

Bezpilotní prostředky

1. Aerodynamika

Aerodynamika - rozdělení

- Letecká
- Dopravních zařízení
- Stavebnictví
- Průmyslová, Energetika
- Životní prostředí
- Volný čas, sport

- Vnější
- Vnitřní
- Výpočtová (CFD)
- Teoretická
- Experimentální

- Nízkorychlostní (Hydrodynamika) $M \sim 0,2 \div 0,3$
- Vysokorychlostní (Subsonická)
- Okolozvuková (Transsonická) $M \sim 1$
- Nadzvuková (Supersonická) $M < 3 (5)$
- Hypersonická $M > 5$

Základní pojmy – vlastnosti plynů

Kontinuum

$$\rho(x,y,z,t) = \lim_{\Delta V \rightarrow \infty} \frac{\Delta m}{\Delta V}$$

- Hmoty rozložena v dV rovnoměrně, spojitě
- Homogenita, izotropie, charakteristický rozměr oblasti

Kinetická teorie plynů

- Střední volná dráha molekul (L)
- Střední doba mezi srážkami (Δt)
- V kontinuu
 - L – malá ve srovnání s charakteristickým rozměrem
 - Δt – krátký, stochastický charakter

Projevy diskontinuálních vlastností

- Nízké teploty
- Velké výšky

Soudržnost (kohezní síly)

- Pevná fáze
- Kapaliny
- Plyny

| h [km] | L |
|--------|----------------------|
| 0 | ~ 0,06 μm |
| 50 | ~ 90 μm |
| 120 | ~ 1 m |
| 150 | ~ 10 m |

| h [km] | Δt [s] |
|--------|------------------------|
| 0 | ~ $1,3 \cdot 10^{-10}$ |
| 50 | ~ $2 \cdot 10^{-7}$ |

| h [km] | p [Pa] |
|--------|---------|
| 0 | 101 325 |
| 50 | 66 |

Stavová rovnice ideálního plynu

$$pv = RT$$

$$\frac{p}{\rho} = RT \text{ [J/kg]}$$

$$R = \frac{\bar{R}}{m}$$

Rychlost zvuku

| Materiál | a [m/s] |
|------------------|---------|
| Ocel | 5300 |
| H ₂ O | 1517 |
| Vzduch | 330 |

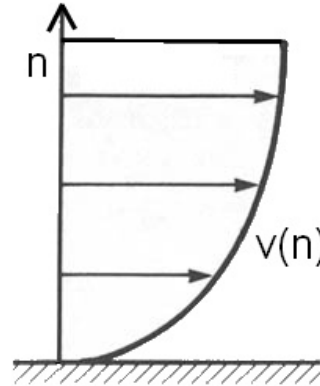
- ✓ R - specifická plynová konstanta
 - Vzduch 287 [J/kg K]
- ✓ m - molární hmotnost
 - Vzduch 28,97 [kg/kmol]
- ✓ \bar{R} - univerzální plynová konstanta
 - 8314,41 [J/kmol K]
- ✓ a – rychlost zvuku [m/s]
- ✓ v – specifický (měrný) objem

$$v = \left(\frac{1}{\rho} \right) \text{ [m}^3\text{/kg}^{-1}\text{]}$$

Newtonův zákon tření

- μ – dynamická vazkost [Ns/m²]

$$\tau = \mu \frac{dv}{dn}$$



- v - rychlost
- Kinetická teorie plynů (Chapman)
- $\mu = \mu(T)$
 - plyny $\uparrow T, \uparrow \mu$
 - kapaliny $\uparrow T, \downarrow \mu$

- ν – kinematická vazkost [m²/s]

$$\nu = \frac{\mu}{\rho}$$

- ✓ SHUTTERLAND

$$\mu = \frac{\beta T^{3/2}}{T + S}$$

- ✓ RAYLEIGH

$$\mu = \mu_0 \left(\frac{T}{T_0} \right)^{3/4}$$

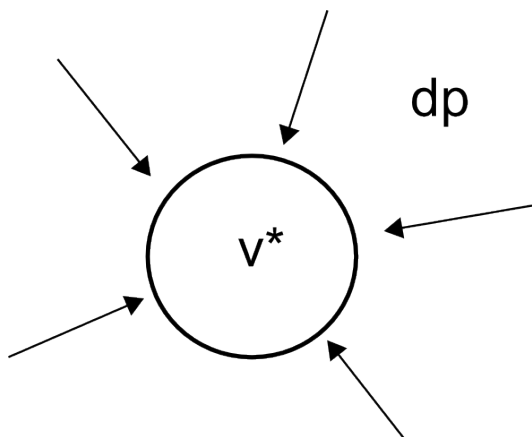
| Konstanty | |
|-----------|--|
| T_0 | 273,15[K] |
| μ_0 | $1,789 \cdot 10^{-5}$ [Ns/m ²] |
| S | 110,4[K] |
| β | $1,458 \cdot 10^{-6}$ [kg/sm \sqrt{K}] |

$$\mu = 0.461 \bar{c} L \varrho$$

$$\bar{c} = \sqrt{3RT} \doteq \sqrt{T}$$

$$L \sim \frac{1}{\varrho}$$

Stlačitelnost tekutin – rychlost zvuku



$$d\rho = f(dp)$$

$$dV^* = \frac{1}{K} V^* dp$$

$$d\rho = \frac{1}{a^2} dp$$

$$\frac{dp}{d\rho} = a^2$$

- **Rychlost zvuku**

- Rychlost šíření malých (elementárních) rozruchů v tekutině.
- Podélný směr, rychlé změny p a Q v elementární tlakové vlně, $\Delta T = 0$

- **Šíření zvuku – izoentropický (adiabatický) jev**

$$a = \sqrt{\kappa \frac{p}{\rho}} = \sqrt{\kappa RT}$$

- ✓ V^* - specifický objem

$$V^* = \frac{1}{\rho}$$

- ✓ K – modul objemového stlačení (pro plyny - Laplace)

$$K = a^2 \rho$$

- ✓ Izoentropický (adiabatický) jev

$$p\rho^{-\kappa} = \text{konst}$$

$$d(p\rho^{-\kappa}) = d(\text{konst})$$

$$\frac{dp}{d\rho} = \kappa \frac{p}{\rho}$$

- ✓ Izoentropický exponent (vzduch)

$$\kappa = 1,4$$

Bezrozměrné charakteristiky

- **Reynoldsovo číslo**

$$\frac{\text{setrvačná síla}}{\text{třecí síla}} \sim \frac{\text{hmota} \cdot \text{zrychlení}}{\text{smykové napětí} \cdot \text{plocha}}$$

$$\frac{ma}{\tau S} = \frac{(\rho l^3) \left(\frac{v^2}{l}\right)}{\left(\mu \frac{v}{l}\right) (l^2)} = \dots = \frac{lv}{\nu} = \mathbf{Re}$$

- **Machovo číslo**

$$\frac{\text{setrvačná síla}}{\text{elastická síla}} \sim \frac{\text{hmota} \cdot \text{zrychlení}}{\text{tlak plocha} \cdot \text{plocha}}$$

$$\frac{ma}{pS} = \frac{(\rho l^3) \left(\frac{v}{t}\right)}{(p) (l^2)} = \frac{(\rho l^3) \left(\frac{v^2}{l}\right)}{(\rho a^2) (l^2)} = \dots = \frac{v^2}{a^2} = \mathbf{M^2}$$

- **Obecně**

- $Re = Re(v, h)$
- $M = M(v, h)$

Zemská atmosféra

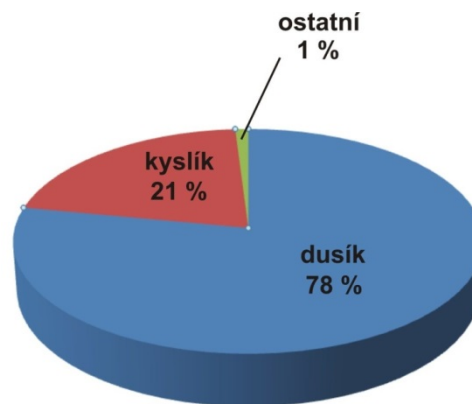
- Fyzikální vlastnosti

- Výška
- Zemská poloha
- Denní / roční doba
- Meteor. Podmínky

- Složení (stř. hodnoty) – do cca 100km [%]

- Suchý, čistý vzduch
- Vodní pára - do 10 km – (0-4)% objemu
- Příměsi (tuhé, plynné,...)
 - Kondenzační jádra

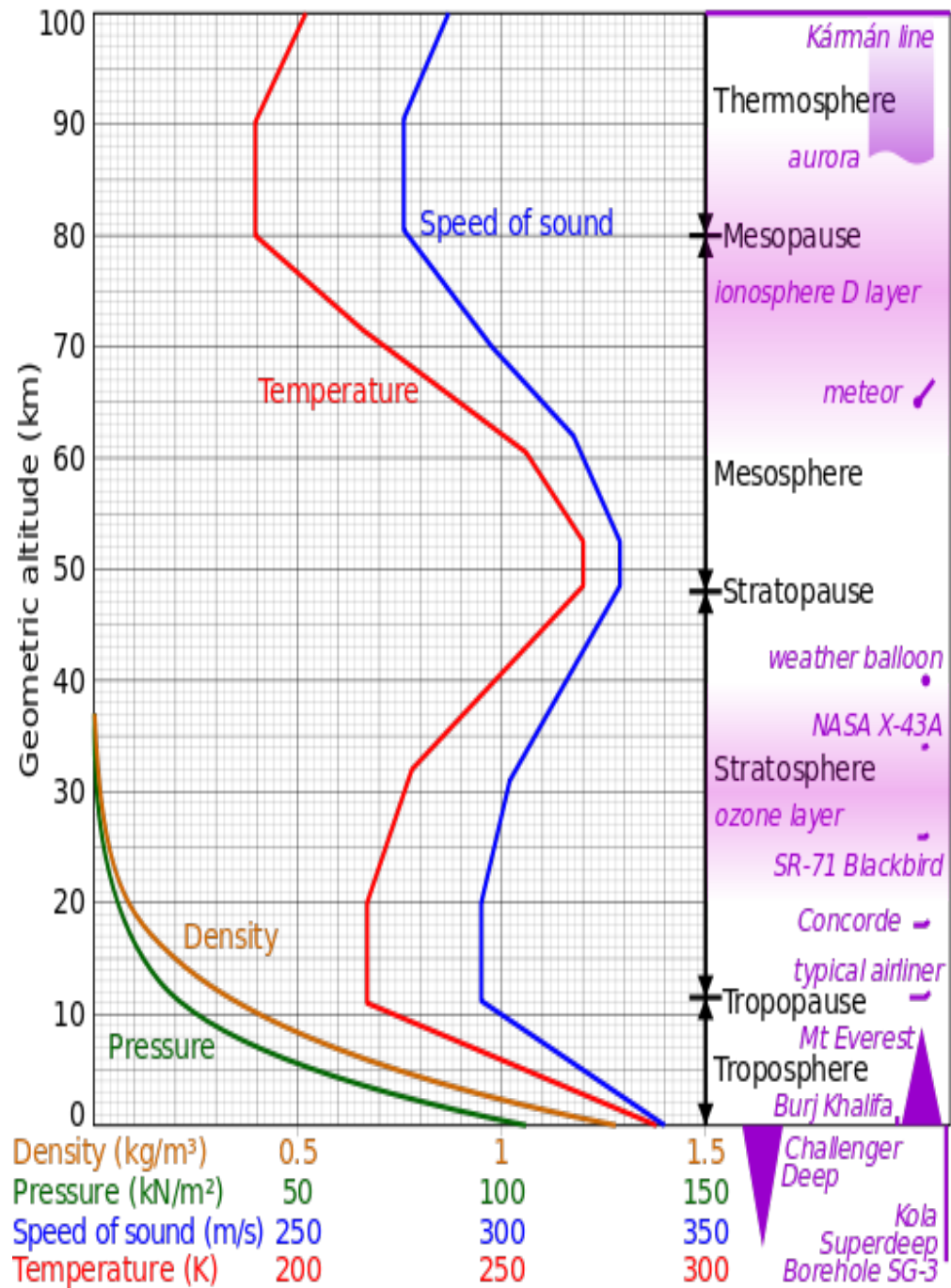
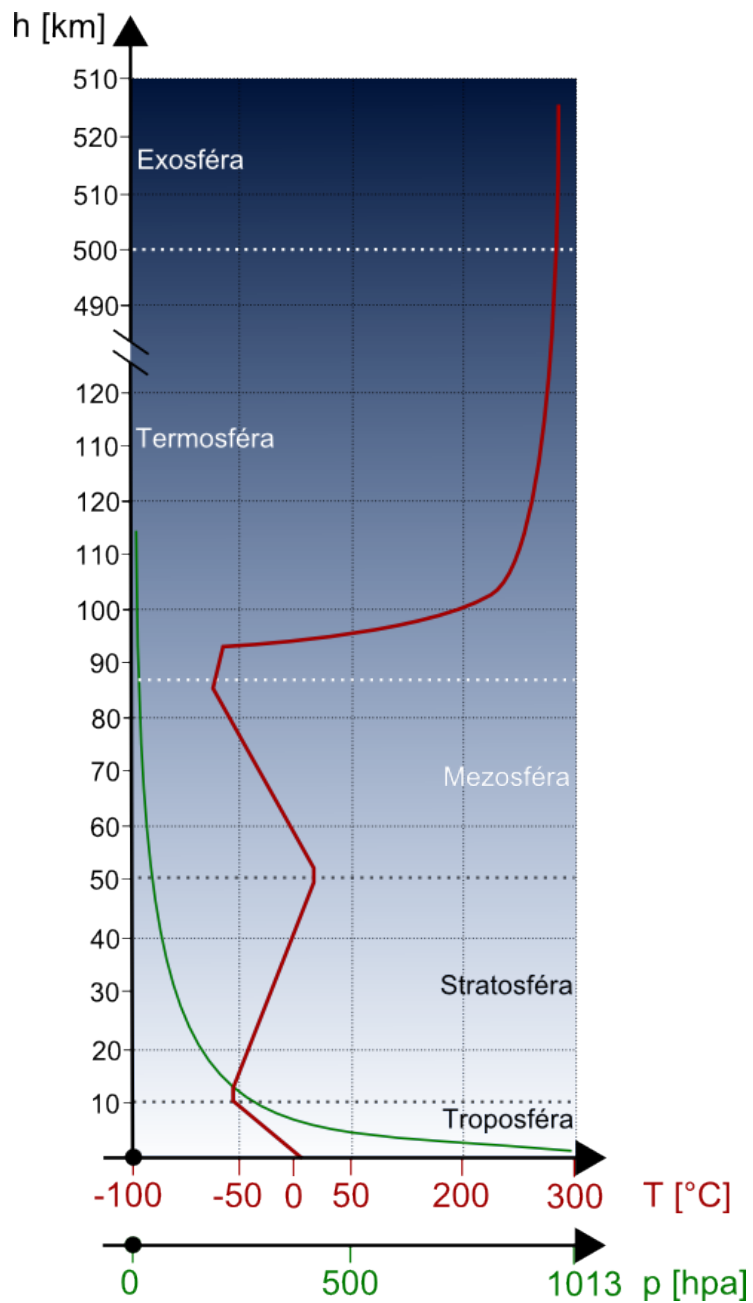
| Název | Označení | Podíl [%] |
|---------------|----------------------------|-----------|
| Dusík | N ₂ | 78 |
| Kyslík | O ₂ | 21 |
| Argon | Ar | 0,93 |
| Oxid uhličitý | CO ₂ | 0,03 |
| Ostatní plyny | He,Ne,Ch ₄ ,... | <0,1 |



- Stavba atmosféry

- „Hustá“ atmosféra do 50km (2% R_z)
- 99% Hmotnosti vzduchu obalu země do 36km
- Horní hranice 3000 km
- Stopy atomů zem. obalu 30 000 km (H₂)

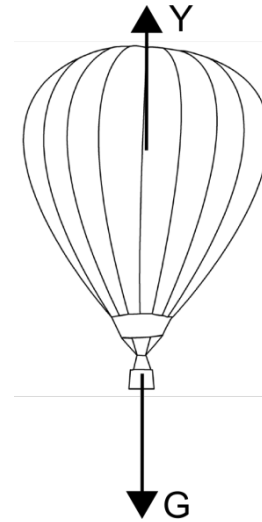
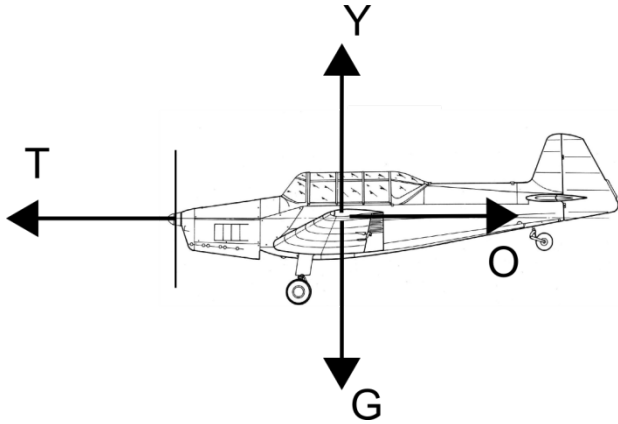
| H = h = 0 | |
|-----------------|----------------------------|
| g ₀ | 9,807 [m/s ²] |
| M _{m0} | 28,97 [kg/kmol] |
| R ₀ | 287,1 [J/kgK] |
| T ₀ | 288,2 [K] |
| p ₀ | 101 325 [Pa] |
| Q ₀ | 1,225 [kg/m ²] |
| μ ₀ | 1,789 [Ns/m ²] |
| v ₀ | 1,461 [m ² /s] |
| a ₀ | 340,3 [m/s] |



Síly na letoun

- Aerodynamické
- Propulzní
- Pozemní (podvozek, havarijní případy, ...)
- Ostatní (cizí tělesa, zbraňové systémy, ...)
- Hmotové
 - Tíha (\approx konst. \rightarrow násobek)
 - Setrvačné síly (pohybový stav letounu)

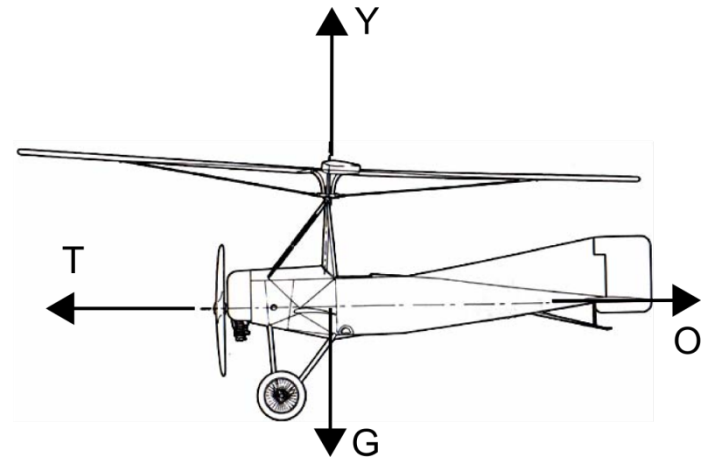
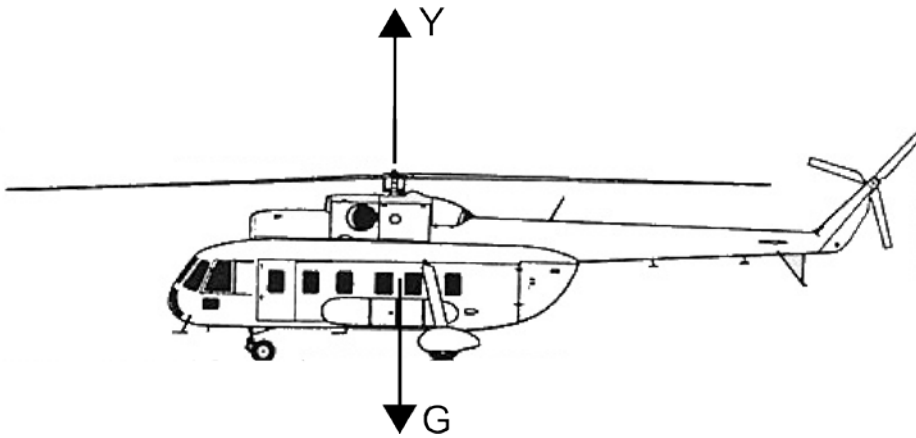
Síly na letoun



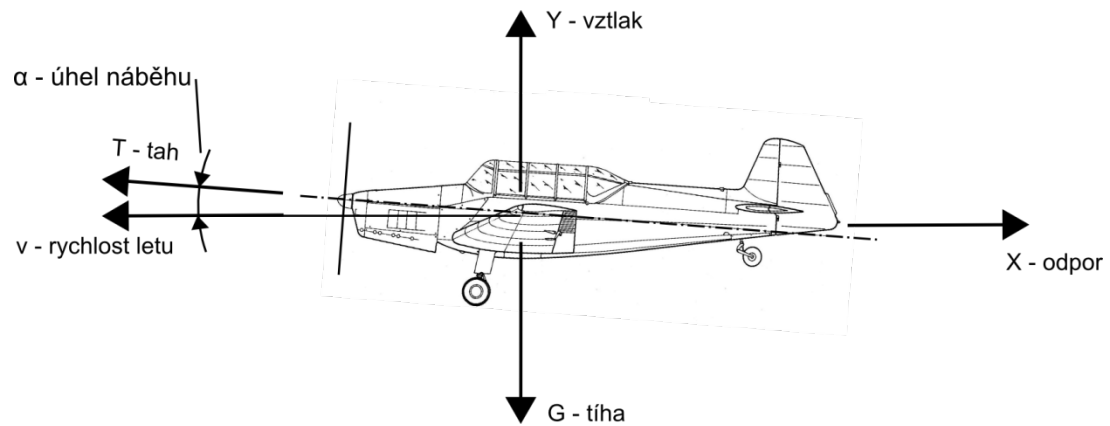
$$Y = V \rho g$$

$$G = \sum m_i g$$

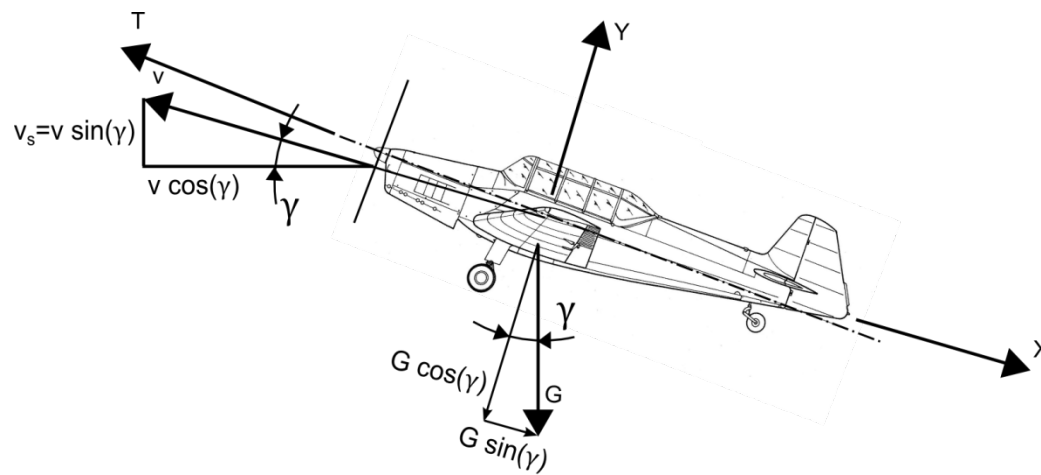
- m_i - konstrukce
- plyn
- užit. zatížení



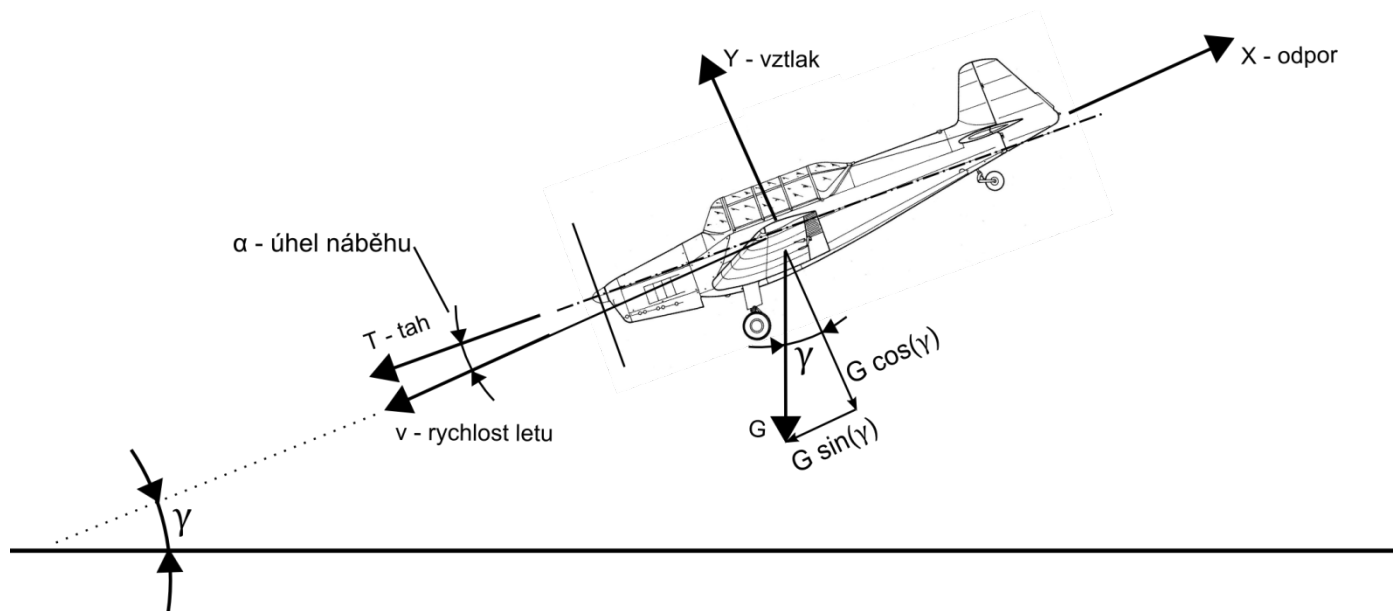
Vodorovný let



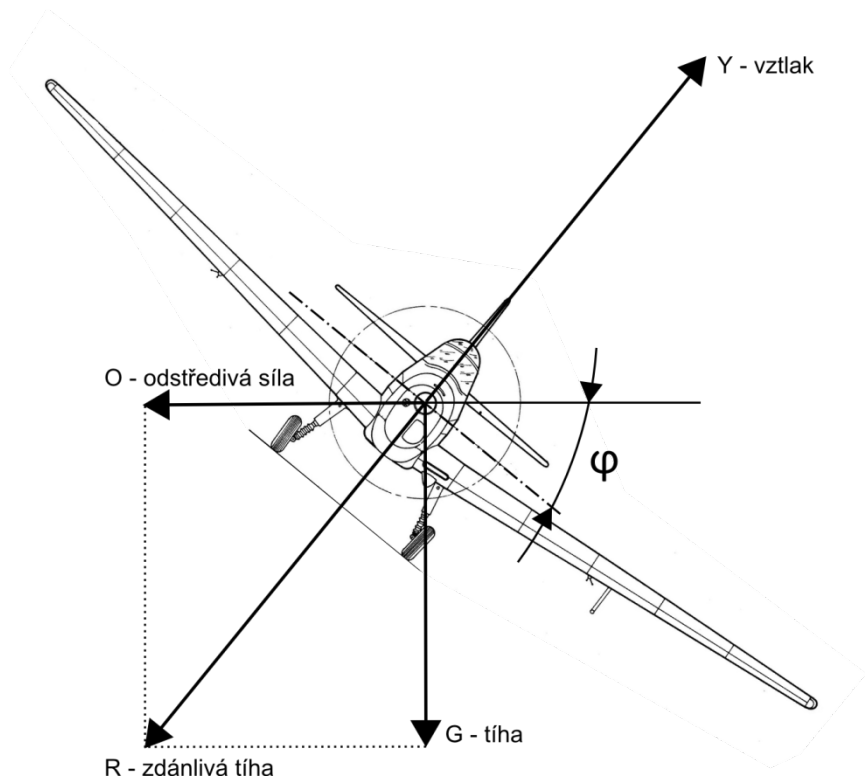
Stoupání



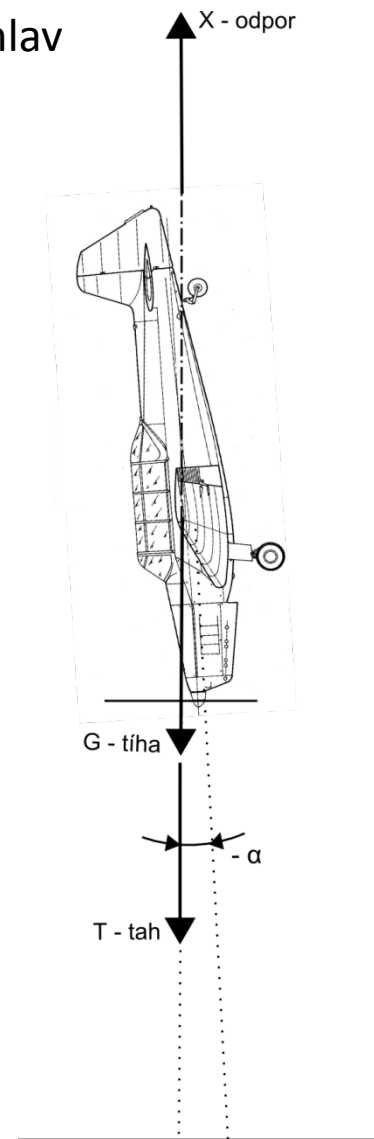
Klesání



Zatáčka



Let střemhlav



Aerodynamické síly a momenty

- **Vztlak**

$$Y = \frac{1}{2} \rho v_{\infty}^2 C_Y S \quad (Y, L)$$

- **Odpor**

$$X = \frac{1}{2} \rho v_{\infty}^2 C_X S \quad (X, D)$$

- **Bočná síla**

$$Z = \frac{1}{2} \rho v_{\infty}^2 C_Z S \quad (Z)$$

- **Klopivý moment**

$$M_Z = \frac{1}{2} \rho v_{\infty}^2 C_{mZ} S b$$

- **Zatáčivý moment**

$$M_Y = \frac{1}{2} \rho v_{\infty}^2 C_{mY} S b$$

- **Klonivý moment**

$$M_X = \frac{1}{2} \rho v_{\infty}^2 C_{mX} S b$$

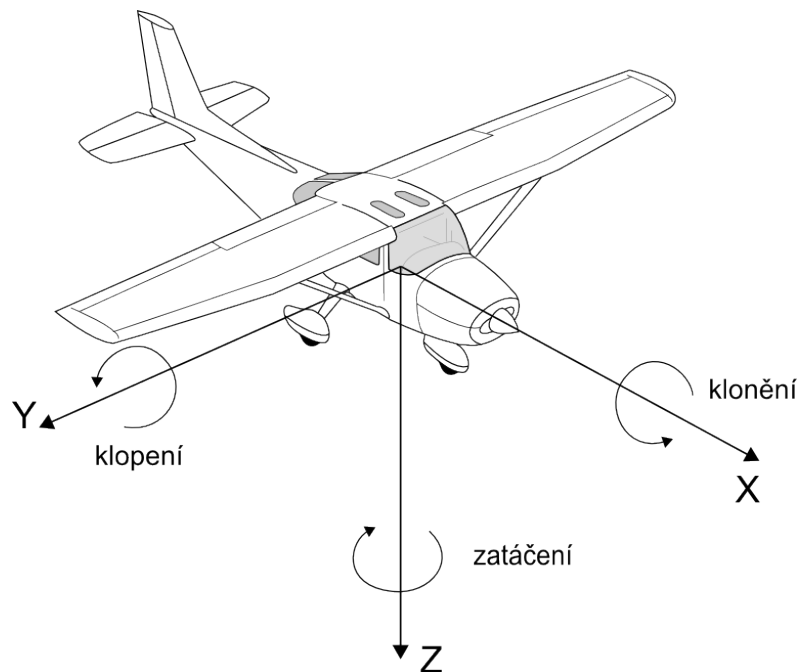
Výsledná Aerodynamická síla

$$\vec{R} = \sqrt{X^2 + Y^2 + Z^2}$$

$$C_R = \sqrt{C_X^2 + C_Y^2 + C_Z^2}$$

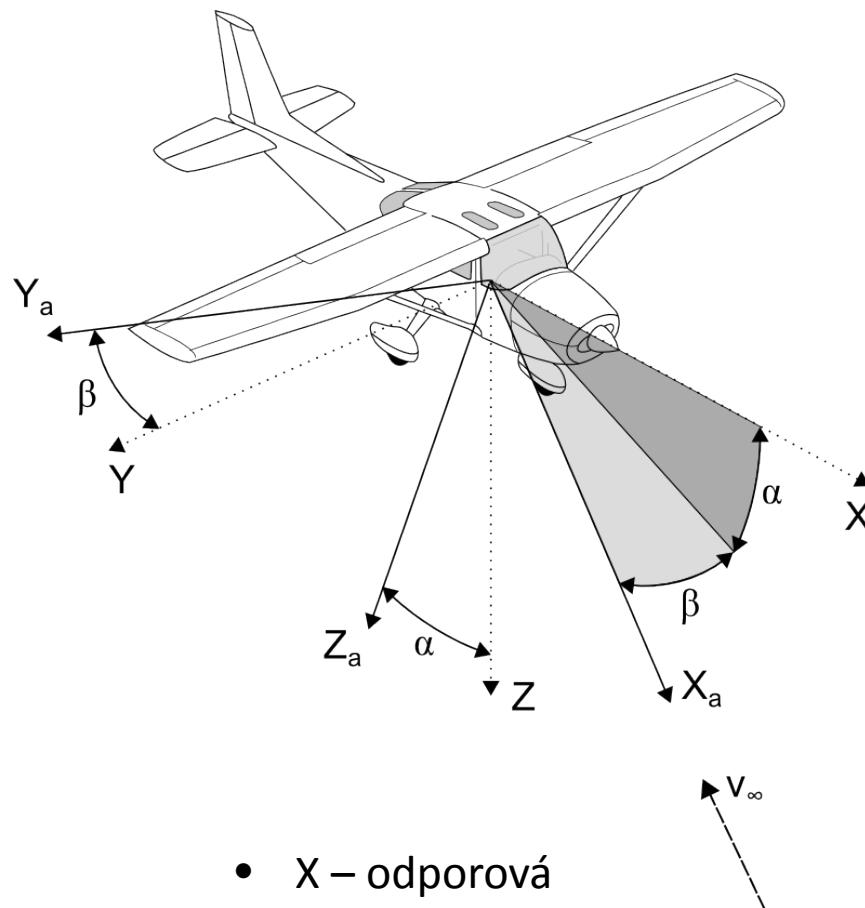
Souřadnicové soustavy

Letadlová souřadnicová soustava



- X – podélná
- Y – bočná
- Z – kolmá

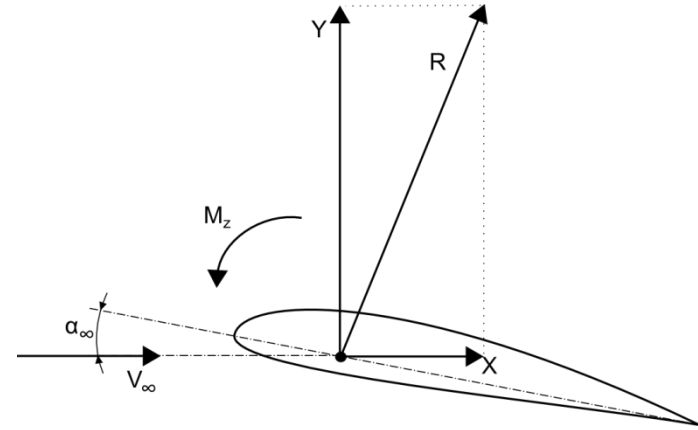
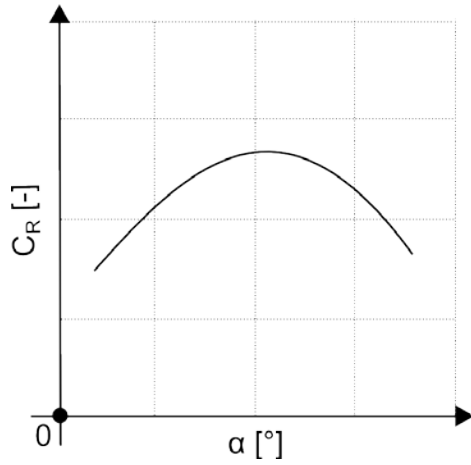
Aerodynamická souřadnicová soustava



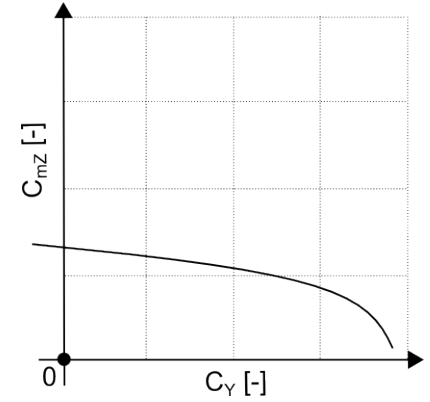
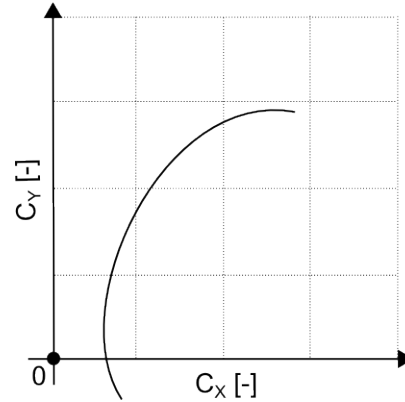
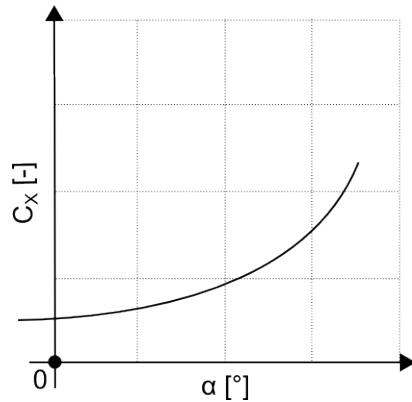
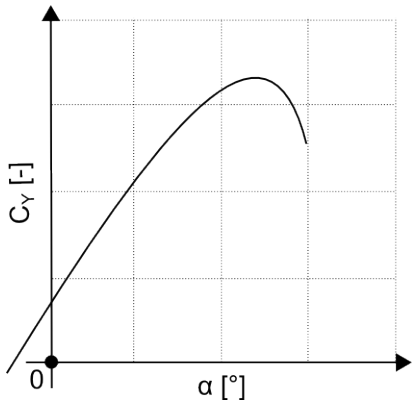
- X – odporová
- Y – příčná
- Z – vztlaková

Aerodynamické charakteristiky

Obecně

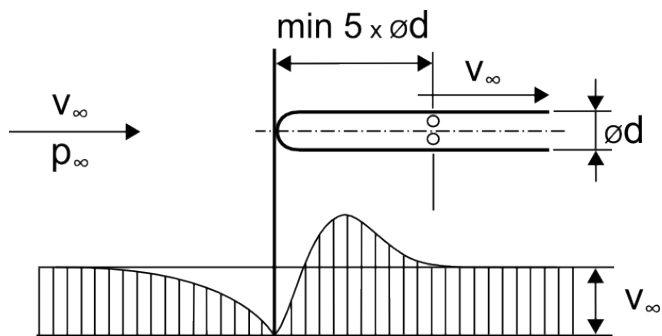


Těleso, profil, křídlo, letoun, ...

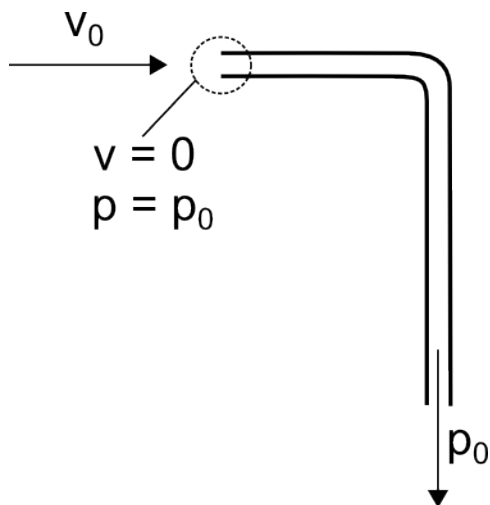


Měření tlaků, rychlostí

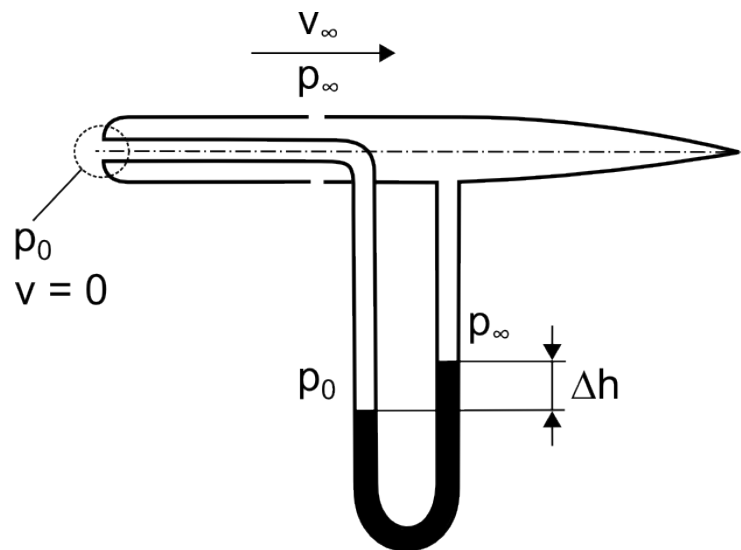
Statická sonda



Pittotova trubice



Pittot – statická (Prandtlova) sonda



$$p_0 = p_\infty + \frac{1}{2} \rho v_\infty^2$$

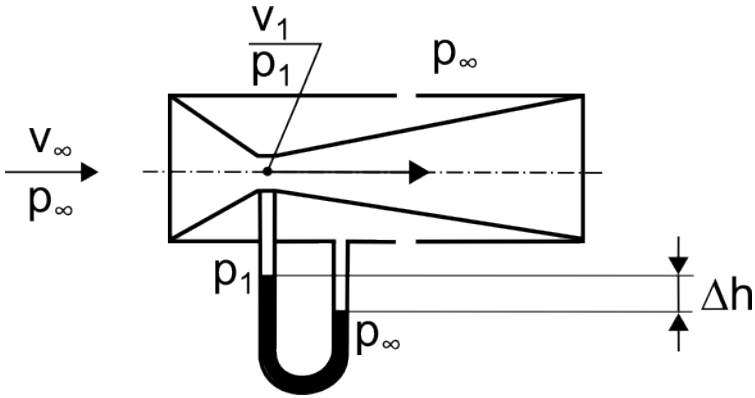
$$\Delta p = p_0 - p_\infty = \frac{1}{2} \rho v_\infty^2$$

$$v_\infty = \sqrt{\frac{2 \Delta p}{\rho}}$$

$$\Delta h \approx \Delta p$$

$$\Delta p = \Delta h g \rho_{\text{kap}}$$

Venturiho sonda



$$\Delta h \approx \Delta p = p_{\infty} - p_1$$

$$p_{\infty} + \frac{1}{2} \rho v_{\infty}^2 = p_1 + \frac{1}{2} \rho v_1^2$$

$$p_{\infty} - p_1 = \Delta p = \frac{1}{2} \rho v_1^2 - \frac{1}{2} \rho v_{\infty}^2$$

$$\Delta p = \frac{1}{2} \rho v_{\infty}^2 \left[\frac{v_1^2}{v_{\infty}^2} - 1 \right]$$

$$v_{\infty} = \sqrt{\frac{2 \Delta p}{\rho \left[\left(\frac{S_{\infty}}{S_1} \right)^2 - 1 \right]}}$$

Vliv stlačitelnosti

- $M_{\infty} \approx 0$

$$\Delta p = p_0 - p_{\infty} \implies v_{\infty} = \sqrt{\frac{2 \Delta p}{\rho}}$$

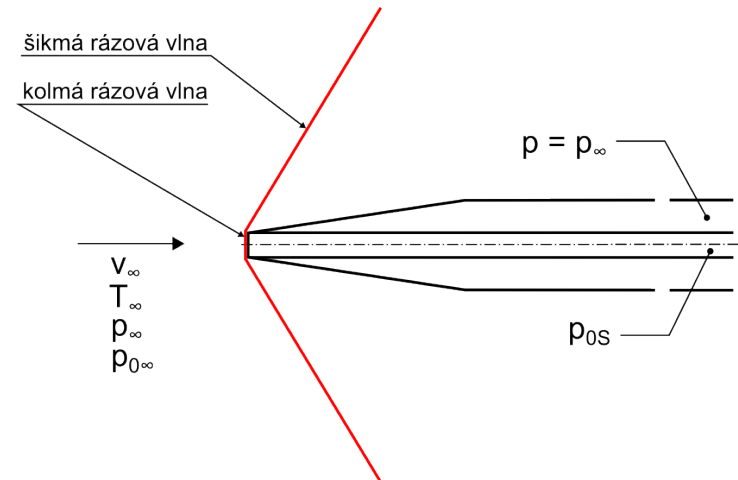
- $M_{\infty} \neq 0, M_{\infty} \leq 1$

$$\frac{p_{\infty}}{p_0} = \left(1 + \frac{\kappa - 1}{2} M_{\infty}^2 \right)^{-\frac{\kappa}{\kappa - 1}} = f(M_{\infty}^2)$$

- $M_{\infty} \geq 1$

$$\frac{p_{\infty}}{p_0} = \frac{\left[1 + \frac{2\kappa}{\kappa+1} (M_{\infty}^2 - 1) \right]^{\frac{1}{\kappa-1}}}{\left(\frac{\kappa+1}{2} M_{\infty}^2 \right)^{\frac{\kappa}{\kappa-1}}} \quad p_{0\infty} > p_{0s}$$

$$T_{0\infty} \stackrel{!}{=} T_{0s}$$



Vliv výšky letu [$\rho = \rho(h)$]

$$v = \sqrt{\frac{2 \Delta p}{\rho}}$$

Stupnice rychloměru je kalibrována na rychlost ve výšce $h = 0$ MSA [ρ_0]

$$v_{\text{ind},0} = \sqrt{\frac{2 \Delta p}{\rho_0}}$$

$$v_{\text{ind},h} = \sqrt{\frac{2 \Delta p}{\rho_h}} = \sqrt{\frac{2 \Delta p}{\rho_0}} \sqrt{\frac{\rho_0}{\rho_h}} = v_{\text{ind},0} \sqrt{\frac{\rho_0}{\rho_h}}$$

Další zdroje nepřesností:

- Aerodynamická polohová chyba
- Směrová charakteristika sondy (úhel vybočení)

Rychlosti používané v letectví

• Indikovaná rychlost letu

- ASIR - Indikovaná na rychloměru kalibrovaném pro $h = 0$ MSA
- δv_{pr} - mechanická chyba přístroje (prakticky IAS = ASIR)

$$\text{IAS} = \text{ASIR} + \delta v_{\text{pr}}$$

• Kalibrovaná rychlost letu

- δv_a - aerodynamická polohová chyba (snímače, poloha na letounu, p_s ...)

$$\text{CAS} = \text{IAS} + \delta v_a$$

• Ekvivalentní rychlost letu

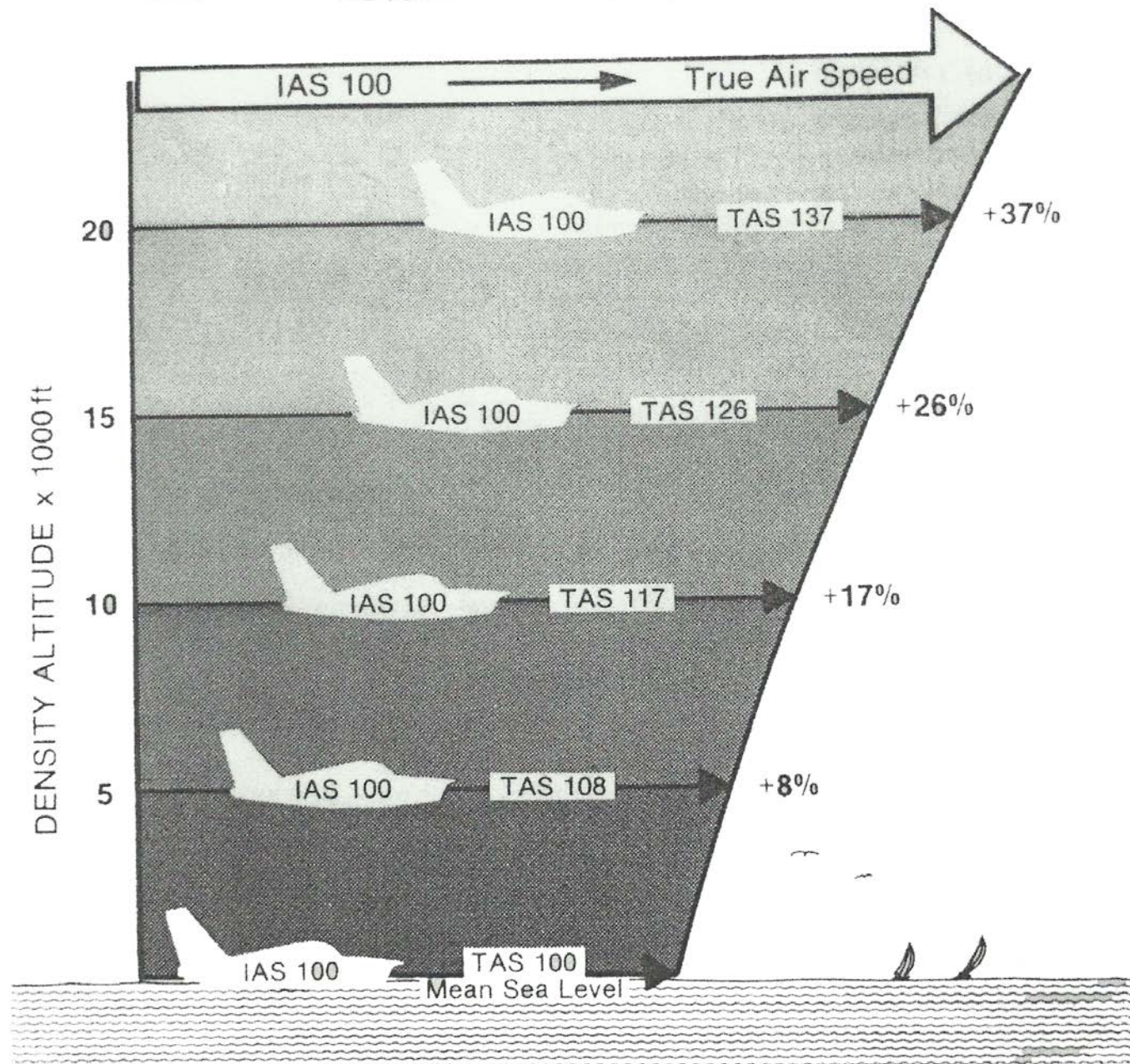
- δv_{stl} - korekce na vliv stlačitelnosti (adiabatická stlačitelnost v závislosti na výšce)

$$\text{EAS} = \text{CAS} + \delta v_{\text{stl}}$$

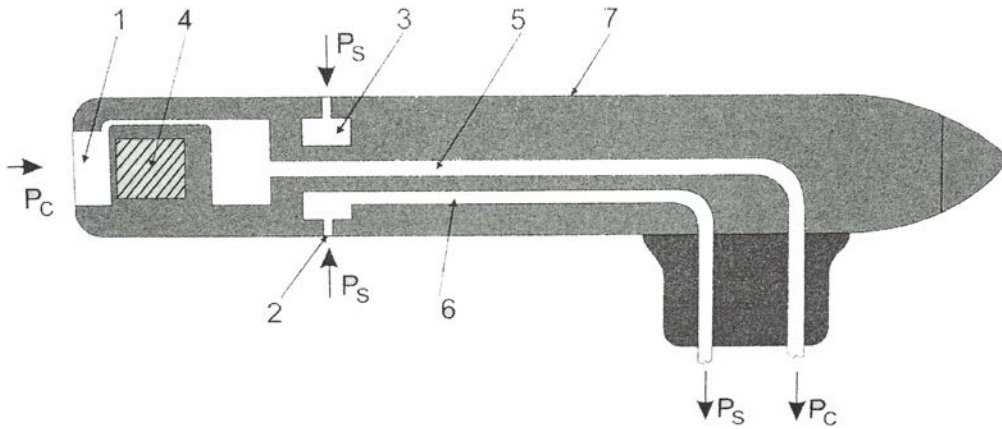
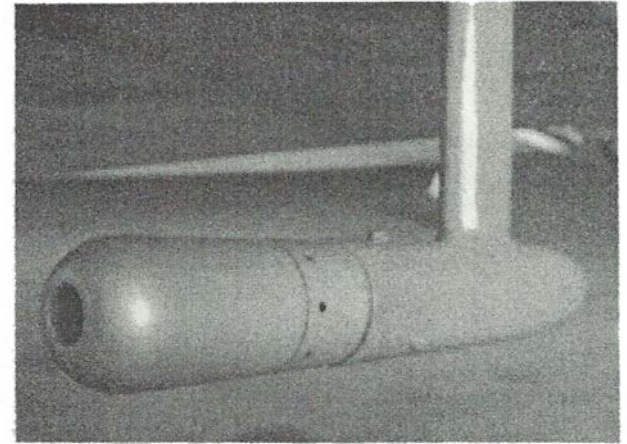
• Skutečná rychlost letu

- Rychlost vůči nerozrušenému proudu
- Oprava na vliv změny hustoty z výškou

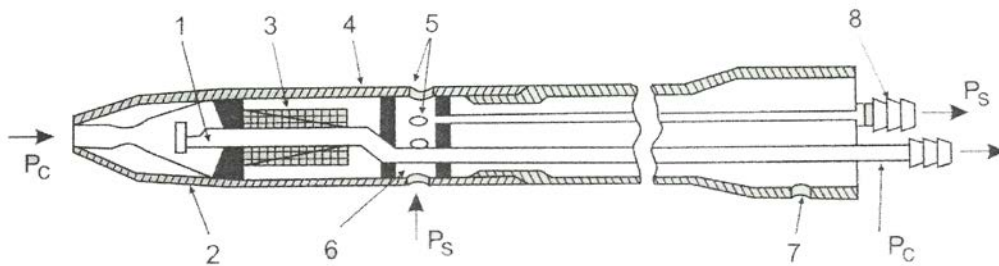
$$\text{TAS} = \text{EAS} \sqrt{\frac{\rho_0}{\rho_h}}$$



Pohled na Prandtlovu trubici



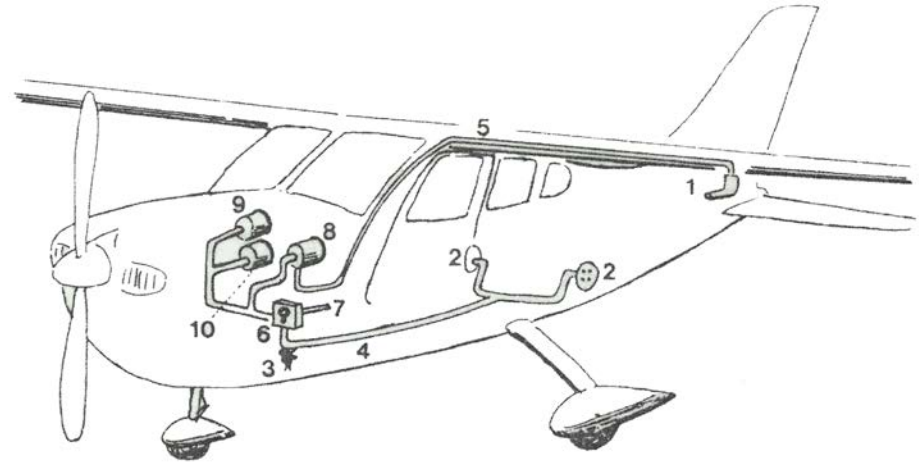
Pohled na snímač statického tlaku



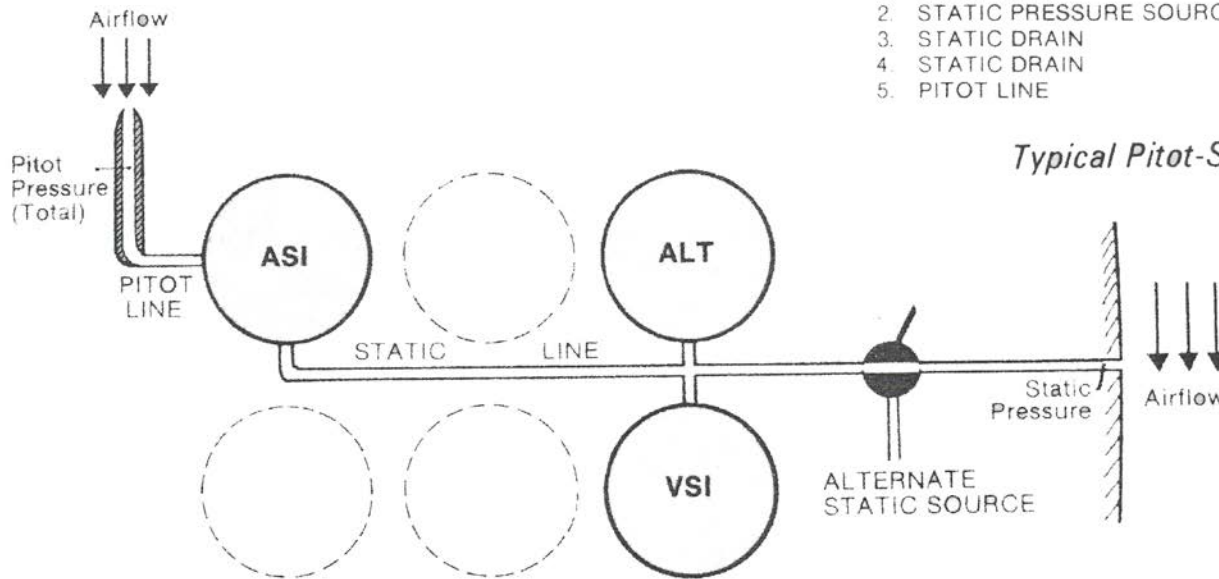
Obr. 3. Schema Prandtlovy trubice

1 – sonda P_c , 2 – komora P_c , 3 – vyhřívací tělísko, 4 – těleso snímače, 5 – snímání P_s ,
6 – komora P_s , 7 – odkalení, 8 – výstup stat.tlaku, P_s – tlak statický, P_c – tlak celkový

Aerometrická soustava letounu



- | | |
|----------------------------|--------------------------------|
| 1. PITOT TUBE | 6. ALTERNATIVE STATIC SELECTOR |
| 2. STATIC PRESSURE SOURCES | 7. ALTERNATIVE STATIC PRESSURE |
| 3. STATIC DRAIN | 8. AIRSPEED INDICATOR |
| 4. STATIC DRAIN | 9. ALTIMETER |
| 5. PITOT LINE | 10. VERTICAL SPEED INDICATOR |



Typical Pitot-Static System Installation.

The Pitot-Static System.

Rychloměr

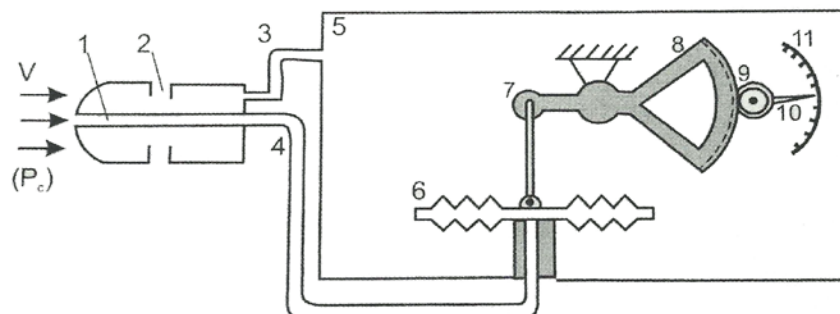


Schéma rychloměru

- 1 – snímač celkového tlaku, 2 – snímač statického tlaku, 3 – vedení stat.talku,
4 – vedení celkového tlaku, 5 – těleso přístroje, 6 – barokrabice (Vidiho),
7 – převodový mechanismus, 8, 9 – ozubený převod, 10 – ukazatel, 11 – stupnice



Výškoměr

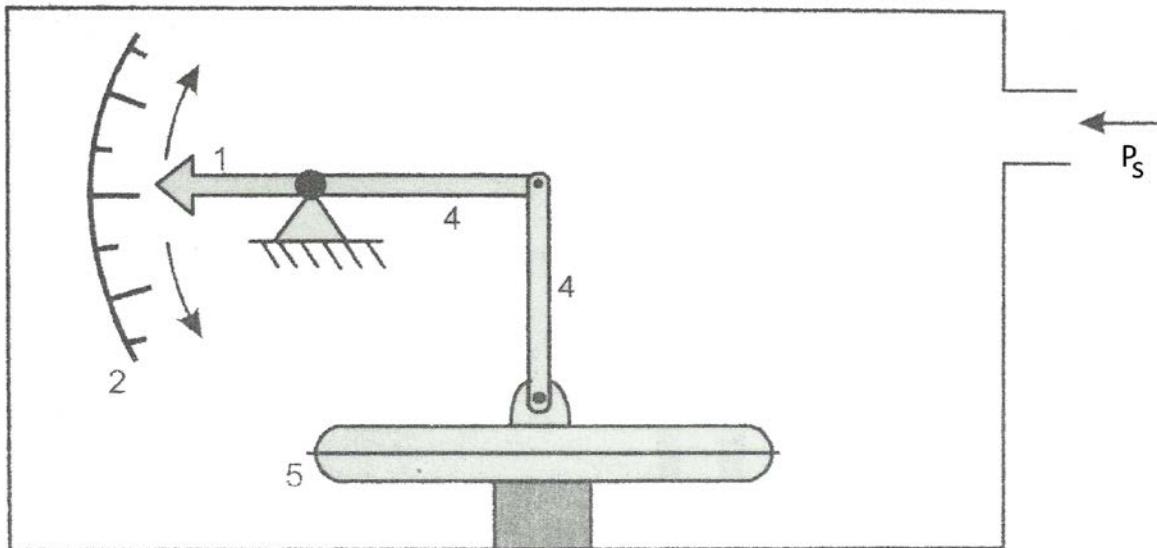
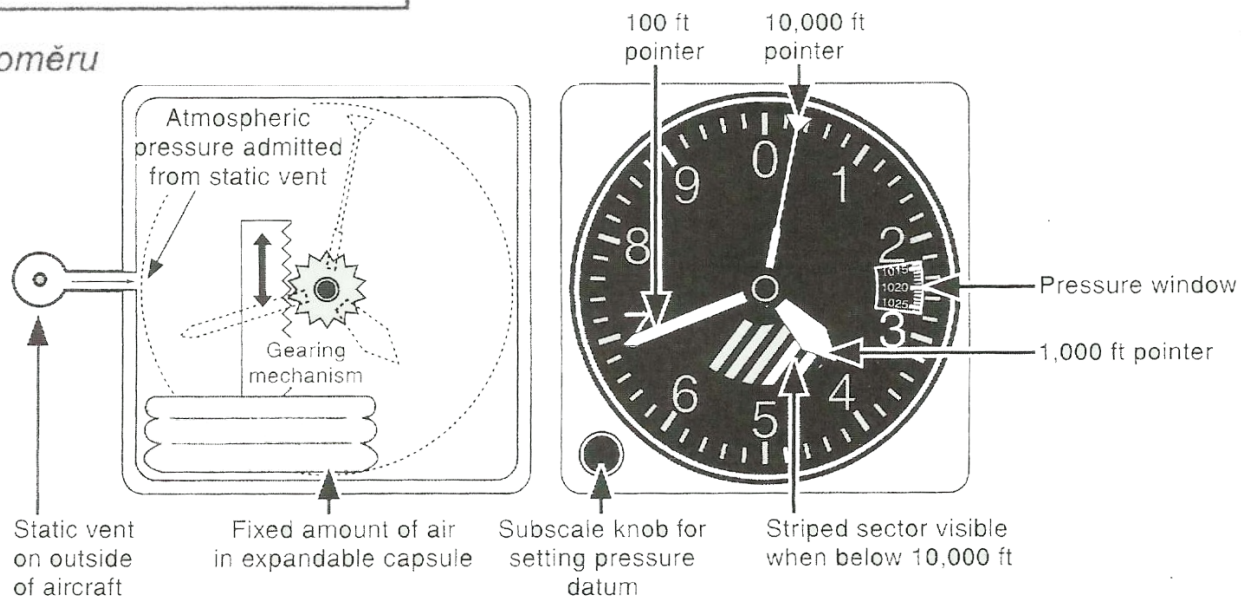


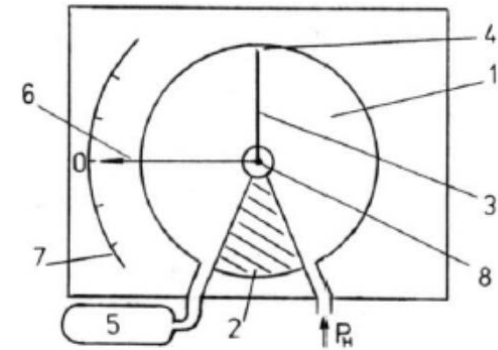
Schéma výškoměru



The altimeter converts variations in static pressure into indications of height (this altimeter is reading 3,690 ft)

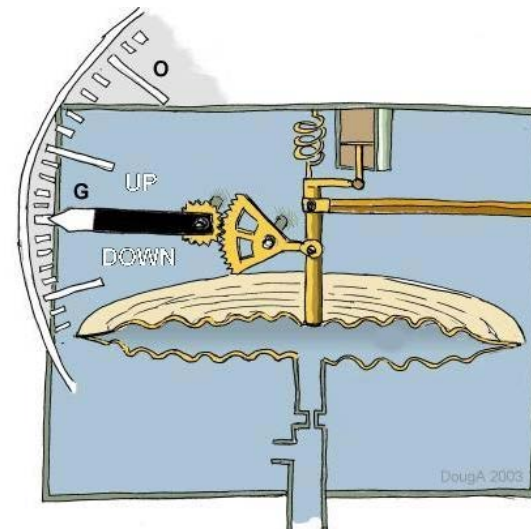
Variometr

- Klapkový
- Membránový
- Elektrický



Obr.6.7 Principiální schéma klapkového variometru

1 – komora; 2 – přepážka; 3 – klapka;
4 – štěrbin; 5 – termoláhev; 6 – indikační
ručka; 7 - stupnice



Obraz proudového pole

Základní pojmy

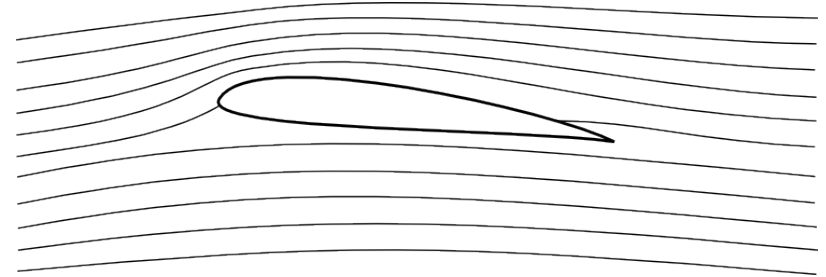
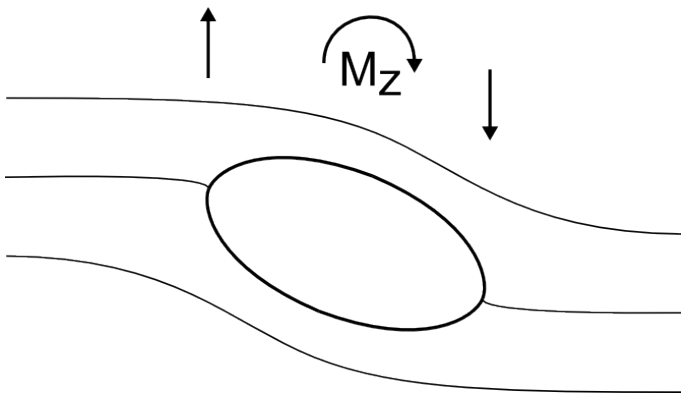
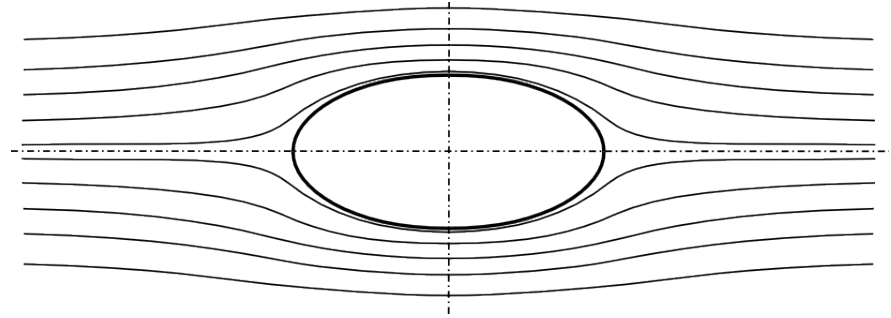
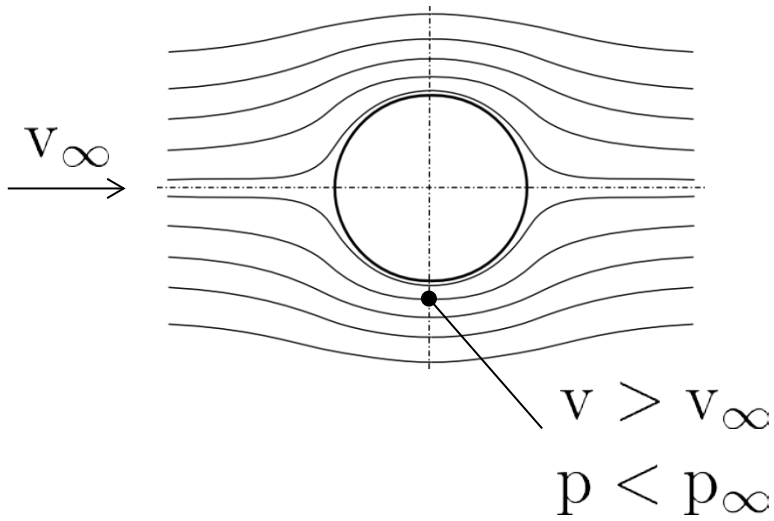
- Vnější proud
- Mezní vrstva
- Úplav
- Odtržený proud



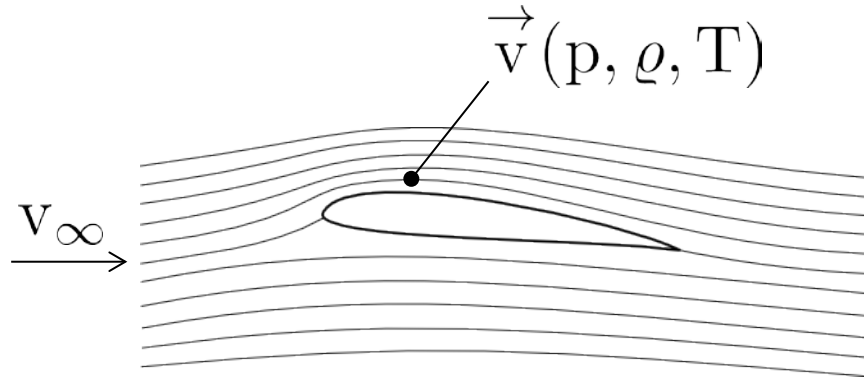
Charakteristiky proudových polí

- Rozložení rychlostí, rychlostní profil
- Charakter vířivosti, frekvence vířivosti
- Třecí napětí, třecí odpor (složka)
- Složka tlakového (vírového, tvarového, úplavu, ...), odporu

Symetrický obraz proudového pole (ideální)



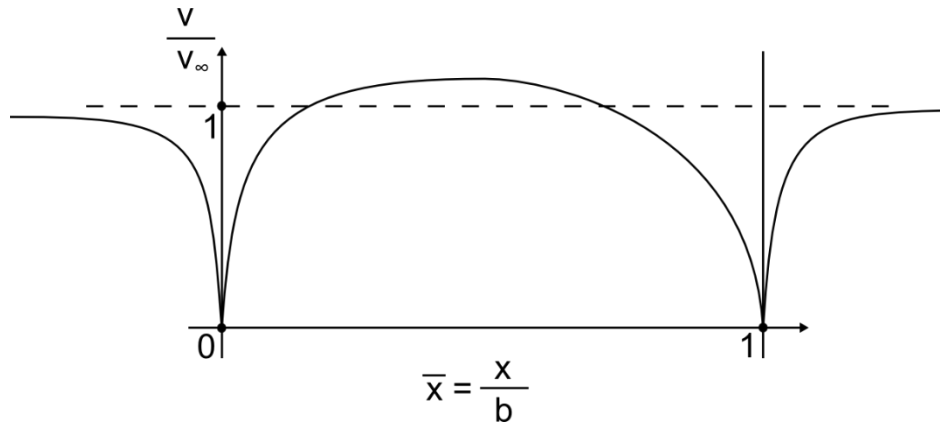
Nesymetrický obraz proudového pole (reálný, vazký)



Situace

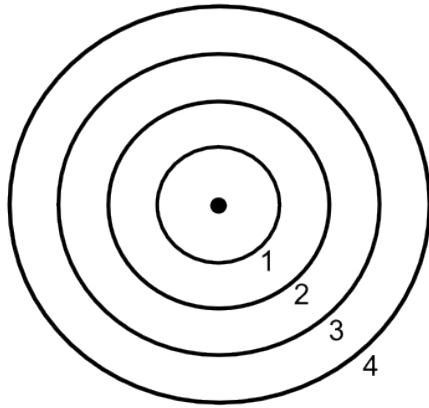
- OH, NH
- Vývoj \vec{v} , p , (ρ, T)
- Úplav
- Nesymetrie - p
 - Vztlak
 - Odpor

Rozložení rychlostí - (\vec{v}, p, ρ, T)

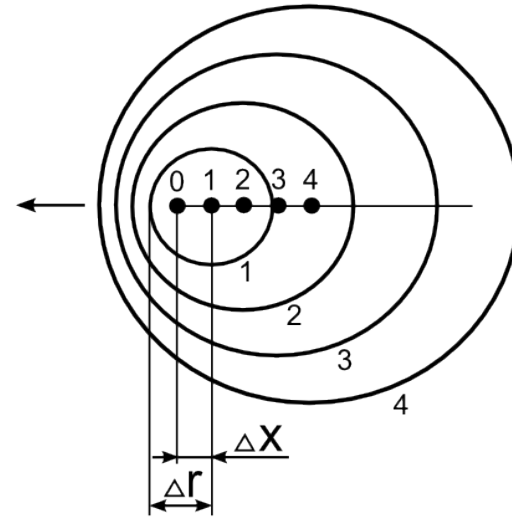


Šíření tlakových rozruchů

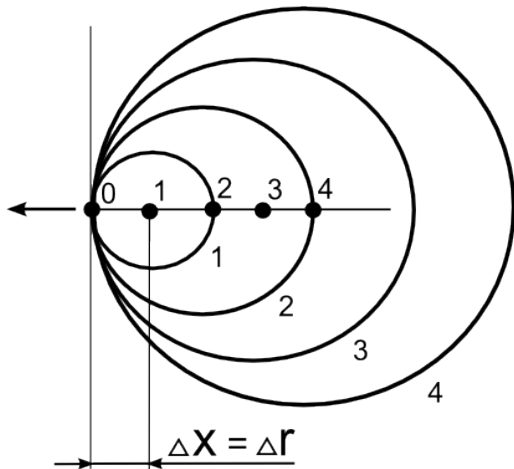
$M = 0$



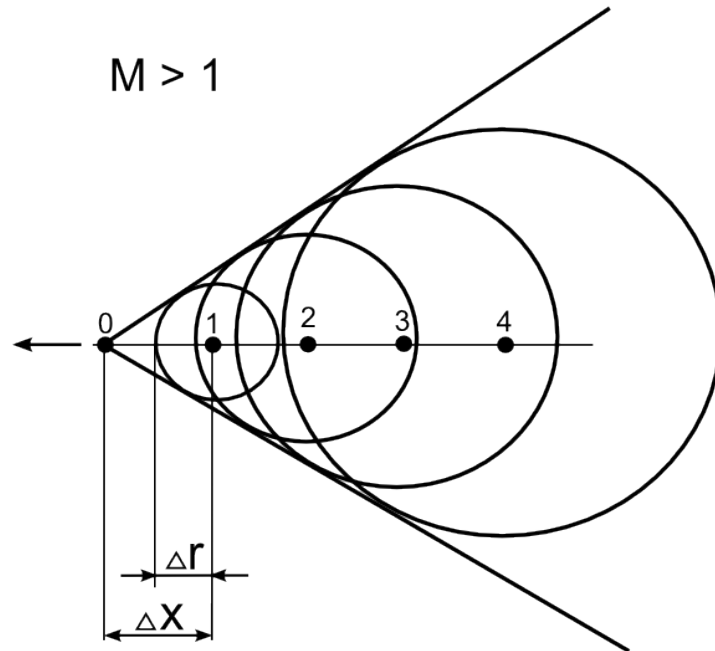
$M < 1$



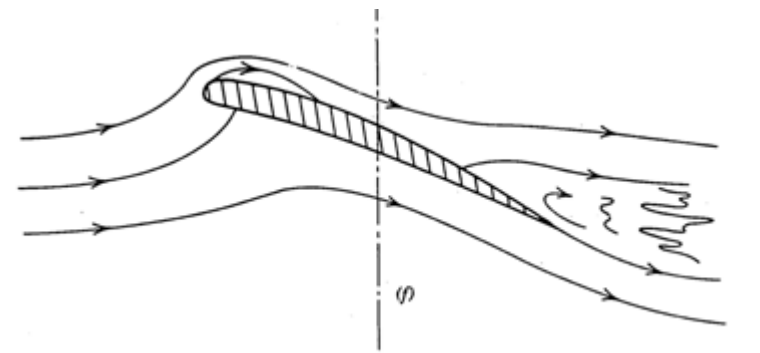
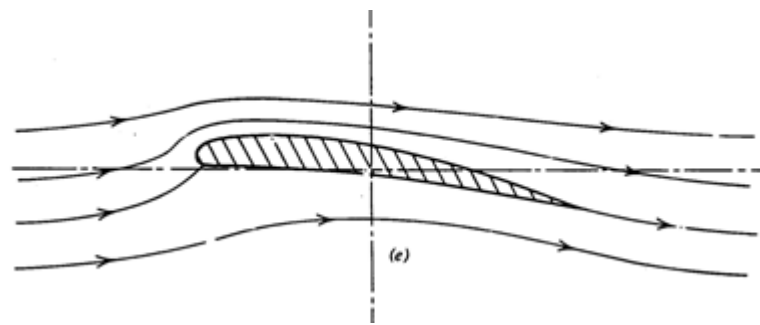
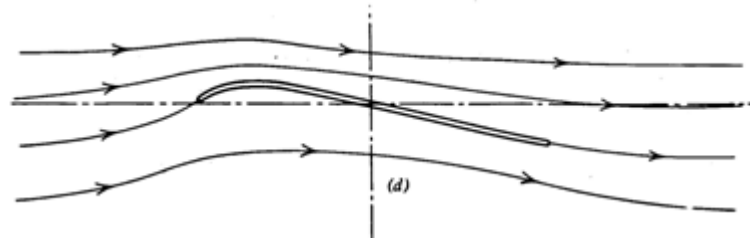
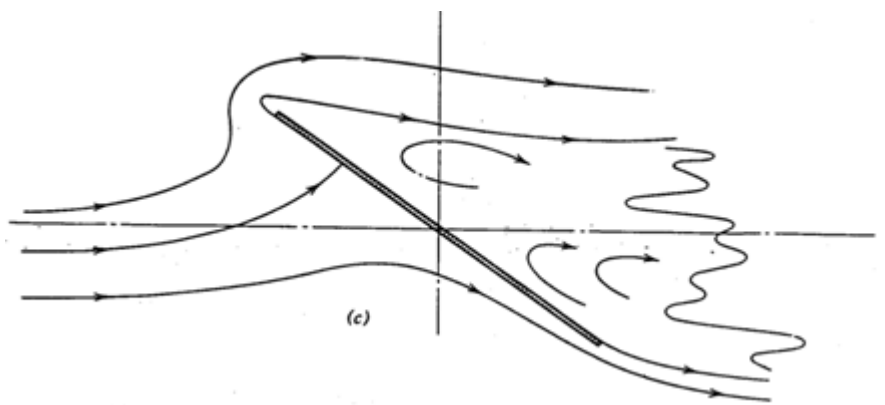
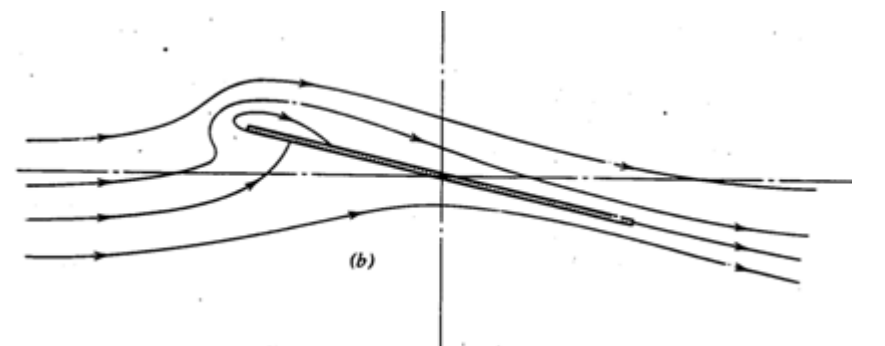
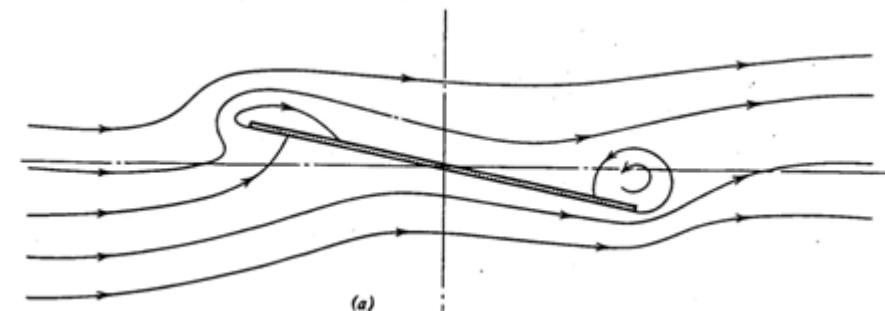
$M = 1$



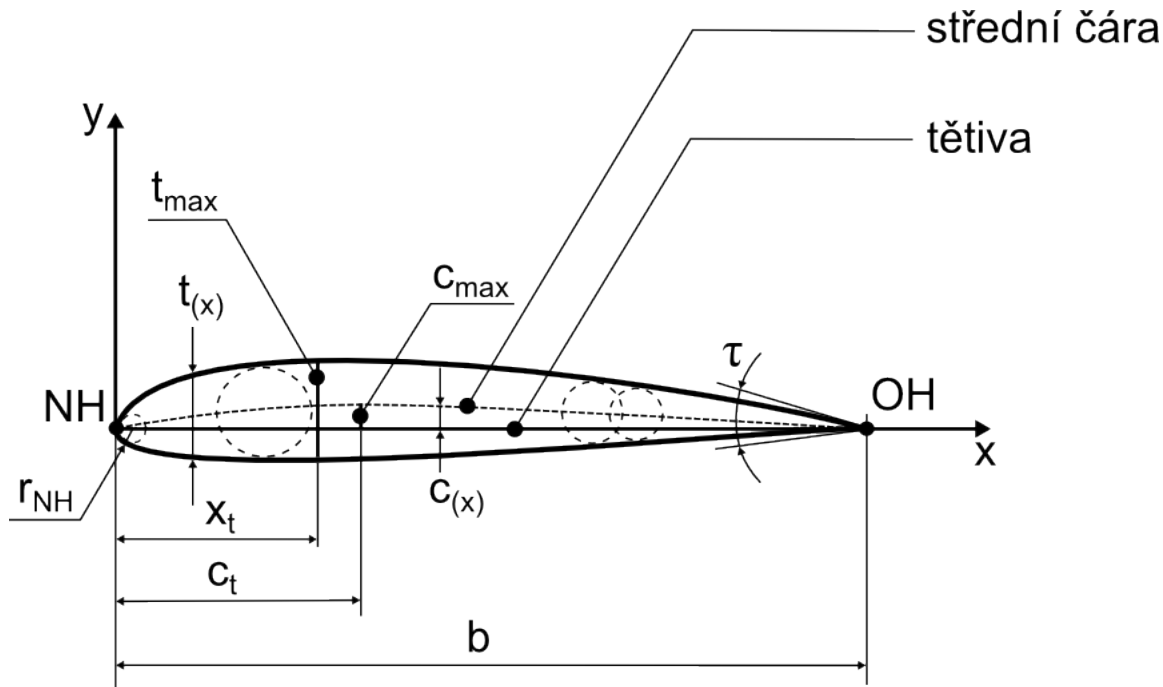
$M > 1$



Reálné proudového pole (vazkost, vířivost, M.V., úplav)



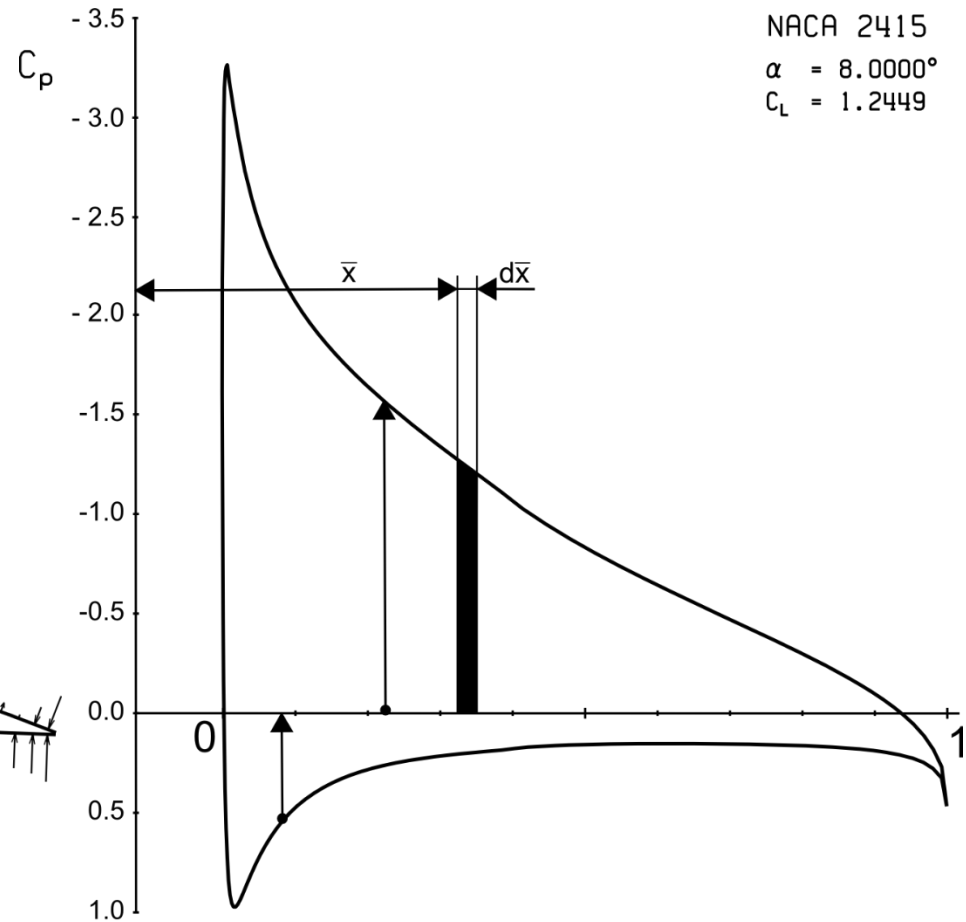
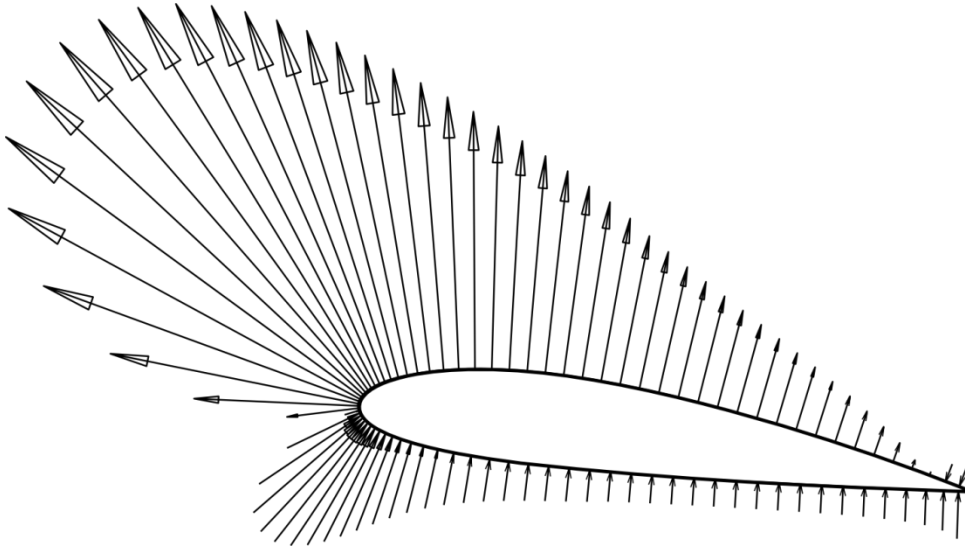
Geometrické charakteristiky, aerodynamického profilu



Typické hodnoty geometrických charakteristik

- **Tloušťka** – t/b , (3 - 4) %, max 21%
- **Prohnutí** – c/b , 0% - symetrické, max (6 - 7) %,
- **NH** – r_{NH}/b , (1 - 3) %, ~ 0 % ostrá NH
- **OH** – $\tau \rightarrow 0$

Tlakové rozložení

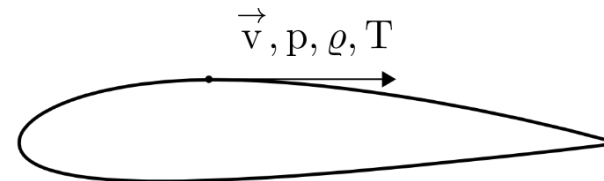


Tlakový součinitel

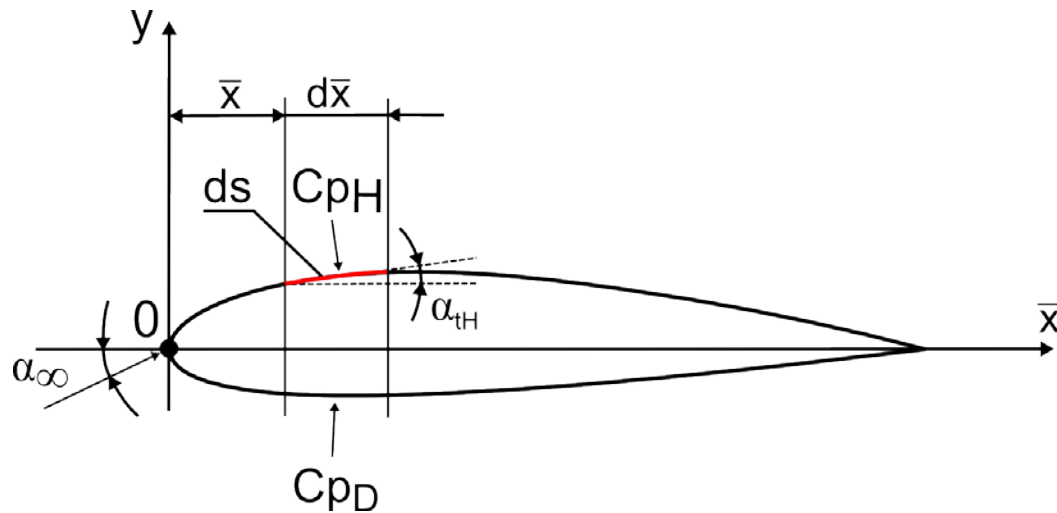
$$M = 0$$

$$C_p = \frac{p - p_\infty}{\frac{1}{2} \rho v_\infty^2} = \dots = 1 - \left(\frac{v}{v_\infty} \right)^2$$

$$\begin{matrix} \vec{v}_\infty \\ p_\infty \\ \rho_\infty \\ T_\infty \end{matrix} \longrightarrow$$



Vztlak profilu



$$dY = -C_{pH} \frac{1}{2} \rho v_{\infty}^2 \cos(\alpha_{tH}) ds + C_{pD} \frac{1}{2} \rho v_{\infty}^2 \cos(\alpha_{tD}) ds$$

$$Y = \frac{1}{2} \rho v_{\infty}^2 \int_0^b (C_{pD} - C_{pH}) dx = \frac{1}{2} \rho v_{\infty}^2 b C_y$$

$$C_y = \frac{1}{b} \int_0^b \Delta C_p dx$$

$$C_y = \int_0^1 \Delta C_p d\bar{x}$$

$$\bar{x} = \frac{x}{b} \quad \bar{x} < 0, 1 >$$

$$x < 0, b >$$

Moment profilu

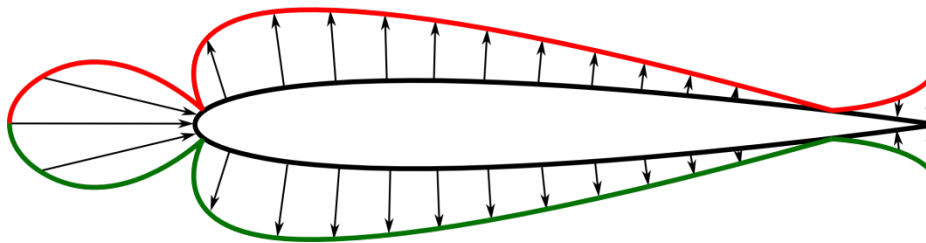
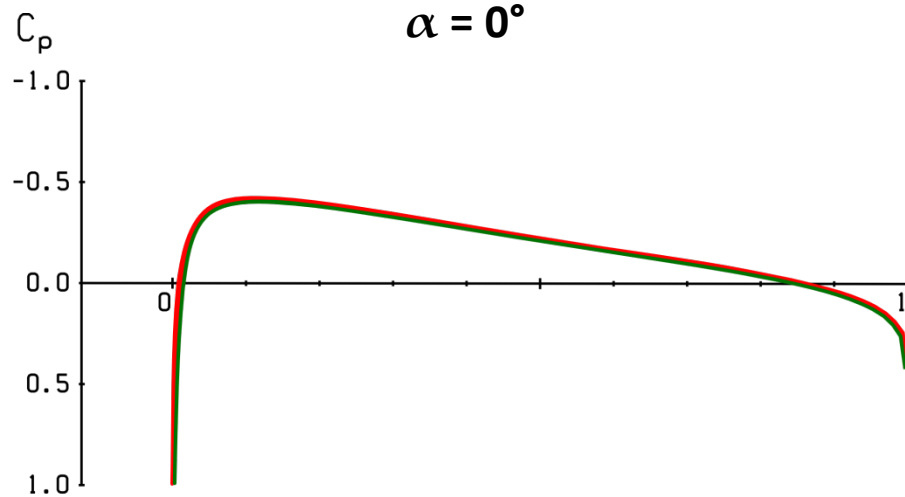
$$m_z = -C_y \frac{x}{b} = -C_y \bar{x}$$



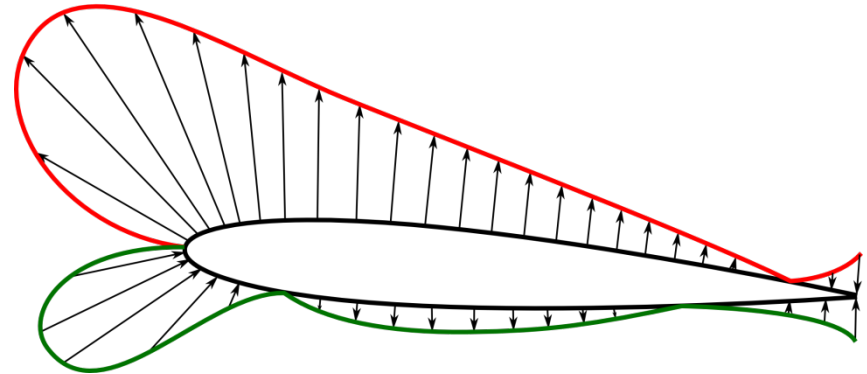
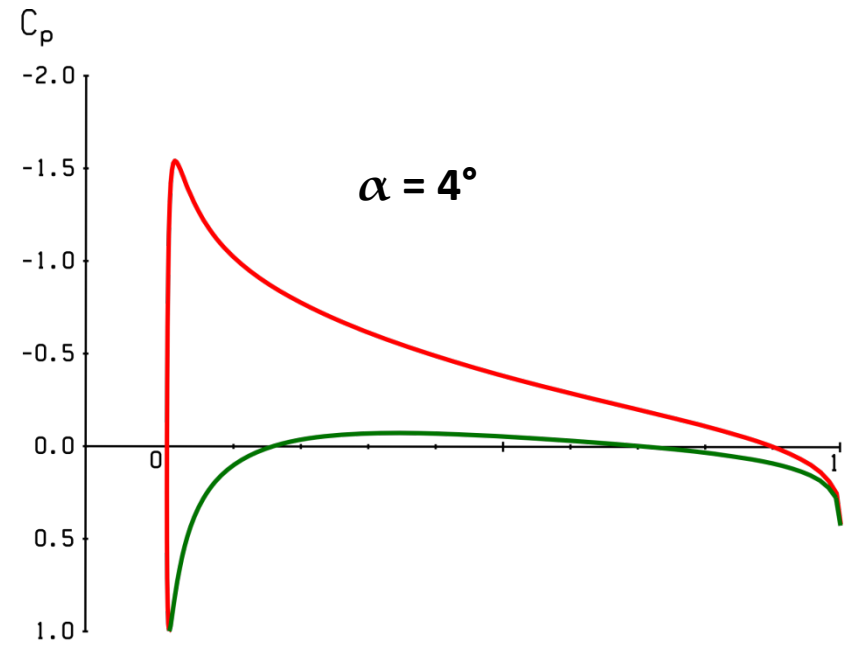
$$m_z = -\frac{1}{b^2} \int_0^b \Delta C_p x dx$$

$$m_z = -\int_0^1 \Delta C_p x d\bar{x}$$

Symetrický profil



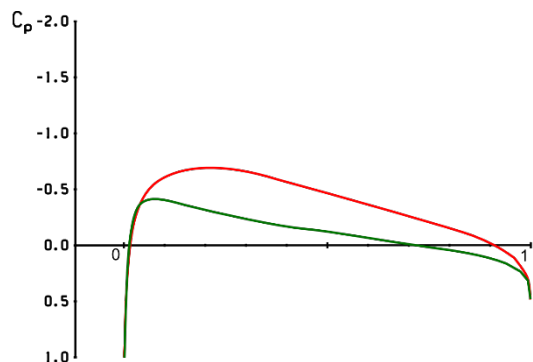
$$\alpha = 0^\circ$$
$$C_y = 0$$
$$Y = 0$$
$$m_z = 0$$



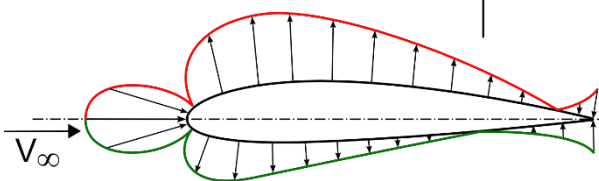
$$\alpha > 0^\circ$$
$$C_y > 0$$
$$Y > 0$$
$$m_z < 0$$

Nesymetrický profil

$\alpha = 0^\circ$



m_z C_y



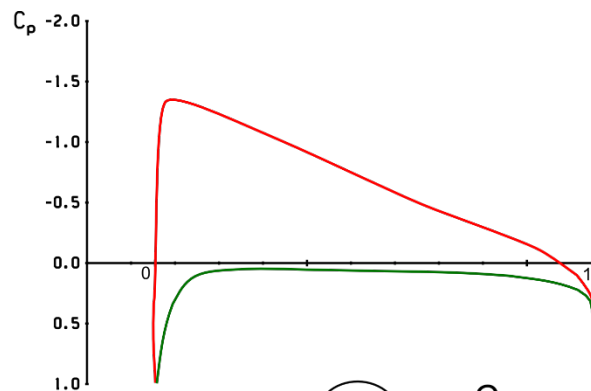
$\alpha = 0^\circ$

$C_y \neq 0$

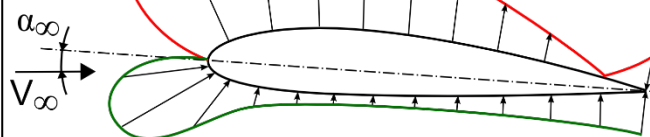
$Y \neq 0$

$m_z \neq 0$

$\alpha = 4^\circ$



m_z C_y



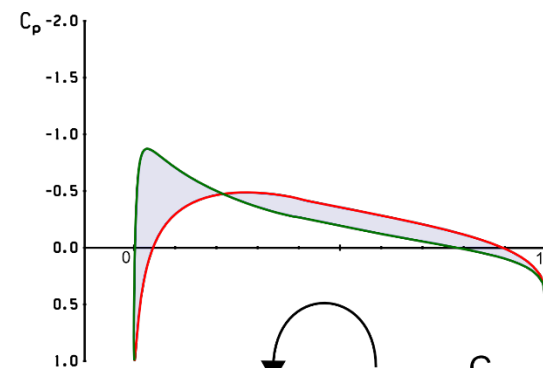
$\alpha > 0^\circ$

$C_y \neq 0$

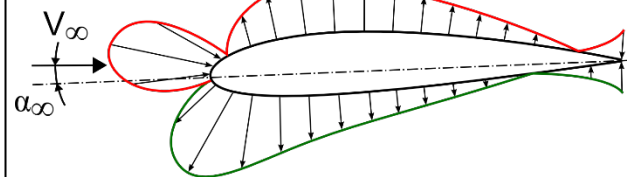
$Y \neq 0$

$m_z \neq 0$

$\alpha = \alpha_0$



$m_z = m_{z0}$ C_y



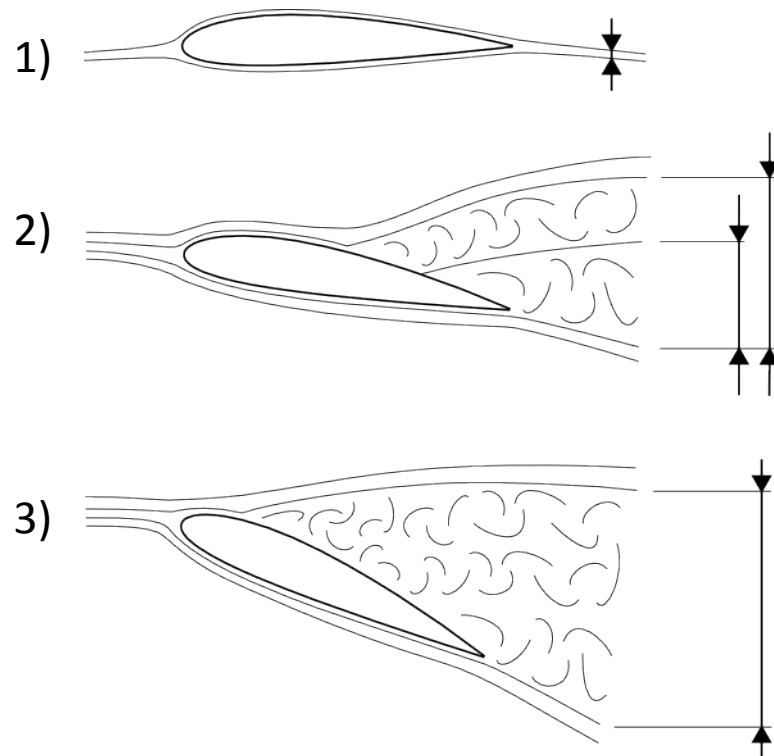
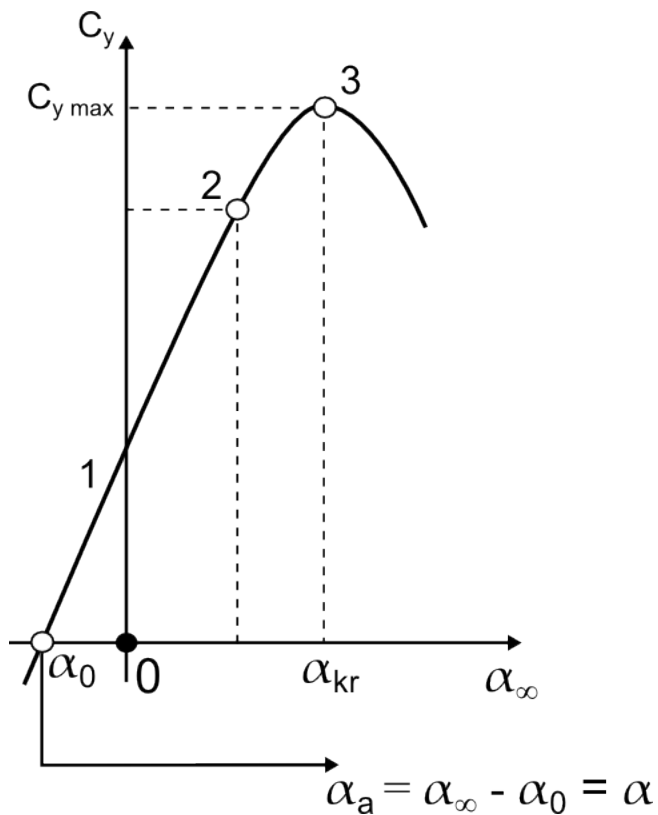
$\alpha \equiv \alpha_0 < 0^\circ$

$C_y = 0$

$Y = 0$

$m_z = m_{z0} \neq 0$

Vztlaková čára

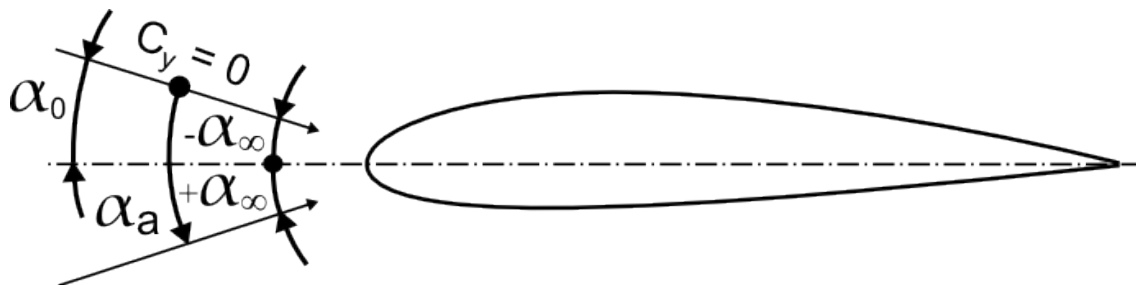


Stoupání vztlakové čáry

$$C_y^\alpha = \frac{dC_y}{d\alpha} \doteq 2\pi \text{ [rad}^{-1}\text{]}$$

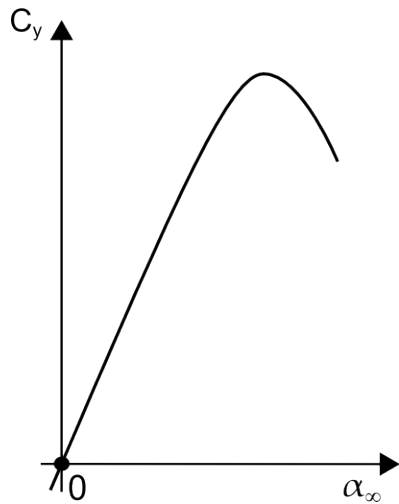
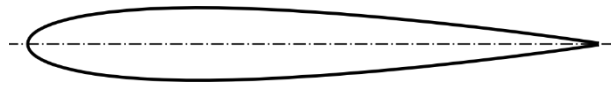
$$\alpha_0 \text{ [}\alpha \text{ při } C_y = 0\text{]}$$

$$\alpha_0 = f(\text{stř.křivky})$$



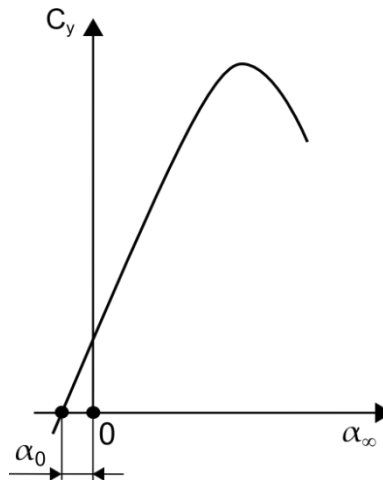
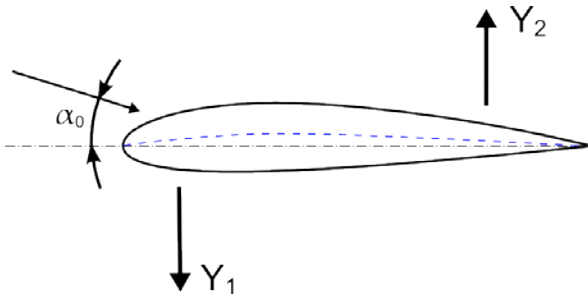
Vliv střední křivky na α_0

Symetrický



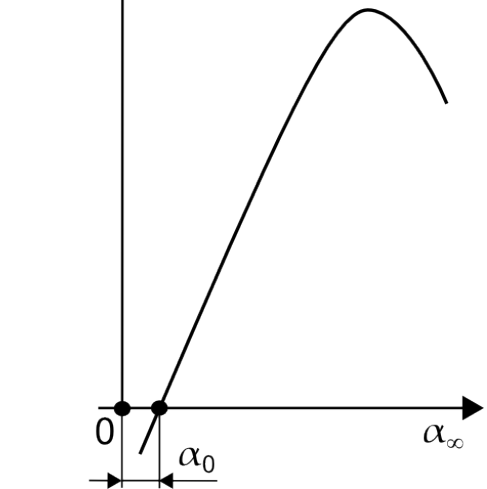
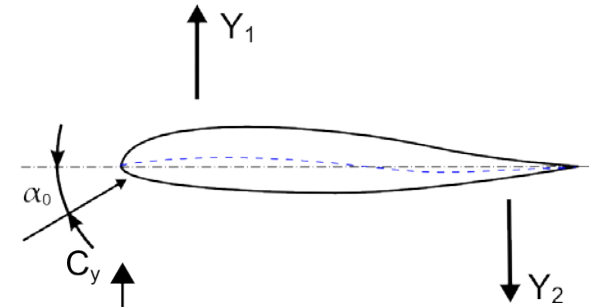
$$\begin{aligned} y(\bar{x}) &= 0 \\ C_y &= 0 \\ Y &= 0 \\ m_{z0} &= 0 \\ \alpha_0 &= 0 \end{aligned}$$

Kladné prohnutí



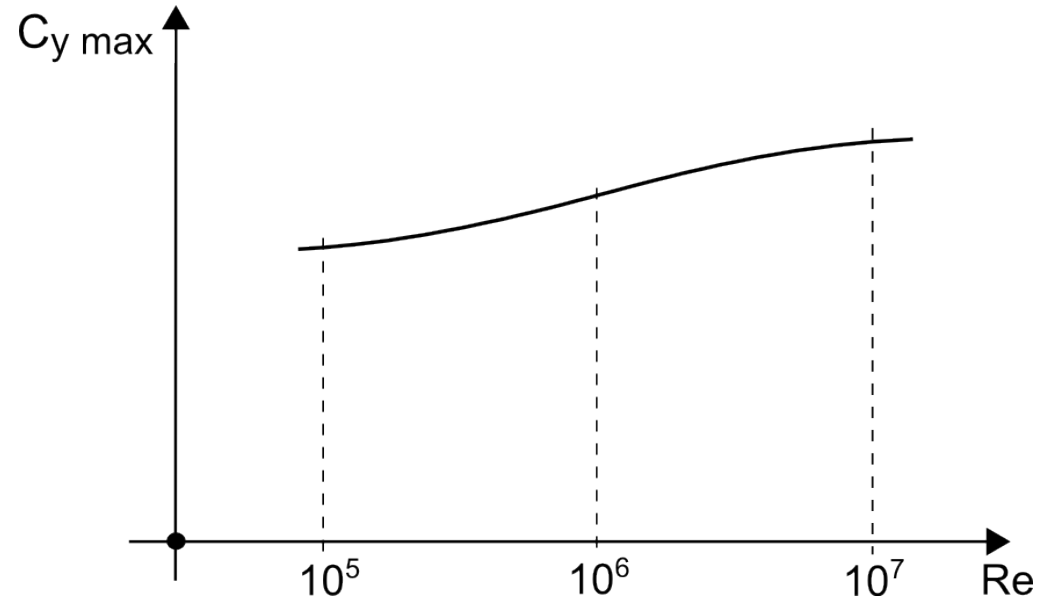
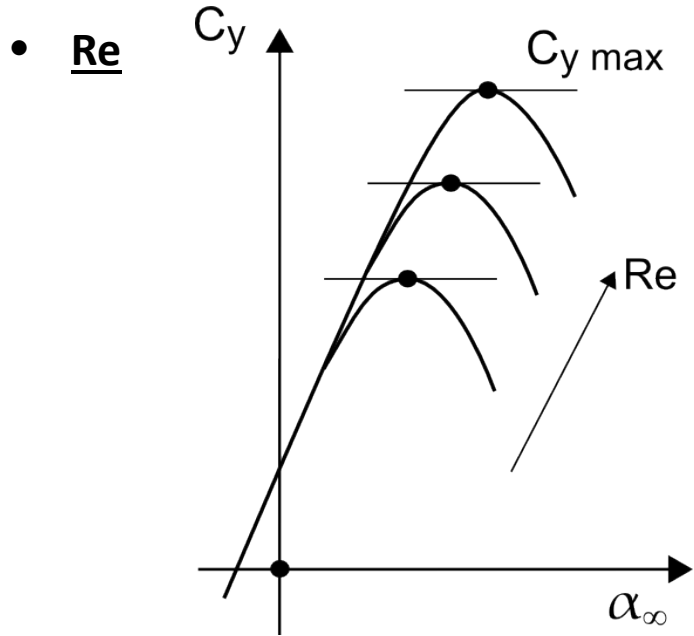
$$\begin{aligned} y(\bar{x}) &> 0 \\ C_y &= 0 \\ Y &= 0 \\ m_{z0} &< 0 \\ \alpha_0 &< 0, Y_1 = -Y_2 \end{aligned}$$

Autostabilní profil



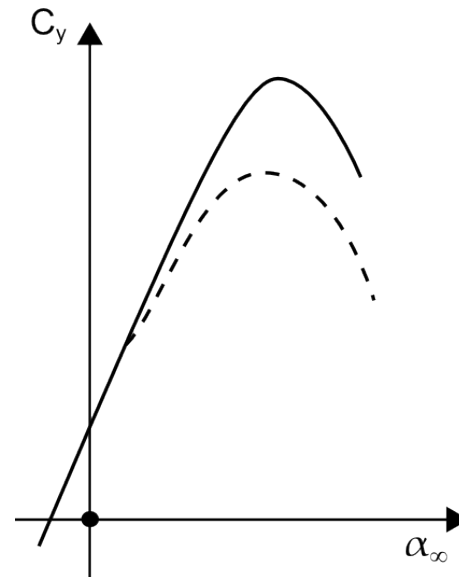
$$\begin{aligned} y(\bar{x}) &\rightarrow \text{"S" křivka} \\ C_y &= 0 \\ Y &= 0 \\ m_{z0} &> 0 \\ \alpha_0 &> 0, Y_1 = -Y_2 \end{aligned}$$

Velikost $C_{y \max}$



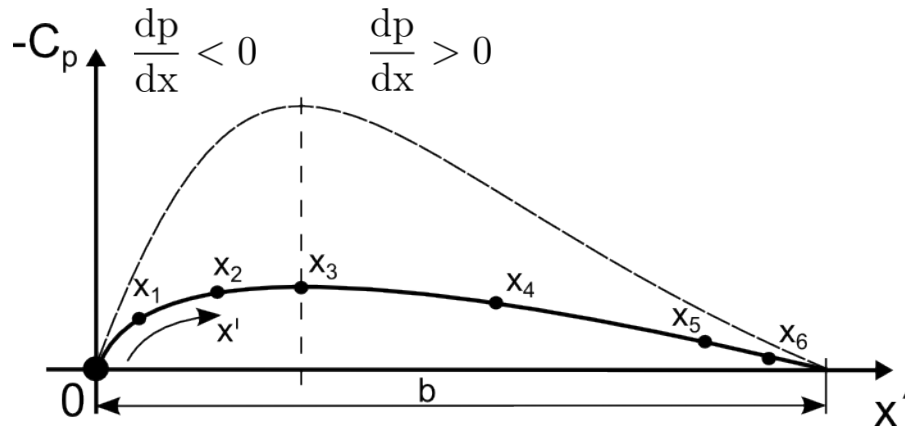
- Charakter M.V. – rozsah odtržení

- Laminární M.V. ($< Re$)
- Turbulentní M.V. ($< Re$)

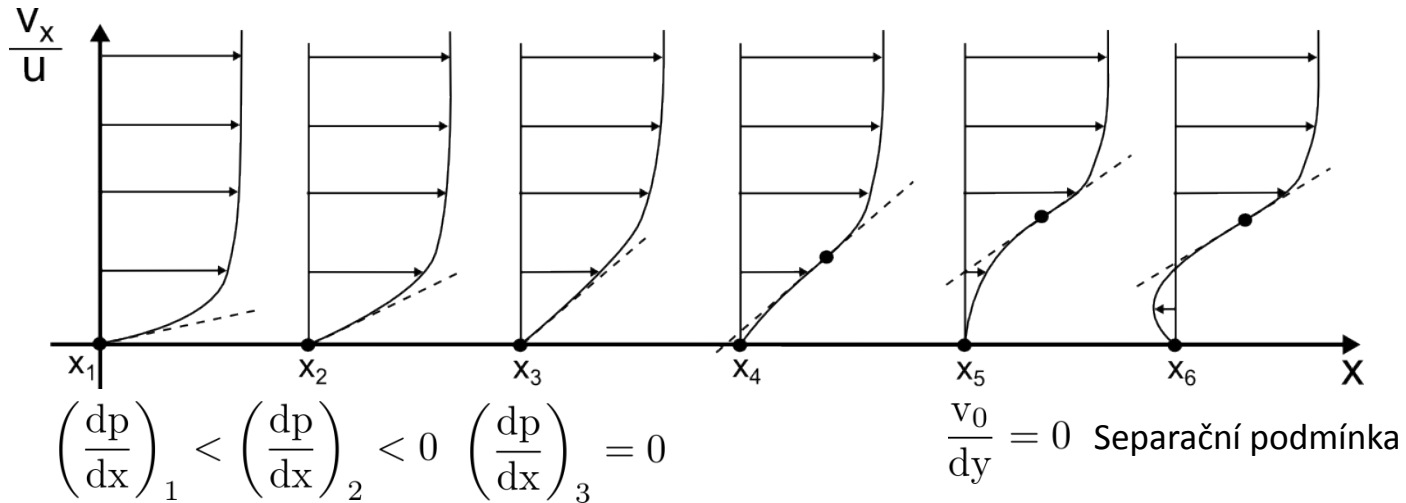


Vývoj rychlostního profilu

- Tlakové rozložení



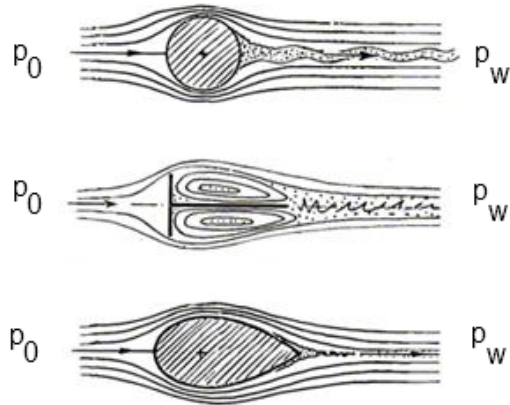
- rychlostní profily



Inflexe pr\u00fb\u011bh\u00fa $v_x(y) \rightarrow$ nestabilita

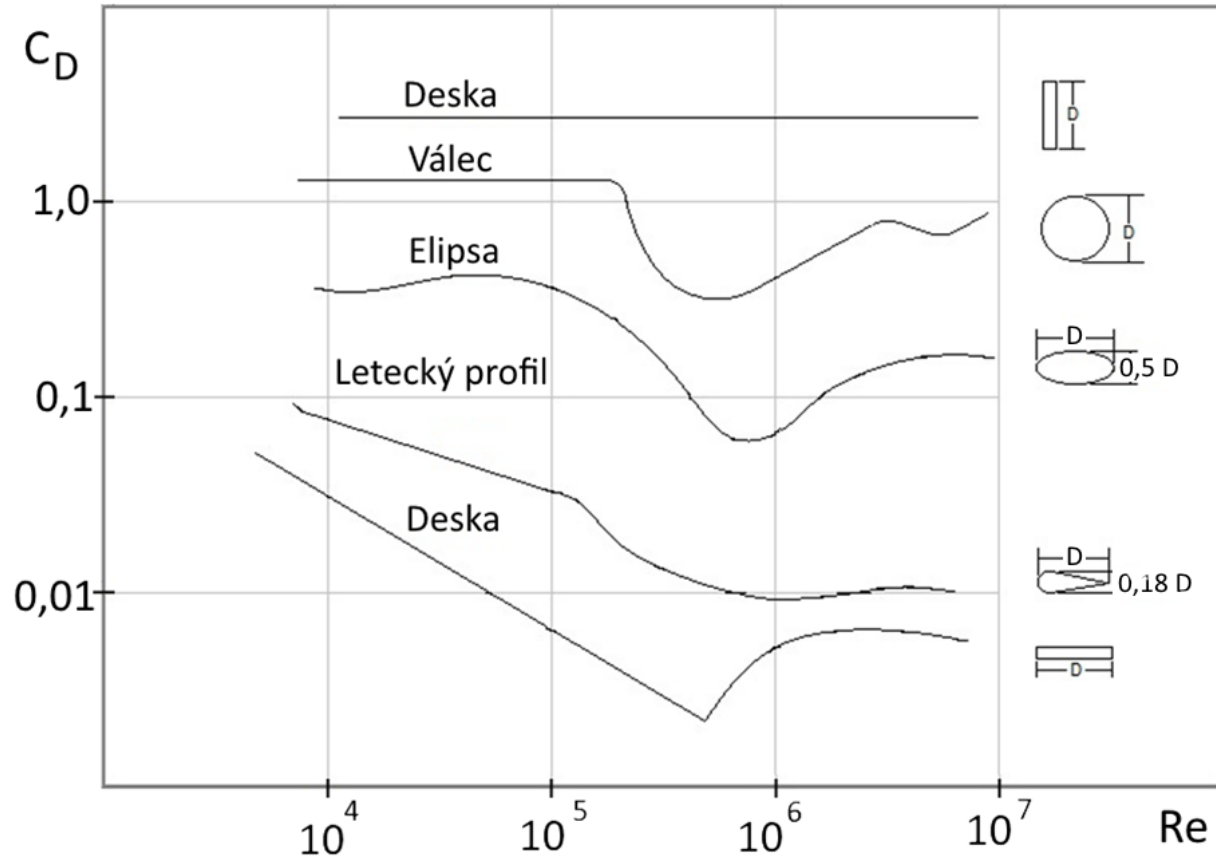
$\leftarrow \frac{dp}{dx} > 0 \rightarrow$

Tlakový odpor (tvarový, odpor úplavu)



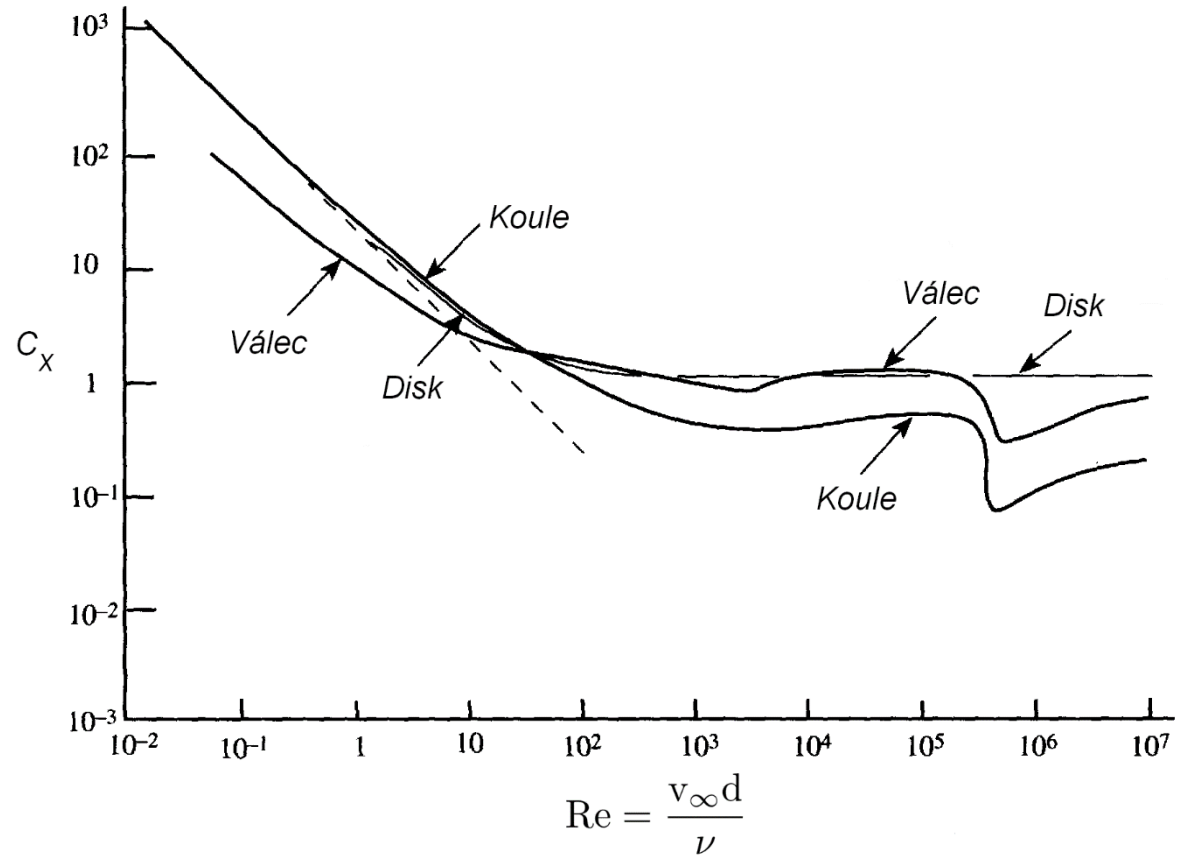
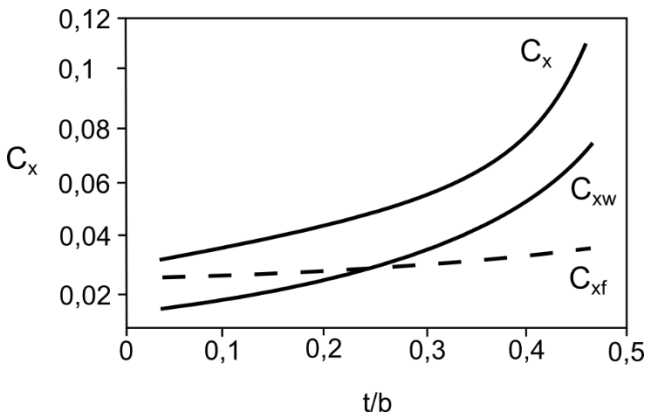
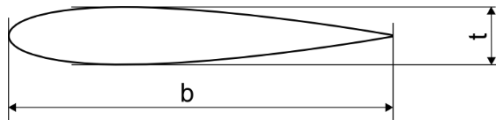
$$x_w \sim \int_S p ds \sim \Delta p = p_0 - p_w$$

| 3D | | 2D | |
|------|-------|------|-------|
| Tvar | C_D | Tvar | C_D |
| | 0,47 | | 1,17 |
| | 0,38 | | 1,20 |
| | 0,42 | | 1,16 |
| | 0,59 | | 1,60 |
| | 0,80 | | 1,55 |
| | 0,50 | | 1,55 |
| | 1,17 | | 1,98 |
| | 1,17 | | 2,00 |
| | 1,42 | | 2,30 |
| | 1,38 | | 2,20 |
| | 1,05 | | 2,05 |

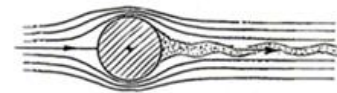


Tvarování těles

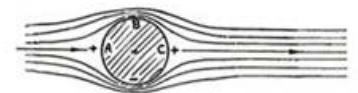
- Dobře tvarovaná, tenká
 $C_x \rightarrow C_{xf}$
- Špatně tvarovaná, tlustá
 $C_x \rightarrow C_{xf} + C_{xw}$



Laminární (podkritické)

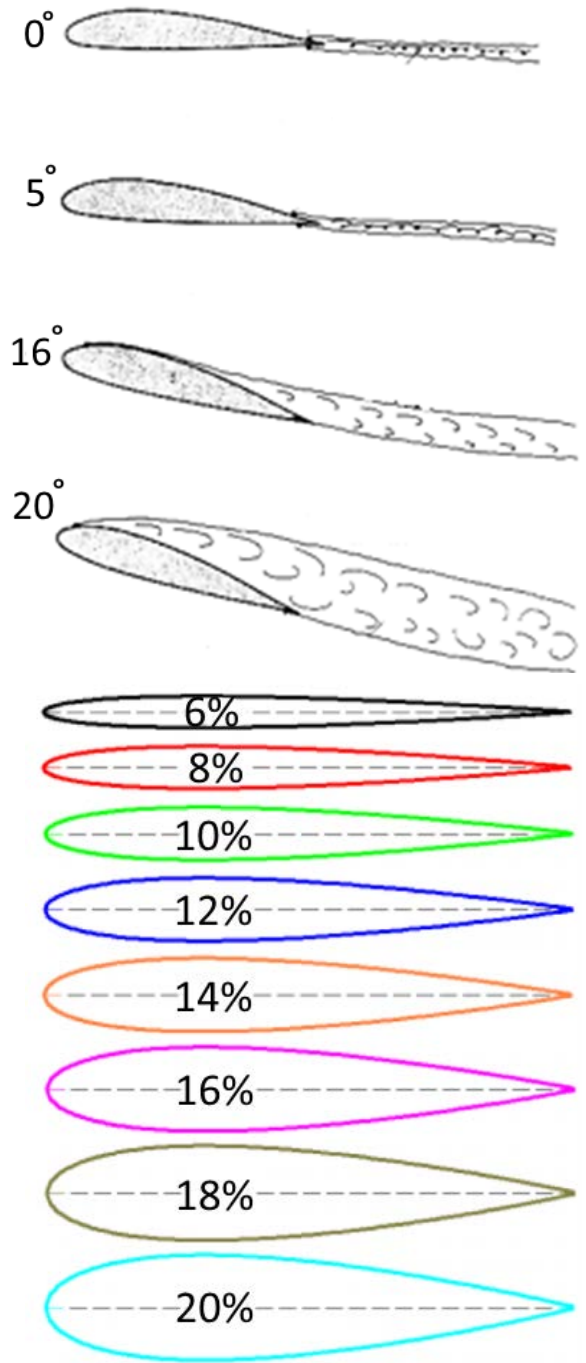
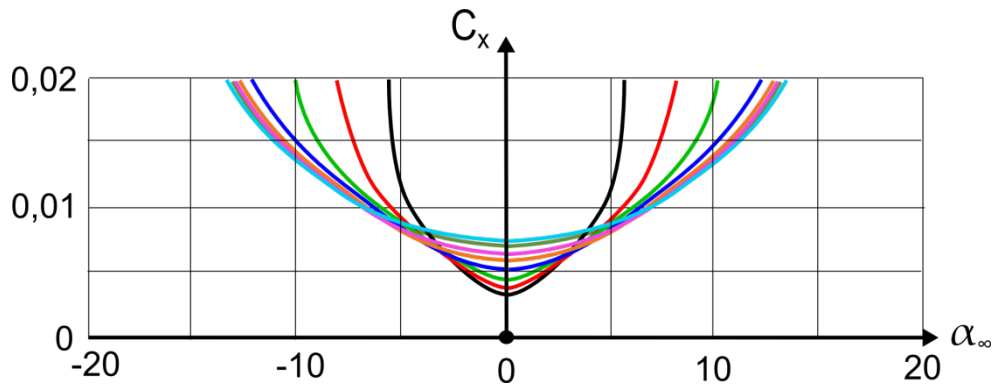
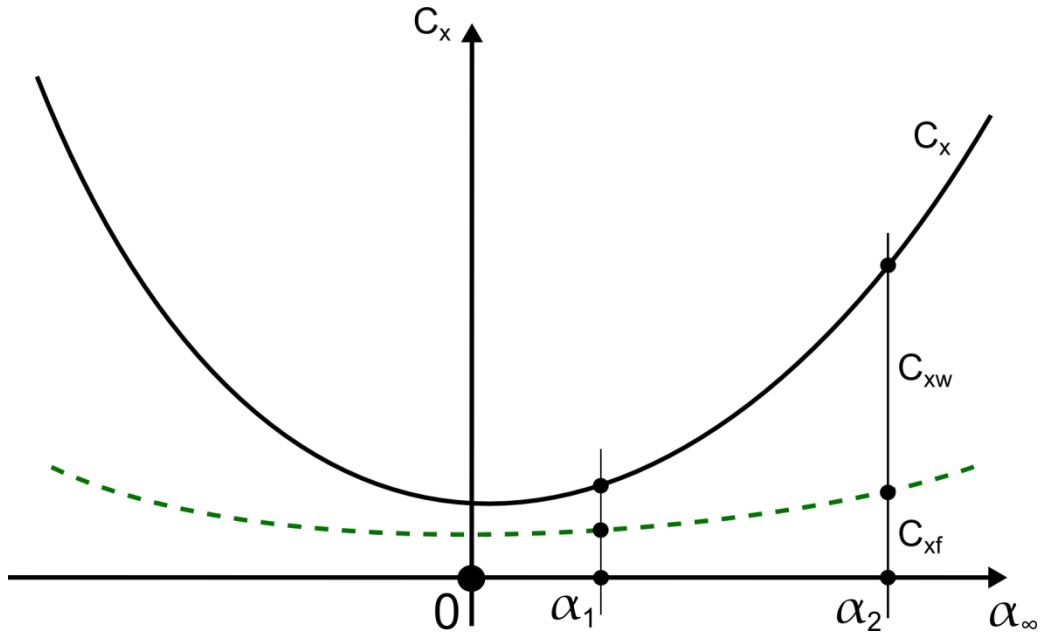


Turbulentní (nadkritické)

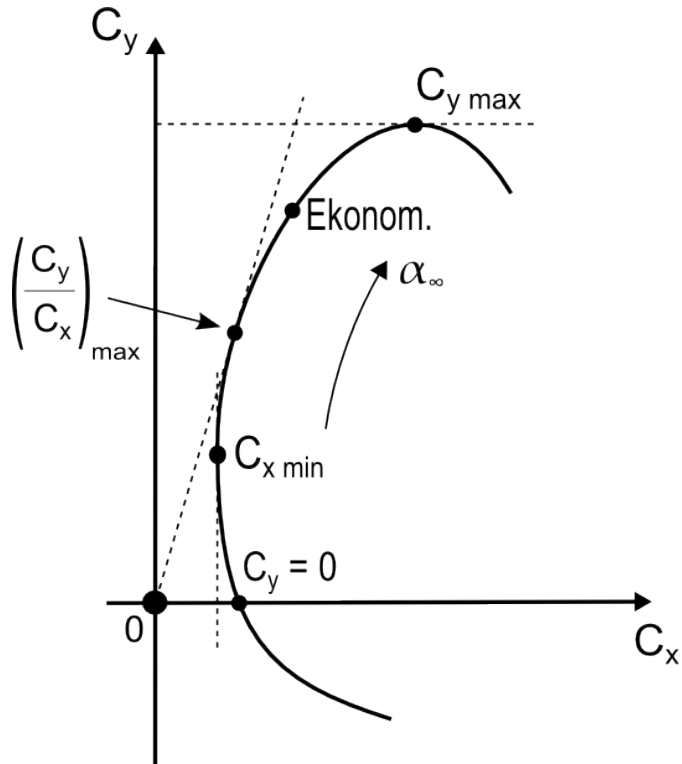


→ Re

Odporová čára



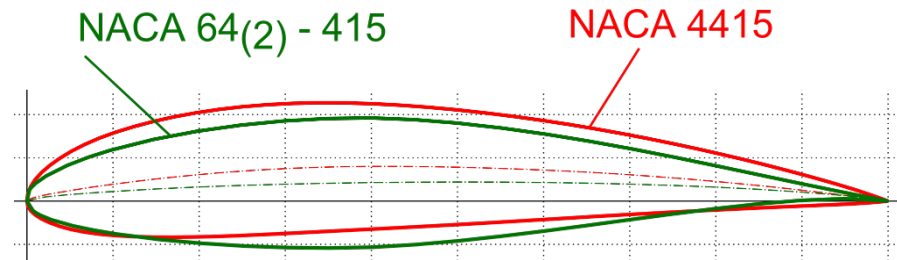
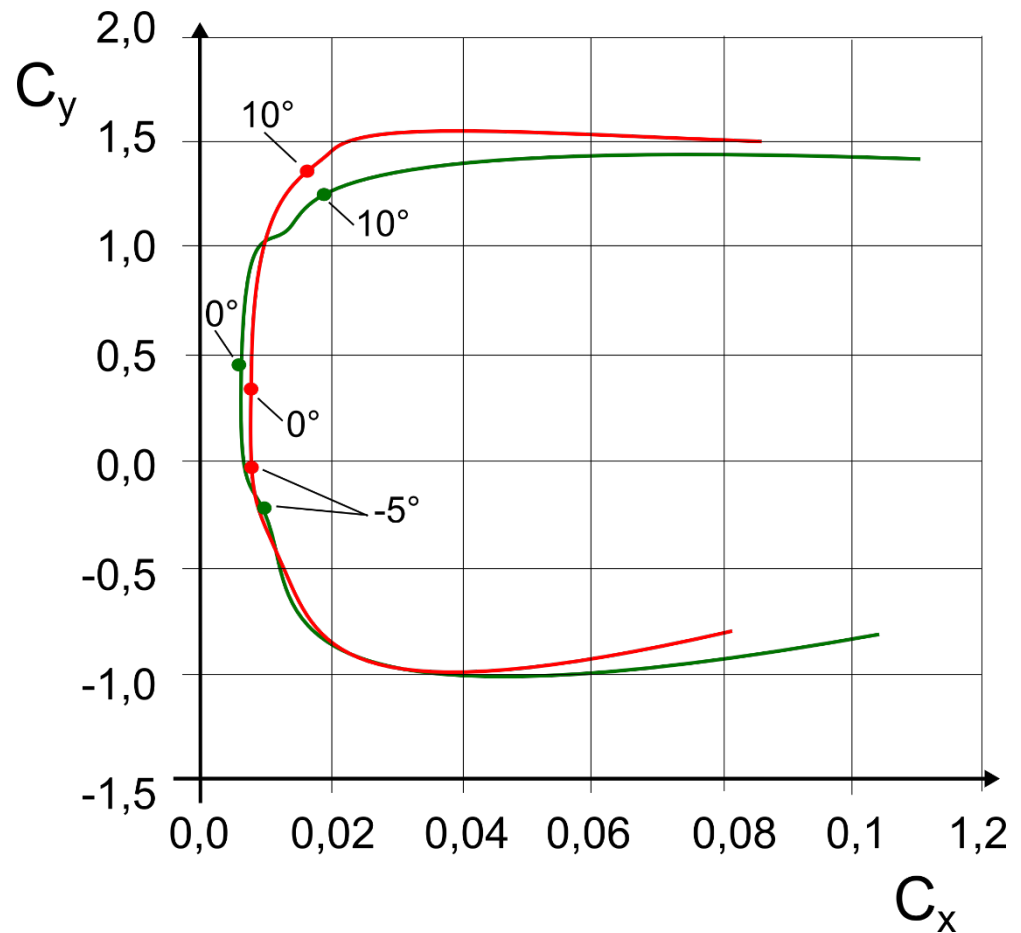
Aerodynamická polára



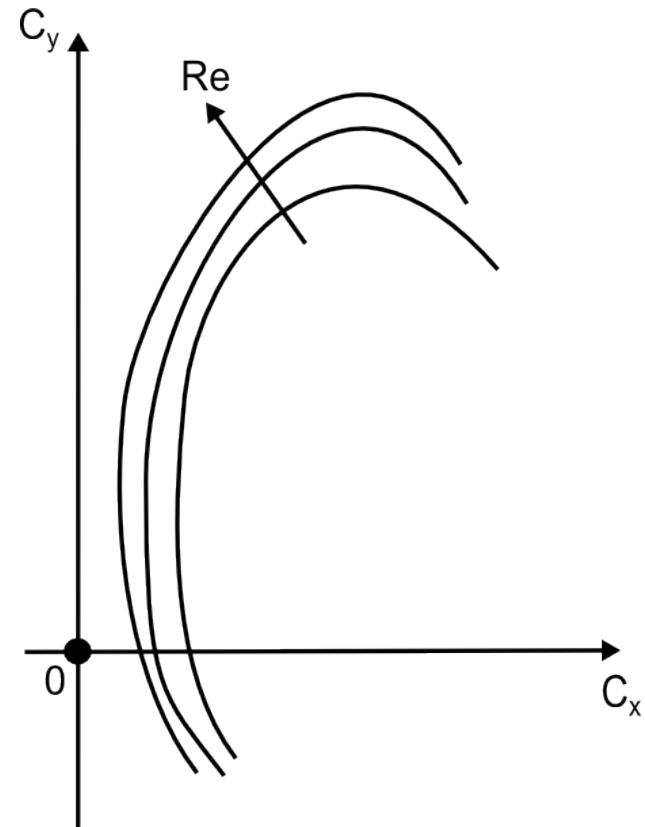
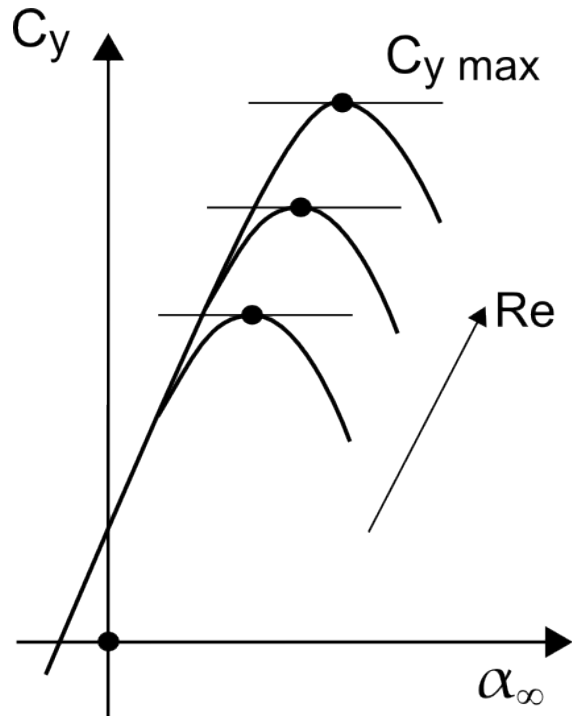
$$T = X = C_x \frac{1}{2} \rho v_\infty^2 S \rightarrow C_{x \min} \rightarrow V_{\max}$$

$$G = Y = C_y \frac{1}{2} \rho v_\infty^2 S \rightarrow C_{y \max} \rightarrow V_{\min}$$

$[C_y / C_x]_{\max} \rightarrow$ aerodynamická „účinnost“
jemnost
klouzavost



Shrnutí vlivu Re na hlavní aerodynamické charakteristiky



Prostředky pro zvýšení

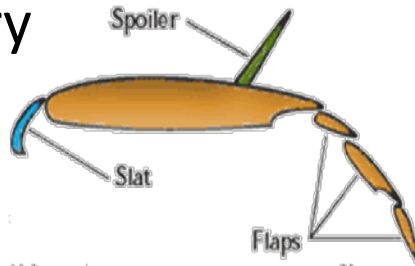
- Vztlaku [C_y]
- Odporu [C_x]

Kategorie letounů

→ poměr V_{\max} / V_{\min}

$$v = \sqrt{\frac{2G}{S \rho C_{y\max}}} \rightarrow V_{\min}$$

- Vztlakové klapky
- Spoilery
- Interceptory

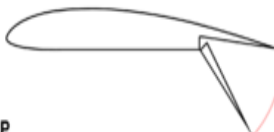


Základní typy klapek

PLAIN FLAP



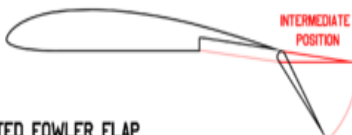
SPLIT FLAP



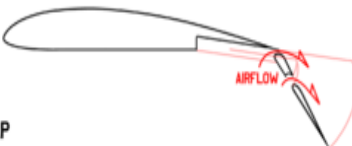
SLOTTED FLAP



FOWLER FLAP



DOUBLE-SLOTTED FOWLER FLAP



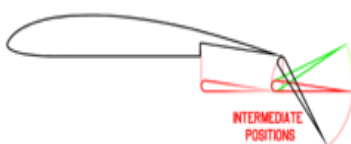
JUNKERS FLAP



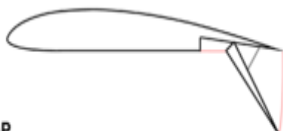
GOUGE FLAP



FAIREY-YOUNGMAN FLAP



ZAP FLAP



KRUEGER FLAP



GURNEY FLAP



LEADING EDGE DROOP



HANDLEY-PAGE SLOT



| | | $C_{L, \max}$ | $\Delta C_{L, \max}$ |
|------------------------------|--|---------------|----------------------|
| plain airfoil | | 1.45 | - |
| plain flap | | 2.25 | 0.80 |
| single-slotted flap | | 2.60 | 1.15 |
| double-slotted flap | | 2.80 | 1.35 |
| split flap | | 2.40 | 0.95 |
| Zap- flap | | 2.50 | 1.05 |
| double wing (Junkers) | | 2.25 | 0.80 |
| Fowler- flap | | 2.80 | 1.35 |
| slat | | 2.00 | 0.55 |
| slat and plain flap | | 2.45 | 1.00 |
| slat and single slotted flap | | 2.70 | 1.25 |
| slat and double slotted flap | | 2.90 | 1.45 |
| slat and Fowler- flap | | 3.00 | 1.55 |

Jednoduchá klapka



$$t \sim 12\%$$

$$\Delta C_y \sim 1,0$$



Odklápěcí klapka

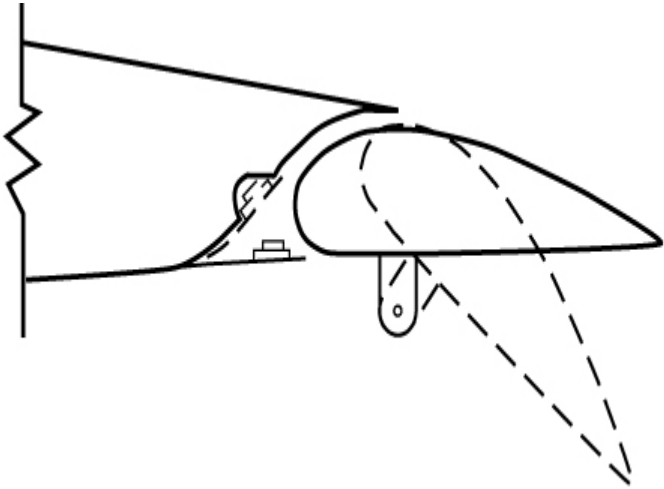


$$t \sim 18\%$$

$$\Delta C_y \sim 1,0$$

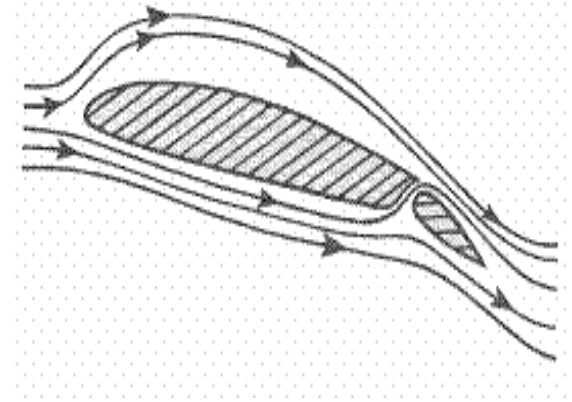


Štěrbínová klapka



$$C_{y \max} \sim 2,6$$

$$\Delta C_y \sim 1,15$$

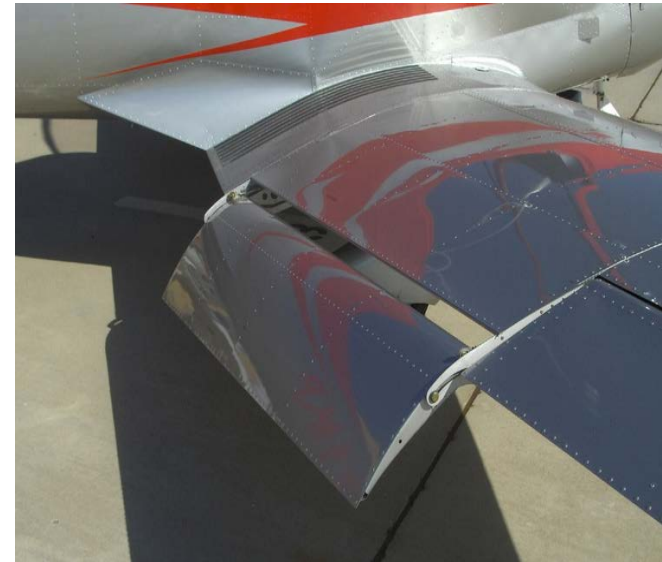


Fowlerova klapka

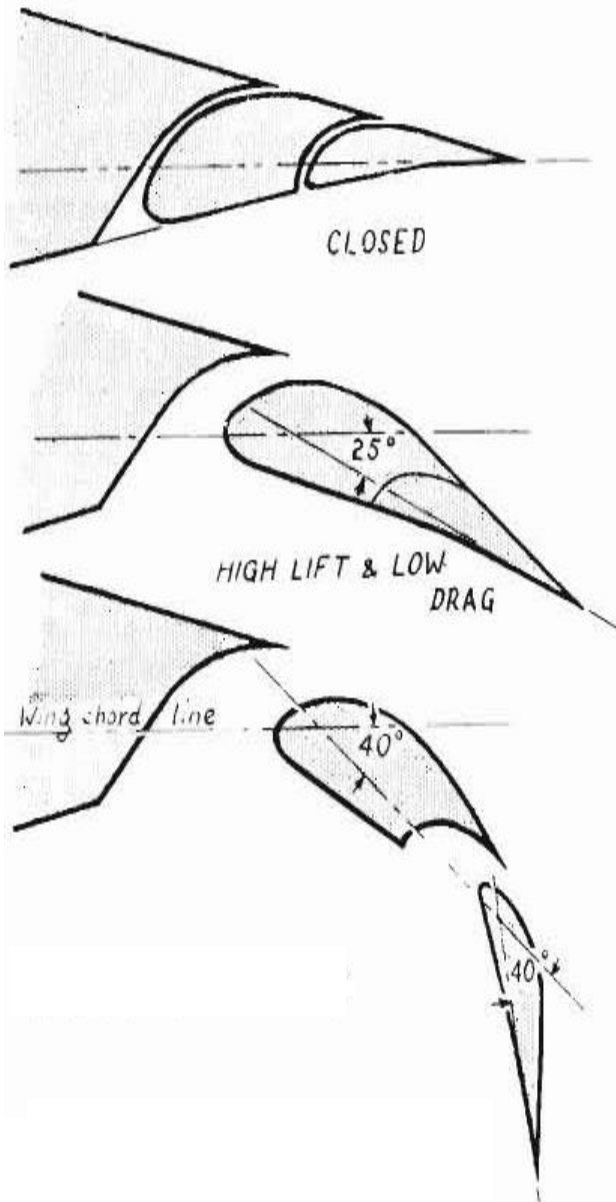


$$C_{y \max} \sim 2,8$$

$$\Delta C_y \sim 1,35$$



Dvou a více štěrbinová klapka



$$C_{y \max} \sim 3,5$$

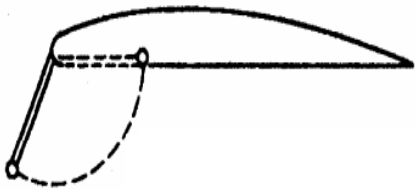
Klapky na náběžné hraně

$$\Delta C_y \sim 0,4 - 0,5$$

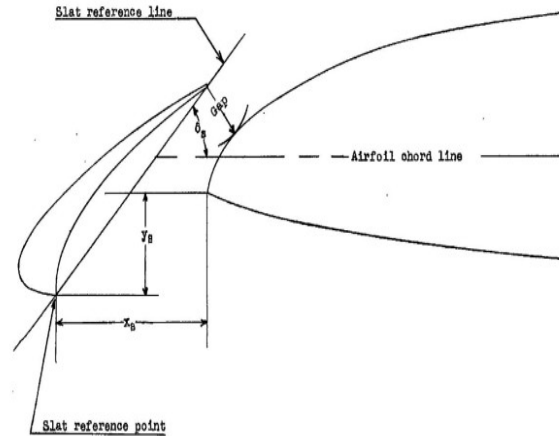
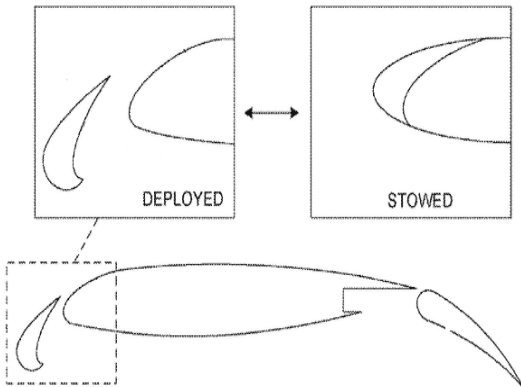
- Sklopná náběžná hrar



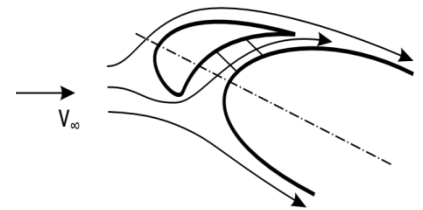
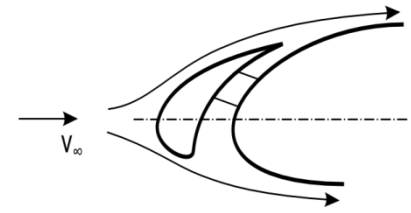
- Krugerova klapka



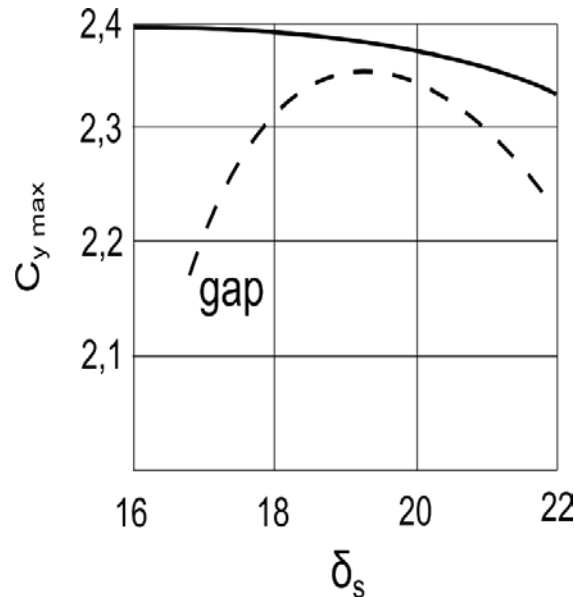
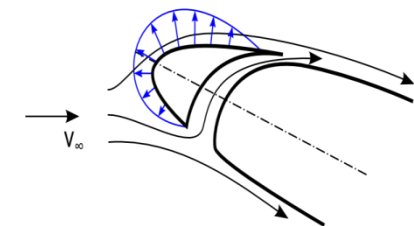
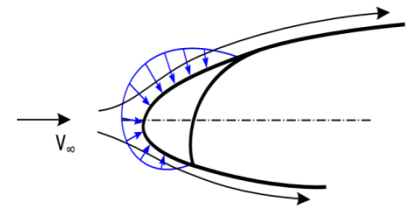
- Pevný/výsuvný slot



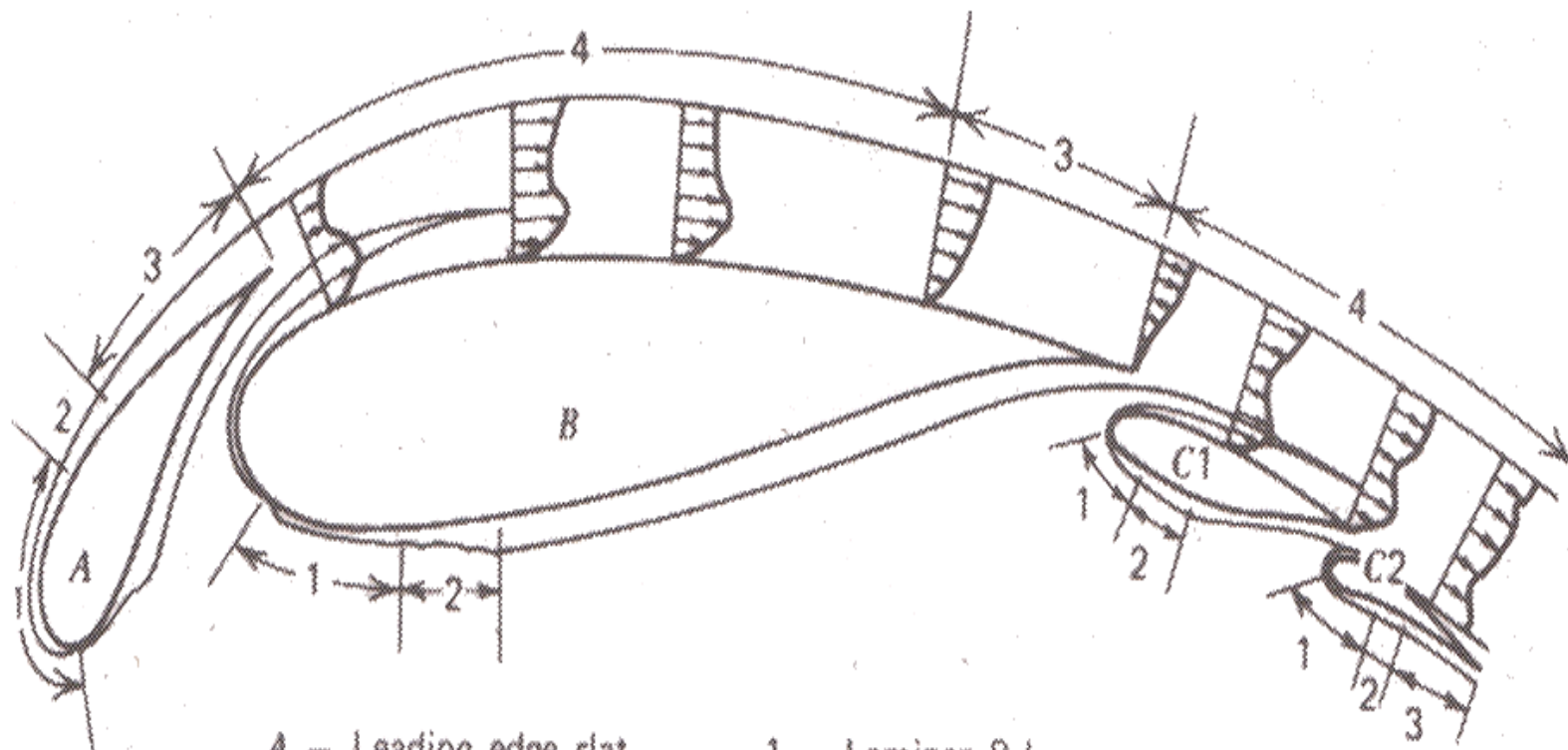
- Pevný slot



- Výsuvný slot



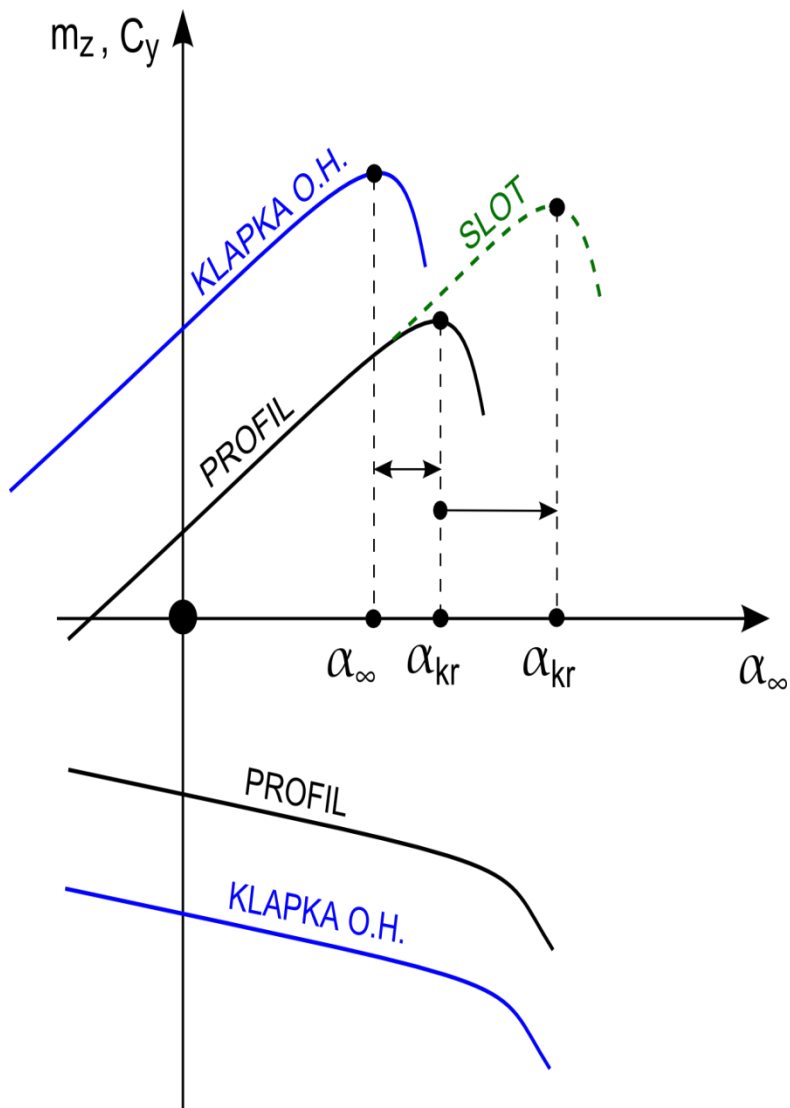
Proudové pole



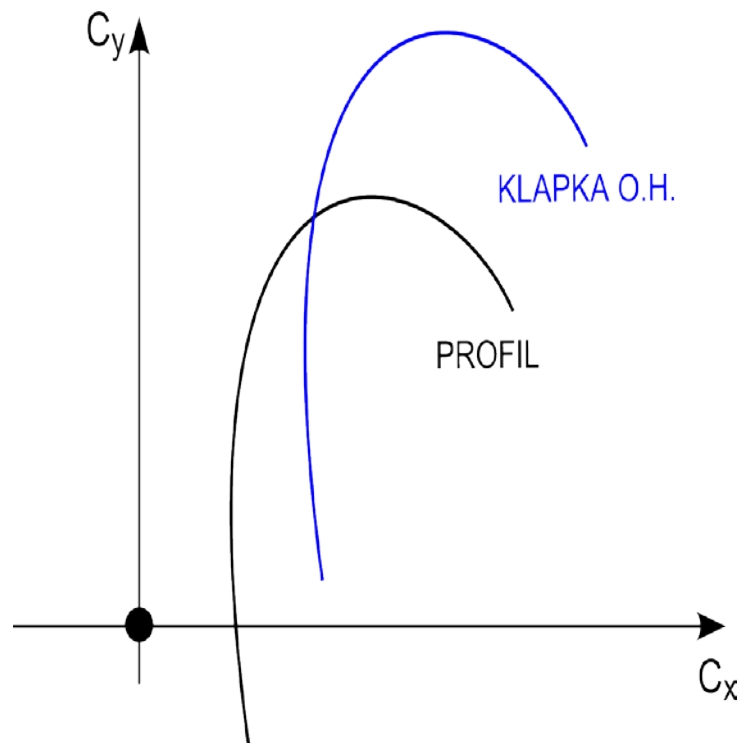
- | | | | |
|----|-------------------------|---|----------------------------|
| A | – Leading edge slat | 1 | – Laminar B.L. |
| B | – Main component | 2 | – Transition region |
| C1 | } – Double slotted flap | 3 | – Ordinary turbulent B.L. |
| C2 | | 4 | – Confluent boundary layer |

Vliv na aerodynamické charakteristiky

- Vztlaková a momentová čára

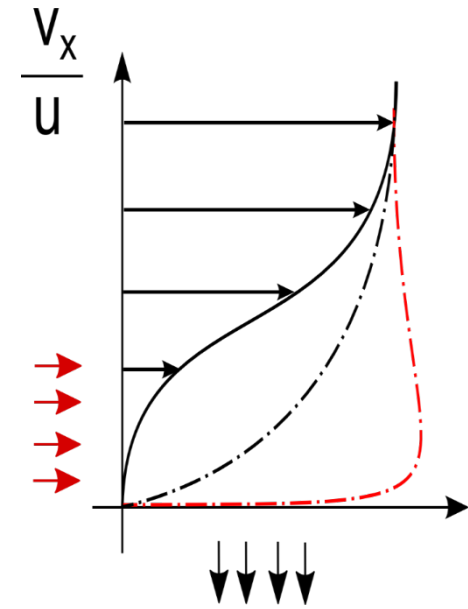


- Polára

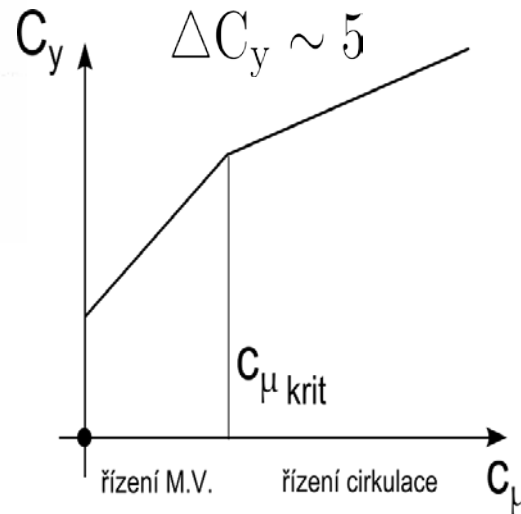
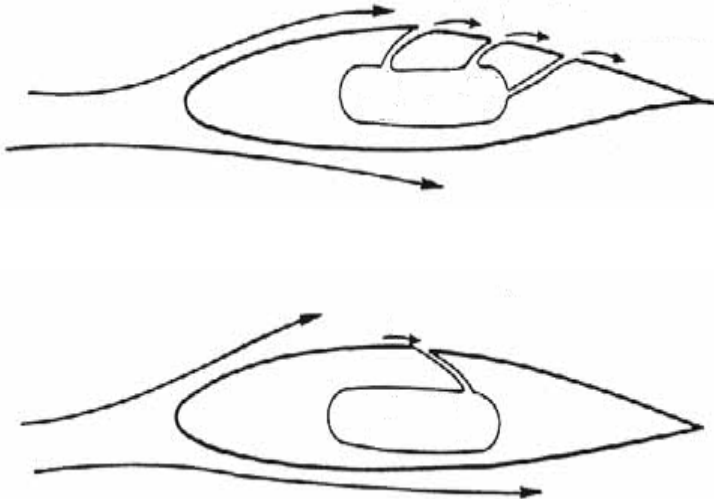


Řízení mezní vrstvy

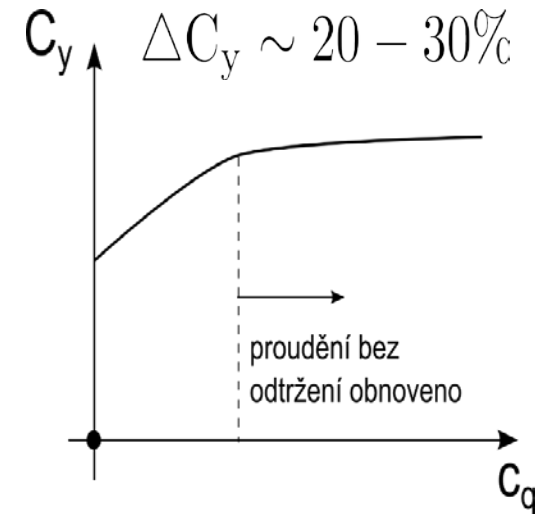
- Ovlivnění pohonem



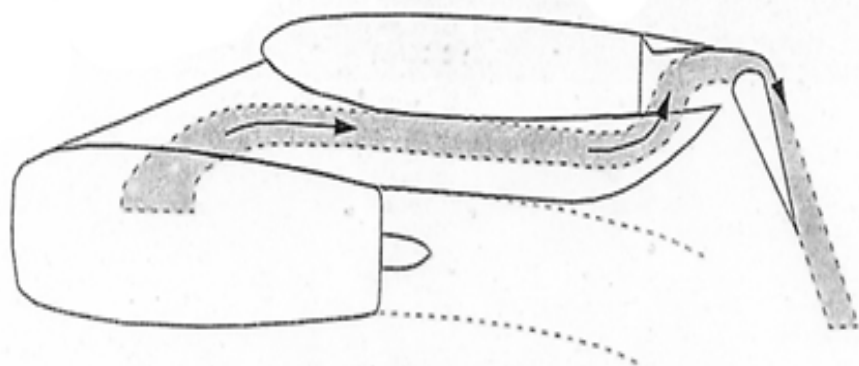
- Vyfukování a odsávání M.V.



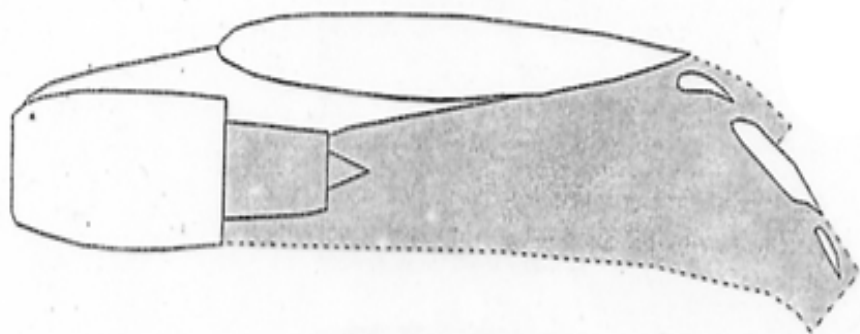
vyfukování do M.V.



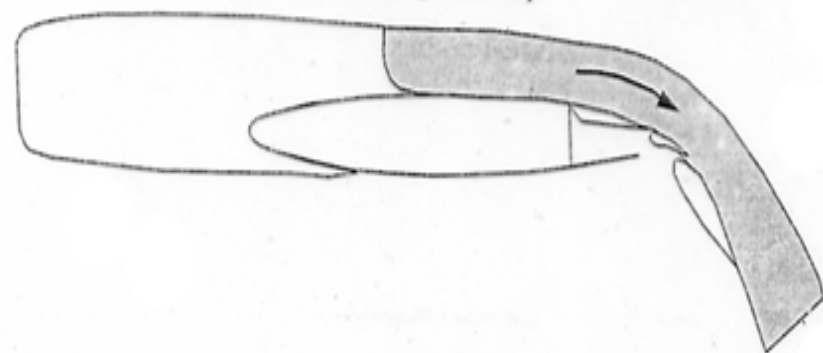
odsávání



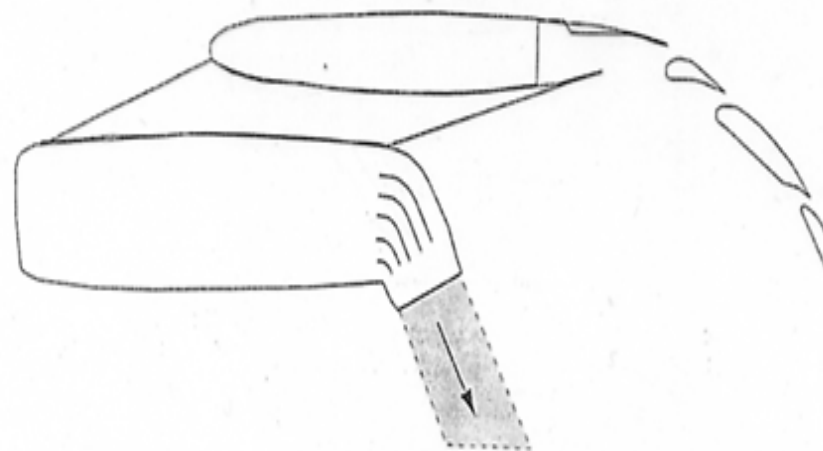
a) Internally blown flap



b) Externally blown flap

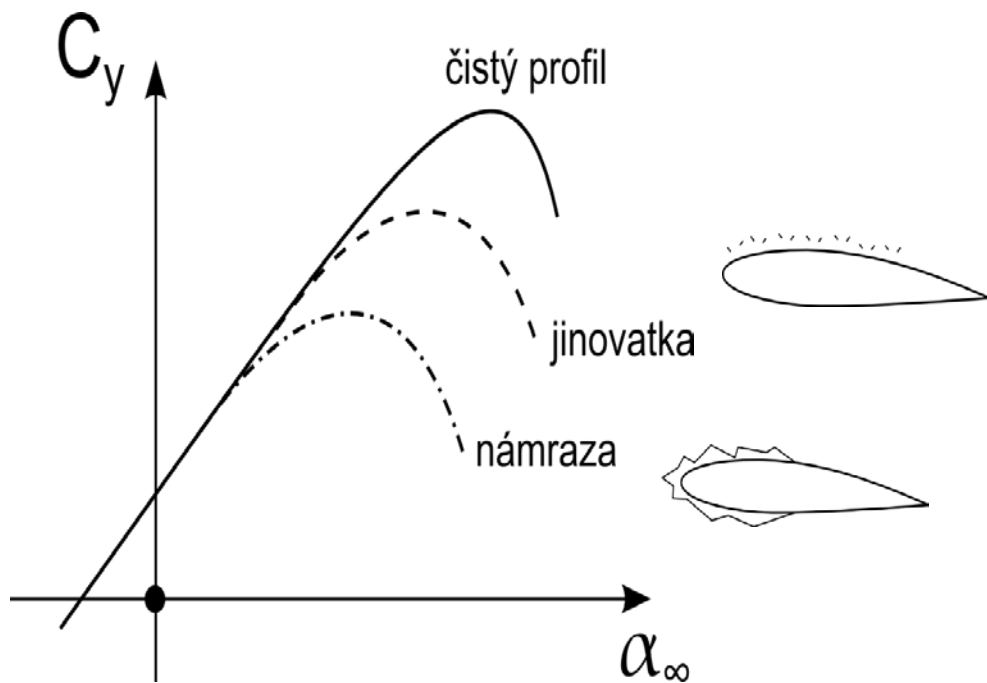


c) Upper-surface blowing



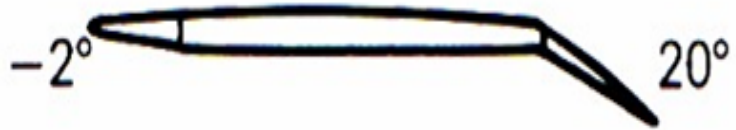
d) Vectored thrust

Znečištění



Transsonické / supersonické křídlo

F-16 Takeoff during ground roll



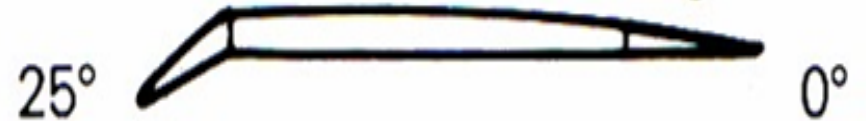
Takeoff after liftoff



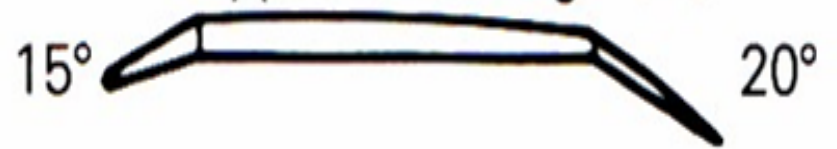
Reflexed for high speed cruise



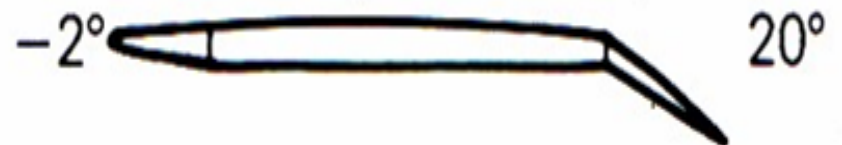
Maximum manoeuvre configuration



Approach configuration

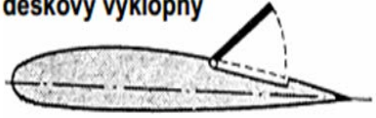


Landing at wheel spin up

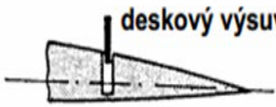


Spoilery

deskový výklopný



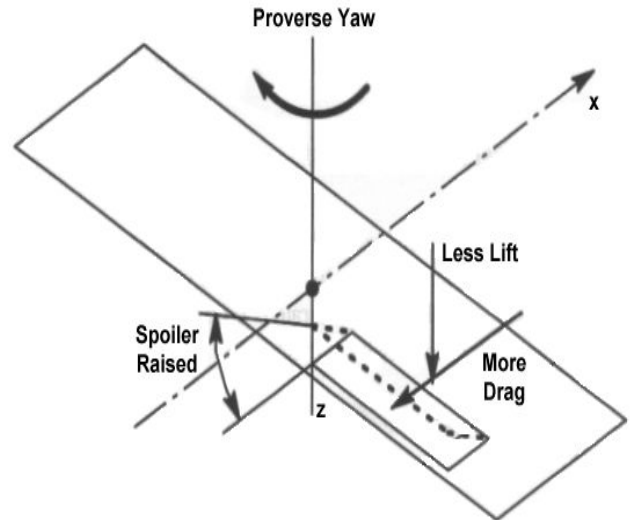
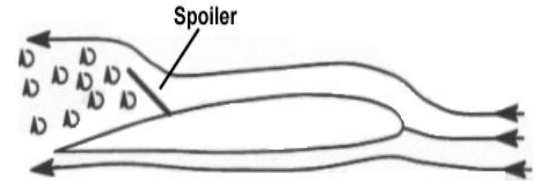
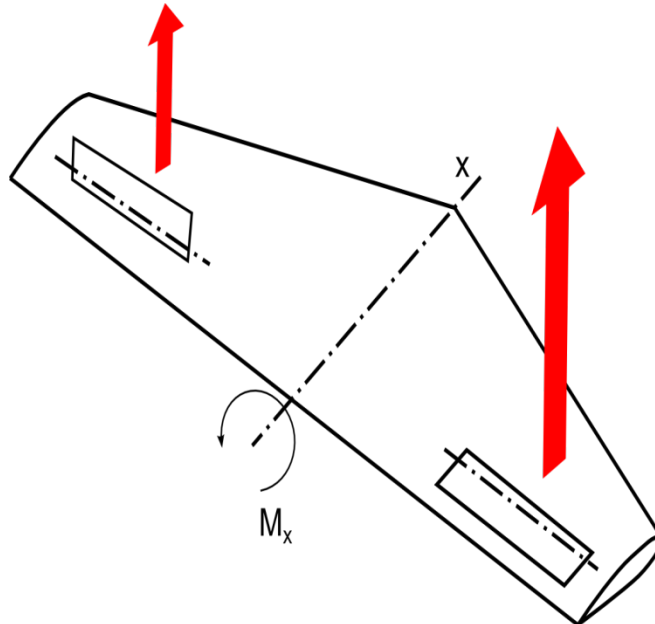
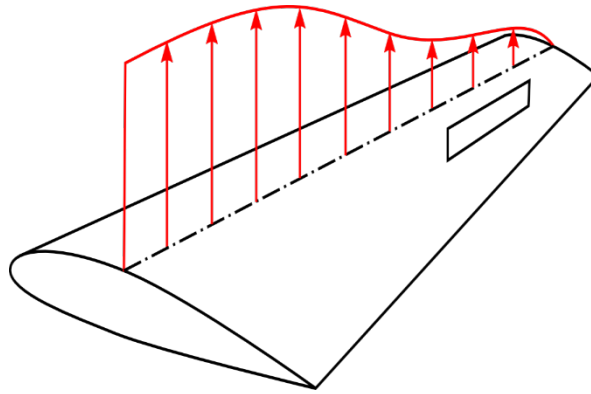
deskový výsuvný



segmentový



klapkový



Aerodynamické brzdy

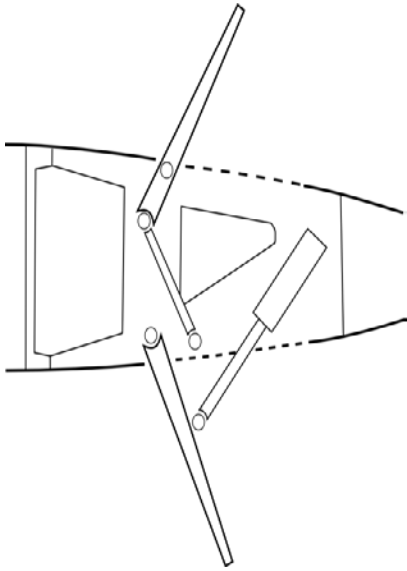
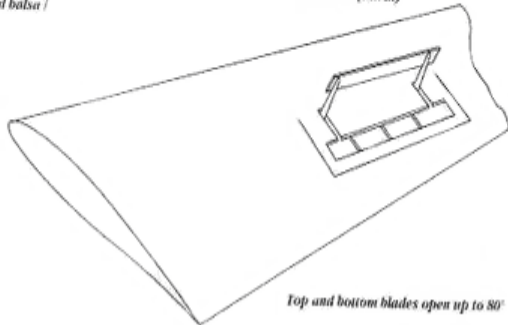
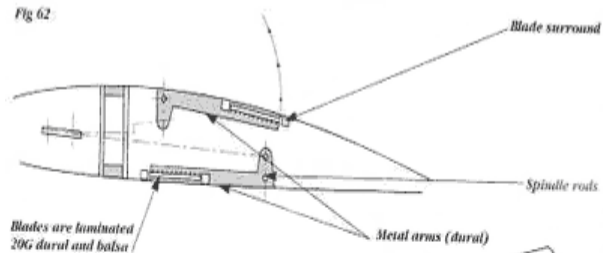


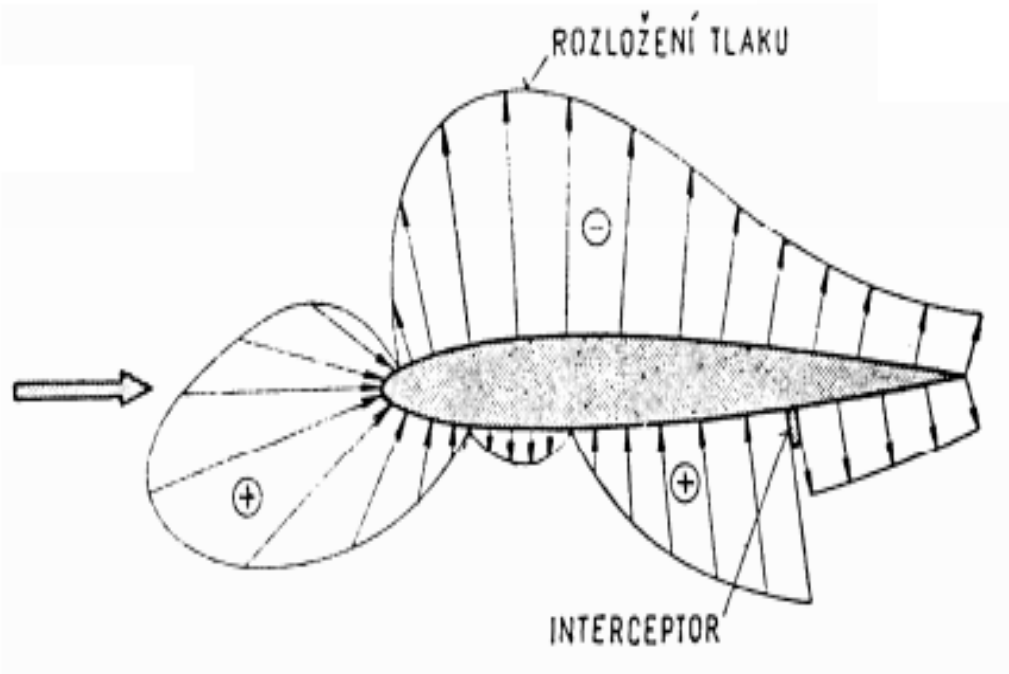
Fig 62



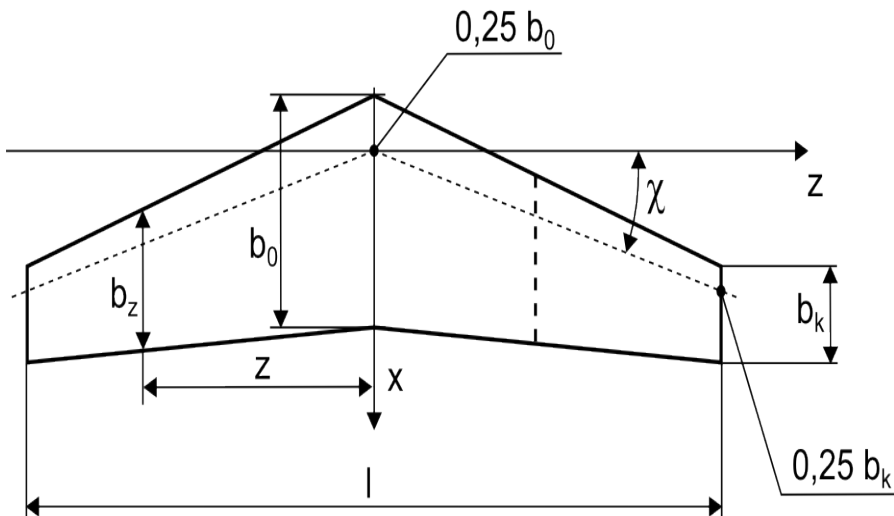
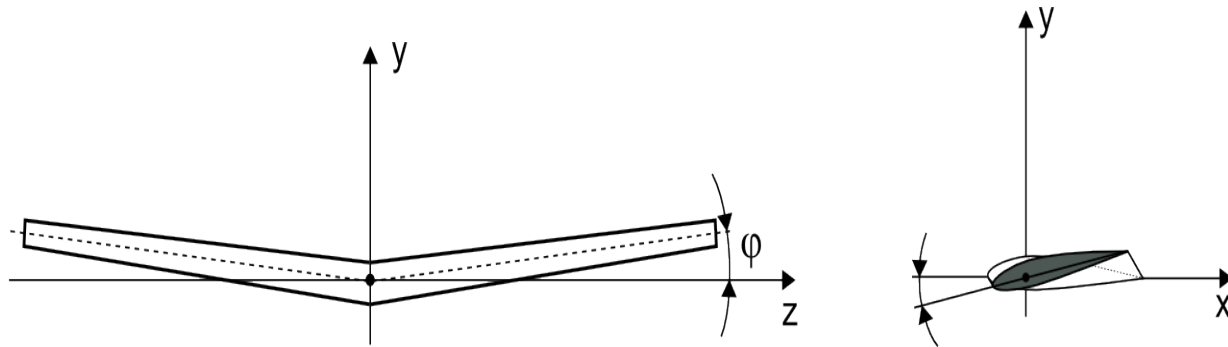
DFS Airbrake Installation MU13-03



Interceptory



Geometrické charakteristiky nosné plochy - křídla



Zúžení

$$\eta = \frac{b_k}{b_0}$$

Štíhlost

$$\lambda = \frac{l^2}{S}$$

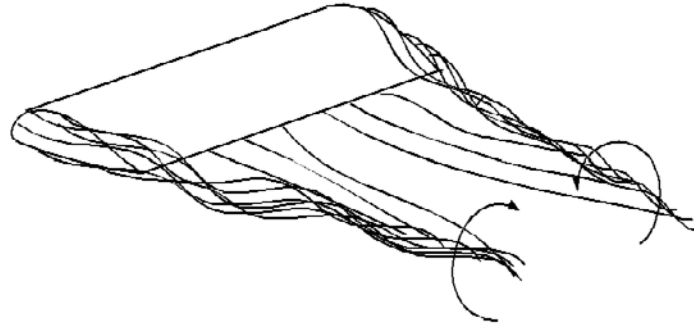
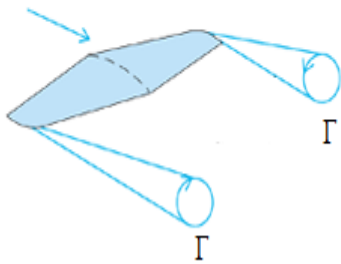
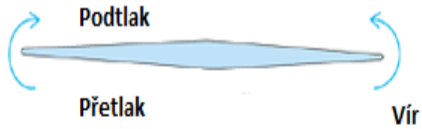
$$\lambda = \frac{l}{b_{stř}}, S = b_{stř}l$$

Půdorys

- Obdélník
- Lichoběžník
- Elipsa

Proudové pole křídla – okrajový (koncový) vír

- Vírový systém

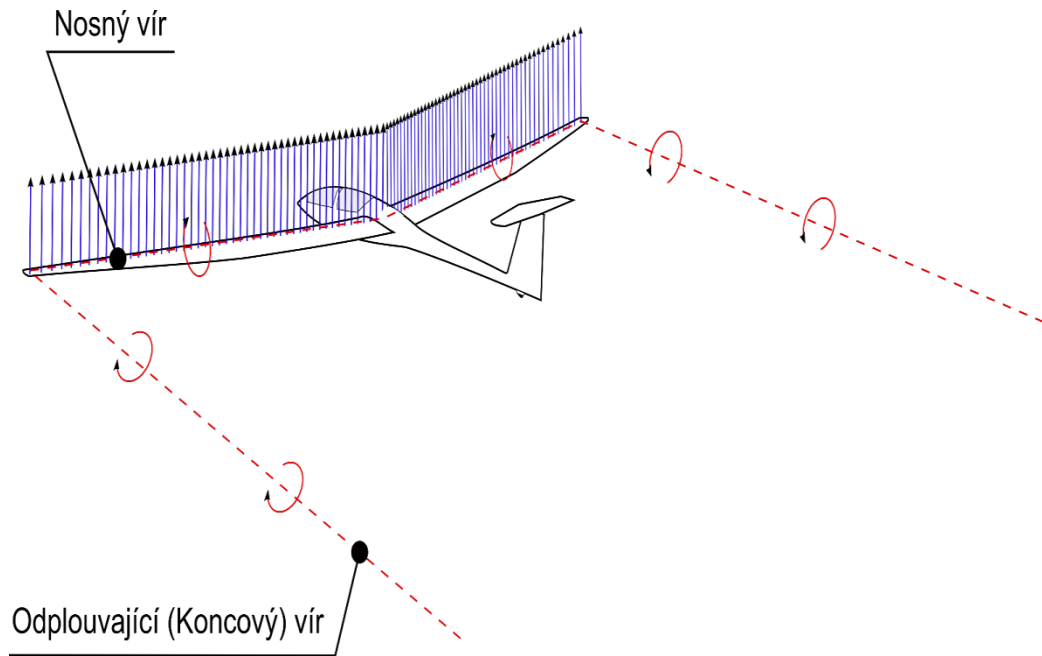


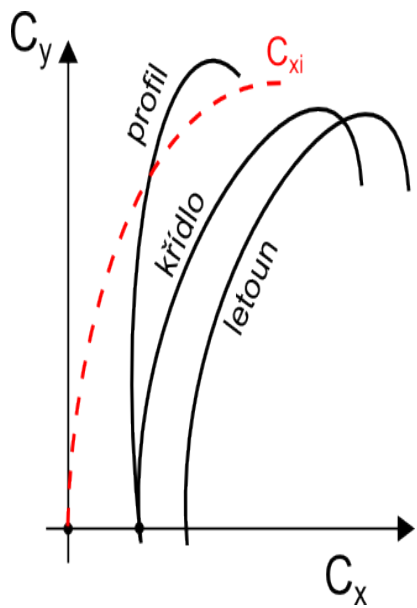
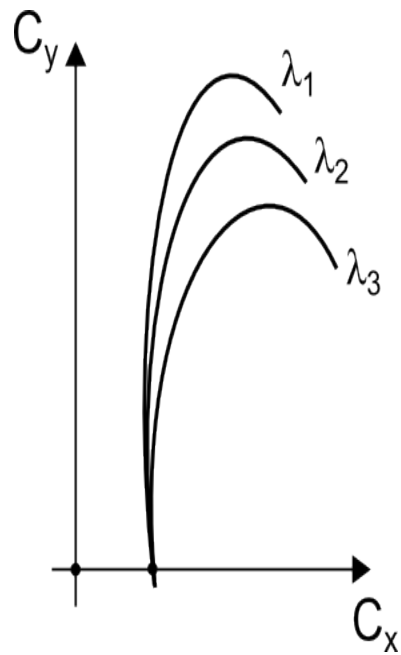
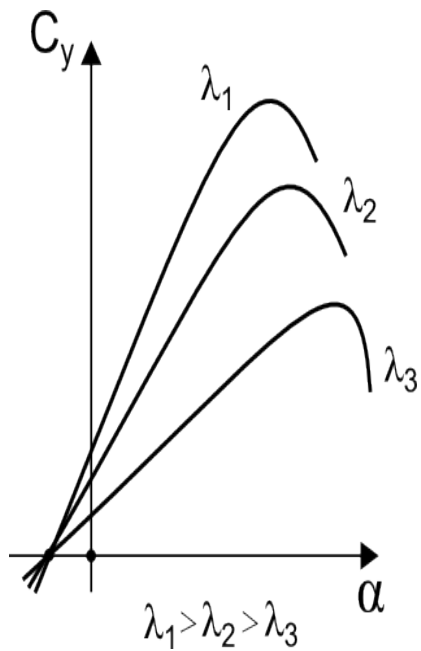
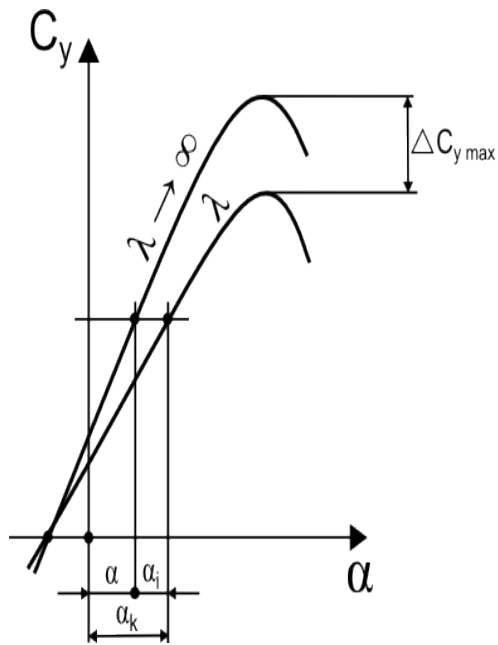
- Vírové schéma

➤ Nosný vír

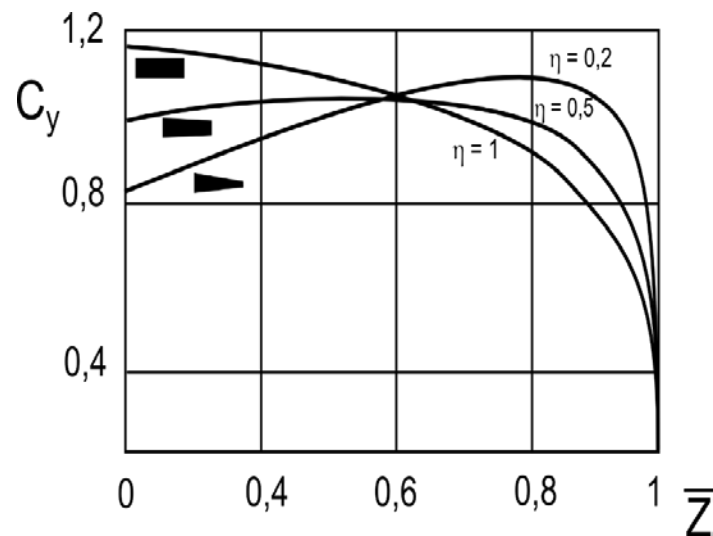
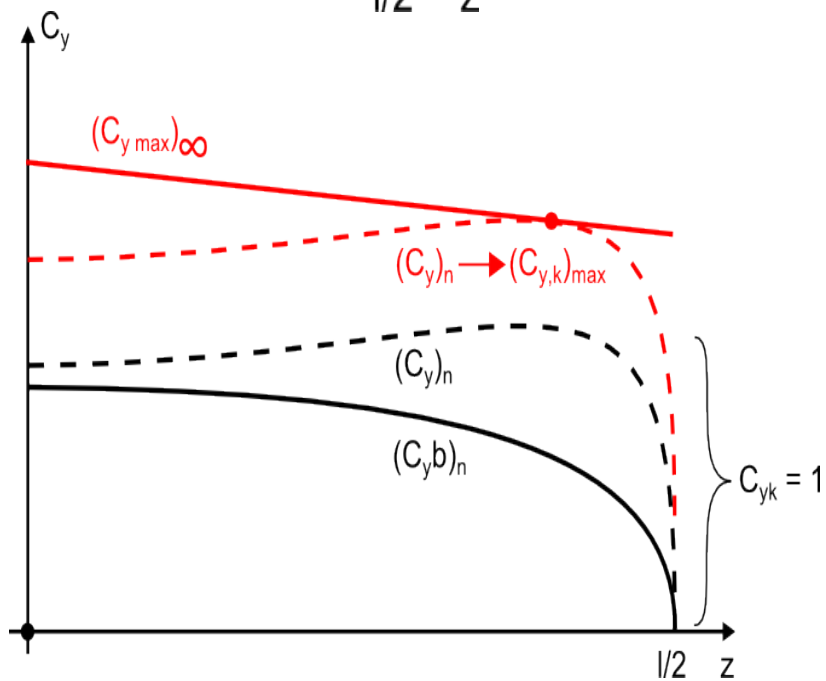
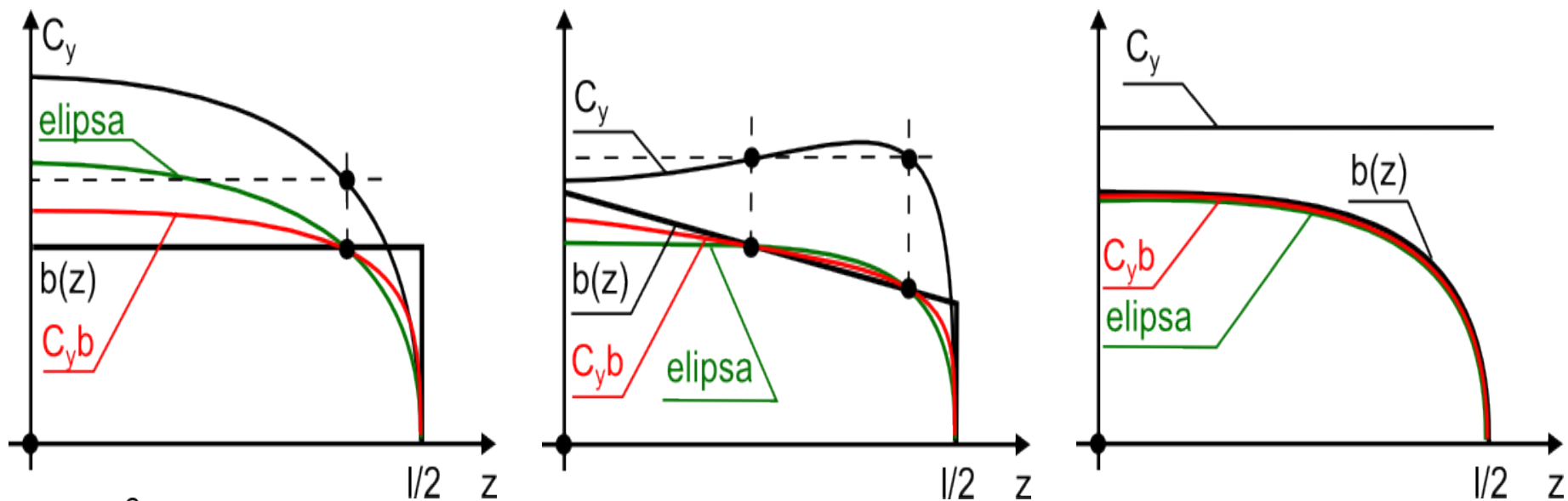
$$Y = \rho v_{\infty}^2 \Gamma$$

➤ Odplouvající, Koncový vír

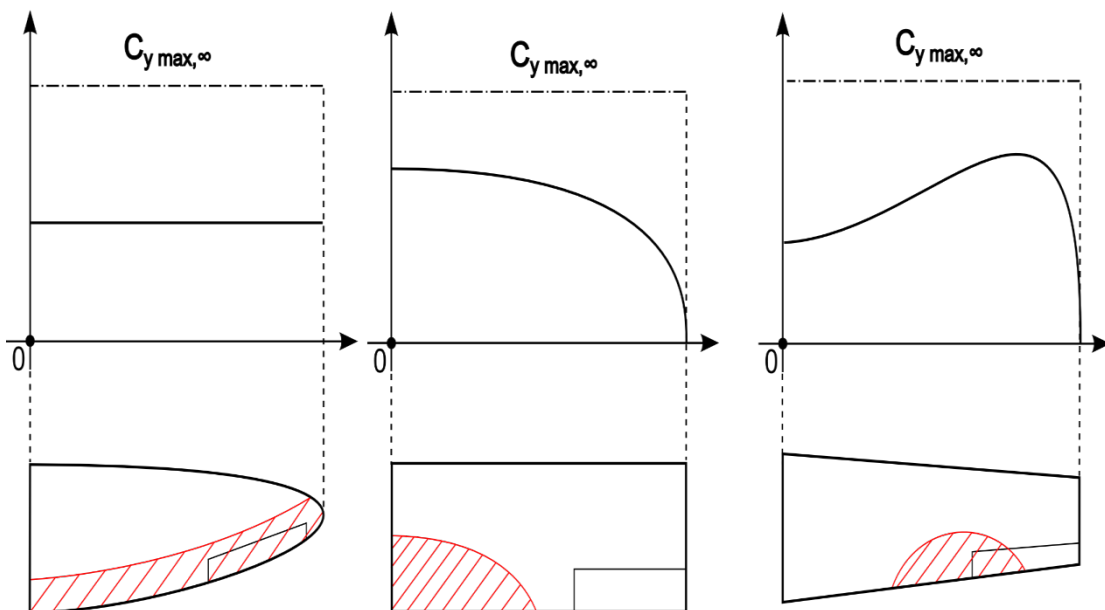




Schrenkova metoda



Održení



Prostředky pro zlepšení vlastností při přetažení

- Geometrické kroucení
- Aerodynamické kroucení
- Lišty na náběžné hraně (odtrhávací)
- Sloty (v oblasti křidélek)

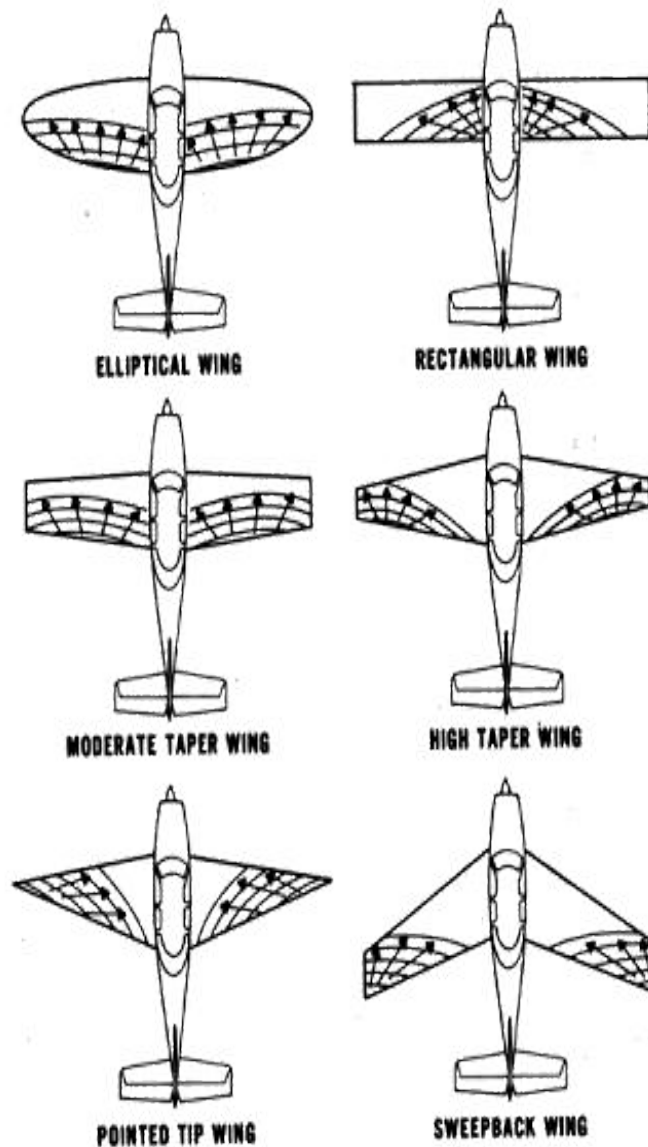


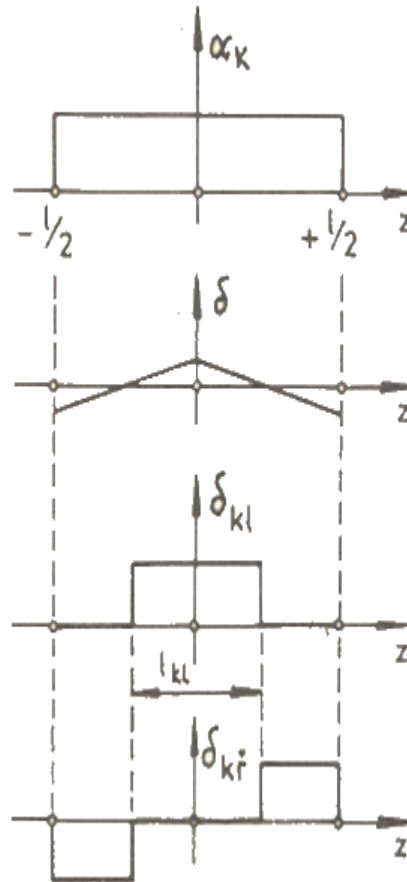
Figure 17-13 Wing Planforms (Exaggerated)

Rozložení

$C_y(z)$, $C_{y b}(z)$, $\Gamma(z)$, $\gamma(z)$, ..

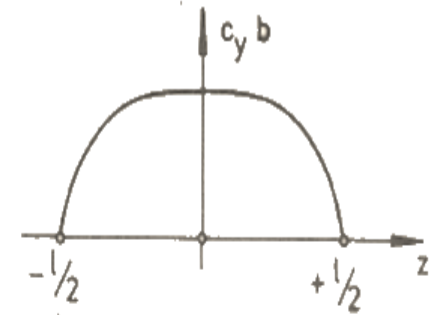
Největší vliv má

- Půdorysný tvar
- Kroucení křídla
 - Aerodynamické
 - Geometrické
- Klapky
- Křidélka

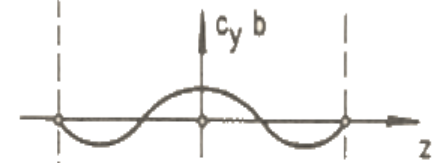


Rozložení :

normální



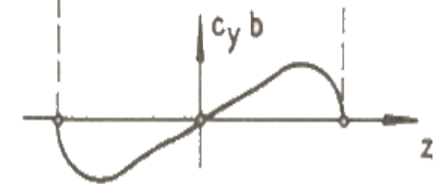
nulové



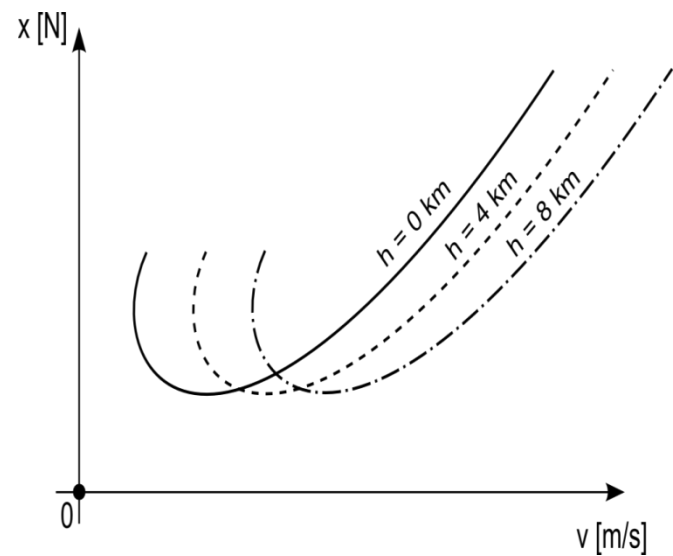
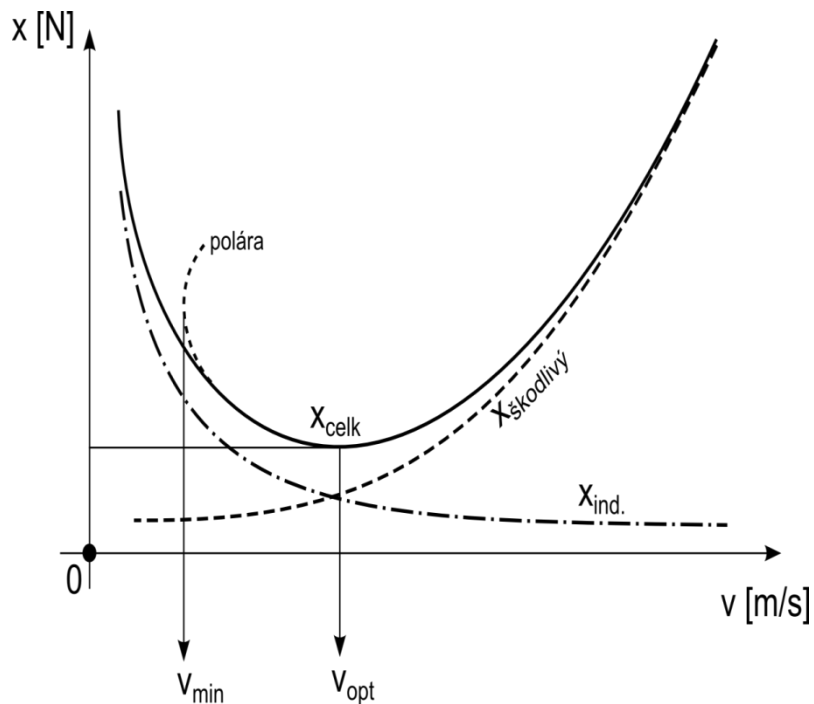
klapky



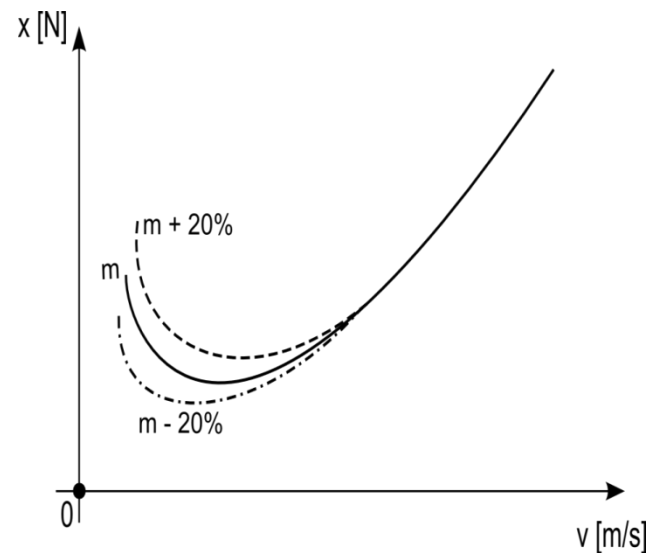
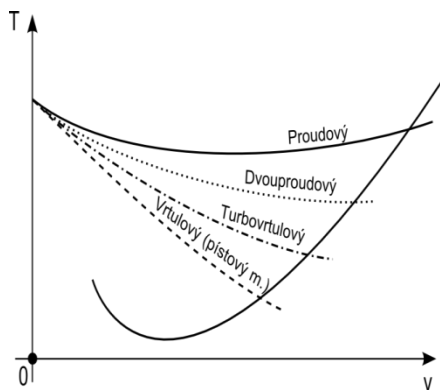
křidélka



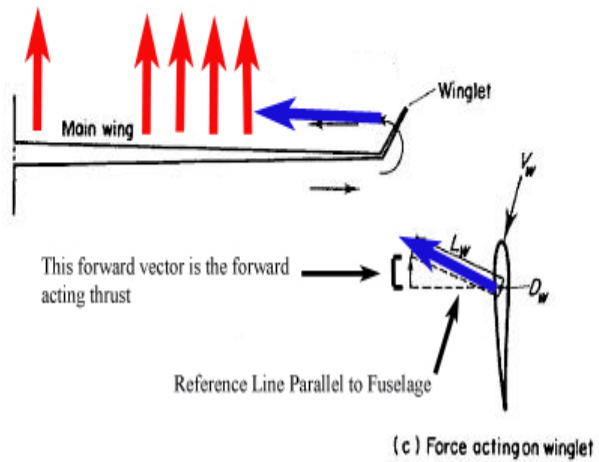
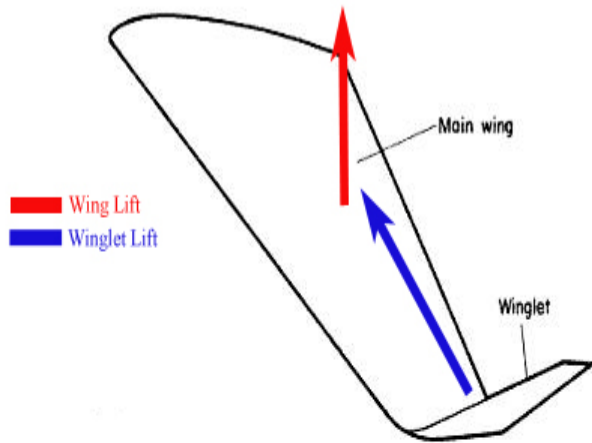
Celkový odpor letounu



- Využitelný tah (rychlostní charakteristika)

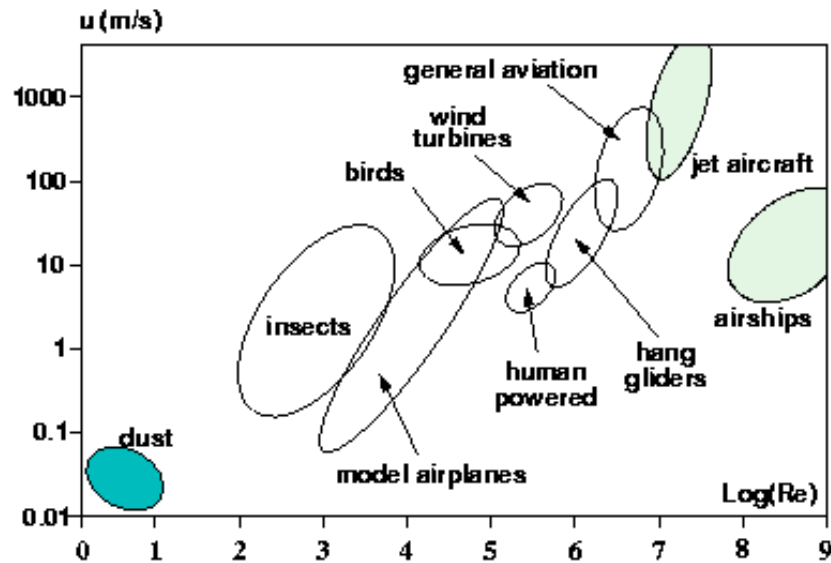
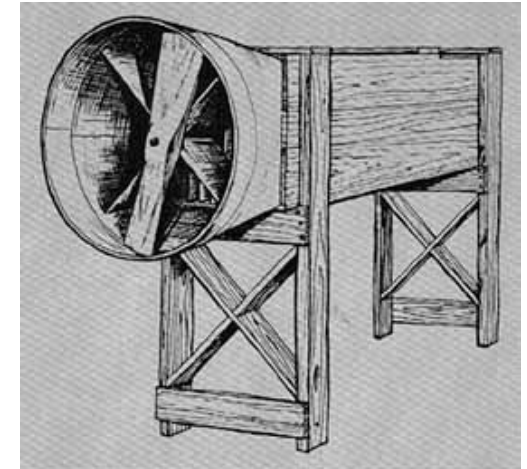


- Tah wingletu

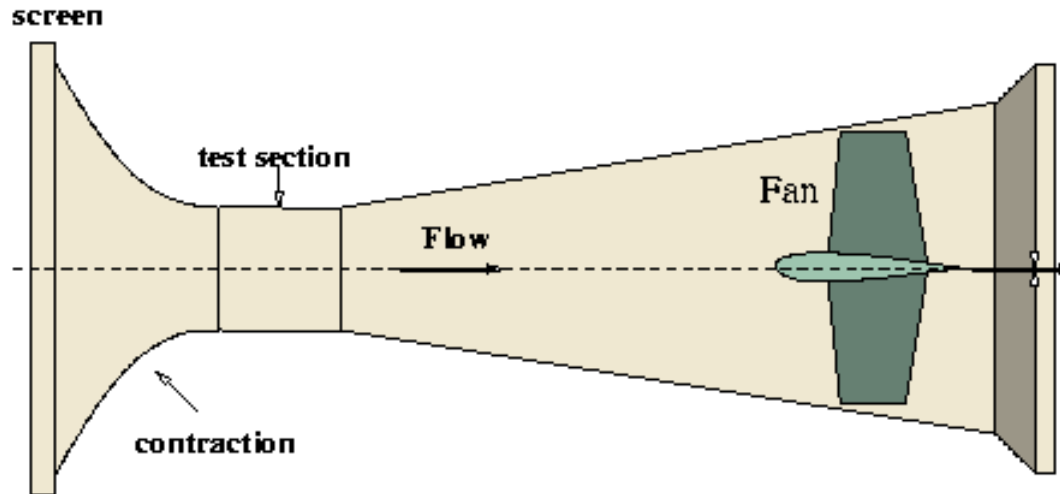


Aerodynamické tunely

- Nízkorychlostní
- Transsonické
- Supersonické
- Hypersonické
- Přetlakové,
- kryogenní
- Ekologické

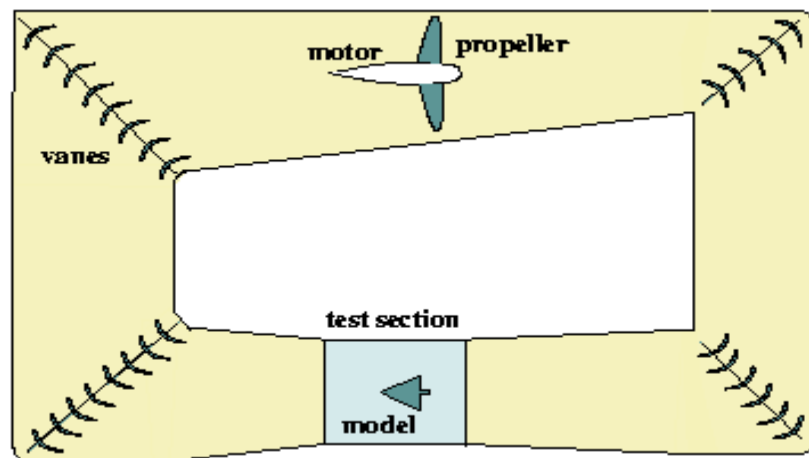


Nízkorychlostní tunely



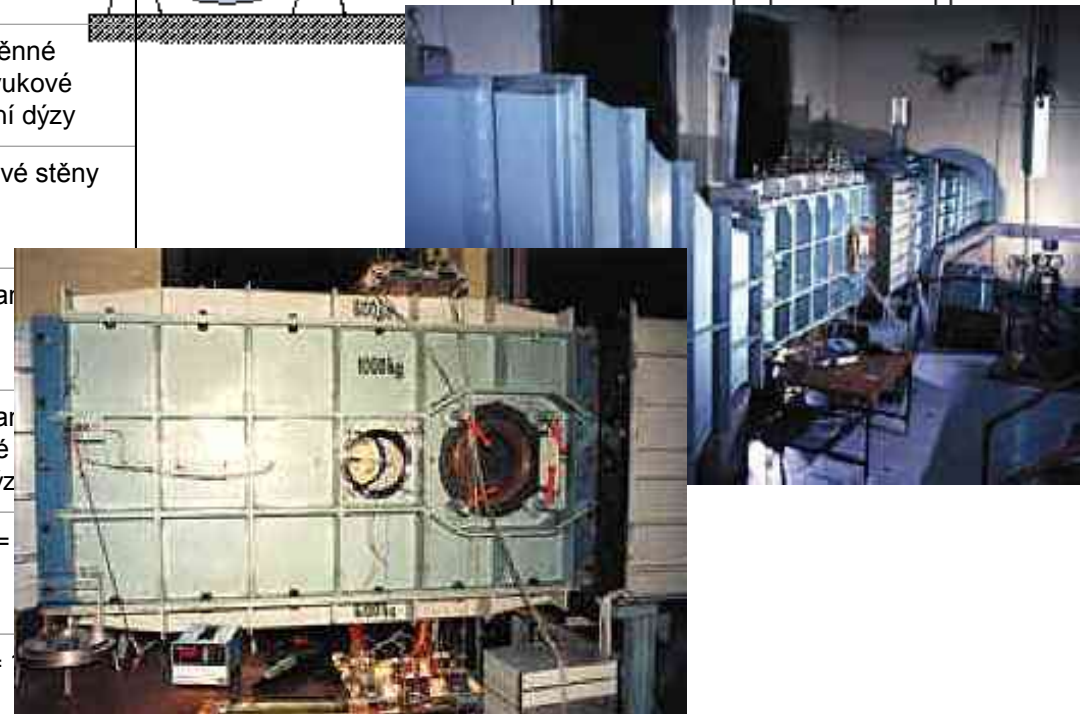
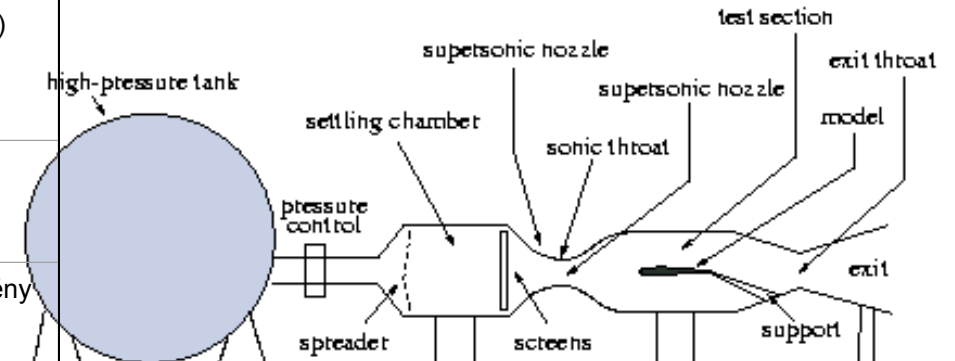
| Wind tunnel | ∅ 3 m | ∅ 1.8 m | BLWT* | ∅ 0.6 m |
|--|--|-----------------------------------|-----------------------------------|------------------------------|
| Type | atmospheric, closed-circuit | atmospheric, open-circuit | atmospheric, open-circuit | atmospheric, closed-circuit |
| Test section | open ∅ 3 m 3 m length | open ∅ 1.8 m 1.75 m length | closed 1.8 x 1.5 m 16 m length | open ∅ 0.6 m 0.6 m length |
| Velocity | up to 70 m/s | up to 55 m/s | up to 16 m/s | up to 65 m/s |
| Max. local deviation of velocity across test section | < 0.5 % | < 0.5 % | simulation of wind effect | < 1 % |
| Typical value of turbulence intensity | 0.3 % | 0.5 % | modelled profile | 0.3 % |
| Balance | external six-component mechanical, internal six-component strain-gauge | external six-component mechanical | | |

Nízkorychlostní tunely



Nadzvukové a transsonické tunely

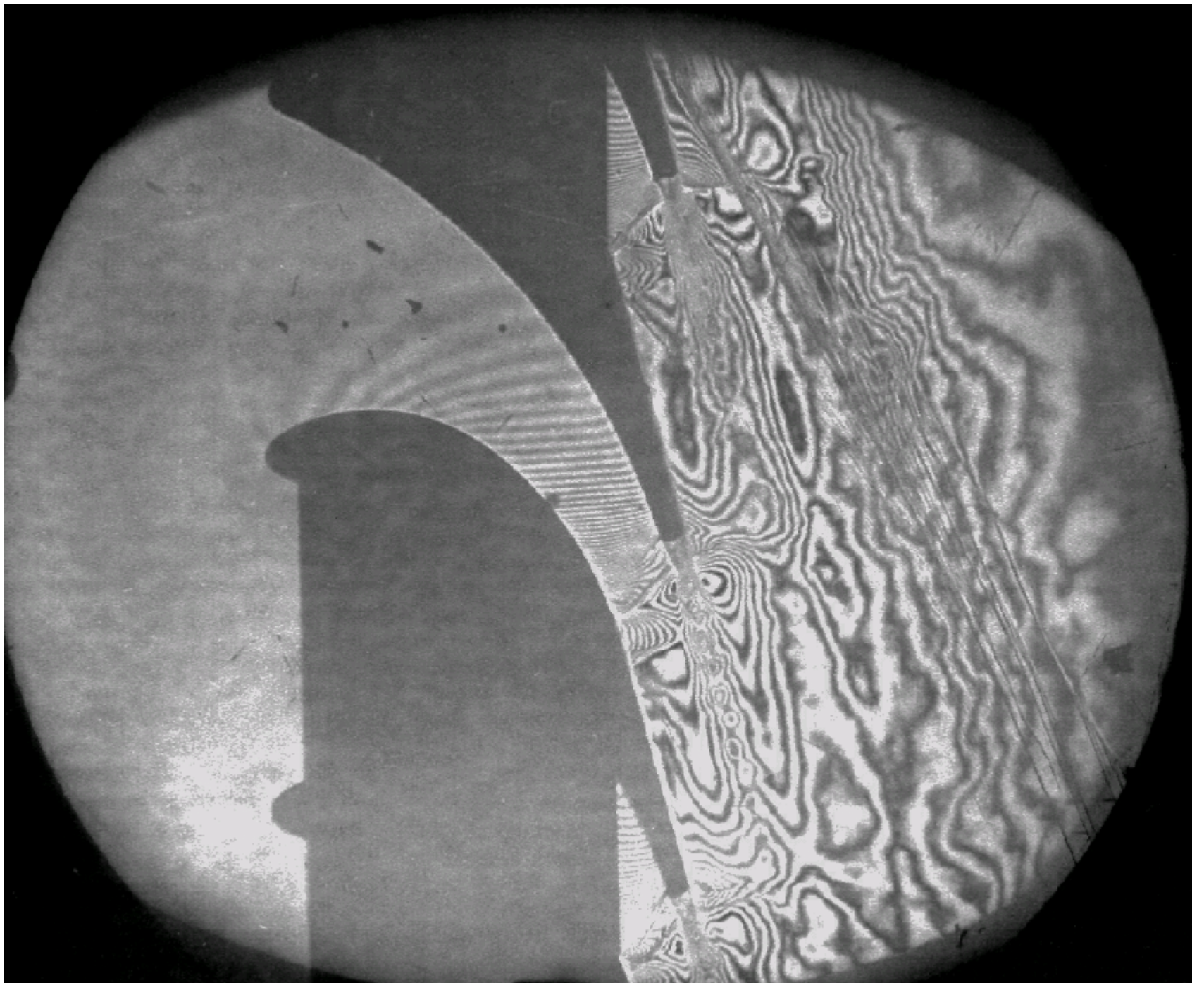
| označení měřicího prostoru | rozměr měřicího prostoru [m] | Machovo číslo | doba chodu | poznámka (měř. prostor) |
|----------------------------|------------------------------|---------------|------------|---------------------------------|
| A1 | 0,9 x 0,6 | 0,2 - 0,75 | 8 s | pevné stěny |
| A2 | 0,6 x 0,6 | 0,3 - 1,1 | 8 s | perforované stěny |
| A3 | 0,6 x 0,6 | 1,4 - 2,1 | 6 s | výměnné nadzvukové vstupní dýzy |
| A4 | 0,4 x 0,8 | 0,15 - 0,9 | 10 s | štěrbinové stěny |
| C | 0,12 x 0,12 | 0,2 - 1,1 | cont. | perforované stěny |
| M | 0,2 x 0,24 | 0,2 - 1,8 | 60 s | perforované stěny, výměnné dýzy |
| T 300 | A 0,3 | 0 - 0,6 | 60 s | Qmax = |
| T 500 | A 0,5 | 0 - 0,6 | 20 s | Qmax = |

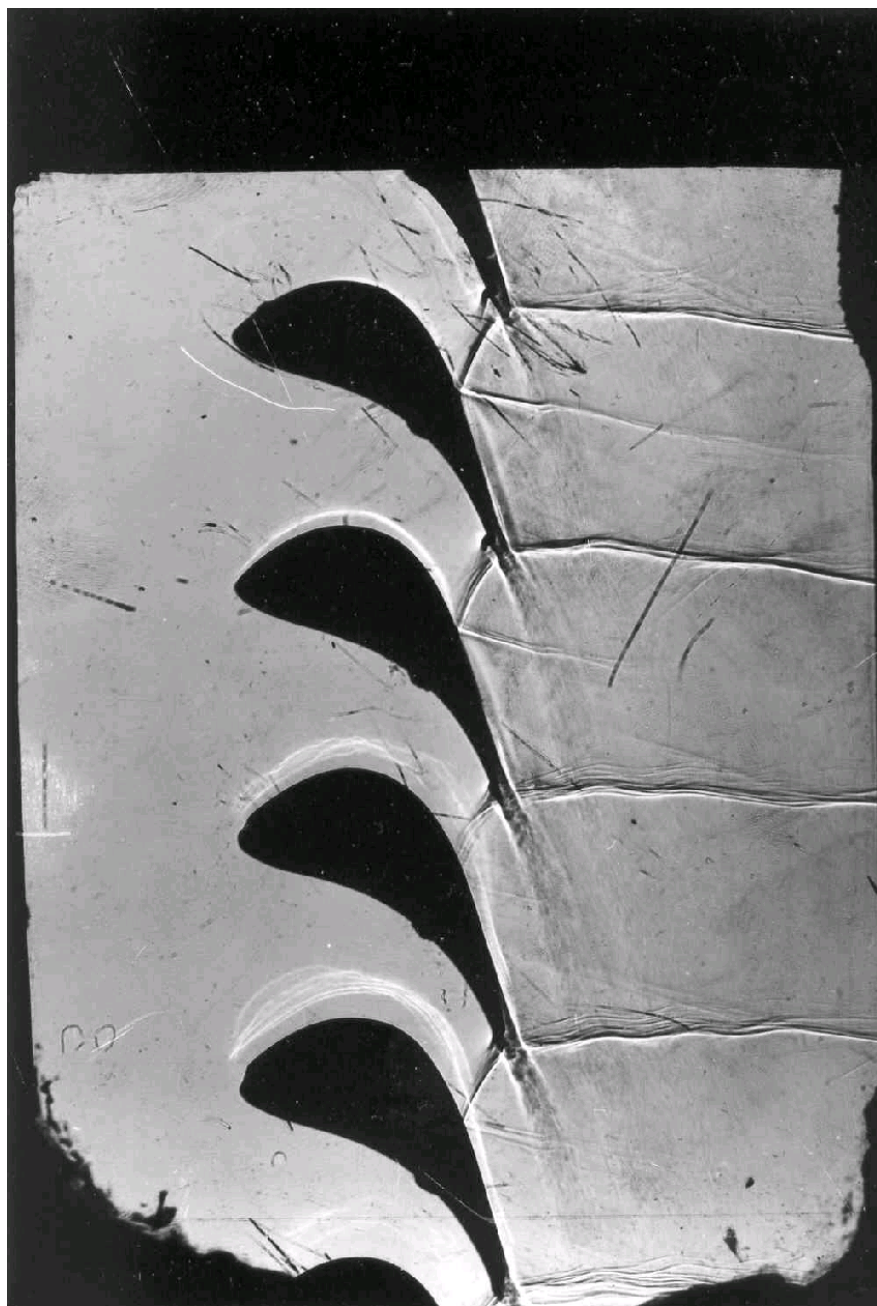


Nadzvukové a transsonické tunely



| označení tunelu | rozměr měřícího prostoru [m] | Machovo číslo | celkový tlak [MPa] | poznámka |
|-----------------|------------------------------|---------------|--------------------|-----------------------|
| NC | 0,25 x 0,25 | 1,5 - 3,5 | 0,02 - 0,16 | třírozměrné modely |
| LM | 0,1 x 0,4 | 0,1 - 0,98 | 0,02 - 0,16 | přímé lopatkové mříže |
| TU | 0,06 m ² | 0,1 - 0,98 | 0,02 - 0,16 | kruhové mříže |

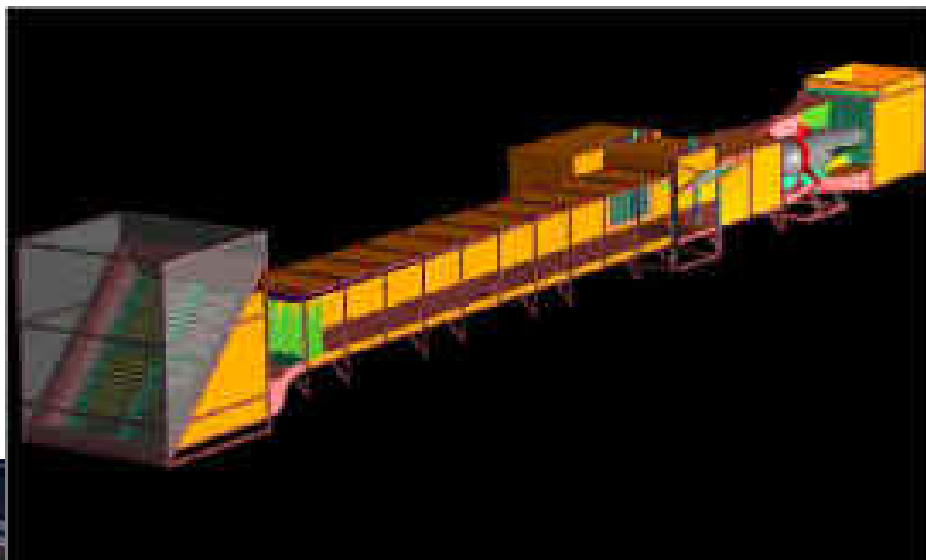






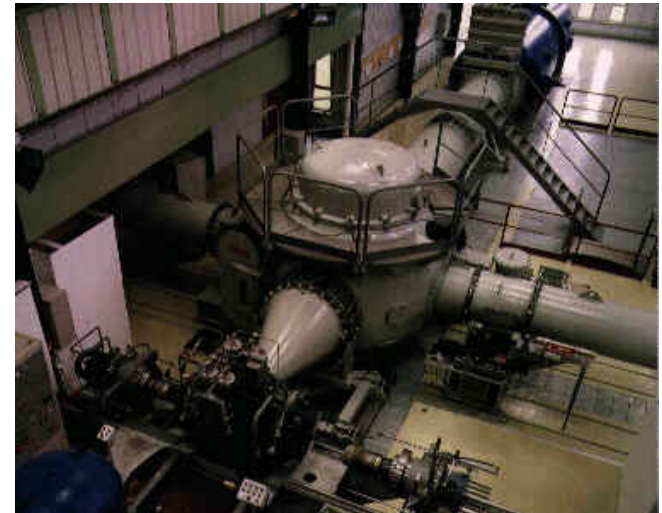
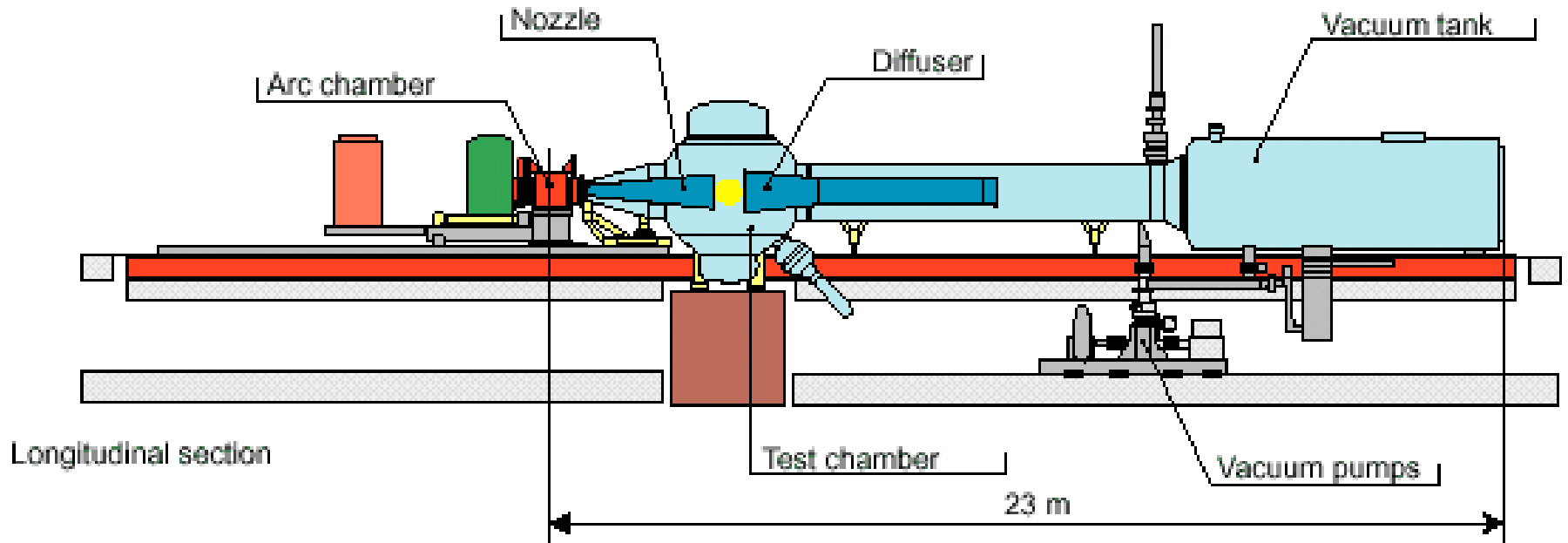
- S1MA wind tunnel is equipped with two counterrotating fans, driven by Pelton turbines, the power of which is 88 MW;
- Minimum time to bring up the speed from Mach 0 to Mach 0.8 is 3 minutes;
- Cooling is performed by air exchange with outside air;
- Mach number is continuously adjustable from 0.05 to 1 by varying the fan speed from 25 to 212 rpm.

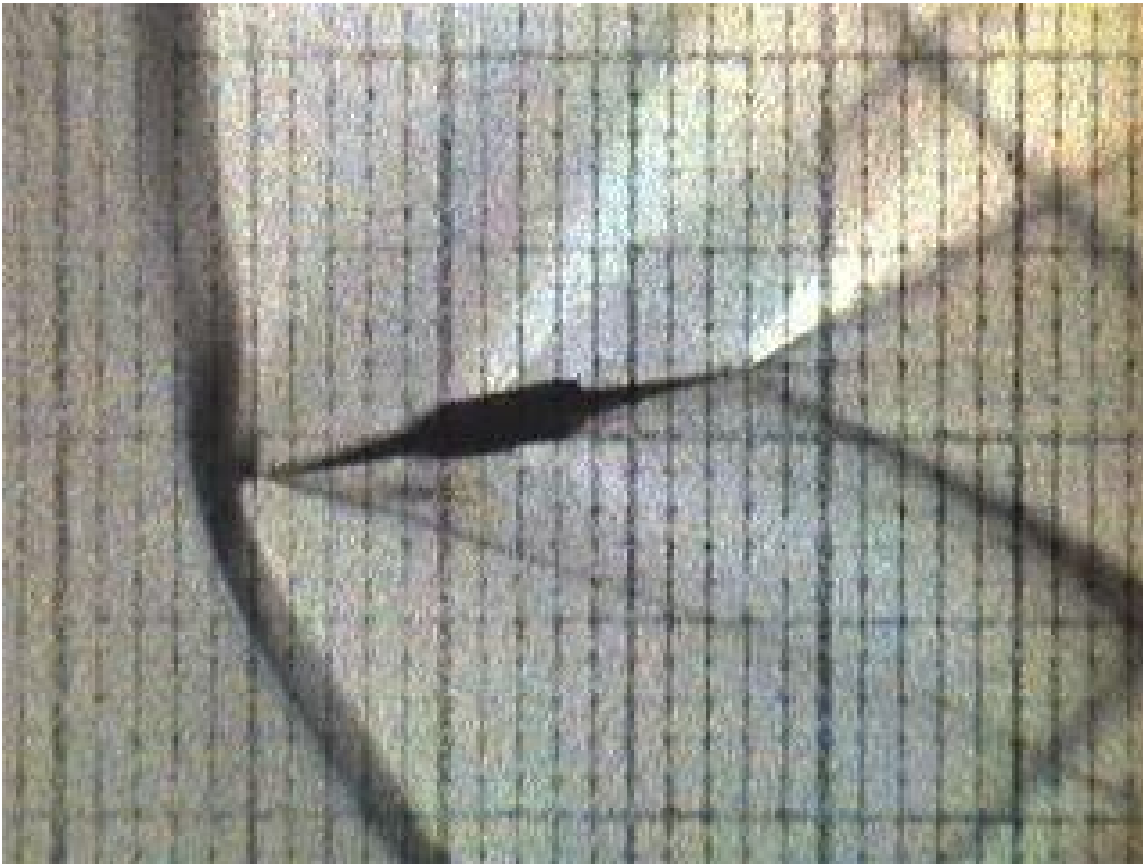
Ekologické tunely (BLWT)



Hypersonické tunely

ONERA F4 Arc Heated Wind Tunnel
Hypersonic - Hypervelocity - Up to 6 Km/s





| | M | T (°K) |
|----------------------|----------|---------------|
| Convair B-58 | 2 | 420 |
| North American XB-70 | 3 | 550 |
| North American X-15 | 6 | 900 |
| Waverider | 8÷10 | 1,000 |
| Space Shuttle | 25 | 1,500 |





McDonnell Douglas F-4J Phantom II

This one-of-a-kind photo was shot by Mr. Harry Gann, of McDonnell Douglas, at the Point Mugu Naval Air Station on 23 October 1971. The aircraft, a McDonnell Douglas F-4J Phantom II "Black Bunny" from Navy flight test squadron VX-4, was captured on film while flying at near supersonic velocity. However, the local velocity on parts of the aircraft were supersonic, causing the two distinctive, diamond-shaped shock wave cones around the leading and trailing edges of the aircraft. A photograph like this is rare, it required split-second timing and a large amount of luck. "At the time, I was using a motorized Nikon F-2 camera with a 300mm lens," states Mr. Gann. "I shot about four frames. The film was Ektachrome 400. As I remember, I was standing about 70 yards from the taxiway during the pass."



