ÉCOLE DE L'AIR ET DE L'ESPACE

EX-MODELI
EXPLOITATION & MODÉLISATION des DYNAMIQUES NON LINÉAIRES
GdR CNRS 2134

Institut Supérieur de l'Aéronautique et de l'Espace
SUPAERO

On the use of nonlinear absorbers for passive flutter control in highly-flexible aircraft

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Outline

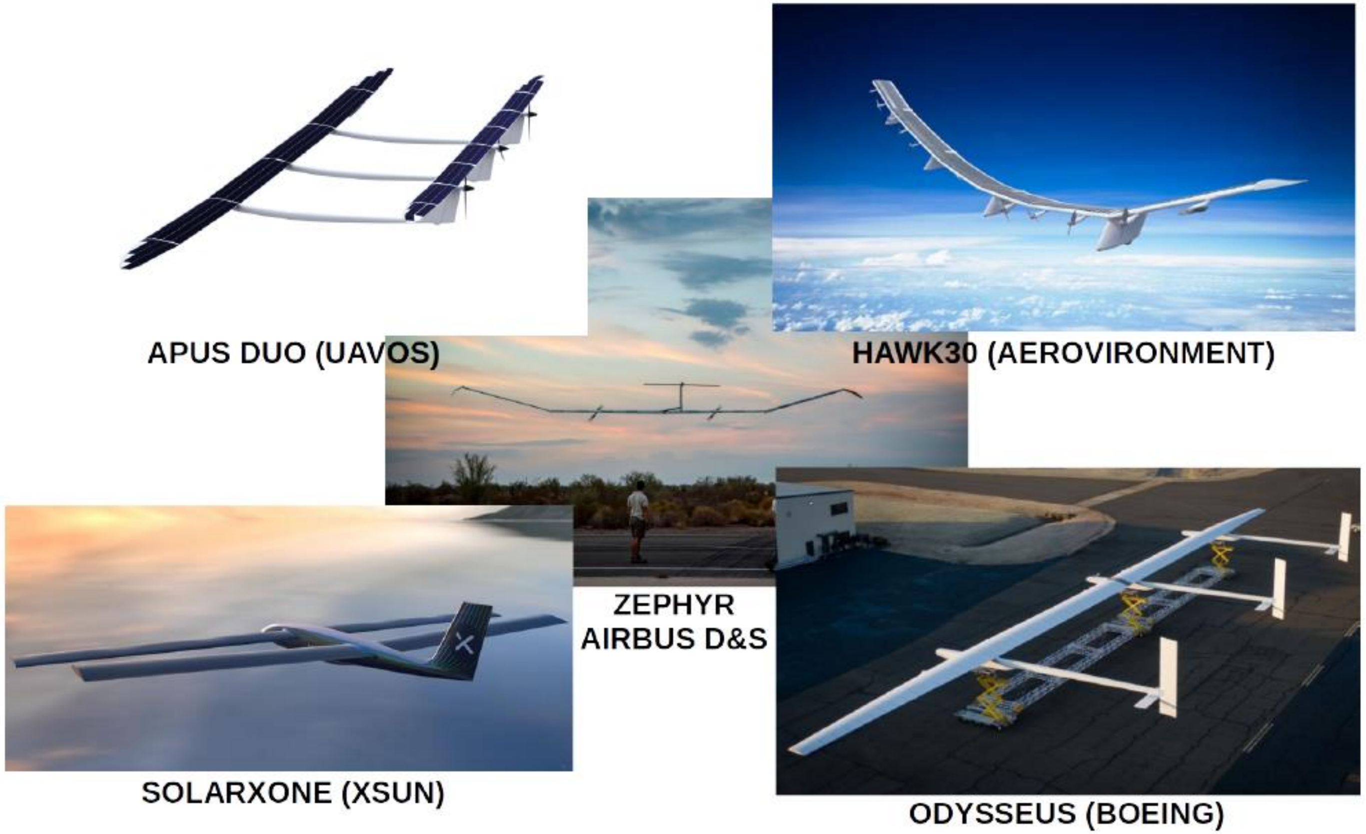
Outline

1. Introduction
    1. The HALION project
    2. Aeroelastic instability
    3. Objective
2. Theoretical framework
    1. System description
    2. NES
    3. Analysis tools
3. Results
4. Discussion / Further Work

1. The HALION Project

Objective: develop control strategies to ensure safe, reliable operation of High-Altitude Long-Endurance (HALE) UAV's.

- Operational HALE UAV's require light wings with very high aspect ratio.



2. Aeroelastic instabilities

- However, this implies:
  ➔ high flexibility
  ➔ low natural frequencies, prone to dynamic instability through aeroelastic coupling

Accident of Helios on the 26th June 2003

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Different scenarios are possible:

Flutter : coupled bending/torsion oscillations.

2. Aeroelastic instabilities

- However, this implies:
  ➔ high flexibility
  ➔ low natural frequencies, prone to dynamic instability through aeroelastic coupling

Different scenarios are possible:

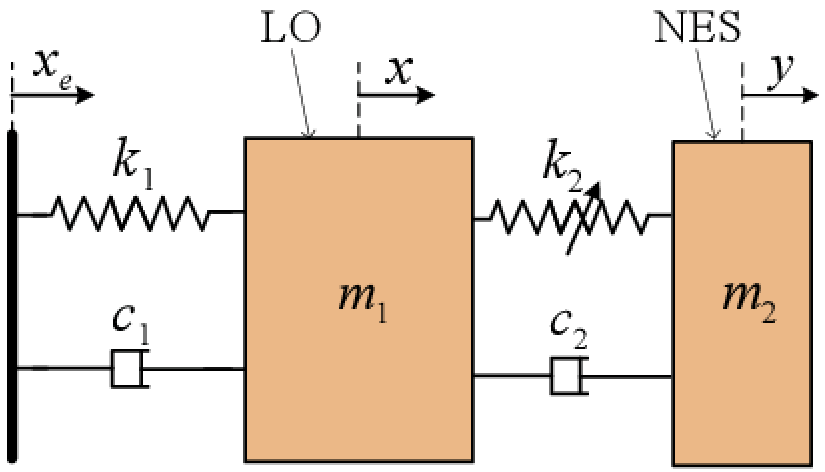
Flutter : coupled bending/torsion oscillations.

Body-freedom flutter (BFF) : coupled rigid-body/bending oscillations.

3. Vibration absorption

Geometric nonlinearity: « traditional » vibration absorption (e.g.: TMD) not well-suited.

Idea → use a **Nonlinear Energy Sink** (NES) instead.



Objective

Modeling → Control methods → Optimization → Testing

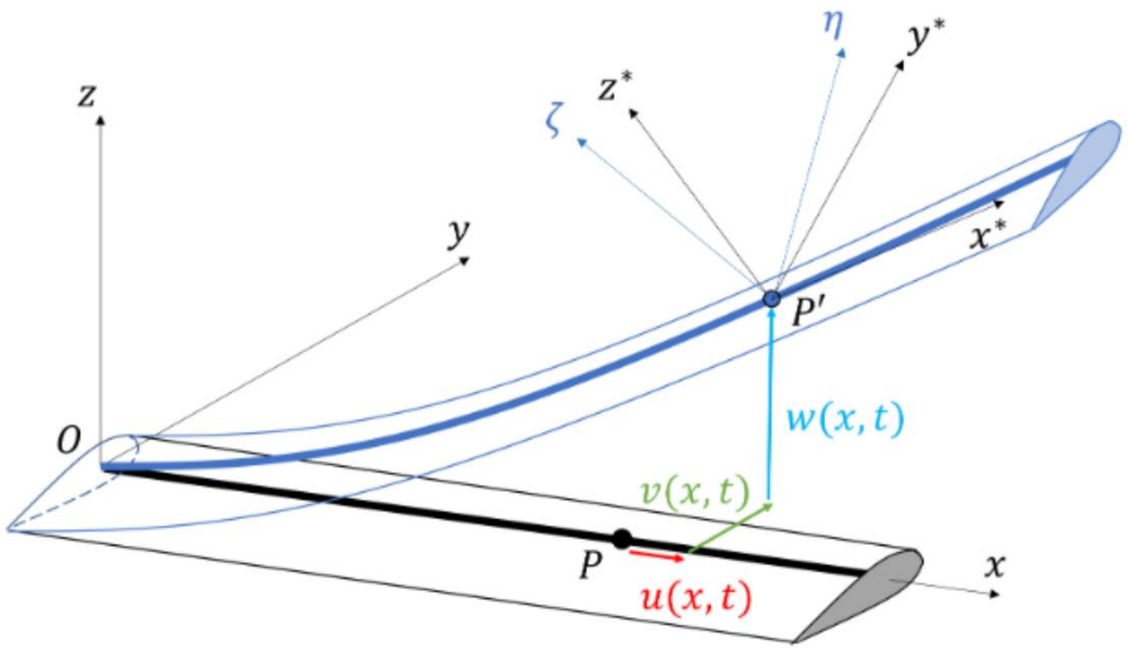
Today's talk:

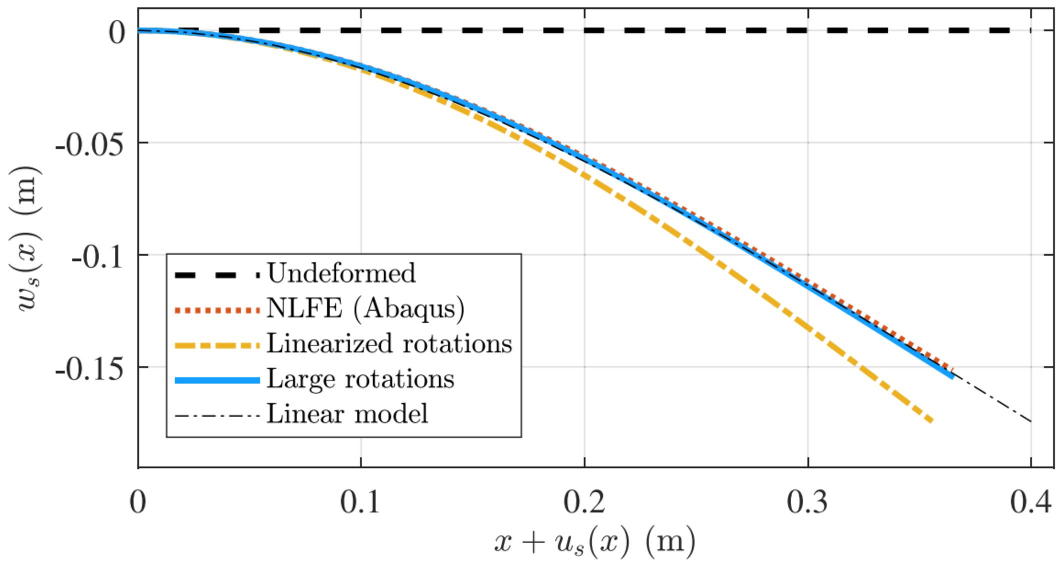
1. Overview of full UAV model (aeroelasticity + flight dynamics).
2. Describe a NES design strategy for BFF mitigation.
3. Brief proof of concept on simplified model.
4. Discuss perspectives.

Outline

1. System description

Previously*, a nonlinear aeroelastic model was developed for highly flexible wings.





$$\begin{bmatrix} u(x,t) \\ v(x,t) \\ w(x,t) \\ \phi(x,t) \end{bmatrix}$$

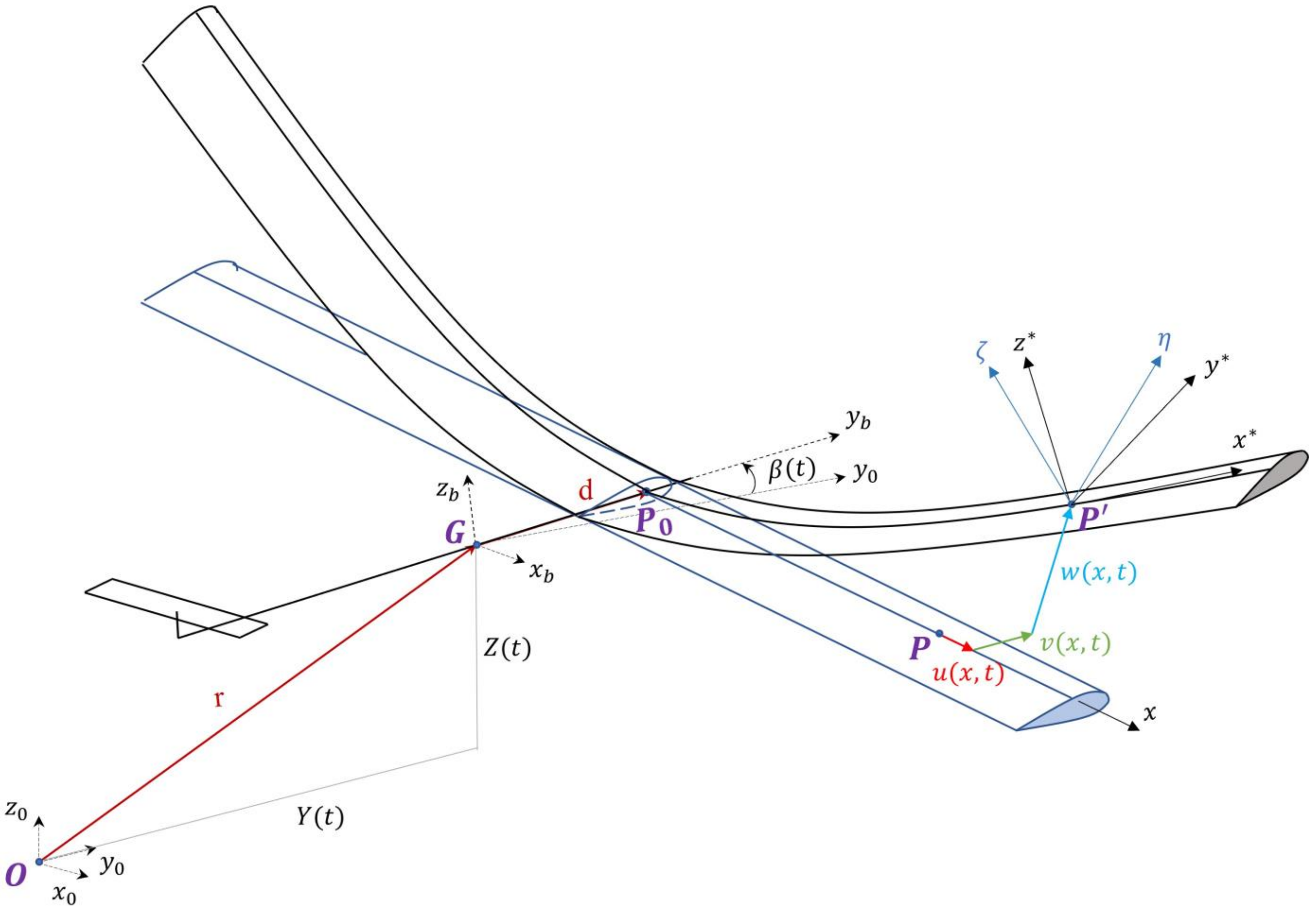
- $u(x,t)$: Axial displacement
- $v(x,t)$: Longitudinal bending
- $w(x,t)$: Transverse bending
- $\phi(x,t)$: Torsion

- Low-order.
- Medium fidelity → thoroughly validated
- Numerically implemented.

[* **R. Alcorta** et al. (2023) *On the use of frictional dampers for flutter mitigation of a highly flexible wing*. Int. J. Nonlin. Mech 156, 104515]

1. System description

- A symmetric aircraft in **longitudinal flight** with **rigid fuselage** and **flexible wings** is considered.
- Subjected to weight, flight dynamics, **quasi-steady aerodynamics**, thrust.
- Degrees of freedom: wing elastic bending + torsion, **planar** aircraft rigid-body displacements and rotation.



Longitudinal flight

$$\begin{bmatrix} u(x,t) \\ v(x,t) \\ w(x,t) \\ \phi(x,t) \\ y(t) \\ z(t) \\ \beta(t) \end{bmatrix}$$

~~$u(x,t)$~~	Axial displacement
~~$v(x,t)$~~	Longitudinal bending
$w(x,t)$	Transverse bending
$\phi(x,t)$	Torsion
$y(t)$	Horizontal displacement
$z(t)$	Vertical displacement
$\beta(t)$	Pitch

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Simplification

➢ Continuous bending and torsion projected on first <u>symmetric</u> eigenmodes ➔

$$\begin{cases} \phi(x,t) \approx \psi_\phi^1(x)\,\theta(t) \\ w(x,t) \approx \psi_w^1(x)\,h(t) \end{cases}$$

Euler-Lagrange equations ➔ Discrete system with 10-dimensional state:

$$\boldsymbol{q}(t) = \left[y(t), z(t), \beta(t), h(t), \theta(t), \dot{y}(t), \dot{z}(t), \dot{\beta}(t), \dot{h}(t), \dot{\theta}(t)\right]^t$$

$$\dot{\boldsymbol{q}} = \begin{bmatrix} \mathbf{0}_{5x5} & \boldsymbol{I}_5 \\ \mathbf{0}_{5x5} & \mathbf{0}_{5x5} \end{bmatrix} \boldsymbol{q} + \begin{bmatrix} \mathbf{0}_{5x1} \\ \boldsymbol{F}_{NL}(\boldsymbol{q}) \end{bmatrix}$$

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Euler-Lagrange equations ➔ Discrete system with 10-dimensional state,
however $\boldsymbol{F_{NL}}(\boldsymbol{q})$ is independent of $y(t), z(t)$.
➔ State reduced to ensure well-posed problem:

$$\boldsymbol{q}(t) = \left[\beta(t), h(t), \theta(t), \dot{y}(t), \dot{z}(t), \dot{\beta}(t), \dot{h}(t), \dot{\theta}(t)\right]^t$$

$$\dot{\boldsymbol{q}} = \begin{bmatrix} \boldsymbol{0}_{3x5} & \boldsymbol{I}_3 \\ \boldsymbol{0}_{5x5} & \boldsymbol{0}_{5x5} \end{bmatrix} \boldsymbol{q} + \begin{bmatrix} \boldsymbol{0}_{3x1} \\ \boldsymbol{F}_{NL}(\boldsymbol{q}) \end{bmatrix} = \boldsymbol{f}(\boldsymbol{q})$$

1. System description

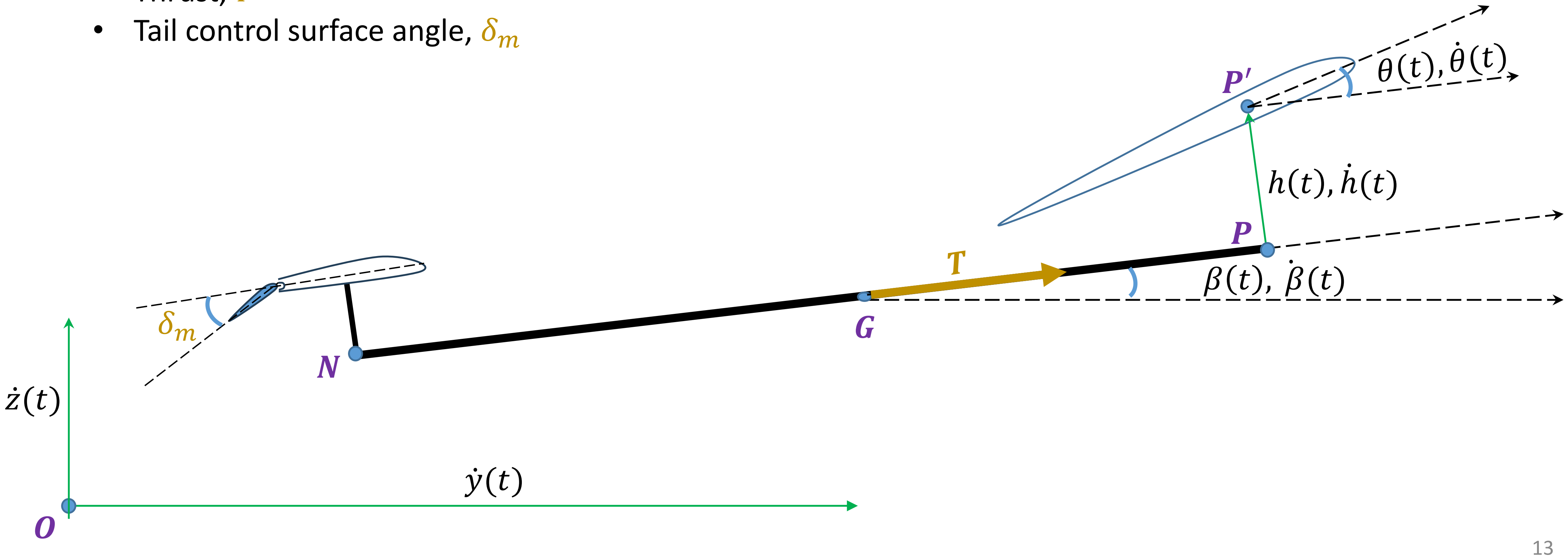
Simplification

System assimilated to 2D-airfoil in longitudinal flight.

$$\dot{\boldsymbol{q}} = \boldsymbol{f}(\boldsymbol{q})$$
$$\boldsymbol{q}(t) = \left[\beta(t), h(t), \theta(t), \dot{y}(t), \dot{z}(t), \dot{\beta}(t), \dot{h}(t), \dot{\theta}(t)\right]^t$$

Free parameters:

- Thrust, T
- Tail control surface angle, δ_m



1. System description

Trim state

For given conditions, a fixed value of δ_m yields ascending, descending, or level flight.

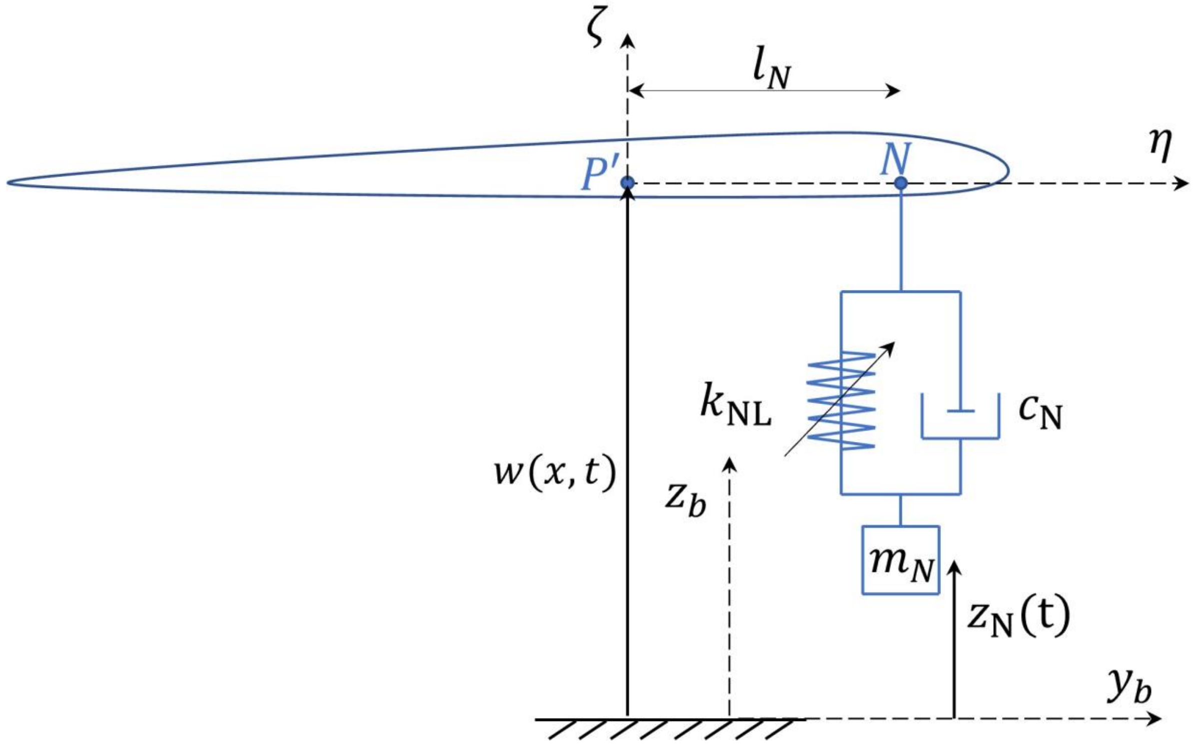
➔ Level flight: there exists δ_{m0}, such that: $\dot{z_0} = 0$

Trim state is defined by: $\dot{\boldsymbol{q}}_{\mathbf{0}} = \mathbf{0}$:

$\mathbf{f}(\boldsymbol{q}_{\mathbf{0}}, \delta_{m0})|_{\dot{z_0}=0} = \mathbf{0}_{\boldsymbol{8x1}}$ for any given T (taken as bifurcation parameter)

2. NES

Architecture intended to directly counter bending oscillations.



Absorber displacement and velocity are appended to state vector: $\mathbf{q}(t) \in \mathbb{R}^{10x1}$

2. NES

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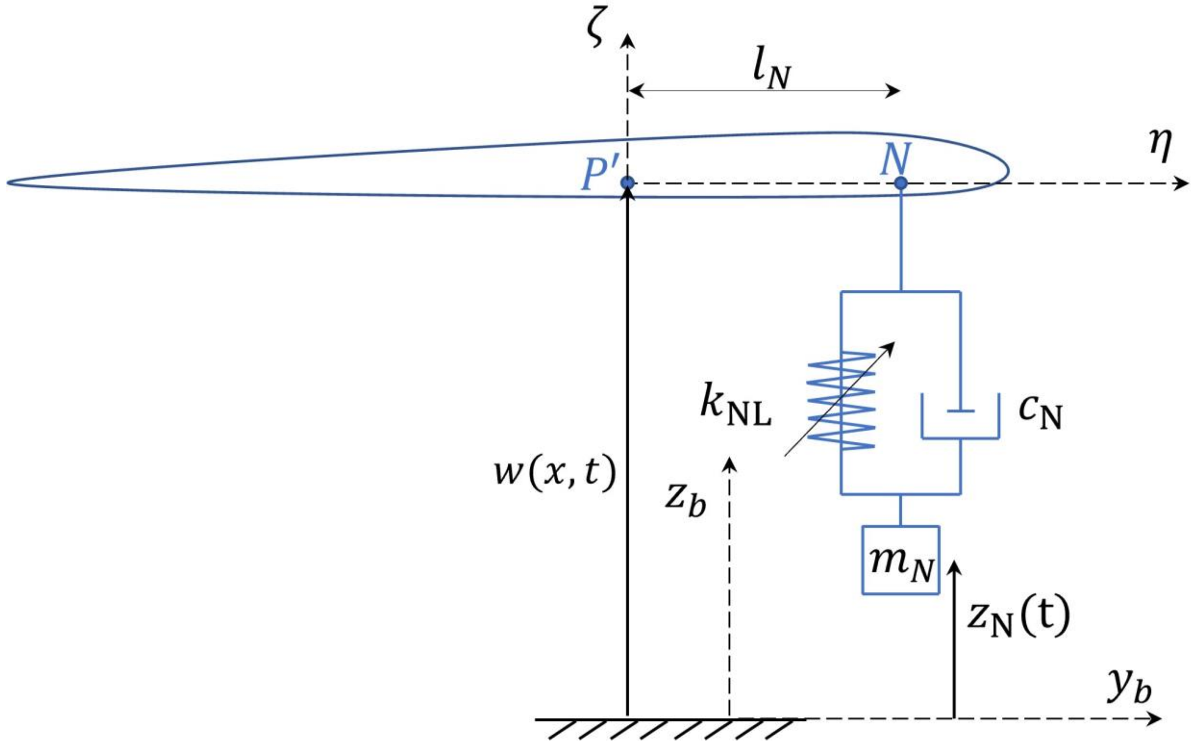


Absorber displacement and velocity are appended to state vector: $\mathbf{q}(\mathrm{t}) \in \mathbb{R}^{10x1}$

Design parameters:

- m_n : mass
- c_n : damping
- k : (residual) linear stiffness
- k_{NL} : nonlinear (cubic) stiffness
- l_n : attachment position

3. Analysis tools

The following criteria are sought in a « good » NES design:

- Maximal possible critical speed (i.e., maximum T_{cr})
- Limited limit cycle oscillation (LCO) amplitudes.
- **Supercritical** bifurcation.
- LCO in **Strongly Modulated Response (SMR) regime**.

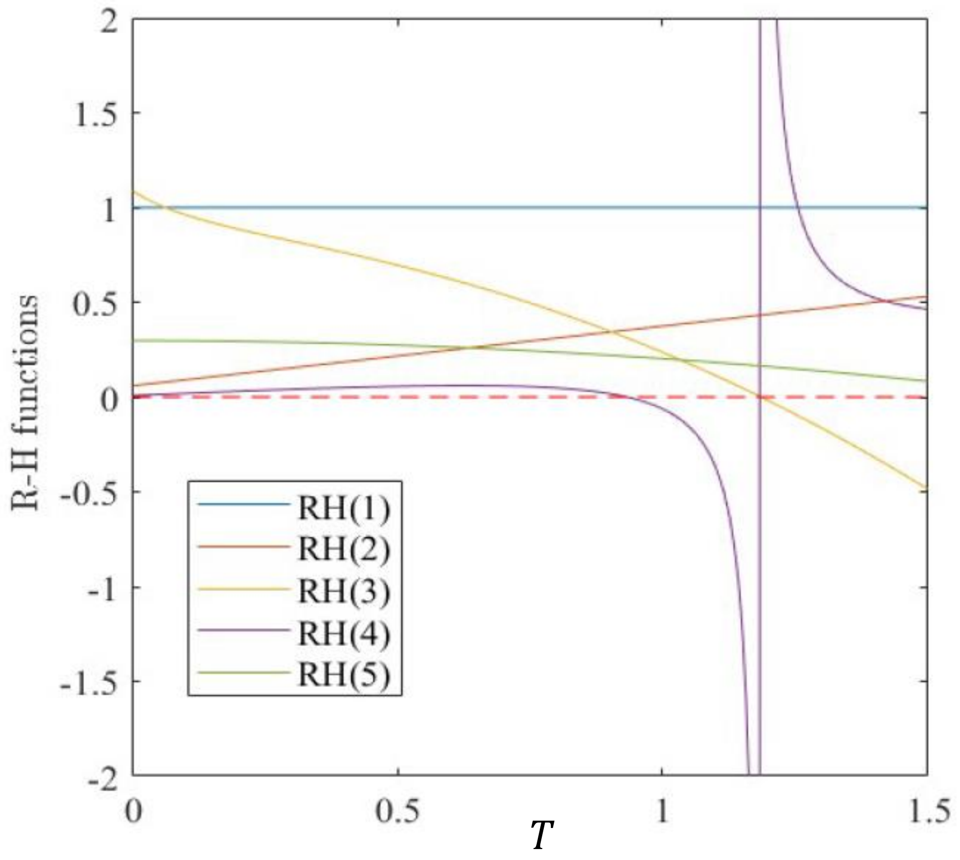
3. Analysis tools

- Maximal possible critical speed (i.e., maximum T_{cr})

Routh-Hurwitz ➔ a « critical » RH criterion RH_c yields T_{cr} as an implicit function of $(\boldsymbol{q_0}, \delta_{m0})$

Extended system to solve:

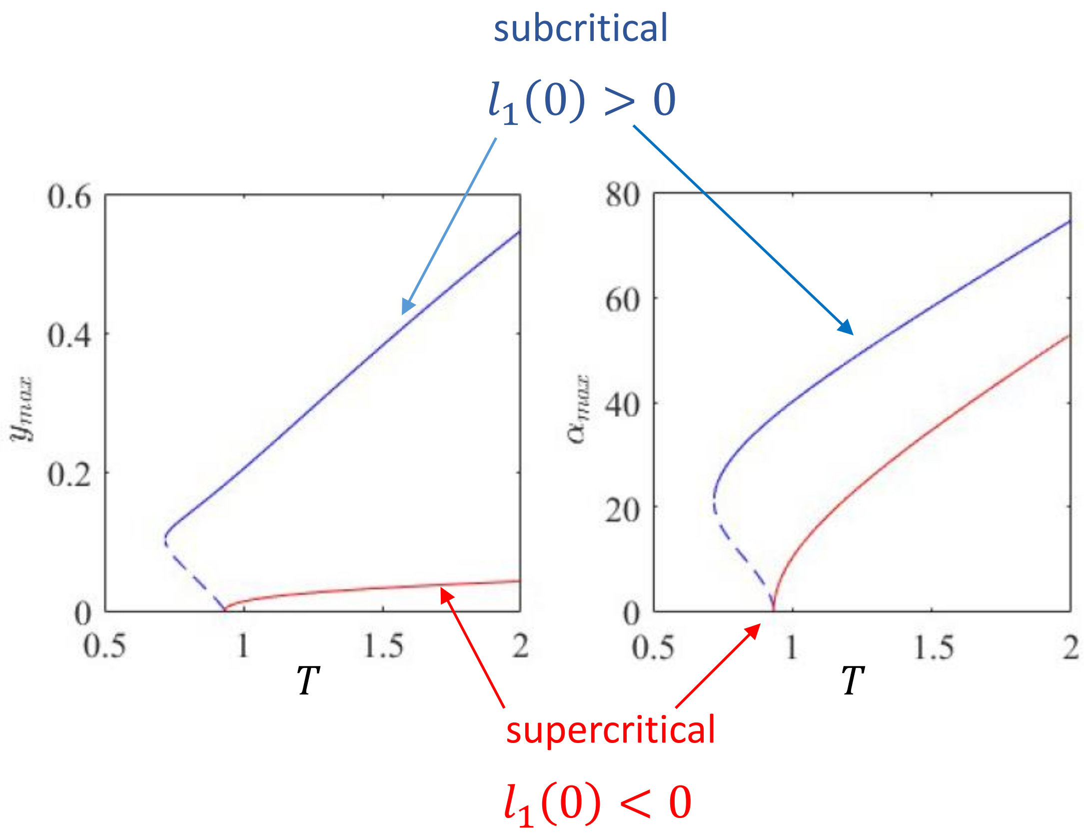
$$r(\boldsymbol{q_0}, \delta_{m0}, T_{cr}) = \begin{bmatrix} \boldsymbol{f}(\boldsymbol{q_0}, \delta_{m0}, T_{cr}) \\ RH_c(\boldsymbol{q_0}, \delta_{m0}, T_{cr}) \end{bmatrix} = \boldsymbol{0_{11x1}}$$



3. Analysis tools

- **Supercritical** bifurcation.

Criticality of a Hopf bifurcation is quantified by the *first Lyapunov coefficient* $l_1(0)$.



3. Analysis tools

- **Supercritical** bifurcation.

Criticality of a Hopf bifurcation is quantified by the *first Lyapunov coefficient* $l_1(0)$.

Knowing $(\boldsymbol{q_0}, \delta_{m0}, T_{cr})$, $l_1(0)$ is computed analytically*:

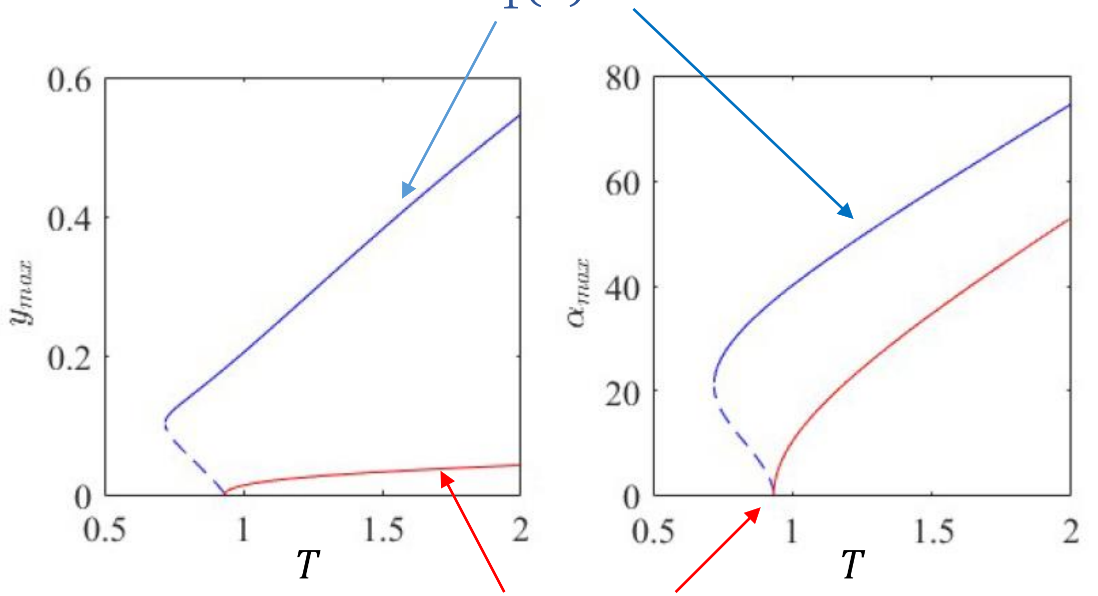
$$l_1(0) = \frac{1}{2\omega}\Re\left\{\langle \mathbf{p}, \mathbf{C}(\mathbf{q},\mathbf{q},\bar{\mathbf{q}})\rangle - 2\left\langle \mathbf{p}, \mathbf{B}(\mathbf{q}, \mathbf{J}^{-1}\mathbf{B}(\mathbf{q},\bar{\mathbf{q}}))\right\rangle + \left\langle \mathbf{p}, \mathbf{B}(\bar{\mathbf{q}}, (2i\omega\mathbf{I}-\mathbf{J})^{-1}\mathbf{B}(\mathbf{q},\mathbf{q}))\right\rangle\right\}$$

$$C_i(\mathbf{x},\mathbf{y},\mathbf{z}) = \sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n}\frac{\partial^3 f_i(\boldsymbol{\xi},T)}{\partial\xi_j\partial\xi_k\partial\xi_l}(\mathbf{v}_0,T_0)x_j y_k z_l$$

$$B_i(\mathbf{x},\mathbf{y}) = \sum_{j=1}^{n}\sum_{k=1}^{n}\frac{\partial^2 f_i(\boldsymbol{\xi},T)}{\partial\xi_j\partial\xi_k}(\mathbf{v}_0,T_0)x_j y_k$$

subcritical

$l_1(0) > 0$



supercritical

$l_1(0) < 0$

[*Y. A. Kuznetsov (2004). *Elements of Applied Bifurcation Theory,* 3rd ed. Springer New York]

3. Analysis tools

- Limited LCO amplitude

Branches of LCOs are computed using **pseudo arc-length continuation** + **harmonic balance** .

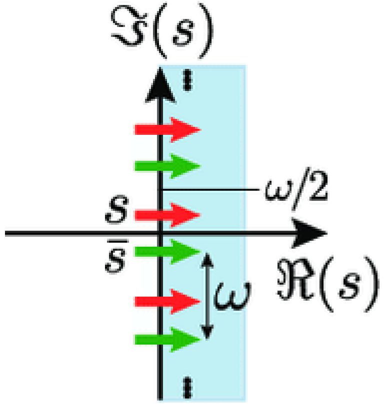
$$\begin{bmatrix} \dot{\boldsymbol{q}} \\ \dot{z}_0 \end{bmatrix} = \begin{bmatrix} \boldsymbol{f}(\boldsymbol{q}, \delta_{mp}) \\ 0 \end{bmatrix} \rightarrow \boldsymbol{R}(\boldsymbol{Q}, \delta_{mp}, \omega) = \boldsymbol{0} = \begin{bmatrix} \boldsymbol{G}(\omega)\boldsymbol{Q} + \boldsymbol{F}(\boldsymbol{Q}, \delta_{mp}) \\ \boldsymbol{p}^t\boldsymbol{Q} \\ s(\boldsymbol{Q}) \end{bmatrix}$$

Dynamic equilibrium
Level-flight trim
Phase condition

- LCO in **SMR** regime.

Quasi-periodic responses occur at an **unstable** LCO branch beginning at a **Neimark-Sacker bifurcation.**

➔ Stability evaluation through Hill's method.
➔ NS bifurcation detection*.



[* **L. Xie** et al. (2017) *Bifurcation tracking by Harmonic Balance Method for performance tuning of nonlinear dynamical systems*. Mech Syst Signal Process. 88, 445-461]

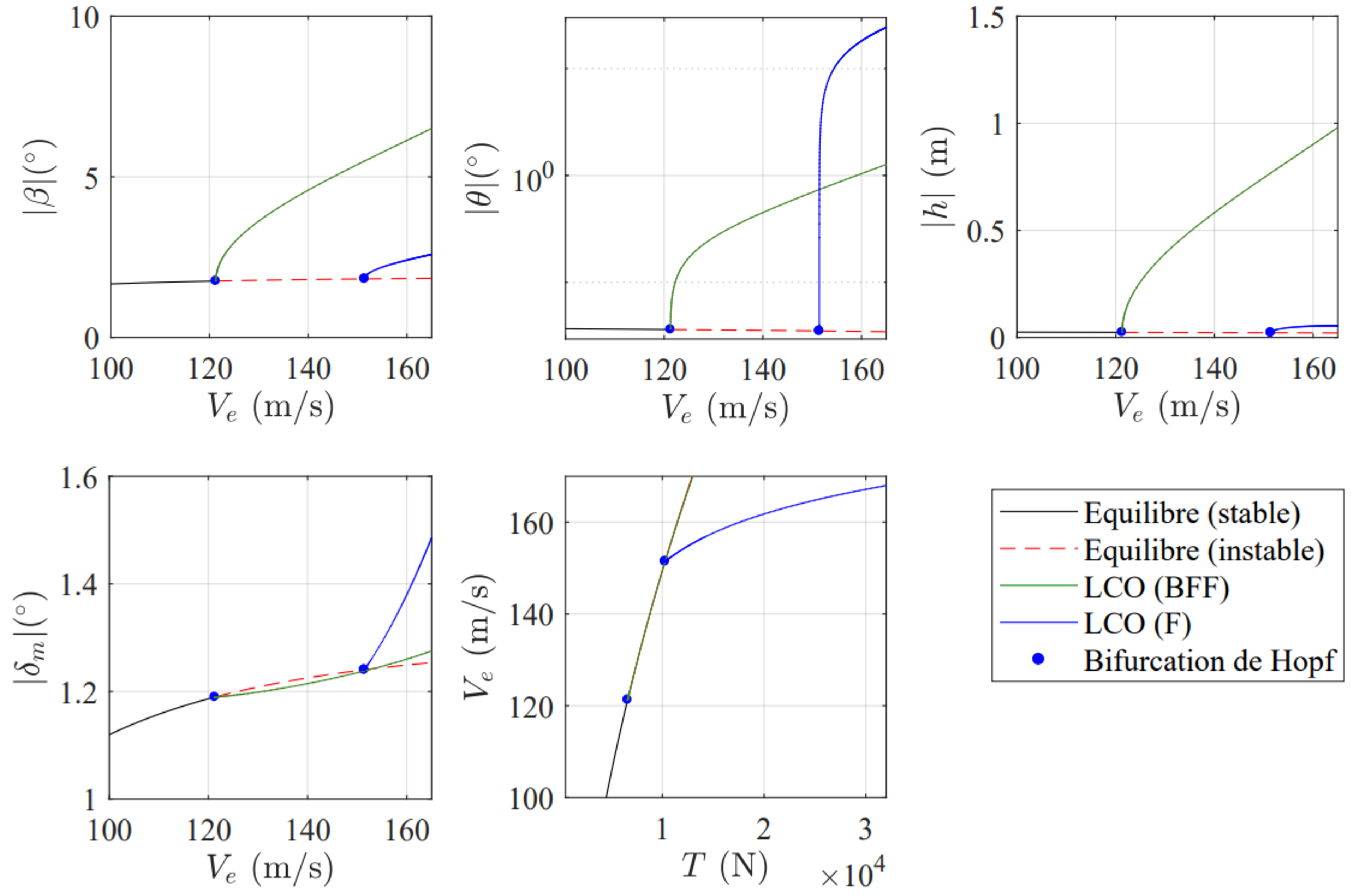
Outline

Parameter study

<u>Without NES</u>

Both Flutter and BFF encountered:

- **BFF:** high pitch (β) and bending (h) amplitudes.
- **F:** high torsion (θ) amplitudes.



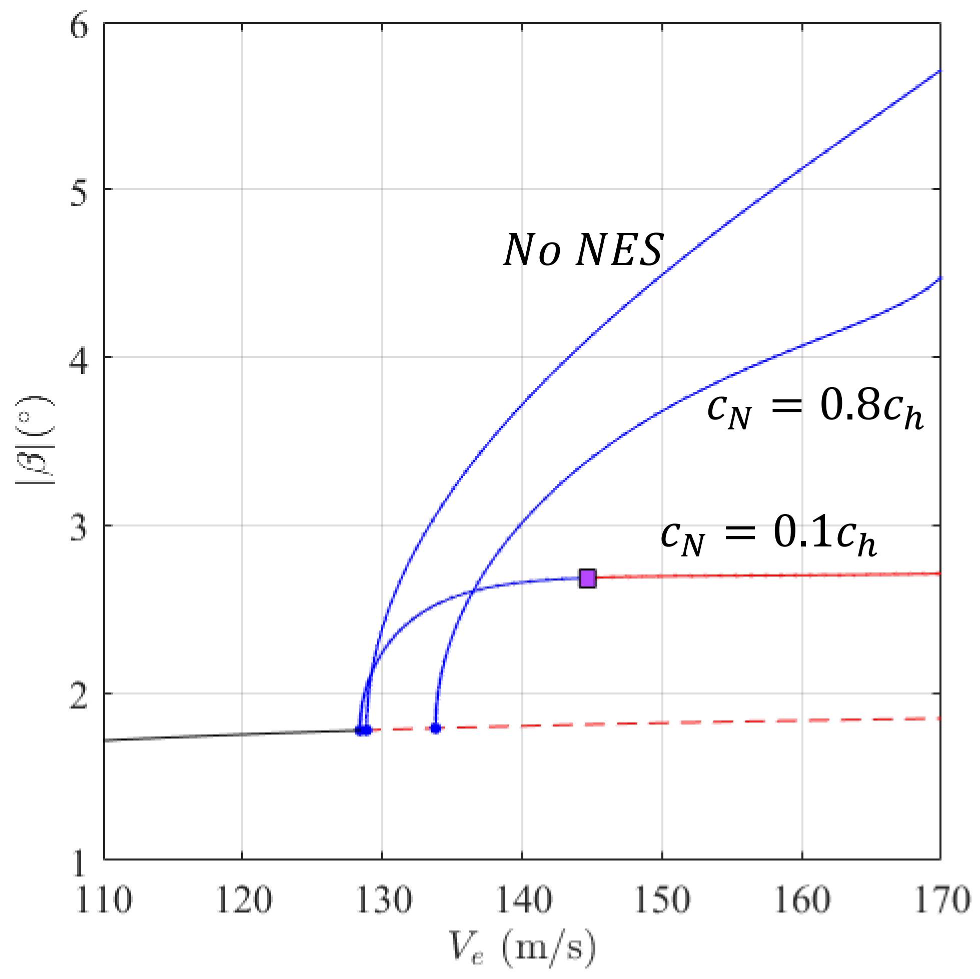
Note: $V_e \equiv \dot{y}_0$ is the aircraft horizontal velocity at trim.

Parameter study

<u>Damping c_N</u>

Heavy damping ➔ V_{cr} increases, but ineffective energy transfer, no SMR.

Light damping ➔ SMR achieved, but V_{cr} decreases with c_N



■ Neimark-Sacker bifurcation

Parameter study

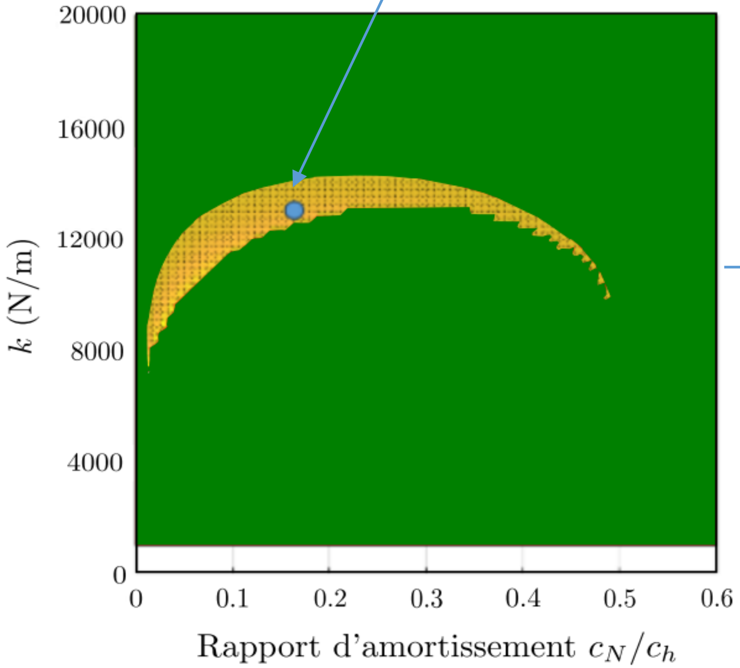
<u>Linear Stiffness</u> k_N

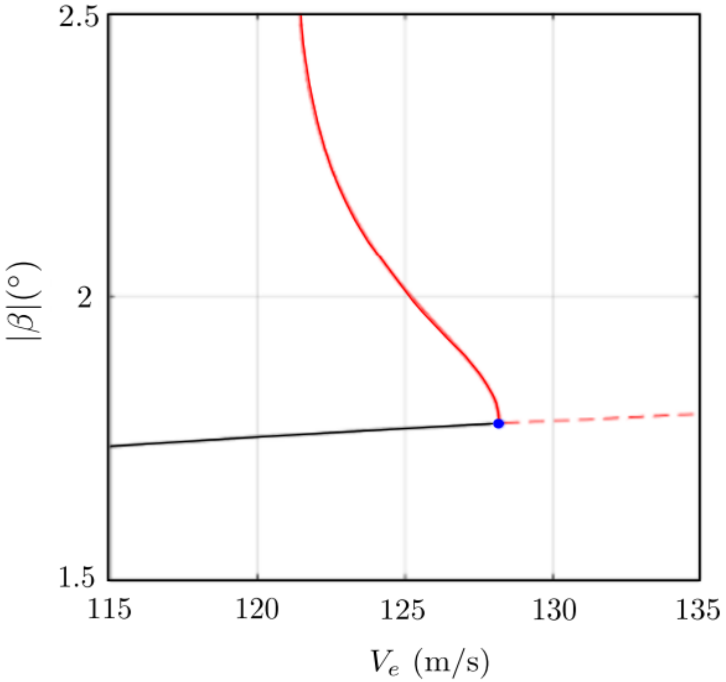
- Important effect on critical speed
  Furthermore, potentially subcritical bifurcation!

Exemple: choosing a configuration in the 'forbidden' region

Yellow:
$l_1(0) > 0$

Green:
$l_1(0) < 0$

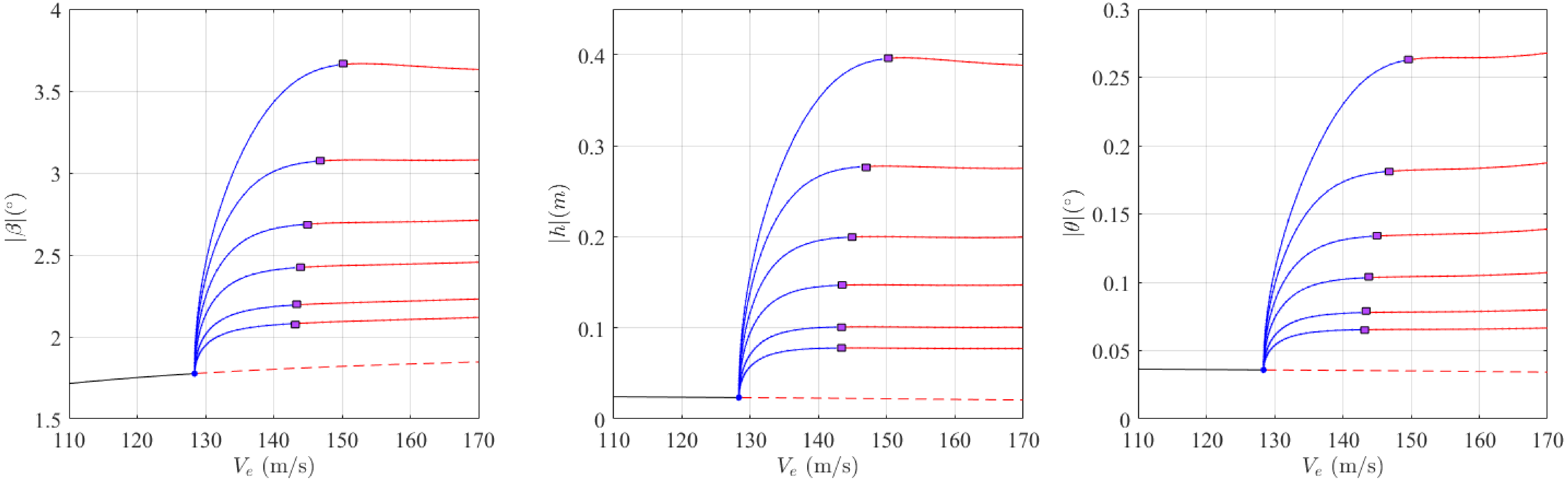




Parameter study

Nonlinear stiffness k_{NL}

No effect on V_{cr}, strong influence on activation threshold.



Parameter study

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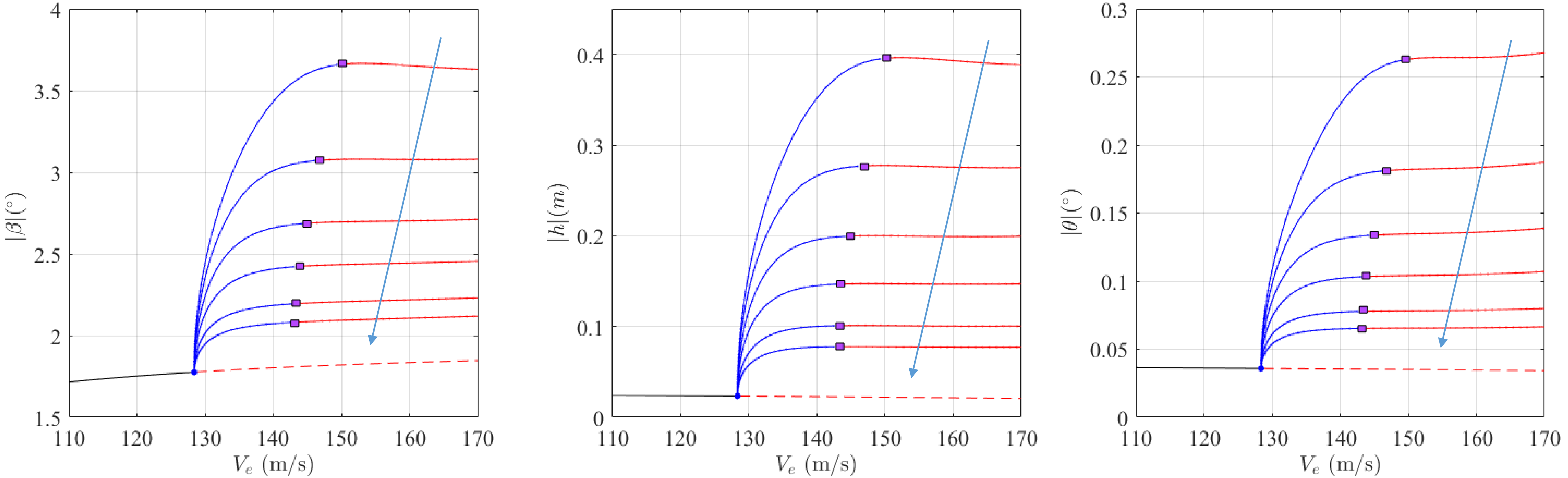


Increasing k_{nl}^{NES}

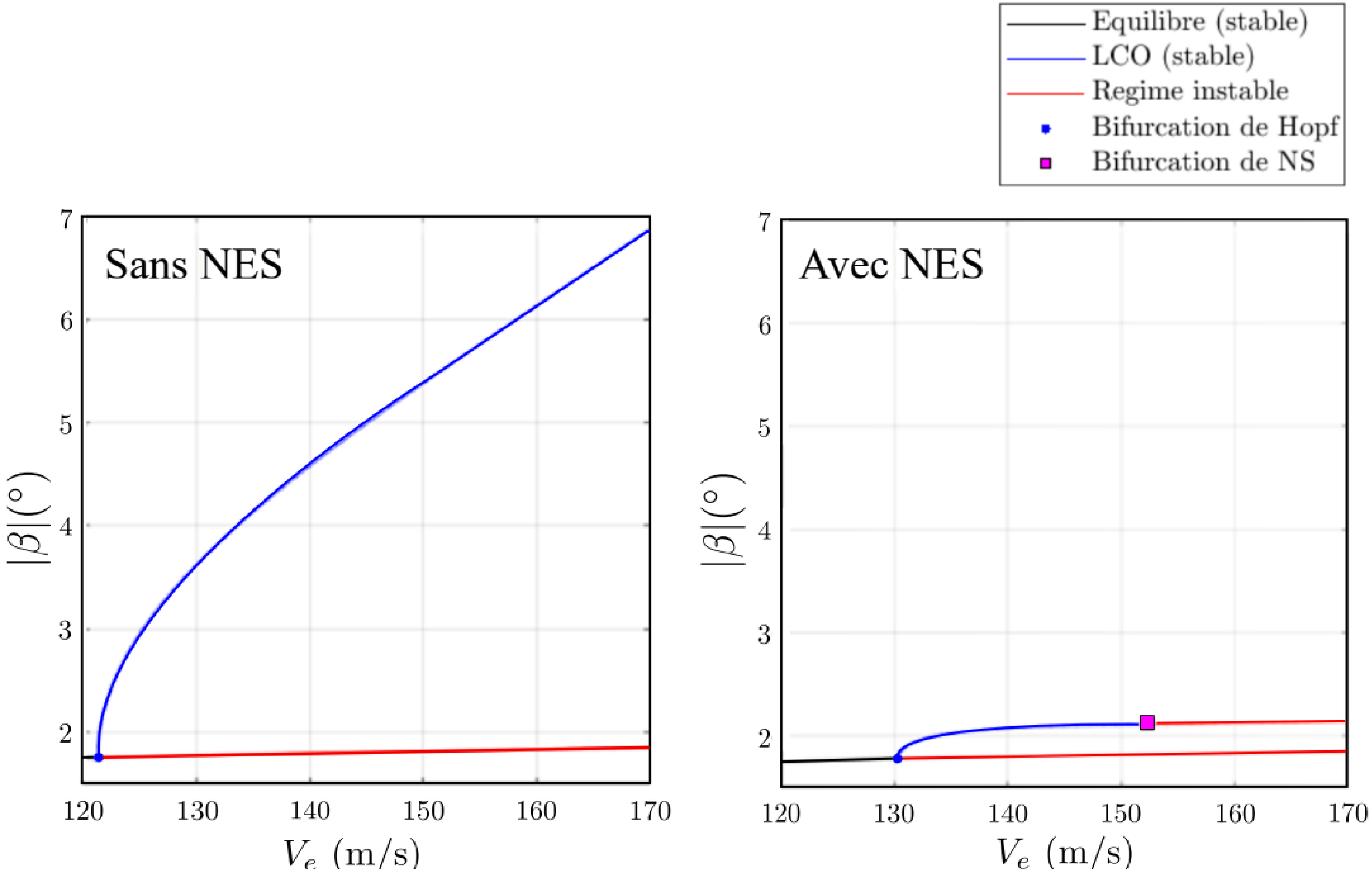
An « optimal » NES

From previous results, sets of values can be chosen so that all objectives are satisfied.

<u>Example of optimal scenario</u>
(trial-and-error) :

- Increased critical speed
- Supercritical bifurcation
- Limited LCO amplitudes
- SMR regime

☺



Discussion

- Successful BFF mitigation for a (very) simplified flexible UAV.

- Different aspects of NES performance (activation threshold, critical velocity, criticality…) are piloted by different combinations of its parameters.

- The type of instability encountered depends strongly on **aircraft geometry** and **aerodynamics model.**

- Acceptable criteria for SMR max amplitude?

Further Work

- Full, multi-mode flexible aircraft simulations.
- Design through optimization methods (e.g. genetic algorithms).
- Practical technological realization.
- In-depth study of quasi-periodic SMR regimes → quasi-periodic HBM*.
- Implement improved aerodynamics model: dynamic stall + unsteady effects.
- Experimental validation.

[* **R. Alcorta** et al. (2023) *Dynamics of a non-linear Jeffcott rotor in supercritical regime*. Int J Non Linear Mech . 148, 104272]

- Open postdoc/PhD positions at CREA! ☺

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Topics:
- Aeroelasticity
- Aerodynamics
- Nonlinear Dynamics
- Vibration Control
- Optimization
- Composite materials

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École de l'air

Kinetic energy (wing)

$$\mathcal{T}_w = m\Bigg(\frac{l}{2}\left(\dot{y}^2+\dot{z}^2+d^2\dot{\beta}^2\right)+\frac{1}{2}\int_0^l\left[\dot{u}^2+\dot{v}^2+\dot{w}^2+\dot{\beta}^2\left(v^2+w^2-2dv\right)\right]\mathrm{d}x$$
$$+\dot{\beta}\int_0^l\left[(v-d)\dot{w}-w\dot{v}\right]\mathrm{d}x+\left(\int_0^l\dot{v}\,\mathrm{d}x\right)\left[\dot{z}\sin(\beta)+\dot{y}\cos(\beta)\right]$$
$$+\left(\int_0^l\dot{w}\,\mathrm{d}x\right)\left[\dot{z}\cos(\beta)-\dot{y}\sin(\beta)\right]-\dot{\beta}\left(\int_0^l w\,\mathrm{d}x\right)\left[\dot{y}\cos(\beta)+\dot{z}\sin(\beta)\right]$$
$$+\dot{\beta}\left(\int_0^l(v-d)\,\mathrm{d}x\right)\left[\dot{z}\cos(\beta)-\dot{y}\sin(\beta)\right]\Bigg)$$
$$+\int_0^l\left[mk_t^2a_\xi+mk_\eta^2a_\eta+mk_\zeta^2a_\zeta+me_\eta b_\eta+me_\zeta b_\zeta+mk_{\eta\zeta}^2b_{\eta\zeta}\right]\mathrm{d}x.$$

$$\omega_\xi = -\dot{\hat{\phi}}-\sin(\theta)\dot{\psi}$$
$$\omega_\eta = -\cos(\hat{\phi})\dot{\theta}+\cos(\theta)\sin(\hat{\phi})\dot{\psi}$$
$$\omega_\zeta = -\sin(\hat{\phi})\dot{\theta}-\cos(\theta)\cos(\hat{\phi})\dot{\psi}$$

$$V_y = \dot{v}-w\dot{\beta}+\cos(\beta)\dot{y}+\sin(\beta)\dot{z}$$
$$V_z = \dot{w}+(v-d)\dot{\beta}+\cos(\beta)\dot{z}-\sin(\beta)\dot{y}$$

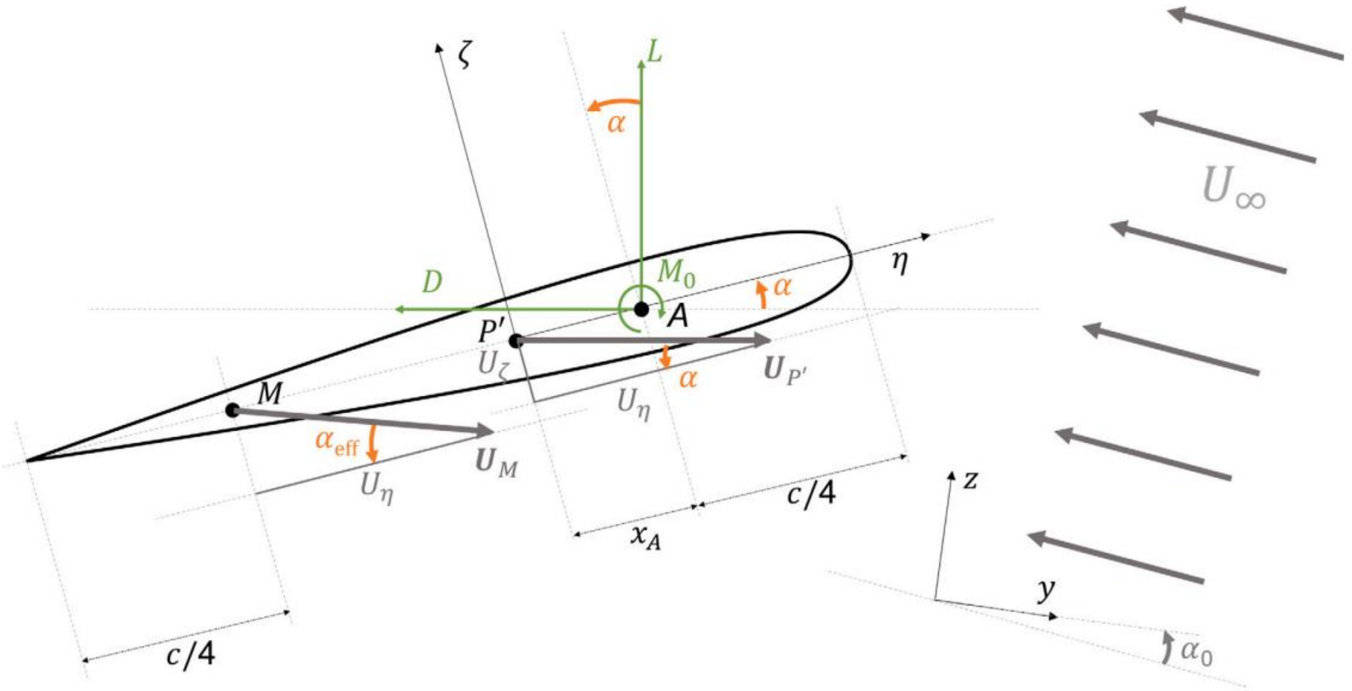
Flight dynamics-induced terms

$$a_\xi = \frac{1}{2}\omega_\xi^2+\dot{\beta}\omega_\xi(T_{22}T_{33}-T_{23}T_{32})$$
$$a_\eta = \frac{1}{2}\omega_\zeta^2+\frac{1}{2}\dot{\beta}^2(T_{32}^2+T_{33}^2)+\dot{\beta}\omega_\zeta(T_{13}T_{32}-T_{12}T_{33})$$
$$a_\zeta = \frac{1}{2}\omega_\eta^2+\frac{1}{2}\dot{\beta}^2(T_{22}^2+T_{23}^2)+\dot{\beta}\omega_\eta(T_{12}T_{23}-T_{13}T_{22})$$
$$b_\eta = (T_{22}V_z-T_{23}V_y)\dot{\beta}+(T_{31}\omega_\xi-T_{11}\omega_\zeta)\dot{u}+(T_{32}\omega_\xi-T_{12}\omega_\zeta)V_y+(T_{33}\omega_\xi-T_{13}\omega_\zeta)V_z$$
$$b_\zeta = (T_{32}V_z-T_{33}V_y)\dot{\beta}+(T_{11}\omega_\eta-T_{21}\omega_\xi)\dot{u}+(T_{12}\omega_\eta-T_{22}\omega_\xi)V_y+(T_{13}\omega_\eta-T_{23}\omega_\xi)V_z$$
$$b_{\eta\zeta} = -\omega_\eta\omega_\zeta+\dot{\beta}^2(T_{22}T_{32}+T_{23}T_{33})+\dot{\beta}(T_{12}(T_{33}\omega_\zeta-T_{23}\omega_\eta)+T_{13}(T_{22}\omega_\eta-T_{32}\omega_\zeta))$$

$$\cos(\psi) = \frac{1+u'}{\sqrt{(1+u')^2+v'^2}} \qquad \sin(\psi) = \frac{v'}{\sqrt{(1+u')^2+v'^2}}$$
$$\cos(\theta) = \sqrt{\frac{(1+u')^2+v'^2}{(1+u')^2+v'^2+w'^2}} \qquad \sin(\theta) = \frac{-w'}{\sqrt{(1+u')^2+v'^2+w'^2}}$$

$$T_b^d = \begin{bmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{bmatrix}$$
$$= \begin{bmatrix} \cos(\theta)\cos(\psi) & \cos(\theta)\sin(\psi) & -\sin(\theta) \\ \cos(\psi)\sin(\theta)\sin(\hat{\phi})-\sin(\psi)\cos(\hat{\phi}) & \sin(\psi)\sin(\theta)\sin(\hat{\phi})+\cos(\psi)\cos(\hat{\phi}) & \cos(\theta)\sin(\hat{\phi}) \\ \cos(\psi)\sin(\theta)\cos(\hat{\phi})+\sin(\psi)\sin(\hat{\phi}) & \sin(\psi)\sin(\theta)\cos(\hat{\phi})-\cos(\psi)\sin(\hat{\phi}) & \cos(\theta)\cos(\hat{\phi}) \end{bmatrix}$$

Aerodynamics model: strip theory



Locally: linear, quasi-steady aerodynamics.

Moderate to large rotations in 3D ==> nonlinear forces in global FoR.