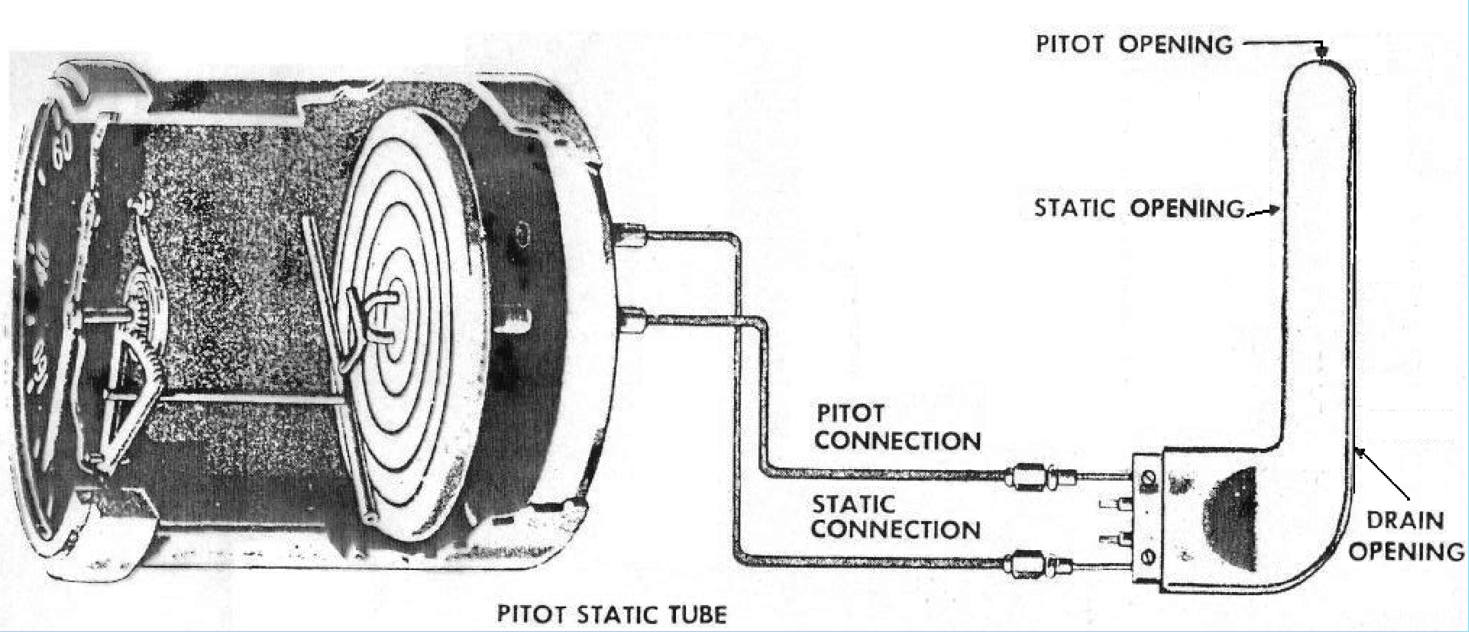
Misura della velocità all'aria

$\mathbf{v} = f\left[\left(\mathbf{p_t} - \mathbf{p_s}\right), \mathbf{k_i}\right]$ o $\mathbf{v} = f\left[\Delta\mathbf{p}, \mathbf{k_i}\right]$ o $\mathbf{v} = f\left[\mathbf{p_d}, \mathbf{k_i}\right]$

Essendo $\mathbf{p_s}$, ρ, $\mathbf{T_s}$, $\mathbf{v}$, $\mathbf{c}$ le grandezze della corrente libera e supponendo che nel processo d'arresto l'aria sia incomprimibile si ha:

$$\mathbf{p_t} - \mathbf{p_s} = \frac{1}{2}\rho\mathbf{v}^2 \Rightarrow \boxed{\mathbf{v}^2 = 2\frac{\mathbf{p_d}}{\rho}} \Rightarrow \mathbf{v} = \sqrt{2\frac{\mathbf{p_d}}{\rho}} \Rightarrow \boxed{\mathbf{v} = \mathbf{f}\left[\mathbf{p_d}, \rho\right]}$$

Sostituendo a ρ il valore di riferimento ρ_0 si ha: $\mathbf{v_{EQU}} = \sqrt{2\frac{\mathbf{p_d}}{\rho_0}} \Rightarrow \boxed{\mathbf{v_{EQU}} = \mathbf{f}\left[\mathbf{p_d}, \rho_0\right] \Rightarrow \mathbf{v_{EQU}} = \mathbf{v}\sqrt{\sigma}}$



Se supponiamo invece che tra le condizioni di corrente libera e la sezione d'arresto il fluido evolva secondo una trasformazione adiabatica: $\mathbf{T_t} = \mathbf{T_s} + \frac{1}{2}\frac{\mathbf{v}^2}{\mathbf{c_p}}$

e isoentropica: $\mathbf{p_t} = \mathbf{p_s}\left(\frac{\mathbf{T_t}}{\mathbf{T_s}}\right)^{\gamma/\gamma-1}$ si ha: $\frac{\mathbf{p_t}}{\mathbf{p_s}} = \left[\left(\mathbf{T_s} + \frac{1}{2}\frac{\mathbf{v}^2}{\mathbf{c_p}}\right)\frac{1}{\mathbf{T_s}}\right]^{\gamma/\gamma-1} = \left(1 + \frac{\gamma-1}{2}\mathbf{M}^2\right)^{\gamma/\gamma-1}$

$$\mathbf{p_t} - \mathbf{p_s} = \mathbf{p_s}\left[\left(1 + \frac{1}{2}\frac{\mathbf{v}^2}{\mathbf{c_p}\mathbf{T_s}}\right)^{\gamma/\gamma-1} - 1\right] \quad \Rightarrow \quad \mathbf{v}^2 = 2\mathbf{c_p}\mathbf{T_s}\left[\left(1 + \frac{\mathbf{p_t} - \mathbf{p_s}}{\mathbf{p_s}}\right)^{\gamma-1/\gamma} - 1\right]$$

da $\mathbf{R} = \mathbf{c_p} - \mathbf{c_v} \quad \Rightarrow \quad \frac{\mathbf{p_s}}{\rho\mathbf{T_s}} = \mathbf{c_p} - \frac{\mathbf{c_p}}{\gamma} \quad \Rightarrow \quad \mathbf{c_p}\mathbf{T_s}\left(1 - \frac{1}{\gamma}\right) = \frac{\mathbf{p_s}}{\rho} \quad \Rightarrow \quad \mathbf{c_p}\mathbf{T_s} = \frac{\gamma}{\gamma-1}\frac{\mathbf{p_s}}{\rho}$

$$\boxed{\mathbf{v}^2 = 2\frac{\gamma}{\gamma-1}\frac{\mathbf{p_s}}{\rho}\left[\left(1 + \frac{\mathbf{p_d}}{\mathbf{p_s}}\right)^{\gamma-1/\gamma} - 1\right]} \quad \Rightarrow \quad \boxed{\mathbf{v} = \mathrm{f}\left[\mathbf{p_d},\ \mathbf{p_s}, \rho\right]}$$

sostituendo a $\mathbf{p_s}$ e ρ i valori $\mathbf{p_{s_0}}$ e ρ_0, si ottiene:

$$\boxed{v_{CAL}^2 = 2\frac{\gamma}{\gamma-1}\frac{\mathbf{p_{s_0}}}{\rho_0}\left[\left(1+\frac{\mathbf{p_d}}{\mathbf{p_{s_0}}}\right)^{\gamma-1/\gamma}-1\right]} \Rightarrow \boxed{v_{CAL} = f\left[\mathbf{p_d},\ \mathbf{p_{s_0}},\ \rho_0\right]}$$

mentre

$$\boxed{v_{IND} = f\left[\mathbf{p_d},\ \mathbf{p_{s_0}},\ \rho_0,\ \mathbf{k_i}\right]}$$ essendo $\mathbf{k_i}$ i parametri di impianto

Definizioni

- Indicated airspeed (IAS) v_{IND}

  Value read on the airspeed indicator

- Calibrated airspeed (CAS) v_{CAL}

  Velocity that provides the same impact pressure when flying at ISA SL

- Equivalent airspeed (EAS) v_{EQU}

  Velocity that provides the same dynamic pressure when flying at ISA SL

- True airspeed (TAS) v_{TAS}

  Velocity of the A/C with respect to the air mass

Impact pressure $q_c = p_t - p_s$

For incompressible flow $q_c = p_t - p_s$ = dynamic pressure $p_d = ½ \rho v^2$

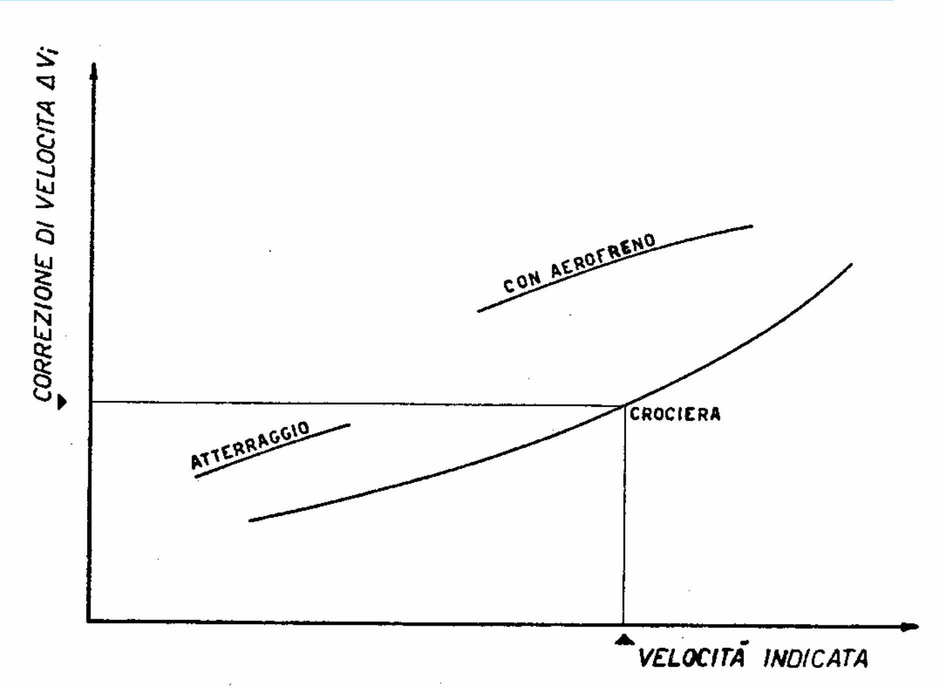
Riduzione delle velocità:

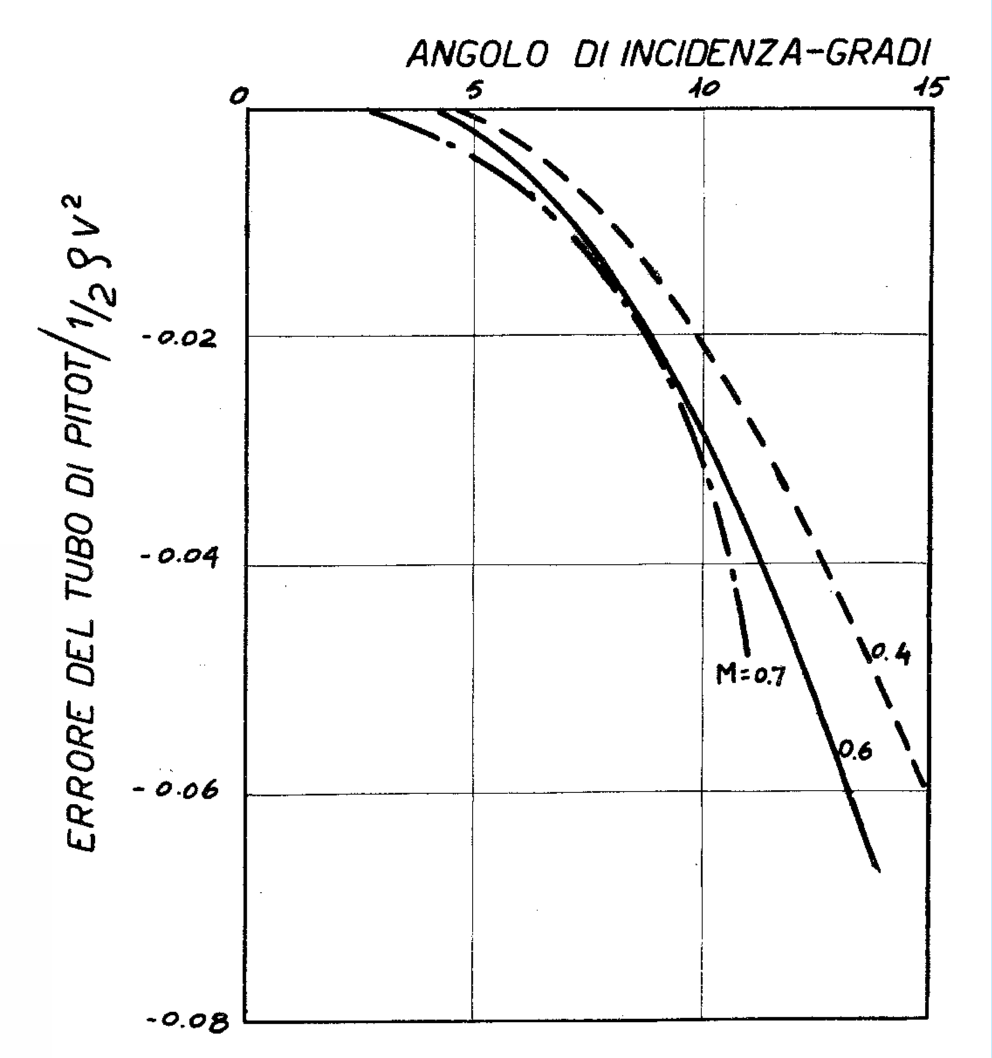
$$v_{IND} \Rightarrow v_{CAL} \Rightarrow v_{EQU} \Rightarrow v$$

La velocita vera ha solo interesse per i problemi di navigazione:

Errori di impianto

Configurazione





Disallineamento del Pitot

Errori di impianto

Cessna FR 172J

TAVOLA CORREZIONI VELOCITA'
(MPH)

	IAS	50	60	70	80	90	100	110	120	130	140	150
FLAPS UP	CAS	57	61	68	77	86	96	106	116	127	138	150
FLAPS DOWN	CAS	55	63	72	82	92	102	.	.	.	.	.

$$v_{EQU}^2 = v^2 \frac{\rho}{\rho_0} \quad \Rightarrow \quad v_{EQU}^2 = 2\frac{\gamma}{\gamma-1}\frac{p_s}{\rho_0}\left[\left(1+\frac{p_d}{p_s}\right)^{\gamma-1/\gamma} - 1\right]$$

da cui:

$$v_{EQU} = v_{CAL}\sqrt{\delta}\sqrt{\frac{\left(1+\frac{p_d}{p_s}\right)^{\gamma-1/\gamma} - 1}{\left(1+\frac{p_d}{p_{s_0}}\right)^{\gamma-1/\gamma} - 1}} \quad \text{e quindi} \quad v_{EQU} \le v_{CAL} \quad \Rightarrow \quad \boxed{EAS=CAS+\Delta v_c}$$

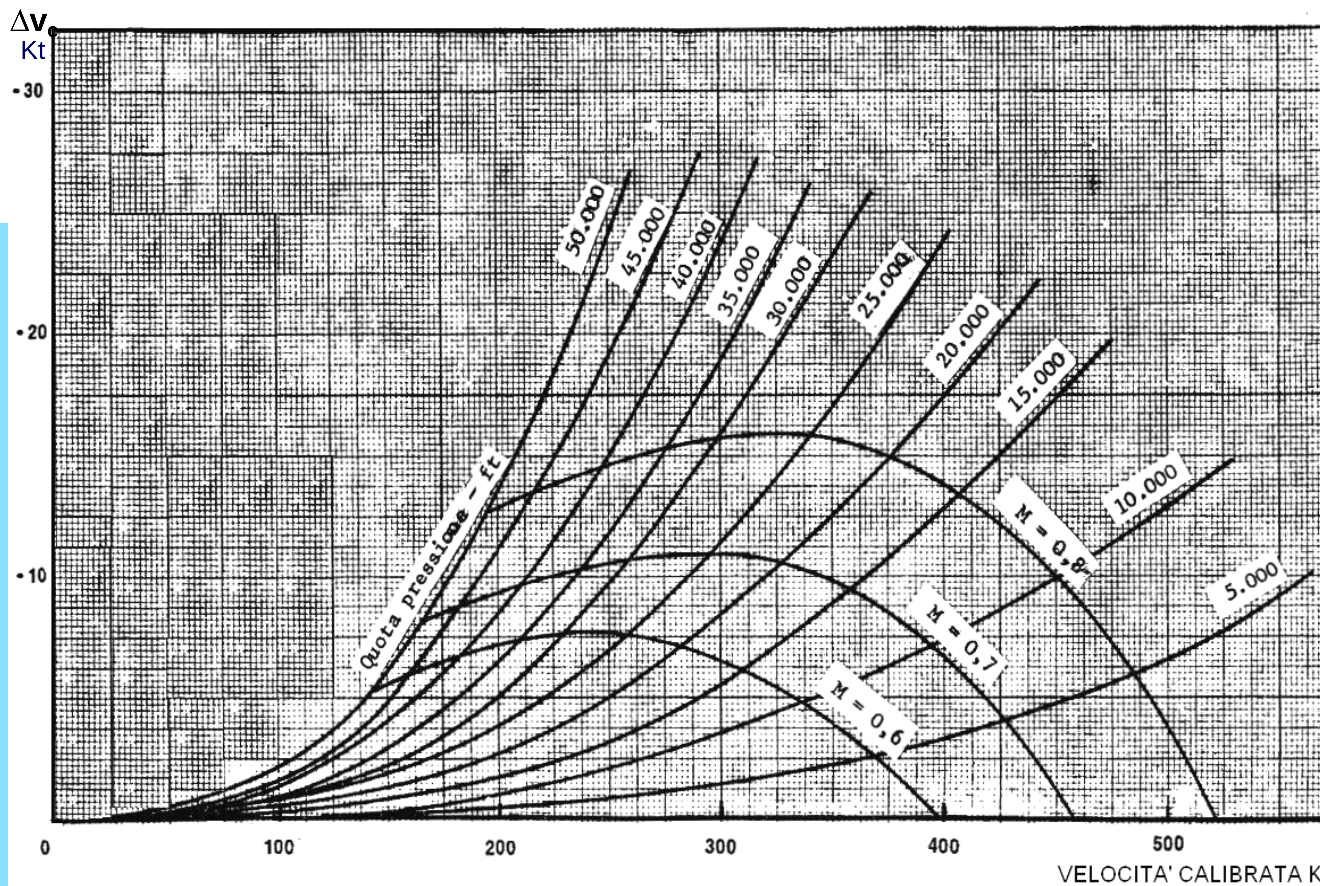
ricordando che:

$$\frac{p_t}{p_s} = \left(1+\frac{\gamma-1}{2}M^2\right)^{\gamma/\gamma-1} \quad \text{si arriva a scrivere:}$$

$$v_{EQU} - v_{CAL} = \Delta v_c = v_{CAL}\left\{\sqrt{\delta}\sqrt{\frac{\left(\frac{\gamma-1}{2}M^2\right)}{\left\{\left[\delta\left(1+\frac{\gamma-1}{2}M^2\right)^{\gamma/\gamma-1}+(1-\delta)\right]^{\gamma-1/\gamma} - 1\right\}}} - 1\right\}$$

supponendo $TAS = \dfrac{CAS}{\sqrt{\sigma}}$ si ha: $\Delta \mathbf{v}_c = \mathbf{v}_{CAL}\left\{\sqrt{\delta}\sqrt{\dfrac{0.2\dfrac{1}{\sigma}\left(\dfrac{\mathbf{v}_{CAL}}{\mathbf{c}}\right)^2}{\left\{\left[\delta\left(1+0.2\dfrac{1}{\sigma}\left(\dfrac{\mathbf{v}_{CAL}}{\mathbf{c}}\right)^2\right)^{3.5}+(1-\delta)\right]^{0.2857}-1\right\}}}-1\right\}$

cioè $\Delta \mathbf{v}_c = \mathbf{f}\left(\mathbf{v}_{CAL}, \mathbf{H}_p\right)$



Seconda formula di calibratura

$$\mathbf{v}^2 = 2\mathbf{c}_p\mathbf{T}_s\left[\left(1+\frac{\mathbf{p}_d}{\mathbf{p}_s}\right)^{\gamma-1/\gamma}-1\right] = \frac{2\mathbf{c}^2}{\gamma-1}\left[\left(1+\frac{\mathbf{p}_d}{\mathbf{p}_s}\right)^{\gamma-1/\gamma}-1\right]$$

quindi

$$\mathbf{v}_{CAL}^2 = \frac{2\mathbf{c}_0{}^2}{\gamma-1}\left[\left(1+\frac{\mathbf{p}_d}{\mathbf{p}_{s_0}}\right)^{\gamma-1/\gamma}-1\right]$$

$$\mathbf{p}_d = \mathbf{p}_{s_0}\left[\left(1+\frac{\gamma-1}{2}\frac{\mathbf{v}_{CAL}^2}{\mathbf{c}_0{}^2}\right)^{\gamma/\gamma-1}-1\right]$$

espandendo in serie il termine tra parentesi tonde si ha:

$$\left(1+\frac{\gamma-1}{2}\frac{\mathbf{v}_{\mathbf{CAL}}^{2}}{\mathbf{c}_{0}^{\ 2}}\right)^{\gamma/\gamma-1}=1+\frac{\gamma}{2}\frac{\mathbf{v}_{\mathbf{CAL}}^{2}}{\mathbf{c}_{0}^{\ 2}}+\frac{\gamma}{8}\frac{\mathbf{v}_{\mathbf{CAL}}^{4}}{\mathbf{c}_{0}^{\ 4}}+\ldots\ldots$$ da cui:

$$\mathbf{p_d}=\frac{\gamma}{2}\mathbf{p}_{\mathbf{s}_0}\frac{\mathbf{v}_{\mathbf{CAL}}^{2}}{\mathbf{c}_{0}^{\ 2}}\left(1+\frac{1}{4}\frac{\mathbf{v}_{\mathbf{CAL}}^{2}}{\mathbf{c}_{0}^{\ 2}}\right)$$

essendo $\mathbf{c}_{0}^{\ 2}=\frac{\mathbf{p}_{\mathbf{s}_0}}{\rho_0}\gamma$ si ricava:

$$\boxed{\mathbf{p_d}=\frac{\rho_0}{2}\mathbf{v}_{\mathbf{CAL}}^{2}\left(1+\frac{1}{4}\frac{\mathbf{v}_{\mathbf{CAL}}^{2}}{\mathbf{c}_{0}^{\ 2}}\right)}$$

che è un'altra formula di calibratura.

$$\mathbf{v}^2 = 2\frac{\gamma}{\gamma-1}\,\frac{\mathbf{p_s}}{\rho}\left[\left(1+\frac{\mathbf{p_d}}{\mathbf{p_s}}\right)^{\gamma-1/\gamma}-1\right]$$ * fluido comprimibile

da

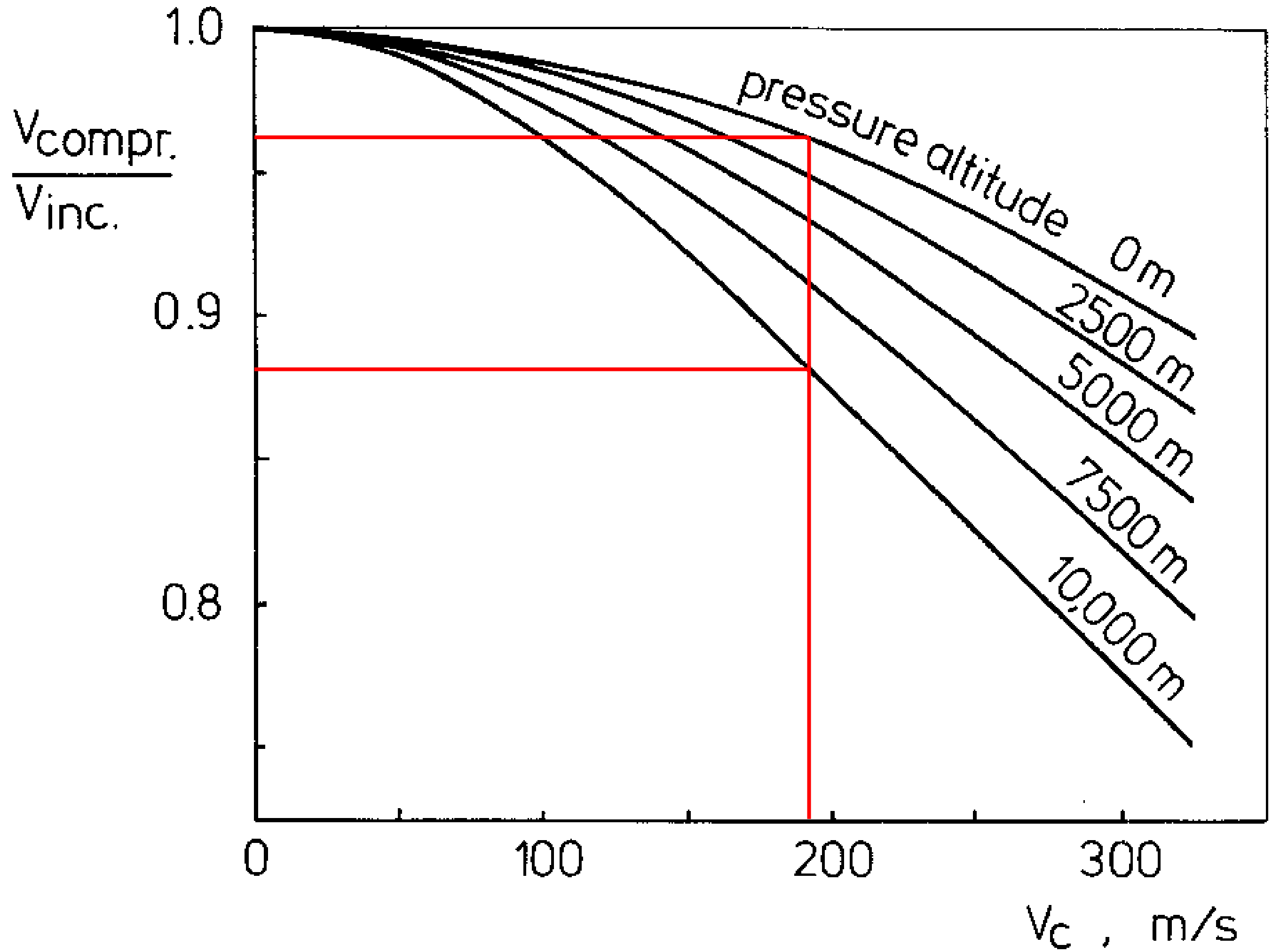
$$\mathbf{v_{CAL}}^2 = 2\frac{\gamma}{\gamma-1}\,\frac{\mathbf{p_{s_0}}}{\rho_0}\left[\left(1+\frac{\mathbf{p_d}}{\mathbf{p_{s_0}}}\right)^{\gamma-1/\gamma}-1\right] \quad \Rightarrow \quad \mathbf{p_d} = \mathbf{p_{s_0}}\left[\left(1+\frac{\gamma-1}{2\gamma}\,\frac{\rho_0}{\mathbf{p_{s_0}}}\mathbf{v_{CAL}}^2\right)^{\frac{\gamma}{\gamma-1}}-1\right]$$

sostituendo in * si ha:

$$\mathbf{v_{compr.}} = \sqrt{2\frac{\gamma}{\gamma-1}\frac{\mathbf{p_s}}{\rho}\left[\left[1+\frac{\mathbf{p_{s_0}}}{\mathbf{p_s}}\left[\left(1+\frac{\gamma-1}{2\gamma}\,\frac{\rho_0}{\mathbf{p_{s_0}}}\mathbf{v_{CAL}}^2\right)^{\frac{\gamma}{\gamma-1}}-1\right]\right]^{\gamma-1/\gamma}-1\right]}$$

$$\mathbf{v} = \sqrt{\frac{2}{\rho}\mathbf{p_d}} \Rightarrow \mathbf{v_{inc.}} = \sqrt{2\frac{\mathbf{p_{s_0}}}{\rho}\left[\left(1+\frac{\gamma-1}{2\gamma}\frac{\rho_0}{\mathbf{p_{s_0}}}\mathbf{v_{CAL}}^2\right)^{\frac{\gamma}{\gamma-1}}-1\right]}$$

$$\frac{\mathbf{v_{compr.}}}{\mathbf{v_{inc.}}} = \sqrt{\frac{\frac{\gamma}{\gamma-1}\left[\left[1+\frac{\mathbf{p_{s_0}}}{\mathbf{p_s}}\left[\left(1+\frac{\gamma-1}{2\gamma}\frac{\rho_0}{\mathbf{p_{s_0}}}\mathbf{v_{CAL}}^2\right)^{\frac{\gamma}{\gamma-1}}-1\right]\right]^{\gamma-1/\gamma}-1\right]}{\frac{\mathbf{p_{s_0}}}{\mathbf{p_s}}\left[\left(1+\frac{\gamma-1}{2\gamma}\frac{\rho_0}{\mathbf{p_{s_0}}}\mathbf{v_{CAL}}^2\right)^{\frac{\gamma}{\gamma-1}}-1\right]}}$$



1.0
0.9
0.8
Vcompr.
Vinc.
pressure altitude
0 m
2500 m
5000 m
7500 m
10,000 m
0
100
200
300
Vc , m/s

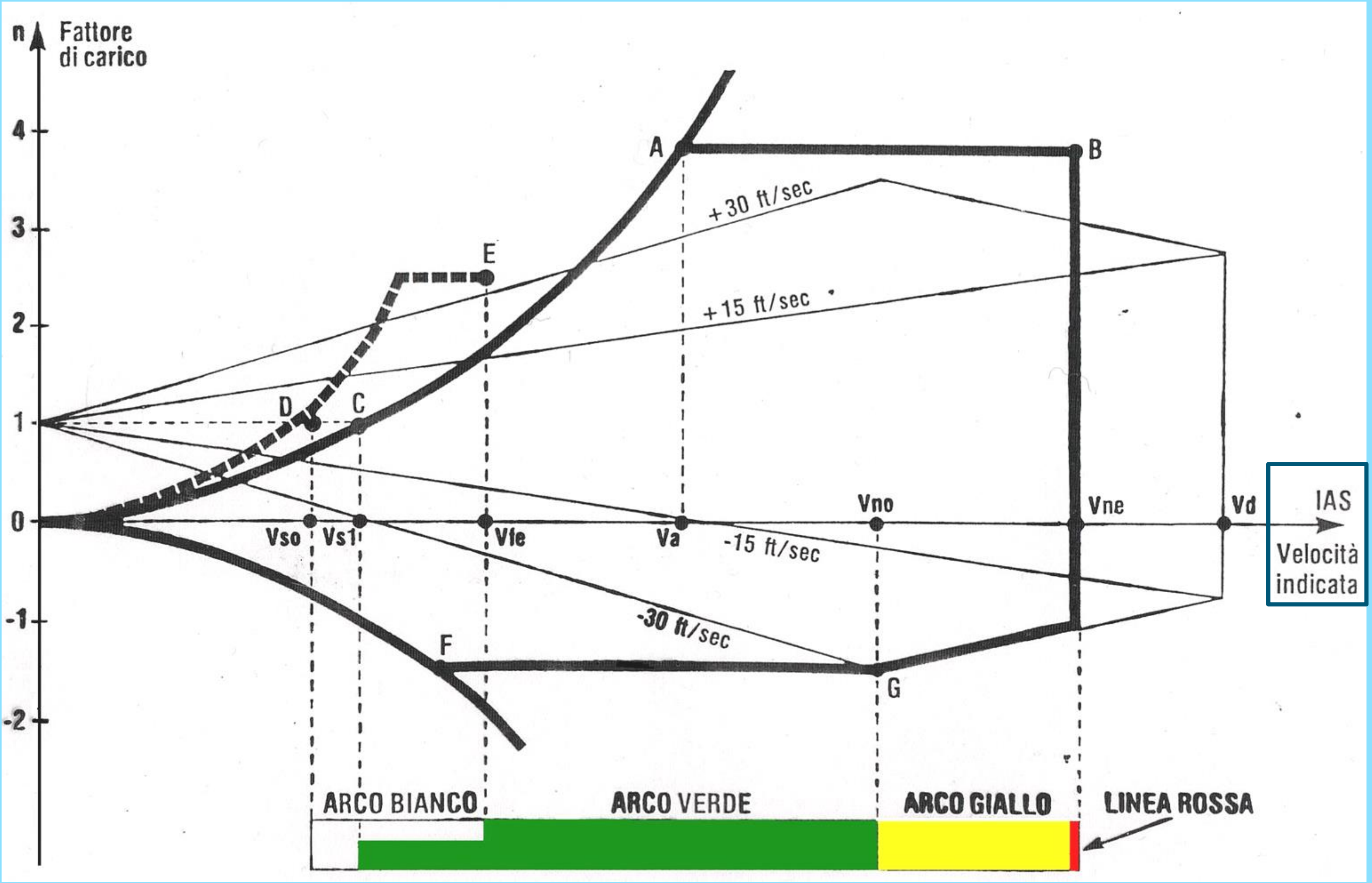
Anemometro

Quadrante di uno strumento per l’aviazione minore

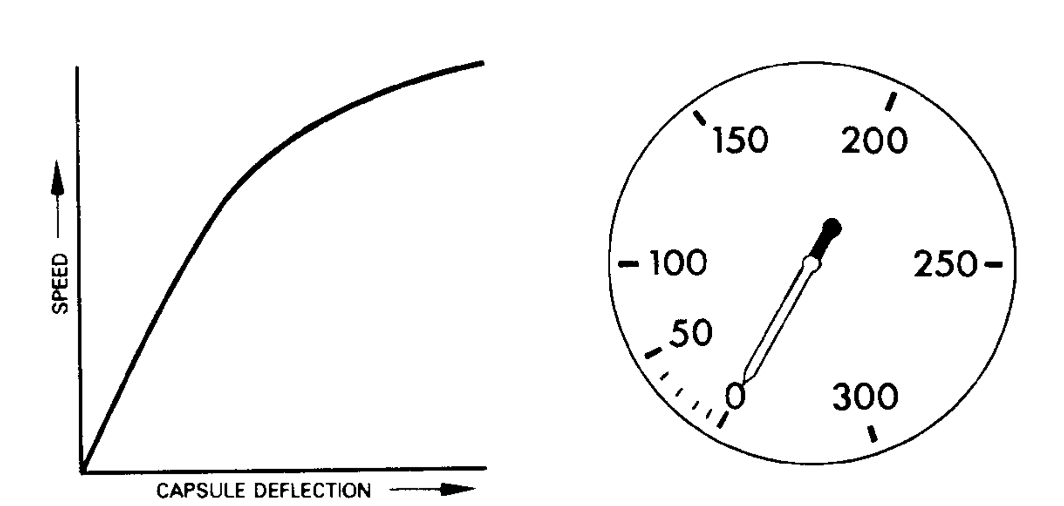
Anemometro

Anemometro sul PFD di un EFIS

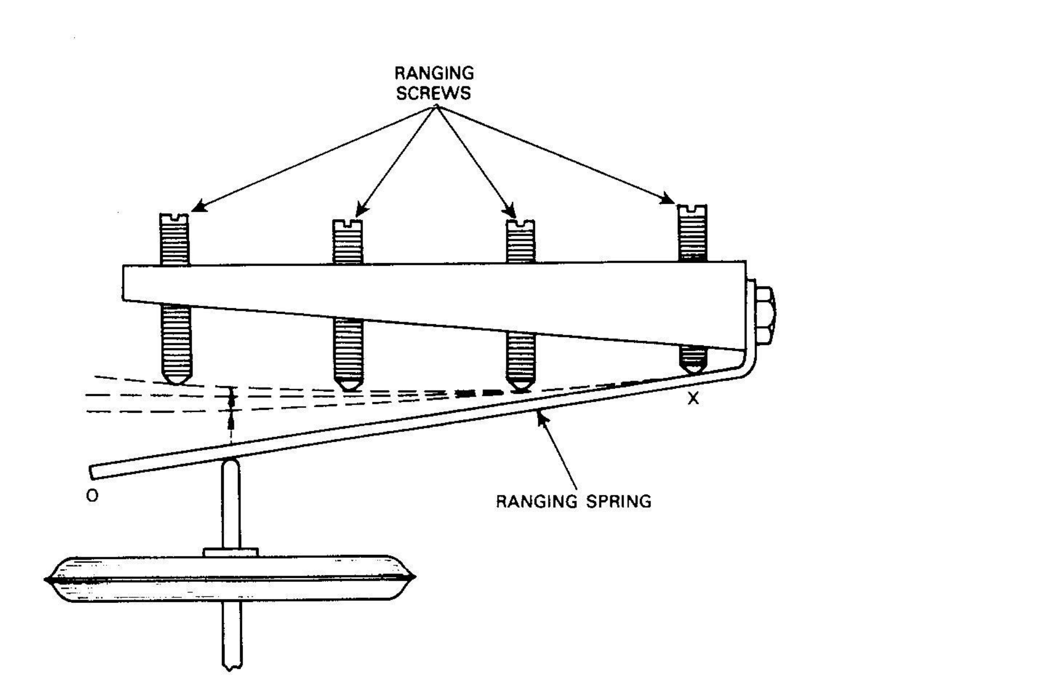
Settori dell'anemometro



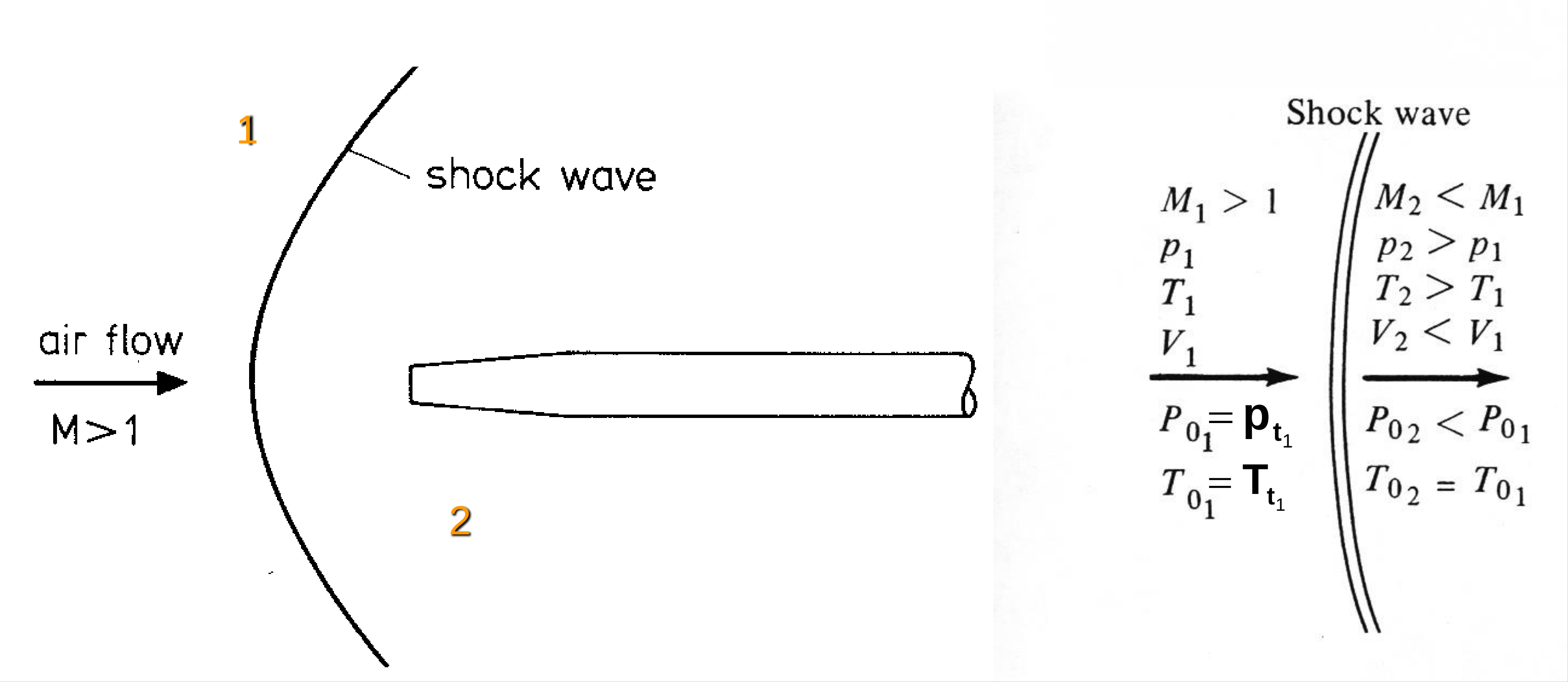
Linearizzazione della scala



(a) (b)



Anemometro supersonico



$$\mathbf{v} = f\left[\left(\mathbf{p}_{t_2} - \mathbf{p}_{s_1}\right),\ \mathbf{k_i}\right]$$

corrente adiabatica e isoentropica ovunque salvo che attraverso l'onda d'urto

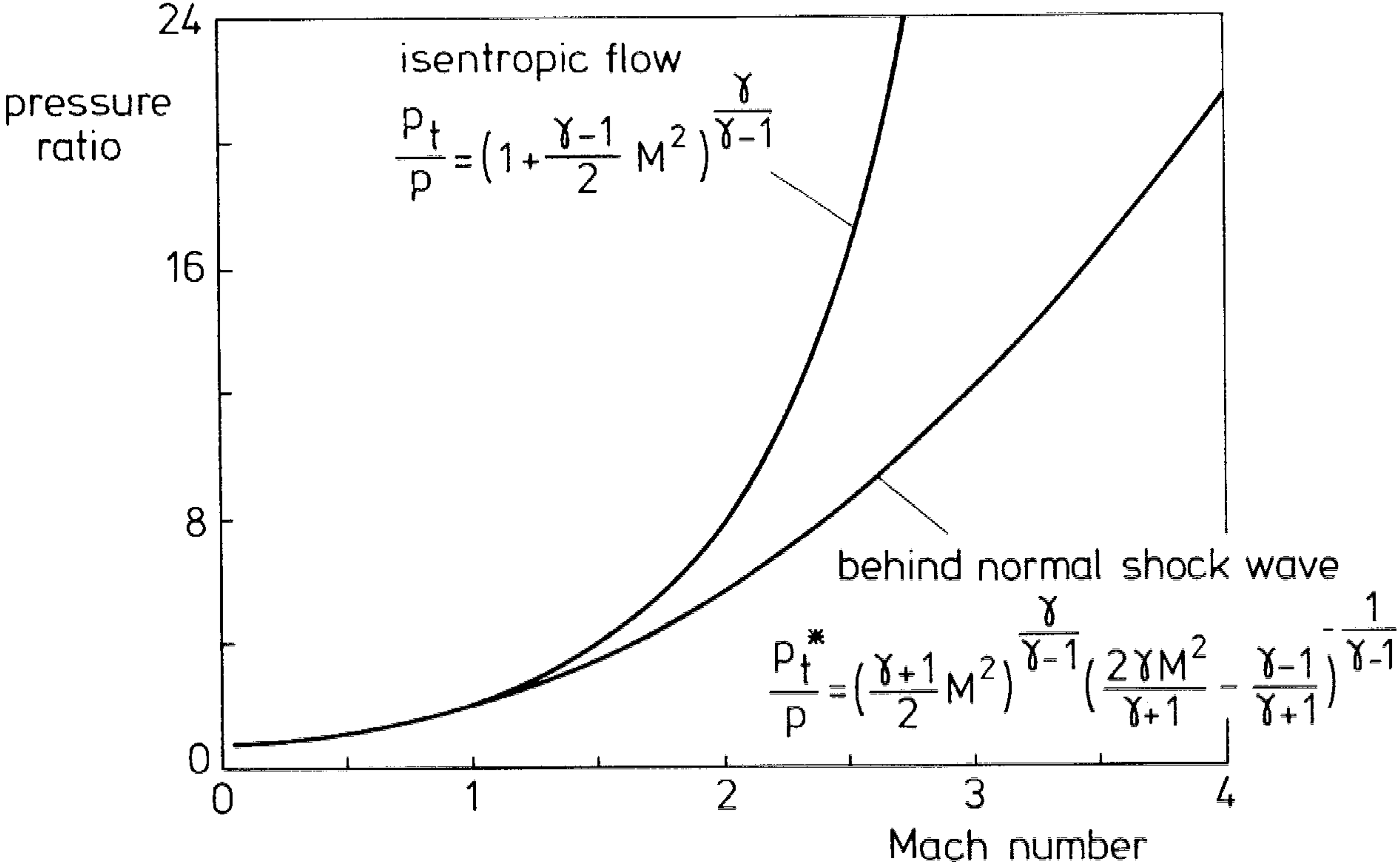
Relazione di Rayleigh

$$\frac{p_{t_2}}{p_{s_1}} = \left(M^2\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}\left(\frac{\gamma+1}{2\gamma M^2-\gamma+1}\right)^{\frac{1}{\gamma-1}}$$

$$\frac{p_{t_2}-p_{s_1}}{p_{s_1}} = \left(\frac{v^2}{c^2}\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}\left(\frac{\gamma+1}{2\gamma\frac{v^2}{c^2}-\gamma+1}\right)^{\frac{1}{\gamma-1}}-1$$

introducendo $p_{s_1}=p_{s_0}$ e $c=c_0$ si ottiene:

$$p_{t_2}-p_{s_1}=p_{s_0}\left(\frac{{v_{CAL}}^2}{{c_0}^2}\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}\left(\frac{\gamma+1}{2\gamma\frac{{v_{CAL}}^2}{{c_0}^2}-\gamma+1}\right)^{\frac{1}{\gamma-1}}-1$$



pressure ratio
isentropic flow
$$\frac{p_t}{p} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}$$
behind normal shock wave
$$\frac{p_t^*}{p} = \left(\frac{\gamma+1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} \left(\frac{2\gamma M^2}{\gamma+1} - \frac{\gamma-1}{\gamma+1}\right)^{-\frac{1}{\gamma-1}}$$
Mach number
24
16
8
0
0
1
2
3
4