The University of Texas at Austin
Aerospace Engineering
and Engineering Mechanics
Cockrell School of Engineering

3 SEPTEMBER 2024

ASE 367K: FLIGHT DYNAMICS

TTH 09:30-11:00
CMA 2.306

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Topics for Today

- Topic(s):
  - Lift of entire airplane
  - Pitch Moment about arbitrary point
  - Longitudinal Stability
  - Trim

Useful website

airplane characteristic

boeing airport

manual 747-600

Trim = equilibrium

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LIFT OF ENTIRE AIRPLANE

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$$\Sigma F_{\perp} = L_w + D_w \alpha + L_t + D_t \alpha_t - W = 0$$

$$\Sigma F_{\parallel} = D_w - L_w \alpha + D_t - L_t \alpha_t + W(\alpha + \gamma) - T = 0$$

$$\Sigma M = M_p + M_f$$

$$+ M_{ac_w} + (L_w + D_w \alpha)(x_{cg} - x_w) + (L_t + D_t \alpha_t)(x_{cg} - x_t)$$
$$+ M_{ac_t} + (D_w - L_w \alpha)(z_w - z_{cg}) + (D_t - L_t \alpha_t)(z_t - z_{cg})$$

$$D_w = qSC_{D_w}$$

where $C'_{D_{0w}} = C_{D_{0w}} + k[C'_{L_{0w}}]^2$

$$= qS[C_{D_{0w}} + kC_{L_w}^2]$$
$$= qS[C_{D_{0w}} + k[C'_{L_{0w}} + C_{L_{\alpha w}}\alpha]^2]$$

α i.e. T

$$= qS[C_{D_{0w}} + k[[C'_{L_{0w}}]^2 + 2C'_{L_{0w}}C_{L_{\alpha w}}\alpha + C_{L_{\alpha w}}^2 \alpha^2]]$$

!! higher order terms

$$= qS[C_{D_{0w}} + k[[C'_{L_{0w}}]^2 + 2C'_{L_{0w}}C_{L_{\alpha w}}\alpha + HOT]]$$
$$\approx qS[C_{D_{0w}} + k[C'_{L_{0w}}]^2 + 2kC'_{L_{0w}}C_{L_{\alpha w}}\alpha]$$
$$\approx qS[C'_{D_{0w}} + 2kC'_{L_{0w}}C_{L_{\alpha w}}\alpha]$$

$$\approx qSC'_{D_{0w}} + 2qSkC'_{L_{0w}}C_{L_{\alpha w}}\alpha$$

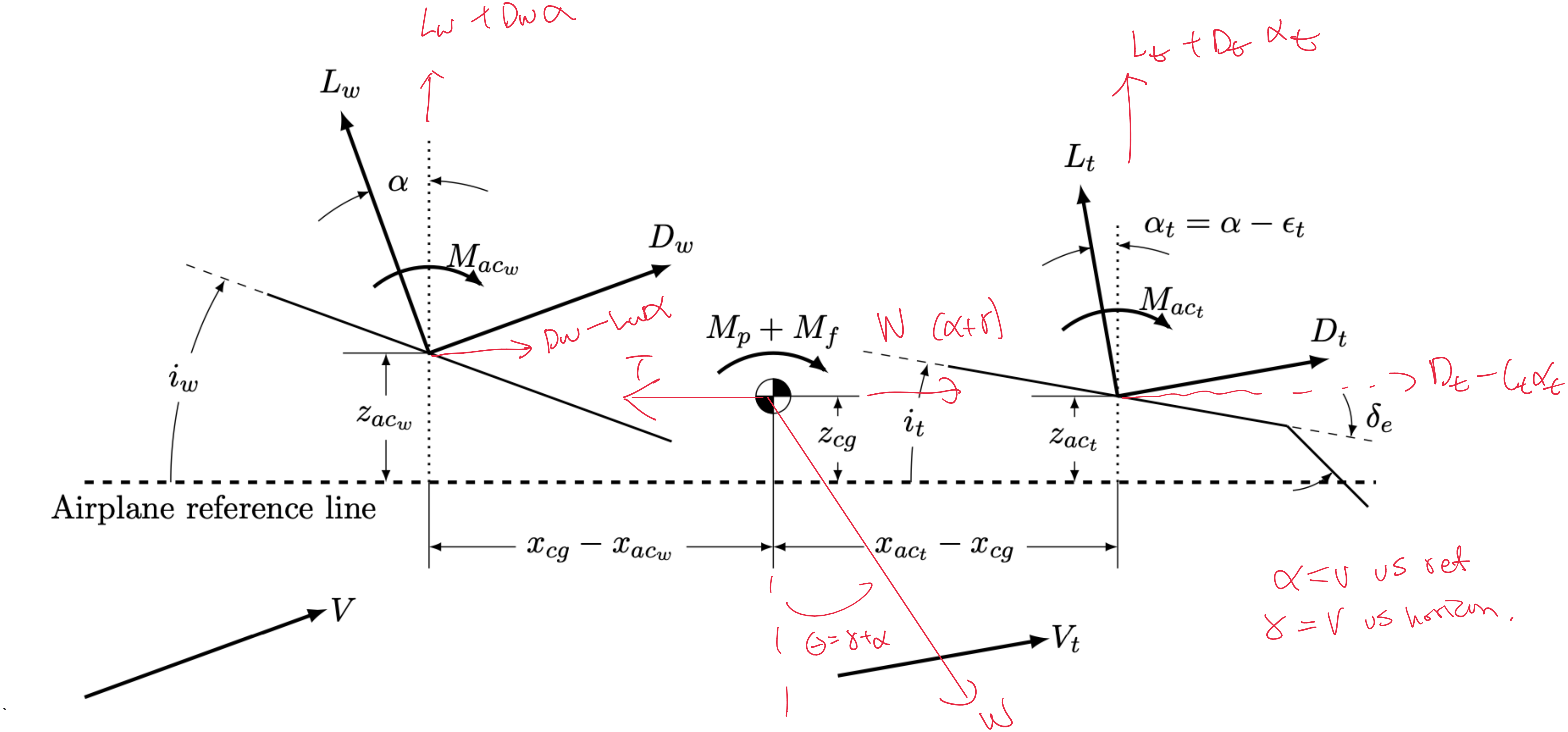

Figure 3.1: Simplified geometry of the wing and tail sections of an aircraft

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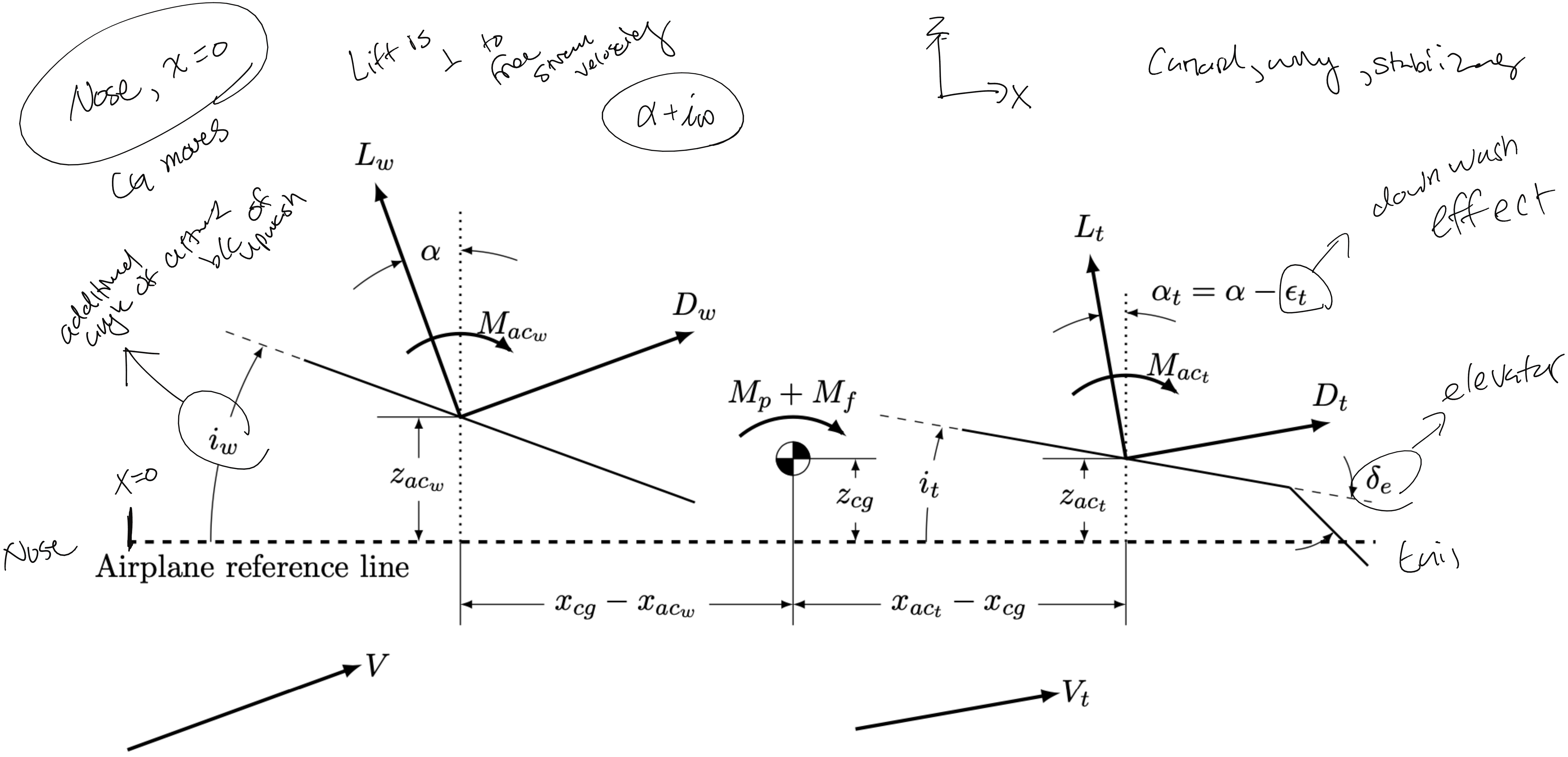

Figure 3.1: Simplified geometry of the wing and tail sections of an aircraft

$$L = L_w + L_t$$

dynamic pressure

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

Lift at $0°$ α

upwash

where

$$L_w = qSC_{L_w} = qS\left[C_{L_{0_W}} + C_{L_{\alpha_W}}(\propto + i_w)\right]$$

Plane area from above

$$L_t = q_t S_t C_{L_t} = q_t S_t\left[C_{L_{0_t}} + C_{L_{\alpha_t}}(\propto_t + i_t) + C_{L_{\delta_e}}\delta_e\right]$$

$$= q_t S_t\left[C_{L_{0_t}} + C_{L_{\alpha_t}}(\alpha - \epsilon_t + i_t) + C_{L_{\delta_e}}\delta_e\right]$$

… but the downwash angle ϵ_t is a function of the angle of attack

$$\epsilon_t = \epsilon_{0_t} + \epsilon_{\alpha_t}\alpha$$

thus

$$L_t = q_t S_t \left[C_{L_{0_t}} + C_{L_{\alpha_t}}\left[i_t - \epsilon_{0_t} + \left(1 - \epsilon_{\alpha_t}\right)\alpha\right] + C_{L_{\delta_e}}\delta_e\right]$$

Combining the expressions for L_w and L_t we get…

$$L = qS\left[C_{L_{0_W}} + C_{L_{\alpha_W}}(\propto + i_w) + \frac{q_t S_t}{qS}\left[C_{L_{0_t}} + C_{L_{\alpha_t}}\left[i_t - \epsilon_{0_t} + (1 - \epsilon_{\alpha_t})\alpha\right] + C_{L_{\delta_e}}\delta_e\right]\right]$$

… and an overall lift coefficient

$$C_L = C_{L_{0_W}} + C_{L_{\alpha_W}}(\propto + i_w) + \frac{q_t S_t}{qS}\left[C_{L_{0_t}} + C_{L_{\alpha_t}}\left[i_t - \epsilon_{0_t} + (1 - \epsilon_{\alpha_t})\alpha\right] + C_{L_{\delta_e}}\delta_e\right]$$

Total Lift Summary

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

where

$$C_{L_0} = C_{L_{0_w}} + C_{L_{\alpha_w}} i_w + \frac{\bar{q}_t}{\bar{q}}\frac{S_t}{S}\left(C_{L_{0_t}} - C_{L_{\alpha_t}}\epsilon_{0_t}\right)$$

$$C_{L_\alpha} = C_{L_{\alpha_w}} + \frac{\bar{q}_t}{\bar{q}}\frac{S_t}{S}C_{L_{\alpha_t}}(1 - \epsilon_{\alpha_t})$$

$$C_{L_{i_t}} = \frac{\bar{q}_t}{\bar{q}}\frac{S_t}{S}C_{L_{\alpha_t}}$$

$$C_{L_{\delta_e}} = \frac{\bar{q}_t}{\bar{q}}\frac{S_t}{S}C_{L_{\delta_{e_t}}}$$

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PITCH MOMENT ABOUT ARBITRARY POINT

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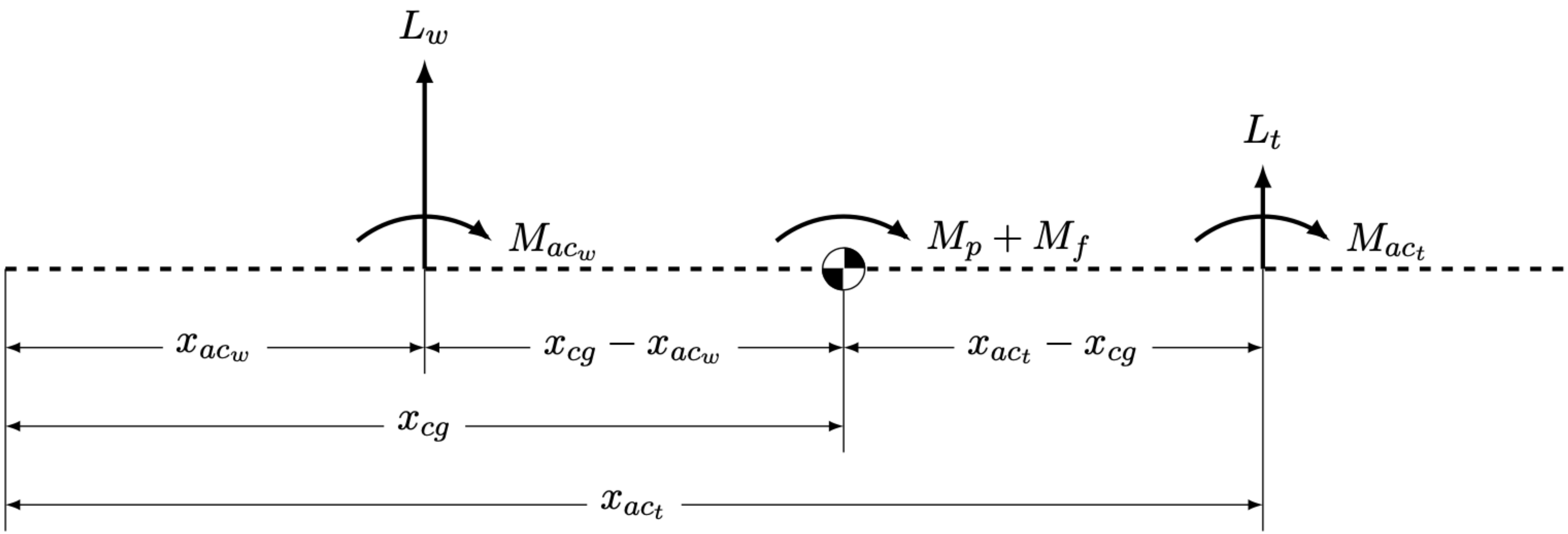
ΣM Eq = The M i met u ♡



The moment about an arbitrary reference point along the body x axis is given by…

$$M_r = M_{ac_w} + L_w\left(x_r - x_{ac_w}\right) + M_{ac_t} + L_t\left(x_r - x_{ac_t}\right) + M_p + M_f$$

where $M_{ac_w} = qS\bar{c}C_{M_{ac_w}}$

$$M_{ac_t} = q_t S_t \bar{c}_t C_{M_{ac_t}}$$

$$M_p = qS\bar{c}C_{M_p}$$

mean aerodynamic chord

$$M_f = qS\bar{c}C_{M_f}$$

The corresponding coefficient is given by…

$$C_{M_r} = C_{M_{ac_w}} + \left[C_{L_{0_W}} + C_{L_{\alpha_W}}(\propto + i_w)\right]\left(\bar{x}_r - \bar{x}_{ac_w}\right) + \frac{q_t S_t \bar{c}_t}{qS\bar{c}} C_{M_{ac_t}}$$

$$+ \left[\frac{q_t S_t}{qS}\left[C_{L_{0_t}} + C_{L_{\alpha_t}}\left[i_t - \epsilon_{0_t} + \left(1 - \epsilon_{\alpha_t}\right)\alpha\right] + C_{L_{\delta_e}}\delta_e\right]\right]\left(\bar{x}_r - \bar{x}_{ac_t}\right)$$

$$+ C_{M_{0_p}} + C_{M_{\alpha_p}}\alpha + C_{M_{0_f}} + C_{M_{\alpha_f}}\alpha$$

where

$$\bar{x}_r = \frac{x_r}{\bar{c}} \qquad \bar{x}_{ac_w} = \frac{x_{ac_w}}{\bar{c}} \qquad \bar{x}_{ac_t} = \frac{x_{ac_t}}{\bar{c}}$$

Pitch Moment Summary

$$C_{M_r} = C_{M_{0_r}} + C_{M_{\alpha_r}}\alpha + C_{M_{i_{t_r}}} i_t + C_{M_{\delta_{e_r}}}\delta_e$$

$$\begin{aligned} C_{M_{0_r}} = C_{M_{ac_w}} &+ \frac{\bar{q}_t}{\bar{q}}\frac{S_t}{S}\frac{\bar{c}_t}{\bar{c}}C_{M_{ac_t}} + C_{M_{0_p}} + C_{M_{0_f}} + (\bar{x}_r - \bar{x}_{ac_w})\left(C_{L_{0_w}} + C_{L_{\alpha_w}} i_w\right) \\ &+ \frac{\bar{q}_t}{\bar{q}}\frac{S_t}{S}(\bar{x}_r - \bar{x}_{ac_t})\left(C_{L_{0_t}} - C_{L_{\alpha_t}}\epsilon_{0_t}\right) \end{aligned}$$

$$C_{M_{\alpha_r}} = C_{M_{\alpha_p}} + C_{M_{\alpha_f}} + (\bar{x}_r - \bar{x}_{ac_w})C_{L_{\alpha_w}} + \frac{\bar{q}_t}{\bar{q}}\frac{S_t}{S}(\bar{x}_r - \bar{x}_{ac_t})C_{L_{\alpha_t}}(1 - \epsilon_{\alpha_t})$$

$$C_{M_{i_{t_r}}} = \frac{\bar{q}_t}{\bar{q}}\frac{S_t}{S}(\bar{x}_r - \bar{x}_{ac_t})C_{L_{\alpha_t}}$$

$$C_{M_{\delta_{e_r}}} = \frac{\bar{q}_t}{\bar{q}}\frac{S_t}{S}(\bar{x}_r - \bar{x}_{ac_t})C_{L_{\delta_{e_t}}}$$

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LONGITUDINAL STABILITY

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lift and drag
are acting

Aerodynamic Center of Aircraft

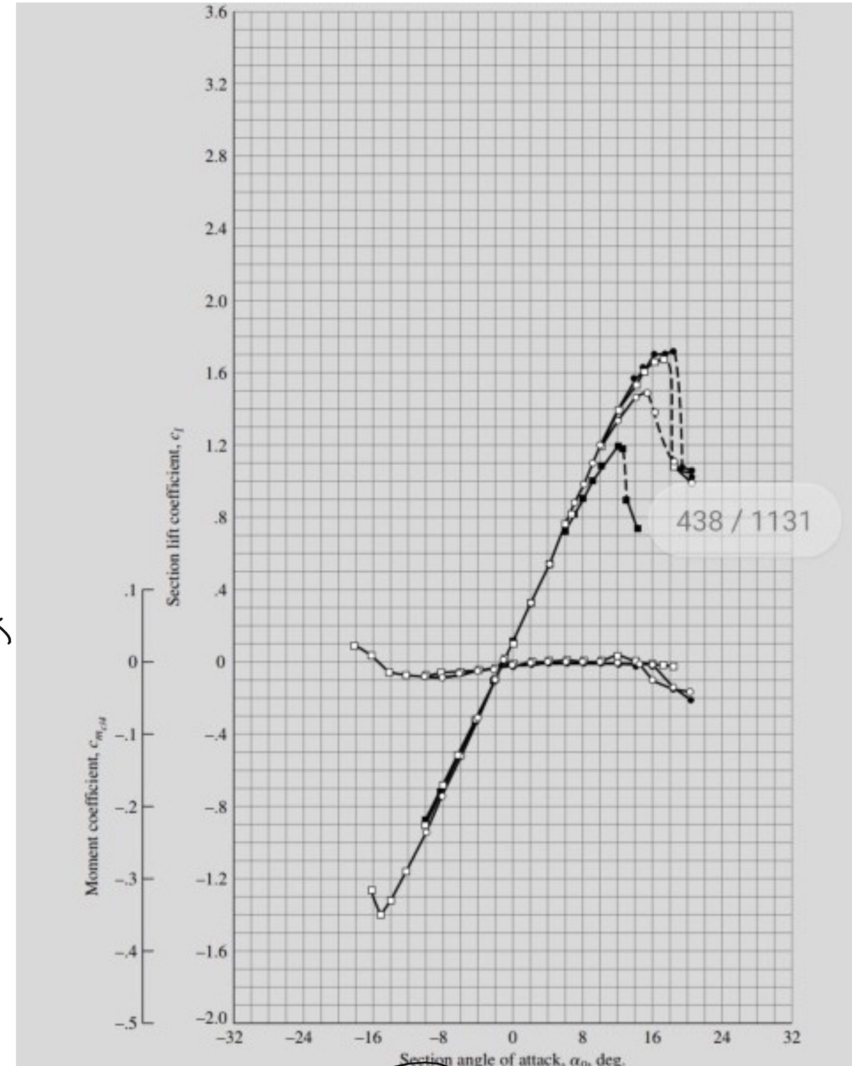
- What is so unique about the aerodynamic center?

$$C_{M_{\alpha_{ac}}} = 0$$

There is
a point where
moment is constant.

gradient of
moment coeff. is 0.

Moment is
constant at
this point



NACA 23015 Wing Section

Figure 5.2*a* Lift coefficient and moment coefficient about the quarter-chord for the NACA 23015 airfoil.

Aerodynamic Center of Aircraft

- How do we determine the aerodynamic center?

arbitrary point on plane chord

$$\bar{x}_r = \bar{x}_{ac}$$

$$C_{M_{\alpha_{ac}}} = C_{M_{\alpha_p}} + C_{M_{\alpha_f}} + (\bar{x}_{ac} - \bar{x}_{ac_w})C_{L_{\alpha_w}} + \frac{q_t S_t}{qS}(\bar{x}_{ac} - \bar{x}_{ac_t})C_{L_{\alpha_t}}(1 - \epsilon_{\alpha_t}) = 0$$

$$\Rightarrow \quad \bar{x}_{ac}\left[C_{L_{\alpha_W}} + \frac{q_t S_t}{qS}C_{L_{\alpha_t}}(1 - \epsilon_{\alpha_t})\right] = \bar{x}_{ac_w}C_{L_{\alpha_w}} + \frac{q_t S_t}{qS}\bar{x}_{ac_t}C_{L_{\alpha_t}}(1 - \epsilon_{\alpha_t}) - C_{M_{\alpha_p}} - C_{M_{\alpha_f}}$$

$$\Rightarrow \quad \bar{x}_{ac}C_{L_\alpha} = \bar{x}_{ac_w}C_{L_{\alpha_w}} + \frac{q_t S_t}{qS}\bar{x}_{ac_t}C_{L_{\alpha_t}}(1 - \epsilon_{\alpha_t}) - C_{M_{\alpha_p}} - C_{M_{\alpha_f}}$$

$$\Rightarrow \quad \bar{x}_{ac} = \frac{1}{C_{L_\alpha}}\left[\bar{x}_{ac_w}C_{L_{\alpha_w}} + \frac{q_t S_t}{qS}\bar{x}_{ac_t}C_{L_{\alpha_t}}(1 - \epsilon_{\alpha_t}) - C_{M_{\alpha_p}} - C_{M_{\alpha_f}}\right]$$

Pitch Moment about the CG

$$C_M = C_{M_0} + C_{M_\alpha}\alpha + C_{M_{i_t}} i_t + C_{M_{\delta_e}}\delta_e$$

$$\begin{aligned}
C_{M_0} &= C_{M_{ac_w}} + \frac{\bar{q}_t}{\bar{q}}\frac{S_t}{S}\frac{\bar{c}_t}{\bar{c}} C_{M_{ac_t}} + C_{M_{0_p}} + C_{M_{0_f}} + (\bar{x}_{cg} - \bar{x}_{ac_w})\left(C_{L_{0_w}} + C_{L_{\alpha_w}} i_w\right) \\
&\quad + \frac{\bar{q}_t}{\bar{q}}\frac{S_t}{S}(\bar{x}_{cg} - \bar{x}_{ac_t})\left(C_{L_{0_t}} - C_{L_{\alpha_t}}\epsilon_{0_t}\right) \\
C_{M_\alpha} &= C_{M_{\alpha_p}} + C_{M_{\alpha_f}} + (\bar{x}_{cg} - \bar{x}_{ac_w})C_{L_{\alpha_w}} + \frac{\bar{q}_t}{\bar{q}}\frac{S_t}{S}(\bar{x}_{cg} - \bar{x}_{ac_t})C_{L_{\alpha_t}}(1 - \epsilon_{\alpha_t}) \\
C_{M_{i_t}} &= \frac{\bar{q}_t}{\bar{q}}\frac{S_t}{S}(\bar{x}_{cg} - \bar{x}_{ac_t})C_{L_{\alpha_t}} \\
C_{M_{\delta_e}} &= \frac{\bar{q}_t}{\bar{q}}\frac{S_t}{S}(\bar{x}_{cg} - \bar{x}_{ac_t})C_{L_{\delta_{e_t}}}
\end{aligned}$$

Static Margin

- Can we simplify the equation for C_{M_α} ?

$$C_{M_\alpha} = C_{M_{\alpha_p}} + C_{M_{\alpha_f}} + (\bar{x}_{cg} - \bar{x}_{ac_w})C_{L_{\alpha_w}} + \frac{q_t S_t}{qS}(\bar{x}_{cg} - \bar{x}_{ac_t})C_{L_{\alpha_t}}(1 - \epsilon_{\alpha_t})$$

$$= \bar{x}_{cg}\left[C_{L_{\alpha_W}} + \frac{q_t S_t}{qS}C_{L_{\alpha_t}}(1 - \epsilon_{\alpha_t})\right] - \left[\bar{x}_{ac_w}C_{L_{\alpha_W}} + \frac{q_t S_t}{qS}\bar{x}_{ac_t}C_{L_{\alpha_t}}(1 - \epsilon_{\alpha_t}) - C_{M_{\alpha_p}} - C_{M_{\alpha_f}}\right]$$

$$= \bar{x}_{cg}C_{L_\alpha} - \bar{x}_{ac}C_{L_\alpha}$$

$$= -\underbrace{(\bar{x}_{ac} - \bar{x}_{cg})}C_{L_\alpha}$$

$\bar{X}_{ac}$ needs to be behind $\bar{X}_{cg}$

$$= -SM \cdot C_{L_\alpha}$$ where SM is the "Static Margin"

Static margin

Why is the Static Margin important?

- Which of the following aircraft is stable?

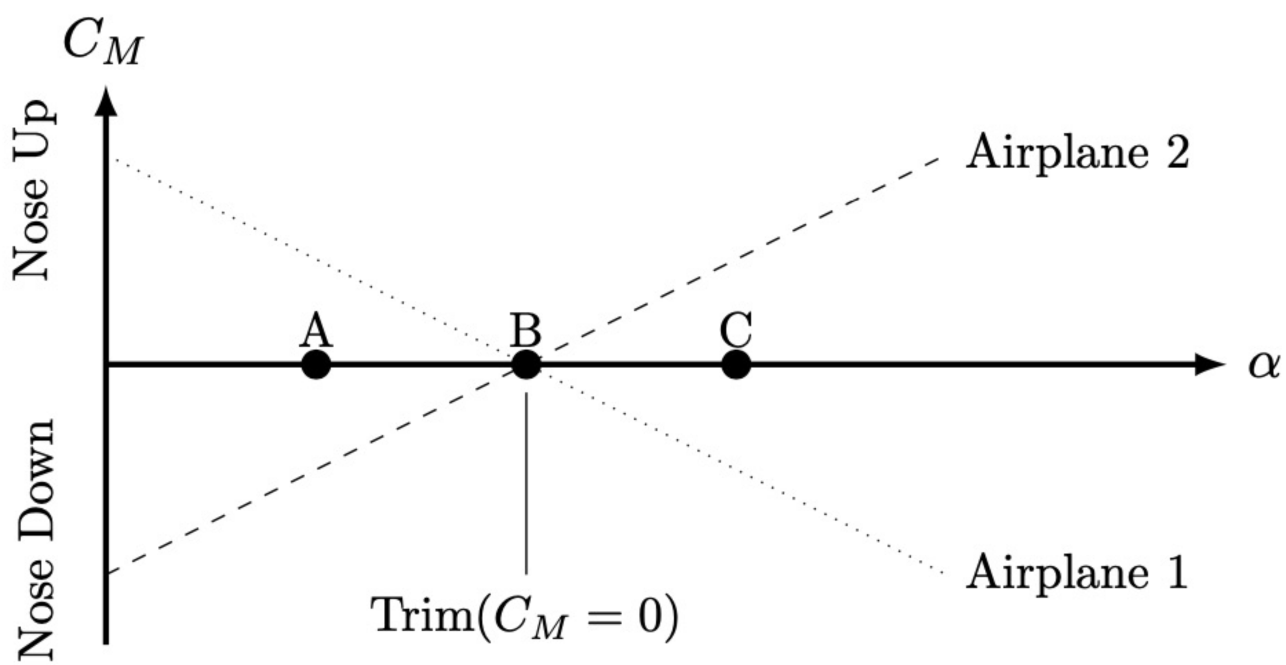


Figure 3.4: Pitch moment coefficient vs. angle of attack

For a trimmed aircraft…

1. If C_{M_α} (the slope of the line) is positive, then an increase in pitch (and thus in the angle of attack) results in a nose up pitching moment.
2. If C_{M_α} is negative, then an increase in pitch (and thus in the angle of attack) results in a nose down pitching moment.
3. Thus, for the aircraft have longitudinal static stability we need C_{M_α} to be negative.
4. Because C_{L_α} is positive…
5. The SM must also be positive, and…
6. The center of gravity must be ahead, i.e., closer to the nose than the aerodynamic center of the aircraft.

the static margin should be positive to achieve longitudinal static stability:

this also means that the center of gravity should be ahead of the aerodynamic center to achieve longitudinal static stability:

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TRIM

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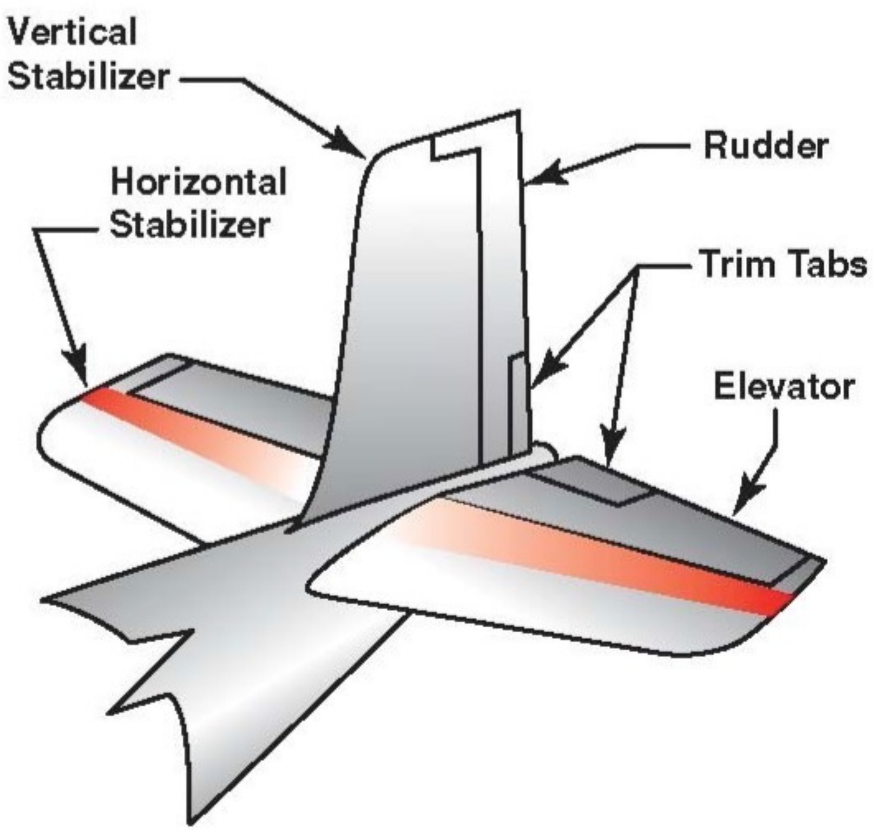
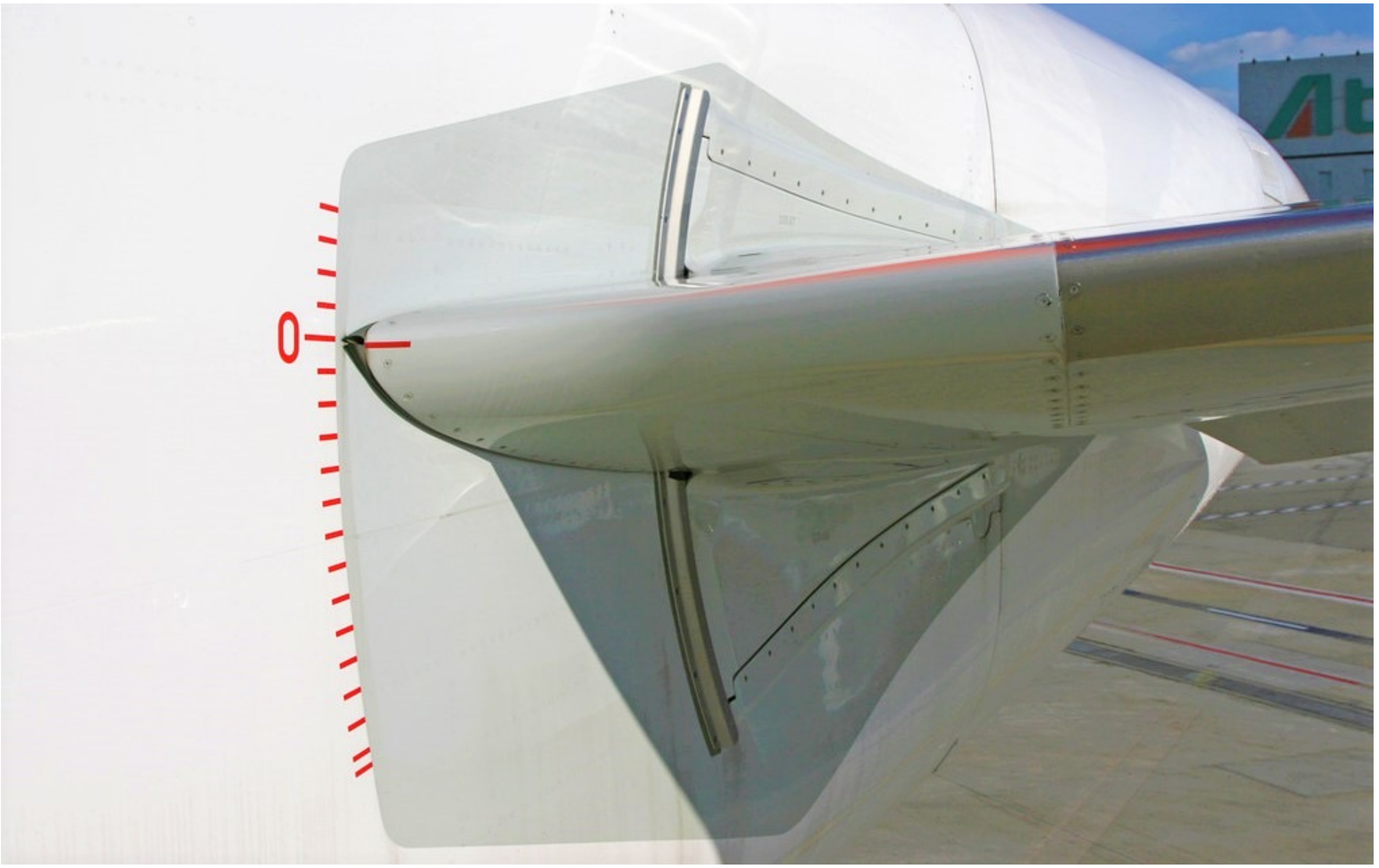
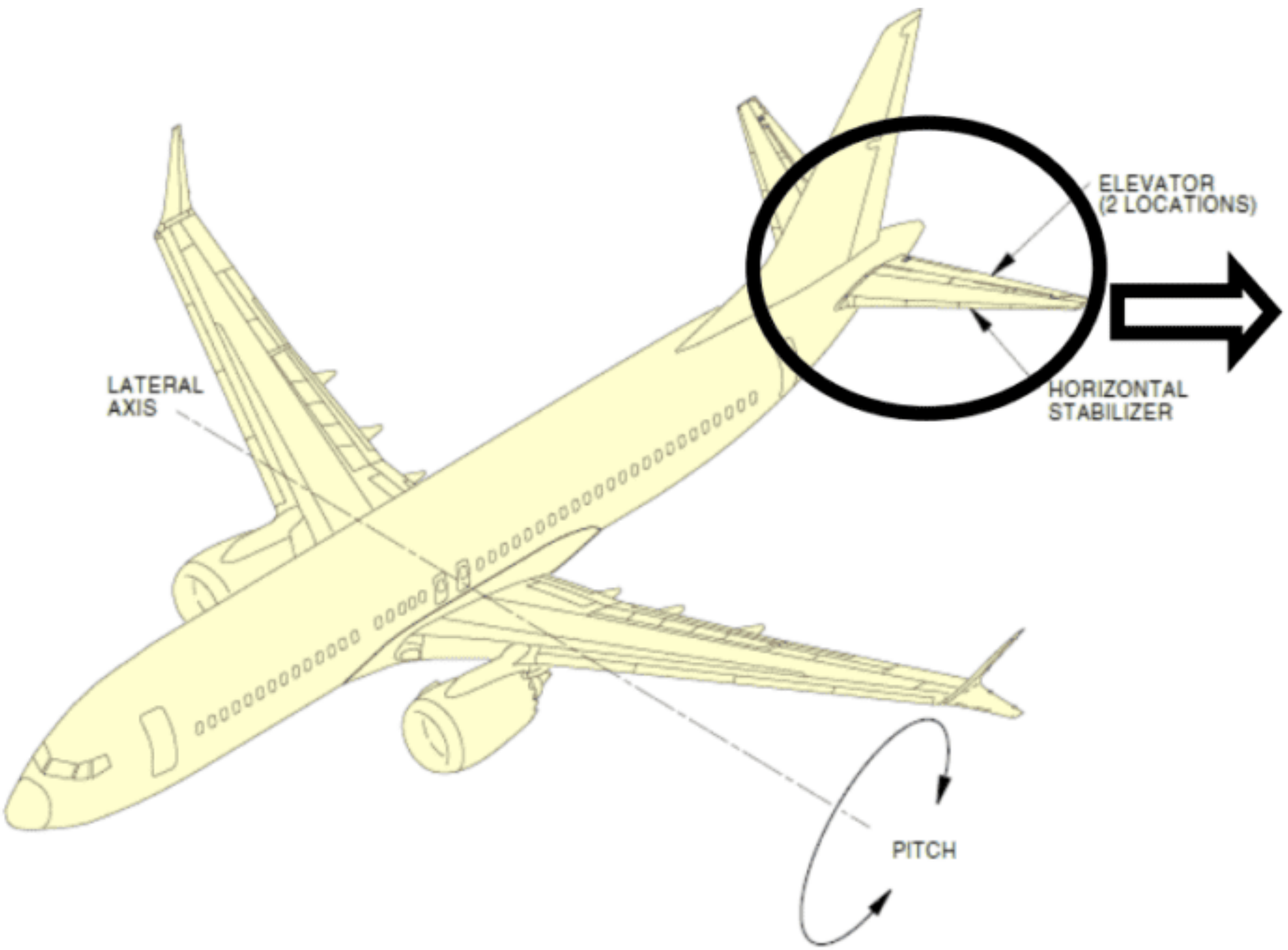
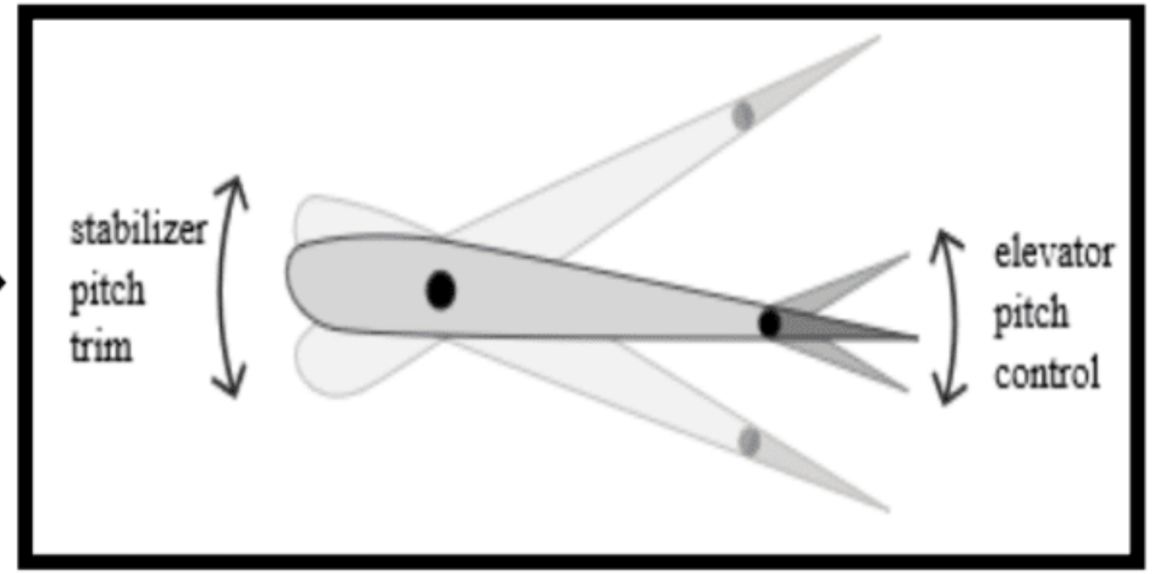
Fixed v. Variable-Position Horizontal Stabilizer





Variable-Position Horizontal Stabilizer (1)





Variable-Position Horizontal Stabilizer (2)

1. Set desired speed, V, and fix $\bar{q} = \rho V^2/2$. Assume that $\delta_e = 0$ at this speed.

2. Determine α_{trim} and $i_{t_{\text{trim}}}$ from

$$\frac{W\cos\gamma}{\bar{q}S} = C_{L_0} + C_{L_\alpha}\alpha + C_{L_{i_t}} i_t$$

$$0 = C_{M_0} + C_{M_\alpha}\alpha + C_{M_{i_t}} i_t$$

which is equivalent to solving the linear system of equations

$$\begin{bmatrix} C_{L_\alpha} & C_{L_{i_t}} \\ C_{M_\alpha} & C_{M_{i_t}} \end{bmatrix} \begin{bmatrix} \alpha_{\text{trim}} \\ i_{t_{\text{trim}}} \end{bmatrix} = \begin{bmatrix} \frac{W\cos\gamma}{\bar{q}S} - C_{L_0} \\ -C_{M_0} \end{bmatrix}$$

Variable-Position Horizontal Stabilizer (3)

and has the solution

$$\alpha_{\mathrm{trim}_{\delta_e=0}} = -\frac{C_{M_{i_t}}\left(\frac{W\cos\gamma}{\bar{q}S} - C_{L_0}\right) + C_{L_{i_t}} C_{M_0}}{C_{M_\alpha} C_{L_{i_t}} - C_{M_{i_t}} C_{L_\alpha}}$$

$$i_{t_{\mathrm{trim}}} = \frac{C_{M_\alpha}\left(\frac{W\cos\gamma}{\bar{q}S} - C_{L_0}\right) + C_{L_\alpha} C_{M_0}}{C_{M_\alpha} C_{L_{i_t}} - C_{M_{i_t}} C_{L_\alpha}}$$

3. With $i_{t_{\mathrm{trim}}}$ determined for the specified $\bar{q}$, define C'_{L_0} and C'_{M_0} as

$$C'_{L_0} = C_{L_0} + C_{L_{i_t}} i_{t_{\mathrm{trim}}}$$

$$C'_{M_0} = C_{M_0} + C_{M_{i_t}} i_{t_{\mathrm{trim}}}$$

Variable-Position Horizontal Stabilizer (4)

4. Determine δ_e to trim at other $\bar{q}$'s. That is, solve

$$\begin{bmatrix} C_{L_\alpha} & C_{L_{\delta_e}} \\ C_{M_\alpha} & C_{M_{\delta_e}} \end{bmatrix} \begin{bmatrix} \alpha \\ \delta_e \end{bmatrix} = \begin{bmatrix} \frac{W\cos\gamma}{\bar{q}S} - C'_{L_0} \\ -C'_{M_0} \end{bmatrix}$$

to find α_{trim} and $\delta_{e_{\text{trim}}}$, which gives

$$\alpha_{\text{trim}} = -\frac{C_{M_{\delta_e}}\left(\frac{W\cos\gamma}{\bar{q}S} - C'_{L_0}\right) + C_{L_{\delta_e}} C'_{M_0}}{C_{M_\alpha} C_{L_{\delta_e}} - C_{M_{\delta_e}} C_{L_\alpha}}$$

$$\delta_{e_{\text{trim}}} = \frac{C_{M_\alpha}\left(\frac{W\cos\gamma}{\bar{q}S} - C'_{L_0}\right) + C_{L_\alpha} C'_{M_0}}{C_{M_\alpha} C_{L_{\delta_e}} - C_{M_{\delta_e}} C_{L_\alpha}}$$

Let's do some number crunching…

	Wing	Horizontal Stabilizer
$S =$	232.00 [ft^2]	54.00 [ft^2]
$\bar{c} =$	7.04 [ft]	3.83 [ft]
$x_{ac/le} =$	4.07 [ft]	2.79 [ft]
$x_{le} =$	16.40 [ft]	36.90 [ft]
$i =$	1.00 [deg]	
$C_{L_0} =$	-0.0443	0.0000
$C_{L_\alpha} =$	5.0800	4.2600
$C_{M_{ac}} =$	-0.0175	0.0000
$C_{L_{\delta_{e_t}}} =$		1.8000
$\epsilon_0 =$		0.642 [deg]
$\epsilon_\alpha =$		0.426
$\eta =$		0.9

- The aircraft is in level flight.
- The gravitational acceleration is 32.174 [ft/s^2].
- The wing and horizontal stabilizer are trapezoidal surfaces.
- The cg of the aircraft is at $x_{cg} = 10.56$ [ft].
- The weight of the aircraft is $W = 9,500$ [lb].
- The propulsive moment coefficients are $C_{M_{0_p}} = 0.0$ and $C_{M_{\alpha_p}} = 0.0$.
- The fuselage moment coefficients are $C_{M_{0_f}} = 0.0$ and $C_{M_{\alpha_f}} = 0.0$.
- The atmospheric density is 0.002378 [slugs/ft^3].
- The horizontal tail incidence can only be set between -0.5 and -7 [deg].

$$\eta = \frac{q_t}{q}$$

Number Crunching (1)

1. Set desired speed, V, and fix $\bar{q} = \rho V^2/2$. Assume that $\delta_e = 0$ at this speed.

Let's assume aircraft is flying at … $500\ knots = 843.9\ ft/s$

given $\rho = 0.002378\ slugs/ft^3$ then $q = 846.8\ lb/ft^2$

Number Crunching (2)

2. Determine α_{trim} and $i_{t_{\text{trim}}}$ from

$$\alpha_{\text{trim}_{\delta_e=0}} = -\frac{C_{M_{i_t}}\left(\frac{W\cos\gamma}{\bar{q}S} - C_{L_0}\right) + C_{L_{i_t}}C_{M_0}}{C_{M_\alpha}C_{L_{i_t}} - C_{M_{i_t}}C_{L_\alpha}}$$

$$i_{t_{\text{trim}}} = \frac{C_{M_\alpha}\left(\frac{W\cos\gamma}{\bar{q}S} - C_{L_0}\right) + C_{L_\alpha}C_{M_0}}{C_{M_\alpha}C_{L_{i_t}} - C_{M_{i_t}}C_{L_\alpha}}$$

First we compute the things we don′t have … $C_{L_{i_t}}, C_{M_{i_t}}, C_{M_0}$

… then we “*plug and chug*"

Number Crunching (3)

3. With $i_{t_{\text{trim}}}$ determined for the specified $\bar{q}$, define C'_{L_0} and C'_{M_0} as

$$C'_{L_0} = C_{L_0} + C_{L_{i_t}} i_{t_{\text{trim}}}$$
$$C'_{M_0} = C_{M_0} + C_{M_{i_t}} i_{t_{\text{trim}}}$$

Number Crunching (4)

4. Determine δ_e to trim at other $\bar{q}$'s. That is, solve

$$\alpha_{\text{trim}} = -\frac{C_{M_{\delta_e}}\left(\frac{W\cos\gamma}{\bar{q}S} - C'_{L_0}\right) + C_{L_{\delta_e}} C'_{M_0}}{C_{M_\alpha} C_{L_{\delta_e}} - C_{M_{\delta_e}} C_{L_\alpha}}$$

$$\delta_{e_{\text{trim}}} = \frac{C_{M_\alpha}\left(\frac{W\cos\gamma}{\bar{q}S} - C'_{L_0}\right) + C_{L_\alpha} C'_{M_0}}{C_{M_\alpha} C_{L_{\delta_e}} - C_{M_{\delta_e}} C_{L_\alpha}}$$

Why is this all important?

- Air Midwest Flight 5481
  - https://www.youtube.com/watch?v=MMsbpLjfWlo
  - https://www.youtube.com/watch?v=CHj9Lmjo2Ng

- Crash at Bagram Air Base
  - https://www.youtube.com/watch?v=5fpxm0D46iQ
  - https://www.youtube.com/watch?v=wXJ_MfAnjgQ

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