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Modeling, Simulation and Control of an Aircraft with Morphing Wing

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Overview

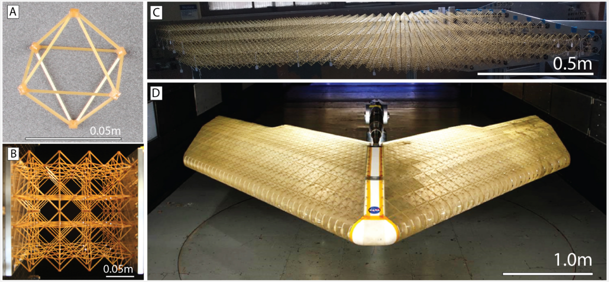
Motivation

- Search for flight performance improvement
- New aircraft concepts
- New materials, long span - flexible structures
- Reserch line: development of variable geometry wings

Motivation

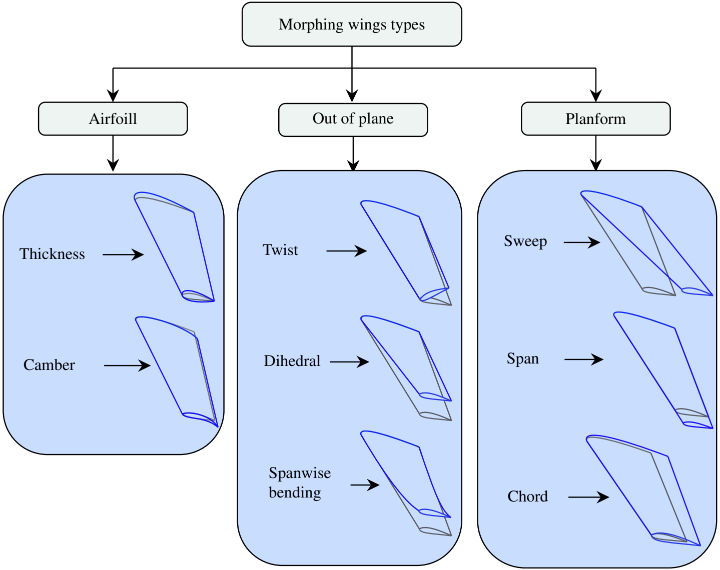
- Search for flight performance improvement
- New aircraft concepts
- New materials, long span - flexible structures
- Reserch line: development of variable geometry wings
  - ◇ $\rightarrow$ **morphing wings**

extreme morphing: NASA/MIT concept



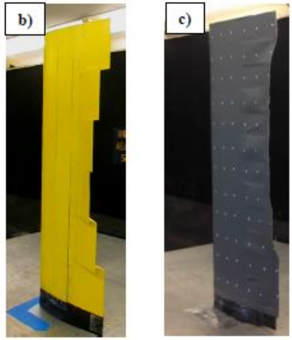
Source: Cramer et al., 2019.

Morphing types

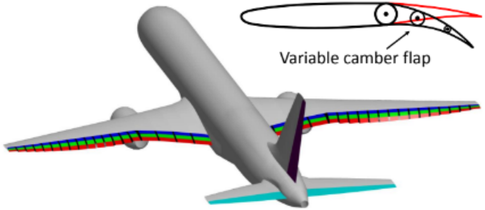


Airfoil camber

- Airfoil camber: only trailing edge morphing (TEM)
- Application to the whole wing span.



Pankonien and Inman, 2013.



(a) Variable camber flap system of 3 chord segments.

Fujiwara et al., 2018.

- Boeing trailing Edge Variable Camber (TEVC)
- Adaptive dropped Hinge Flap (ADHF)

Overall research goals

- Establish a framework for simulation of morphing wings considering flight dynamics of flexible aircraft.
- At the moment, the work is divided into two main tasks:
  - control of trailing edge morphing
  - simulation of flexible aircraft with a multi-body approach

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  - ◇ control of trailing edge morphing → **this work**
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Present work goal

Propose and implement a methodology to simulate and control the flight mechanics of a rigid aircraft with trailing edge morphing

Mathematical models

Tasks:

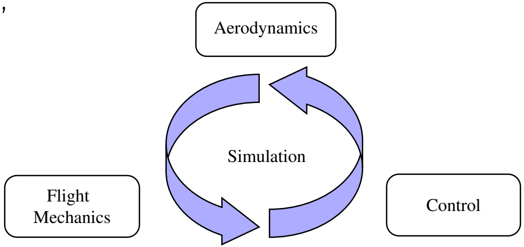
- implement the flight mechanics of a 6 DOF rigid body aircraft
  - ◇ include variable inertia due to TEM
- implement unsteady aerodynamics
  - ◇ model different wing zones;
- control design;
- establish the interface between disciplines;

Mathematical models

- Flight mechanics
- Aerodynamics
- Control design

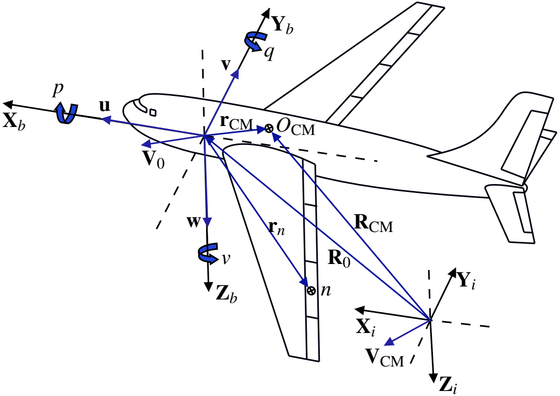
⇓

Complete framewok

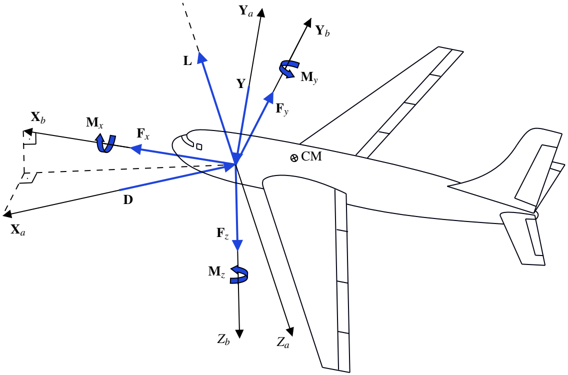


Reference systems

Inertial and body reference systems



Forces and moments on body RS



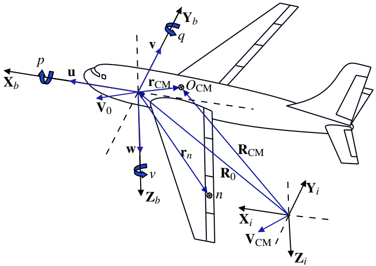
Dynamics and kinematics

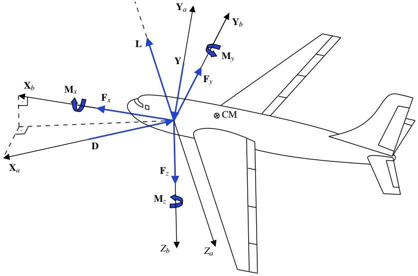
$$\begin{bmatrix} m\bar{\mathbf{I}} & (m\tilde{\mathbf{r}}_{\text{cm}})^T \\ m\tilde{\mathbf{r}}_{\text{cm}} & \bar{\mathbf{J}} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{V}}_0 \\ \dot{\boldsymbol{\omega}} \end{bmatrix} = \begin{bmatrix} \mathbf{Q}_F \\ \mathbf{Q}_M \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} \dot{x}_0 \\ \dot{y}_0 \\ \dot{z}_0 \end{bmatrix} = (\bar{\mathbf{C}}^i_b)^T \begin{bmatrix} u \\ v \\ w \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin(\phi)\tan(\theta) & \cos(\phi)\tan(\theta) \\ 0 & \cos(\phi) & -\text{sen}(\phi) \\ 0 & \text{sen}(\phi)\sec(\theta) & \cos(\phi)\sec(\theta) \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (3)$$

The variable camber affects the mass and inertia properties.





Trailing Edge model

Modeling of the trailing edge

- option: multibody dynamics Shabana, 2005
- option: consider only modification in the reference system, with displacements from the mass center Obradovic and Subbarao, 2011
  - ◇ good alternative: less computational cost

Mass properties variation

$$\mathbf{r}_{\text{cm}} = \frac{1}{m} \cdot \sum_{i=1}^{N_n} (m_n)_i \cdot (\mathbf{r}_n)_i \quad (4)$$

$$\bar{\mathbf{J}} = \bar{\mathbf{J}}_F + \sum_{i=1}^{N_n} (m_n)_i \cdot (\tilde{\mathbf{r}}_n)_i \cdot (\tilde{\mathbf{r}}_n)_i^T \quad (5)$$

$$\mathbf{r}_{\text{cm}} = f(\delta_1, \delta_2, .., \delta_{Nn})$$

$$\dot{\mathbf{r}}_{\text{cm}} = \sum_{k=1}^{Nn} \frac{\partial \mathbf{r}_{\text{cm}}}{\partial \delta_k} \cdot \dot{\delta}_k$$

$$\ddot{\mathbf{r}}_{\text{cm}} = \dot{\boldsymbol{\delta}}^T \cdot \left(\sum_{j=1}^{Nn} \sum_{k=1}^{Nn} \frac{\partial^2 \mathbf{r}_{\text{cm}}}{\partial \delta_j \partial \delta_k} \right) \cdot \dot{\boldsymbol{\delta}} + \sum_{k=1}^{Nn} \frac{\partial \mathbf{r}_{\text{cm}}}{\partial \delta_k} \cdot \ddot{\delta}_k$$

$$\dot{\delta}_p = -2\zeta\omega_n \cdot \delta_p + \omega_n^2 \cdot (\delta_c - \delta)$$

$$\dot{\delta} = \delta_p$$

Typical section and strip theory

Kier, 2005 compares flight loads between:

- Quasi-steady strip theory
- Vortex Lattice Method (VLM),
- Unsteady strip theory
- Doublet Lattice Method (DLM).

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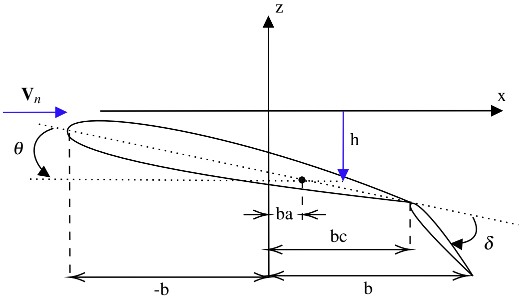
3DOF Typical section.



- Unsteady strip theory

→ currently the best candidate

◇ good computational cost / precision rate

$$\begin{Bmatrix} \bar{\mathbf{F}}_1 \\ \bar{\mathbf{F}}_2 \\ \bar{\mathbf{F}}_3 \\ \vdots \\ \bar{\mathbf{F}}_N \end{Bmatrix} = \pi\rho \begin{bmatrix} b_1^4\mathbf{A}_1(ik) & 0 & \dots & \dots & 0 \\ 0 & b_2^4\mathbf{A}_2(ik) & \dots & \dots & 0 \\ 0 & 0 & b_3^4\mathbf{A}_3(ik) & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & \dots & b_N^4\mathbf{A}_N(ik) \end{bmatrix} \begin{Bmatrix} \bar{\mathbf{x}}_1 \\ \bar{\mathbf{x}}_2 \\ \bar{\mathbf{x}}_3 \\ \vdots \\ \bar{\mathbf{x}}_N \end{Bmatrix} \quad (6)$$

- Unsteady modified strip theory (UMST)

- Barmby et al., 1951

Stability and control derivatives

Once the aerodynamic influence coefficients are computed:

- Rational functions approximation (Roger method):

$$\mathbf{F}(t) = \overline{\mathbf{A}}_S + \overline{\mathbf{A}}_0 \Delta\mathbf{x}(t) + \overline{\mathbf{A}}_1 \left(\frac{b_{ref}}{V}\right) \Delta\dot{\mathbf{x}}(t) + \overline{\mathbf{A}}_2 \left(\frac{b_{ref}}{V}\right)^2 \Delta\ddot{\mathbf{x}}(t) + \sum_{i=1}^{n_{\mathsf{lag}}} \overline{\mathbf{A}}_{i+2} \cdot \mathbf{x}_i^{\mathsf{lag}}(t)$$

Stability and control

- Linearized condition : $L(s) = L_{eq} + \Delta\mathbf{L}(s)\Delta\mathbf{x}(s)$
- Roger method - rational functions
- inverse Laplace transform - bring the loading vector to time domain;

$$\mathbf{F}(t) = \begin{bmatrix} F_x(t) & F_y(t) & F_z(t) & M_x(t) & M_y(t) & M_z(t) \end{bmatrix}^T$$

Control project model

- Present work:

Exponential Mapping Controller (EMC)
Castro et al., 2012.

- Based on *Sliding Mode Control* (SMC) and *Neuro-Fuzzy Control* (NFN).

- currentlySISO

Highlights

- Only four steps and two parameters
- Able of solving problems with variable terms, such as the Inertia Matrix, in the present case.

EMC implementation

- Switched error calculation:
$e_t = \frac{x_{ref} - x}{e_r}$
- Contraint on e_t:

$$e_s = \begin{cases} -1, & \text{if } e_t < -1 \\ e_t, & \text{if } -1 \leq e_t \leq 1 \\ 1, & \text{if } e_t > 1 \end{cases}$$

- compute exponential function:
$u_e = \text{sign}(e_s)\left(1 - ||e_s| - 1|^{2^{-B}}\right)$
- Control action:

$$u = \frac{u_{\max} - u_{\min}}{2}(u_e - 1) + u_{\max}$$

Control diagrama and state-space solution

- State-space model, considering a linearized matrix $\overline{\mathbf{A}}_t$ to assemble the system equation:

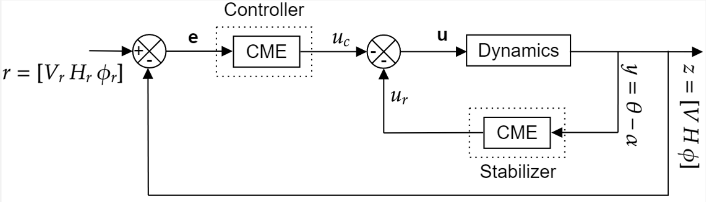
$$\begin{bmatrix} \dot{\mathbf{V}}_0 \\ \dot{\boldsymbol{\omega}} \end{bmatrix} = \begin{bmatrix} m\bar{\mathbf{I}} & (m\tilde{\mathbf{r}}_{\text{cm}})^T \\ m\tilde{\mathbf{r}}_{\text{cm}} & \bar{\mathbf{J}} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{Q}_F \\ \mathbf{Q}_M \end{bmatrix}$$

Solution obtained with a variable order method (ode15s)

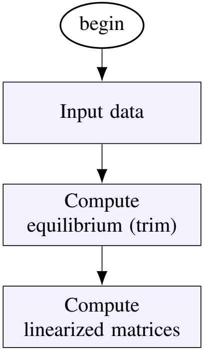
Parameters e_r and B are obtained from minimization of function:

$$f_{\text{crit}} = \int_0^{\infty} t|e(t)| \cdot dt$$

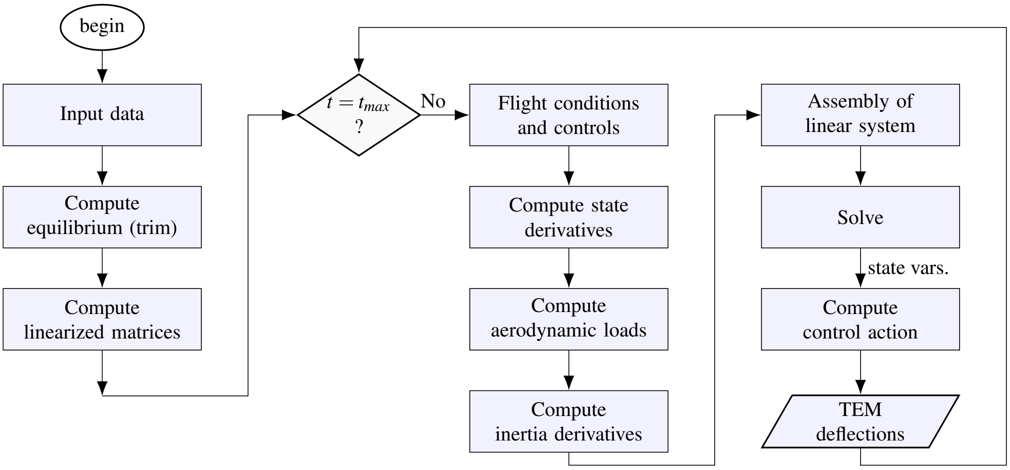
Control diagram



Simulation flowchart



Simulation flowchart



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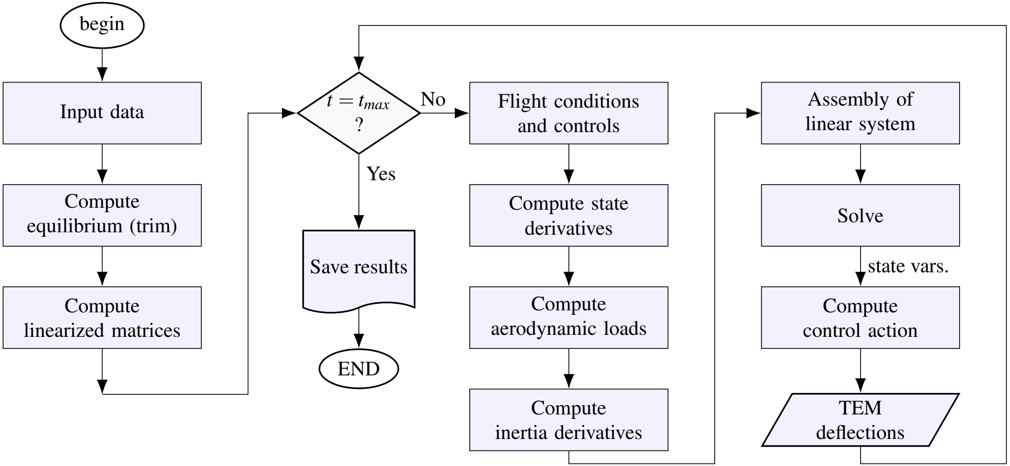
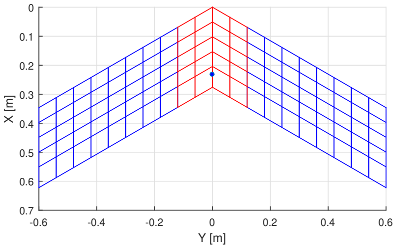


The framework is implemented in Matlab

Reference Aircraft

Grankvist, 2006



Parameters

Chord	0,276 m
Span	1,2 m
Mass	0,9 kg
Sweep angle	30°
Max Power	260 W
Speed range	9 to 22 m/s

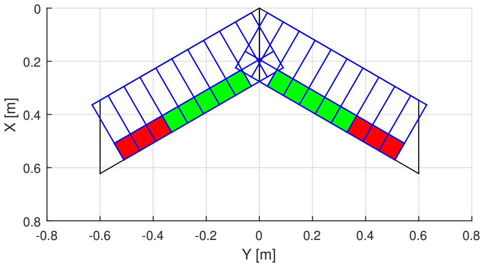
Mass and inertia

I_{xx}	0,0681
I_{yy}	0,0116
I_{zz}	0,0797
x_{CM}	0,2317
$y_{CM} = z_{CM}$	0

Study: stability analysis

Strip model with two control zones and a central zone

$$\begin{Bmatrix} V \\ \alpha \\ \theta \\ H \\ (\delta_c)_{\text{tail}} \\ \Pi_p \\ (\delta_c)_{\text{aileron}} \end{Bmatrix} = \begin{Bmatrix} 12 \quad (m/s) \\ 3,72^\circ \\ 3,72^\circ \\ 100 \quad (m) \\ -1,64^\circ \\ 0,00875 \\ 0 \end{Bmatrix}$$

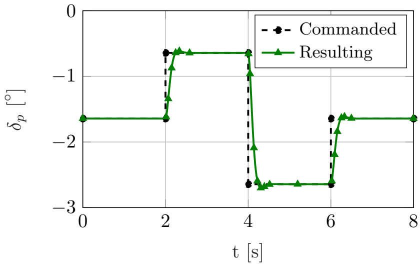


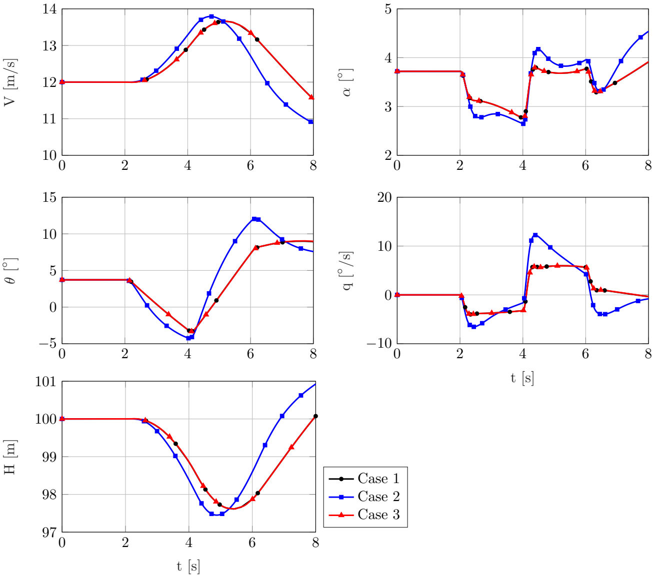
Poles of linearized system $(\overline{\mathbf{A}}) \Rightarrow$

longitudinal dynamics	lateral and directional dynamics
-15,9 + 6,12i	-0,0278
-15,9 - 6,12i	0
-0,0627 + 0,416i	-17,1
-0,0627 - 0,416i	0
0	0

Study: response to control surface disturbances

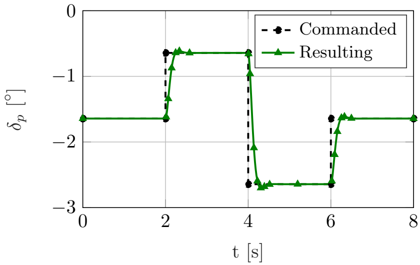
	Aerodynamic coefficients	Mass and inertia
Case 1	constant	constant
Case 2	variable	constant
Case 3	constant	variable

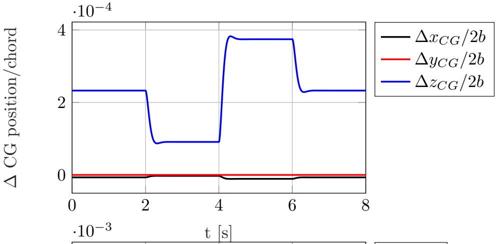


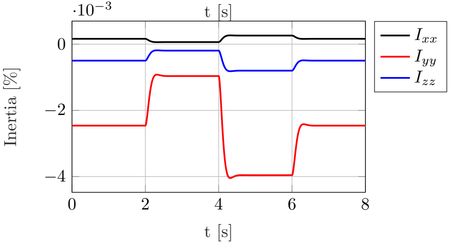


Study: variation of mass properties with control deflection

Variation of aircraft mass properties with TEM deflection





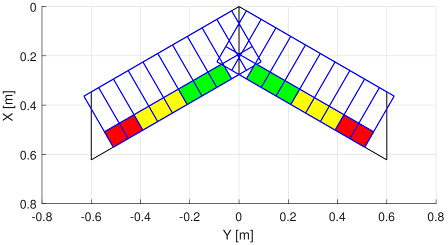


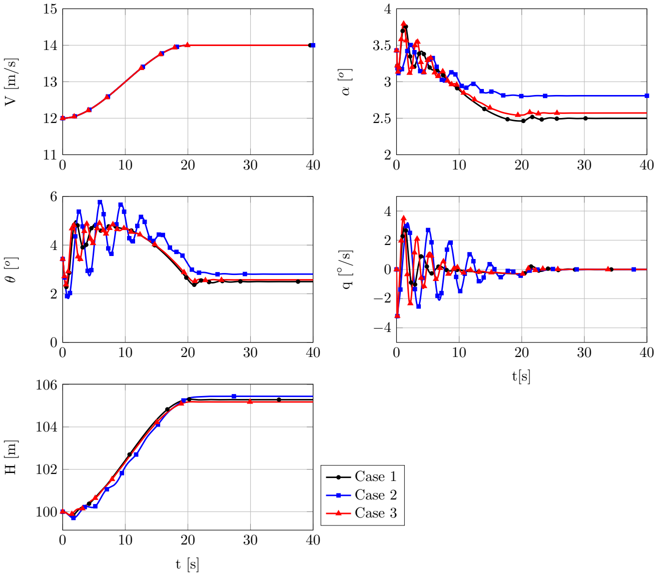
Study: three TE zones

Reference maneuver:

5 m climb - 2 m/s increase - $\Delta t = 20$ s

	TEM zones: active (y/n)		
	tip	mid	root
Case 1	yes	yes	yes
Case 2	yes	no	yes
Case 3	yes	yes	no





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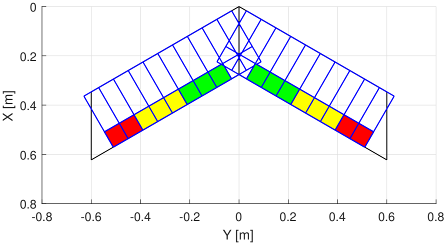
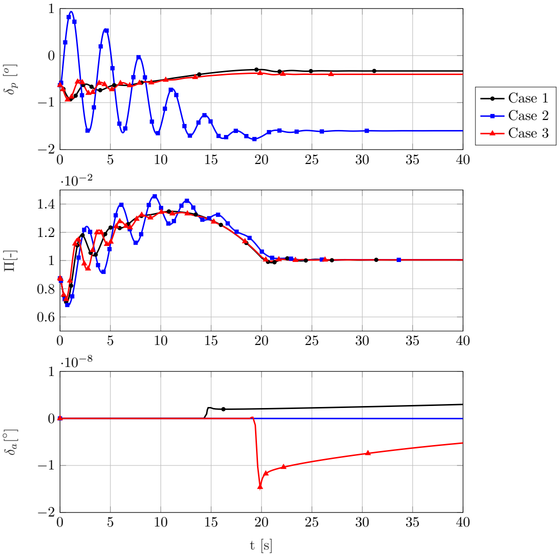




Conclusions from current implementation and studies

- Achieved: initial modeling of flight mechanics of an aircraft with morphing wings

- Including mass properties variation is a challenge $\rightarrow$ the mass matrix has to be updated constantly

- The time response solution requires a variable time step $\rightarrow$ integration scheme
- The chosen control method was able to deal with inertia matrix variation

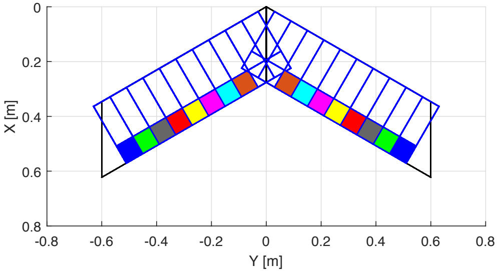
- For the presented aircraft model, the mass properties variations where very small
  - ◇ What about other models and flexible aircraft?

- Due to the variable time step, the choice of aerodynamic solution is affected (UVLM requires adaption, for example)

- The unsteady aerodynamics is necessary to a better representation of flight mechanics

Next steps

- Currently, running cases with more TE control zones
- Evaluate other aircraft models
- Extend the control project to a larger range of maneuvers
- Couple the present framework to a flexible aircraft framework



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