# E-flap aerodynamic modelling Part II: Multibody dynamics approach

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## Motivation

- **Goal:** Accurate aerodynamic forces model identification.
- **Last work:** Volterra Model: (Memory -> Phase)

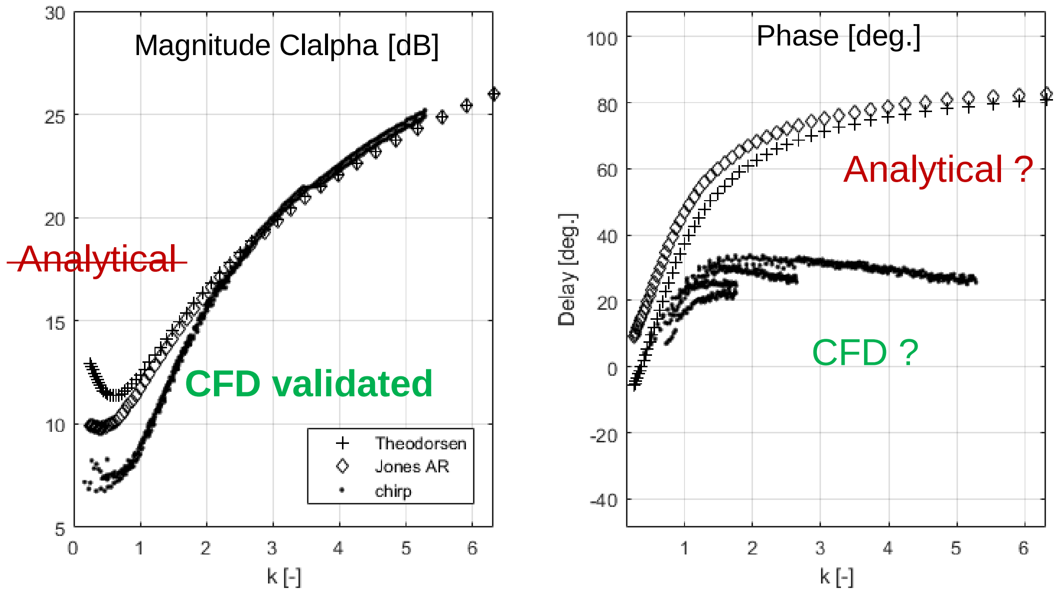


Figure 1: Frequency response: CFD vs Classical Models

Only magnitude validation by flight data.

What about the phase?

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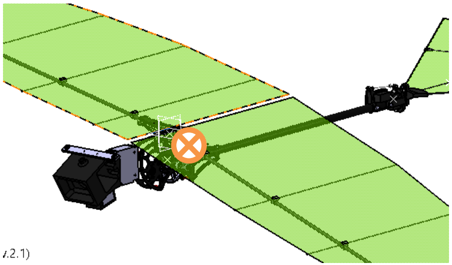
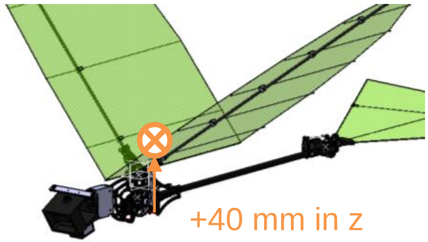
## Proposal

**1. Data:** Use flight data directly instead of CFD simulations.

**2. Multibody dynamics:** Inertia and GC changes up to 50% during flapping.






**3. Loads Phase measurement*:** Wings and control surfaces tracking.

*Discussion between the aerodynamic loads phase and their nature:
H. E. Taha, A. S. Rezaei, On the high-frequency response of unsteady lift and circulation: A dynamical systems perspective, Journal of Fluids and Structures 93 (2020) 102868.

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# Multibody Dynamics Model derivation (I)

$$T = \frac{1}{2} m_0 v^T v + \frac{1}{2} \omega^T I_0 \omega + \frac{1}{2} \sum_{j=1}^{Nk} \sum_{i=1}^{Nj} m_{ij} v_{ij}^T v_{ij} + \omega_{ij}^T I_{ij} \omega_{ij}$$

$$\boldsymbol{x} = \begin{bmatrix} \boldsymbol{p} \\ \boldsymbol{v} \end{bmatrix}$$

Position and velocity of:
Fuselage in body frame.
Joints in local frames.

Boltzmann-Hamel equations for quasi-velocities

$$\frac{d}{dt}\left[\frac{\partial T}{\partial v}\right] + \left(\sum_{k=1}^{N} \frac{\partial T}{\partial v_k} \Gamma_k\right) v - \left(J_k^{\mathrm{I},0}\right)^T \left[\frac{\partial T}{\partial p}\right]^T = u$$

$$\Gamma_k = \left(J_k^{\mathrm{I},0}\right)^T \Lambda_k \left(J_k^{\mathrm{I},0}\right)$$

$$\{\Lambda_k\}_{ij} = \frac{\partial}{\partial p_j}\left(J_k^{0,\mathrm{I}}\right)_{ki} - \frac{\partial}{\partial p_i}\left(J_k^{0,\mathrm{I}}\right)_{kj}$$

$$\boldsymbol{M}(\boldsymbol{p})\dot{\boldsymbol{v}} + \boldsymbol{C}(\boldsymbol{p},\boldsymbol{v}) + \mathbf{E}(\boldsymbol{p},\boldsymbol{v}) = \boldsymbol{u}$$

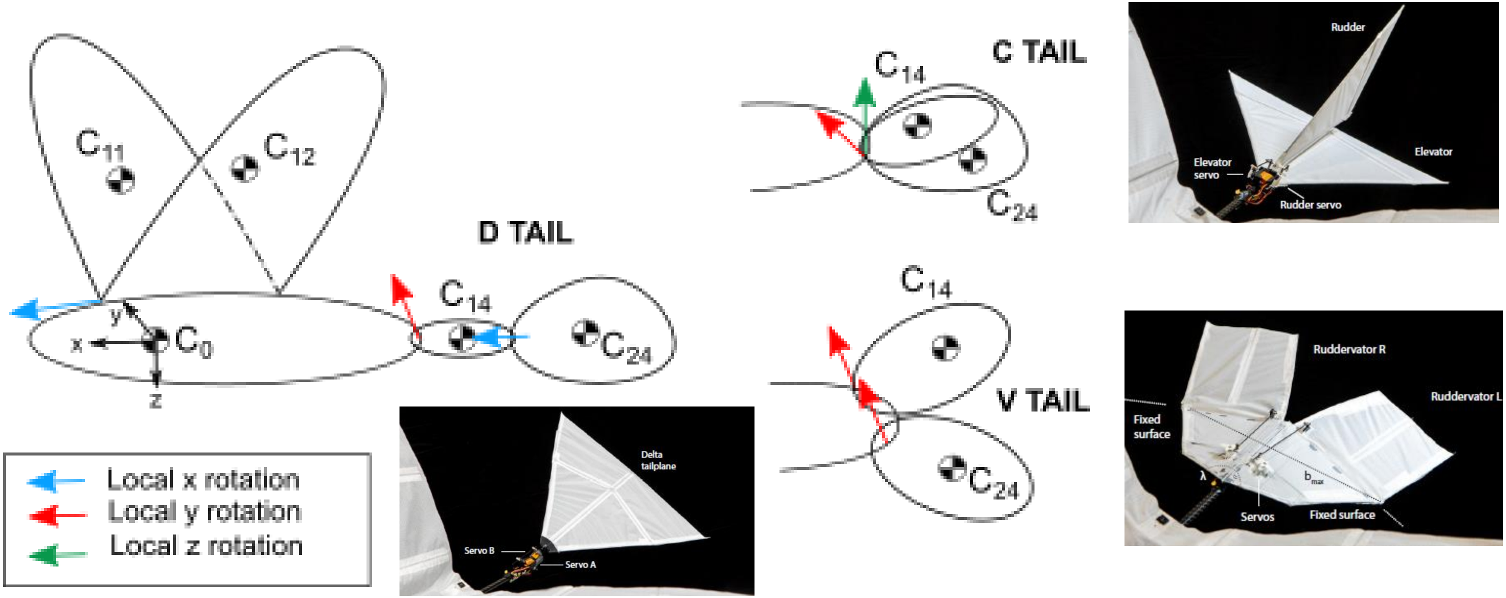
$\boldsymbol{M}$: Mass/Inertia matrix.

$\boldsymbol{C}$: Nonlinear Dynamic coupling matrix.

$\mathbf{E}$: Generalized external forces. (Gravity and aerodynamics).

$\boldsymbol{u}$: Control forces.

# Multibody Dynamics Model derivation (II)



# Multibody Dynamics Model derivation (III)

$$\boldsymbol{M}(\boldsymbol{p})\dot{\boldsymbol{v}} + \boldsymbol{C}(\boldsymbol{p},\boldsymbol{v}) + \mathbf{E}(\boldsymbol{p},\boldsymbol{v}) = \boldsymbol{u}$$

$$p_{10x1} = \begin{bmatrix} r_{0,I}^{I} \\ \eta_{0,I}^{0} \\ \theta \end{bmatrix} \quad v_{10x1} = \begin{bmatrix} v_{0,I}^{I} \\ \omega_{0,I}^{0} \\ \dot{\theta} \end{bmatrix} \quad \dot{p} = \underbrace{\begin{pmatrix} \boldsymbol{R}^{I0} & \vec{0}_{3x3} & \vec{0}_{3x4} \\ \vec{0}_{3x3} & \boldsymbol{J}_{\boldsymbol{\eta}}^{I0} & \vec{0}_{3x4} \\ \vec{0}_{4x3} & \vec{0}_{4x3} & \boldsymbol{I}_{4x4} \end{pmatrix}}_{J_k^{I0}} v$$

$$C = \frac{1}{2}\dot{M} + \sum_{k=1}^{N} \frac{\partial T}{\partial v_k}\Gamma_k + \frac{1}{2}\frac{\partial M}{\partial p}(v \otimes \mathrm{I})\left(J_k^{\mathrm{I},0}\right) - \frac{1}{2}\left(J_k^{\mathrm{I},0}\right)^T (\mathrm{I} \otimes v^T)\left[\frac{\partial M}{\partial p}\right]^T$$

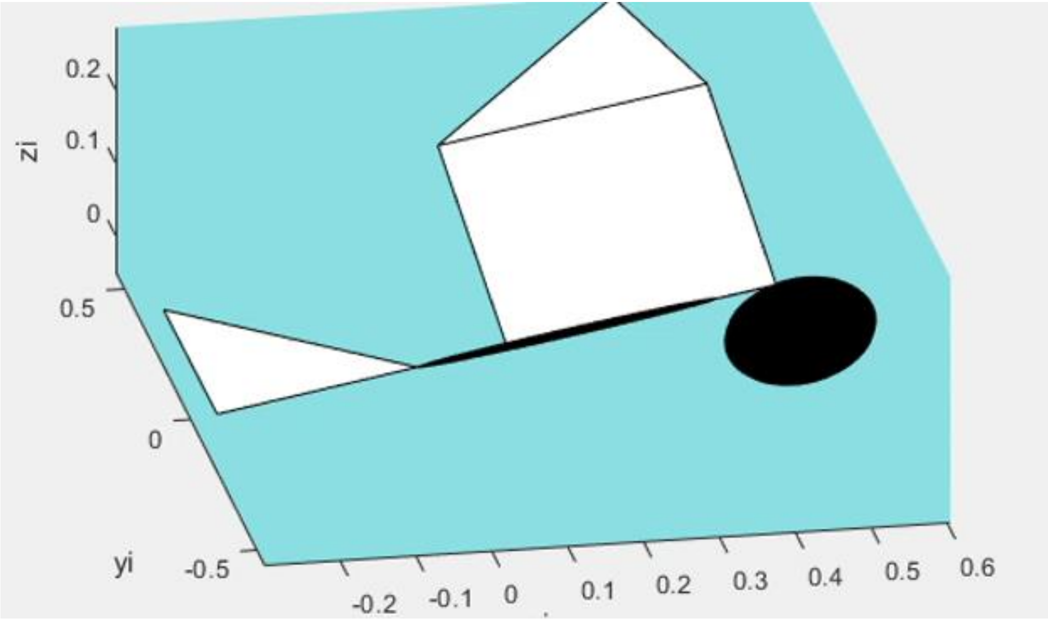
$$\{M\}_{ij} = \frac{\partial T}{\partial v_i \partial v_j}$$

$$\mathbf{E}(\boldsymbol{p},\boldsymbol{v}) = \mathbf{E}_{grav} + \mathbf{E}_{aerodyn}$$

$$\begin{bmatrix} \dot{\boldsymbol{r}} \\ \dot{\boldsymbol{\eta}} \\ \dot{\boldsymbol{\theta}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{R}^{I0}\boldsymbol{v} \\ \boldsymbol{J}_{\boldsymbol{\eta}}^{I0}\boldsymbol{\omega} \\ \dot{\boldsymbol{\theta}} \end{bmatrix}, \quad \begin{bmatrix} \dot{\boldsymbol{v}} \\ \dot{\boldsymbol{\omega}} \\ \ddot{\boldsymbol{\theta}} \end{bmatrix} = -\boldsymbol{C}\boldsymbol{v} - \boldsymbol{E} + \boldsymbol{u}$$

# Multibody Dynamics Model derivation (IV)

**Verification:**



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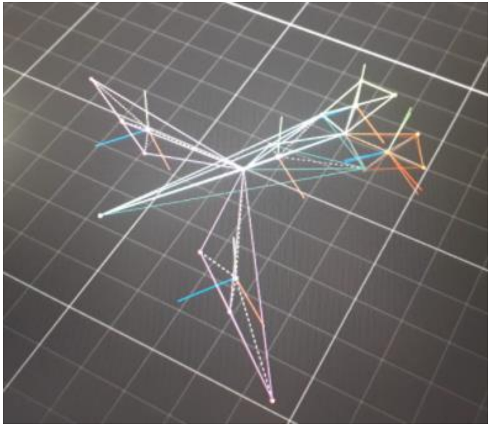
# Experimental Setup (I)

- Optimal markers location: Asymetric (mínimum 4 per body)



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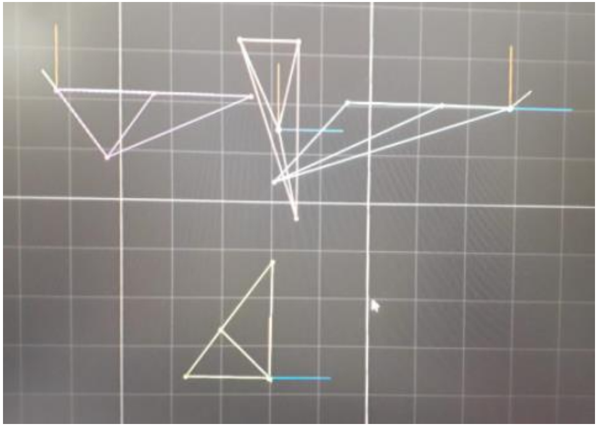

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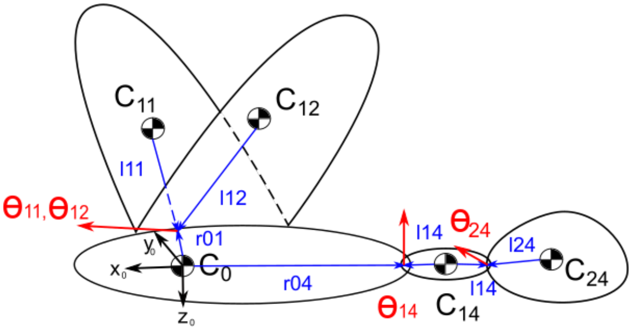
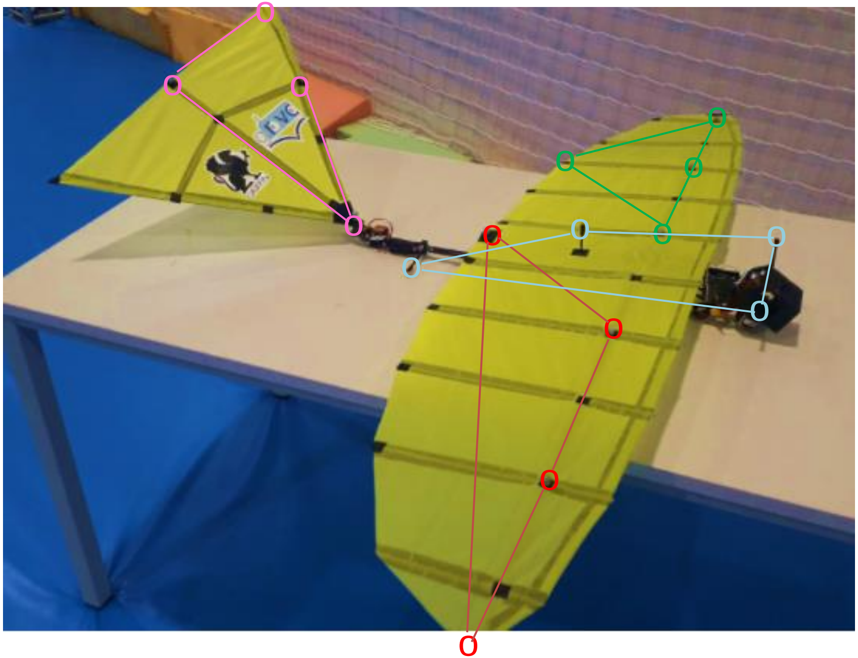
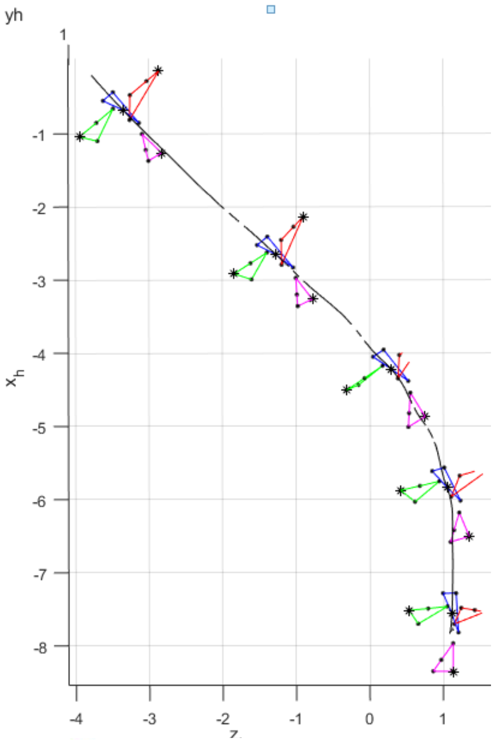
# Experimental Setup (II)

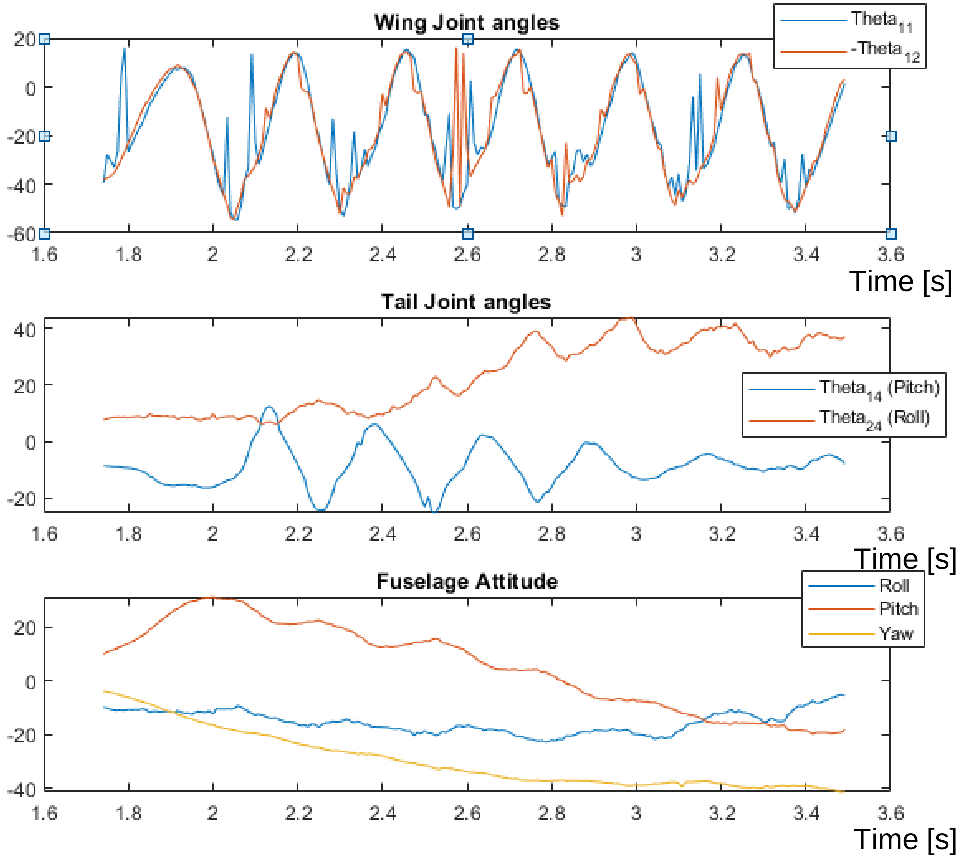
- Inertia and geometry measurement:



# Experimental Setup (III): First test.

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# Future work

- Flight experiments to obtain a flight database including joint position tracking.
- Aerodynamic forces reconstruction.
- Aerodynamic model identification.

Thanks for your attention!

Questions?

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