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# Tail aerodynamics of Bird-scale flapping-wing robots

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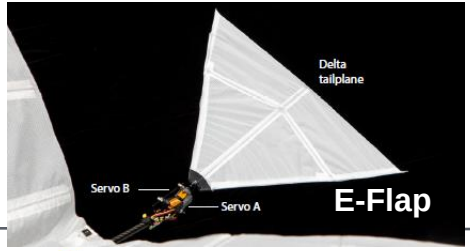
# Ornithopter tails

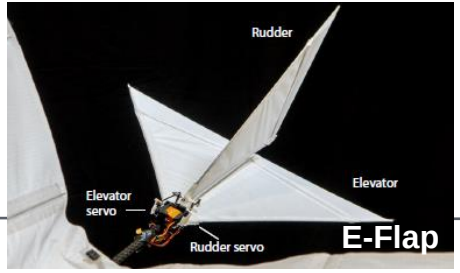
## D-Tail





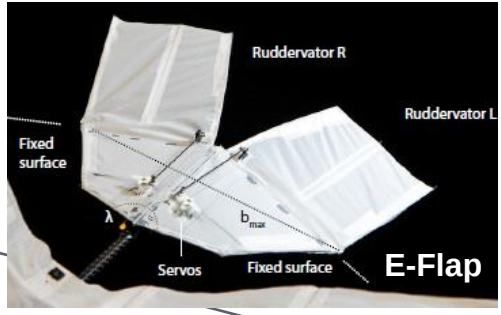

## C-Tail



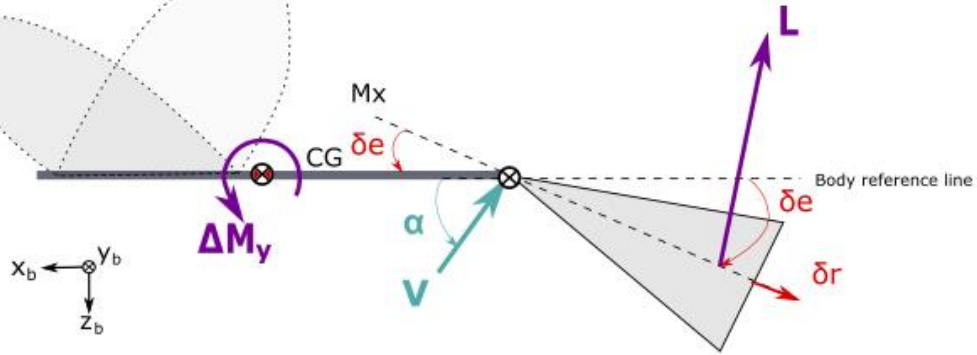


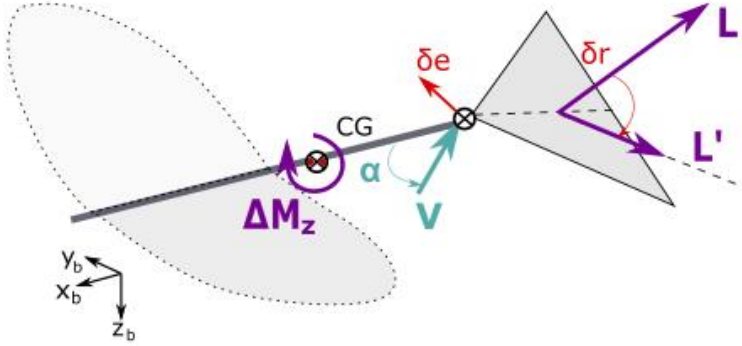

## V-Tail

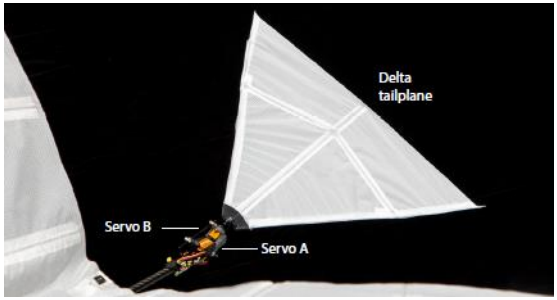




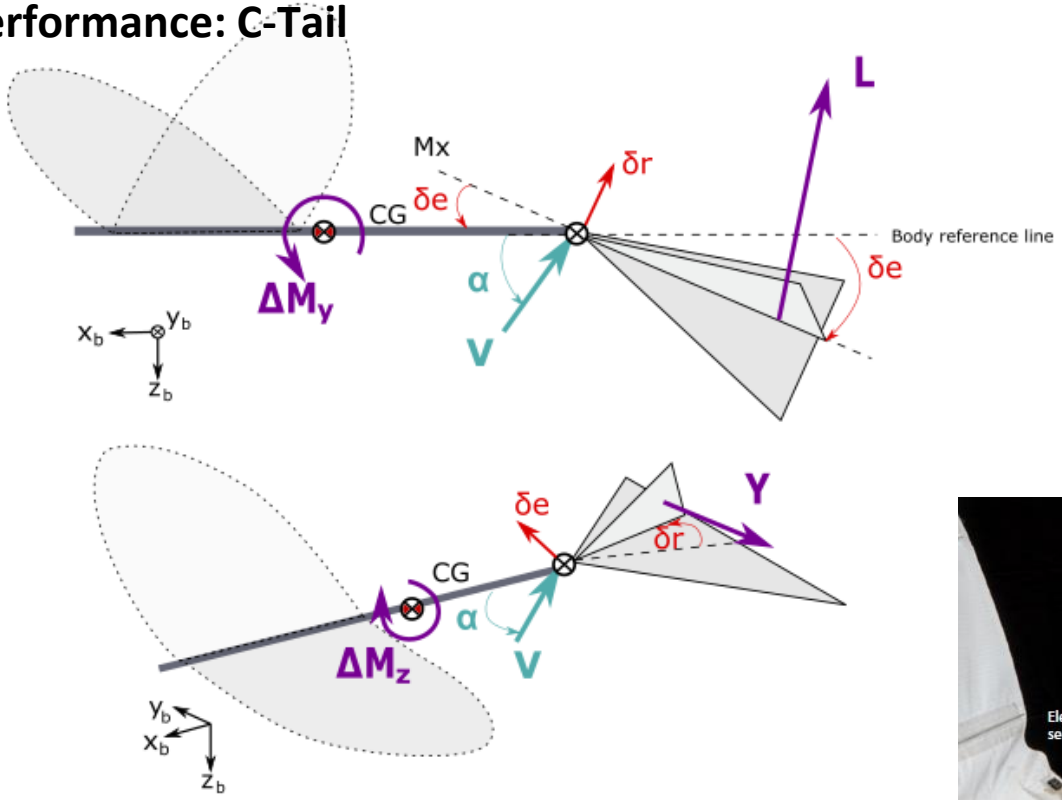
# Performance: D-Tail

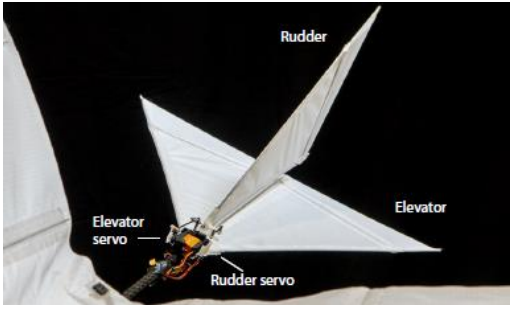


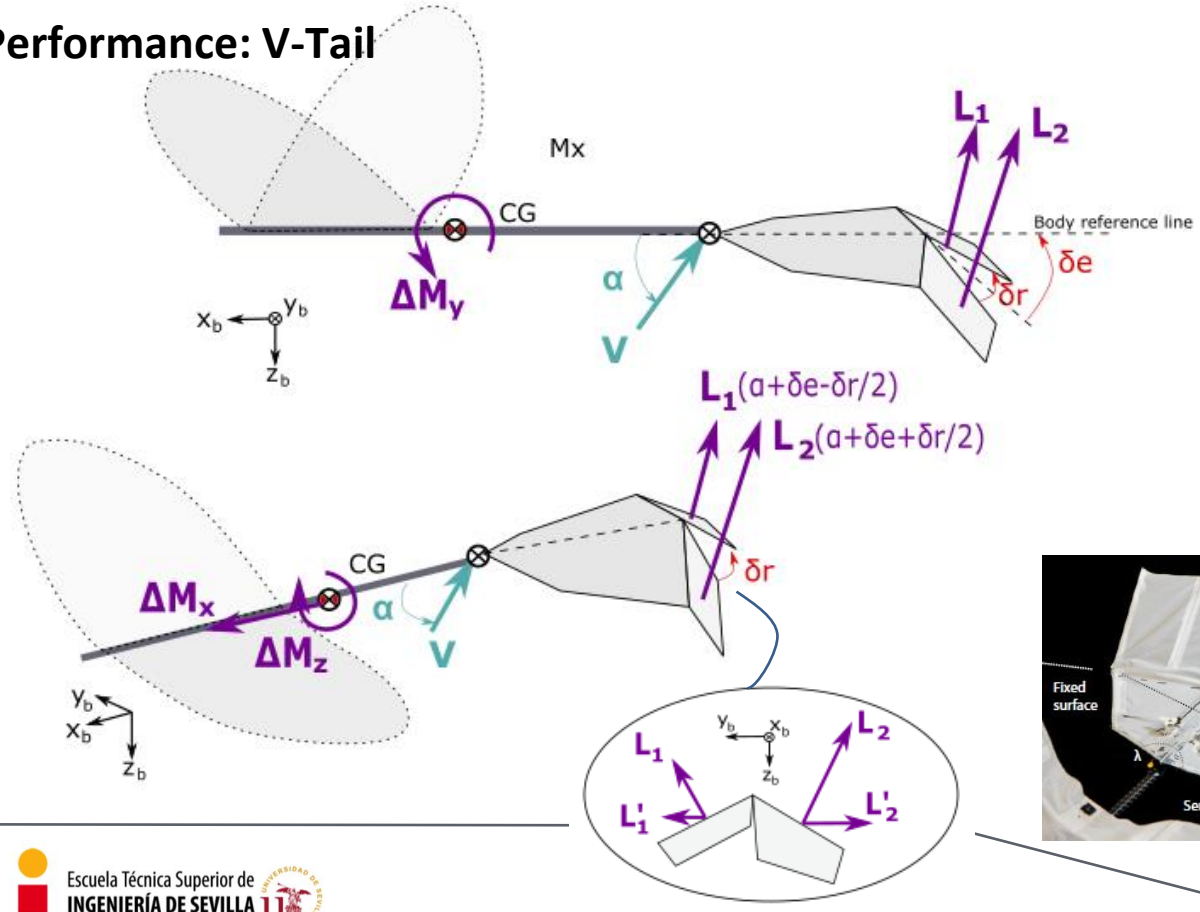



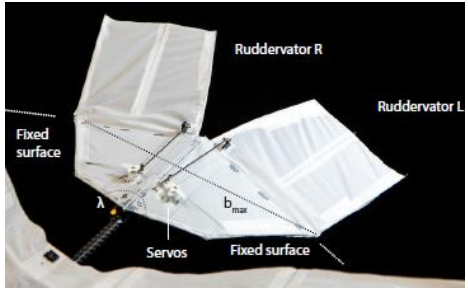
# Performance: C-Tail



# Performance: V-Tail

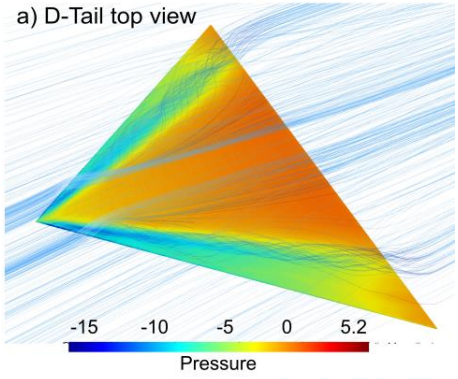


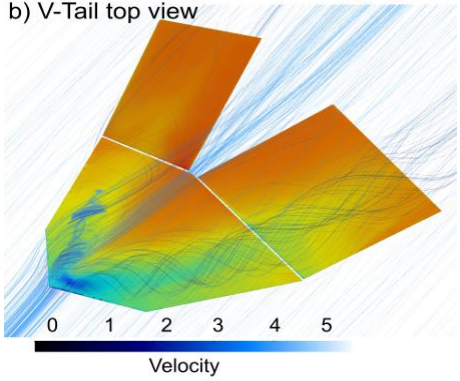



# CFD simulations: D/V-Tail

- Static simulations: k-ω RANS model SST.
- V=4 m/s (typical flight)
- 1 Mesh per configuration, ≈3 M elements.
- 729 configurations: 2-3 days computation (32 cores CPU, 128 GB RAM)
- Assuming symmetry: reduce computational load.

$$V = 4\mathrm{m/s}$$
$$\alpha = [-30, 30]^\circ$$
$$\delta_{e,r} = [-30, 30]^\circ$$



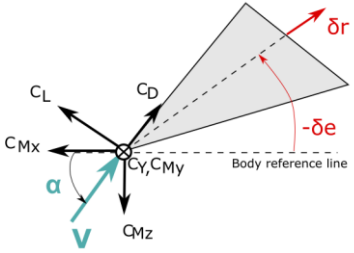




Pressure and streamlines at:
α=20º, δe=-10º, δr=20º

# Modelling:

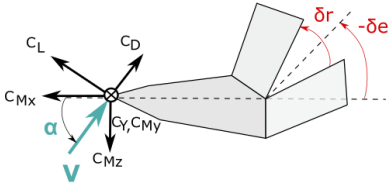
## C-Tail

$$
\begin{aligned}
c_L &= c_{L,max}\sin\left(a_\alpha(\alpha+\delta_e)\right)\cos(\delta_r)\\
c_D &= c_{D,max}-(c_{D,max}-c_{D,0})\cos\left(b_\alpha(\alpha+\delta_e)\right)\cos(\delta_r)\\
c_{MY} &= c_{MY,max}\sin\left(c_\alpha(\alpha+\delta_e)\right)\cos(\delta_r)\\
c_Y &= c_{Y,max}\sin\left(d_\alpha(\alpha+\delta_e)\right)\sin(\delta_r)\\
c_{MX} &= c_{MX,max}\sin\left(e_\alpha(\alpha+\delta_e)\right)\sin(\delta_r)\\
c_{MZ} &= c_{MZ,max}\sin\left(f_\alpha(\alpha+\delta_e)\right)\sin(\delta_r)
\end{aligned}
$$




## V-Tail

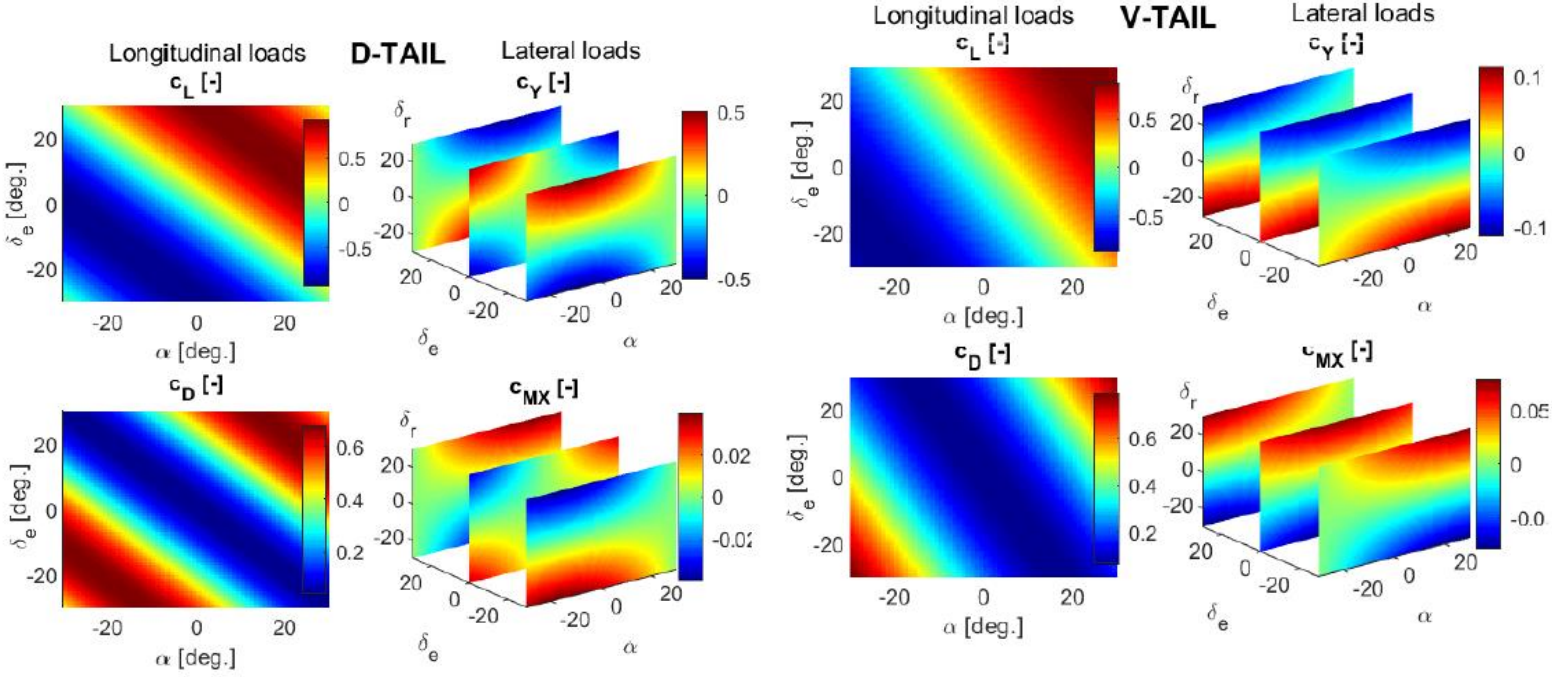
$$
\begin{aligned}
c_L &= c_{L,max}\sin(a_\alpha\alpha+a_{\delta_e}\delta_e)\\
c_D &= c_{D,max}-(c_{D,max}-c_{D,0})\cos(b_\alpha\alpha+b_{\delta_e}\delta_e)\\
c_{MY} &= c_{MY,max}\sin(c_\alpha\alpha+c_{\delta_e}\delta_e)\\
c_Y &= c_{Y,max}\cos\left(d_\alpha(\alpha+\delta_e)\right)\sin(d_\alpha\delta_r/2)\\
c_{MX} &= c_{MX,max}\cos\left(e_\alpha(\alpha+\delta_e)\right)\sin(e_\alpha\delta_r/2)\\
c_{MZ} &= c_{MZ,max}\cos\left(f_\alpha(\alpha+\delta_e)\right)\sin(f_\alpha\delta_r/2)
\end{aligned}
$$



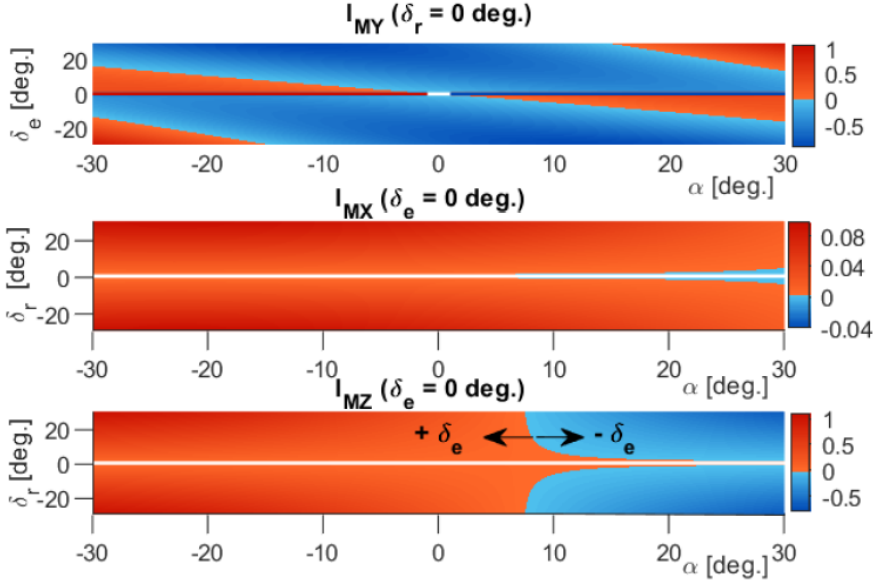

| Parameter | D-TAIL | V-TAIL |
|---|---|---|
| $c_{L,max}$ | 0.94 | 0.88 |
| $a_\alpha$ | 2.92 | 2.32 |
| $a_{\delta_e}$ | 2.92 | 1.43 |
| $c_{D,max}$ | 0.36 | 0.46 |
| $c_{D,0}$ | 0.04 | 0.06 |
| $b_\alpha$ | 4.23 | 3.12 |
| $b_{\delta_e}$ | 4.23 | 1.72 |
| $c_{MY,max}$ | -0.65 | -0.55 |
| $c_\alpha$ | 2.26 | 1.71 |
| $c_{\delta_e}$ | 2.26 | 1.23 |
| $c_{Y,max}$ | -1.02 | -0.36 |
| $d_\alpha$ | 2.3 | 1.3 |
| $c_{MX,max}$ | 0.08 | 0.22 |
| $e_\alpha$ | 1.9 | 1.48 |
| $c_{MZ,max}$ | 0.64 | 0.33 |
| $f_\alpha$ | 1.94 | 1.2 |

R>0.97

# Forces and moments comparison:



# Performance: C-Tail vs V-Tail




Comparative index between V and C-Tail for pitch, roll and yaw moment. Red zone means better performance for V-tail than D-tail, the opposite occurs in blue zones. The boundary between these zones for $I_{MX}$ and $I_{MY}$ shifts to left or right if $\delta_e$ increases or decreases respectively.

$$
\begin{aligned}
I_{MY} &= -\text{sign}(\delta_e)(c'_{MY,V-T} - c'_{MY,D-T}) \\
I_{MX} &= \text{sign}(\delta_r)(c'_{MX,V-T} - c'_{MX,D-T}) \\
I_{MZ} &= \text{sign}(\delta_r)(c'_{MZ,V-T} - c'_{MZ,D-T})
\end{aligned}
$$

- D-Tail: higher pitch moment (except near stall)
- V-Tail: higher roll moment, higher yaw moment (for δe<0)

## Conclusions

- Stall effect occurs earlier in D-Tail ->
  Narrower operating range / lower lateral performance.

- D-Tail lateral moments depends on α ->
  Impact on the control of flapping-wing robots: large flapping perturbation.

- V-Tail performs higher roll moment ->
  Desirable characteristic for maneuverability (faster dynamics, $I_{zz}/I_{xx} \approx 4$)

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**Thanks for your attention!**

**Questions?**

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