E-flap aerodynamic modelling Part II: Multibody dynamics approach
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1. Motivation.
2. Proposal.
3. Multibody Dynamics Model derivation.
4. Experimental setup.
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5. Future work: Accurate aerodynamic identification
Motivation

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

**Figure 1:** Frequency response: CFD vs Classical Models

- **Analytical?**
- **CFD validated**
- **CFD?**
- **Analytical?**

*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.

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Multibody Dynamics Model derivation (I)

\[ T = \frac{1}{2} m_0 v^T v + \frac{1}{2} \omega^T I_0 \omega + \frac{1}{2} \sum_{j=1}^{N} \sum_{i=1}^{N} m_{ij} v_{ij}^T v_{ij} + \omega_{ij}^T I_{ij} \omega_{ij} \]

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

\[ \Gamma_k = (J_k^{1,0})^T \Lambda_k (J_k^{1,0}) \]

\[ \{\Lambda_k\}_{ij} = \frac{\partial}{\partial p_j} (J_k^{0,1})_{ki} - \frac{\partial}{\partial p_i} (J_k^{0,1})_{kj} \]

\[ \mathbf{x} = \begin{bmatrix} p \\ v \end{bmatrix} \]


\[ M(p) \dot{v} + C(p, v) + E(p, v) = u \]

\( M \): Mass/Inertia matrix.

\( C \): Nonlinear Dynamic coupling matrix.

\( E \): Generalized external forces. (Gravity and aerodynamics).

\( u \): Control forces.
Multibody Dynamics Model derivation (II)
Multibody Dynamics Model derivation (III)

\[ M(p) \dot{v} + C(p,v) + E(p,v) = u \]

\[ p_{10x1} = \begin{bmatrix} r_{0,I}^l \\ \eta_{0,I}^0 \\ \theta \end{bmatrix}, \quad v_{10x1} = \begin{bmatrix} v_{0,I}^l \\ \omega_{0,I}^0 \\ \dot{\theta} \end{bmatrix}, \quad \dot{p} = \begin{pmatrix} R^{I0} & \overrightarrow{0}_{3x3} & \overrightarrow{0}_{3x4} \\ \overrightarrow{0}_{3x3} & J_{\eta}^{I0} & \overrightarrow{0}_{3x4} \\ \overrightarrow{0}_{4x3} & \overrightarrow{0}_{4x3} & I_{4x4} \end{pmatrix} \begin{pmatrix} v \\ \eta \end{pmatrix} \]

\[ C = \frac{1}{2} \dot{M} + \sum_{k=1}^{N} \frac{\partial T}{\partial v_k} \Gamma_k + \frac{1}{2} \frac{\partial M}{\partial \nu} \left( v \otimes I \right) \left( J_k^{I0} \right) - \frac{1}{2} \left( J_k^{I0} \right)^T \left( I \otimes v^T \right) \frac{\partial M}{\partial \nu} \]

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

\[ E(p,v) = E_{grav} + E_{aerody} \]

\[ \begin{bmatrix} \dot{r} \\ \dot{\eta} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} R^{I0} & \nu \\ J_{\eta}^{I0} & \omega \end{bmatrix}, \quad \begin{bmatrix} \dot{\nu} \\ \dot{\omega} \end{bmatrix} = -Cv - E + u \]
Multibody Dynamics Model derivation (IV)

Verification:
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Experimental Setup (I)

- Optimal markers location: Asymmetric (minimum 4 per body)

V-TAIL

C-TAIL
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?