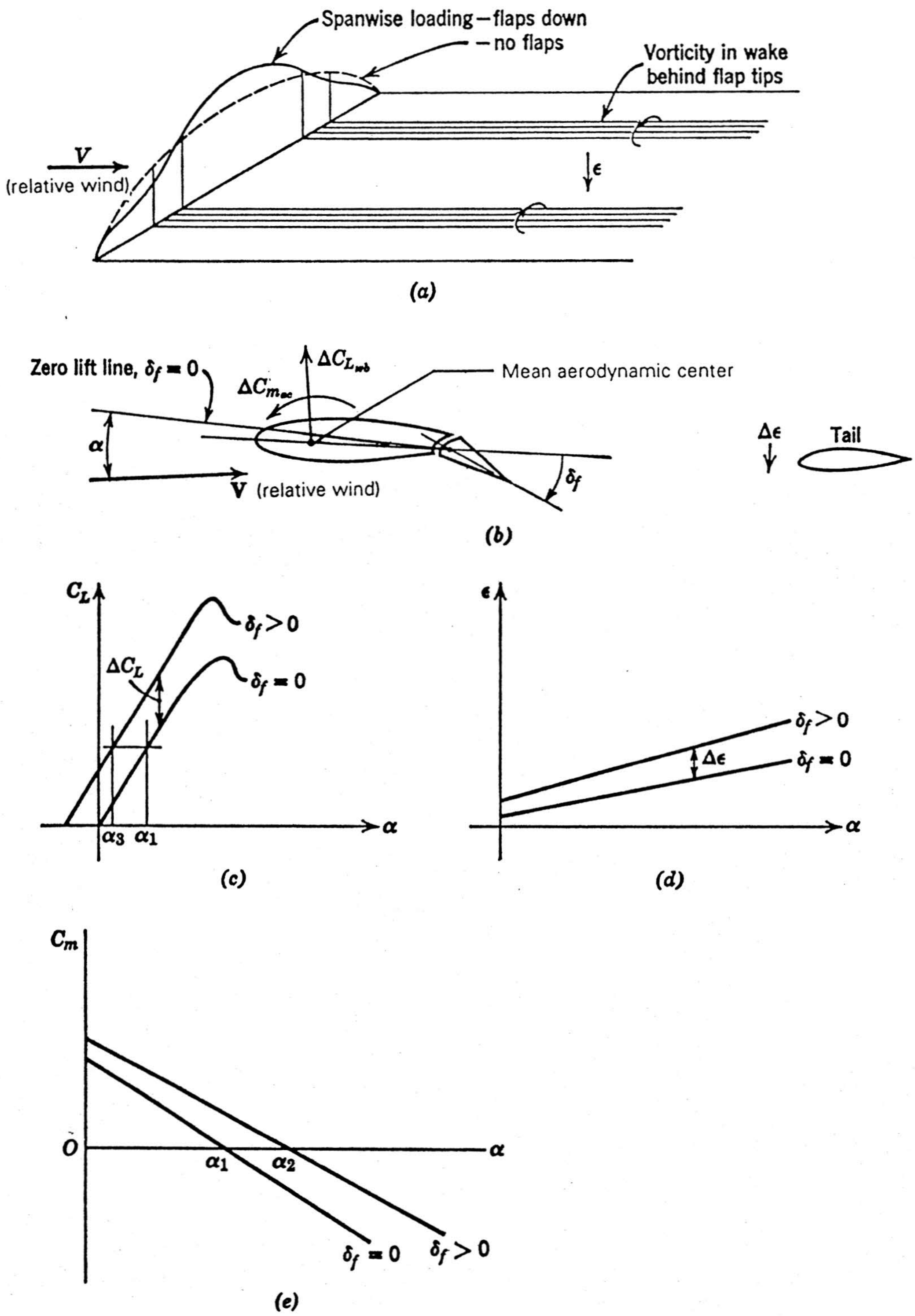


Figure 3.4 Effect of part-span flaps. (*a*) Change of lift distribution and vorticity. (*b*) Changes in forces and moments. (*c*) Change in C_L. (*d*) Change in downwash. (*e*) Change in C_m.

3.4 *Influence of the Propulsive System on Trim and Pitch Stiffness*

The influences of the propulsive system upon trim and stability may be both important and complex. The range of conditions to be considered in this connection is extremely wide. There are several types of propulsive units in common use—recipro-

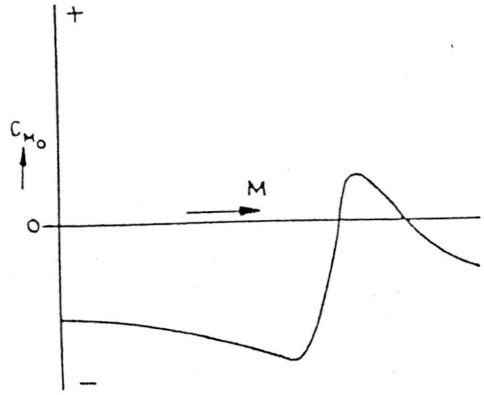


Fig. 15.10. Zero-lift pitching moment characteristics

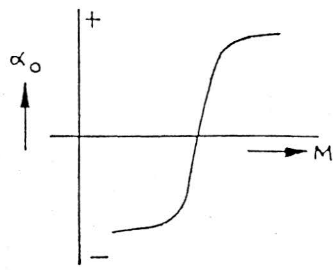


Fig. 15.11. Effect of Mach number on the no-lift angle

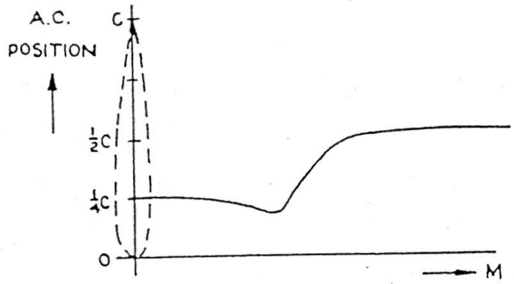


Fig. 15.12. Effect of Mach number on the position of the aerodynamic centre

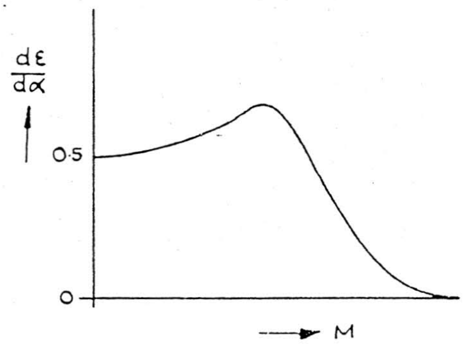


Fig. 15.14. Variation of $d\varepsilon/d\alpha$ with Mach number

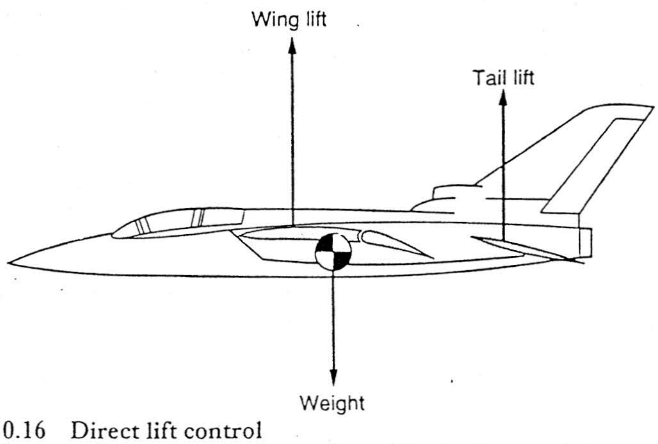


Fig. 10.16 Direct lift control

By deflecting a flap or similar wing surface while simultaneously increasing the tail lift by increasing its incidence or camber, the overall lift can be increased directly, with no change in pitch angle

This procedure can only be used if the centre of gravity lies aft of the wing centre of lift; an arrangement that is naturally unstable in a conventional configuration aircraft

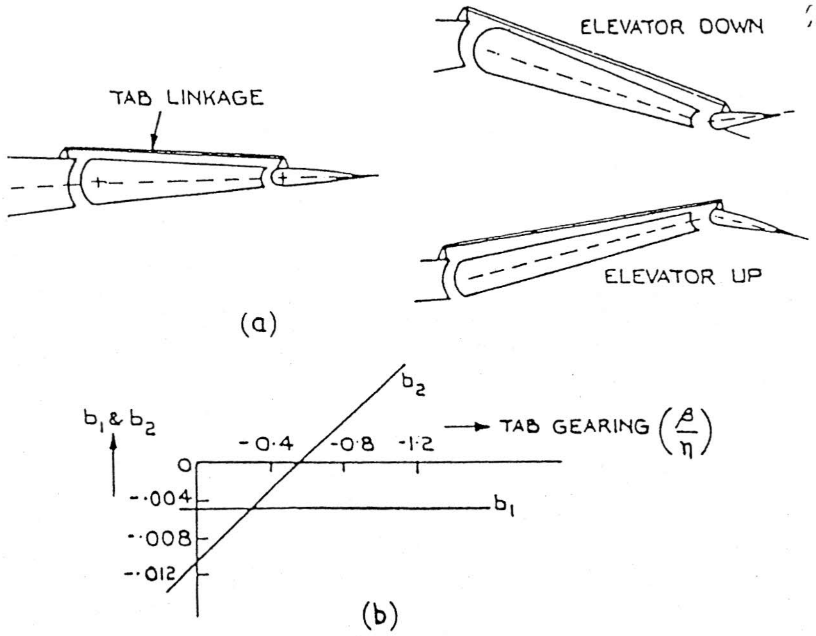


Fig. 10.18. Geared balance tab [From Ref. 1]

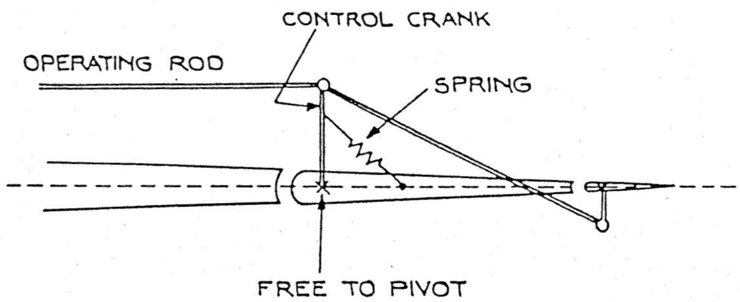
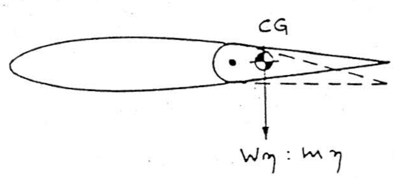
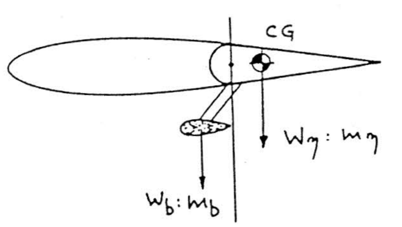


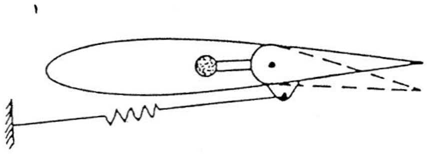
Fig. 10.19. Spring tab system



a. Unbalanced surface with centre of gravity aft of hinge (thus the weight of the surface acts as a bob-weight, which applies a moment proportional to normal acceleration. Bob-weights are used to increase static margins stick-free, increasing too stick-force per applied g).



b. Mass balanced control.



c. Mass balanced control with elevator down-spring. The latter is used to increase stick-free stability.

Fig. 12.10 Mass balancing and improvement of stick-free stability: the use of weight and spring.

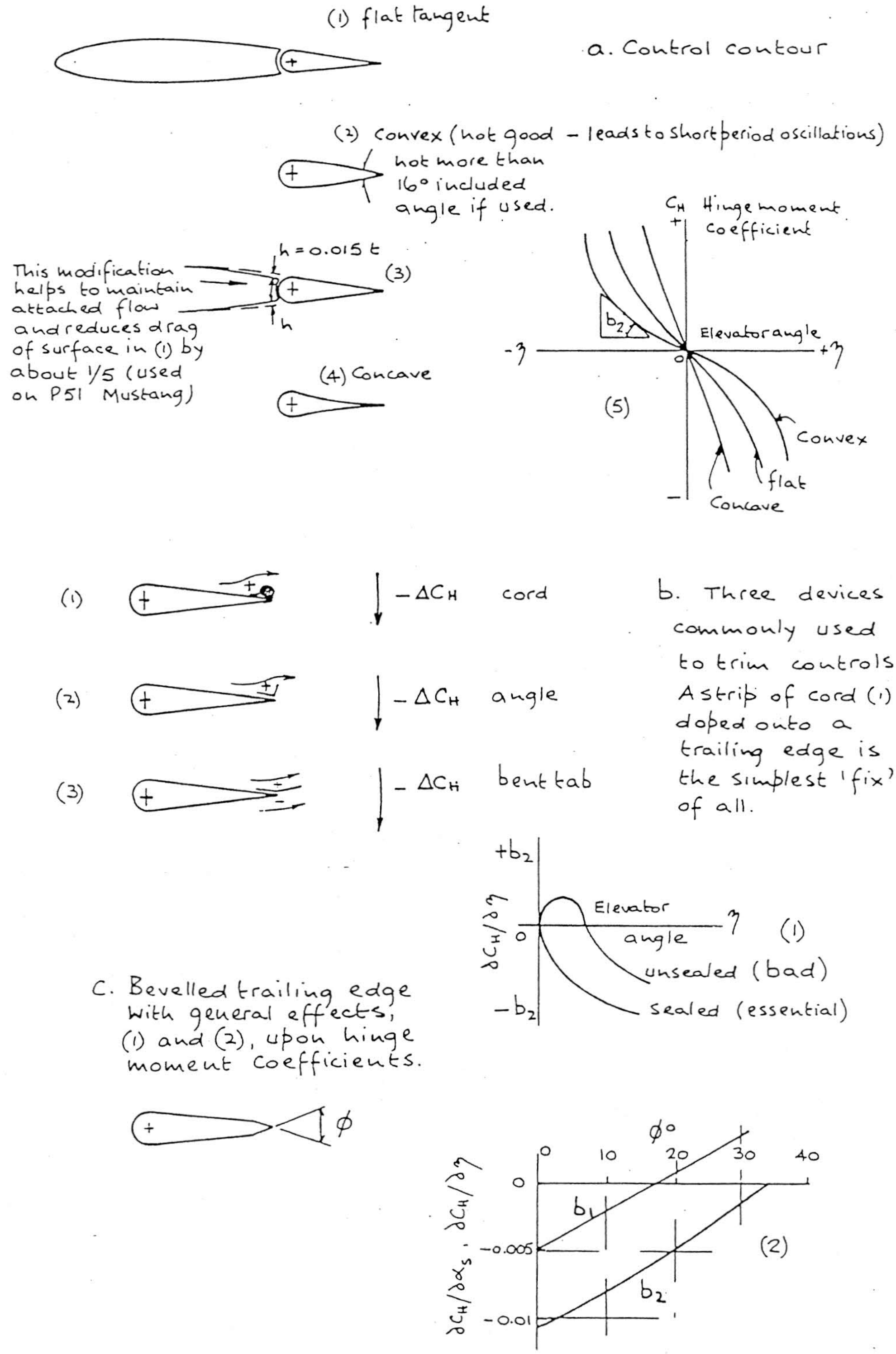


Fig. 12.6 Tricks for modifying control feel characteristics. Note that in b. each device has the effect of heavying the control in only one direction.

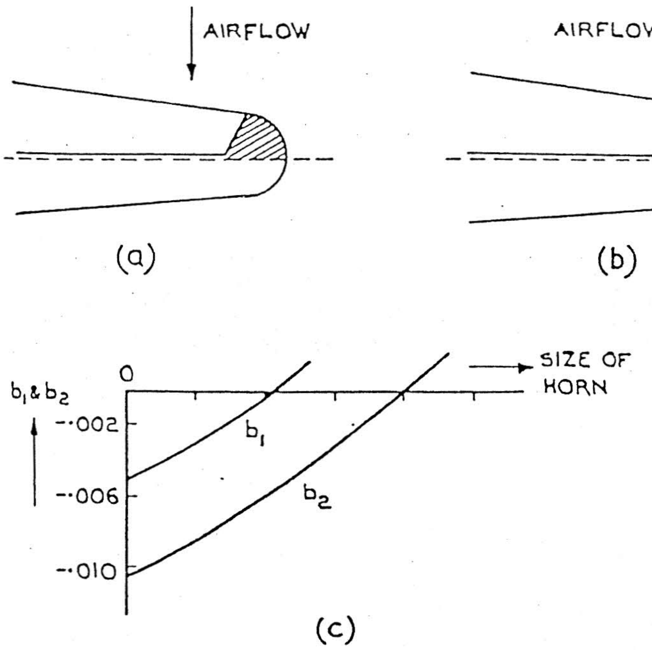


Fig. 10.13. Horn balance [From Ref. 1]

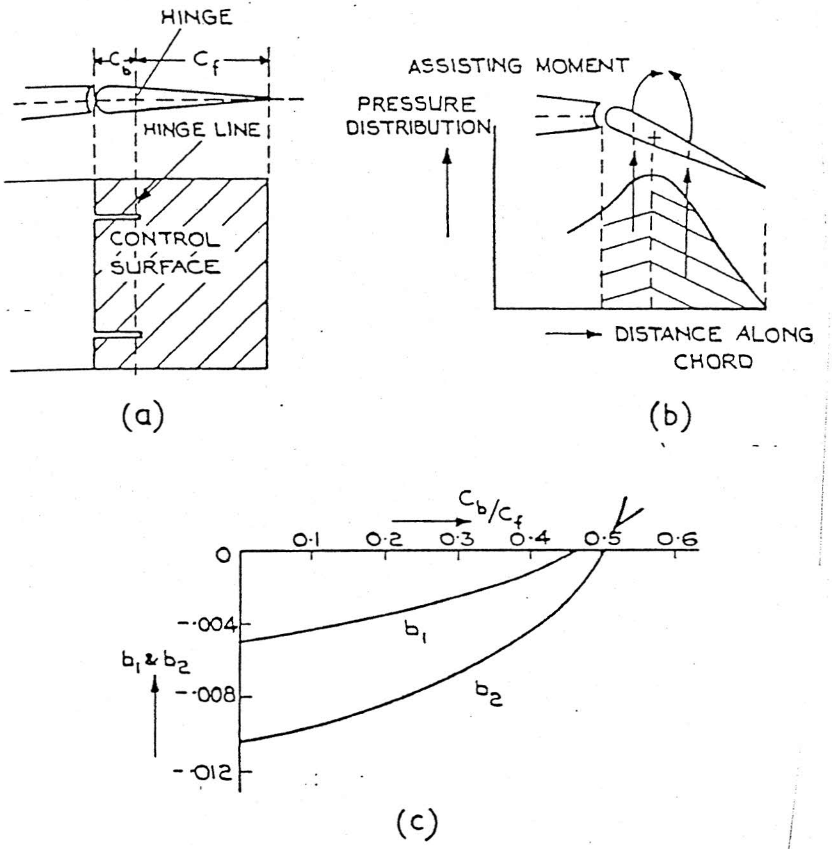


Fig. 10.12. Set-back hinge balance [From Ref. 1]

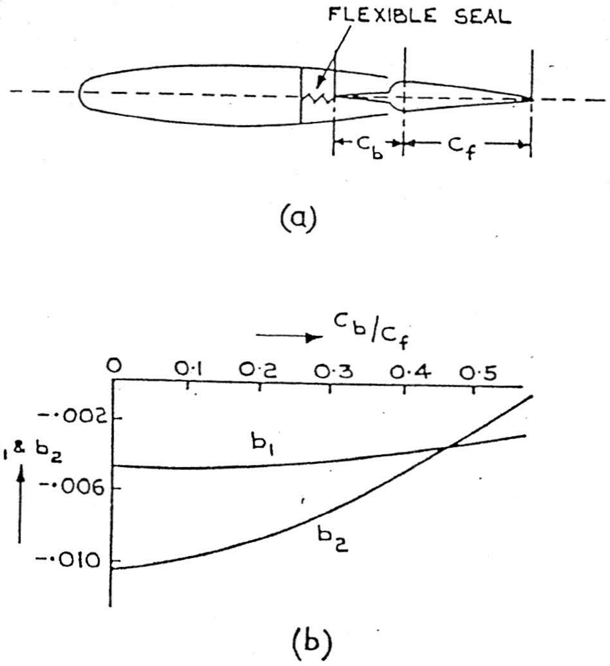
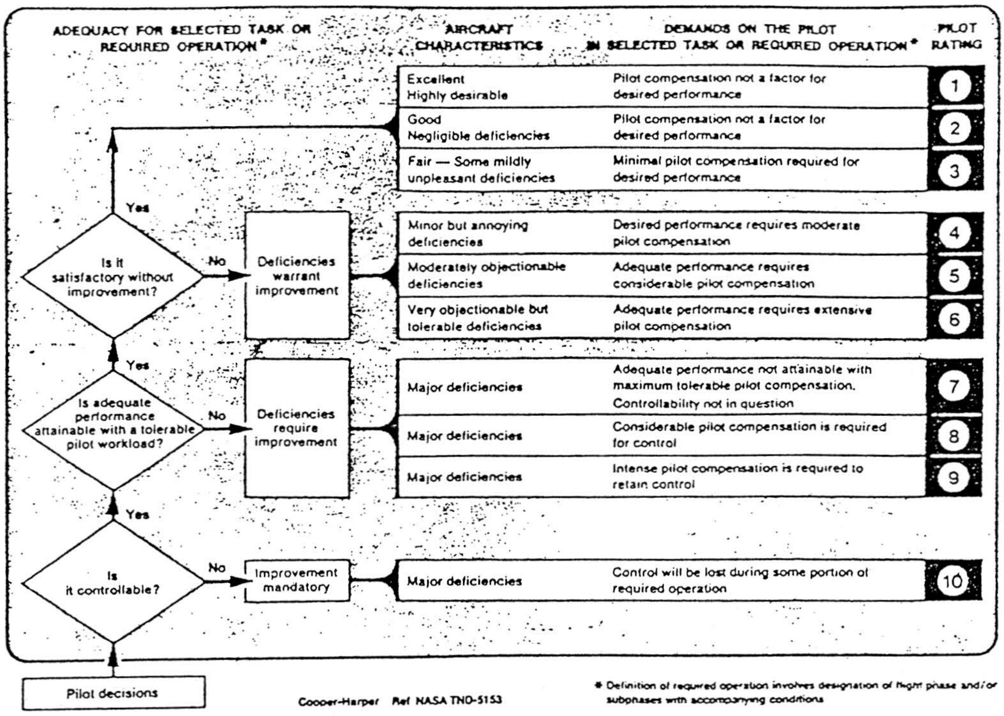


Fig. 10.14. Internal (Westland-Irving) balance [From Ref. 1]

Fig. 10.6. Handling qualities rating scale.



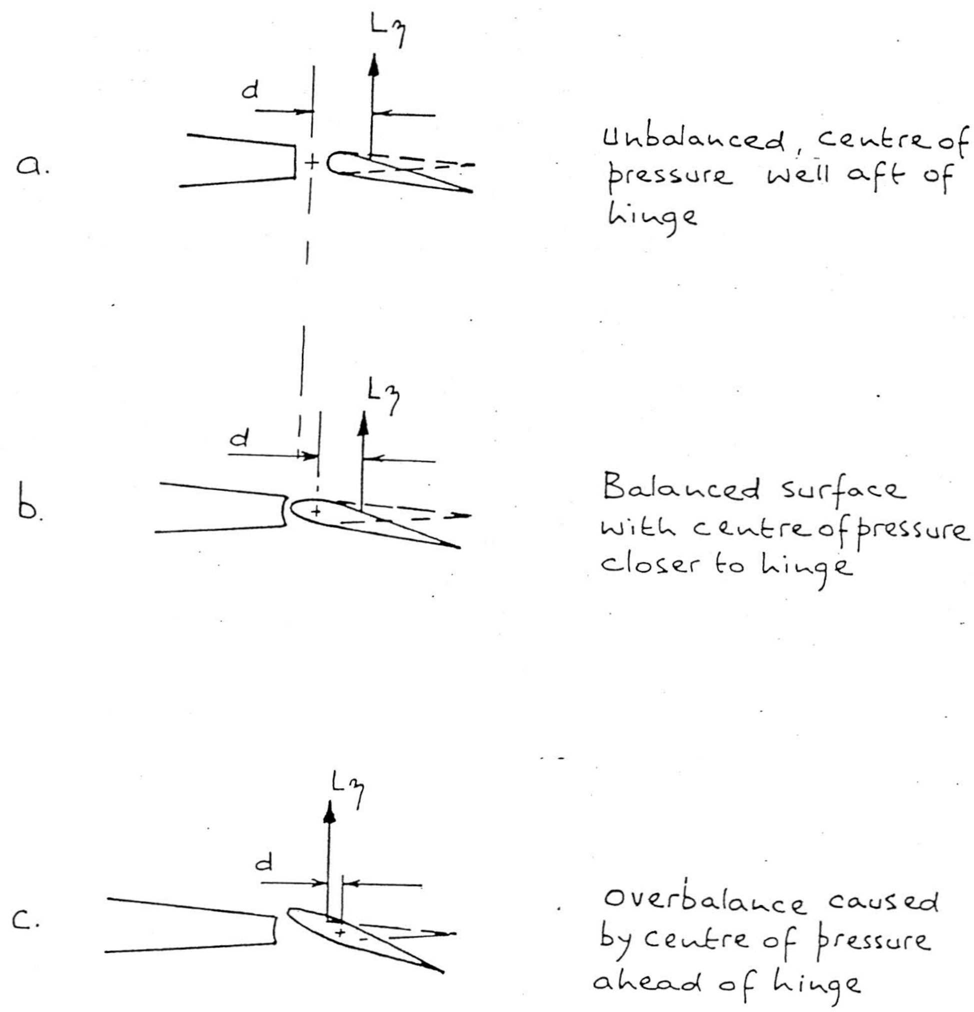


Fig. 12.1 Control balance and overbalance, which affect the stick force felt by the pilot and the mathematical term b_2: a measure of the rate of change of hinge moment (felt by the pilot) and elevator deflection.