

Progettazione di veicoli  
aerospaziali (AA-LZ)

E2. Conceptual Design of hybrid-  
electric aircraft

## 13. **HEA Performance** *(live demo)*

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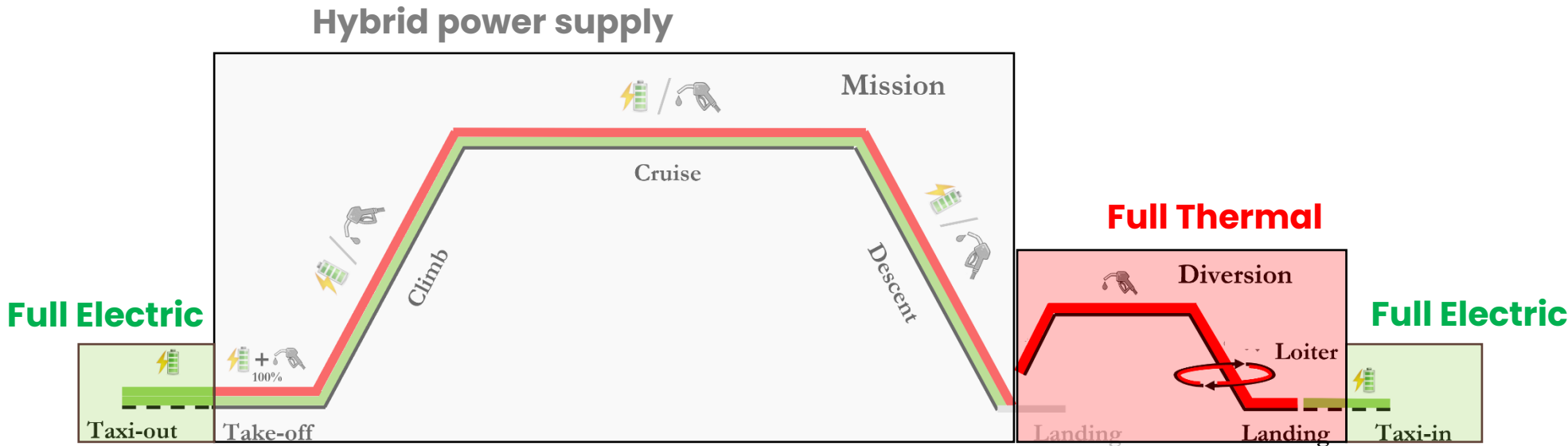
giuseppe.palaia@polito.it



# Analisi di Missione: power management



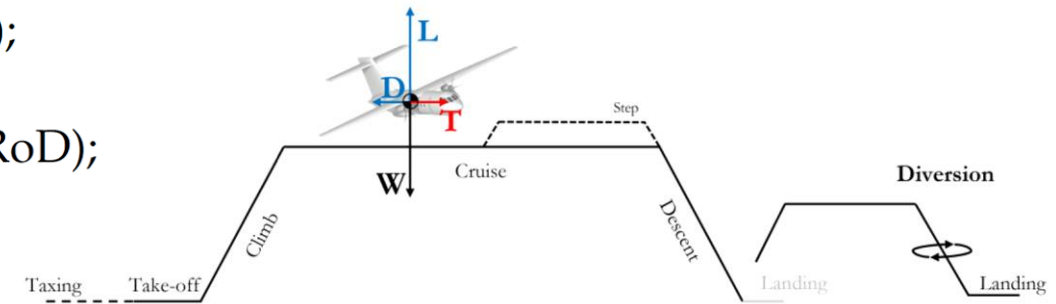
		Thermal Power Fraction	Electric Power Fraction
Mission	Taxi-out/in	$\Phi^{ice}(t) = 0$	$\Phi^{el}(t) = 0.07 P_{inst}^{tot}$
	Take-off	$\Phi^{ice}(t) = 1$	$\Phi^{el}(t) = 1$
	Climb	$\Phi^{ice}(t) = \text{const.}$	$\Phi^{el}(t) = f(\Phi(t), \Phi_{climb\ opt}^{ice})$
	Cruise	$\Phi^{ice}(t) = \text{const.}$	$\Phi^{el}(t) = f(\Phi(t), \Phi_{cruise\ opt}^{ice})$
	Descent	$\Phi^{ice}(t) = \text{const.}$	$\Phi^{el}(t) = f(\Phi(t), \Phi_{desc\ opt}^{ice})$
Diversion	Climb <sub>div</sub>	$\Phi^{ice}(t) = \Phi(t)$	$\Phi^{el}(t) = 0$
	Cruise <sub>div</sub>	$\Phi^{ice}(t) = \Phi(t)$	$\Phi^{el}(t) = 0$
	Descent <sub>div</sub>	$\Phi^{ice}(t) = \Phi(t)$	$\Phi^{el}(t) = 0$



# Analisi di Missione: programmi di volo



- Taxi-out: ground manoeuvring with constant power supply for 240 s;
- Take-off: full-power supply for 45 s;
- Climb: constant indicated air speed (IAS) and rate of climb (RoC);
- Cruise: constant speed and altitude;
- Descent: constant indicated air speed (IAS) and rate of descent (RoD);
- Loiter: 30 min of level flight at maximum L/D;
- Approach: constant RoD;
- Landing: neglected;
- Taxi-in: ground manoeuvring with constant power supply for 240 s.

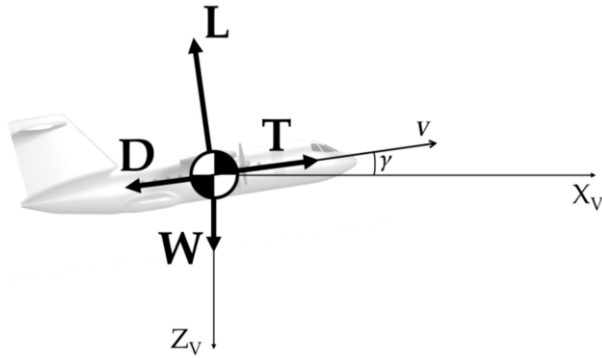


Mission			Diversion	
Climb	IAS = 170 kt	RoC = 900 ft/min	IAS = 150 kt	RoC = 600 ft/min
Cruise	Mach = 0.4	h = 6100 m	Mach = 0.27	h = 3050 m
Descent	IAS = 220 kt	RoD = -1100ft/min	IAS = 150 kt	RoD = -1100ft/min

# Simulazione missione



1. Velivolo punto materiale
2. Volo nel piano verticale
3. Volo quasi-stazionario



$$\left\{ \begin{array}{l} \frac{W}{g} \dot{\gamma} = T - D - W \sin \gamma \\ \frac{W}{g} V \dot{\gamma} = L - W \cos \gamma \\ V_x = V \cos \gamma \\ V_z = -V \sin \gamma \\ \dot{W} = -k_c P^{ice} \end{array} \right. + \text{condizioni iniziali}$$

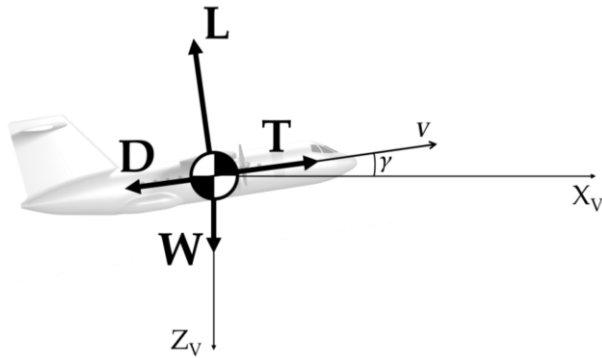
$$\left\{ \begin{array}{l} P^{fly} = DV + VW \sin \gamma \\ P^{ice} + P^{emot} = \frac{P^{fly}}{(\eta_{gear} \eta_{prop})} = P^{nec} \end{array} \right.$$

$$\Phi^{ice}(t) = \frac{P^{ice}(t)}{P_{inst}^{ice}} \quad \Phi^{el}(t) = \frac{P^{emot}(t)}{P_{inst}^{emot}}$$

# Simulazione missione



1. Velivolo punto materiale
2. Volo nel piano verticale
3. Volo quasi-stazionario



$$\left\{ \begin{array}{l} \frac{W}{g} \dot{V} = T - D - W \sin \gamma \\ \frac{W}{g} V \dot{\gamma} = L - W \cos \gamma \\ V_x = V \cos \gamma \\ V_z = -V \sin \gamma \\ \dot{W} = -k_c P^{ice} \end{array} \right. + \text{condizioni iniziali}$$

$$\left\{ \begin{array}{l} P^{fly} = DV + VW \sin \gamma \\ P^{ice} + P^{emot} = \frac{P^{fly}}{(\eta_{gear} \eta_{prop})} = P^{nec} \end{array} \right.$$

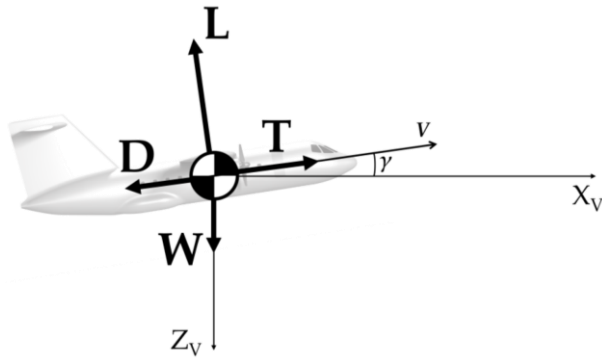
$$\Phi^{ice}(t) = \frac{P^{ice}(t)}{P_{inst}^{ice}} \quad \Phi^{el}(t) = \frac{P^{emot}(t)}{P_{inst}^{emot}}$$

$$P^{fly} = TV$$

# Simulazione missione



1. Velivolo punto materiale
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$$\left\{ \begin{array}{l} \frac{W}{g} \dot{\gamma} = T - D - W \sin \gamma \\ \frac{W}{g} V \dot{\gamma} = L - W \cos \gamma \\ V_x = V \cos \gamma \\ V_z = -V \sin \gamma \\ \dot{W} = -k_c P^{ice} \end{array} \right. + \text{condizioni iniziali}$$

$$\left\{ \begin{array}{l} P^{fly} = DV + VW \sin \gamma \\ P^{ice} + P^{emot} = \frac{P^{fly}}{(\eta_{gear} \eta_{prop})} = P^{nec} \end{array} \right.$$

$$\Phi^{ice}(t) = \frac{P^{ice}(t)}{P_{inst}^{ice}}$$

$$\Phi^{el}(t) = \frac{P^{emot}(t)}{P_{inst}^{emot}}$$

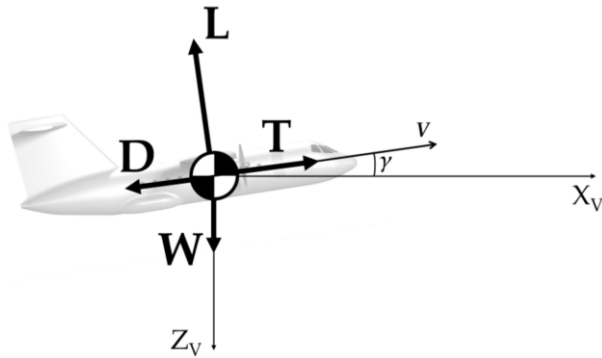


$$W(t + dt) = W(t) + \dot{W}(t) dt$$

# Simulazione missione



1. Velivolo punto materiale
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$$\left\{ \begin{array}{l} \frac{W}{g} \dot{\gamma} = T - D - W \sin \gamma \\ \frac{W}{g} V \dot{\gamma} = L - W \cos \gamma \\ V_x = V \cos \gamma \\ V_z = -V \sin \gamma \\ \dot{W} = -k_c P^{ice} \end{array} \right. \quad \left\{ \begin{array}{l} P^{fly} = DV + VW \sin \gamma \\ P^{ice} + P^{mot} = \frac{P^{fly}}{(\eta_{gear} \eta_{prop})} = P^{nec} \end{array} \right.$$

**+condizioni iniziali**

$$\Phi^{ice}(t) = \frac{P^{ice}(t)}{P^{ice}_{inst}} \quad \Phi^{el}(t) = \frac{P^{mot}(t)}{P^{mot}_{inst}}$$

Se assegniamo un valore noto a  $\Phi^{ice}$



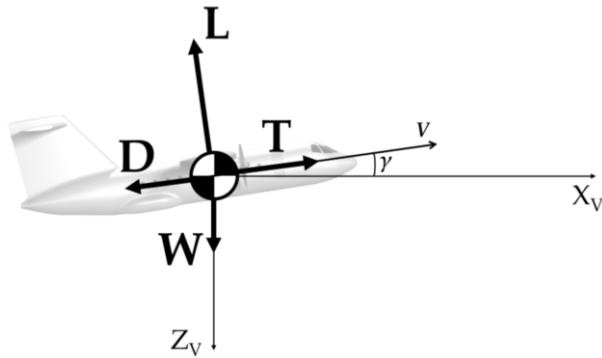
$$W(t + dt) = W(t) + \dot{W}(t) dt$$



# Simulazione missione



1. Velivolo punto materiale
2. Volo nel piano verticale
3. Volo quasi-stazionario



$$\left\{ \begin{array}{l} \frac{W}{g} \dot{\gamma} = T - D - W \sin \gamma \\ \frac{W}{g} V \dot{\gamma} = L - W \cos \gamma \\ V_x = V \cos \gamma \\ V_z = -V \sin \gamma \\ \dot{W} = -k_c p^{ice} \end{array} \right. \quad \left\{ \begin{array}{l} p^{fly} = DV + VW \sin \gamma \\ p^{ice} + p^{emot} = \frac{p^{fly}}{(\eta_{gear} \eta_{prop})} = p^{nec} \end{array} \right.$$

$$\Phi^{ice}(t) = \frac{p^{ice}(t)}{p^{ice}_{inst}} \quad \Phi^{el}(t) = \frac{p^{emot}(t)}{p^{emot}_{inst}}$$

+condizioni iniziali

Se assegniamo un valore noto a  $\Phi^{el}$

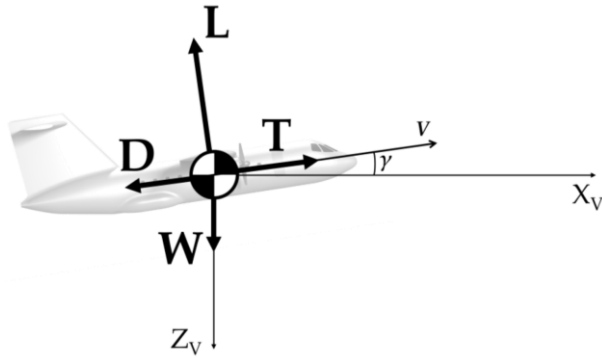
$$W(t + dt) = W(t) + \dot{W}(t) dt$$



# Simulazione missione



1. Velivolo punto materiale
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$$\left\{ \begin{array}{l} \frac{W}{g} \dot{\gamma} = T - D - W \sin \gamma \\ \frac{W}{g} V \dot{\gamma} = L - W \cos \gamma \\ V_x = V \cos \gamma \\ V_z = -V \sin \gamma \\ \dot{W} = -k_c P^{ice} \end{array} \right.$$

$$\begin{array}{l} \text{+condizioni iniziali} \\ W(t_0) = W_0 \end{array}$$

$$\left\{ \begin{array}{l} P^{fly} = DV + VW \sin \gamma \\ P^{ice} + P^{mot} = \frac{P^{fly}}{(\eta_{gear} \eta_{prop})} = P^{nec} \end{array} \right.$$

$$\Phi^{ice}(t) = \frac{P^{ice}(t)}{P_{inst}^{ice}} \quad \Phi^{el}(t) = \frac{P^{mot}(t)}{P_{inst}^{mot}}$$

$$W(t_1) = W(t_0) + \dot{W}(t_0) dt$$

$$W(t_2) = W(t_1) + \dot{W}(t_1) dt$$

... ..

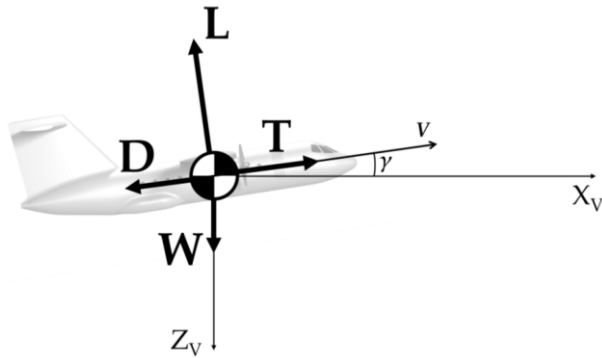
$$W(t_{k+1}) = W(t_k) + \dot{W}(t_k) dt$$

$$\dot{W}(t_k) = -k_c P^{ice}(t_k)$$

# Simulazione missione - Crociera



1. Velivolo punto materiale
2. Volo nel piano verticale
3. Volo quasi-stazionario



$$\left\{ \begin{array}{l} \frac{W}{g} \dot{\gamma} = T - D - W \sin \gamma \\ \frac{W}{g} V \dot{\gamma} = L - W \cos \gamma \\ V_x = V \cos \gamma \\ V_z = -V \sin \gamma \\ \dot{W} = -k_c P^{ice} \end{array} \right. + \text{condizioni iniziali}$$

$$\left\{ \begin{array}{l} P^{fly} = DV + VW \sin \gamma \\ P^{ice} + P^{emot} = \frac{P^{fly}}{(\eta_{gear} \eta_{prop})} = P^{nec} \end{array} \right.$$

$$\Phi^{ice}(t) = \frac{P^{ice}(t)}{P_{inst}^{ice}} \quad \Phi^{el}(t) = \frac{P^{emot}(t)}{P_{inst}^{emot}}$$

## Crociera

$$\gamma = 0$$

$$\dot{W}(t_k) = -k_c P^{ice}(t_k)$$

Variazione peso

$$\dot{x}(t_k) = V_x(t_k)$$

Traiettoria

$$\dot{z}(t_k) = \dot{V}_z(t_k)$$

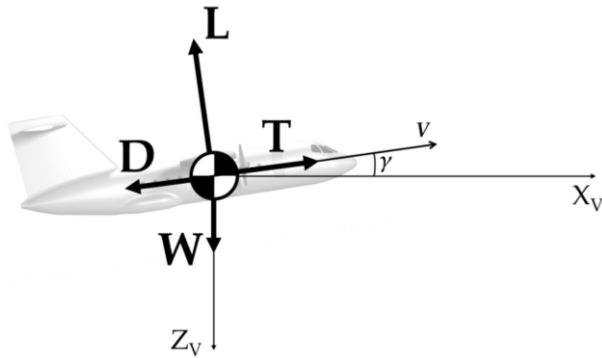
$$\dot{E}_b(t_k) = P_b(t_k)$$

Variazione di carica delle batterie

# Simulazione missione - Crociera



1. Velivolo punto materiale
2. Volo nel piano verticale
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$$\left\{ \begin{array}{l} \frac{W}{g} \dot{\gamma} = T - D - W \sin \gamma \\ \frac{W}{g} V \dot{\gamma} = L - W \cos \gamma \\ V_x = V \cos \gamma \\ V_z = -V \sin \gamma \\ \dot{W} = -k_c P^{ice} \end{array} \right. + \text{condizioni iniziali}$$

$$\left\{ \begin{array}{l} P^{fly} = DV + VW \sin \gamma \\ P^{ice} + P^{emot} = \frac{P^{fly}}{(\eta_{gear} \eta_{prop})} = P^{nec} \end{array} \right.$$

$$\Phi^{ice}(t) = \frac{P^{ice}(t)}{P_{inst}^{ice}} \quad \Phi^{el}(t) = \frac{P^{emot}(t)}{P_{inst}^{emot}}$$

## Crociera

$$\gamma = 0$$

$$\dot{W}(t_k) = -k_c P^{ice}(t_k)$$

$$P^{ice} = f(\Phi^{ice})$$

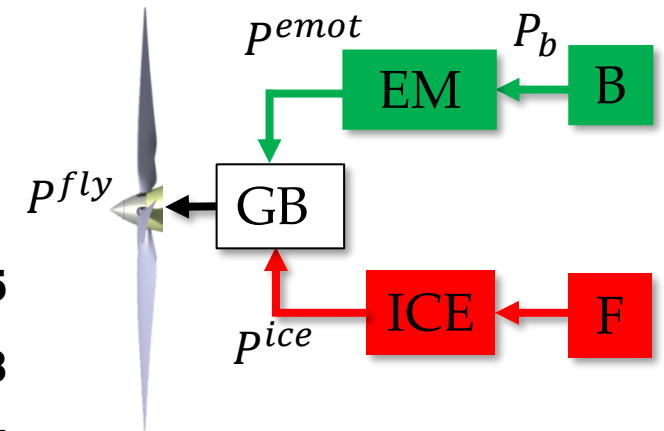
$$P_b = P^{emot} / (\eta_{em})$$

$$\dot{E}_b(t_k) = P_b(t_k)$$

$$\eta_{em} = 0,95$$

$$\eta_{gear} = 0,98$$

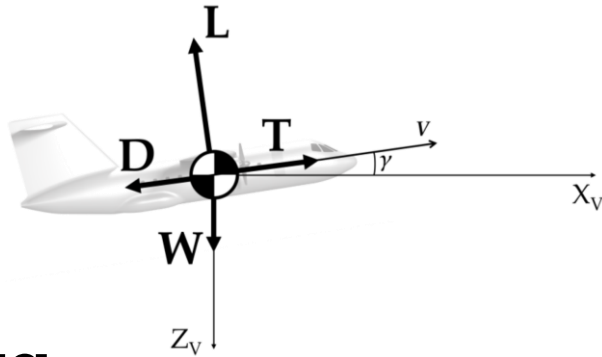
$$\eta_{prop} = 0,85$$



# Simulazione missione - Salita



1. Velivolo punto materiale
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$$\left\{ \begin{array}{l} P^{fly} = DV + VW \sin \gamma \\ P^{ice} + P^{emot} = \frac{P^{fly}}{(\eta_{gear} \eta_{prop})} = P^{nec} \end{array} \right.$$

$$\Phi^{ice}(t) = \frac{P^{ice}(t)}{P_{inst}^{ice}} \quad \Phi^{el}(t) = \frac{P^{emot}(t)}{P_{inst}^{emot}}$$

## Salita

$$\gamma = \arctan(V_z/V_x)$$

$$V_z = RoC$$

$$\rho = f(h)$$

$$V = f(IAS)$$



$$\dot{W}(t_k) = -k_c P^{ice}(t_k) \quad \text{Variazione peso}$$

$$\dot{x}(t_k) = V_x(t_k)$$

Traiettoria

$$\dot{z}(t_k) = V_z(t_k)$$

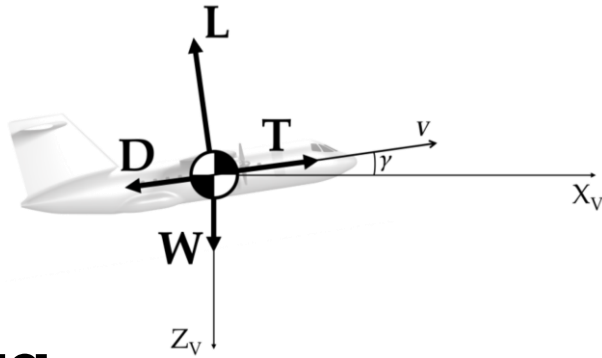
$$\dot{E}_b(t_k) = P_b(t_k)$$

Variazione di carica delle batterie

# Simulazione missione - Salita



1. Velivolo punto materiale
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$$\left\{ \begin{array}{l} P^{fly} = DV + VW \sin \gamma \\ P^{ice} + P^{emot} = \frac{P^{fly}}{(\eta_{gear} \eta_{prop})} = P^{nec} \end{array} \right.$$

$$\Phi^{ice}(t) = \frac{P^{ice}(t)}{P_{inst}^{ice}} \quad \Phi^{el}(t) = \frac{P^{emot}(t)}{P_{inst}^{emot}}$$



$$\gamma = \arctan(V_z/V_x)$$

$$V_z = RoC$$

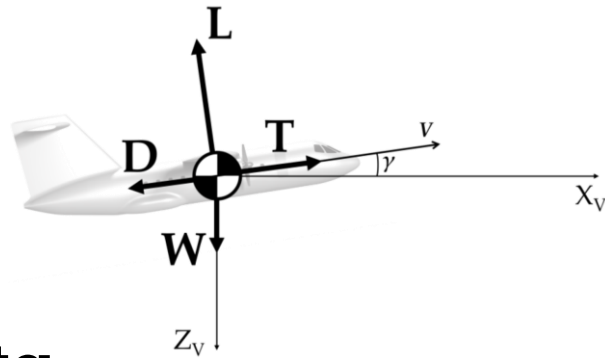
$$\rho = f(h)$$

$$V = f(IAS)$$

# Simulazione missione - Salita



1. Velivolo punto materiale
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3. Volo quasi-stazionario



$$\left\{ \begin{array}{l} \frac{W}{g} \dot{\gamma} = T - D - W \sin \gamma \\ \frac{W}{g} V \dot{\gamma} = L - W \cos \gamma \\ V_x = V \cos \gamma \\ V_z = -V \sin \gamma \\ \dot{W} = -k_c P^{ice} \end{array} \right. + \text{condizioni iniziali}$$

$$\left\{ \begin{array}{l} P^{fly} = DV + VW \sin \gamma \\ P^{ice} + P^{emot} = \frac{P^{fly}}{(\eta_{gear} \eta_{prop})} = P^{nec} \end{array} \right.$$

$$\Phi^{ice}(t) = \frac{P^{ice}(t)}{P^{ice}_{inst}} \quad \Phi^{el}(t) = \frac{P^{emot}(t)}{P^{emot}_{inst}}$$

**Salita**

$$\gamma = \arctan(V_z/V_x)$$

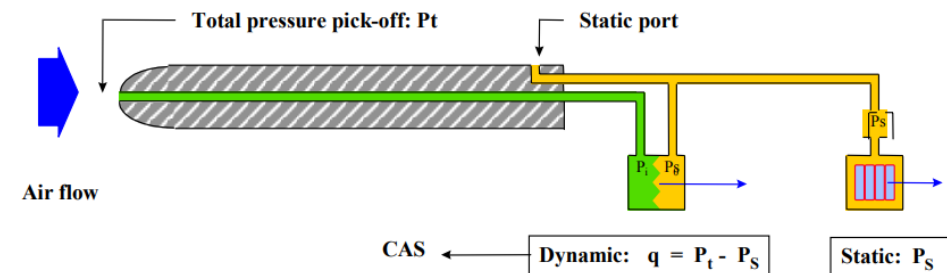
$$V_z = RoC$$

$$\rho = f(h)$$

$$V = f(IAS)$$



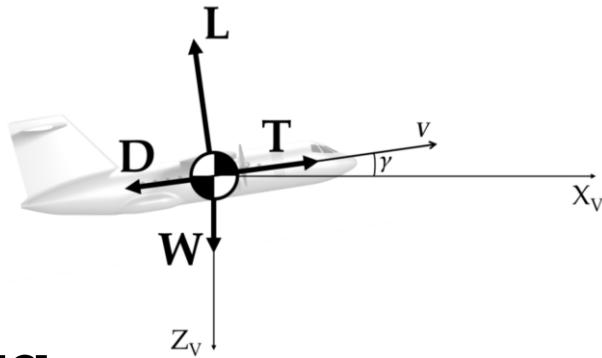
La velocità dell'aria calibrata (CAS) si ottiene dalla differenza tra la pressione totale ( $P_t$ ) e la pressione statica ( $P_s$ ). Questa differenza è chiamata pressione dinamica ( $q$ ).



# Simulazione missione - Salita



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$$\left\{ \begin{array}{l} P^{fly} = DV + VW \sin \gamma \\ P^{ice} + P^{emot} = \frac{P^{fly}}{(\eta_{gear} \eta_{prop})} = P^{nec} \end{array} \right.$$

$$\Phi^{ice}(t) = \frac{P^{ice}(t)}{P_{inst}^{ice}} \quad \Phi^{el}(t) = \frac{P^{emot}(t)}{P_{inst}^{emot}}$$

**Salita**

$$\gamma = \arctan(V_z/V_x)$$

$$V_z = RoC$$

$$\rho = f(h)$$

$$V = f(IAS)$$



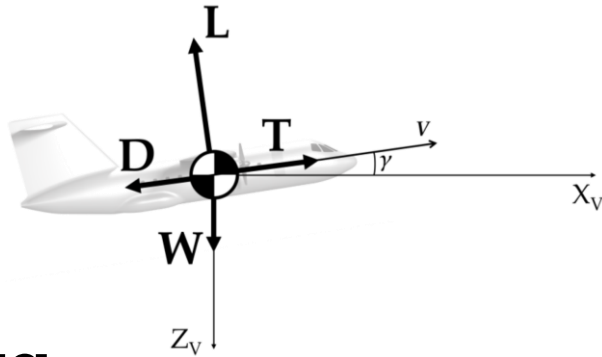
La velocità dell'aria indicata (IAS) è la velocità indicata dall'**indicatore di velocità** dell'aria. Tuttavia, a seconda dell'angolo d'attacco dell'aeromobile, della configurazione dei flap, della vicinanza al suolo (effetto suolo o meno), della direzione del vento e di altri **parametri** vengono introdotti alcuni **errori** di misura, principalmente sulla **pressione statica**. Ciò comporta una piccola differenza tra i valori **CAS** e IAS.



# Simulazione missione - Salita



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$$\left\{ \begin{array}{l} \frac{W}{g} \dot{\gamma} = T - D - W \sin \gamma \\ \frac{W}{g} V \dot{\gamma} = L - W \cos \gamma \\ V_x = V \cos \gamma \\ V_z = -V \sin \gamma \\ \dot{W} = -k_c P^{ice} \end{array} \right. + \text{condizioni iniziali}$$

$$\left\{ \begin{array}{l} P^{fly} = DV + VW \sin \gamma \\ P^{ice} + P^{emot} = \frac{P^{fly}}{(\eta_{gear} \eta_{prop})} = P^{nec} \end{array} \right.$$

$$\Phi^{ice}(t) = \frac{P^{ice}(t)}{P_{inst}^{ice}} \quad \Phi^{el}(t) = \frac{P^{emot}(t)}{P_{inst}^{emot}}$$

**Salita**

$$\gamma = \arctan(V_z/V_x)$$

$$V_z = RoC$$

$$\rho = f(h)$$

$$V = f(IAS)$$

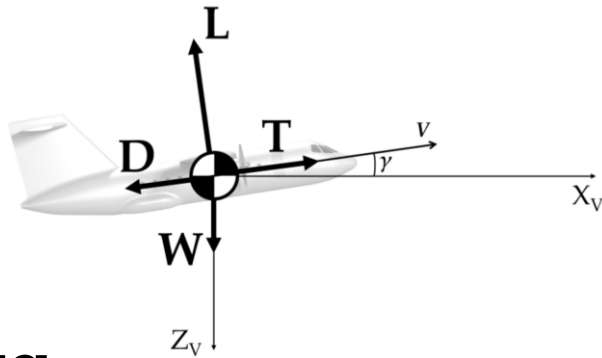


Successivamente, si **corregge** la IAS per gli effetti della **compressibilità** dell'aria

# Simulazione missione - Salita



1. Velivolo punto materiale
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+condizioni iniziali

$$\Phi^{ice}(t) = \frac{P^{ice}(t)}{P_{inst}^{ice}} \quad \Phi^{el}(t) = \frac{P^{emot}(t)}{P_{inst}^{emot}}$$

**Salita**

$$\gamma = \arctan(V_z/V_x)$$

$$V_z = RoC$$

$$\rho = f(h)$$

$$V = f(IAS)$$



$\gamma_{air} = 1.4$  Ideal diatomic gas value

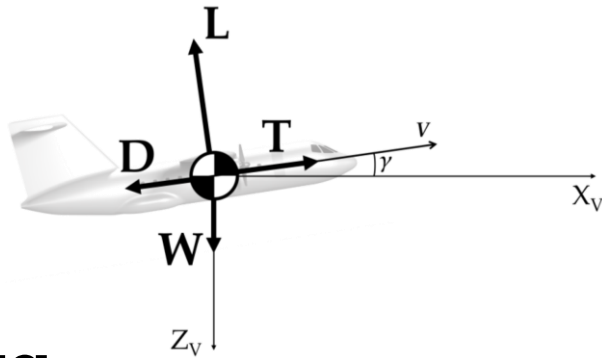
$p_t = p + \frac{1}{2} \rho_0 IAS^2$  [Pa] Total pressure read by the IAS anemometer

$$EAS = \sqrt{2 \frac{a^2}{\gamma_{air} - 1} \left( \frac{\rho}{\rho_0} \right) \left( \left( \frac{p_t}{p} \right)^{\frac{\gamma_{air} - 1}{\gamma_{air}}} - 1 \right)} \text{ [m/s]}$$

# Simulazione missione - Salita



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$$\left\{ \begin{array}{l} P^{fly} = DV + VW \sin \gamma \\ P^{ice} + P^{emot} = \frac{P^{fly}}{(\eta_{gear} \eta_{prop})} = P^{nec} \end{array} \right.$$

$$\Phi^{ice}(t) = \frac{P^{ice}(t)}{P_{inst}^{ice}} \quad \Phi^{el}(t) = \frac{P^{emot}(t)}{P_{inst}^{emot}}$$

**Salita**

$$\gamma = \arctan(V_z/V_x)$$

$$V_z = RoC$$

$$\rho = f(h)$$

$$V = f(IAS)$$



Infine, si corregge l'EAS per tenere conto della variazione della densità dell'aria

$$TAS = EAS \sqrt{\frac{\rho_0}{\rho}}$$



**End**